OBSERVATOIRE DE PARIS

SYSTÈMES DE RÉFÉRENCE TEMPS-ESPACE

UMR8630 / CNRS

61 avenue de l'Observatoire, Paris
F-75014, France

Fundamental Astronomy:
New concepts and models
for high accuracy observations

Astronomie Fondamentale:
Nouveaux concepts et nouveaux modèles
pour les observations de grande exactitude

Actes publiés par

Edited by

N. CAPITAINE

JOURNÉES 2004 ☆

SYSTÈMES DE RÉFÉRENCE SPATIO - TEMPORELS

☆ PARIS, 20-22 SEPTEMBER

ISBN 2-901057-51-9

TABLE OF CONTENTS

PREFACE

The Journées 2004 “Systèmes de référence spatio-temporels”, with the sub-title “Fundamental Astronomy: New concepts and models for high accuracy observations”, have been held at Observatoire de Paris from 20 to 22 September 2004. These Journées were the sixteenth conference in this series organized in Paris each year from 1988 to 1992 and alternately, since 1994, in Paris (1996, 1998, 2000) and the following European cities: Warsaw (1995), Prague (1997), Dresden (1999), Brussels (2001), Bucharest (2002) and St. Petersburg (2003). In 2004, we have received financial supports from the Scientific Council of Paris Observatory, the French Ministry of Education and Research, the European “Descartes-nutation” project and the International Astronomical Union; we are grateful to these institutions for their support and also to the Institut d'Astrophysique de Paris for making the Henri-Mineur Amphitheatre available for the scientific sessions of this meeting.

The main goal of the Journées 2004 was to discuss the issues of the International Celestial Reference System (ICRS), including new concepts in fundamental astronomy, the associated nomenclature and the astronomical models for Earth rotation (precession, nutation, atmospheric and oceanic effects, etc.) at the highest level of accuracy consistent with the current and future precision and temporal resolution of the observations of Earth rotation.

There were 94 participants from 21 countries. The scientific programme of the meeting included 6 invited papers, 38 oral communications and 39 posters. It was composed of the five following sessions: I) Recent and future developments in the realization of the ICRS, II) Models for Earth's rotation: from Poincaré to IAU 2000, III) Nomenclature in fundamental astronomy, IV) Astronomical reference systems and V) Future of UTC: Consequences in astronomy. The sessions contained special discussions relevant to the IAU Division I Working Groups and the future organization of this division in the framework of the upcoming IAU by-laws on commissions and working groups. Moreover, 2004 being the 150 anniversary of Poincaré's birth, there was a special emphasis on Poincaré's work on Earth rotation. A kickoff meeting for the “Descartes-Nutation' Project (Chair: V. Dehant) was also included in Session II with presentations of posters summarizing the proposals selected by the Advisory Board of this project.

We had the great sadness to learn that Baron Paul Melchior passed away on 15 September 2004, just a few days before the beginning of the Journées 2004. Given the outstanding international role that P. Melchior had on geodynamics and astrometry, this represents a very significant loss for the scientific fields of this meeting. We recall that P. Melchior had still contributed to the Proceedings of the Journées 2000 with a beautiful review paper on nutation. We pay here a special homage to his immense works on rotation of the Earth, nutation and tides studies.

These Proceedings are divided into five sections corresponding to the sessions of the meeting. The Table of Contents is given on pages iii to v, the list of participants on pages vii and viii and the scientific programme on pages ix to xii. The Postface on page 277 gives the announcement for the “Journées” 2005 in Warsaw. I am very grateful to the Scientific Organizing Committee for its valuable contribution to the elaboration of the scientific programme and the chair of the Sessions and to all the authors of the papers who have sent their contribution in the required form and within the required deadline. I thank the Local Organizing Committee and its Chair, Jean Souchay, for the very efficient work before and during the meeting. I am also grateful to O. Becker for his efficient technical help for the publication.

Nicole CAPITAINE
Chair of the SOC

July 2005

List of Participants

ANDREI Alexandre Humberto, *Observatoire de Paris - IMCCE and GEA-ON/OV, Brazil*, oat1@on.br

ARIAS Elisa Felicitas, *Bureau International des Poids et Mesures, France*, farias@bipm.org

BĂDESCU Octavian, *Astronomical Institute of the Romanian Academy, Romania*, octavian@aira.astro.ro

BARACHE Christophe, *Observatoire de Paris - Syrte, France*, christophe.barache@obspm.fr

BARLIER François, *Observatoire de la Côte d'Azur - Gemini, France*, francois.barlier@obs-azur.fr

BIANCALE Richard *CNES/GRGS, France*, richard.biancale@cnes.fr

BIZOUARD Christian, *Observatoire de Paris - Syrte, France*, bizouard@danof.obspm.fr

BOLOTIN Sergei, *Main Astronomical Observatory, Ukraine*, bolotin@mao.kiev.ua

BOLOTINA Olga, *Main Astronomical Observatory, Ukraine*, olga@mao.kiev.ua

BOURDA Géraldine, *Observatoire de Paris - Syrte, France*, bourda@danof.obspm.fr

BRZEZIŃSKI Aleksander, *Space Research Centre, Polish Academy of Sciences, Poland*, alek@cbk.waw.pl

CAMARGO Julio, *Observatoire de Bordeaux - OASU/L3AB, France*, camargo@obs.u-bordeaux1.fr

CAMPBELL Bob, *Joint Institute for VLBI in Europe, Netherlands*, campbell@jive.nl

CAPITAINE Nicole, *Observatoire de Paris - Syrte, France*, capitain@danof.obspm.fr

CARLUCCI Teddy, *Observatoire de Paris - Syrte, France*, teddy.carlucci@obspm.fr

CHAO Benjamin, *NASA Goddard Space Flight Center, USA*, chao@bowie.gsfc.nasa.gov

CHAPRONT Jean, *Observatoire de Paris - Syrte, France*, jean.chapront@obspm.fr

CHARLOT Patrick, *Observatoire de Bordeaux, France*, charlot@obs.u-bordeaux1.fr

COLL Bartolome, *Observatoire de Paris - Syrte, France*, bartolome.coll@obspm.fr

COULOT David, *IGN/LAREG and OCA/Gemini, France*, david.coulot@obs-azur.fr

DAMLJANOVIC Goran, *Astronomical Observatory, Serbia and Montenegro*, gdamljanovic@aob.bg.ac.yu

DE VIRON Olivier, *Observatoire Royal de Belgique, Belgium*, o.deviron@oma.be

DÉBARBAT Suzanne, *Observatoire de Paris - Syrte, France*, debarbat@danof.obspm.fr

DEFRAIGNE Pascale, *Observatoire Royal de Belgique*, Belgium, p.defraigne@oma.be

DEHANT Véronique, *Observatoire Royal de Belgique, Belgium*, v.dehant@oma.be

EFROIMSKY Michael, *US Naval Observatory, USA*, me@usno.navy.mil

ESCAPA Alberto, *Dpto. Matemtica Aplicada. Universidad de Alicante, Spain*, alberto.escapa@ua.es

EXERTIER Pierre, *Observatoire de la Côte d'Azur - Gemini, France*, Pierre.Exertier@obs-azur.fr

FEY Alan, *U.S. Naval Observatory*, USA, afey@usno.navy.mil

FOLGUEIRA Marta, *Complutense University of Madrid, Spain*, martafl@mat.ucm.es

FRANCOU Gérard, *Observatoire de Paris - Syrte, France*, gerard.francou@obspm.fr

FUKUSHIMA Toshio, *National Astronomical Observatory of Japan, Japan*, Toshio.Fukushima@nao.ac.jp

GAMBIS Daniel, *Observatoire de Paris - Syrte, France*, daniel.gambis@obspm.fr

GAUME Ralph, *U.S. Naval Observatory, USA*, rgaume@usno.navy.mil

GONTIER Anne-Marie, *Observatoire de Paris - Syrte, France*, anne-marie.gontier@obspm.fr

GUINOT Bernard, *Observatoire de Paris - Syrte, France*, guinot.bernard@wanadoo.fr

HILTON James, *U.S. Naval Observatory, USA*, jhilton@aa.usno.navy.mil

HOHENKERK Catherine, *HM Nautical Almanac Office, RAL, UK*, cyh@nao.rl.ac.uk

HUANG Cheng-li, *Shanghai Astronomical Observatory, China*, clhuang@shao.ac.cn

KOLACZEK Barbara, *Space Research Centre Polish Academy of Sciences, Poland*, kolaczek@cbk.waw.pl

KOOT Laurence, *Observatoire Royal de Belgique, Belgium*, laurence.koot@oma.be

KOVALEVSKY Jean, *Observatoire de la Côte d'Azur - Gemini, France*, jean.kovalevsky@obs-azur.fr

KRYNSKI Jan, *Institute of Geodesy and Cartography, Poland*, krynski@igik.edu.pl

KUDRYAVTSEV Sergey, *Sternberg Astronomical Institute of Moscow State University, Russia*, ksm@sai.msu.ru

KUMAKSHEV Serguei, *Institute for Problems in Mechanics of RAS, Russia*, kumak@ipmnet.ru

KUMKOVA Irina, *Sobolev Scientific Research Astronomical Institute, Russia*, kumkova@iperas.nw.ru

LAMBERT Sebastien, *U.S. Naval Observatory, USA*, sbl@usno.navy.mil

LE PONCIN-LAFITTE Christophe, *Observatoire de Paris - Syrte, France*, leponcin@danof.obspm.fr

LOPEZ ORTI Jose Antonio, *Universid Jaume I de Castellon, Spain*, lopez@mat.uji.es

MA Chopo, *Goddard Space Flight Center, USA*, chopo.ma@nasa.gov

MARCO Francisco J., *Universidad Jaume I, Spain*, marco@mat.uji.es

MARTINEZ Mara-Jos, *Universidad Politcnica de Valencia, Spain*, mjmartin@mat.upv.es
MASAKI Yoshimitsu, *Geographical Survey Institute, Japan*, ymasaki@gsi.go.jp
MCCARTHY Dennis, *U. S. Naval Observatory, USA*, dmc@maia.usno.navy.mil
MIGNARD Francois, *Observatoire de la Côte d'Azur - Cassiopée, France*, francois.mignard@obs-nice.fr
MIOC Vasile, *Astronomical Institute of the Romanian Academy, Romania*, vmioc@aira.astro.ro
MUELLER Juergen, *Institut fuer Erdmessung (Inst. of Geodesy), Germany*, mueller@ife.uni-hannover.de
NEDELCU Alin, *Astronomical Institute of the Romanian Academy, Romania*, nedelcu@aira.astro.ro
NOTHNAGEL Axel, *Geodetic Institute of the University of Bonn, Germany*, nothnagel@uni-bonn.de
PASHKEVICH Vladimir, *Central (Pulkovo) Astronomical Observatory of RAS, Russia*, apeks@gao.spb.ru
PETIT Gérard, *Bureau International des Poids et Mesures, France*, gpetit@bipm.org
PIREAUX Sophie, *Observatoire Midi-Pyrénées, UMR DTP - GRGS, France*, sophie.pireaux@cnes.fr
POPESCU Petre, *Astronomical Institute of the Romanian Academy, Romania*, petre@aira.astro.ro
POPESCU Radu, *Astronomical Institute of the Romanian Academy, Romania*, pradu@aira.astro.ro
RAMBAUX Nicolas, *Observatoire Royal de Belgique, Belgium*, Nicolas.Rambaux@oma.be
ROGISTER Yves, *Obs. des Sciences de la Terre de Strasbourg, France*, yves.rogister@eost.u-strasbg.fr
RON Cyril, *Astronomical Institute, Czech Republic*, ron@ig.cas.cz
SAIL Morad, *Observatoire de Paris - Syrte, France*, morad.sail@obspm.fr
SALSTEIN David, *Atmospheric and Environmental Research, USA*, salstein@aer.com
SCHUH Harald, *Institute of Geodesy and Geophysics, TU Wien, Austria*, harald.schuh@tuwien.ac.at
SHUYGINA Nadia, *Institute of Applied Astronomy of RAS, Russia*, nvf@quasar.ipa.nw.ru
SIDORENKOV Nikolay, *Hydrometcentre of the Russian Federation, Russia*, sidorenkov@rhmc.mecom.ru
SOFFEL Michael, *Lohrmann Observatory, Technische Univ Dresden, Germany*, soffel@rcs.urz.tu-dresden.de
SOKOLOVA Julia, *Saint-Petersburg State University, Russia*, S0lei@yandex.ru
SOMA Mitsuru, *National Astronomical Observatory of Japan, Japan*, somamt@cc.nao.ac.jp
SOUCHAY Jean, *Observatoire de Paris - Syrte, France*, jean.souchay@obspm.fr
TEYSSANDIER Pierre, *Observatoire de Paris - Syrte, France*, pierre.teyssandier@obspm.fr
THORANDT Volkmar, *BKG, Germany*, volkmar.thorandt@bkg.bund.de
THUILLOT William, *Observatoire de Paris - IMCCE, France*, thuillot@imcce.fr
TUCKEY Philip, *Observatoire de Paris - Syrte, France*, philip.tuckey@obspm.fr
URAS Silvano, *Instituto di Radioastronomia - Cagliari, Italia*, uras@ca.astro.it
URBAN Sean, *U.S. Naval Observatory, USA*, seu@usno.navy.mil
VAN HOOLST Tim, *Observatoire Royal de Belgique, Belgium*, tim.vanhoolst@oma.be
VARGA Peter, *Geodetic and Geophysical Research. Inst., Seismological Obs., Hungary*, varga@seismology.hu
VICENTE Raimundo, *Centre for Geophysics,Lisbon University, Portugal*, rovicente@fc.ul.pt
VONDRÁK Jan, *Astronomical Institute, Czech Republic*, vondrak@ig.cas.cz
WALLACE Patrick, *CLRC/Rutherford Appleton Laboratory, UK*, ptw@star.rl.ac.uk
WOODEN William, *U.S Naval Observatory, USA*, wooden.william@usno.navy.mil
YATSKIV Yaroslav, *Main Astronomical Observatory, Ukraine*, yatskiv@mao.kiev.ua
YU Yong, *Shanghai Astronomical Observatory, Chinese Academy of Sciences, China*, yuy@shao.ac.cn
ZHANG Bo, *Shanghai Astronomical Observatory, Chinese Academy of Sciences, China*, zb@shao.ac.cn
ZHANG Hong, *Astronomy Department, Nanjing University, China*, zhangh@nju.edu.cn
ZHAROV Vladimir, *Sternberg State Astronomical Institute, Russia*, zharov@sai.msu.ru
ZHU Zi, *Department of Astronomy, Nanjing University, China*, zhuzi@nju.edu.cn

SCIENTIFIC PROGRAMME

Scientific Organizing Committee: BRZEZIŃSKI Aleksander, Poland, CAPITAINE Nicole (Chair), France, DEFRAIGNE Pascale, Belgium, FUKUSHIMA Toshio, Japan, MCCARTHY Dennis, USA, SOFFEL Michael, Germany, VONDRÁK Jan,Czech Republic, YATSKIV Yaroslav

Local Organizing Committee: BAUDOIN Pascale, BECKER Olivier, BIZOUARD Christian, BOURDA Geraldine, GONTIER Anne-Marie, NGUYEN Jean-Baptiste, SOUCHAY Jean (Chair)

Monday 20 September, 9h00-13h00

OPENING OF THE JOURNÉES 2004

Welcome from D. Egret, President of Paris Observatory
Introduction to the Journées 2004 by N. Capitaine (Chair of the SOC) and J. Souchay (Chair of the LOC)

SESSION I: RECENT AND FUTURE DEVELOPMENTS IN THE REALIZATION OF THE ICRS, Chair: J. Vondrák

Ma C.: *Steps towards the next radio realization of the ICRS*
Petit G., McCarthy D.D.: *Updating the IERS Conventions to improve reference frames*
Bolotin S.: *Extension of the celestial reference frame*
Souchay J., Gaume R.: *Activities of the ICRS Product Center of the IERS*
Arias E.F., Bouquillon S.: *Maintenance of the ICRS: stability of the axes by different sets of selected radio sources*
Charlot P., Fey, A. L., Jacobs, C. S., Ma, C., Sovers, O. J., Baudry, A.: *Densification of the International Celestial Reference Frame: Results of EVN + Observations*
Yatskiv Y., Bolotin S., Kuryanova A.: *"GAOUA" realizations of the Celestial reference frame*

Discussion 1 on the tasks that were previously part of the ICRS working group of the IAU
Chair: T. Fukushima

Monday 20 September, 14h15-18h30

SESSION II: MODELS FOR EARTH'S ROTATION: FROM POINCARÉ TO IAU 2000
Chair: A. Brzeziński

Dehant V., de Viron O., Van Hoolst T.: *Poincaré fluid in the Earth core (invited)*
Capitaine N.: *Improvements in the precession-nutation models*
Hilton J.: *Report on the IAU WG Precession and the ecliptic (invited) + Discussion*

Short oral presentations of posters
Chair: N. Capitaine

"Kickoff" meeting for the Project "Descartes-Nutation"
Chair: V. Dehant

POSTER SESSION 1

Tuesday 21 September, 9h00-13h00

SESSION II: CONTINUATION
Chair: Ya. Yatskiv, V. Dehant

Salstein D., Chao, B., Ponte, R., Chen, J., Zhou, Y.: *Plans for high accuracy computations of Earth rotation/polar motion excitations (invited)*
Brzeziński A.: *Non-tidal oceanic excitation of diurnal and semidiurnal polar motion estimated from a barotropic ocean model*
Escapa A, Getino J, Ferrándiz J.M.: *On the effect of the redistribution tidal potential on the rotation of the non-rigid Earth: discrepancies and clarifications*
Efroimsky. M.: *A possible reason for the discrepancy between the Kinoshita-Souchay theory and the other theories of rigid-Earth rotation*
Pashkevich V.V., Eroshkin G.I.: *Spectral analysis of the numerical theory of the rigid Earth rotation*
Huang C-L.: *On the coupling between geomagnetic field and Earth nutation in numerical integration approach*
Chao B. F., Cox C. M.: *Length-of-Day and Polar Motion Excitation "Observed" by Time-Variable Gravity*
McCarthy D.D.: *The Free Core Nutation*
Zharov V.: *Model of the Free Core Nutation for improvement of the Earth nutation theory*
Ron C., Capitaine N., Vondrák J.: *A precession study based on the astrometric series and the combined astrometric catalogue EOC-2*
Shuygina N.: *UT1 variations obtained from the combination of LLR, SLR and VLBI data at the observation level*
Varga P., Gambis D., Bizouard C., Bus Z.: *What can we say on the relationship between the global sismicity and the rotation vector of the Earth?*
Mueller J.: *Earth Rotation and Global Dynamic Processes - Joint Research Activities in Germany*

Tuesday 21 September, 14h00 - 18h30

POSTER SESSION 2

SESSION III: NOMENCLATURE IN FUNDAMENTAL ASTRONOMY
Chair: D.D. McCarthy

Capitaine N.: *Report of the NFA Working Group*
de Viron O., Dehant V.: *3D representation of the Non-Rotating Origin*
Hohenkerk C.: *Implementation of the new nomenclature in the Astronomical Almanac*
Wallace P.: *Post-IAU-2000 nomenclature for the telescope pointing application*
Soffel M., Klioner S.: *The ICRS, BCRS and GCRS: astronomical reference-systems and frames in the framework of Relativity, problems of nomenclature*

Discussion 2 on Nomenclature in fundamental astronomy
Chair: N. Capitaine

Wednesday 22 September, 9h00-13h00

SESSION IV: ASTRONOMICAL REFERENCE SYSTEMS
Chair: M. Soffel

Soffel M., Klioner S.: *Relativity in the problems of astronomical reference systems and Earth rotation: status and prospects (invited)*
Mignard F.: *Inertial frame with Gaia : selection of sources and limitations (invited)*
Leponcin-Lafitte C., Teyssandier P.: *Influence of the multipole moments of a giant planet on the propagation of light: application to Gaia*
Vondrák J., Ron C.: *Combined astrometric catalogue EOC-2 - an improved reference frame for long-term Earth rotation studies*
Chapront J., Francou G.: *The lunar libration, Comparison between various models*
Fukushima T.: *Efficient Orbit Integration by Integrating Orbital Longitude*

SESSION V: FUTURE OF UTC: CONSEQUENCES IN ASTRONOMY
Chair: T. Fukushima

McCarthy D.D.: Future of UTC: Consequences in astronomy: *Report on the UTC Working Group and the latest developments (invited)*
Arias E.F., Guinot, B.: *UTC: Historical background and perspectives*
Gambis D., Bizouard, C., Francou, G., Carlucci T., Sail M.: *Prediction of UT1 and length of day variations*
Wooden W.H., Johnson, T. J., Kammeyer, P. C., Carter, M. S., Myers, A. E.: *Determination and Prediction of UT1 at the IERS rapid service/prediction center*

Discussion
Chair: D.D. McCarthy

Closing of the Journées 2004 and Announcement of the Journées 2005
N. Capitaine, A. Brzeziński

LIST OF POSTERS

SESSION I

Bucciarelli B., Lattanzi M.G., Massone G., Poma A., Tang Z., Uras S.: *Realisation of faint Reference catalogues around ICRF radio sources from photographic observations*
Camargo J.I.B., Daigne G., Ducourant C., Charlot P.: *Precise near-IR astrometry and photometry of southern ICRF quasars*
Fey A.L.: *Improving the ICRF in the southern hemisphere*
Sokolova J.R.: *Influence of the early VLBI observations on the ICRF stability*

SESSION II

Akulenko L.D., Kumakshev S.A., Markov YU.G.: *The model and the prediction of the Earth's pole motion*
Bădescu O., Popescu P., Popescu P.: *A method for accuracy and efficiency increase of geodetic-astronomical determination of the vertical's deviation*
Bolotina O.V.: *Implementation of new models for Earth rotation in data analysis at the Ukrainian Centre of the determination of the EOP*

Bourda G.: *Earth rotation and variations of the gravity field, in the framework of the "Descartes-Nutation" Project*

Coulot D., Berio P., Biancale R. & al.: *Combination of space geodesy techniques for monitoring the kinematics of the Earth*

Folgueira M., Capitaine N., Souchay J.: *The equations of the Earth's rotation in the framework of the IAU 2000 resolutions*

Koot L., de Viron O., Dehant V.: *Atmospheric angular momentum time series: Characterization of their internal noise and construction of a combined series*

Kosek W., Kalarus M., Johnson T.J., Wooden W.H., McCarthy D.D., Popiński W.: *A comparison of UT1-UTC forecasts by different prediction techniques*

Kudryavtsev S.M.: *KSM03 harmonic development of the Earth TGP in the ITRS*

Lambert S.: *Non-linear terms in the non-rigid Earth's nutation*

Nastula J., Kolaczek B.: *Studies of regional atmospheric pressure excitation function of polar motion*

Nastula J., Gambis D.:*Assessment of quality of polar motion series derived from space-geodetic techniques*

Rambaux N., Van Hoolst T., Dehant V.: *Earth librations due to core-mantle couplings*

Rogister Y., Rochester M.G.: *Normal mode theory of a rotating Earth model using a Lagrangian perturbation of a spherical model of reference*

Sidorenkov N.: *The decade fluctuations of the Earth rotation velocity and of the secular polar motion*

Stavinschi M., Gambis D., Maris G., Mioc V., Oncica A.: *Common periodicities in the solar activity and the Earth rotation*

Stavinschi M., Mioc V.: *Astronomical researches in Poincaré's and Romanian works*

Zhang B., Li J.L., Wang G.L., Zhao M.: *A discussion on the solution of high frequency variations of ERP*

SESSION IV

Andrei A.H., Fienga A., Assafin M., Penna J.L., Schulteis M., da Silva Neto D.N., Vieira Martins R.: *Véron & Véron based extragalactic reference frame*

Damljanović G., Vondrák J.: *Improved proper motions in declination of some Hipparcos stars derived from observations of latitude*

Kumkova I.I., Stepashkin M.V.: *Estimation of relativistic contributions in the GCRS-ITRS transformation*

López J.A., Martinez M.J., Marco F.J.: *A new method for dynamical analysis of orientation errors from non regular samples*

Marco F.J., Martinez M.J., López J.A.: *Infinitesimal variations in the Reference and their implications on the minor planets elements and masses*

Martinez M.J., Marco F.J., López J.A.: *Two independent estimations for the epsilon$_z$ values in the Hipparcos-FK5 catalogues*

Pireaux C.: *Relativistic modeling of the orbit of geodetic satellites equipped with accelerometers*

Popescu R., Nedelcu A.: *Astrometrical positions of NEO inferred from CCD observations at Bucharest*

Yu Y., Tang Z.H., Li J.L., Zhao M.: *Application of block adjustment of overlapping CCD frames*

Zhu Z., Zhang H: *Galactic warping motion from Hipparcos proper motions and radial velocities*

SESSION V

Soma M., Tanikawa K.: *TT-UT obtained from ancient solar eclipses observed at plural sites*

Session I

RECENT AND FUTURE DEVELOPMENTS

IN THE REALIZATION OF THE ICRS

DÉVELOPPEMENTS RÉCENTS ET FUTURS

DANS LA RÉALISATION DE L'ICRS

STEPS TOWARDS THE NEXT RADIO REALIZATION OF THE ICRS

C. MA
Goddard Space Flight Center
Greenbelt, MD 20771, USA
e-mail: Chopo.Ma@nasa.gov

ABSTRACT. The VLBI data and analysis leading to the ICRF were completed in 1995. Since then there have been considerable refinements in both areas. A regular monitoring program has begun to increase the data set for identified stable and potentially stable sources. Several steps need to be taken in the next few years to generate the next radio realization of the ICRS. These include: a) enhancement of the data set for possible defining sources, b) comparison of source catalogues from VLBI analysis centers using a variety of approaches and software to identify systematic errors, c) time series analysis of past and as-available data to identify the set of defining sources for the next realization, d) discussion and decision on the final analysis configuration, particularly for the data to be included, troposphere modeling, treatment of unstable sources, and whether a combination of normal matrices of individual solutions is better than a single selected solution.

1. ENHANCEMENT OF THE DATA SET FOR POSSIBLE DEFINING SOURCES

A long-standing difficulty of the radio realization of the celestial reference system has been the paucity of VLBI (Very Long Baseline Interferometry) observations of astrometric sources, including the ICRF (International Celestial Reference Frame) defining sources. Figure 1 shows the distribution of observations for the ICRF defining sources and for the geodetic sources used in sessions to monitor Earth orientation parameters (EOP) and the terrestrial reference frame (TRF). The dearth of astrometric observations available in 1995 resulted in setting the criteria for ICRF defining sources at a low threshold in order to have a reasonable geometric distribution over the sky, especially in the southern hemisphere where observations were particularly scarce. Two recent developments should remedy or at least ameliorate this problem. The first is the systematic analysis of source position time series by Feissel-Vernier (2003). Her published results and subsequent analysis identified sources that are demonstrably or potentially stable in position, a prerequisite for an ICRF defining source. Her analysis showed that not all ICRF defining sources, which were selected using data from 1979-1995.6, are stable in the time interval 1990-2002 and that some ICRF defining sources have too few observations for useful time series analysis. See Figure 2. The second development is a systematic program of celestial reference frame (CRF) monitoring by the IVS (International VLBI Service for Geodesy and Astrometry) utilizing the on-going geodetic sessions. The goal is to observe each target source in at least one session every six months. The 307 target sources (see Figure 3) are drawn from four categories: (1) stable sources identified in Feissel-Vernier (2003), (2) stable sources found in subsequent analysis of position time series where the CRF was set by the stable sources of category 1 (Feissel-Vernier, private communication), (3) potentially stable sources from sources with insufficient data for proper time series analysis, and (4) ICRF defining sources. The last category overlaps the first three. In Figure 3 "Other ICRF defining" includes both unstable and insufficiently observed ICRF defining sources. "Stable other" and "Potentially stable other" are candidates for new defining sources in the next radio realization. Stable sources, both ICRF defining and other, that are also geodetic sources are not included in the CRF monitoring list. Since the IVS EOP/TRF sessions use predominantly northern hemisphere networks, the IVS continues to devote its CRF sessions (∼10 per year) to southern hemisphere sources. The southern hemisphere CRF networks are smaller than the EOP/TRF networks, so the number of observations per source per session is less for southern astrometric sources than for northern sources. Figure 4 shows the development of the CRF monitoring program, which began in February 2004. The "0 sessions" line goes to zero at the right, which indicates that all CRF monitoring sources will have been observed in one or more sessions in the previous 12 months by the end of 2004. Over the next few years the CRF monitoring program and the CRF sessions should provide sufficient data to select a new set of defining sources that is larger and better distributed than the current ICRF defining sources as well as augmenting the data set of the current ICRF defining sources.

2. COMPARISON OF SOURCE CATALOGUES

In 1995 there were only two VLBI analysis systems at three analysis centers used for the ICRF studies. Nonetheless, comparisons of software, models, and test results were important in deciding the actual uncertainty of the ICRF catalogue. At present there are ten analysis centers using six different software packages that have generated catalogues with all or a large part of the VLBI data set. See Table 1. This abundance of catalogues will permit a more robust analysis of differences for the next radio realization of the ICRS (International Celestial Reference System).

Australia	Geoscience Australia
China	Shanghai Astronomical Observatory (SHAO)
Germany	Bundesamt für Kartographie und Geodäsie (BKG)
	Deutsches Geodätisches Forschungsinstitut (DGFI)
Italy	Matera Space Geodesy Center (ASI/CGS)
Russia	Institute of Applied Astronomy (IAA)
Ukraine	Main Astronomical Observatory (MAO)
USA	Goddard Space Flight Center (GSFC)
	Jet Propulsion Laboratory (JPL)
	U.S. Naval Observatory (USNO)

Table 1: VLBI catalogues

3. ANALYSIS OF POSITION TIME SERIES

Systematic time series analysis is an essential tool in selecting the next set of defining sources, which all should possess exemplary position stability. The time series can also show the changes in position related to evolution of source structure. While sources with detectable structure are generally undesirable as defining sources, some sources with unchanging structure may be useful if time series analysis confirms position stability. The comparison of time series from different analyses (varying software, analysis configuration, etc.) will contribute to the identification and quantification of systematic analysis errors. Likewise the consistency of position rates derived from time series with apparent motion parameters estimated globally will provide an indication of the reliability of the solutions.

4. ANALYSIS CONFIGURATION FOR THE NEXT ICRS REALIZATION

The 1995 ICRF analysis was the state of the art at that time. The analyses for ICRF-Ext.1 and ICRF-Ext.2 (Fey et al. 2004) used all the same data as the ICRF (Ma et al. 1998) augmented by subsequent observations and also used essentially the same analysis configuration. In particular, the defining sources were used at their published ICRF positions. Some small systematic errors are known to be present in the ICRF and its extensions. No substantial changes were made in the modeling or data although significant improvement is now possible. There is evidence that data before 1990 is inferior in quality (Gontier et al. 2001). Improvements in modeling the troposphere and station motions should now permit the simultaneous estimation of CRF, TRF and EOP without degrading the CRF results. A better and larger set of defining sources will significantly decrease the uncertainties of the CRF axes. It should be possible to accommodate source position instabilities more smoothly than by treating unstable sources as arc parameters, perhaps through apparent motion parameters or linear position changes over shorter time intervals. An issue that probably can only be resolved by empirical testing is whether a new ICRS realization should be determined by a single, finely tuned, well understood solution or by a combination, perhaps even including non-VLBI data to ensure consistency of TRF, CRF and EOP.

5. CONCLUSIONS

Substantial progress has been made in CRF and VLBI analysis since 1995. The recent initiation of a systematic CRF monitoring program by the IVS will provide much better data in the next few years. A concerted effort must be made to coordinate the generation and comparison of source catalogues and to decide the analysis configuration of the next radio realization of the ICRS. For this work it may be useful to have some formal organization that would also prepare the astronomical community to accept a new realization.

6. REFERENCES

Feissel-Vernier, M., 2003, Selecting stable extragalactic compact radio sources from the permanent astrogeodetic VLBI program, Astron. Astrophys., 403, 105-110.

Fey, A.L., Ma, C., Arias, E.F., Charlot, P., Feissel-Vernier, M., Gontier, A.-M., Jacobs, C.S., Li, J., and MacMillan, D.S., 2004, The second extension of the International Celestial Reference Frame: ICRF-Ext.2, Astron. J., 127, 3587-3608.

Gontier, A.-M., Le Bail, K., Feissel, M., and Eubanks, T.M., Stability of the extragalactic VLBI reference frame, Astron. Astrophys., 375, 661-669.

Ma, C., Arias, E.F., Eubanks, T.M., Fey, A.L., Gontier, A.-M., Jacobs, C.S., Sovers, O.J., Archinal, B.A., and Charlot, P., 1998, International Celestial Reference Frame as realized by very long baseline interferometry, Astron. J., 116, 516-546.

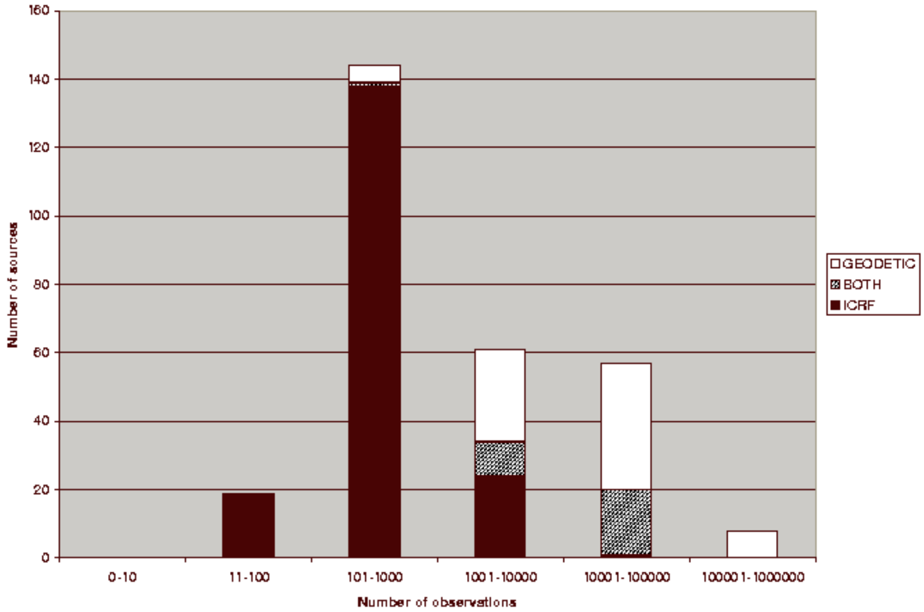

Figure 1: Distribution of Observations of ICRF Defining vs. Geodetic Sources, 1979-2003

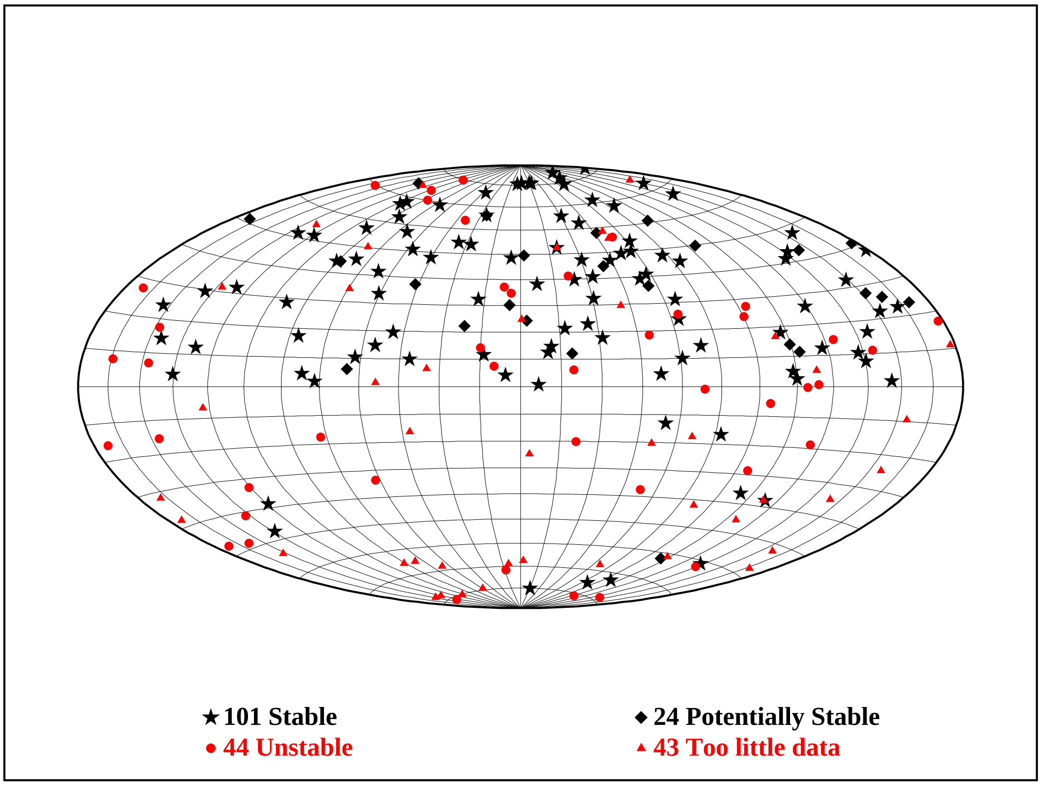

Figure 2: ICRF Defining Sources

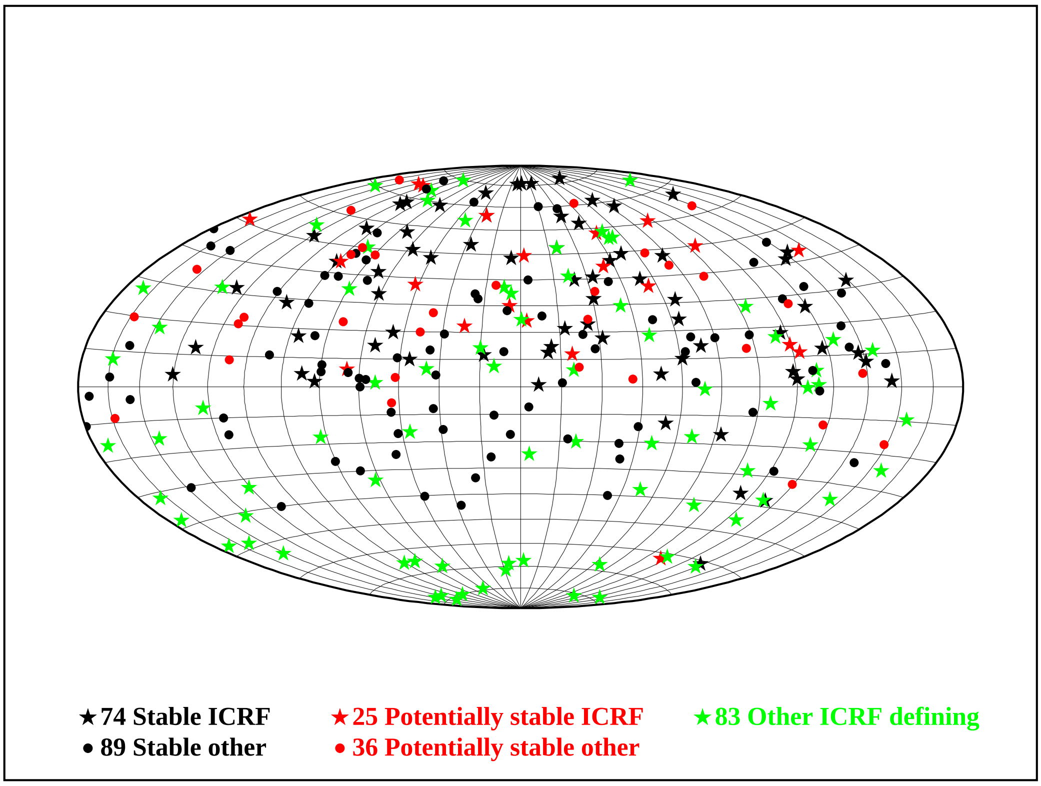

Figure 3: CRF Monitoring Sources

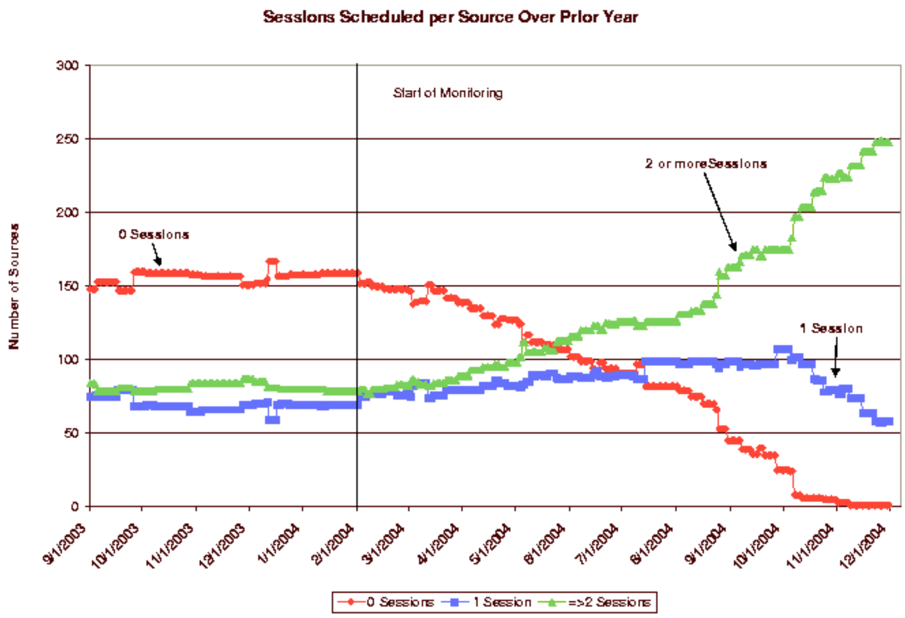

Figure 4: Sessions Scheduled per Source over Prior Year

UPDATING THE IERS CONVENTIONS TO IMPROVE REFERENCE FRAMES

G. PETIT[1], D. D. MCCARTHY[2]

[1] Bureau International des Poids et Mesures
92312 Sèvres France
e-mail: gpetit@bipm.org

[2] U. S. Naval Observatory
Washington, DcC 20392 USA
e-mail: dmc@maia.usno.navy.mil

ABSTRACT. The consistency of the reference frames provided by the IERS and its different centers relies on the set of conventional models and procedures that are used to realize them. These conventional models and procedures are mostly the product of the IERS Conventions Center, provided jointly by the Bureau International des Poids et Mesures (BIPM) and the U.S. Naval Observatory (USNO). The latest issue is the IERS Conventions (2003), recently published. In this paper we address issues related to this publication and consider the work under way to provide the future updates of the IERS Conventions.

1. THE IERS CONVENTIONS (2003)

After final work on remaining issues, mostly in Chapters 5 (Transformation Between the Celestial and Terrestrial Systems), 9 (Tropospheric Model), 10 (General Relativistic Models for Space-Time Coordinates and Equations of Motion) and in the general outline of the document, the final edition of the IERS Conventions (2003) was submitted to the IERS in November 2003. At that same time, the corresponding files were made available in electronic form on the USNO web site ftp://maia.usno.navy.mil/conv2003/ (see also the new site at ftp://tai.bipm.org/iers/conv2003/ which opened in June 2004). The paper edition was released at the end of 2004 (McCarthy and Petit, 2004). The general structure of the IERS Conventions (2003) is described in the Annex.

This electronic release was accompanied by a questionnaire to the general IERS community asking for comments on the present version and future evolution of the IERS Conventions. Although less than ten completed questionnaires were returned, several replies contained detailed answers and suggestions summarized below. The questionnaire was divided into 3 main sections: (i) On the value of the just released IERS Conventions (2003), the structure and overall quality were generally considered fine but the delay of publication was generally considered to be a problem. Some inconsistencies / deficiencies were pointed at (see next section). (ii) On the future IERS Conventions, there was unanimous agreement that any update should be by discrete increments (e.g. yearly) even though some continuously updated version may be available unofficially in the mean time. It was also recommended to continue with a paper version. In order to gather new and updated information, several techniques were proposed: (a) call to the community, (b) expert groups, and/or (c) use the existing technique services. (iii) Finally on the interactions between the Conventions center and the rest of the IERS, it was recommended to create an Advisory Board. The importance of a formal approval of any update of the Conventions was stressed, although the body for approval was sometimes an issue (Advisory Board or IERS Directing Board). It was recommended that the routine interactions with other groups should be enhanced, although no precise method was stated for this purpose.

2. UPDATING THE IERS CONVENTIONS

The Conventions Center has begun preparing the next update of the IERS Conventions. The fundamental hypothesis is that the IERS Conventions should provide the basic models, software and procedures for effects common to several or all space geodetic techniques used by the IERS. On the other hand, items which are specific to one technique (generally hardware-dependent) should be covered by technique-specific conventions. Because the IERS products, notably the terrestrial reference frame (Boucher et al., 2004) and the Earth Orientation parameters are obtained from a combination of the results of different techniques, it is essential that all analysis be consistent by following the same IERS Conventions. It is also necessary that the IERS Conventions themselves provide a complete and consistent set. General rules to be followed in this aim are the following: Ensure global consistency in the document itself e.g. remove ambiguous statements or recommended a unique model / procedure. Update missing or outdated models. Provide all necessary routines. Provide the magnitude of effects and the magnitude of model changes, possibly with numerical examples. In order to fully achieve these goals in the future, two directions of work are taken: Provide new electronic tools to the community and obtain agreement on new (or existing) conventional models.

2.1. New electronic tools

New tools have been developed to help in the process of updating the IERS Conventions. A new web site and a discussion forum have been installed at the BIPM. The web site for Conventions updates (http://tai.bipm.org/iers/convupdt/convupdt.html) is continuously modified, as required by changes in the texts, routines or data files. However, the site is expected to retain the complete history of updates thus ensuring the archiving and the traceability of the changes. It should also contain new products such as numerical examples or explanatory material, as they become available. The discussion forum (http://tai.bipm.org/iers/forum) is for users to offer their comments, criticism, and suggestions regarding the update of the IERS Conventions. It is organized in themes following the present structure of the IERS Conventions (2003). Reading the contributions is open and anonymous but, to post a contribution, it is necessary to be registered. Registration is mandatory so that the forum administration can identify participants, but it is a very simple procedure and the only requirement is to accept the terms of the forum, which is designed only for "discussions on the IERS Conventions".

2.2. Topics for updates

Corrections to the IERS Conventions (2003) are already under way, starting with typos that were discovered after the official release and with some limited text changes that improve the readability of the document (see http://tai.bipm.org/iers/convupdt/convupdt.html) .

More technical or complex issues are first debated, e.g. on the discussion forum (http://tai.bipm.org/iers/forum), numerical examples and test cases are proposed, and topics are being identified as needing investigation and possible new developments for future versions of the Conventions. Several such topics concern contributions to the difference between the instantaneous position of a site and its regularized position, such as the effects of geocenter motion or atmospheric loading. It is expected that all effects (such as station displacement) that are periodic and have a consistent and accurate a-priori model, expressed in closed form, should be included in the IERS Conventions. To be considered in updating IERS Conventions (2003) are e.g. models for sub-daily effects concerning geocenter motion due to ocean tides and atmosphere pressure loading, revision of models for tidal effects on Earth orientation parameters, etc. Models for long-term or non-periodic effects, which have an impact on the definition of reference frames, are also to be studied, although their inclusion as conventional effects will need to be discussed.

The Conventions Center also intends to gather information by participating to other studies, such as the development of rigorous multi-technique product combinations through the new Combination Pilot Project (http://www.iers.org/iers/about/wg/wg3/cpp.html).

3. CONCLUSIONS

After the completion of the IERS Conventions (2003), the Conventions Center has provided new tools and methods to prepare the future updates of the Conventions. To achieve this aim it encourages discussions and developments for models, software and procedures that are relevant to the IERS techniques. It also encourages studies on the application of the IERS Conventions by analysis centers of specific techniques, particularly those that study the impact of current or proposed conventional models on the accuracy or on the performance limits of space geodetic results.

4. ACKNOWLEDGEMENTS

We thank all those that provided input and advice by responding to the Questionnaire or posting questions and answers through the Conventions forum or other means. Particular thanks are due to Jim Ray for his help in establishing the discussion forum.

5. REFERENCES

Boucher C., Altamimi Z., Sillard P., Feissel-Vernier M., 2004; The ITRF2000, IERS TN31, Verlag des BKG, 270 p.

McCarthy D.D., Petit G., 2004; IERS Conventions (2003), IERS TN32, Verlag des BKG, 127 p.

APPENDIX: CONTENTS OF THE IERS CONVENTIONS (2003)

EXTENSION OF THE CELESTIAL REFERENCE FRAME

S. BOLOTIN
Main Astronomical Observatory
National Academy of Sciences of Ukraine
27 Akademika Zabolotnoho St, 03680 Kiev, Ukraine
e-mail: bolotin@mao.kiev.ua

ABSTRACT. A set of VLBI observations carried out since 1992 till August 2004 were analyzed to construct a Celestial Reference Frame. Data processing was conducted according to IERS Conventions 2003 with the software SteelBreeze. Coordinates of stations and Earth Rotation Parameters were fixed and their values were taken as a priori from the VTRF2003 and EOP(IERS) C 04 solutions. In total, the obtained extension of Celestial Reference Frame consists of positions of 2028 radio sources.

1. CONSTRUCTION OF EXTENDED CELESTIAL REFERENCE FRAME

In common practice of Very Long Baseline Interferometry (VLBI) observations a set of determined radio sources are used. These 667 radio sources from ICRF-Ext.1 catalogue are defining the realization of the International Celestial Reference System (IERS, 1999). However, there are VLBI experiments which are aimed on observing and determining positions of new radio sources (Beasley at al., 2002).

Available geodetic VLBI observations contain about 2300 radio sources. Most of them were observed during one or two sessions, and, usually, these sessions are not suitable for determining TRF, CRF and EOP in common solution due to geometry of network.

In order to extend the Celestial Reference Frame on these rarely observed radio sources we fixed Terrestrial Reference Frame (TRF) by the values from VTRF2003 catalogue, the motion of the Celestial Intermediate Pole (CIP) in TRF by the EOP(IERS) C 04 solution and the motion of the CIP in Celestial Reference Frame by the model of IAU-2000A Nutation-Precession Theory.

2. OBSERVATIONS AND ANALYSIS

Almost all available VLBI observations, which were conducted since begin of 1992 till the end of August 2004 were processed. In total, 3,830,124 dual frequency delays acquired on 1,911 VLBI sessions were analyzed. Observations of 2256 radio sources were carried out by 72 stations.

Data analysis was performed by the software SteelBreeze. Coordinates of radio sources were estimated as global parameters. Station clock function, wet zenith delay and its gradients were estimated as the stochastic ones.

VLBI data processing was performed according to models which are described in IERS Conventions (2003): the IAU-2000A Nutation-Precession Theory with non-rotating origin procedure was applied for transformation between CRF and TRF; hydrostatic zenith delays were modeled according to Saastamoinen (1972) and wet zenith delays were estimated from the observations; mapping functions for hydrostatic and wet zenith delays were calculated according to: MTT mapping functions (Herring, 1992), if meteoparameters of a station were reliable, and NMF2 mapping functions (Niell, 1996), if the meteoparameters were suspicious. Stochastic parameters were modeled as random walk process.

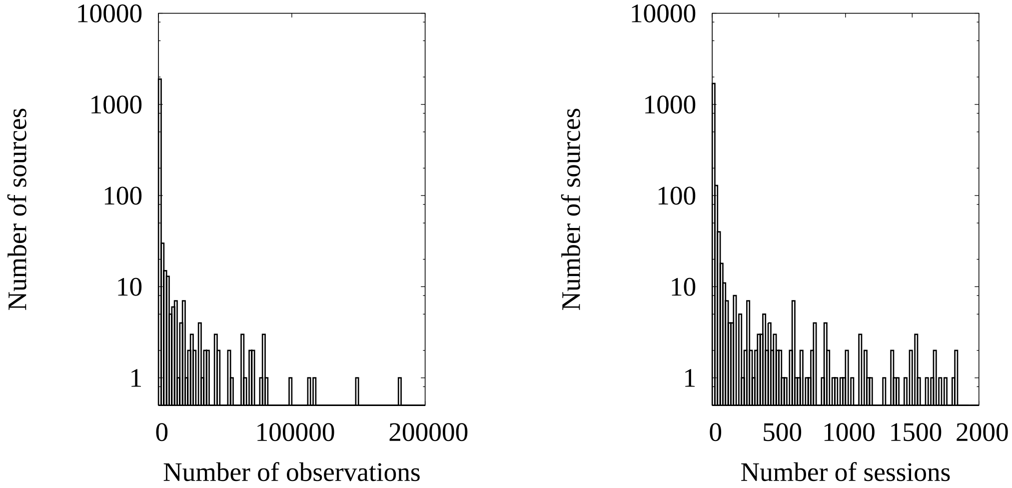

Figure 1: Distribution of observations.

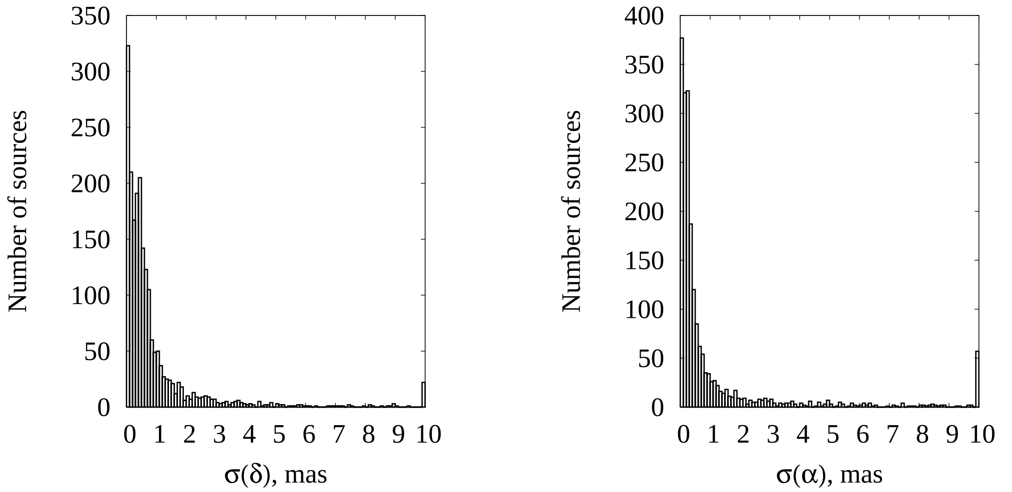

Figure 2: Distribution of errors.

After eliminating outliers during pre-processing, VLBI data were analyzed. Coordinates of radio sources which were observed 5 or more times were estimated. The results are based on 3,447,906 time delays acquired by 71 VLBI stations. Constructed Celestial Reference Frame consist 2028 radio sources. Weighted post fit residuals were 8.8 ps.

The histograms of distribution of numbers of observed radio sources are shown on the Fig. 1. The distributions of the uncertainties of the coordinates of radio sources are presented on the Fig. 2.

Obtained solution of the extended CRF is available online on the following URL:

$$ftp://ftp.mao.kiev.ua/pub/users/bolotin/VLBI/mao\_new.crf$$

3. CONCLUSIONS

Data analysis of the VLBI observations 1992–2004 were performed to extend CRF on rarely observed radio sources. The orientation of the obtained CRF is defined by VTRF2003, the solution EOP(IERS) C 04 and IAU-2000A Nutation-Precession Theory. Extended CRF contains positions of 2028 radio sources.

Acknowledgments. This solution is based on the VLBI observations provided by the International VLBI Service for Geodesy and Astrometry (IVS).

The author is grateful to the Organizing Committee of the conference Journees-2004 for the financial support.

4. REFERENCES

Beasley A.J., Gordon D., Peck A.B., Petrov L., MacMillan D.S., Fomalont E.B., Ma C., 2002, "The VLBA Calibrator Survey - VCS1", *Asrophys. J., Supp.*, **141**, pp. 13–21.

Herring, T.A., 1992, "Modeling Atmospheric Delays in the Analysis of Space Geodetic Data", *Proceedings of Refraction of Transatmospheric Signals in Geodesy*, Netherlands Geodetic Commission Series, **36**, The Hague, Netherlands, pp. 157–164.

IVS: International VLBI Service data available electronically at http://ivscc.gsfc.nasa.gov

IERS, 1999: 1998 IERS Annual Report, D Gambis (ed.), Observatoire de Paris, p. 87-114.

IERS Conventions, McCarthy, D.D. (ed.), IERS Technical Note 32, Observatoire de Paris, Paris, 2003.

Niell, A.E., 1996, "Global Mapping Functions for the Atmosphere Delay of Radio Wavelengths", *J. Geophys. Res.*, **101**, pp. 3227–3246.

Saastamoinen, J., 1972, "Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging of Satellites", *Geophysical Monograph 15*, Henriksen (ed), pp. 247–251.

ACTIVITIES OF THE ICRS-PC OF THE IERS

J. SOUCHAY[1], R. GAUME[2]

[1] IERS ICRS Product Center
SYRTE/UMR8630-CNRS, Observatoire de Paris
61 Avenue de l'Observatoire, 75014 Paris, France

[2] IERS ICRS Product Center
U. S. Naval Observatory
Washington, DC 20392, USA

ABSTRACT. From January 2001, the Paris Observatory and the US Naval Observatory (USNO) propose to act jointly as the International celestial reference System Product Centre (ICRS-PC) of the IERS. We present hereafter the various activities of this product centre, insisting particularly on the present studies.

1. INTRODUCTION

The IERS shares the responsibility of monitoring the International Celestial Reference Frame (ICRF) as well as maintaining and improving the links with other celestial reference frames. Starting in 2001, these activities are run jointly by the ICRS Product Centre and the International VLBI Servive for geodesy and astrometry (IVS). Information about the ICRS-PC can be found on the ICRS Product Centre web site (http://hpiers.obspm.fr/icrs-pc) or via anonymous ftp (hpiers.obspm.fr/icrs-ps). We summarize in the following the various activities of the Product Centre.

2. MAINTENANCE OF THE ICRF AND OF ITS TIME STABILITY

Since the adoption of the ICRF as a catalogue giving the coordinates of 212 sources qualified as "'defining"' objects of the frame (Ma et al.,1997,1998), the ICRS-PC has performed several analysis in order to investigate the way by which the ICRF might be improved in the future. Recently an alternative selection of sources, based on an analysis of time series of radio sources coordinates over the period 1989-2002 has been proposed (Feissel-Vernier,2002). The improvement of the quality of the ICRS which might result from such a selection has been shown (Arias and Bouquillon, 2004). In particular the last authors selected two independent VLBI catalogues elaborated from two independent VLBI analysis. After comparison of the catalogues above to a rigid frame, that is, to ICRF-Ext.1, they concluded that the orientation of the axes of the ICRS is better realized by using the set of stables sources selected by Feissel-vernier(2003). This significant result suggests that statistical tests be considered when selecting a set of sources to materialize the ICRS in the future.

3. INVESTIGATIONS OF FUTURE REALIZATIONS OF THE ICRF

The personnel from the ICRS Centre has been deeply involved in the recent VLVI programs and their evolution with an increasing number of quasars observed in the southern celestial hemisphere and a lot of new additional observations of the ICRF quasars in the northern hemisphere. This densification has enabled the construction of a second extension of the ICRF, called ICRF-Ext.2 (Fey et al.,2004) which was accompanied by an improvement in the accuracy of the coordinates of the "candidate" and "‘other"’ sources, according to the usual terminology used for the ICRS (IERS Technical Note,2003). Notice that the ICRF-Ext.2 solution differs from the precedent versions (ICRF and ICRF-Ext.1) in the use of the NMF mapping function (Niell,1996) for the tropospheric modelling, which constitutes one of the leading limitations in the reductions of VLBI observations.

4. INVOLVEMENT OF THE ICRS-PC IN VARIOUS VLBI ASTROMETRIC PROGRAMS

The USNO personnel of the ICRS-PC, in collaboration with other teams from the NASA, the NRAO (National Radio Astronomy Observatory), the GSFC (Goddard Space Flight Center) is presently working to the extension of the ICRF to 24GHz and 43 Ghz in addition to the two "classical" frequencies of 2.3 GHz and 8.4 Ghz, through the important VLBA (very Long Baseline Array) program. A Radio Reference Frame Image Database (RRFID) can be accessed through the site “www.usno.navy.mil/RRFID”, containing more than 3000 VLBA images at 2.3 GHz and 8.4 Ghz and more than 500 images at 24 and 43 Ghz. A joint program between USN staff and Whitier College consists in measuring apparent jet velocities from the motion of extragalactic sources components using RRFID data at 8.4 Ghz (Piner et al.,2003), showing apparent component speeds at rather low values (of the order of $1c$, where c is the speed of light), but with some values extending as high as $30c$ (IERS Technical Note,2003).

5. MAINTENANCE OF THE LINK TO THE HIPPARCOS AND OTHER OPTICAL CATALOGS

One of the most fundamental tasks of the ICRS-PC is to maintain the link between the ICRF, whose characteristics are determined at radio-wavelengths, and the primary optical Hipparcos catalog. This link is possible through the recent UCAC (USNO CCD Astrograph Catalog) observation program which is now achieved. The catalog contains the coordinates and magnitudes of roughly 50 million of stars with proper motions, covering roughly 90 % of the sky. Proper motions were derived from various other catalogs, as AC2000, Tycho, and remeasurements from older programs as AGK2, NPM and SPM plates. the extragalactic link was possible by identifying about 70 QSO's source fields within the UCAC fields, with the KPNO (0.9 m) and NOFS (1.3 m) telescopes.

The ICRS-PC also worked to the cross-identification between the quasars of the ICRF and those given by an up-dated version of the most extended quasars catalog (Véron-Cetty and Véron ,2003) at optical wavelengths. Notice that below a threshold of 0.4" for the search of a couterpart, only 132 sources among the 212 defining sources of the ICRF, i.e. roughly 62.2 % where found in the Véron-Cetty and Véron catalog. We can conclude that it should be interesting to complete the optical observations of ICRF source fields (IERS Annual Report,2003).

6. LLR AND PULSAR TIMING OBSERVATIONS FOR THE LINK TO THE DYNAMICAL SYSTEM

One of the important taks of the ICRS-PC concerns the link of the ICRF to the dynamical frame which is materialized by the position of the ecliptic. Indeed, all the motions of celestial bodies belonging to the solar system are referred to the ecliptic, and the accuracy in the determination of the orbital elements of these bodies is directly dependent on the accuracy of the position of the ecliptic. This can be done in two completely different ways, through pulsar timing analysis (Fairhead, 1988) and through Lunar Laser Ranging (Chapront et al.,2002; Chapront and Francou,2003). The first kind of analysis lead to the interesting result that the angular distance between selected pulsars is nearly not sensitive to the choice of the ephemerides used for the orbital motion of the Earth (as JPL ephemerides DE405 and DE200). Even when changing the ephemerides, these inter-pulsar angular distances are constant at the level of $1mas$" whereas on the contrary the equatorial coordinates are changed at the level of $10mas$. This suggests the elaboration of a very accurate and rigid celestial reference frame based on the positions of pulsars, from which in return a more accurate positioning of the ecliptic might be deduced. In parallel, Lunar Laser Ranging analysis enable to determine, through a complex combination of ephemerides (rotation of the Earth, librations of the Moon, orbital motion of the Moon etc...) and with high accuracy, the relative motions of the equator and the ecliptic at a given date (for instance J2000.0). Results concerning the position of the equinox as well as the obliquity are given at the level of a sub-milliarsecond accuracy (IERS Technical Note, 2003).

7. REFERENCES

Arias, E.F., Bouquillon,S., 2004, A&A in press

Chapront, J., Chapront-Touzé, M.,Francou, G.,2002, A&A 38, 700

Chapront, J., Francou, G., 2003, A&A 404, 735

Fairhead, L., 1988, PhD Thesis

Feissel-Vernier, M., 2003, A&A 403, 105

Fey,A.L., Ma,C., Arias,E.F., Charlot,P., Feissel-Vernier, M., Gontier, A.M., Jacobs, C.S., Mc.Millan, D.S., 2004, AJ 127, 3587

IERS Annual Report, 2003, Verlag Des BKG, Frankfurt

Niell, A.E., 1996, JGR 101, 3227

Piner, B.G., Mahmud,M., Gospidinova, K., 2003, A&AS 203, 9207

Souchay, J., Cognard,I., 2004, *AGU General Assembly, Fall meeting, San Fransisco*, abstracts

Véron-Cetty,M.P., Véron,P., 2003, A&A 412, 399

Zacharias, N., Urban, S.E., et al., 2004, AJ 127, 3043

MAINTENANCE OF THE ICRS: STABILITY OF THE AXES BY DIFFERENT SETS OF SELECTED RADIO SOURCES

E.F. ARIAS[1,3], S. BOUQUILLON[2]

[1] Bureau International des Poids et Mesures
Pavillon de Breteuil, 92310 Sèvres, France
e-mail: farias@bipm.org

[2] IERS ICRS Product Centre
SYRTE/UMR8630-CNRS, Observatoire de Paris
61 Avenue de l'Observatoire, 75014 Paris, France
e-mail: seb@danof.obspm.fr

[3] Associated Astronomer to SYRTE, Observatoire de Paris

EXTENTED ABSTRACT. The International Astronomical Union (IAU) recommended (1994) the adoption of a celestial reference system realized on the basis of precise coordinates of extragalactic radio sources observed with the technique of Very Long Baseline Interferometry (VLBI). The celestial reference system of the International Earth Rotation Service (IERS) (Arias et al., 1995) has been adopted as the International Celestial Reference System (ICRS); the ICRS is materialized in the radio frequencies by the coordinates of the radio sources in the International Celestial Reference Frame (ICRF); the Hipparcos catalogue is the ICRS realization in the optical frequencies (Kovalevsky et al., 1997).

The first realization of the ICRF (Ma et al., 1998) is the result of the effort of the Working Group on Reference Frames (WGRF) of the IAU. Extension of the ICRF, published under the name ICRF-Ext.1 (IERS, 1999) and ICRF-Ext.2 (Fey et al., 2004) made the frame more dense by including about one hundred new radio sources. Three sets of criteria were adopted by the WGRF to classify the sources in the ICRF: quality of data and observational history; consistency of coordinates derived from subsets of data; repercussions of source structure. The so-called "defining sources" were used in the first realization of the ICRF to align the axes of the resulting catalogue to the ICRS, they are used as fiducial points in the process of maintenance of the frame and in the catalogue comparisons.

A different approach for the selection of stable radio sources has been proposed by Feissel-Vernier (2003); she focused her analysis on VLBI data acquired since 1989.5, and proved that it is possible to make a judicious classification of radio sources based on statistical studies of their coordinate time series, among other tests. Comparing the sets issued from the two classifications, it has been found that the criteria often diverge, and consequently the sources in each set are different.

We performed an analysis of two independent VLBI celestial reference frames by using the sources selected by the WGRF to realize the ICRS on one side, and those from the Feissel-Vernier selection on the other. The model used for catalogue comparison at the IERS has been used in the analysis. The results show that in either case, the orientation of the axes of the ICRS is better realized by using the set of stable sources selected at Feissel-Vernier (2003).

This shows that in the selection of the more stable sources for the realization of the celestial reference system, statistical tests on the time-varying behaviour of source coordinates should be included. VLBI observations from 1979 – 1995 were used in the construction of the ICRF and in the classification of its radio sources. The selection of sources by Feissel-Vernier is applied to observations during the period 1989.5 – 2002.4, indicating that limiting the time span of observations to the last ten years favours the quality of the frame. It is desirable to densify the set of stable sources south of -50° declination.

This contribution has been published in extenso in A&A, **422**, 1105.

REFERENCES

Arias, E.F., Bouquillon, S., 2004, A&A, **422**, 1105

Arias, E.F., Charlot, P., Feissel, M., Lestrade, J.-F. 1995, A&A, **303**, 604

Feissel-Vernier, M. 2003, A&A, **403**, 105

Fey, A.L., Ma C., Arias, E.F., Charlot, P., Feissel-Vernier, M., Gontier, A. -M., Jacobs, C. S., Li, J., MacMillan, D. S. 2004, AJ , **127**, 3587

Kovalevsky, J. et al. 1997, A&A, **323**, 620

IERS 1996, International Earth Rotation Service Annual Report 1995 (Observatoire de Paris, Paris), II-19

IERS 1999, International Earth Rotation Service Annual Report 1998 (Observatoire de Paris, Paris), 87

IERS 2003, International Earth Rotation and Reference Systems Service Annual Report 2002 (BKG, Frankfurt am Main), 56

Ma, C., Arias, E.F., Eubanks, T.M., Fey, A., Gontier, A.-M., Jacobs, C.S., Sovers, O.J., Archinal, B.A., Charlot, P. 1998, AJ , **116**, 516

DENSIFICATION OF THE INTERNATIONAL CELESTIAL REFERENCE FRAME: RESULTS OF EVN+ OBSERVATIONS

P. CHARLOT[1], A. L. FEY[2], C. S. JACOBS[3], C. MA[4], O. J. SOVERS[5], A.BAUDRY[1]

[1] Observatoire de Bordeaux (OASU) – CNRS/UMR 5804
BP 89, 33270 Floirac, France
e-mail: charlot@obs.u-bordeaux1.fr

[2] U. S. Naval Observatory
3450 Massachusetts Avenue NW, Washington, DC 20392-5420, USA
e-mail: afey@usno.navy.mil

[3] Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109, USA
e-mail: csj@logos.jpl.nasa.gov

[4] National Aeronautics and Space Administration, Goddard Space Flight Center
Greenbelt, MD 20771, USA
e-mail: Chopo.Ma@nasa.gov

[5] Remote Sensing Analysis Systems
2235 N. Lake Avenue, Altadena, CA 91101
e-mail: ojars@rsasys.com

ABSTRACT. The current realization of the International Celestial Reference Frame (ICRF) comprises a total of 717 extragalactic radio sources distributed over the entire sky. An observing program has been developed to densify the ICRF in the northern sky using the European VLBI network (EVN) and other radio telescopes in Spitsbergen, Canada and USA. Altogether, 150 new sources selected from the Jodrell Bank–VLA Astrometric Survey were observed during three such EVN+ experiments conducted in 2000, 2002 and 2003. The sources were selected on the basis of their sky location in order to fill the "empty" regions of the frame. A secondary criterion was based on source compactness to limit structural effects in the astrometric measurements. All 150 new sources have been successfully detected and the precision of the estimated coordinates in right ascension and declination is better than 1 milliarcsecond (mas) for most of them. A comparison with the astrometric positions from the Very Long baseline Array Calibrator Survey for 129 common sources indicates agreement within 2 mas for 80% of the sources.

1. INTRODUCTION

The International Celestial Reference Frame (ICRF), the most recent realization of the extragalactic fundamental frame, is currently defined by the radio positions of 212 sources observed by Very Long Baseline Interferometry (VLBI) between August 1979 and July 1995 (Ma *et al.* 1998). These *defining* sources, distributed over the entire sky, set the initial direction of the

ICRF axes and were chosen based on their observing histories with the geodetic networks and the accuracy and stability of their position estimates. The accuracy of the individual source positions is as small as 0.25 milliarcsecond (mas) while the orientation of the frame is good to the 0.02 mas level. Positions for 294 less-observed *candidate* sources and 102 *other* sources with less-stable coordinates were also reported, primarily to densify the frame. Continued observations through May 2002 have provided positions for an additional 109 new sources and refined coordinates for candidate and "other" sources (Fey *et al.* 2004).

The current ICRF with a total of 717 sources has an average of one source per $8° \times 8°$ on the sky. While this density is sufficient for geodetic applications, it is clearly too sparse for differential-VLBI applications (spacecraft navigation, phase-referencing of weak targets), which require reference calibrators within a-few-degree angular separation, or for linking other reference frames (e.g. at optical wavelengths) to the ICRF. Additionally, the frame suffers from a inhomogeneous distribution of the sources. For example, the angular distance to the nearest ICRF source for any randomly-chosen sky location can be as large as 13° in the northern sky and 15° in the southern sky (Charlot *et al.* 2000). This non-uniform source distribution makes it difficult to assess and control any local deformations in the frame. Such deformations might be caused by tropospheric propagation effects and apparent source motions due to variable intrinsic structure (see Ma *et al.* 1998).

This paper reports results of astrometric VLBI observations of 150 new sources to densify the ICRF in the northern sky. These observations were carried out using the European VLBI Network (EVN) and additional geodetic antennas that joined the EVN for this project. The approach used in selecting the new potential ICRF sources was designed to improve the overall source distribution of the ICRF. Sources with no or limited extended emission were preferably selected to guarantee high astrometric suitably. Sections 2 and 3 below describe the source selection strategy in further details, the network and observing scheme used in these EVN+ experiments, and the data analysis. The astrometric results that have been obtained are discussed in Sect. 4, including a comparison with the Very Long Baseline Array (VLBA) Calibrator Survey astrometric positions for 129 common sources.

2. STRATEGY FOR SELECTING NEW ICRF SOURCES

The approach used for selecting new sources to densify the ICRF was to fill first the "empty" regions of the frame. The largest such region for the northern sky is located near $\alpha = 22$ h 05 min, $\delta = 57°$, where no ICRF source is to be found within 13°. A new source should thus be preferably added in that part of the sky. By using this approach again and repeating it many times, it is then possible to progressively fill the "empty" regions of the frame and improve the overall ICRF source distribution. The input catalog for selecting the new sources was the Jodrell Bank–VLA Astrometric Survey (JVAS) which comprises a total 2118 compact radio sources with peak flux density at 8.4 GHz larger than 50 mJy (at a resolution of 200 mas) in the northern sky (Patnaik *et al.* 1992, Browne *et al.* 1998, Wilkinson *et al.* 1998). For every "empty" ICRF region, all JVAS sources within a radius of 6° (about 10 sources on average) were initially considered. These sources were then filtered out using the VLBA Calibrator Survey, which includes VLBI images at 8.4 and 2.3 GHz for most JVAS sources (Beasley *et al.* 2002), to eventually select the the source with the most compact structure in each region.

The results of this iterative source selection scheme show that 30 new sources are required to reduce the angular distance to the nearest ICRF source from a maximum of 13° to a maximum of 8°. Another 40 new sources would further reduce this distance to a maximum of 7° while for a maximum distance of 6°, approximately 150 new sources should be added. Carrying this procedure further, it is found that the number of required new sources doubles for any further decrease of this distance of 1° (approximately 300 new sources for a maximum distance of 5°

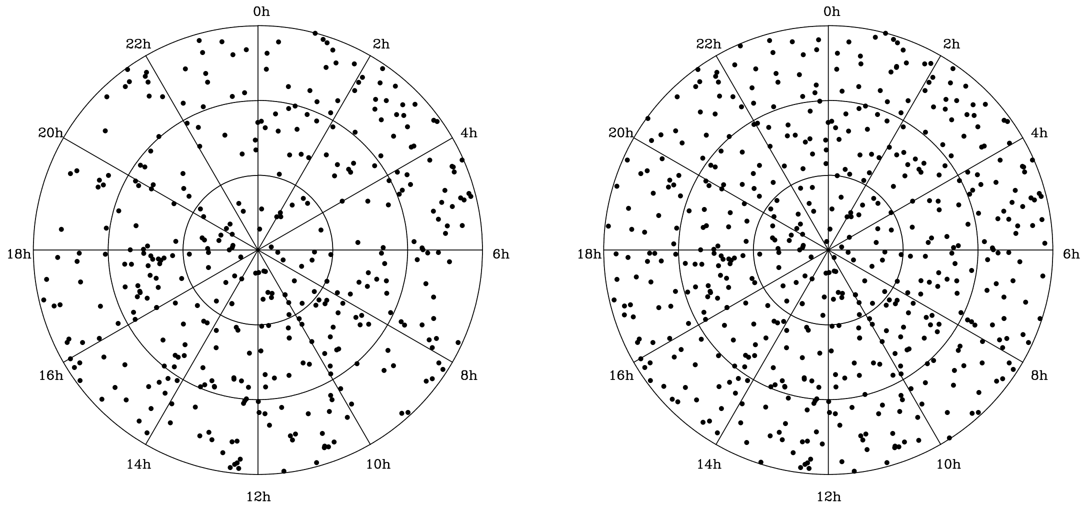

Figure 1: Northern-sky source distribution in polar coordinates. *Left:* for the current ICRF, including defining, candidate, and "other" sources plus the additional sources published in ICRF-Ext.1 (see Fey *et al.* 2004). *Right:* same plot after adding the 150 new sources identified to fill the "empty" regions of the frame. The outer circle corresponds to a declination of 0° while the inner central point is for a declination of 90° . The intermediate circles correspond to declinations of 30° and 60°.

and 600 new sources for a maximum distance of 4°) with the limitation that the JVAS catalog is not uniform enough to fill all the regions below a distance of 6°. Based on this analysis, we have selected the first 150 sources identified through this procedure for observation with the EVN+ network described below. As shown in Fig. 1, the overall source distribution is potentially much improved with these additional 150 sources in the northern sky.

3. OBSERVATIONS AND DATA ANALYSIS

The observations were carried out in a standard geodetic mode during three 24-hour dual-frequency (2.3 and 8.4 GHz) VLBI experiments conducted on May 31, 2000, June 5, 2002, and October 27, 2003, using the EVN (including the Chinese and South African telescopes) and up to four additional geodetic radio telescopes (Algonquin Park in Canada, Goldstone/DSS 13 and Greenbank/NRAO20 in USA, and Ny-Alesund in Spitsbergen). There were between 10 and 12 telescopes scheduled for each experiment. Such a large network permits a geometrically-strong schedule based on sub-netting which allows tropospheric gradient effects to be estimated from the data. The inclusion of large radio telescopes (Effelsberg, Algonquin Park) in this network was essential because the new sources are much weaker than the ICRF ones (median total flux of 0.26 Jy compared to 0.83 Jy for the ICRF sources, see Charlot *et al.* 2000). Each experiment observed a total of 50 new sources along with 10 highly-accurate ICRF sources so that the positions of the new sources can be linked directly to the ICRF.

The data were correlated with the Bonn Mark 4 correlator, fringe-fitted using the Haystack software fourfit, and exported in the standard way to geodetic data base files. All subsequent analysis employed the models implemented in the VLBI modeling and analysis software MOD-EST (Sovers & Jacobs 1996). Standard geodetic VLBI parameters (station clock offsets and rates with breaks when needed, zenith wet tropospheric delays every 3 hours, and Earth orientation) were estimated in each experiment along with the right ascension and declination of the new sources. The positions of the 10 ICRF link sources were held fixed as were station coordinates. Observable weighting included added baseline-dependent noise adjusted for each baseline in each experiment in order to make χ^2 per degree of freedom approximately equal to 1.

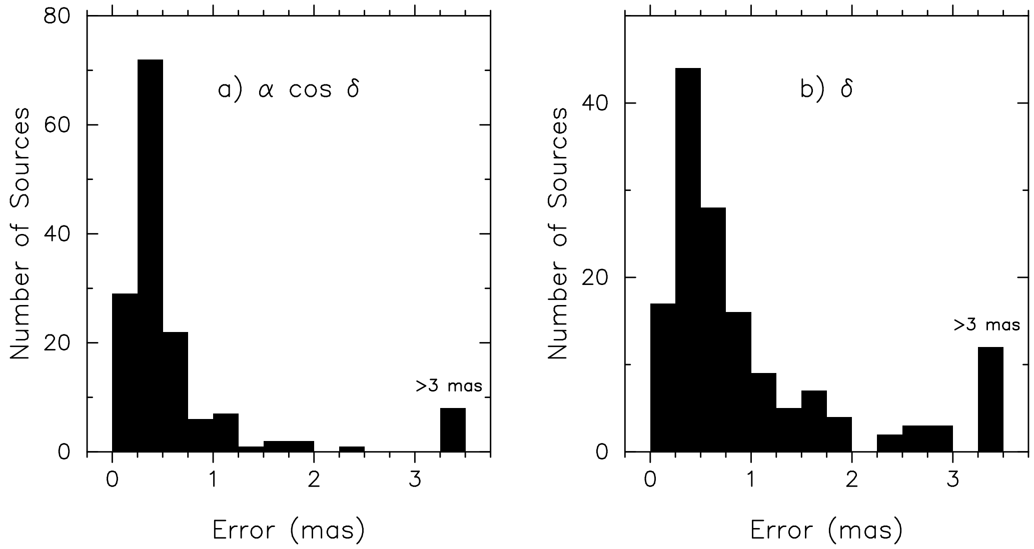

Figure 2: Astrometric precision of the estimated coordinates in *a)* right ascension and *b)* declination for the 150 newly-observed sources. All errors larger than 3 mas are placed in a single bin marked with the label "> 3 mas" on each plot.

4. RESULTS

The three EVN+ experiments described above have been very successful in observing the selected targets. All 150 new potential ICRF sources have been detected, hence indicating that the source selection strategy and observing scheme set up for these experiments were appropriate. In the first two experiments (2000 May 31 and 2002 June 5), there were generally between 20 and 60 pairs of delay and delay rates usable for each source to estimate its astrometric position. Conversely, more than half of the sources observed in the third experiment (2003 October 27) had less than 20 pairs of usable delay and delay rates because of the failure of three telescopes in that experiment.

Figure 2 shows the error distribution in right ascension and declination for the 150 newly-observed sources. The distribution indicates that about 70% of the sources have position errors smaller than 1 mas, consistent with the high quality level of the ICRF. The median coordinate uncertainty is 0.37 mas in right ascension and 0.63 mas in declination. The larger declination errors are most probably caused by the predominantly East-West network used for these observations. Figure 2 also shows that a dozen sources have very large errors (> 3 mas). Most of these sources were observed during the 2003 October 27 experiment and have only a few available observations or data only on short intra-Europe baselines. Such sources should be re-observed to obtain improved coordinates if these are to be considered for inclusion in the next ICRF realization.

Among our 150 selected targets, 129 sources were found to have astrometric positions available in the VLBA Calibrator Survey (Beasley *et al.* 2002). A comparison of these positions with those estimated from our analysis shows agreement within 1 mas for half of the sources and within 2 mas for 80% of the sources. While the magnitude of the differences is consistent with the reported astrometric accuracy of the VLBA Calibrator Survey, further investigation is necessary to determine whether these differences are of random nature or show systematic trends. Such trends may be caused by the limited geometry used in observing the VLBA Calibrator Survey (see Beasley *et al.* 2002).

5. CONCLUSION

A total of 150 new potential ICRF sources have been successfully detected using the EVN and additional geodetic radio telescopes located in USA, Canada and Spitsbergen. About two-third of the sources observed with this EVN+ network have coordinate uncertainties better than 1 mas, and thus constitute valuable candidates for extending the ICRF. The inclusion of these sources would largely improve the ICRF sky distribution by naturally filling the "empty" regions of the current celestial frame.

Extending further the ICRF will require observing weaker and weaker sources as the celestial frame fills up and hence will depend closely on how fast the sensitivity of VLBI arrays improves in the future. Charlot (2004) estimates that an extragalactic VLBI celestial frame comprising 10 000 sources may be possible by 2010 considering foreseen improvements in recording data rates (disk-based recording, modern digital videoconverters) and new radio telescopes of the 40–60 meter class that are being built, especially in Spain, Italy and China. In the even longer term, increasing the source density beyond that order of magnitude is likely to require new instruments such as the Square Kilometer Array envisioned by 2015–2020.

Acknowledgments. The European VLBI Network (EVN) is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils. The non-EVN radio telescopes in Algonquin Park (Canada), Ny-Alesund (Spitsbergen), Goldstone (USA), and Greenbank (USA) are sponsored by Natural Resources Canada, the Norvegian Mapping Authority, the National Aeronautics and Space Administration, and the U. S. Naval Observatory, respectively. We thank all participating observatories, with special acknowledgements to the staff of the non-EVN geodetic stations, for their enthousiasm in participating in this project. We are also grateful to Nancy Vandenberg for help in scheduling, Walter Alef and Arno Mueskens for data correlation and advice in fringe-fitting, and Axel Nothnagel for export of the data to geodetic data base files. This research was supported by the European Commission's I3 Programme "RADIONET", under contract No. 505818.

6. REFERENCES

Beasley, A. J., Gordon, D., Peck, A. B., Petrov, L., MacMillan, D. S., Fomalont, E. B., Ma, C. 2002, ApJS, 141, 13.

Browne, I. W. A., Patnaik, A. R., Wilkinson, P. N., Wrobel, J. M. 1998, MNRAS, 293, 257

Charlot, P. 2004, in International VLBI Service for Geodesy and Astrometry 2004 General Meeting Proceedings, eds. N. R. Vandenberg & K. D. Beaver, NASA/CP-2004-212255, 12

Charlot, P., Viateau, B., Baudry, A., Ma, C., Fey, A. L., Eubanks, T. M., Jacobs, C. S., Sovers, O. J. 2000, in International VLBI Service for Geodesy and Astrometry 2000 General Meeting Proceedings, eds. N. R. Vandenberg & K. D. Beaver, NASA/CP-2000-209893, 168

Fey, A. L., Ma, C., Arias, E. F., Charlot, P., Feissel-Vernier, M., Gontier, A.-M., Jacobs, C. S., Li, J., MacMillan, D. S. 2004, AJ, 127, 3587

Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L., Gontier, A.-M., Jacobs, C. S., Sovers, O. J., Archinal, B. A., Charlot, P. 1998, AJ, 116, 516

Patnaik, A. R., Browne, I. W. A., Wilkinson, P. N., Wrobel, J. M. 1992, MNRAS, 254, 655

Sovers, O. J., Jacobs, C. S. 1996, Observation Model and Parameter Partials for the JPL VLBI Parameter Estimation Software "MODEST"–1996, JPL Publ. 83-89, Rev. 6, August 1996

Wilkinson, P. N., Browne, I. W. A., Patnaik, A. R., Wrobel, J. M., Sorathia, B. 1998, MNRAS, 300, 790

GAOUA REALIZATIONS OF THE CELESTIAL REFERENCE FRAME

Ya. YATSKIV, S. BOLOTIN and A. KUR'YANOVA
Main Astronomical Observatory
National Academy of Sciences of Ukraine
27 Akademika Zabolotnoho St, 03680 Kiev, Ukraine
e-mail: yatskiv@mao.kiev.ua

ABSTRACT. Short overview of the activity of the Main Astronomical observatory of National Academy of Science of Ukraine for maintenance and extension of the International Celestial Reference Frame (ICRF) is presented. Special attention is paid on the time stabilities of positions of radio sources (RS) and on the selection of a subset of RS to be used for maintenance of the ICRF. It is shown that seven RS qualified by the IERS as defining sources are unstable.

1. INTRODUCTION

Main Astronomical Observatory of the National Academy of Sciences of Ukraine (MAO NASU, GAOUA is the acronym used by the IERS) is engaged in construction of realizations of the International Celestial Reference System (ICRS) at optical and radio wavelengths. This activity is concentrated on:

- the extensive use of the Hipparcos catalogue as reference for the ICRS in works of densification and extension to fainter stars according to the FON-project;
- the construction of two different series of catalogues of radio source (RS) positions as realizations of the ICRS, namely initial catalogues of RSC(GAOUA)YY R NN and combined catalogue of RSC(GAOUA)YY C NN;
- the establishment of tie between the International Celestial Reference Frame (ICRF) and the reference frame at optical wavelengths according to the KMAC project.

2. THE FON ASTROGRAPHIC CATALOGUE (FONAC)

FONAC is the catalogue of positions, proper motions and B_J-magnitudes for $2,004,701$ stars of the Astrographic Catalogue (AC) including the $(B-V)_J$-magnitudes for $1,712,420$ stars and $(B-R)_J$-values for $1,779,442$ stars covering the northern sky between declinations $+90$ and -2 degrees (Kislyuk et al., 2000). The average epoch of positions is 1988.19. The catalogue is based on measurements of more than 1700 plates which were taken with the wide-angle astrograph of the Main Astronomical Observatory in Kiev within the FON (Photographic Survey of the Northern Sky) project. The AC data were used both as the input catalogue for measuring machine PARSEC (Programming Automatic Radial-Scanning Coordinatometer) and as the first epochs for determination of proper motions of stars. The ACT Reference Catalogue as well as the Guide Star and USNO A2.0 catalogues were applied for the reductions of positions and determination of photometric characteristics of stars. Median precision of the FONAC data are $\pm 0.2''$, $\pm 0.003''/yr$ and $\pm 0.18^m$ in positions, proper motions and magnitudes of stars, respectively.

The catalogue FONAC is available on the MAO NASU home page (ftp://ftp.mao.kiev.ua/pub/astro/fonac). It was transfered to the Strasbourg Centre of Stars Data (http://vizier.u-strasbg.fr/viz-bin/Vizie?-source=I/261).

3. THE FIRST KYIV MERIDIAN AXIAL CIRCLE CCD CATALOGUE (KMAC1) OF STARS IN FIELDS WITH EXTRAGALACTIC RADIO SOURCES

KMAC1 is the catalogue of astrometric (positions, proper motions) and photometric (B, V, R, r', J) data of stars in fields with the ICRF objects which has been compiled by MAO NASU in cooperation with the Kyiv University Observatory (Lazorenko et al., 2004). All fields are located in declination zone from 0 to +30 degrees; nominal field size is $46'$ (right ascension) $\times$ $24'$ (declinations). The observational basis of this catalogue is 1100 CCD scans deep to $V = 17$ mag which were obtained with the Kyiv meridian axial circle in 2001-2003 and which contains one million of images. Astrometric reduction has included the correction depending on image size fluctuations and position of a star on the CCD along the declination axis. A special approach was used for correction of magnitude-dependent errors since images of bright stars were oversaturated. The catalogue KMAC1 is presented in two versions. The first version named as KMAC1-T which contains 156 fields (106417 stars) was obtained with use of the Tycho2 catalogue as reference one. Astrometric reduction for another 36 fields was found to be unreliable due to a low sky density of Tycho2 stars. Therefore the second version KMAC1-CU was made for 192 fields using UCAC2 and CAMC13 catalogues as reference ones; it contains 115032 stars and has a slightly better accuracy. Proper motions have been found using the USNOA2.0 catalogue as a first epoch catalogue. An "external" uncertainty (based on comparison to UCAC2 and CAMC13) of one catalogue position is about 60-70 mas for 14-15 mag stars. An average error of photometry is better than 0.1 mag for stars up to 16 mag.

4. THE GAOUA INITIAL CATALOGUES OF RS POSITIONS

Series of the initial catalogues RSC(GAOUA)YY R NN has been constructed using several versions of the SteelBreeze software for reduction of the VLBI observations (Bolotin, 2001). The overview of these catalogues is given in (Yatskiv, Kur'yanova and Bolotin, 2004). The latest version of the catalogue of this type RSC(GAOUA)03 R 01 is based upon a solution for all applicable VLBI data since 1979 till July 2003. In total $3,550,143$ dual frequency delays acquired on $2,970$ astrometric and geodetic sessions have been processed. The initial values of RS positions have been taken from the ICRF-Ext.1. Orientation of constructed reference frame was defined by a No-Net-Rotation condition between the ICRF-Ext.1 and the derived catalogue using 35 defining radio sources. The catalogue contains the positions of 1558 RS, including 211 defining RS. The average internal positional precision of these RS is about 0.1 mas (Bolotin, 2004).

The relative orientation between this initial frame and the ICRF-Ext.1 is given in Table 1 (first line).

5. GAOUA COMBINED CATALOGUES OF RS POSITIONS

The Kyiv arc length method proposed by Ya. Yatskiv and A. Kur'yanova, 1990, was used for construction of catalogues of type RSC(GAOUA)YY C NN since 1991. This method combines a geometrical arc length calculation with a statistical evaluation of uncertainties of initial and combined catalogues. Several combined solutions based upon initial catalogues of RS positions provided by IERS and/or IVS were constructed (Yatskiv, Molotaj, Kur'yanova and Tel'nyuk-Adamchuk, 2003). The latest version of such combined catalogue is RSC(GAOUA)03 C 02 which contains the positions of 1667 RS, including 211 defining sources (Yatskiv, Kur'yanova, Bolotin, 2004). The positional accuracy of the defining RS is better than about 0.1 mas. The relative orientation between the RSC(GAOUA)03 C 02 and the ICRF-Ext.1 is given in Table 1 (second line).

Frame	N_d	A_1	A_2	A_3
RSC(GAOUA)03 R 01	211	$+24 \pm 30$	$+20 \pm 30$	-15 ± 35
RSC(GAOUA)03 C 02	211	$+4 \pm 26$	-13 ± 26	-11 ± 30

Table 1: Relative orientation between initial frame RSC(GAOUA)03 R 01, combined catalogue RSC(GAOUA) 03 C 02 and ICRF-Ext.1. A_1, A_2, A_3 are the rotation angles (in μas); N_d is the number of common defining sources

IERS Des.	RSC(GAOUA)										St.
	98 C 01		99 C 03		00 C 01		01 C 01		03 C 02		
	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	
0138 − 097	2.22	—	1.63	—	1.64	—	2.34	—	2.03	—	D
0259 + 121	—	—	—	4.70	—	1.25	—	1.45	—	1.39	C
0440 − 003	—	-1.11	—	-1.25	—	-1.08	—	-1.26	—	-1.00	D
0454 − 463	—	—	—	-6.56	—	-17.97	—	-16.73	—	—	C
0529 + 075	-1.38	—	—	—	-1.31	—	—	—	-1.01	—	C
0600 + 219	—	—	—	—	—	1.18	—	1.22	—	2.26	O
0823 − 500	-1.48	—	-1.40	—	-1.32	—	-1.67	—	-7.09	—	C
1156 − 094	1.42	—	1.33	—	1.36	—	1.11	—	1.04	—	C
1323 + 321	-10.74	—	-1.10	—	—	—	-2.36	—	—	—	C
1328 + 307	—	—	-1.01	—	-0.97	—	-0.98	—	-1.32	—	C
1402 − 012	—	1.04	—	0.97	—	0.94	—	2.47	—	2.77	C
1409 + 218	—	—	—	1.10	—	0.99	—	0.91	—	—	C
1540 − 828	2.04	—	2.24	—	2.44	—	1.01	—	—	—	C
1604 − 333	—	—	—	—	0.94	—	1.08	–	0.76	–	D
1718 − 649	—	1.06	—	1.08	—	—	—	1.62	—	1.34	D
1733 − 565	—	—	0.86	—	0.80	—	1.30	—	1.57	—	C
1740 − 517	-2.57	—	-1.71	—	-2.46	—	—	—	—	—	C
1806 − 458	-2.76	—	-1.93	—	-0.92	—	—	—	-1.38	—	C
1934 − 638	-1.95	—	-1.99	—	-2.30	—	-1.08	—	—	—	C
1951 + 355	—	-2.05	—	-1.89	—	-1.79	—	-1.75	—	-1.26	C
2128 + 048	—	—	1.05	—	0.96	—	1.02	—	1.20	—	O
2312 − 319	—	-0.98	—	-1.14	—	-1.19	—	-0.79	—	—	D

Table 2: Statistics of large differences of type "Combined catalogue − ICRF-Ext.1" (in mas). D is defining RS, C is candidate RS and O is other RS

IERS Des.	RSC(GAOUA)									
	98 C 01		99 C 03		00 C 01		01 C 01		03 C 02	
	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$
$0039+230$	—	—	—	—	—	0.54	—	0.53	—	0.68
$0123+257$	—	—	—	-0.47	—	—	—	-0.68	—	-0.57
$0131-522$	—	—	—	0.71	—	0.58	—	—	—	1.53
$0138-097$	2.22	—	1.63	—	1.64	—	2.34	—	2.03	—
$0437-454$	-0.54	—	-0.48	—	-0.47	—	-0.44	—	—	—
$0440-003$	—	-1.11	—	-1.25	—	-1.08	—	-1.26	—	-1.00
$0458+138$	—	-0.76	—	-0.97	—	-0.84	—	-0.85	—	-0.39
$0518+165$	—	0.69	—	0.56	—	0.48	—	0.47	—	0.36
$0537-286$	0.40	—	0.42	—	0.46	—	0.51	—	0.63	—
$0733-174$	-0.30	—	-0.52	-0.48	-0.50	—	-0.52	-0.51	-0.60	-0.93
$0812+367$	—	—	—	0.72	—	0.71	—	0.73	—	0.52
$0829+046$	—	—	—	0.52	—	0.52	—	0.47	—	0.48
$1038+064$	—	-0.60	—	-0.62	—	-0.58	—	-0.54	—	-0.47
$1143-245$	—	—	-0.79	—	-0.87	—	-0.90	—	-0.74	—
$1448+762$	0.75	—	0.84	—	0.88	—	0.98	—	0.72	—
$1604-333$	—	—	—	—	0.94	—	1.08	—	0.76	—
$1616+063$	—	—	—	-0.66	—	-0.61	—	-0.60	—	—
$1718-649$	—	1.06	—	1.08	—	—	—	1.62	—	1.34
$1727+502$	—	—	—	—	-0.53	—	-0.57	—	0.89	—
$2059+034$	—	-1.03	—	-0.76	—	-0.66	—	-0.63	—	-0.62
$2312-319$	—	-0.98	—	-1.14	—	-1.19	—	-0.79	—	-0.46

Table 3: Statistics of large differences of type "Combined catalogue $-$ ICRF-Ext.1" for common defining RS (in mas)

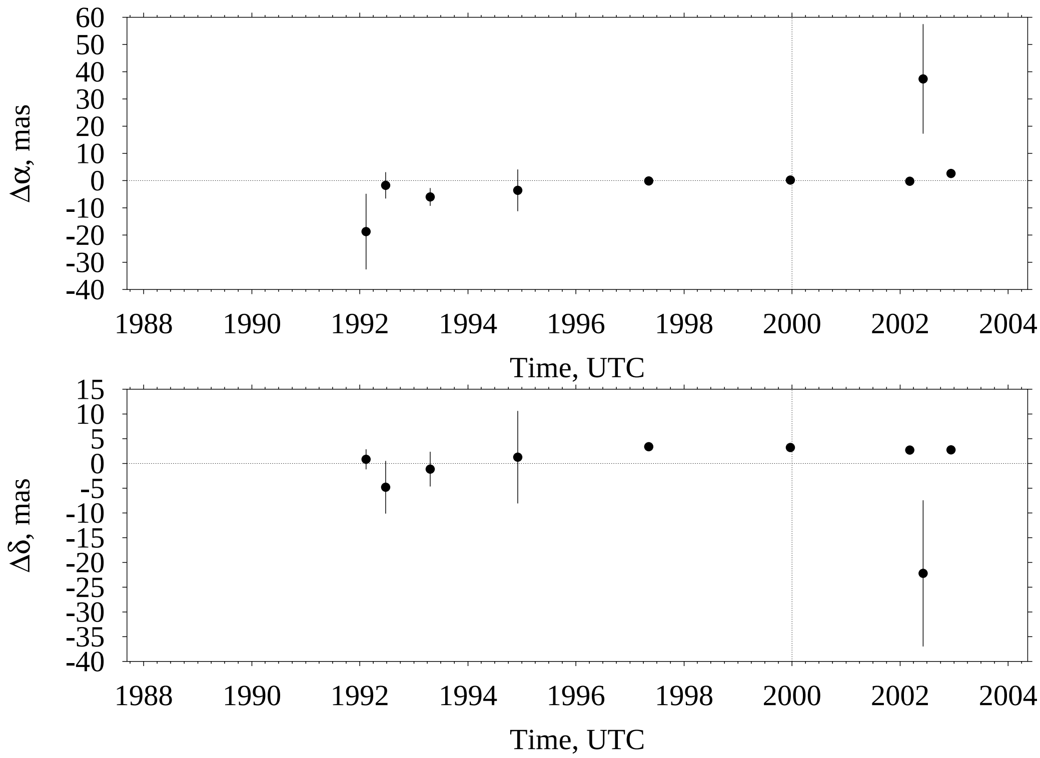

Figure 1: Estimated variations of the coordinates of radio source 1402-012, right ascension (upper figure) and declination.

IERS Des.	A_α *mas*	V_α *mas*/yr	A_δ *mas*	V_δ *mas*/yr	σ_α *mas*	σ_δ *mas*	σ *mas*	N_s	N_d	St.
$0039+230$	-0.06	0.02	0.89	0.16	0.16	0.27	0.32	5	350	D
$0123+257$	0.17	0.02	-0.84	-0.08	0.18	0.26	0.32	9	477	D
$0138-097$	1.85	-0.01	0.03	-0.04	0.14	0.18	0.23	3	232	D
$0259+121$	0.11	-0.03	1.67	-0.02	0.55	0.20	0.58	4	228	C
$0437-454$	-0.11	0.06	-0.73	-0.21	0.27	0.81	0.85	6	46	D
$0440-003$	-0.46	-0.11	-1.53	-0.09	0.23	0.23	0.32	11	459	D
$0458+138$	-0.09	-0.08	-0.07	-0.10	0.16	0.51	0.53	4	272	D
$0518+165$	-3.45	-0.45	5.39	0.55	0.97	1.71	1.97	6	64	D
$0529+075$	3.36	0.84	0.21	0.11	1.01	1.72	1.99	7	63	C
$0537-286$	0.79	0.03	-0.58	-0.00	0.27	0.43	0.50	14	305	D
$0733-174$	-0.61	-0.11	-1.69	-0.22	0.23	0.55	0.59	7	182	D
$0812+367$	0.37	-0.01	0.77	0.04	0.26	0.45	0.52	7	286	D
$0829+046$	0.00	-0.02	0.50	0.04	0.36	0.38	0.52	13	426	D
$1038+064$	-0.05	-0.04	-0.47	0.04	0.30	0.52	0.60	38	752	D
$1143-245$	-1.19	-0.14	0.42	0.03	0.51	0.37	0.63	9	299	D
$1156-094$	0.78	-0.00	0.25	-0.30	0.09	1.01	1.01	4	96	C
$1323+321$	15.34	3.92	-9.60	-2.26	3.23	1.37	3.51	5	119	C
$1328+307$	-1.31	0.15	-0.66	0.05	0.83	0.55	0.99	4	149	C
$1402-012$	0.08	0.10	3.05	-0.08	0.63	0.39	0.74	6	218	C
$1409+218$	0.69	0.12	1.15	-0.14	0.33	0.30	0.44	4	218	C
$1448+762$	0.88	-0.09	0.11	0.01	0.22	0.17	0.28	29	3530	D
$1604-333$	0.24	-0.04	-0.75	-0.10	1.02	0.88	1.35	8	159	D
$1616+063$	0.08	-0.01	-0.57	-0.03	0.16	0.49	0.51	7	384	D
$1718-649$	-2.12	-0.31	4.52	0.62	0.73	1.03	1.26	3	29	D
$1727+502$	1.31	0.36	-0.53	0.03	0.38	0.47	0.60	3	96	D
$1951+355$	-0.08	-0.03	-1.29	0.08	0.48	0.52	0.71	5	164	C
$2059+034$	-0.31	0.01	-0.65	-0.01	0.18	0.29	0.35	13	750	D
$2128+048$	-0.66	-0.32	-2.91	-0.35	0.78	0.59	0.97	4	35	O
$2312-319$	-0.49	0.04	-0.63	0.30	0.35	0.77	0.85	6	262	D

Table 4: Statistics of time series of coordinates of radio sources, unstable or suspected of instability according to adopted criterion; N_s is number of sessions, N_d is number of observations

6. MAINTENANCE OF THE TIME STABILITY OF THE ICRF

The IAU has charged the IERS with the responsibility of monitoring the ICRS and maintaining its current realization. The MAO NASU being involved in the IERS activity has undertaken the study of the time stabilities of RS coordinates. With this end in view we have analyzed the year-to-year differences between positions of RS in the combined frames RSC(GAOUA) constructed since 1998, and the ICRF-Ext.1 (Yatskiv et al. 2004). The large differences in RA and Dec were identified with the help of simple criteria, namely the differences larger then 1 mas (for all RS) and 0.45 mas (for defining RS) were considered as large ones in case that they occur not less than three times. Table 2 and 3 summarize the results of this study.

Based on this study we concluded that there were about 22 RSs which have exhibited large systematic differences. Four of these RSs are defining sources, namely 0138-097, 0440-003, 1718-649 and 2312-319. These RS are suspected of instabilities and should be excluded from a subset of objects that is used for the maintenance of the ICRF.

To reach a final conclusion on this problem we have analyzed the time stabilities of coordinates of these "unstable" RS using the approach proposed by M. Feissel (Feissel-Vernier, 2004).

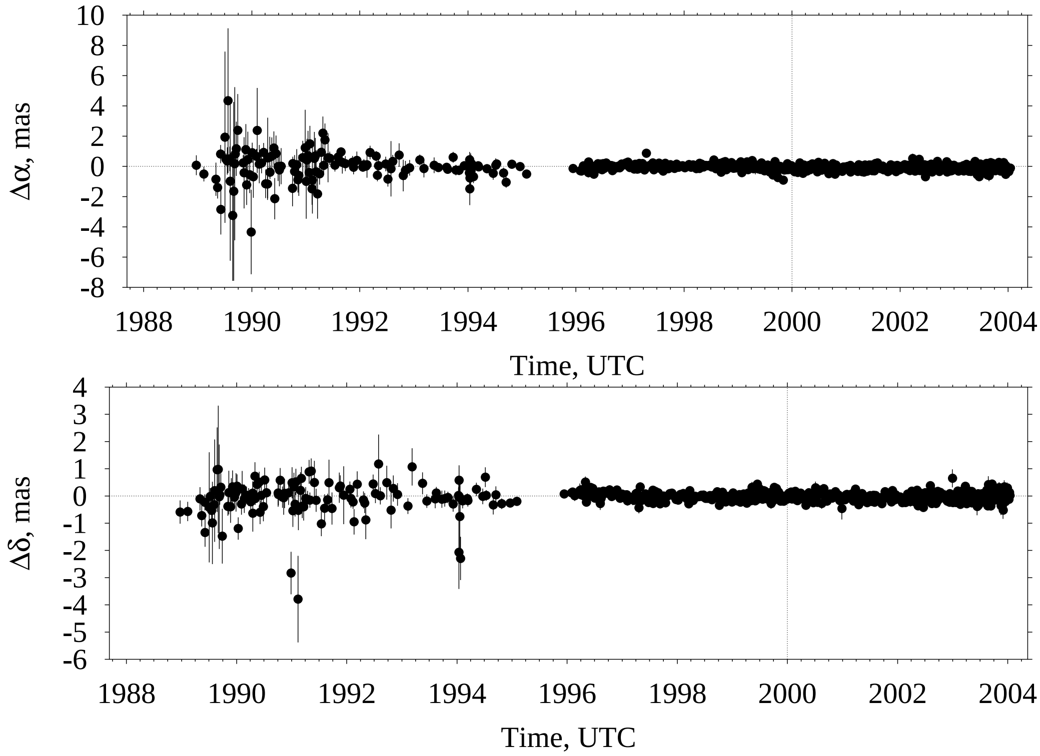

Figure 2: l Estimated variations of the coordinates of radio source 0133+476, right ascension (upper figure) and declination.

IERS Des.	A_α mas	V_α mas/yr	A_δ mas	V_δ mas/yr	σ_α mas	σ_δ mas	σ mas	N_s	N_d
$0014+813$	-0.07	-0.01	0.19	0.03	0.15	0.18	0.23	629	41870
$0133+476$	-0.04	-0.01	-0.03	-0.01	0.11	0.14	0.18	658	58061
$0642+449$	0.01	0.00	0.02	-0.01	0.13	0.16	0.21	641	39146
$0804+499*$	0.08	-0.00	-0.01	-0.01	0.13	0.16	0.21	825	57321
$0955+476$	-0.09	-0.03	0.01	0.00	0.13	0.16	0.21	1157	71070
$1128+385$	-0.03	-0.01	0.01	0.00	0.14	0.21	0.25	713	39793
$1308+326*$	0.04	0.00	0.07	0.01	0.23	0.23	0.33	1189	70529
$1606+106*$	0.08	0.02	0.01	-0.00	0.19	0.22	0.29	1339	64916
$2037+511*$	-0.13	-0.01	-0.14	-0.00	0.15	0.20	0.25	443	17602
$2145+067*$	-0.18	-0.03	0.03	0.01	0.29	0.27	0.39	1535	64450

Table 5: Estimates of trends of coordinates of defining RS (considered as sufficiently stable)

For this purpose all applicable VLBI data since 1988 were reduced using the SteelBreeze software. Firstly the standard solution for terrestrial and celestial frames as well as for ERP was made. Then solved for parameters obtained on this stage were used for determination of the year-to-year variations of coordinates of those RS which were suspected to be unstable. These variations were approximated by linear trends

$$\begin{aligned}\Delta\alpha_i cos\delta_i &= A_\alpha + V_\alpha(t_i - t_o)\\ \Delta\delta_i &= A_\delta + V_\delta(t_i - t_o),\end{aligned}$$

where t_o is a mean epoch of observations.

The estimates obtained are given in Table 4, where σ_α and σ_δ are rms of the post-fit residuals in $\Delta\alpha_i cos\delta_i$ and $\Delta\delta_i$ respectively and σ is the modulus of their vectorial sum.

On the basis of these results we come to a conclusion that the coordinates of some of RS exhibit considerable time variations. An example of such variations for RS 1402-012 is shown on Fig. 1.

To answer the question on a reality of the coordinate variations of RS given in Table 4 we have to define the stability level σ_0. Then we will consider the sources as unstable for which the values σ are larger than σ_o. We derived $\sigma_o = 0.40mas$ on the basis of analysis of the year-to-year variations of the coordinates of those RS which is known are sufficiently stable ones (see Table 5 and Fig. 2).

One can see that there are 23 RS for which $\sigma > \sigma_o$. Among them there are two defining RS which were suspected to be unstable on the first step of analysis, namely 1718-649 and 2312-319.

Acknowledgment. The authors are grateful to Dr. V.S. Kislyuk and Dr. P.F. Lazorenko for their contributions to this paper. This work was partly supported by the STCU grant NN43.

7. REFERENCES

Bolotin S.L., 2001. Analysis of VLBI observations. Estimation of parameters, Kinematics and Physics of Celestial Bodies, **17**, No. 3, Kiev, pp. 240-248.

Bolotin S., 2004. Estimation of the Celestial Intermediate Pole motion in the Terrestrial and Celestial reference frames for VLBI observations on the interval 1979 - 2003, Proc. Journees 2003, Astrometry, Geodynamics and Solar System Dynamics: from Milliarcseconds to Microarcseconds, St. Petersburg (Russia) (in print)

Feissel-Vernier M.,2004. Assessing astrometric quality: stability of the VLBI-derived extragalactic celestial frame, IERS Technical Note, Ed. J.Souchay (in preparation).

Kislyuk V.S., Yatsenko A.I., Ivanov G.A., Pakuliak L.K., Sergeeva T.P., 2000. FONAC: The astrographic catalogue of the FON project, Kinematiks and Physics of Celestial Bodies, **16**, 6, pp. 483-496.

Lazorenko P., Babenko Yu., Karbovsky V., Buromsky N., Kasjan S., Denusyuk O., 2004. Astrometric Reference Catalogue KMAC1 in 192 Fields with Extragalactic Radiosources, Abstract book of the conference "Astronomy in Ukraine - Past, Present and Future" (July 15-17, 2004, Kiev, Ukraine), P.143.

Yatskiv Ya.S., Kur'yanova A.N., 1990. A new approach to the construction of a compiled catalogue of positions of extragalactic radio sources, In: Inertial Coordinate System on the Sky, Proc. 141 th IAU Symp., pp. 295-296.

Yatskiv Ya., Kur'yanova A. and Bolotin S., 2004. ICRF consistency check by comparison of the ICRF-Ext.1 with the GAOUA series of RS catalogues, Proc. Journées 2003, Astrometry, Geodynamics and Solar System Dynamics: from milliarcseconds to microarcseconds, St. Petersburg (Russia), pp. 39-46.

Yatskiv Ya.S., Bolotin S.L., Kur'yanova A.N., 2004. GAOUA - realizations of celestial reference frame, Kinematics and Physics of Celestial Bodies, Vol. **20**, No 4, pp. 291–299.

Yatskiv Ya., Molotaj O., Kur'yanova A. and Tel'nyuk - Adamchuk V., 2003. Recent compiled catalogue of radio source positions RSC(GAOUA)01 C 01, Proc. Journées Systèmes de Référence Spatio-Temporels 2002, Astrometry from Ground and Space, Bucharest (Romania), pp. 60–65.

FAINT REFERENCE CATALOGUES AROUND ICRF RADIO SOURCES FROM PHOTOGRAPHIC OBSERVATIONS

B. BUCCIARELLI[1], M.G. LATTANZI[1], G. MASSONE[1], A. POMA[2], Z. TANG[3], S. URAS[4]

[1] INAF - OATo Osservatorio Astronomico di Torino
Via dell'Osservatorio 20, 10025 Pino Torinese (TO), Italy
e-mail: bucciarelli@to.astro.it, lattanzi@to.astro.it, massone@to.astro.it

[2] INAF - OAC Osservatorio Astronomico di Cagliari
Loc. Poggio dei Pini, Str. 54, 09012 Capoterra (CA), Italy
e-mail: poma@ca.astro.it

[3] SHAO - Shanghai Astronomical Observatory
Nandan Road 80, Shanghai, 200080 China
e-mail: zhtang@shao.ac.cn

[4] INAF/CNR - Istituto di Radioastronomia - Sezione di Cagliari
Loc. Poggio dei Pini, Str. 54, 09012 Capoterra (CA), Italy
e-mail: uras@ca.astro.it

ABSTRACT. A *by-product* of the method of photographic observations of the radio reference frame sources is the realization of astrometric fields around each QSO, with accuracy less than 100 mas. We present here some results derived from plates collected during a photographic campaign on 89 QSOs.

1. INTRODUCTION

The procedure of photographic observations applied to the optical link of the VLBI defined celestial reference frame was commonly carried out in two steps, which consists in obtaining two exposures of the QSO target field, thereby combining the capabilities of medium and long focus telescopes. Specifically, precise positions of anonymous stars from the larger field telescope are first reduced by using available astrometric catalogues (primary reference stars); then, they are employed as secondary reference positions for the reduction of the deeper, smaller field plates where the radio source is well visible but which cannot support a direct link to the primary reference stars due to their paucity and to their often saturated images. A *by-product* of this technique is the realization of astrometric fields around each QSO target, whose accuracy is typically in the range of 50 to 100 mas, and therefore suitable for a varieties of astrometric studies.

We briefly discuss here some very preliminary results derived from a small sample of plates from the ones collected during a photographic campaign on 89 QSOs carried out between 1986 and 1994. The observations were made mostly with the Torino astrometric reflector REOSC

(D= 105 cm, F= 9942 mm) and photographic refractor Morais (D= 38 cm, F= 6875 mm). All 350 plates were measured in Cagliari on the automatic ToCaMM (Torino Cagliari Measuring Machine) with an accuracy of about 1 μm per stellar image coordinate (Del Bò et al., 2000; Lattanzi et al. 2001). The ToCaMM machine is presently also used for testing results obtained with commercial scanners in the framework of the national project *Digitization of the Archives of Photographic Plates of Italian Astronomical Observatories* aimed to perform a 2yr program of selective digitization of plates (both images and spectra) present in the Italian photographic archives.

2. FIRST RESULTS AND REMARKS

Due to the limits of this paper, we will only give a first evaluation of the quality of the results. To test our software, we have considered more than 4,200 secondary stars around three radio sources (0716+714, 0839+187 and 1928+738). The number of plates available for each of the three sources varied from two to six. We have therefore compared the plate solutions of the stars in common for each source and calculated the standard deviation around the mean for each object; this resulted in an average positional error of less than 100 mas - about as good as one would expect. Such an error accounts for uncertainties coming from the characteristics of the exposure itself, the stability of the measuring process, and the ability to centroid the stellar image, but it includes also possible unmodelled sistematic residuals coming from the plate reduction.

Preliminary results (Bucciarelli et al, 2003) based on a sample of 20 radio sources have shown that the QSO's optical and radio positions are well in agreement within the stated formal errors; however, there is evidence that the proper modelling of a magnitude-dependent effect can in general improve the quality of the final results. With such a refined reduction procedure we expect to be able to get new astrometric positions for about 120,000 stars measured in the neighbourhood of about 90 QSO's. We note that all these stars belong to the GSC-I catalogue, from which the *anonymous* objects measured on our plates were originally extracted.

Acknowledgements. We wish to thank G.L. Deiana, V. Gusai and G. Meloni for their help with the daily operation of the TOCAMM machine and the measurements of the plates.

3. REFERENCES

Bucciarelli, M.T. Crosta, M.G. Lattanzi, G. Massone, R.Morbidelli, Z. Tang, W. Jin, G. Deiana, A. Poma, S. Uras, Astrometric measurements of radio sources optical counterparts OATo Campaign: Some Final Results, 2003, IAU G.A., Joint Discussion 16, The International Celestial References System, Maintenance and Future Realizations.

Del Bò, M., Deiana, G.L., Lattanzi, M.G., Massone, G., Poma, A., Porcu, F., Salvati, F.,Uras, S., The TOCCAM Project, 2000, in Proceedings of the 178th Colloquium of the IAU, ASP Conference series Proceedings of the IAU coll. 178, Dick S., McCarthy D. & Luzum B. eds., ASP Conference series vol. 208

Lattanzi M.G., Massone G., Poma A., Uras S., A contribution to the link of the Hipparcos catalogue to ICRS, 2001, Journées 2000 - systèmes de référence spatio-temporels, Paris 18-20 September 2000; edited by N. Capitaine, Paris: Observatoire de Paris, ISBN 2-901057-45-4, p. 33-36

PRECISE NEAR-IR ASTROMETRY AND PHOTOMETRY OF SOUTHERN ICRF QUASARS

J.I.B. CAMARGO[1,2], G. DAIGNE[1], C. DUCOURANT[1], P. CHARLOT[1]

[1] UMR 5804, Observatoire Aquitain des Sciences de l'Univers
BP-89 F-33270 Floirac

[2] CNPq, Brésil
e-mail: camargo, daigne, ducourant, charlot@obs.u-bordeaux1.fr

ABSTRACT. We present high quality astrometry along with photometry for 30 southern ICRF quasars observed with the ESO NTT/SOFI at La Silla, in the J, H and K_s bands. While the internal precision for the positions of these quasars is generally better than 10 mas, our best positional accuracy, as given by a set of 14 quasars observed in an enlarged field of view, is 25 mas. Corrections for the field distortion of the camera have been applied to all images. The precision in magnitude determination is generally better than 0.04 mag. One of the objectives of this project is to provide initial candidates to the optical extension of the ICRF.

1. INTRODUCTION

The International Celestial Reference System (ICRS; Arias et al. 1995) is realized by the sub-milliarcsecond accurate positions of 212 extragalactic compact radio sources listed in the International Celestial Reference Frame (ICRF; Ma et al. 1998). In the GAIA perspective, a primary realization of the ICRS in the optical range is being considered, and the coincidence of the optical and radio frames is a natural concern.

In this context, a pilot observing program of 30 southern ICRF quasars was carried out in January 2003 with the ESO NTT/SOFI, with emphasis on astrometry but also with photometric objectives. The presented work is, in particular, an initial step towards the determination of very accurate optical positions of sources in the ICRF. The major results of this observing program are summarized below. For a more detailed discussion about the observations and data analysis, see Camargo et al. (2004).

2. RESULTS

Observed magnitudes, with precisions generally better than 0.04 mag, were derived from photometric measurements (calibrated with the 2MASS) in the J, H and K_s bands, and cover a range (11.5 - 17.3 mags in the K_s band) that includes most of the ICRF quasars. Figure 1, left panel, shows the distribution of the observed quasar magnitudes in these 3 bands. The derived mean spectral index $< \alpha >$ of the observed quasars is -1 ($F_\nu \propto \nu^\alpha$). These photometric measurements are important to evaluate the feasibility of detailed imaging of quasars with nearinfrared interferometry, considering that objects as faint as $K_s = 19$ may be detectable in the future with large optical telescopes and spatial phase-referenced imaging (Glindemann et al. 2003; Daigne & Lestrade 2003).

The astrometric reduction was carried out for single images and enlarged fields of view, all images being corrected for the field distortion of the camera. The enlarged fields of view consist of mosaics of overlapping images taken for a selected sub-sample of 14 quasars. Observations in this mode benefit from a larger number of reference (UCAC2) stars, as compared to single images. A global reduction technique was used for the astrometric analysis of these mosaics, with a resulting positional accuracy of 25 mas. This value should be compared to 35 mas, the positional accuracy derived for all 30 quasars from single-image analyses. Figure 1, right panel, shows individual gains of accuracy in the positions of the 14 selected quasars, by comparing their single-image and mosaic analysis results.

The quasar positions derived from the measurements in the 3 photometric filters show an internal precision generally better than 10 mas, a value comparable to the typical size of extended structures observed in quasar radio maps. An accuracy to this level may be reached from observations with the NTT/SOFI by means of denser stellar fields around the quasar positions, and would imply a more physical approach when comparing radio and optical positions in the future.

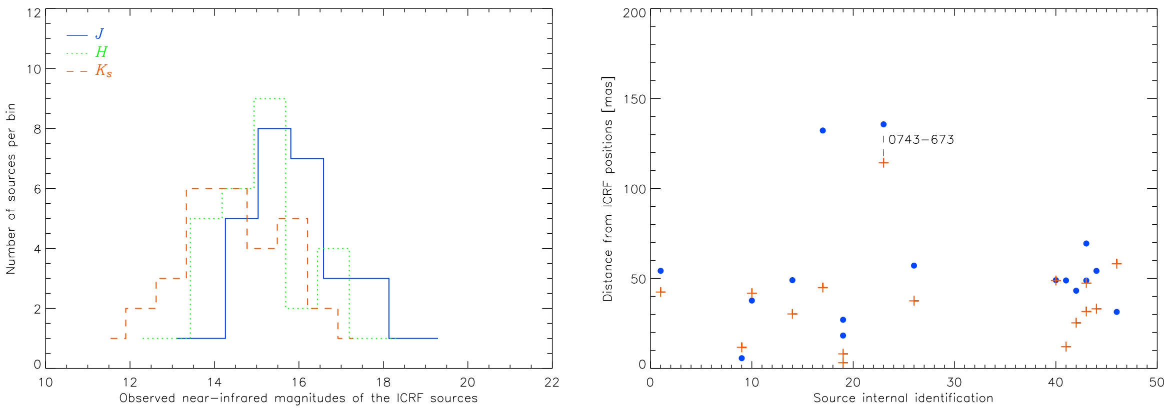

Figure 1: Left panel: Distribution of the observed quasar magnitudes in the J, H and K_s bands. Right panel: Accuracy of the positions derived from the astrometric analysis of single images (dots) and mosaics (crosses) to the 14 quasars observed with enlarged fields of view. It is interesting to notice that the ICRF candidate source 0743−673 (see right panel), presented a large systematic effect from both its single-image and mosaic analyses.

3. REFERENCES

Arias, E.F., Charlot, P., Feissel, M., & Lestrade, J.-F. 1995, A&A , 303, 604

Camargo, J.I.B., Daigne, G., Ducourant, C. & Charlot, P. 2004, A&A , submitted

Daigne, G. & Lestrade, J.-F. 2003, A&A, 406, 1167

Glindemann, A., Algomedo, J., Amestica, R., et al. 2003, in Interferometry for Optical Astronomy II (Ed. W. Traub), Proc. SPIE, Vol. 4838, 89

Ma, C., Arias, E.F., Eubanks, T.M., et al. 1998, AJ , 116, 516

IMPROVING THE ICRF IN THE SOUTHERN HEMISPHERE

A.L. FEY
U.S. Naval Observatory
3450 Massachusetts Avenue, NW
Washington, DC 20392-5420 USA
afey@usno.navy.mil

ABSTRACT. It is well known that the ICRF has a less than desirable density of sources on the sky, particularly in the southern hemisphere. To address concerns about the non-uniform distribution of ICRF sources and to monitor sources for structural variations, various observing programs have been initiated. In this paper, we concentrate primarily on two programs specifically aimed at improving the ICRF in the southern hemisphere. The U.S. Naval Observatory (USNO) currently has a joint program with the Australia Telescope National Facility (ATNF) for astrometry and imaging of southern hemisphere ICRF sources. Additionally, the IVS schedules regular CRF observations for the specific purpose of maintenance of the ICRF. In recent years, these CRF sessions have concentrated primarily on observations of sources in the southern hemisphere. Results to date of these dedicated observing programs are briefly described.

1. USNO/ATNF OBSERVING PROGRAM

The USNO currently has a joint program with the ATNF for astrometry and imaging of southern hemisphere ICRF sources. Geodetic and/or astronomical telescopes located in Australia, South Africa, Japan and Hawaii are used and scheduled on an ad-hoc basis. The goals of this joint program are to 1) image all southern hemisphere ICRF sources at least twice for structure monitoring and 2) search for new astrometric sources for densification of the ICRF in the southern hemisphere. The interested reader is referred to Ojha et al. (2004, AJ, 127, 3609) for a discussion of the imaging

2. IVS OBSERVING PROGRAM

The IVS schedules regular CRF observations for the specific purpose of maintenance of the ICRF. In recent years, these CRF sessions have concentrated primarily on observations of sources in the southern hemisphere. Of order 10 CRF sessions per year are scheduled and observed. Geodetic and/or astronomical telescopes located in Australia, South America, South Africa, Japan and Hawaii are used. IVS CRF observations concentrate primarily on 1) obtaining more accurate positions of existing ICRF sources by adding additional observations and 2) obtaining source position stability information from time series at useful time resolution. Sources chosen for CRF sessions consist mostly of ICRF Defining sources and those sources determined to be stable by the criteria of Feissel-Vernier (2003, A&A, 403, 105).

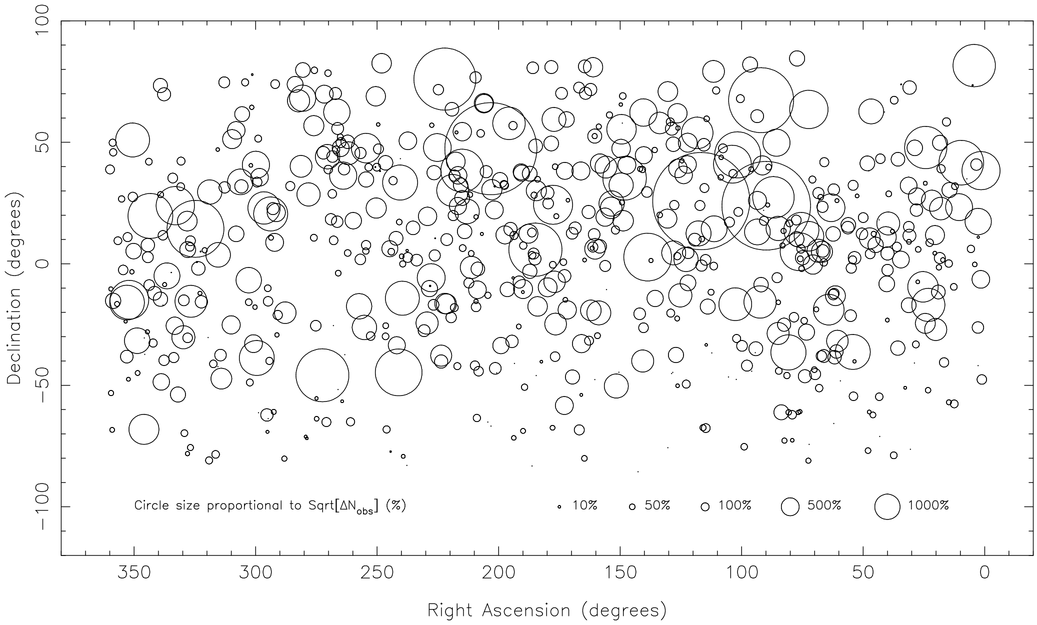

Figure 1: The percentage increase in the number of delay observations obtained for 650 ICRF-Ext.1 sources as of 2004 June 8 as a function of sky position. Circle size is linearly proportional to the square-root of the percentage increase. Note that results of observing programs in addition to the ones discussed here are also included. Sources new to the ICRF since ICRF-Ext.1 are not included.

3. OBSERVATIONAL RESULTS TO DATE

Positions for a total of 228 sources new to the ICRF have been obtained since the definition of the ICRF (see Fey et al. 2004, AJ, 127, 1791; Fey et al. 2004, AJ, 127, 3587). Seventy-seven of these sources are south of $\delta = 0°$ and 58 are south of $\delta = -30°$. The percentage increase in the number of observations per source obtained for ICRF-Ext.1 sources has increased for all but 7% of the sources. However, the percentage increase in the number of observations per source decreases for southern sources with far south sources having the smallest increase (see Figure 1). Additionally, the percentage of sources with no increase in the number of observations since ICRF-Ext.1 increases for southern sources with far south sources having the largest percentage of sources with no additional observations (see Table 1).

Table 1.

Declination Range	# Sources	Sources with no new observations since ICRF-Ext.1 (%)
$-90° < \delta < 90°$	650	7
$\delta < 0°$	270	13
$\delta < -40°$	108	25

INFLUENCE OF THE EARLY VLBI OBSERVATIONS ON THE ICRF STABILITY

J.R. SOKOLOVA
Astronomical Institute of St.-Petersburg State University
S-Petersburg, University pr.,28, NIAI
e-mail: S0lei@yandex.ru

ABSTRACT. We studied the cumulative effect of the early VLBI observations (before 1990 year) on the CRF solution stability. Three CRF solutions on different time intervals have been obtained using the Occam6.0 software. All sources were treated as global parameters. Calculation of the estimated coordinate differences between the individual solutions provides a criteria for detection of the highly unstable sources. Several sources with high visible motions are detected.

1. INTRODUCTION

The problem of stable radiosources selection is important for the next ICRF realization. The goal of the paper is to study a combined effect of early VLBI observations (before 1990). Discussion about quality of the early observation has arisen recently. Gontier et al., (2001) found that the yearly CRF solutions significantly vary from year to year before 1990. Therefore, Feissel-Vernier (2003) recommended to use a set of 199 'stable' radiosources studying the position time series over 1989.5 - 2002 from data set by Fey (2002). The set of 199 'stable' sources demonstrates better stability by a factor 3-5 than the set of 212 'defining' sources through the 13-year period. Nevertheless, general strategy for global solution preparation requires all VLBI observations to be included. We try to evaluate stability of the 'stable' source list over the period 1980-1989.

2. CATALOGUES

About 2.6 million of time delays have been processed by least squares collocation using OCCAM software (Titov et al., 2004). Three solutions covering 1980-2003, 1990-2003 and 1996-2003, respectively were produced. Then we made up differences between the radiosource positions in the three catalogues. The range of position differences between 1980-2003 and 1990-2003 solutions is a measure of stability for individual radiosources for the first decade of VLBI observations. The last solution (covering 1996-2003) is used for additional control.

3. DISCUSSION

Fig. 1,2 show position differences between two first catalogues. The radiosources observed only after 1990 are plotted on the Fig.1. Their differences were made up from the same set of observation, therefore, they are small because they reflect just internal instability of the solutions. All the values are less than 0.003 msec in RA and 0.02 mas in DEC. In opposite, the radiosources observed both before as well as after 1990 show greater differences (fig.2), that reach 0.01 msec in RA and 0.2 mas in DEC The largest offset was found for the radiosource 2134+00 - almost 1 mas.

-	Solution 1	Solution 2	Solution 3
Years	1980 - 2003	1990 - 2003	1996 - 2003
Num of obs	2.584,417	2.274,925	1.369,344
WRMS(cm)	0.6274	0.6058	0.5902

Table 1: Solution statistics

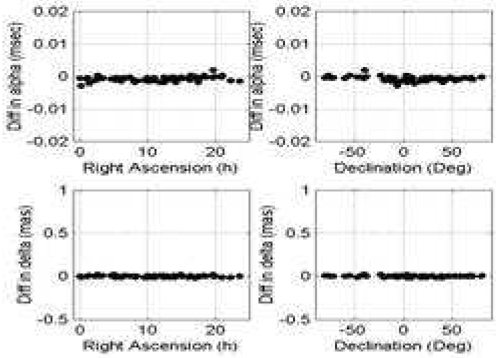

Fig. 1 Coordinate differences between two first catalogues for radiosources observed after 1990 year.

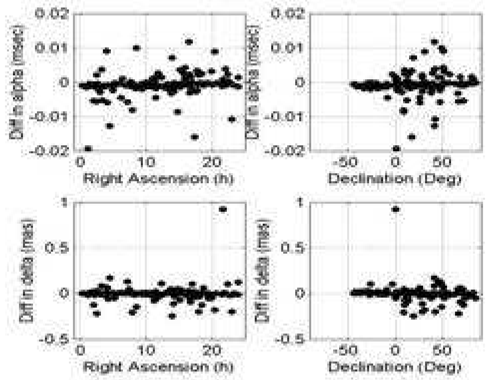

Fig. 2 Coordinate differences between two first catalogues for radiosources observed both before and after 1990 year.

To study a behavior of the 199 'stable' sources over 1980-1990 we developed a special criteria dividing all the sources into two groups - observed after 1990 only and observed both before and after 1990. For the latter case the small differences in positions are caused by inner instability of the solution. We used the maximum difference by factor three sigma as a criteria for random deviation. For those sources observed both before and after 1990 the position differences would reflect an actual displacement due to instability over 1980-1990. Using the combined formal error the significance of the every source instability can be evaluated. Almost all 'stable' sources are really stable over the period 1980-1990. Only 8 sources should be excluded from the list if the early VLBI data to be used for the CRF solution.

Acknowledgments. I am very grateful to 'Descartes - Nutation' fund, Harald Schuh and Nicole Capitaine for support for participation in the Journées 2004 Conference.

4. REFERENCES

Feissel-Vernier, M., 2003., AA 403, 105-110
Titov et al., IVS 2004 General Meeting Proc., pp. 257-271
Fey A., 2002 (private communication).
Gontier A.-M., et al., 2001, AA 375, 661-669.

SUMMARY OF THE DISCUSSION ON THE FUTURE ORGANISATION OF THE ICRS ACTIVITIES WITHIN IAU DIVISION I

T. FUKUSHIMA[1], N. CAPITAINE[2]

[1] National Astronomical Observatory of Japan
2-21-1, Ohsawa, Mitaka, Tokyo 181-8588, Japan
e-mail: Toshio.Fukushima@nao.ac.jp

[2] SYRTE/UMR8630-CNRS, Observatoire de Paris
61 avenue de l'Observatoire, 75014, Paris, France
e-mail: capitain@syrte.obspm.fr

This discussion (chaired by T. Fukushima) was related to the organization of Division I in the framework of the upcoming IAU by-laws on Commissions and Working Groups.

The focus of the discussion was where to put the activities of the Division I Working Group on ICRS that, although it was considered as being a successful WG, was disabled in 2003 to comply with the new IAU rules on Commissions and Working Groups.

The ICRS Working Group was actually disabled at the IAU GA in 2003 with the plan that the most topical tasks of the former WG (see the list below) will be included into the future terms of reference of certain IAU commissions (namely Commission 8 and Commission 19).

The ICRS Working Group for the period 2000-2003 (Chair: F. Mignard) was composed of the following tasks (the name of their corresponding chair being between parentheses)

T_1 : Maintenance and extension of the ICRS (C. Ma)

T_2 : Densification at optical and IR (S. Urban)

T_3 : Space astrometry and reference frames (F. Mignard)

T_4 : Link to the dynamical system (M. Standish)

T_5 : Computational tools (P. Wallace)

T_6 : Astronomical standards (T. Fukushima)

T_7 : Relation with IERS (F. Arias)

The objectives of the above tasks being, respectively:

T_1 : Checks of the sources already included and monitoring of additional sources that would be included in the future,

T_2 : Survey of optical sources to be included in the optical counterpart alongside the Hipparcos and Tycho stars,

T_3 : Starting a reflection on the impact of space astrometry missions on the ICRS,

T_4 : Relationship between the ICRS and the dynamical frame(s) used in solar system dynamics,

T_5 : Establish and maintain a reference set of constants, algorithms and procedures in fundamental astronomy,

T_6 : Consequences of the adoption of the ICRS on standards, precession, celestial pole,

T_7 : To maintain a constant connection with the IERS and its activities.

The terms of reference of the IAU commissions being about to be discussed by the IAU Executive Committee at the time of the Journées 2004, this was an appropriate time to discuss this issue and to have the most possible exchanges between (i) people involved in the ICRS/ICRF studies as well as the former Chairs of the ICRS WG tasks and (ii) the former, current and future IAU relevant commissions and Division I Presidents. As many of those people participated in the Journés 2004, it could be expected that such a discussion would be an opportunity to make some progress with this problem.

The points to be discussed were 1) the most important tasks regarding the ICRS issue and 2) the best way to include them into the terms of References of the IAU Commissions.

Several solutions for organizing the activities of the previous ICRS Working Group were debated.

One was a possible distribution of the seven tasks of the former ICRS WG into the most appropriate Division 1 commissions according to their recently revised terms of reference.

Another solution was the creation of a new commission to embrace all the activities of the seven tasks.

An intermediate proposal was to expand Commission 31 (Time) to include reference systems in general, and to make each of the seven tasks a WG in that expanded commission.

It was concluded that these different options needed to be futher discussed within the Division I Special group, chaired by the current Division I President, T. Fukushima, that is looking at ways to rationalize the current structure and advise on future arrangements.

Session II

MODELS FOR EARTH'S ROTATION :

FROM POINCARÉ TO IAU 2000

MODÈLES DE LA ROTATION DE LA TERRE :

DE POINCARÉ A UAI 2000

POINCARÉ FLOW IN THE EARTH'S CORE

V. DEHANT, O. DE VIRON, T. VAN HOOLST
Royal Observatory of Belgium
Avenue Circulaire, 3, B-1180, Brussels Belgium
e-mail: v.dehant@oma.be

ABSTRACT. In this paper, we discuss the motion inside the Earth's core. At low frequency, torsional oscillations occur associated with magneto-hydrodynamic effects. At high frequency, the Poincaré flow is believed to be a good approximation of the fluid dynamics. This simple flow is deduced in a very simplified case, but it appears to be true in a broader range of configurations.

1. INTRODUCTION

The rotation of the Earth is irregular in time: the Earth's rotation rate, and the associated length-of-day, present variations at the millisecond level, and the Earth's rotation axis moves both in the Earth and in space. The new definition of the IAU of polar motion and precession/nutation separate the two in terms of frequency: any motion which is low frequency in the inertial frame, and consequently retrograde diurnal in the Earth fixed frame, is called nutation, while the polar motion is all what remains. The nutation motion is at the level of 600 meters at the Earth's surface, and the polar motion is about 20 meters.

The main causes of the irregularities in the length-of-day and polar motion are the interactions between the solid Earth and the geophysical fluids: the atmosphere, the ocean, the hydrosphere, and the core. The gravitational interactions between the Earth and the other celestial bodies are the main causes of the precession/nutation motion.

Classically, the effect of the fluid layer on the rotation of the Earth is estimated using the angular momentum budget of the (supposedly isolated) Earth-fluid system: any change in the fluid angular momentum is associated with an opposite change in the Earth's angular momentum. As a consequence, when knowing the variation of the fluid angular momentum, we can deduce the variation in the Earth rotation due to the interaction with this fluid. For this reason, the International Earth Rotation and Reference Systems Service (IERS) has created the Global Geophysical Fluids Center, composed of 7 special bureaus in charge of collecting data such as the angular momentum of the major fluids in the Earth system.

In this study, we focus on the effect of the core on the Earth rotation. It is now well accepted that the core is the major cause of variation of the length-of-day for periods ranging between a few years to several dozen years.

Obviously, the estimation of the effect of the core on the Earth rotation is not as easy as the estimation of the atmospheric effect, for instance. Indeed, at present, it is impossible to get direct observations of the core flow. The best option is to use information deduced from the observed surface magnetic field and from hypotheses as meaningful as possible to make reasonable estimates of the core flow and angular momentum. Order of magnitude considerations allow us to see that the core dynamics will be dominated by the effect of magnetism at decadal timescale, while the magnetic effect will be much smaller at high frequency.

In Section 2, we discuss how the effect of the core on the Earth rotation at decadal timescales can be estimated using the observation of the magnetic field at the Earth surface. In Section 3, we present the basic idea of the Poincaré flow in the case of high frequency motion. Section 4 is devoted to discussion and conclusion.

2. DECADAL CORE FLOW AND EARTH ROTATION

As mentioned above, the effect of the magnetic field is very important at decadal frequency. The main part magnetic field observed at the Earth's surface has a core origin, but the mantle screens part of the field. Nevertheless, using the observed magnetic field at the Earth surface, it is possible to infer the poloidal field at the Core Mantle Boundary (CMB). We know that the magnetic field is linked to the motion inside the fluid by the induction equation

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \wedge \left(\vec{B} \wedge \vec{v}\right) + \eta \Delta \vec{v} \tag{1}$$

where $\vec{B}$ is the magnetic field, $\vec{v}$ the velocity of the core flow, and η the magnetic diffusion.

At decadal timescale, the last term, associated with diffusion, is negligible, and the equation simply tells us that the cause of variation of the magnetic field is its advection by the core flow. As a consequence, we can deduce the velocity field from the knowledge of the observed magnetic field and its variations. Unfortunately, this problem is underdetermined. Consequently, we have to make assumptions on the core flow at the CMB in order to be able to get the full flow there. Several different assumptions have been shown to be successful (see, e.g., Ponsar *et al.,* 2002). In order to get the flow inside the core, it is necessary to continue the flow inside the core.

This continuation is classically done using the Taylor column hypothesis: the velocity is supposed to be the same on a set of cylinders coaxial with the Earth's rotation axis. Using that method, we can estimate the core flow and the core angular momentum for every hypothesis. They all give core angular momentum fluctuations and associated length-of-day variations that look more or less similar to the observed variations of the length-of-day, as shown in Figure 1..

Note that this method has some important additional drawbacks. First, the magnetic field is observed with only a limited temporal resolution. The present solution has only independent data every 5 years, limiting the resolution of the core angular momentum data. With the new satellite mission Oersted, the time resolution of the magnetic field will strongly improve. Secondly, the magnetic field coming from the crust and the solar wind is also included in the observed magnetic field. This field is mostly high spatial frequency, it hides consequently the higher spatial resolution of the core induced magnetic field. The limit is classically put at degree 12.

Those last years, some other attempts has been done. They are mostly based on magneto hydrodynamic models, with no observation included. Some attempts have been made to include gravimetric coupling (Mound and Buffet, 2003) or magnetic observations (Kuang, 1999, Kuang and Chao, 2001).

3. HIGH FREQUENCY POINCARÉ CORE FLOW

The Poincaré motion was first derived in the case of a homogeneous, incompressible, inviscid core, with no magnetic coupling. Using those hypotheses, an analytical solution to the flow equations can be obtained (see for instance Hough 1895). The solution method is the following:

- The CMB is supposed to be rotating.

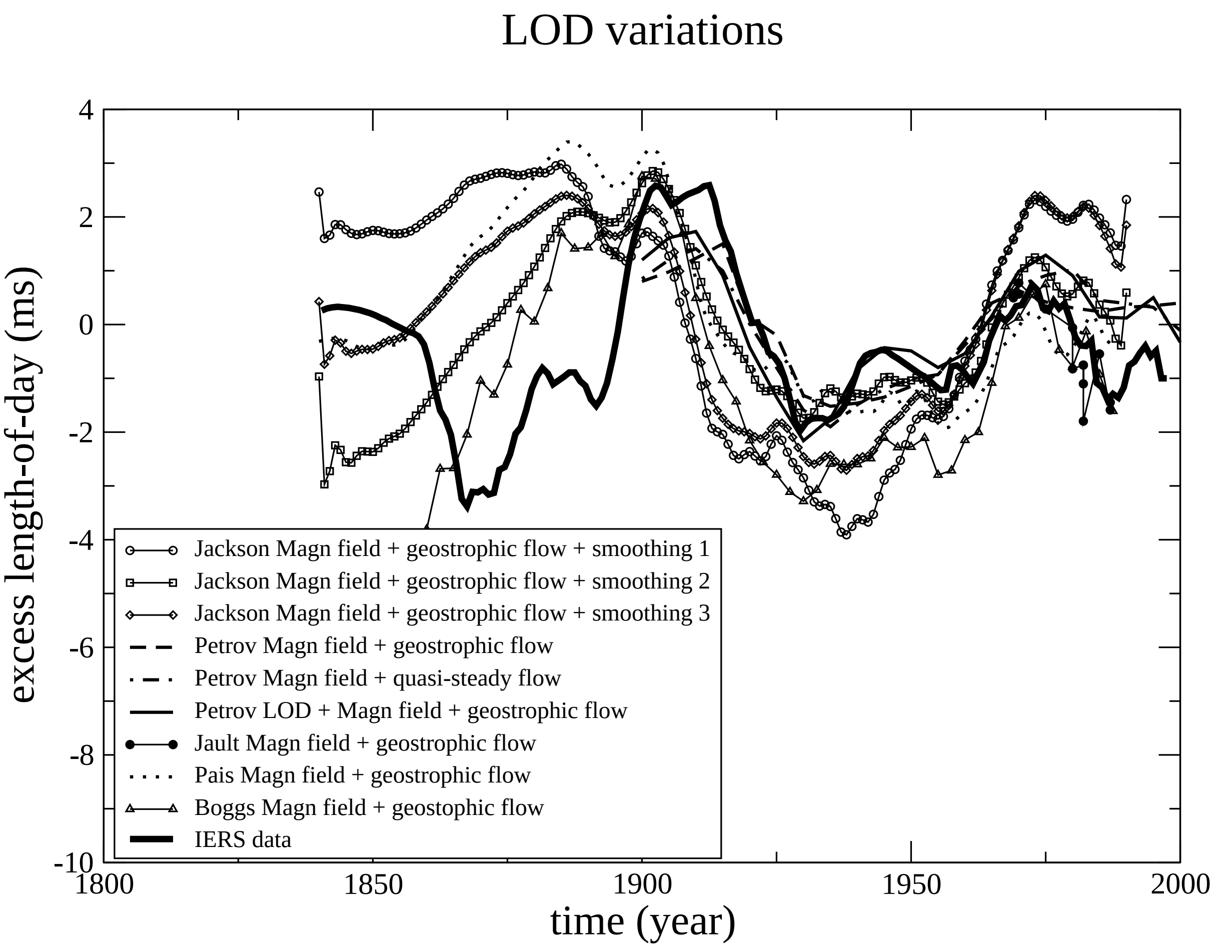

Figure 1: Length-of-day variations for various models and IERS observational LOD data. The data can be found on the SBC website.

- By using some heavy algebra, the core flow is shown to be decomposed into two parts: a rigid rotation of the core and a (small) irrotational flow, verifying the boundary condition (impermeability of the CMB),
- From the Helmholtz vortex equations, the flow in the core, which mainly is a rigid rotation, as a function of time in response to the CMB motion can be obtained.

It is possible to extend the Poincaré flow when some of the hypotheses are dropped. The Poincaré flow seems to be true for slightly viscous compressible flow, in presence of a magnetic field and has also been observed experimentally by Noir et al. (2003). Using a numerical approach, Smith (1974) was able to reproduce this behavior of the core fluid, for the Earth's rotational core normal mode (the Free Core Nutation, FCN). The Poincaré flow is often used in the modelling of the non-rigid Earth nutational response to gravitational forcing (see Mathews et al., 1991, Greff-Lefftz et al., 2000, ...). In the case of the FCN, the differential rigid rotation of the core with respect to the mantle becomes very large, allowing an observable motion of the mantle.

4. DISCUSSION AND CONCLUSION

The dynamics of the core is very complex, as it responds to the magneto-hydrodynamic equations. In addition, the core is not observed directly, and only limited information can be gathered, using indirect methods. From the magnetic field observations, it is possible to infer part of the core flow at decadal period. Nevertheless, this needs some hypotheses (the solution is not unique). The solutions found present variations of the angular momentum of the right order of magnitude, but differences as large as 100% remain.

5. REFERENCES

Greff-Lefftz, M., Dehant, V., Legros, H., 2000, Effects of inner core viscosity on gravity changes and spatial nutations induced by luni-solar tides, PEPI 129, Issue 1-2, p. 31-41

Hough, S.S., 1895, The oscillations of a rotating ellipsoidal shell containing fluid, Phil. Trans. R. Soc. Lond. A, 186, 469-506.

Kuang, W., 1999, Force Balances and Convective State in the Earth's Core, *Phys. Earth. Planet. Inter.*, 116, 65-79.

Kuang, W., and Chao B.F., 2001, Topographic Core-mantle coupling in geodynamo modeling, *Geophys. Res. Lett.*, 28, no. 9, 1871-1874.

Mathews, P.M., Buffett, B.A., Herring, T.A., Shapiro, I.I., 1991, Forced nutations of the Earth: Influence of inner core dynamics, 1 - Theory. 2 - Numerical results and comparisons, 3 - Very long baseline interferometry data analysis, JGR, vol. 96, p. 8219-8257, 8259-8273.

Mound, J.E., Buffett B.A., 2003, Interannual oscillations in length of day: Implications for the structure of the mantle and core, J. Geophys. Res. , 108(B7), pp. ETG 2-1, CiteID 2334, DOI 10.1029/2002JB002054.

Noir, J., Cardin, P., Jault, D., MAsson, J.-P., 2003, Experimental evidence of non-linear resonance effects between retrograde precession and the tilt-over mode within a spheroid, Geophysical Journal International, 154, 407-416

Ponsar S., Dehant V., Van Hoolst T., 2002, Electromagnetic Core-Mantle Coupling, in: *IERS Technical Note No. 30*, Proc. IERS Workshop on 'Combination Research and Global Geophysical Fluids', Eds Bernd Richter, Wolfgang Schwegmann, and Wolfgang R. Dick, pp 216-218.

Smith, M. L., 1974, The scalar equations of infinitesimal elastic-gravitational motion for a rotating, slightly elliptical Earth, *Geophys. J. R. Astron. Soc.*, 37, 491-526.

IMPROVEMENTS IN THE PRECESSION-NUTATION MODELS

N. CAPITAINE[1], P.T. WALLACE[2]

[1] SYRTE/UMR8630-CNRS, Observatoire de Paris
61 avenue de l'Observatoire, 75014, Paris, France
e-mail: capitain@syrte.obspm.fr

[2] HMNAO, SST/CLRC/Rutherford Appleton Laboratory, U.K.
e-mail: ptw@star.rl.ac.uk

ABSTRACT. This paper reviews a number of effects that must be taken into account in developing improved expressions for the precession of the Earth's equator in order to be dynamically consistent and compliant with up to date models for the ecliptic and the non-rigid Earth. These effects have been considered in the P03 and the parameterized P04 precession solutions of Capitaine et al. (2003, 2004b); they are related to the ecliptic precession, to parameters of the non-rigid Earth such as the J_2 rate (Bourda & Capitaine 2004) and to the expressions of the precession rates. We also report on similar effects to be considered in nutation, as well as on the influence, on precession-nutation, of the variations in Earth rotation that was recently clarified (Lambert & Capitaine 2004). Some recommendations are given on the best form of the precession-nutation expressions and the appropriate parameters to be fitted to observations.

1. INTRODUCTION

The IAU 2000 precession-nutation model was adopted by IAU 2000 Resolution B1.6 to replace the IAU 1976 Precession and the IAU 1980 Nutation. The nutation series was generated by the convolution of the MHB 2000 transfer function (Mathews et al. 2002) with the nutation series of Souchay et al. (1999) obtained by solving the equations of Earth's rotation for a rigid-Earth. The transfer function was based upon basic Earth parameters estimated from VLBI observations, one of them being the Earth's dynamical flattening H. The precession component of the IAU 2000 model consists simply of VLBI MHB-estimated corrections to the precession rates in longitude and obliquity of the IAU 1976 precession and is therefore not dynamically consistent. Thus, IAU 2000 Resolution B1.6 encouraged the development of new expressions for precession consistent with the IAU 2000A model; then, in 2003, the 25th IAU General Assembly established a WG on "Precession and the Ecliptic" to recommend a new model.

The P03 precession provided by Capitaine et al. (2003) was proposed as a possible replacement for the IAU 1976 ecliptic precession and for the IAU 2000 equator precession. In this paper, we report on the various effects that contribute to the P03 equator precession and make it dynamically consistent as well as on similar contributions to nutation; we also discuss the most appropriate form for the precession expressions and parameters.

2. VARIOUS EFFECTS ON THE PRECESSION OF THE EQUATOR

A number of effects influence the dynamical solution for the precession of the equator. They are related to the expressions of precession rates, to the ecliptic precession and to parameters of the non-rigid Earth. These effects have been considered in the P03 solution and each of them has been evaluated by Capitaine et al. (2004a) and compared with the difference between P03 and other precession solutions. Additionally to IAU 1976 and IAU 2000, these solutions are those obtained by Williams (1994), Bretagnon et al. (2003) and Fukushima (2003), which will be denoted W94, B03 and F03, respectively.

(i) *Effects of the integration constants*

The integration constants to be used for solving the equations for the equator precession are directly related to the precession rate values ψ_1 and ω_1 (at J2000) in longitude and obliquity, respectively. Table 1 provides the values corresponding to the various precession models as well as the precession rates differences with respect to IAU 2000. The precession rate values in longitude are all "observed quantities", the IAU 1976 value being determined by optical astronomy and the other ones by VLBI observations. The obliquity rate values are either theoretical values without any observational constraint (i.e. rigid Earth values for IAU 1976 and B03, and non-rigid Earth value for W94), or VLBI-estimated values. The IAU 2000 values are based on the VLBI MHB-estimated corrections to IAU 1976 (i.e. -299.65 mas/cy in longitude and -25.24 mas/cy in obliquity), whereas the P03 precession rates were obtained by correcting the MHB estimated values for some pertubing effects; the largest of these effects, of 2.8 mas/cy in the precession rate in longitude, is due to the fact that the actual "estimated quantity" is not ψ_1 itself, but is $X_1 \approx \psi_1 \sin\epsilon_0$, ϵ_0 being the obliquity at J2000 of the associated precession model (i.e. IAU 1976 for the MHB estimates). Table 1 also provides the corresponding values for ϵ_0 and X_1 and the X_1 differences with respect to the IAU 2000 value, which are the relevant differences when fitting the various models to VLBI observations. The differences with respect to

Table 1: Comparison between precession rates values (unit: mas).

Model	ψ_1	$\psi_1 \sin\epsilon_0$	$\mathrm{d}\psi_1$	$\mathrm{d}X_1$	ϵ_0	ω_1	$\mathrm{d}\omega_1$
IAU1976	5038778.4	2004310.94	299.65	+119.19	84 381.448	0.0	25.24
IAU2000	5038478.75	2004191.747	0.00	0.00	84 381.448	−25.24	0.00
W94	5038456.501	2004182.023	−22.25	−9.72	84 381.409	−24.4	−0.84
B03	5038478.750	2004190.869	0.00	0.88	84 381.4088	−26.501	0.00
F03	5038478.143	2004190.569	−0.61	−1.18	84 381.406	−21.951	−51.74
P03	5038481.507	2004191.903	+2.76	−0.16	84 381.406	−25.754	−0.51

the IAU 2000 precession rates are responsible for differences in the precession expressions which can be derived from the theoretical developments of the coefficients of the precession quantities provided in Table 7 of the P03 paper (i.e. Capitaine et al. 2003), as for example:

$$\frac{\partial\psi_2}{\partial r_{01}} \approx \frac{c_1(\cot\epsilon_0 - \tan\epsilon_0)}{2}; \ \frac{\partial\psi_2}{\partial u_{01}} \approx -\frac{r_{01}\tan\epsilon_0}{2}; \ \frac{\partial\omega_2}{\partial r_{01}} = \frac{s_1}{2}; \ \frac{\partial\omega_2}{\partial u_{01}} = -\frac{u_{01}\tan\epsilon_0}{2}, \tag{1}$$

r_{01} and u_{01} being the first order terms in r_0 ($= \psi_1$) and u_0 ($= \omega_1$), which are the actual integration constants to be used in the precession equations, and c_1 and s_1 the coefficients of the linear terms in the ecliptic precession expressions P_A and Q_A, respectively. The largest differences with respect to the IAU 2000 equator precession due to the differences dr_{01} and du_{01} in the integration constants can be written as:

$$d\psi_A = dr_{01}\,t - (212\,dr_{01} + 5297\,du_{01}) \times 10^{-6}\,t^2; \ d\omega_A = du_{01}\,t + (10\,dr_{01} - 4\,du_{01}) \times 10^{-6}\,t^2. \tag{2}$$

Relation (2) shows that, additionally to their direct effect on the linear terms, the MHB corrections to the IAU 1976 precession have a dynamical effect of the order of 200 μas/cy^2 in ψ_A and 2 μas/cy^2 in ω_A. This relation also shows that the largest uncertainty that can be expected in the precession expressions due to the uncertainty in the VLBI-estimated precession rates (which is of the order of 1 mas/cy), is of a few μas/cy^2 in the quadratic term of the expression for ψ_A, coming from the du_{01} term only.

(ii) *Effects of the model for the ecliptic precession*

The dependence of the ψ_A and ω_A expressions on the ecliptic are provided in Table 7 of the P03 paper. The largest terms due to variations dc_1 and ds_1 in the linear terms of the P_A and Q_A quantities, respectively and $d\epsilon_0$ in the obliquity value at J2000 are:

$$d\psi_A = -0.001059\, d\epsilon_0 \ + 0.02288\, dc_1\, t^2\,; \quad d\omega_A = (0.01221\, dc_1 - 0.00530\, ds_1)\, t^2. \tag{3}$$

Relation (3) shows that, additionally to their direct effect on the precession angles referred to the ecliptic of date (i.e. obliquity and planetary precession), changes in the ecliptic precession have dynamical effects which, given the dc_1 and ds_1 values reported in the P03 paper, are of the order of 100 μas/cy^2 and 25 μas/cy^2 in the t^2 terms in ψ_A and ω_A, respectively.

(iii) *Effects of the expression for the precession rates*

Expressions for the precession rates include constant terms which are the precession rate values at J2000, $r_0(=\psi_1)$, $u_0(=\omega_1)$, and linear and quadratic terms, r_1, u_1 and r_2, u_2, respectively, to which the quadratic and cubic terms in the ψ_A and ω_A solutions of the precession equations are directly related. The precession rates components used in the P03 solution are provided in Table 3 of the P03 paper; they include rigid-Earth and non-rigid-Earth parts. One improvement in the rigid-Earth part of r_1 with respect to the IAU 1976 one is a change of 0.295 mas/cy in the largest component (due to changes in the the eccentricity of the Earth's orbit); the second improvement is including the 1.074 mas/cy J_2 and planetary tilt effect, firstly considered by Williams (1994), which is also responsible for the main component of the obliquity rate (and a -0.044mas/cy^2 quadratic variation in ω_A). Note that considering this effect is compliant with the IAU 2000 precession in obliquity and also with the nutation series of Souchay et al. (1999) on which the IAU 2000 nutation is based. The change also includes a 3 μas/cy^2 additional contribution in the geodesic precession.

(iv) *Effects of the Earth model*

Additionally to its direct contribution to the precession rates at J2000 that was considered in (i), the influence of the Earth model on the equator precession appears through its contribution to the linear variations of the precession rates; this includes tidals terms in r_1 and a term proportional to the time variation in the Earth's dynamical flattening H to which the main component of r_0 and u_0 are proportional. Using the values provided by Williams (1994) both for the J_2 rate variations (i.e. $\dot{J}_2/J_2 = -2.7774 \times 10^{-6}$) and the tidal terms (i.e. with a total contribution of -235 μas/cy), the largest differences in the expressions for the equator precession relative to the non rigid and rigid Earth are (1) of -7 mas/cy^2 and -118 μas/cy^2 in the t^2 term in longitude due to the J_2 rate effect and the tidal effect, respectively, and (2) of 2.4 mas/cy in the t term in obliquity due to the tidal effect.

The large uncertainties in the theoretical models for the J_2 variations is one of the most important limiting factors in the accuracy of the precession-nutation models (Williams 1994, Capitaine et al. 2003). Bourda & Capitaine (2004) investigated how the use of the variations of J_2 observed by space geodetic techniques can influence the theoretical expressions for precession and nutation. The conclusion was that a realistic estimation of the J_2 rate should rely not only on space geodetic observations over the limited available period but also on other kinds of observations. The uncertainty in this model is such that the expected uncertainty in the t^2 term in longitude is of the order of 1.5 mas/cy^2.

(v) *The various dynamical contributions*

Table 2 provides the dynamical contributions to the equator precession described in the previous sections that have been obtained by solving the P03 equations, based on (i) the IAU 1976 and IAU 2000 integration constants, (ii) the IAU 1976 and P03 ecliptic precessions, (iii) the IAU 1976 and P03 expressions for the precession rates and (iv) the rigid Earth and non-rigid Earth models. Additional tests of dynamical consistency have been made by Capitaine et al. (2004a) by evaluating the differences with respect to a dynamical solution, denoted "P03-like", using exactly the same equations than for the P03 solution (and thus considered as having a perfect dynamical consistency), but based on ecliptics, precession rates and Earth models of the other precession solutions. Discrepancies were found that reached -3 mas/cy and -529 mas/cy2 in obliquity for the F03 model and 488 mas/cy2 in longitude for the IAU 2000 model.

Table 2: Various contributions to be applied to the IAU 2000 equator precession to make it a dynamically consistent solution, compliant with up to date models for the ecliptic and the non-rigid Earth (unit: mas).

Effect		t^2	t^3	t^4
(i) of the MHB precession rate correction ($-$ 299.650)		0.214	0.002	
(ii) of upgrading the ecliptic to P03 ($r_{01} = r_{01}$+ 0.445)	ψ_A	0.090	0.006	0.002
(iii) of upgrading the precession rates expressions to P03		0.685		
(iv) of upgrading the Earth model to P03 (tides + $J2$ rate)		-7.130	0.003	
(i) of the MHB precession rate correction (-25.240)		-0.002	0.001	
(ii) of upgrading the ecliptic to P03 ($\epsilon_0 = \epsilon_0 - 42.000$)	ω_A	0.018	-0.003	
(iii) of upgrading the precession rates expressions to P03		-0.022	0.002	
(iv) of upgrading the Earth model to P03 (tides + $J2$ rate)		-0.001		

3. EFFECTS ON NUTATION

In order that the IAU 2000 nutation be compliant with the P03 precession, the effects of the change of the obliquity value at J2000 with respect to the IAU 1976 value and of the J_2 rate have to be taken into account. Improvements in the model for the precession-nutation of the equator also requires considering all the effects that may not have been included in the IAU 2000 model, such as the coupling effects appearing in the global equations for Earth's rotation.

(i) *Effects of the obliquity value at J2000 and of the J_2 rate model*

a) The MHB nutation amplitudes in longitude, $\Delta\psi_{\mathrm{IAU2000}}$, which were estimated along the IAU 1976 ecliptic, have to be transformed into amplitudes along the P03 ecliptic; similarly to the effect on the observed precession rate mentioned in Sect. 2 (i), this means multiplying $\Delta\psi_{\mathrm{IAU2000}}$ by: $\sin\epsilon_{\mathrm{IAU1976}}/\sin\epsilon_{\mathrm{P03}} = 1.000000470$. The corrections to the IAU 2000 nutation amplitudes larger than 1 μas corresponding to this change are, in μas:

$$d_1\psi = -8.1\ \sin\Omega - 0.6\ \sin(2F - 2D + 2\Omega). \qquad (4)$$

b) The nutation angles being proportional to J_2, the consideration of the same J_2 rate model than in P03 gives the following additional Poisson terms to be added to the IAU 2000 nutation:

$$d_2\psi \ = \ (\dot{J}_2/J_2)\ t\,\Delta\psi_{\mathrm{IAU2000}}\,;\ \ d_2\varepsilon = (\dot{J}_2/J_2)\ t\,\Delta\varepsilon_{\mathrm{IAU2000}}\,. \qquad (5)$$

The largest terms are of 50 μas/cy and 30 μas/cy, respectively in the 18.6-yr nutation.

(ii) *Effects of the variations in Earth rotation*

Coupling effects between the Earth's rotation rate and precession-nutation were considered to be negligible as compared to the accuracy of the observations. However, recent studies by Bretagnon et al. (2001) predicted that the Earth's rotation rate variations due to zonal tides had noticeable effects on precession-nutation with an amplitude of the order of 700 μas in the 18.6-yr nutation in obliquity and of 4 mas/cy in the precession in longitude. Although this effect was not included in IAU 2000 because it could not be detected in VLBI observations, the need of taking it into account was still questioned. This question was recently clarified by Lambert & Capitaine (2004) who showed that the contribution to precession-nutation coming from the coupling with the rotation rate variations due to zonal tides was an artefact coming from an incomplete way of taking into account the effect of the rotation rate variations; if the zonal variations are also considered in the computation of the external torque in the celestial reference system, such an effect is cancelled out and there is in fact no contribution from the coupling between axial and equatorial components of the rotation vector larger than 0.1 μas. Moreover, this effect was shown to be distinct from the contribution due to the tidal variations in the dynamical ellipticity, although it had sometimes been understood as being so, and this latter effect has to be considered. The contributions of the second-order torque induced by the variations of the dynamical ellipticity due to Earth's zonal deformations were evaluated by Lambert & Capitaine (2004) to be of the order of 200 μas and -10 μas in the 18.6-yr nutation in longitude and obliquity, respectively and -5 mas/cy in precession. However, other second order contributions of the luni-solar torque on precession-nutation should also be considered and the total effect is still under discussion (see Lambert and Escapa et al., this Volume).

4. PRECESSION PARAMETERS AND PRECESSION-NUTATION EXPRESSIONS

Suitable precession-nutation parameters would integrate the computation of bias, precession and nutation and provide a transformation between celestial and terrestrial coordinates that involves a minimum number of variables and coefficients. Moreover, as the precession-nutation solution strongly relies on quantities that are fitted to observations, the choice of the parameters that are the best suitable for being used with these observations is essential.

As VLBI observations provide the actual position of the pole in the GCRS, the precession parameters most suitable for use with VLBI observations are based on the x, y coordinates of the CIP unit vector in the GCRS which include precession, nutation, coupling between precession and nutation, and frame biases. IAU 2000A expressions for X and Y have been provided by Capitaine et al. (2003), the polynomial part of which being for the precession of the equator. The polynomial differences between the P03 and IAU 2000 expressions for X and Y are, in μas, with t expressed in Julian centuries of TT since J2000 TT:

$$dX = 155t - 2564t^2 + 2t^3 + 54t^4 \ ; \quad dY = -514t - 24t^2 + 58t^3 - 1t^4 - 1t^5. \tag{6}$$

Then, linear fits of the P03 and IAU 2000 precessions to VLBI by Capitaine et al. (2004b) provided $dX_1 = -180t$ and $dY_1 = -70t$ for P03 and $dX_1 = -528t$ and $dY_1 = -441t$ for IAU 2000, showing that P03 fits VLBI distinctly better than IAU 2000.

Due to the strong dependence of (i) the P03 precession expressions on the precession rates values in longitude and obliquity, respectively, and (ii) the precession rate in longitude on the J_2 rate model, both of which being handicapped by large uncertainties, a P04 parameterized precession solution has been provided in Capitaine et al. (2004b) as function of these parameters, both for the equinox based and CIO based quantities. The P04 parameterized solution corresponds to expressions of the precession quantities as functions of the corrections dr_0, du_0 to the P03 precession rates r_0 and u_0, respectively, and of $\dot{J}_2/J_2$ and retains only the parameterized terms that, given the expected values for the parameters considered, can contribute to the expressions with amplitudes larger than one microarcsecond.

The parameterized P04 expressions for the X and Y quantities can be expressed as functions of the corrections dX_1 and du_0, and dξ_0, dη_0, d(dα_0) to the IAU 2000 frame biases, as:

$$\begin{aligned} X(P04_{par}) &= X(P03) + d\xi_0 + 0.0001\, d(d\alpha_0)\, t^2 + dX_1\, t + 0.0203\, du_0\, t^2 \\ &\quad +[0''.002784\, t^2 - 0''.000001\, t^3] + (\dot{J}_2/J_2) \times (1002''.5\, t^2 - 0''.4\, t^3) \\ \\ Y(P04_{par}) &= Y(P03) + d\eta_0 + X_1\ d(d\alpha_0)\, t + du_0\, t - 0.0224\, dX_1\, t^2 \\ &\quad -[0''.000062\, t^3] - (\dot{J}_2/J_2) \times (22''.5\, t^3). \end{aligned} \tag{7}$$

Such a form of the solution is intended to be used to produce (or check) future precession models based on extended VLBI records and improved geophysical models.

Other formulations are being studied, including various series of Euler angles and use of the "rotation vector" (Capitaine et al. 2003).

5. SUMMARY

In this paper we have reviewed the largest dynamical effects that were taken into account in developing the P03 expressions for the precession of the Earth's equator. We also reviewed the effects to be taken into account in the IAU 2000 nutation to make it compliant with P03. The parameterized P04 solution associated with P03 was shown to be the best form of the precession expression for use for further improvements to produce (or check) future precession models based on extended VLBI records and improved geophysical models.

6. REFERENCES

Bourda, G., Capitaine, N., 2003, Precession, nutation and space geodetic determination of the Earth's variable gravity field, A&A 428, pp. 691–702.

Bretagnon, P., Rocher, P., & Simon, J.-L. 2001, "Toward the construction of a new precession-nutation theory of nonrigid Earth," Celest. Mech. Dyn. Astr. 80, pp. 177–184.

Bretagnon, P., Fienga, A., Simon, J.-L., 2003,"Expressions for precession consistent with the IAU 2000A model. Considerations about the ecliptic and the Earth Orientation Parameters," A&A 400, pp. 785–790.

Capitaine, N., Wallace, P.T, Chapront J., 2003, "Expressions for IAU 2000 precession quantities," A&A 412, pp. 567–586.

Capitaine, N., Wallace, P. T., and Chapront, J., 2004a, "Comparison between high precision precession models for the ecliptic and the equator," A&A 421, pp. 365–379.

Capitaine, N., Wallace, P. T., and Chapront, J., 2004b, "Improvement of the IAU 2000 precession model," in press, A&A preprint doi:10.1051/004-6361:20041908.

Fukushima, T., 2003, "A new precession formula," AJ 126, pp. 494–534.

Lambert S., Capitaine N., 2004, "Effects of zonal deformations and Earth's rotation rate variations on precession-nutation", A&A 428, pp. 255–260.

Mathews P.M., Herring, T.A., Buffett B.A., 2002,"Modeling of nutation-precession: New nutation series for nonrigid Earth, and insights into the Earth's Interior," J. Geophys. Res. 107, B4, 10.1029/2001JB000165.

Souchay, J., Loysel, B., Kinoshita, H., Folgueira, M., 1999, "Corrections and new developments in rigid Earth nutation theory : III. Final tables REN-2000 ," A&AS 135, pp. 111-131.

Williams, J. G., 1994, "Contributions to the Earth's obliquity rate, precession, and nutation," AJ 108, pp. 711–724.

PROGRESS REPORT OF THE INTERNATIONAL ASTRONOMICAL UNION DIVISION I WORKING GROUP ON PRECESSION AND THE ECLIPTIC

J.L. HILTON
U.S. Naval Observatory
3450 Massachusetts Ave., NW, Washington, DC 20392, USA
e-mail: jhilton@aa.usno.navy.mil

ABSTRACT. The IAU Working group on Precession and the Ecliptic was formed at the XXVth General Assembly of the IAU, Sydney 2003, in response to requests for a dynamically consistent precession theory compatible with the IAU 2000A nutation theory. Since that time, the working group has made significant progress towards the adoption of just such a theory. This paper looks at the current state of the process and includes the author's thoughts on the definition of the ecliptic and a recommendation for an adjustment in the nomenclature of precession.

1. INTRODUCTION

Precession or, more precisely, precession of the equinox is the result of the motions of two planes in inertial space. The first motion is that of the plane of the Earth's equator. The second is the motion of the ecliptic, the mean plane of the Earth's orbit about the Sun. These two planes have been chosen because the equinox has historically provided a convenient fiducial point in the observation of the heavens and the passage of time. For example, the civil calendar year is tuned to follow the tropical year from equinox to equinox rather than any other definition of the year such as perihelion passage or the complete revolution of the Earth about the Sun in inertial space. These planes are also both dynamically involved in the motion of the Earth's pole. By definition, the mean latitude of the Sun with respect to the ecliptic is $0°$, and, averaged over the 18.6 year period of the motion of its node, the average plane of the Moon's orbit is nearly coincidental with the ecliptic.

In the past, the motion of the Earth's equator in inertial space has been called *lunisolar precession* while the motion of the ecliptic has been called *planetary precession*. The names of the individual components are based on the dominant source for each of the motions. However, the accuracy to which the precession can now be measured has reached the point where the contribution of the planets to the motion of the Earth's equator is significant. Thus, these names have become misnomers. Fukushima (2003) proposed renaming lunisolar precession as *equator precession* and planetary precession as *ecliptic precession* to more accurately describe these two components of precession. Similarly, Capitaine et al. (2003) proposed the terms *precession of the equator* and *precession of the ecliptic*. Although the terms of Capitaine et al. are more unwieldy than Fukushima's terms, the term *precession of the equator* does make a distinction between it and precession *along* the equator which the term *equator precession* does not. Thus, this paper will adopt the use of precession of the equator and, for symmetry, precession of the ecliptic. Further, we recommend that these terms be adopted for general use.

Since its adoption, it has become apparent the IAU 1976 theory of general precession (Lieske et al., 1977) (henceforth Lieske) is in error by approximately 300 mas cent^{-1}, where 1 mas = $0''.001$ and the century consists of 36525 Julian days TT. In addition, Williams (1994) showed there should also be a secular motion in the latitude of the Earth of about 24 mas cent^{-1}. This motion in latitude is caused by the slight inclination of the lunar orbit to the ecliptic when averaged over the period of its node. When the IAU 2000 precession-nutation theory (IERS 2004) was adopted (IAU 2001) the emphasis of the analysis was on the periodic nutations and correcting the linear portion of the the VLBI observations. The effect of these changes on the higher-order terms in the precession theory were ignored. Ignoring the higher-order terms results in an error in the precession of about 6.4 mas cent^{-2} in longitude and 0.01 mas cent^{-2} in latitude. Thus, the precession theory was not dynamically consistent.

Fukushima (2003) showed that ζ_A, one of the traditional angles for parameterizing the precession, becomes unstable near the epoch of precession unless an additional assumption is made about its value at epoch. Thus, the traditional precession parameters may not provide the best representation of it.

Finally, the ecliptic in use was defined by Lieske using a simplified variant for the determination of proper elements devised by Newcomb (1894). However, Resolution A4, Recommendation VII, Note 3 of IAU (1992) recommends determining the ecliptic from the mean values as derived from a planetary ephemeris for the Earth.

The IAU Working Group on Precession and the Ecliptic was formed at the XXVth General Assembly of the IAU in Sydney, Australia to address these topics and make recommendations regarding them to the IAU. In addition to the author, the working group consists of: N. Capitaine, Systèmes de Référence Temps-Espace, France; J. Chapront, Systèmes de Référence Temps-Espace, France; J.M. Ferrandiz, U. de Alicante, Spain; A. Fienga, Institut de Mécanique Céleste, France; T. Fukushima, National Astronomical Observatory Japan, Japan; J. Getino, U. de Valladolid, Spain; P. Mathews, U. of Madras, India; J.-L. Simon, Institut de Mécanique Céleste, France; M. Soffel, U. Tübingen, Germany; J. Vondrák, Czech Acad. Sci., Czech Republic; P. Wallace, Her Majesty's Nautical Almanac Office, U.K.; and J. Williams, Jet Propulsion Laboratory, U.S.A. All of these scientists have provided insight and guidance to the working group. This paper constitutes the author's understanding of the current consensus of the working group. Should there be any mistakes or misrepresentations in this paper they are unintended and the sole responsibility of the author.

The precession of the equator will be addressed in Section 2. Section 3 will look at the ecliptic and precession of the ecliptic, and Section 4 will present the draft recommendations of the working group.

2. PRECESSION OF THE EQUATOR

Recently, four high precision precession theories (Bretagnon et al. 2003, Capitaine et al. 2003, Fukushima 2003, and Harada & Fukushima 2004) have been published to address the shortcomings of the precession portion of the IAU 2000A precession-nutation theory. All four of these theories are designed to be dynamically consistent, but took different approaches in their methods for determining the higher-order terms in the precession theory. Additionally, all four theories used a different definition for the ecliptic.

The initial task of the working group was to determine if these precession theories actually are physically consistent, and which is the best suited to complement the nutation portion of the IAU 2000 precession-nutation theory. Capitaine et al. (2004a) provides just such a comparison.

Regarding the equatorial precession the most important results of Capitaine et al. (2004a) are:

- The equator of precession is the plane perpendicular to the celestial intermediate pole.
- The accuracy of the expression for the precession is limited by the uncertainty in the long term change of J_2, ΔJ_2, as a function of time. More recently, Bourda & Capitaine (2004) estimate the uncertainty in ΔJ_2 limits the accuracy of the rate of precession to about 1.5 mas cent^{-1}.
- A new precession theory for the equator should be based on the most recent precession rates and geophysical model determined from VLBI observations.
- VLBI observations do not yet span a long enough period of time to discriminate between the different solutions.
- Only the Capitaine et al. (2003) solution includes both a realistic Earth model and integration constants. More recently, Capitaine et al. (2004b) has determined Mathews et al.'s (2002) use of the Lieske ecliptic in determining the precession requires a small correction of approximately 1 mas cent^{-1} in the precession of the equator.

Since both the uncertainty in the long-term rate of change in J_2 and the ability to discriminate between the different theories will require VLBI observations over an extended period of time, the only true discriminant is the whether the Earth model is realistic. Only the Capitaine et al. (2003) model meets this criterion. Thus, the working group recommends the adoption of the Capitaine et al. (2003) theory, designated P03, for the precession of the equator.

3. THE ECLIPTIC AND PRECESSION OF THE ECLIPTIC

The equinox is the intersection of the equator and the ecliptic, two non-inertial planes. Both the equinox and the ecliptic are still of use. The equinox serves as the basis of the civil calendar, and is still the origin of the azimuthal celestial coordinate recognized by most of the astronomical community. However, this does not require high accuracy (more accurate than $0\overset{\prime\prime}{.}1$) for most applications. Similarly, high accuracy celestial mechanics problems have reached the level of accuracy that knowledge of the true rather than the mean plane of the Earth's orbit is required. However, many problems with lesser accuracy requirements, such as the dynamics of asteroids, find the ecliptic useful as a slowly changing fiducial plane for solar system dynamics.

3.1. Definitions

Before an expression for the ecliptic can be agreed upon, two problems regarding the definition of the ecliptic have to be addressed. First, there is the question of whether the ecliptic should be defined with respect to inertial space or with respect to an observer on the non-inertial platform of the Earth. Second, there is the question of how the equinox can be defined as the intersection of the Earth's equator, a plane defined in the geocentric reference system, and the ecliptic, a plane defined in the barycentric reference frame. This second question arises because solar system dynamics has reached the point where general relativistic considerations are significant, and the gauge transformation does not allow a plane in one reference system to be transferred to another reference system.

Standish (1981) pointed out there are two definitions of the ecliptic that have been used in the past: the inertial definition and the rotating definition. The difference between these two definitions arise from whether the reference frame defining the ecliptic is situated in inertial space (inertial definition) or comoving with the Earth (rotating definition). The difference between these two definitions results in a difference in the position of the equinox of 93.66 mas and a difference in the obliquity of the ecliptic of 3.34 mas at J2000.0. In the working group's opinion, the inertial definition of the ecliptic should be used for two reasons. First, it is the definition in which the dynamics are most easily represented. Second, it is the definition that is used in IAU 2000A. However, the rotating definition of the ecliptic has also been used in several places such as Lieske. Thus, for the foreseeable future, the inertial nature of ecliptic definition being used should be explicitly stated to avoid confusion.

The second question, how to define a barycentric plane in a geocentric reference frame, arises from the distortion caused trying to transform a plane from one reference frame to another using a paradigm where space is no longer separate from time. However, although the ecliptic is thought of and formally defined as a plane, it has been practically defined (e.g. Newcomb 1906, Lieske, Simon et al. 1994) in terms of the mean direction of the Earth's orbital angular momentum vector. While there is not complete agreement on what constitutes angular momentum in a general relativistic sense, the size of the effect of transforming a vector from a barycentric reference frame to a geocentric one is extremely small. On the other hand the uncertainty in the Earth's orbit, on the order of 1 mas (Standish 2004), is orders of magnitude larger than the possible loss of precision that would be introduced by ignoring relativity. Thus, the problem of transforming a plane from a barycentric to a geocentric frame of reference is sidestepped by using the Newtonian angular momentum vector as the practical realization of the ecliptic and acknowledging that those digits more precise than 1 mas in the orientation of the ecliptic are arbitrary.

3.2. Determining the Mean Plane

How to determine the mean direction of the angular momentum vector is the third problem in determining the ecliptic.

Newcomb (1906) determined the ecliptic using a modified approach to determining the proper elements of the Earth's orbit. In this method, Newcomb estimated the motion of the Earth's orbital plane at three different epochs (1600.0, 1850.0, and 2100.0), in terms of the parameters $\mathrm{d}p/\mathrm{d}t = \mathrm{d}/\mathrm{d}t(\sin\pi\sin\Pi)$ and $\mathrm{d}q/\mathrm{d}t = \mathrm{d}/\mathrm{d}t(\sin\pi\cos\Pi)$ where π is the inclination of the ecliptic of date to the ecliptic of 1850.0 and Π is the node of the ecliptic of date on the ecliptic of 1850.0 measured from the equinox of 1850.0. The motions at these epochs were determined using a method similar to that described in chapters 6 and 7 of Murray & Dermott (2000). In this technique, the disturbing function is expanded in an infinite series and those perturbations depending on the mean motions of the perturbing bodies are dropped. The remaining perturbations are considered secular (although, in fact, they may have periodicities as short as 45,000 years). The elements, called *proper elements*, were then derived from the integration of the resulting equation. What was left are the mean elements in the sense that the short-period perturbations caused by the mean motions of the planets have been removed. In his work Newcomb used only the first order of the expansion to determine the motion of the pole of the ecliptic. The ecliptic was then determined by fitting a polynomial to the rate of motion at these three dates and integrating using the position of the equinox and the obliquity at 1850.0 as the initial conditions. This method had the advantage of using the very-long-term change in the Earth's orbital elements, but avoiding the use of numerical integration that would have been difficult in the pre-computer era using a polynomial approximation for the slowly changing mean elements.

The ecliptic of Lieske followed the same method used by Newcomb but with updated values for the masses and elements of the planets, and the equinox and obliquity of J2000.0 as the initial conditions.

The determination of proper elements does have a drawback. Laskar (1988) showed that numerous overlapping weak resonances in the inner solar system result in a large number of low amplitude periodic terms when using a higher-order expansion of the disturbing function. However, all of these terms have amplitudes smaller than the current accuracy of the Earth's ephemeris (Standish 2004). Hence, including these higher-order terms would *not* increase the ecliptic's accuracy. Thus, as with the relativistic transformation of the angular momentum vector, the higher-order portion of the expansion can be ignored as long as we acknowledge that the equation for the ecliptic is arbitrary at accuracies less than about a milliarcsecond.

The IAU (1992), however, presented a different definition for the ecliptic. Here it is the uniformly rotating plane of the orbit of the Earth-Moon barycenter averaged over the entire period for which the ephemerides are valid. This definition has been used by the most of the recent determinations of the ecliptic such as Simon et al. (1994), Harada (2003), and Capitaine et al. (2003). While this definition of the ecliptic is simpler, it is in conflict with the previous definition of the ecliptic, that is the mean plane of the *Earth's* orbit. Since the Earth and Moon form a closed system, the mean orbital plane of the Earth-Moon barycenter and the mean orbital plane of the Earth's orbit are the same thing, so it would seem that using the Earth-Moon barycenter would result in the same ecliptic. However, perturbations to the lunar orbit directly affect the Earth-Moon barycenter. Thus, the mean must be taken over an integral number of the periodic perturbations arising from the lunar motion. Otherwise, the mean orbital plane of the Earth-Moon barycenter as determined from the ephemeris will not be the same as the ecliptic. Meeting this condition is difficult to do with an integrated ephemeris.

Also, as Capitaine et al. (2004a) demonstrated, long-period planetary perturbations may cause a significant difference in the ecliptic determined. These are the perturbations that the proper element method is designed to remove. Thus, an ecliptic determined from an ephemeris is tied to that ephemeris and has no validity outside the time range of the ephemeris. On the other hand, an ecliptic derived from the Earth's proper elements could be extended indefinitely.

For both methods the accuracy of the ecliptic as a physical entity is limited by the accuracy of the initial conditions. The ecliptic's applications are now purely fiducial, that is it provides an equinox for use for both astronomical and civil purposes and a fiducial plane for use in solar system dynamics. Observations have become accurate enough that the true orbital plane, rather than the ecliptic, is required for celestial mechanics computations of the Earth-Moon system to match the accuracy of the observations. Thus, there is no compelling reason to choose either definition for the ecliptic. To avoid confusion, however, both the source for the ecliptic and the set of equations defining it should be explicitly stated.

Since there is no compelling reason to do otherwise and the parameters for the Capitaine et al. (2003), P03, precession of the ecliptic are already being used along with the P03 precession of the equator, the working group recommends the adoption of the Capitaine et al. (2003) precession of the ecliptic.

4. RECOMMENDATIONS

The Working Group on Precession and the Ecliptic has not yet proposed a set of recommendations. However, discussions on what should be in the recommendations has begun. The following represents the author's understanding of the current consensus of the working group.

The Working Group on Precession and the Ecliptic recognizing:

1. The need for a dynamically consistent precession theory compatible with the IAU 2000A nutation theory,

2. Recent improvements in the accuracy to which the precession can be determined blurs the distinction between the terms *lunisolar precession* and *planetary precession*,

3. The need for an ecliptic that acts as a fiducial plane for both astronomical and civil purposes,

4. In the past, the ecliptic has been defined both with respect to an observer situated in inertial space (inertial definition) and an observer co-moving with the Earth (rotating

definition), and

5. The loss of precision in the definition of the ecliptic caused by ignoring the relativistic transformations is insignificant compared to the accuracy of the ephemerides from which the ecliptic is determined

makes the following recommendations:

1. The IAU should adopt the Capitaine et al. (2003) precession theory, designated P03,

2. The terms *lunisolar precession* and *planetary precession* be replaced by *precession of the equator* and *precession of the ecliptic*, respectively,

3. The inertial definition of the ecliptic should be used, and should be explicitly stated to avoid confusion.

4. The ecliptic should be defined as the plane perpendicular to the Earth's mean orbital angular momentum vector.

5. There is no compelling reason to choose whether future realizations of the ecliptic are determined using either the proper element or the averaged ephemeris method. However, the method used and defining relations for the ecliptic should be clearly stated.

5. REFERENCES

Bourda, G. & Capitaine, N. 2004, A&A 428, 691

Bretagnon, P., Fienga, A., & Simon, J.-L. 2003, A&A 400, 785

Capitaine, N., Wallace, P.T., & Chapront, J. 2003, A&A 412, 567

Capitaine, N., Wallace, P.T., & Chapront, J. 2004a, A&A 421, 365

Capitaine, N., Wallace, P.T., & Chapront, J. 2004b, in press, A&A preprint doi:10.1051/004-6361:20041908

Fukushima, T. 2003, AJ 126, 494

Harada, W. 2003, Master's Thesis, University of Tokyo

Harada, W. & Fukushima, T. 2004, AJ 127, 531

IAU 1992, *Proceedings of the Twenty-First General Assembly, Buenos Aires 1991*, in Transactions of the International Astronomical Union, Vol. XXIB, J. Begeron, ed., (Dordrecht: Kluwer 1992), pp. 49-50

IAU 2001, *Proceedings of the Twenty-Fourth General Assembly, Manchester 2000*, in Transactions of the International Astronomical Union, Vol. XXIVB, H. Rickman, ed., (Provo, UT: Astronomical Society of the Pacific 2001), pp. 43-44

IERS 2004, Conventions (2000), in preparation

Laskar, J. 1988, A&A 198, 341

Lieske, J.H., Lederle, T., Fricke, W., & Morando, B. 1977, A&A 58, 1

Mathews, P.M., Herring, T.A., & Buffet, B.A. 2002, J. Geophys. Res. 107, B4, 10.1029/2001JB000390

Murray, C.D. & Dermott, S.F. 2000, *Solar System Dynamics*, (Cambridge, UK: Cambridge U. Press)

Newcomb, S. 1894, Astron. Papers Am. Ephemeris, 5, Part 4, pp. 301-378

Newcomb, S. 1906, *A Compendium of Spherical Astronomy*, (reprint) (New York: Dover Publications, 1960)

Simon, J.L., Bretagnon, P., Chapront, J., Chapront-Touzé, M., Franco, G., & Laskar, J. 1994, A&A 282, 663

Standish, E.M., Jr. 1981, A&A 101, L17

Standish, E.M. 2004, A&A 417, 1165

Williams, J.G. 1994, AJ 108, 711

INTRODUCTION TO KICKOFF MEETING FOR THE PROJECT "DESCARTES-NUTATION"

V. DEHANT
Royal Observatory of Belgium
Avenue Circulaire, 3, B-1180, Brussels Belgium
e-mail: v.dehant@oma.be

The Descartes Prize 2003 was awarded to the IAU/IUGG Working Group on "Nutation for a nonrigid Earth" chaired by Veronique Dehant. This prize is awarded for a fruitful collaboration in Europe and outside Europe, in order to achieve a goal in the frame of Science and Society. This prize was for their development of a new model of the nutations and precession of the Earth. The model was adopted by the International Astronomical Union (IAU) in 2000 and the International Union of Geodesy and Geophysics (IUGG) in 2003. It provides the link between the terrestrial frame, 'fixed' in relation to the Earth's crust and rotating with the Earth, and the celestial frame, which is immobile in space. The relationship between these frames is complicated by the fact that the rotation and orientation of the Earth is subject to irregularities caused by the gravitational pull of the Sun and Moon, as well as by many other factors that are progressively being identified by geodesists, geophysists, and astronomers. Because the Earth is an ellipsoid flattened at its poles, the combined forces acting upon it produce changes in both the speed of rotation and the orientation of the Earth symmetry axis. The term 'precession' describes the long-term trend of this latter motion, while 'nutation' is the name given to periodic variations, which were the prime focus of the present project. We have presented this work to the European Union and defended it in front of the Grand Jury. We have learned at the 2003 ceremony that we have been awarded and this was really a very nice surprise!

The EU has given the following citation: *An award of 300 000 Euros was presented to a project which considerably improves the efficiency of positioning and navigation systems. Led by Prof. Veronique Dehant of the Royal Observatory of Belgium, in association with researchers from France, Poland, Spain, Germany, Austria, the Czech Republic, the Ukraine, Russia (+USA, India, Japan, Canada, and China), this project has produced a highly accurate reference model to predict future variations in the Earth's axis. The new model will have major concrete applications for European and international satellite systems.*

The project was coordinated by Prof. Veronique Dehant of the Royal Observatory of Belgium in association with researchers from her institution, from the Bureau International des Poids et Mesures in Sèvres, the Institut de Mécanique Céleste et de Calcul des Ephémérides and the Department "Systèmes de référence Temps-Espace" of Observatoire de Paris (France), the Space Research Centre of the Polish Academy of Sciences in Warsaw (Poland), Universidad Complutense of Madrid, the Universities of Alicante and Valladolid (Spain), Technical Universities of Dresden and Munich and GeoForschungsZentrum Potsdam (Germany), the Technical University of Vienna (Austria), Astronomical Institute of the Academy of Sciences of Czech Republic in

Prague (Czech Republic), the Main Astronomical Observatory of the National Academy of Sciences of Ukraine in Kiev (Ukraine) and the Sternberg State Astronomical Institute of Moscow State University (Russia). In addition to these European countries, USA, India, Japan, Canada, and China were also participating in the project.

Since that time, an advisory board was created; it is composed of Veronique Dehant, Aleksander Brzezinski, Nicole Capitaine, Juan Getino, and Harald Schuh. have announced a call for proposals for financing PhD students or post-doctoral fellowships and received a lot of good proposals. The advisory board decided to finance the following subjects (cf. Table). The call for proposals was not limited to European projects and several non-European projects have been accepted for financing.

The Descartes Nutation advisory board has also decided to provide some financial support for participation in these Journées Systèmes de Référence.

The Descartes Nutation advisory board is also willing to organize a summer school in Les Houches in May 2006. This will allow the previous WG members and other scientists to share their knowledge in the frame of research for the next decimal of the nutation model and observation.

Project Name	Institution	Contract Person	Length	Status
Dynamical Flattening Geophysical Fluids Combination	Vienna TU	Laura Fernandez	6 months post-doc	running
Investigation of Excitations of nutation from geophysical fluids	AER, USA	Yonghong Zhou	6 months post-doc	running
Relations between the Earth Orientation Parameters and the variations of the Earth gravity field, through the inertia tensor	Vienna TU	Géraldine Bourda	6 months post-doc	running
Estimation and modelling of the Free Core Nutation parameters (FCN)	Valladolid University	Vladimir Zharov	4 months	running
Part I - Advances in the integration of the equations of the Earth's rotation in the framework of the new parameters adopted by the IAU 2000 Resolutions	Observatoire de Paris	Marta Folgueira	6 months post-doc	running
Part II - Geophysical effects of considering the new solutions for the Earth's rotation in the framework of the new parameters adopted by the IAU 2000 Resolutions	Observatoire Royal de Belgique	Marta Folgueira	3 months post-doc	running
Modeling and prediction of the FCN Study of the atmospheric and nontidal oceanic effects on nutation	RSC Warsaw & USNO	Maciej Kalarus	6 months PhD student	running
Combination of AAM series for a IERS product	Observatoire Royal de Belgique	Laurence Koot	2 months PhD student	finished
Modeling atmospheric and oceanic contribution to nutation	Polish Academy of Sciences in Warsaw	Sergei Bolotin	6 months post-doc	running
Study of the Chandler Wobble and sub daily variability of polar motion and length of day	Polish Academy of Sciences in Warsaw	Maria Kudryashova	4 months PhD student	running
GPS-GALILEO-VLBI for nutations	Vienna TU & Observatoire Royal de Belgique	Kristyna Snajdrova	2 years PhD student	running
Combined effects of electromagnetic and topographic coupling on nutation	GSFC	Laurent Metivier	6 months post-doc	accepted
"Missioner" - Exchange program to study nutation Part 1	Observatoire Royal de Belgique	Cheng-Li Huang		running*
"Missioner" - Exchange program to study nutation Part 2	Shanghai Observatory	Véronique Dehant		running*

* The project was foreseen withing the Descartes Nutation Prize but a bilateral agreement budget between Belgium and China has been obtained in the mean time.

PLANS FOR HIGH ACCURACY COMPUTATIONS OF EARTH ROTATION/POLAR MOTION EXCITATIONS

D.A. SALSTEIN
Atmospheric and Environmental Research, Inc.
131 Hartwell Ave., Lexington, MA, 02421, USA
e-mail: salstein@aer.com

ABSTRACT. Knowledge from atmospheric analyses and/or models is very important for calculations of the excitations of the Earth, including length of day, polar motion, and nutation, and has further consequences for understanding of the geophysical structure of the Earth's interior, that is, mantle and core. With some of the nutation parameters especially dependent on the diurnal variability of the atmosphere's equatorial angular momentum, it is important to seek the best series for such terms. We are grateful to the winners of the Descartes Prize for their nutation studies with having chosen our team for an award to study the relevant excitation functions.

1. TEAM MEMBERS

Ben Chao, NASA GSFC, Greenbelt, MD, USA Rui Ponte, Atmospheric and Environmental Research, Inc., Lexington, MA, USA Jianli Chen, Center for Space Research, University of Texas, Austin, TX, USA Yonghong Zhou, Shanghai Astronomical Observatory, Shanghai, China, and Atmospheric Environmental Research, Inc., USA

2. SPECIAL BUREAU FOR THE ATMOSPHERE ISSUES

The Special Bureau for the Atmosphere (SBA) of the Global Geophysical Fluids Center of the International Earth Rotation and Reference Systems Service, has been calculating, accessing, archiving, and distributing data for the atmospheric excitation of Earth rotation and polar motion. During the more than 15 years of this bureau and its predecessor, the Sub-Bureau for Atmospheric Angular Momentum, a number of weather centers have supplied the SBA with atmospheric data, including both operational and reanalysis series. the other geophysical fluid, the ocean, has diurnal terms as well, relevant to nutation. These terms are only now starting to be estimated using ocean models and much work is needed to assess their quality and usefulness for nutation studies. Plans for a postdoctoral fellow to help in these data improvement endeavors are presented.

Subdiurnal values for the atmospheric excitation function for polar motion are the heart of the project. Atmospheric weather analysis systems typically produce values every 6 hours, largely because that is the frequency of many of the best observations that are assimilated by the system. Some systems have produced a limited number of meteorological parameters, in this case, the surface variables, every 3 hours. We will consider if this, or even higher temporal resolution, based upon the independence of the analyses, is worthwhile.

Because the atmosphere is a major excitation source for Earth rotation and polar motion, we turn to its analyses to determine global excitation values of these excitations, based on winds and mass (surface pressure). Also, torques that dynamically effect momentum transfer are calculated. Outlined here is the basic three-step process by which analyses are performed: modeling, data assimilation, initialization; also they assimilate a variety of heterogeneous observed data

As high frequency atmospheric data (retrograde diurnal) are required for nutation studies, at present 6 hourly data are available. In this project we explore the issue of obtaining or determining such excitation values with any accuracy on higher frequency. Values from the SBA (Special Bureau for the Atmosphere) of the IERS (International Earth Rotation and Reference Frames Service), currently based on the Barnes et al. (1983) formulation, need updating. For example, the particular constants, some approximations that have been used, and methods of organization will be reviewed, well as data handling at the SBA for all our products, including a full notation of all angular momentum data archives. Ocean angular momentum at short time scales requires modeling with a variety of improvements.

Torque is the dynamic mechanism that transfers angular momentum across the atmosphere's lower boundary. Three main torques can be computed (for axial), with a fourth for equatorial: (1) The mountain torque against topography, based upon normal forces, (2) the friction torque, from the tangential stress term; (3) a gravity wave torque, based on the subgrid scale friction-like process over topography, and (4) the gravitational torque arising from the impact of uneven mass, acts principally from bulge of Earth on equatorial torque (de Viron et al. 1999). We will analyze torque and angular momentum balances.

3. ATMOSPHERIC ANALYSES FROM A METEOROLOGICAL FORECAST -ANALYSIS SYSTEM

To appreciate what is needed to improve the data sets in the SBA it is necessary to have an understanding of how the analysis-forecast systems produce meteorological information relevant to the variations in the Earth Orientation Parameters (EOP).

Meteorological centers have access to the huge amount of information from in situ (radiosonde), aircraft-based, and information from a variety of weather satellites. The information from this heterogeneous set is assembled and combined with output from a weather forecast model. Such a model advances the state of the atmosphere in time, typically by six hours, from which the forecasted fields of atmospheric parameters are obtained. The combination is performed with specific data assimilation techniques that combine the various observations within a time window in an optimal way, based upon the error characteristics of both the data sources and the forecast model. A third step is often needed, known as initialization, that makes analysis usable as initial state for the forecast model.

The result is a full set of atmospheric parameters including temperature, moisture, pressure and winds. Surface pressures and winds are needed by the formulas for excitations of Earth rotation and polar motion. The present formulations, based on Barnes et al. (1983) will be updated in new procedures, as noted above.

Thus, we need to make improvements in the atmospheric data as follows: We wish to improve the representation of AAM at short periods, essentially sub-daily. An issue arises, however, when attempting either possibility: the characteristics of forecast and analysis fields are not the same, and so great care must be used if one is to combine information from these different time steps. This effort will require either accessing the intermediate time steps of a model-assimilation system, or running such a system ourselves, and we are investigating both options. As another possibility, we may access the intermediate time steps of a general circulation model without benefit of data-in this case more understanding about the characteristics of higher temporal frequency data, such as spectral resolution, will be apparent.

First we examine suggested improvements to the Barnes et al. simulation that have been published (e.g., Eubanks 1993; Wahr, 1982, Wahr, 2004). Second, we investigate better distribution/archiving procedures those present in the SBA and GGFC websites. Included are closer examinations of the calculations of the excitation terms, including issues of the integration including vertical limits near bottom topography. We also investigate the torques, which effect the changes of angular momentum. The torque and angular momentum approaches need to be more consistent: the torque values are derived from the forecast models, and angular momentum from analyses.

4. IMPROVEMENTS NEEDED FOR THE OCEAN-RELATED STUDIES

A number of steps must be taken to enhance the usefulness of ocean-related products for use in studying Earth rotation issues. The major relevant issue to consider here is the representation of OAM at short periods (daily and shorter). Also, the uncertainties in ocean results must be reduced to the extent possible. Achieving these ends will require efforts in the following areas: (1) Obtaining more frequently sampled and/or better representation of daily cycle in atmospheric forcing fields, as the atmospheric fields form boundary conditions for an ocean model. The fields include the winds and surface pressures. (2) Use of truly global ocean models, including effects of semi-enclosed seas and the Arctic. (3) Tuning ocean model parameterizations of friction, which will help in the overall angular momentum balance., (4) Use of state estimation techniques to better constrain short period variability in ocean models, (5) Accounting for the effects of self-attraction and loading in calculations of non-tidal effects, and (6) Attempting to ensure consistency in modeling non-tidal and tidal effects, with regard to radiational and gravitational effects (Ponte and Ray 2002) .

5. GLOBAL GEOPHYSICAL FLUIDS CENTER

The User community is served by the Global Geophysical Fluids Center, a product center of the IERS. The SBA has eight different special bureaus, namely, those for the atmosphere, oceans, hydrology, tides, mantle, core, gravity/geocenter, and loading. Activities of the whole GGFC are centered at the NASA Goddard Space Flight Center. Information about the GGFC and IERS can be found on its website. We will address issues of commonality to the special bureaus and attempt to unify the data sets resident at the GGFC that are derived from the various special bureaus.

6. HIGH RESOLUTION ATMOSPHERIC ANGULAR MOMENTUM

We are attempting to produce AAM at the high subdaily resolution. This is important when one considers the strong diurnal and semidiurnal tides that influence the wind terms in such a way as to strongly impact the equatorial term. Hsu and Hoskins (1989), for example have shown that such tides are caused by thermal effects of radiation, and are, moreover, seasonally modulated. Thus we will make an effort to use atmospheric models, as noted above, to produce the wind terms necessary to calculate the excitation terms at the highest resolution. It should be noted though, that at such high frequencies, the excitation terms, such as mentioned in Barnes et al. are not subject to the full set of approximations used in that formulation.

As noted above, the integrations at the weather centers are organized so that data are archived typically at 6 hour intervals. The equations of motion of the atmospheric models have time steps that are far shorter, as little as 15-seconds for very high spatial resolution. So atmospheric parameters are produced at that very high frequency, but these are very rarely saved or used for any other purpose. Because the nutation studies would benefit from data at the 1-hour resolution, our goal in this project and succeeding efforts is to investigate the characteristics and usefulness of such information.

7. REFERENCES

Barnes, R.T.H., R. Hide, A.A. White, and C.A. Wilson, 1983: Atmospheric angular momentum fluctuations, length of day changes, and polar motion. Proc. R. Soc. Lond., 387, 31-73.

deViron, O., C. Bizouard, D.A. Salstein, and V. Dehant, 1999: Atmospheric torque on the Earth and comparison with atmospheric angular momentum variations. J. Geophys. Res., 104, 4861-4875.

Eubanks, T.M., 1993: Variations in the rotation of the Earth. In Contributions of Space Geodesy to Geodynamics - Earth Dynamics, Geodyn. Ser. Vol 24, edited by D.E. Smith and D.L. Turcotte, pp. 1-54, AGU, Washingthon, DC.

Hsu, H.H., and B.J. Hoskins, 1989. Tidal fluctuations as seen in the ECMWF data. Quart. J. Roy. Meter. Soc., 115, 247-264.

Ponte, R.M. and Ray, R.D., Atmospheric pressure correction in geodesy and oceanography: A strategy for handling air tides, Geophys. Res. Let., vol. 29, (24), 2153, doi:10.1029/2002GL016340, 2002.

Salstein, D.A., D.M. Kann, A.J. Miller, and R.D. Rosen, 1993: The Sub-bureau for Atmospheric Angular Momentum of the International Earth Rotation Service, Bull. Amer. Meteorol. Soc., 74, 67-80.

Wahr, J.M., 1982: The effects of the atmosphere and the oceans on the Earth's wobble. -1. Theory, Geophys. J. R. astr. Soc., 70, 349-372.

Wahr, J.M.,2004: Polar motion models: Angular momentum approach. Proceedings, Chandler Wobble Workshop. April 2004, European Center for Geodynamics and Seismology,

NONTIDAL OCEANIC EXCITATION OF DIURNAL AND SEMIDIURNAL POLAR MOTION ESTIMATED FROM A BAROTROPIC OCEAN MODEL

A. BRZEZIŃSKI
Space Research Centre, Polish Academy of Sciences
Bartycka 18A, 00-716 Warsaw, Poland
e-mail: alek@cbk.waw.pl

1. INTRODUCTION

The nontidal variability in the ocean is expected to have a significant influence on Earth rotation over a broad range of frequencies. We used a new 7.5-year time series of ocean angular momentum (OAM) with high temporal resolution (sampling interval 1 hour) calculated from a barotropic numerical model (Ponte and Ali, 2002), to study the influence of wind- and pressure-driven ocean signals on nutation and diurnal/semidiurnal polar motion. Here we will describe briefly the second part of the work, that is this concerning the oceanic contribution to high frequency polar motions; for details see (Brzeziński et al., 2004).

2. DATA ANALYSIS AND RESULTS

We process all terms of the OAM series by applying the procedure developed by Bizouard *et al.* (1998) and Petrov *et al.* (1998): 1) extract the components contributing to the three spectral bands of interest, prograde diurnal, retrograde and prograde semidiurnal, by performing the complex demodulation at frequencies +1, −2, +2 cycles per sidereal day (cpsd); 2) perform spectral analysis; 3) compute parameters of the harmonic model including all detected periodical constituents; 4) remove the model and consider separately the irregular remainder. The same procedure is applied to the 6-hourly atmospheric angular momentum (AAM) series (Salstein *et al.*, 1993) calculated from the NCEP-NCAR reanalysis fields (Kalnay *et al.*, 1996).

Prograde diurnal polar motion. The demodulated excitation series are shown in Fig. 1. The corresponding perturbation in polar motion $p = x_p - iy_p$ can be computed by multiplying the excitation $\chi = \chi_1 + i\chi_2$ first by the theoretical transfer coefficient -2.4×10^{-3}, then by the diurnal rotation factor $e^{i\,GST}$ (GST – Greenwich sidereal time) accounting for the demodulation. From Fig. 1, the motion terms of the AAM and OAM are of similar size but there is a large difference in phase. In case of the matter term, the AAM and AAMIB signals are quite similar while the OAM term has larger amplitude and is significantly delayed in phase. After removal of the model, the residual signal has a negligible influence on polar motion, at the level of 1 μas.

When considering the periodical components of excitation and adding various contributions (motion AAM+OAM plus matter AAMIB+OAM), the only significant contribution found is the S_1^+ harmonic with a period of +1 cycle per solar day. The dynamic model atmosphere-ocean yields a total amplitude in polar motion of 9 μas, which is slightly larger than the atmosphere alone (between 6 μas and 8 μas) and with phase delay of about 17°.

Semidiurnal polar motion. With the 6-hourly AAM estimates it is impossible to resolve the retrograde and prograde semidiurnal bands. The OAM series is sampled hourly but as the underlying barotropic model has been forced by the 6-hourly wind and pressure fields from

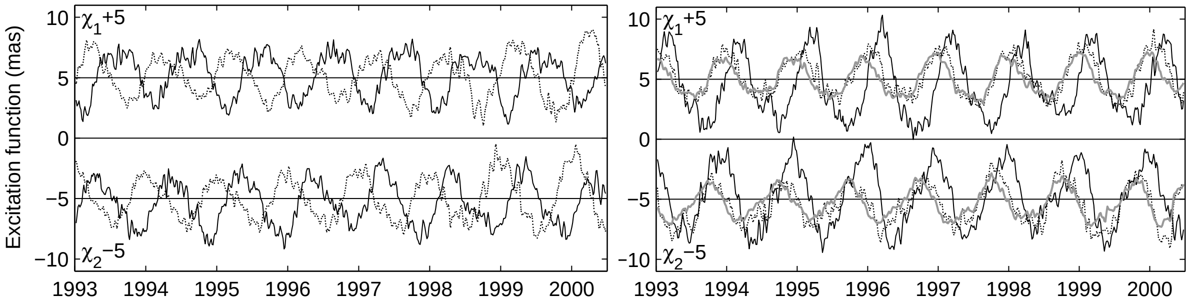

Figure 1: Effective angular momentum functions of the atmosphere (AAM - dotted line, AAMIB - solid gray line) and of the ocean (OAM - solid line), demodulated at frequency +1 cycle per sidereal day: motion terms (left) and matter terms (right). From (Brzeziński *et al.*, 2004).

the NCEP-NCAR reanalysis (Kalnay *et al.*, 1996), the reliability of the results concerning the semidiurnal excitation is low. Our analysis show that the only significant contribution to polar motion is from the S_2 constituent of the OAM, about 6 μas. Adding the influence estimated from the AAM can increase the amplitude up to 9 μas.

3. CONCLUSIONS

The estimated nontidal oceanic excitation of prograde diurnal polar is rather small – after accounting for the atmospheric excitation the peak-to-peak size is about 18 μas. But as the corresponding contribution from the S_1 ocean tide is about 7 times smaller, there is a good chance that future subdiurnal determinations of polar motion will verify our estimate. In case of the semidiurnal component the estimated nontidal contribution from the ocean is of similar size, but 1) its reliability is low due to the problem of data sampling, and 2) it will be difficult to separate this effect observationally from the much larger influence of the S_2 ocean tide.

Acknowledgments. This research has been supported by the Polish Ministry of Scientific Research and Information Technology under grant No. 5 T12E 039 24. Participation costs were covered by the French Ministry of Education and Research in the framework of the programme ACCES.

4. REFERENCES

Bizouard Ch., A. Brzeziński and S. D. Petrov (1998). Diurnal atmospheric forcing and temporal variations of the nutation amplitudes, *Journal of Geodesy*, **72**, 561–577.

Brzeziński A., R. M. Ponte and A. H. Ali (2004). Nontidal oceanic excitation of nutation and diurnal/semidiurnal polar motion revisited, *J. Geophys. Res. - Solid Earth*, **109**, No. B11, doi: 10.1029/2004JB003054.

Kalnay E., et al. (1996). The NMC/NCAR 40-year reanalysis project, *Bull. Amer. Met. Soc.*, **77** (3), 437–471.

Petrov S. D., A. Brzeziński, and J. Nastula (1998). First estimation of the non- tidal oceanic effect on nutation, in *Proc. Journées Systèmes de Référence Spatio-Temporels 1998*, edited by N. Capitaine, Paris Observatory, 136–141.

Ponte R. M., and A. H. Ali (2002). Rapid ocean signals in polar motion and length of day, *Geophys. Res. Lett.*, **29** (15), doi: 10.1029/2002GL015312.

Salstein, D. A., D. M. Kann, A. J. Miller, and R. D. Rosen (1993). The subbureau for atmospheric angular momentum of the International Earth Rotation Service: a meteorological data center with geodetic applications, *Bull. Am. Meteorol. Soc.*, **74**, 67–80.

ON THE EFFECT OF THE REDISTRIBUTION TIDAL POTENTIAL ON THE ROTATION OF THE NON-RIGID EARTH: DISCREPANCIES AND CLARIFICATIONS

A. ESCAPA[1], J. GETINO[2], J. MANUEL FERRÁNDIZ[1]

[1] Dpto. Matemática Aplicada.Escuela Politécnica Superior.
Universidad de Alicante.E-03080 Alicante. Spain
E-mail: Alberto.Escapa@ua.es

[2] Grupo de Mecánica Celeste. Facultad de Ciencias
Universidad de Valladolid. E-47005 Valladolid. Spain

ABSTRACT. In the last years several works have dealt with the effect of the redistribution tidal potential on the Earth rotation, that is to say on the rotational effects of the additional potential due to the elastic deformations caused on the Earth by gravitational interaction with the Moon and the Sun. However, analytical or numerical results derived by some of these approaches seem to provide significant discrepancies. In this research we compare some of these approaches when considering the motion of the rotational angular momentum axis of a perfect elastic Earth model. To this end, we revise the Hamiltonian formulation of the problem, contrasting it with others approaches well suited for the purposes of comparison and determining the source of the discrepancies.

1. INTRODUCTION

The characteristic feature of elastic Earth models is that there is a relative motion of the parts of the Earth with respect to a frame attached to it. This fact gives rise to additional effects that do not appear in the rigid cases and that provide significative contributions to the rotational motion of the Earth. ¿From a variational approach point of view, the elastic deformation affects both to the kinetic and potential energies of the body, or in terms of the Euler-Liouville type formulations, to the angular momentum of the body and the torques exerted on it.

In the last three decades, Earth rotation studies based on the above mentioned formulations have focused their attention on studying the effects on the rotation due to the elastic variations in the kinetic energy (or angular momentum) of the Earth, since this increment provides the main part of the elastic contribution. This is the case (among others) of the investigations by Sasao *et al.* 1980; Mathews *et al.* 2002; Getino and Ferrándiz 2001; Krasinsky 2003, etc. On the contrary, the effects of the elastic variations in the potential energy (or exerted torque) on the rotation of the Earth, specially on nutation and precession, have only been tackled recently.

In this note, we analice the influence on the rotation of the Earth of the variation of the gravitational potential energy due to the deformation caused on the Earth by the tidal interactions with the Moon and the Sun. This additional potential energy produced by an elastic redistribution of mass will be named as redistribution tidal potential. This name aims to avoid confusions with other parts of the gravitational potential considered in the rigid cases.

2. HAMILTONIAN TREATMENT

Next we sketch the procedure to account for the contributions on the rotation of the Earth of the redistribution tidal potential. A detailed explanation can be found in Escapa *et al.* 2005.

A convenient way to obtain the analytical expression of the redistribution tidal potential is to relate it with the variation that the deformation causes in the inertia matrix of the Earth. By so doing, we reduce our problem to compute the increment in the moments and products of inertia due to the deformation. To this end, it is necessary to find a solution of the Earth elastic problem, that is to say, to know the expression of the displacement vector due to the tidal interactions with the external bodies (the Moon and the Sun). On the basis of different simplifying hypothesis that model the elastic response of the Earth (Takeuchi 1950, Jeffreys and Vicente 1957, Sasao *et al.* 1980, etc.), it is possible to provide the analytical expression for the displacement vector which, for the purposes of computation, is usually written as a sum of spheroidal and toroidal terms. From this elastic solution, we can compute the increment of the inertia matrix, which can be splitted as

$$\Delta\Pi = \Delta\Pi^Z + \Delta\Pi^T + \Delta\Pi^S, \tag{1}$$

accordingly they contain zonal (Z), tesseral (T) or sectorial (S) spherical harmonics of the second degree in the geocentrical coordinates of the external bodies causing the tidal deformation, which are assumed to be known functions of time. Likewise, this increment depends on some rheological parameters which specify the elastic properties of the Earth. It is also expedient to separate the effects of the permanent tide (p), which are only present in $\Delta\Pi^Z$, so, finally, we have

$$\Delta\Pi = \Delta\Pi^Z_p + \Delta\Pi^Z_{np} + \Delta\Pi^T + \Delta\Pi^S. \tag{2}$$

Once we have obtained the variation of the inertia matrix, we can take advantage of MacCullagh formula to write out the analytical expression of the redistribution tidal potential, which in a similar way is put as

$$\Delta U = \Delta U^Z_p + \Delta U^Z_{np} + \Delta U^T + \Delta U^S. \tag{3}$$

To evaluate the contributions of redistribution tidal potential on the nutational and precessional motions of the Earth, we employ the Hamiltonian formalism developed by Getino and Ferrándiz. To this end, and following a standard procedure (see Getino and Ferrándiz 2001) we construct the Hamiltonian of a two–layer Earth model composed of an elastic mantle that encloses a fluid core, incorporating the part relative to the redistribution tidal potential. By applying the Hori's perturbation technique we obtain analytical expressions for the nutations in longitude and obliquity and the precession in longitude of the angular momentum axis.

3. DISCUSSION

The numerical computation of the former analytical formula is performed by considering the numerical values of Earth parameters given in Getino and Ferrándiz 1995, 2001. The values derived for the long period terms of the nutation in obliquity for the angular momentum axis are displayed in Table 1. We have splitted the total contribution in different parts according to eq. 3. Similar results are obtained for the nutation and precession in longitude. ¿From these values, we can stress two fundamental conclusions. First, under the elastic hypothesis considered the total effect of the redistribution tidal potential on nutation and precession of the angular momentum axis is zero. This result have been confirmed by means of analytical developments based on some properties fulfilled by the trigonometric expansions of the perturbing bodies coordinates.

l_m	l_S	F	D	Ω	ΔU_p^Z	ΔU_{np}^Z	ΔU^T	ΔU^S	Total
+0	+0	+0	+0	+1	+72.244	-7.535	-118.197	+53.488	+0.000
+0	+0	+0	+0	+2	-0.706	-1.603	+3.060	-0.752	+0.000
+0	+1	+0	+0	+0	+0.000	-0.000	+0.000	+0.000	+0.000
+0	-1	+2	-2	+2	-0.072	+0.068	+0.010	-0.006	+0.000
+0	+0	+2	-2	+2	+4.309	+0.002	-9.515	+5.205	-0.000
+0	+1	+2	-2	+2	+0.168	+0.023	-0.421	+0.230	-0.000
+1	+0	+0	+0	+0	+0.000	+0.000	+0.000	-0.000	-0.000
+0	+0	+2	+0	+2	+0.693	-0.005	-1.534	+0.846	+0.000
+0	+0	+2	+0	+1	+0.143	-0.015	-0.237	+0.109	-0.000
+1	+0	+2	+0	+2	+0.089	+0.026	-0.253	+0.138	-0.000

Table 1: Nutations in obliquity in μas: angular momentum axis

Second, the different parts of the redistribution tidal potential (see eq. 3) give raise to numerical contributions of the same order of magnitude, therefore to explain properly the influence of this effect in the rotation of the Earth it is necessary to take all the contributions of the redistribution tidal potential (zonal, tesseral and sectorial), treating them in an homogeneous way.

It may be not out of place to compare our results with other investigations that have also considered the same issue. In particular, we will consider the approaches worked out by Souchay and Folgueira 1998; Mathews *et al.* 2002; Krasinsky 2003 and Lambert and Capitaine 2004. In Souchay and Folgueira 1998 the contribution of the redistribution tidal potential is also investigated under a Hamiltonian approach. The authors only consider the part of the potential related to ΔU_{np}^Z providing analytical and numerical values for the nutations by means of an expression of $\Delta\Pi_{np}^Z$ taken from Melchior (1978).

Mathews *et al.* 2002 treat the problem with the aid of an Euler-Liouville equation for the whole Earth, as a part of a set of effects named "nonlinear terms". However, the treatment is quite opaque since details of the derivations and justifications used are omitted. The torque due to the deformation of the Earth is constructed through the redistribution tidal potential, although the contribution due to the tesseral part ΔU^T, coming from $\Delta\Pi^T$, seems to be omitted[1]. Besides, the term relative to the permanent tide ΔU_p^Z also seems not to be considered here but included as a part of the ordinary nutation and precession amplitudes. The contributions to the nutations and precession are computed numerically, obtaining the values from two different models of deformation: the terms arising from $\Delta\Pi_{np}^Z$ are taken from the tables of the axial spin rate variation (IERS Conventions 1996) and those ones arising from $\Delta\Pi^S$ are obtained with the help of the tables of tides provided by Cartwright and Tayler (1971).

Lambert and Capitaine 2004 tackle the issue together with the effects that the Earth's rotation rate variations due to zonal tides have on precession-nutation. As in the investigation by Mathews *et al.* 2002, the authors evaluate the influence of the redistribution tidal potential on nutations and precession by computing its torque and inserting it in the equations of Sasao *et al.* 1980. To this end, only the part ΔU_{np}^Z of the redistribution tidal potential is considered and the torque is numerically evaluated, taking for $\Delta\Pi_{np}^Z$ the values given in IERS Conventions 2003 and using ELP2000 (Chapront-Touzé and Chapront 1983) and VSOP87 (Bretagnon and Francou 1988) orbital theories.

Krasinsky 2003 works out the problem in a comprehensive framework which generalices the work of Sasao *et al.* 1980. With respect to the effect of the redistribution tidal potential on the rotation, the author considers a classical expression of the redistribution tidal potential in terms

[1]N. Capitaine has informed us that this part was included by the authors in a work presented at 2003 AGU Fall Meeting, but as far as we know it has not been incorporated to MHB 2000 tables.

of the Love number k_2. By taking the vectorial product of the gradient of the redistribution tidal potential, it is shown that in the elastic case the torques vanish due to the proportionality of the vectors entering in the vectorial product and to the cancellation of the crossed effect between the Moon and the Sun. Therefore, since the total torque is zero, there is no net effect on the rotation of the Earth, that is to say, there is no contribution to the nutation and precession of the angular momentum axis arising from this effect.

Acknowledgements. This work has been partially supported by Spanish projects I+D+I, AYA2004-07970 and AYA2001-0787, Spanish project ESP2001-4533-PE and *Junta de Castilla y León* project VA015/04.

4. REFERENCES

Bretagnon, P. and Francou, G., 1988, A&A 202, 309.
Cartwright, D. E. and Tayler, R. J., 1971, Geophys. J. R. Astron. Soc. 23,45.
Chapront-Touzé, M. and Chapront, J., 1983, A&A 124, 50.
Escapa, A., Getino, J. and Ferrándiz, J.M., 2005, Influence of the redistribution tidal potential on the rotation of the non-rigid Earth (to be submitted).
Getino, J. and Ferrándiz, J.M., 1995, Celest. Mech. Dyn. Astr. 61, 117.
Getino, J. and Ferrándiz, J.M., 2001, MNRAS 322, 785.
IERS Conventions 1996, 1996, IERS Tech. Note 21, ed. D. D. McCarthy.
IERS Conventions 2003, 2003, IERS Tech. Note 32, ed. D. D. McCarthy and G. Petit.
Jeffreys, H. and Vicente, R. O., 1957, MNRAS 117, 142.
Krasinsky G.A., 2003, Communications of the IAA RAS, 157, 1.
Lambert, S. and Capitaine, N., 2004, A&A 428, 255.
Mathews, P.M., Buffet, B.A. and Herring T.A., 2002, J. Geophys. Res. 107, 10.1029.
Melchior, P., 1978, The Tides of the Planet Earth, ed. Pergamon Press.
Sasao, T., Okubo, S. and M. Saito, 1980, Proceedings of IAU Symposium 78, ed. E. P. Federov, M. L. Smith, and P. L. Bender, 165.
Souchay, J. and Folgueira, M., 1998, Earth, Moon, and Planets, 81, 201.
Takeuchi, H., 1950, Trans. Am. Geophys. Union, 31, 651

ON THE THEORY OF CANONICAL PERTURBATIONS AND ITS APPLICATIONS TO EARTH ROTATION: A SOURCE OF INACCURACY IN THE CALCULATION OF ANGULAR VELOCITY

M. EFROIMSKY
US Naval Observatory
Washington DC 20392 USA
e-mail: me@usno.navy.mil

ABSTRACT. When the dynamical equations, written in terms of variable "constants," are demanded to be symplectic, these "constants" make conjugated pairs and are called Delaunay elements, in the orbital case, or Serret-Andoyer elements, in the rotational case. These sets of elements share a feature not readily apparent: in certain cases, the standard equations render them non-osculating. Non-osculating orbital elements parametrise instantaneous conics **not** tangent to the orbit. The non-osculating i, may differ much from the physical inclination of the orbit, given by the osculating i. Similarly, in the case of rotation, non-osculating Serret-Andoyer variables yield correct orientation angles for the body figure but not for the instantaneous spin axis. As a result, the Kinoshita-Souchay theory (which tacitly employs non-osculating Serret-Andoyer elements) gives correct results for the figure axis but needs corrections for the rotation axis.

1. KEPLER AND EULER

In orbital dynamics, a Keplerian conic, emerging as an undisturbed two-body orbit, is regarded as a sort of "elementary motion," so that all the other available motions are conveniently considered as distortions of such conics, distortions implemented through endowing the orbital constants C_j with their own time dependence. Points of the orbit can be contributed by the "elementary curves" either in a non-osculating fashion, as in Fig. 1, or in the osculating way, as in Fig. 2.

The disturbances, causing the evolution of the motion from one instantaneous conic to another, are the primary's oblateness, the gravitational pull of other bodies, the atmospheric and radiation-caused drag, and the non-inertiality of the reference system.

Similarly, in rotational dynamics, a complex spin can be presented as a sequence of configurations borrowed from a family of some elementary rotations. The easiest possibility here will be to employ in this role the Eulerian cones, i.e., the loci of the rotational axis, corresponding to non-perturbed spin states. These are the simple motions exhibited by an undeformable free top with no torques acting thereupon.[1] Then, to implement a perturbed motion, we shall have to

[1] Here one opportunity will be to employ in the role of "elementary" motions the non-circular Eulerian cones described by the actual triaxial top, when this top is unforced. Another opportunity will be to use, as "elementary" motions, the circular Eulerian cones described by a dynamically symmetrical top (and to treat its actual triaxiality

go from one Eulerian cone to another, just as in Fig. 1 and 2 we go from one Keplerian ellipse

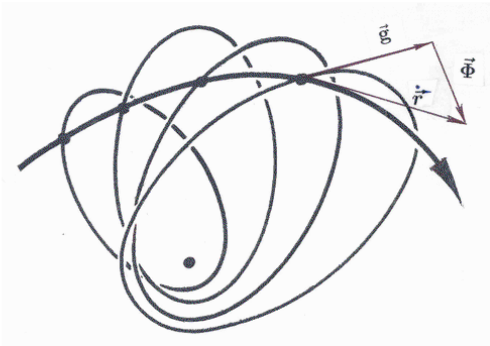

Figure 1: The perturbed trajectory is a set of points belonging to a sequence of confocal instantaneous ellipses. The ellipses are **not** supposed to be tangent, nor even coplanar to the orbit at the intersection point. As a result, the physical velocity $\dot{\mathbf{r}}$ (tangent to the trajectory at each of its points) differs from the Keplerian velocity $\tilde{\mathbf{g}}$ (tangent to the ellipse). To parametrise the depicted sequence of non-osculating ellipses, and to single it out of all the other such sequences, it is suitable to employ the difference between $\dot{\mathbf{r}}$ and $\vec{\boldsymbol{g}}$, expressed as a function of time and six (non-osculating) orbital elements: $\vec{\boldsymbol{\Phi}}(t, C_1, ..., C_6) = \dot{\mathbf{r}}(t, C_1, ..., C_6) - \tilde{\mathbf{g}}(t, C_1, ..., C_6)$. Since $\dot{\mathbf{r}} = \frac{\partial \tilde{\mathbf{r}}}{\partial t} + \sum_{j=1}^{6} \frac{\partial C_j}{\partial t} \dot{C}_j = \vec{\boldsymbol{g}} + \sum_{j=1}^{6} \frac{\partial C_j}{\partial t} \dot{C}_j$, then the difference $\vec{\boldsymbol{\Phi}}$ is simply the convective term $\sum \left(\partial \vec{\boldsymbol{r}} / \partial C_j\right) \dot{C}_j$ which emerges whenever the instantaneous ellipses are being gradually altered by the perturbation (and the orbital elements become time-dependent). In the literature, $\vec{\boldsymbol{\Phi}}(t, C_1, ..., C_6)$ is called the gauge function or gauge velocity or, simply, gauge.

to another. Hence, similar to those pictures, a smooth "walk" over the instantaneous Eulerian cones may be osculating or non-osculating.

The physical torques, the actual triaxiality of the top, and the non-inertial nature of the reference frame will then be regarded as perturbations causing the "walk." The latter two perturbations depend not only upon the rotator's orientation but also upon its angular velocity.

2. DELAUNAY AND SERRET

In orbital dynamics, we can express the Lagrangian of the reduced two-body problem via the spherical coordinates $q_j = \{r, \varphi, \theta\}$, then calculate their conjugated momenta p_j and the Hamiltonian $\mathcal{H}(q, p)$, and then carry out the Hamilton-Jacobi procedure (Plummer 1918), to arrive to the Delaunay variables

$$\begin{aligned} &\{Q_1, Q_2, Q_3; P_1, P_2, P_3\} \equiv \{L, G, H; l, g, h\} = \\ &\{\sqrt{\mu a}, \sqrt{\mu a\,(1 - e^2)}, \sqrt{\mu a\,(1 - e^2)} \cos i; -M_o, -\omega, -\Omega\}, \end{aligned} \tag{1}$$

where μ denotes the reduced mass.

Similarly, in rotational dynamics one can define a spin state of a top by means of the three Euler angles $q_j = \psi, \theta, \varphi$ and their canonical momenta p_j, and then perform a canonical transformation to the Serret-Andoyer elements L, G, H, l, g, h. A minor technicality is that, historically, these variables were introduced by Serret (1866) in a manner slightly different from the set of canonical constants: while, for a free rotator, the three Serret-Andoyer variables G, H, h are constants, the other three, L, l, g do evolve in time (for the Serret-Andoyer Hamiltonian of

as another perturbation). The main result of our paper will be invariant under this choice.

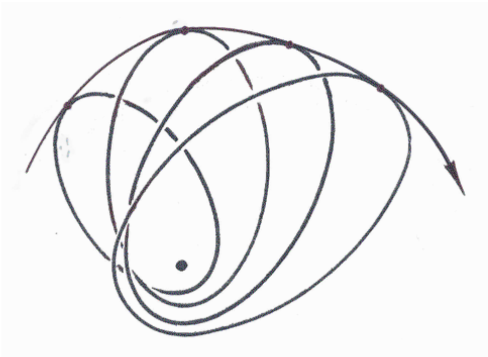

Figure 2: The perturbed trajectory is represented through a sequence of confocal instantaneous ellipses which are tangent to the trajectory at the intersection points, i.e., are osculating. Now, the physical velocity $\dot{\vec{\mathbf{r}}}$ (which is tangent to the trajectory) will coincide with the Keplerian velocity $\tilde{\mathbf{g}}$ (which is tangent to the ellipse), so that their difference $\vec{\mathbf{\Phi}}(tC_1, ..., C_6)$ vanishes everywhere: $\vec{\mathbf{\Phi}}(t, C_1, ..., C_6) \equiv \dot{\vec{r}}(t, C_1, ..., C_6) - \vec{g}(t, C_1, ..., C_6) = \sum_{j=1}^{6} \frac{\partial C_j}{\partial t} \dot{C}_j = 0$. This equality, called Lagrange constraint or Lagrange gauge, is the necessary and sufficient condition of osculation.

a free top is not zero, but a function of l, L and G). This way, to make our analogy complete, we may carry out one more canonical transformation, from the Serret-Andoyer variables $\{L, G, H, l, g, h\}$ to "almost Serret-Andoyer" variables $\{L_o, G, H, l_o, g_o, h\}$, where L_o, l_o and g_o are the initial values of L, l and g. The latter set consists only of the constants of integration; the corresponding Hamiltonian becomes nil. Therefore, these constants are the true analogues of the Delaunay variables (while the conventional Serret-Andoyer set is analogous to the Delaunay set with M used instead of M_o.). The main result obtained below for the modified Serret-Andoyer set $\{L_o, G, H, l_o, g_o, h\}$ can be easily modified for the regular Serret-Andoyer set of variables $\{L, G, H, l, g, h\}$ (see the Appendix).

To summarise this section, in both cases we start out with

$$\dot{q} = \frac{\partial \mathcal{H}^{(o)}}{\partial p}, \quad \dot{p} = -\frac{\partial \mathcal{H}^{(o)}}{\partial q} \quad . \tag{2}$$

q and p being the coordinates and their conjugated momenta, in the orbital case, or the Euler angles and their momenta, in the rotation case. Then we switch, via a canonical transformation

$$\begin{aligned} q &= f(Q, P, t) \\ p &= \chi(Q, P, t), \\ \text{to } \dot{Q} &= \frac{\partial \mathcal{H}^*}{\partial P} = 0, \ \dot{P} = -\frac{\partial \mathcal{H}^*}{\partial Q} = 0, \ \mathcal{H}^* = 0, \end{aligned} \tag{3}$$

where Q and P denote the set of Delaunay elements, in the orbital case, or the (modified, as explained above) Serret-Andoyer set $\{L_o, G, H, l_o, g_o, h\}$, in the case of rigid-body rotation. This scheme relies on the fact that, for an unperturbed Keplerian orbit (and, similarly, for an undisturbed Eulerian cone) its six-constant parametrisation may be chosen so that:

1. the parameters are constants and, at the same time, are canonical variables $\{Q, P\}$ with a zero Hamiltonian: $\mathcal{H}^*(Q, P) = 0$;

2. for constant Q and P, the transformation equations (3) are mathematically equivalent to the dynamical equations (2).

3. WHEN DO THE ELEMENTS COME OUT NON-OSCULATING?

3.1 General-type motion

Under perturbation, the "constants" Q, P begin to evolve so that, after their substitution into

$$\begin{aligned} q &= f\,(Q(t), P(t), t) \\ p &= \chi(Q(t), P(t), t) \end{aligned}$$

(f and χ being the same functions as in (3)), the resulting motion obeys the disturbed equations

$$\dot{q} = \frac{\partial\left(\mathcal{H}^{(o)} + \Delta\mathcal{H}\right)}{\partial p}, \quad \dot{p} = -\frac{\partial\left(\mathcal{H}^{(o)} + \Delta\mathcal{H}\right)}{\partial q} \quad . \tag{4}$$

We also want our "constants" Q and P to remain canonical and to obey

$$\dot{Q} = \frac{\partial\left(\mathcal{H}^* + \Delta\mathcal{H}^*\right)}{\partial P}, \quad \dot{P} = -\frac{\partial\left(\mathcal{H}^* + \Delta\mathcal{H}^*\right)}{\partial Q} \tag{5}$$

$$\text{where } \mathcal{H}^* = 0 \text{ and } \Delta\mathcal{H}^*\,(Q, Pt) = \Delta\mathcal{H}\,(q(Q,P,t), p(Q,P,t), t)\,. \tag{6}$$

Above all, an optimist will expect that the perturbed "constants" $C_j \equiv Q_1, Q_2, Q_3, P_1, P_2, P_3$ (the Delaunay elements, in the orbital case, or the modified Serret-Andoyer elements, in the rotation case) will remain osculating. This means that the perturbed velocity will be expressed by the same function of $C_j(t)$ and t as the unperturbed one used to. Let us check to what extent this optimism is justified. The perturbed velocity reads

$$\dot{q} = g + \Phi \tag{7}$$

$$\text{where } g(C(t), t) \equiv \frac{\partial q(C(t), t)}{\partial t} \tag{8}$$

is the functional expression for the unperturbed velocity; and

$$\Phi(C(t), t) \equiv \sum_{j=1}^{6} \frac{\partial q(C(t), t)}{\partial C_j}\dot{C}_j(t) \tag{9}$$

is the convective term. Since we chose the "constants" C_j to make canonical pairs (Q, P) obeying (5 - 6), with vanishing $\mathcal{H}^*$, then insertion of (5) into (9) will result in

$$\Phi = \sum_{n=1}^{3} \frac{\partial q}{\partial Q_n}\dot{Q}_n(t) + \sum_{n=1}^{3} \frac{\partial q}{\partial P_n}\dot{P}_n(t) = \frac{\partial \Delta\mathcal{H}(q,p)}{\partial p}. \tag{10}$$

So the canonicity demand is incompatible with osculation. In other words, whenever a momentum-dependent perturbation is present, we still can use the ansatz (4) for calculation of the coordinates and momenta, but can no longer use (12) for calculating the velocities. Instead, we must use (11). Application of this machinery to the case of orbital motion is depicted on Fig.1. Here the constants $C_j = (Q_n, P_n)$ parametrise instantaneous ellipses which, for nonzero Φ, are **not** tangent to the trajectory. (For more details see Efroimsky & Goldreich (2003).) In the case of orbital motion, the situation will be similar, except that, instead of the instantaneous Keplerian conics, one will deal with instantaneous Eulerian cones (i.e., with the loci of the rotational axis, corresponding to non-perturbed spin states).

3.2 Orbital motion

In the orbital-motion case, osculation means the following. Let the unperturbed position be given, in some fixed Cartesian frame, by vector function $\vec{\boldsymbol{f}}$:

$$\vec{\boldsymbol{r}} = \vec{\boldsymbol{f}}\,(C_1, ..., C_6, t)\,, \vec{\boldsymbol{r}} \equiv \{x, y, z\}. \tag{11}$$

Employing this functional ansatz also under disturbance, we get the perturbed velocity as

$$\dot{\vec{\boldsymbol{r}}} \;=\; \vec{\boldsymbol{g}}\,(C_1(t), ..., C_6(t), t) + \vec{\boldsymbol{\Phi}}\,(C_1(t), ..., C_6(t), t) \tag{12}$$

$$\text{where } \vec{\boldsymbol{g}} \;\equiv\; \frac{\partial \vec{\boldsymbol{f}}}{\partial t} \;\text{ and }\; \vec{\boldsymbol{\Phi}} \equiv \sum_{j=1}^{\infty} \frac{\partial \vec{\boldsymbol{f}}}{\partial C_j} \dot{C}_j. \tag{13}$$

The osculation condition is a convenient (but totally arbitrary!) demand that the perturbed velocity $\dot{\vec{\boldsymbol{r}}}$has the same functional dependence upon t and C_j as the unperturbed velocity $\vec{\boldsymbol{g}}$:

$$\vec{\boldsymbol{r}}\,(C_1(t), ..., C_6(t), t) = \vec{\boldsymbol{f}}\,(C_1(t), ..., C_6(t), t)\,,$$
$$\dot{\vec{\boldsymbol{r}}}(C_1(t), ..., C_6(t), t) = \vec{\boldsymbol{g}}\,(C_1(t), ..., C_6(t), t)\,.$$

or, equivalently, that the so-called Lagrange constraint is satisfied:

$$\sum_{j=1}^{\infty} \frac{\partial \vec{\boldsymbol{f}}}{\partial C_j} \dot{C}_j = \vec{\boldsymbol{\Phi}}\,(C_1(t), ..., C_6(t), t)\,\text{where}\vec{\boldsymbol{\Phi}} = 0. \tag{14}$$

Fulfilment of these expectations, however, should in no way be taken for granted, because the Lagrange constraint (14) and the canonicity demand (5 - 6) are now two independent conditions whose compatibility is not guaranteed. As shown in Efroimsky (2002a,b), this problem has gauge freedom, which means that any arbitrary choice of the gauge function $\vec{\boldsymbol{\Phi}}\,(C_1(t), ..., C_6(t), t)$ will render, after substitution into (11 - 12), the same values for $\vec{\boldsymbol{r}}$ and $\dot{\vec{\boldsymbol{r}}}$as were rendered by Lagrange's choice (14).[2] As can be seen from (10), **the assumption, that the "constants" Q and P are canonical, fixes the non-Lagrange gauge**

$$\sum_{j=1}^{\infty} \frac{\partial \vec{\boldsymbol{f}}}{\partial C_j} \dot{C}_j = \vec{\boldsymbol{\Phi}}\,(C_1(t), ..., C_6(t), t)\,\text{where}\vec{\boldsymbol{\Phi}} = \frac{\partial \Delta\mathcal{H}}{\partial \vec{\boldsymbol{p}}}. \tag{15}$$

It is easy to show (Efroimsky & Goldreich 2003; Efroimsky 2004b) that this same non-Lagrange gauge simultaneously guarantees fulfilment of the momentum-osculation condition:

$$\vec{\boldsymbol{r}}\,(C_1(t), ..., C_6(t), t) = \vec{\boldsymbol{f}}\,(C_1(t), ..., C_6(t), t)\,,$$
$$\vec{\boldsymbol{p}}\,(C_1(t), ..., C_6(t), t) = \vec{\boldsymbol{g}}\,(C_1(t), ..., C_6(t), t)\,.$$

Any gauge different from (15), will prohibit the canonicity of the elements. In particular, for momentum-dependent $\Delta\mathcal{H}$, the choice of osculation condition $\vec{\boldsymbol{\Phi}} = 0$ would violate canonicity.

For example, an attempt of a Hamiltonian description of orbits about a precessing oblate primary will bring up the following predicament. On the one hand, it is most natural and convenient to define the Delaunay elements in a co-precessing (equatorial) coordinate system. On the other hand, these elements will not be osculating in the frame wherein they were introduced, and therefore their physical interpretation will be difficult, if at all possible. Indeed, instantaneous ellipses on Fig.1 may cross the trajectory at whatever angles (and may be even perpendicular

[2] Physically, this simply means that $\dot{\vec{\boldsymbol{r}}}$ on Fig.1 can be decomposed into $\vec{\boldsymbol{g}}$ and $\vec{\boldsymbol{\Phi}}$ in a continuous variety of ways. Mathematically, this freedom reflects a more general construction that emerges in the ODE theory. (Newman & Efroimsky 2003)

thereto). Thence, their orbital elements will not describe the real orientation or shape of the physical trajectory (Efroimsky & Goldreich 2004; Efroimsky 2004a).

For the first time, non-osculating elements obeying (16) implicitly emerged in (Goldreich 1965) and then in Brumberg et al (1971), though their exact definition in terms of gauge freedom was not yet known at that time. Both authors noticed that these elements were not osculating. Brumberg (1992) called them "contact elements." The osculating and contact variables coincide when the disturbance is velocity-independent. Otherwise, they differ already in the first order of the velocity-dependent perturbation. Luckily, in some situations their secular parts differ only in the second order (Efroimsky 2004), a fortunate circumstance anticipated yet by Goldreich (1965).

3.3 Rotational motion

In rotational dynamics, the situation of an axially symmetric unsupported top at each instant of time is fully defined by the three Euler angles $q_n = \theta, \phi, \psi$ and their derivatives $\dot{q}_n = \dot{\theta}, \dot{\phi}, \dot{\psi}$. The time dependence of these six quantities can be calculated from three dynamical equations of the second order and will, therefore, depend upon the time and six integration constants:

$$\begin{aligned} q_n &= f_n\left(S_1, ..., S_6, t\right), \\ \dot{q}_n &= \mathrm{g}_n\left(S_1, ..., S_6, t\right), \end{aligned}$$

the functions g_n and f_n being interconnected via $\mathrm{g}_n \equiv \partial f_n / \partial t$, for $n = 1, 2, 3 = \psi, \theta, \phi$.

Under disturbance, the motion will be altered:

$$\begin{aligned} q_n &= f_n\left(S_1(t), ..., S_6(t), t\right), \\ \dot{q}_n &= \mathrm{g}_n\left(S_1(t), ..., S_6(t), t\right) + \Phi_n\left(S_1(t), ..., S_6(t), t\right), \\ \text{where} \quad \Phi_n &\quad \left(S_1(t), ..., S_6(t), t\right) \equiv \sum_{j=1}^{6} \frac{\partial f_n}{\partial S_j} \dot{S}_j. \end{aligned} \tag{16}$$

Now choose the "constants" S_j to make canonical pairs (Q, P) obeying (5 - 6), with $\mathcal{H}^*$ being zero for $(Q, P) = (L_o, G, H, l_o, g_o, h)$. Then insertion of (5) into (16) will result in

$$\Phi_n\left(S_1(t), ..., S_6(t), t\right) \equiv \sum \frac{\partial f_n}{\partial Q} \dot{Q} + \sum \frac{\partial f_n}{\partial P} \dot{P} = \frac{\partial \Delta \mathcal{H}(q, p)}{\partial p_n}, \tag{17}$$

so that the canonicity demand (5 - 6) violates the gauge freedom in a non-Lagrange fashion. This is merely a particular case of (10).

This yields two consequences. One is that, in the canonical formalism, calculation of the angular velocities via the elements must be performed not through the second equation of (16) but through the second equation of (16), with (17) substituted therein. This means, for example, that in Kinoshita (1977) formula (2.6) and equations (6.26 - 6.27) for the instantaneous spin axis orientation must be amended. (While equations (6.24 - 6.25) remain in force because they pertain to the body figure.) After this amendment is introduced, the Kinoshita formalism will yield correct direction angles not only for the body figure but also for the rotation axis. (Even though the non-osculating elements, employed in it, will lack the evident physical interpretation inherent in the osculating variables.) Importance of this improvement is dictated by the fact that at present not only the body figure but also the instantaneous axis of rotation are directly observed (Schreiber et al 2004).

The second consequence is that, if we wish to make our Serret-Andoyer variables osculating (so that the second equation of (16) could be used), the price to be payed for this repair will be the loss of canonicity. (Angular-velocity-dependent perturbations cannot be accounted for by merely amending the Hamiltonian!) The osculating elements will obey non-canonical dynamical equations.

To draw to a close, we would add that, under some special circumstances, the secular parts of contact elements may coincide in the first order with those of their osculating counterparts.[3] Whether this will be the case for the Earth or Mars remains to be investigated. This matter will be crucial for examining the validity of the presently available computations of the history of Mars' obliquity.

APPENDIX: The case of regular Serret-Andoyer variables

For the purpose of convenience, above we assumed that the variable elements (Q_n, P_n) reduce, in the unperturbed case, to integration constants. This way, in the orbital case we employed the modified Delaunay set (the one with M_o instead of M), while in the rotation case we used the modified Serret-Andoyer set (L_o, G, H, l_o, g_o, h) instead of the regular set (L, G, H, l, g, h).

Here we shall demonstrate how our formalism should be reformulated for the regular set of variables. As everywhere in this article, (q, p) will denote the coordinates (Cartesian, in the orbital case; or Eulerian, in the rotation case) and their conjugated momenta. They will depend upon the regular set of canonical elements (α, β). (In the orbital case, these will be the regular Delaunay parameters $(L, G, H, -M, -\omega, -\Omega)$; while in the rotation case they will be the regular Serret-Andoyer ones (L, G, H, l, g, h).) Finally, (Q, P) will be the "constants": the modified Delaunay set $(L, G, H, -M_o, -\omega, -\Omega)$ in the case of orbital motion, and the modified Serret-Andoyer set (L_o, G, H, l_o, g_o, h) in the case of spin. Since

$$q = q\left(\alpha(Q, P, t), \beta(Q, P, t), t\right) \tag{18}$$

then, evidently,

$$\dot{q} = \left(\frac{\partial q}{\partial t}\right)_{\alpha\beta} + \left(\frac{\partial q}{\partial \alpha}\right)_{\beta t}\frac{d\alpha}{dt} + \left(\frac{\partial q}{\partial \beta}\right)_{\alpha t}\frac{d\beta}{dt} = \left[\left(\frac{\partial q}{\partial t}\right)_{\alpha\beta} + \left(\frac{\partial q}{\partial \alpha}\right)_{\beta t}\left(\frac{\partial \alpha}{\partial t}\right)_{QP} + \left(\frac{\partial q}{\partial \beta}\right)_{\alpha t}\left(\frac{\partial \beta}{\partial t}\right)_{QP}\right]$$

$$+\left[\frac{\partial q}{\partial \alpha}\frac{\partial \alpha}{\partial Q} + \frac{\partial q}{\partial \beta}\frac{\partial \beta}{\partial Q}\right]\frac{dQ}{dt} + \left[\frac{\partial q}{\partial \alpha}\frac{\partial \alpha}{\partial P} + \frac{\partial q}{\partial \beta}\frac{\partial \beta}{\partial P}\right]\frac{dP}{dt}$$

$$\text{where } \left[\left(\frac{\partial q}{\partial t}\right)_{\alpha\beta} + \left(\frac{\partial q}{\partial \alpha}\right)_{\beta t}\left(\frac{\partial \alpha}{\partial t}\right)_{QP} + \left(\frac{\partial q}{\partial \beta}\right)_{\alpha t}\left(\frac{\partial \beta}{\partial t}\right)_{QP}\right] = \left(\frac{\partial q}{\partial t}\right)_{QP},$$

$$\left[\frac{\partial q}{\partial \alpha}\frac{\partial \alpha}{\partial Q} + \frac{\partial q}{\partial \beta}\frac{\partial \beta}{\partial Q}\right] = \left(\frac{\partial q}{\partial Q}\right)_{Pt}, \qquad \left[\frac{\partial q}{\partial \alpha}\frac{\partial \alpha}{\partial P} + \frac{\partial q}{\partial \beta}\frac{\partial \beta}{\partial P}\right] = \left(\frac{\partial q}{\partial P}\right)_{Qt}.$$

In our paper, when introducing osculation, we have in mind osculation relative to the constants $(Q, P) = (L_o, G, H, l_o, g_o, h)$. This osculation condition reads: $\dot{q} = (\partial q/\partial t)_{QP}$, so that the gauge function $\Phi \equiv \dot{q} - (\partial q/\partial t)_{QP} = (\partial q/\partial Q)_{Pt}\,\dot{Q} + (\partial q/\partial P)_{Qt}\,\dot{P}$ becomes the measure of non-osculation. When Kinoshita (1977), on the fourth page of his paper, referred to osculation, he implied osculation relative to the canonical elements $(\alpha, \beta) = (L, G, H, l, g, h)$. The corresponding osculation condition was: $\dot{q} = (\partial q/\partial t)_{\alpha\beta}$, while the appropriate measure of non-osculation, $\tilde{\Phi} \equiv \dot{q} - (\partial q/\partial t)_{\alpha\beta} = (\partial q/\partial \alpha)_{\beta t}\,\dot{\alpha} + (\partial q/\partial \beta)_{\alpha t}\,\dot{\alpha}$, was different from our Φ. By comparing the two expressions,

$$\dot{q} = (\partial q/\partial t)_{QP} + \Phi \text{and} \dot{q} = (\partial q/\partial t)_{\alpha\beta} + \tilde{\Phi}, \tag{19}$$

[3] In regard to orbital motions, this possibility was anticipated yet in 1965 by Peter Goldreich. As demonstrated by Efroimsky (2004a), this is true for constant rate of frame precession (but not for variable precession).

and by applying the first equation of (19) we see that

$$\tilde{\Phi} = \Phi - \left(\frac{\partial q}{\partial \alpha}\right)_{\beta t}\left(\frac{\partial \alpha}{\partial t}\right)_{QP} - \left(\frac{\partial q}{\partial \beta}\right)_{\alpha t}\left(\frac{\partial \beta}{\partial t}\right)_{QP} . \tag{20}$$

In particular, if we want all three sets, (q,p), (α,β), and (Q,P), to be canonical, then the non-osculation (in the sense of Kinoshita) will be:

$$\tilde{\Phi} = \frac{\partial \Delta \mathcal{H}}{\partial p} - \left(\frac{\partial q}{\partial \alpha}\right)_{\beta t}\left(\frac{\partial \alpha}{\partial t}\right)_{QP} - \left(\frac{\partial q}{\partial \beta}\right)_{\alpha t}\left(\frac{\partial \beta}{\partial t}\right)_{QP} . \tag{21}$$

It is this quantity that should be added to the partial derivatives of the Euler angles, in order to get the right values of the angular velocities. This way, the above formula will be the starting point for correcting equations (2.6) and (6.26 - 6.27) in the Kinoshita (1977) theory.

4. REFERENCES

Brumberg, V. A., L. S. Evdokimova, & N. G. Kochina. 1971. "Analytical Methods for the Orbits of Artificial Satellites of the Moon." *Celestial Mechanics*, Vol. **3**, pp. 197 - 221.

Brumberg, V.A. 1992. *Essential Relativistic Celestial Mechanics.* Adam Hilger, Bristol.

Efroimsky, Michael. 2002a. "Equations for the orbital elements. Hidden symmetry." Preprint No 1844 of the Institute of Mathematics and its Applications, University of Minnesota http://www.ima.umn.edu/preprints/feb02/feb02.html

Efroimsky, Michael. 2002b. "The Implicit Gauge Symmetry Emerging in the N-body Problem of Celestial Mechanics." astro-ph/0212245

Efroimsky, M., & P. Goldreich. 2003. "Gauge Symmetry of the N-body Problem in the Hamilton-Jacobi Approach." *Journal of Mathematical Physics*, Vol. **44**, pp. 5958 - 5977 astro-ph/0305344

Efroimsky, M., & Goldreich, P. 2004. "Gauge Freedom in the N-body Problem of Celestial Mechanics." *Astronomy & Astrophysics*, Vol. **415**, pp. 1187 - 1199 astro-ph/0307130

Efroimsky, M. 2004a. "Long-term evolution of orbits about a precessing oblate planet. The case of uniform precession." To be published in *Celestial Mechanics and Dynamical Astronomy.* astro-ph/0408168

Efroimsky, M. 2004b. "The Serret-Andoyer variables, rendered by the canonical theory of rigid-Earth rotation, are non-osculating." In preparation.

Goldreich, P. 1965. "Inclination of satellite orbits about an oblate precessing planet." *The Astronomical Journal*, Vol. **70**, pp. 5 - 9.

Kinoshita, H. 1977. "Theory of the Rotation of the Rigid Earth." *Celestial Mechanics*, Vol. **15**, pp. 277 - 326

Newman, W., & M. Efroimsky. 2003. "The Method of Variation of Constants and Multiple Time Scales in Orbital Mechanics." *Chaos*, Vol. 13, pp. 476 - 485.

Plummer, H. C. 1918. *An Introductory Treatise on Dynamical Astronomy.* Cambridge University Press, UK.

Serret, J. A. 1866. "Mémoire sur l'emploi de la méthode de la variation des arbitraires dans la théorie des mouvements de rotation." *Mémoires de l'Academie des Sciences de Paris*, Vol. **55**, pp. 585 - 616

Schreiber, K. U.; Velikoseltsev, A.; Rothacher, M.; Klugel, T.; Stedman, G. E.; & Wiltshire, D. L. 2004. "Direct Measurement of Diurnal Polar Motion by Ring Laser Gyroscopes." *Journal of Geophysical Research*, Vol. **109**, p. B06405

SPECTRAL ANALYSIS OF THE NUMERICAL THEORY OF THE RIGID EARTH ROTATION

V.V. PASHKEVICH, G.I. EROSHKIN
Central (Pulkovo) Astronomical Observatory of Russian Academy of Science
196140,Pulkovskoe shosse, 65/1, St.Petersburg, Russia
e-mail: apeks@gao.spb.ru, eroshkin@gao.spb.ru

ABSTRACT. The discrepancies of the comparison between the high-precision numerical solutions of the rigid Earth rotation problem and the semi-analytical solutions SMART97 (Bretagnon *et al.*, 1998), (Brumberg and Bretagnon, 2000) are processed by means of the spectral analysis methods for the kinematical and dynamical cases over the time interval of 2000 years. The secular trends in the discrepancies are processed by the least squares method and the new temporal polynomials of the 6-th degree for the precessional parameters and for GMST are presented. The power spectra of the periodic parts of the discrepancies are constructed by using the arguments of the nutational harmonics of SMART97 solutions. Starting from the maximum term of the spectra, the coefficients of the harmonics are determined successively. The set of these harmonics and those of SMART97 solutions represent the new nutational series consisting of more than 9000 periodic terms. The comparison between the quadruple precision numerical solutions of the problem and the new rigid Earth rotation series reveals that the discrepancies do not surpass 10μas over 2000 years in Euler angels.

1. INTRODUCTION

The previous papers (Eroshkin *et al.*, 2003, 2004) were devoted to the problem of the construction of the high-precision long-term numerical theory of the rigid Earth rotation dynamically adequate to the ephemerides DE404/LE404. The high-precision semi-analytical solutions of the rigid Earth rotation problem SMART97 were used for calculating the initial conditions, and also for the control and the refinement of the algorithm of the numerical solution. The comparison between the numerical and semi-analytical solutions over 2000 year time span revealed the discrepancies of both secular and periodic characters. The main part of these discrepancies was explained by not sufficiently long time span of the validity of SMART97 solutions: only for several centuries. Besides, it was discovered in the result of the numerical experiments that the linear part of the secular trend in the discrepancies in the angle of the proper rotation was related to an insufficient accuracy of the SMART97 solutions for calculating the initial conditions (Eroshkin *et al.*, 2003, 2004). For the further development of the high-precision numerical theory of the rigid Earth rotation it is very useful to construct alternative semi-analytical solutions of the problem, which are more adequate to the ephemerides DE404/LE404 than SMART97 solutions.

2. ALGORITHM

The problem is solved both for the Newtonian case (Dynamical case) and for the relativistic one (Kinematical case) in which the geodetic perturbations representing the most essential relativistic perturbations in the Earth rotation are taken into account. The numerical solutions of the rigid Earth rotation problem are constructed in the result of the numerical integration with the quadruple precision. The initial conditions are calculated from SMART97 solutions. The numerical solutions are compared with SMART97 solutions over 2000 year time span with one day spacing and the arrays of the discrepancies are constructed.

In (Eroshkin *et al.*, 2003, 2004) only the secular terms and the main periodic ones were determined in the discrepancies of the comparison. For the systematic determination of all periodic terms the spectral analysis methods have to be used.

The investigation of the discrepancies is carried out by the least squares (LSQ) method and by the spectral analysis (SA) methods:

1. The secular parts of the discrepancies are processed by the LSQ method and then removed from the discrepancies. The new precessional and GMST polynomials are constructed by summing the determined secular terms and the precessional and GMST polynomials of SMART97.

2. For the periodic parts of the discrepancies the power spectra are constructed by using the arguments of the nutational harmonics of SMART97 solutions. The power spectra are bounded by the periods from 1.0003 days till 1000 years. The determination of the coefficients of the harmonics is accomplished successively starting from the maximum term in the power spectra (Roberts *et al.*, 1987) by the SA methods. The new nutation series are constructed in the result of summing the determined periodic terms and the corresponding harmonics of SMART97. This procedure is accomplished in the following manner.

a) The amplitude spectra of the discrepancies are computed by the LSQ method for each nutational harmonic of SMART97.

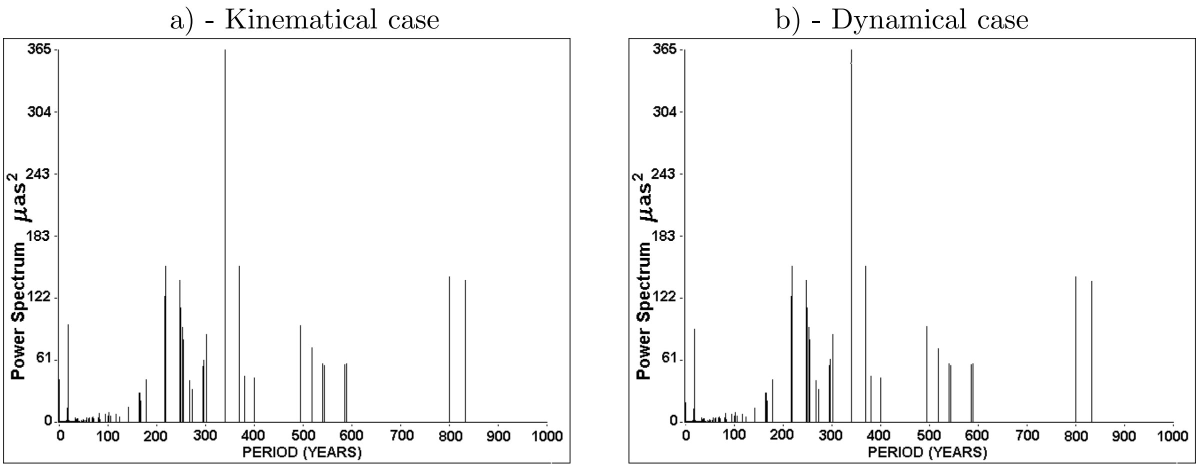

Figure 1: Complete spectra of the periodic discrepancies of the comparison between the numerical solutions and SMART97 solutions in the proper rotation angle

b) The amplitude of the largest harmonic is determined by the LSQ method.

c) If the absolute value of the amplitude of a harmonic exceeds the absolute value of its mean square error then this harmonic is removed from the discrepancies. The new nutational term is determined as a sum of the calculated periodic term and the corresponding nutational term of SMART97.

d) The steps b) and c) are performed up to the end of the spectra.

The spectra for all Euler angles are similar. The spectra for the Kinematical and for the Dynamical cases are similar for the long-period parts but have some difference for the short-period parts (Figures 2a, 2b).

Figures 1–2 demonstrate the main groups of the harmonics with the periods close to 1 day, 1 year, 20 years and so on. The maximum amplitude of the periodic terms has a harmonic with the period 341.3724 years. There are altogether around 9000 periodic terms which are determined. The new precession, GMST parameters and the nutational terms form the new high-precision rigid Earth rotation series S9000.

a) - Kinematical case   b) - Dynamical case

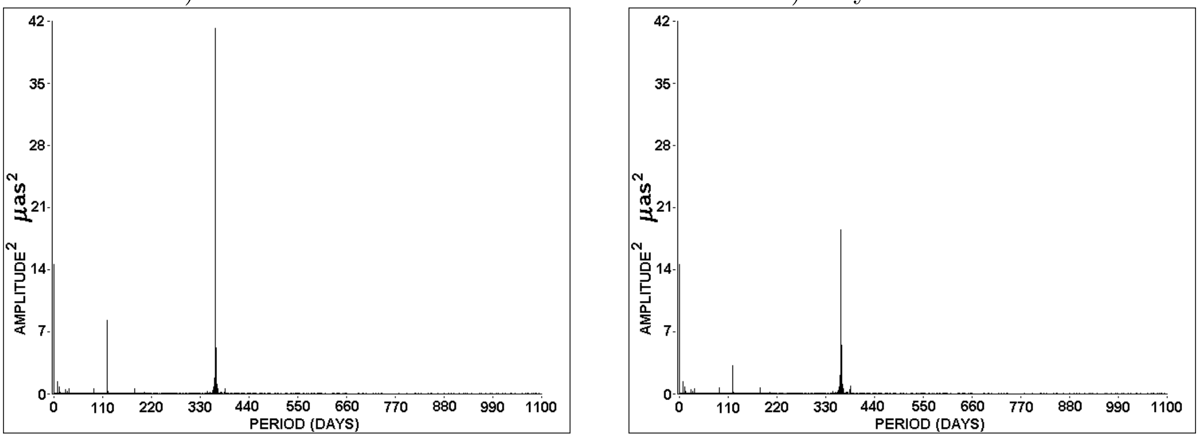

Figure 2: Spectra of the short-period part of the discrepancies of the comparison between the numerical solutions and SMART97 in the proper rotation angle

3. NEW HIGH-PRECISION RIGID EARTH ROTATION SERIES — S9000

The constructed new high-precision rigid Earth rotation series S9000 are compared with the semi-analytical solution SMART97 over 2000 year time interval from AD 1000 to 3000.

a) - Kinematical case   b) - Dynamical case

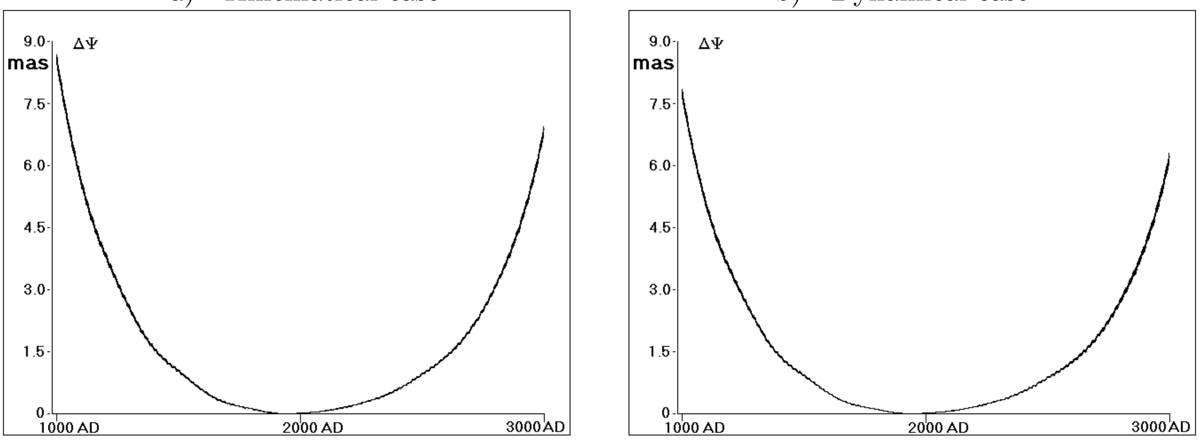

Figure 3: S9000 series minus solutions SMART97 in the angle ψ

In Figures 3—5 the comparison between SMART97 and S9000 is presented in Euler angles: the longitude of the ascending node ψ (Figures 3a, b), the proper rotation angle ϕ (Figures 4a, b) and the inclination angle θ (Figures 5a, b), (a - Kinematical case, b - Dynamical case). It is necessary to notice that the Figures 3, 5 are very similar to the Figures 1, 3 in (Eroshkin *et al.*,

a) - Kinematical case b) - Dynamical case

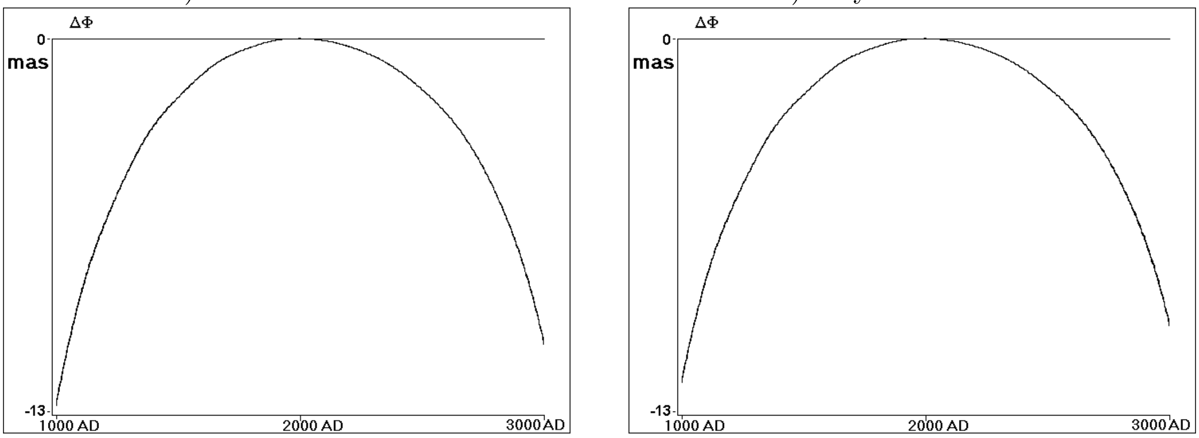

Figure 4: S9000 series minus solutions SMART97 in the angle ϕ

a) - Kinematical case b) - Dynamical case

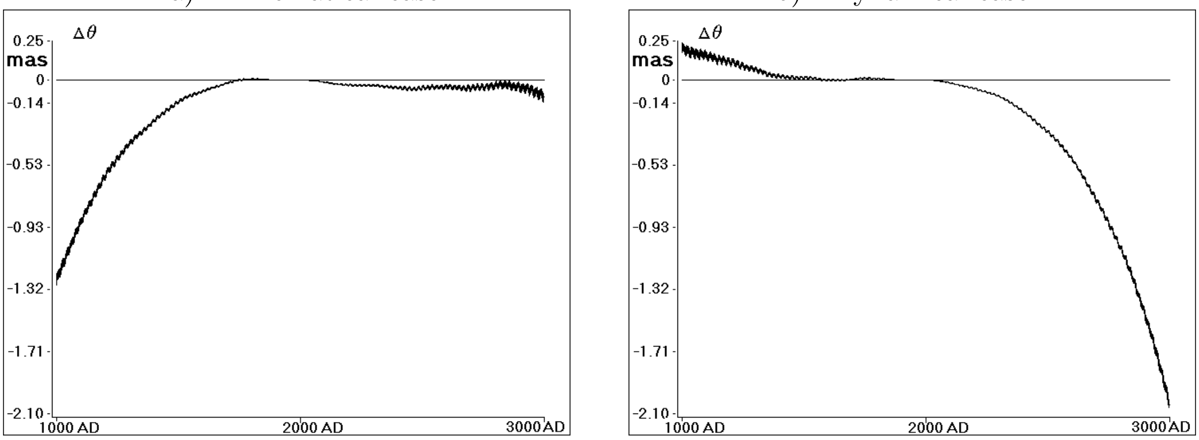

Figure 5: S9000 series minus solutions SMART97 in the angle θ

2003) representing the comparison between the numerical solutions of the rigid Earth rotation problem and the semi-analytical solutions SMART97.

The numerical solutions of the rigid Earth rotation are constructed over 2000 year time span from AD 1000 to 3000, with the quadruple precision of the calculations. The initial epoch of numerical integration is January 1, 2000. The initial conditions are calculated by means of S9000 series. The results of the numerical integration are compared with S9000 series in Euler angles (Figures 6a, b). There are no secular trends in the residuals in the angles ψ and θ but they present in the angle ϕ. The secular trend in the Dynamical case is smaller than that in the Kinematical case. As it was stated in (Eroshkin *et al.*, 2003, 2004) the linear part of the secular trend of the discrepancies in the angle of the proper rotation was due to an insufficient accuracy of the SMART97 series for calculating the initial conditions. In the present investigation the initial conditions are calculated by S9000 series and consequently the new series are also not sufficiently accurate. However, the values of the linear parts of the trends in the residuals for the proper rotation angle ϕ (51mas/tjy in Kinematical case and 32mas/tjy in Dynamical case) are smaller than in the same residuals (Eroshkin *et al.*, 2003, 2004), when comparing the results of the numerical integration and SMART97 solutions (90mas/tjy in both cases).

Figures 7a, b demonstrate the behaviour of the residuals of the comparison between the nu-

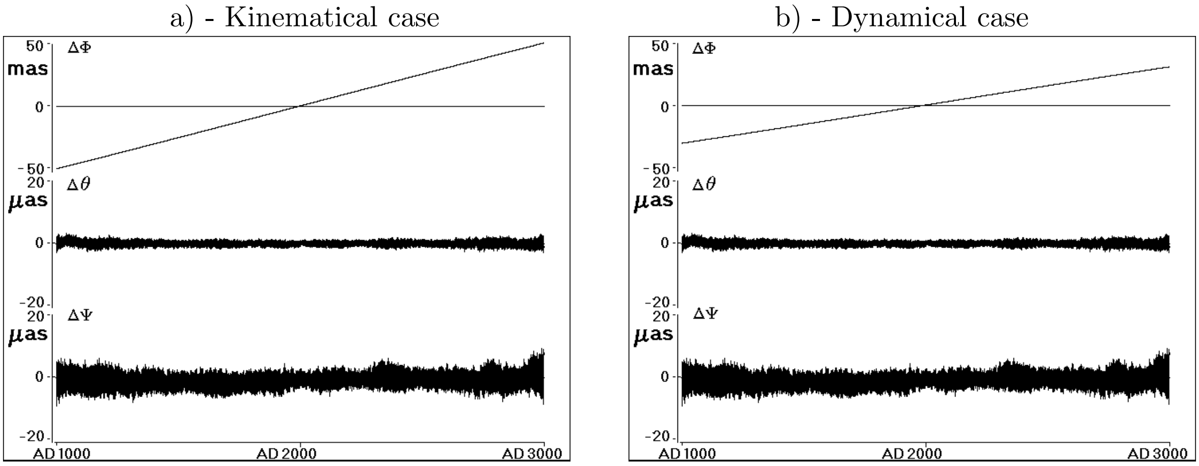

Figure 6: Numerical solutions minus S9000

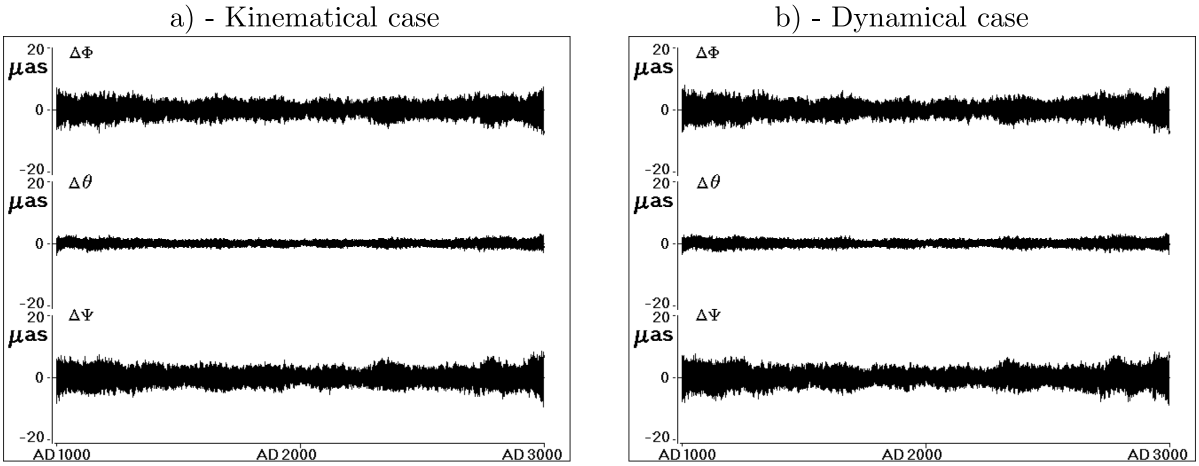

Figure 7: Numerical solutions minus S9000 after the formal removal of the secular trends in the proper rotation angle

merical solutions and S9000, after the formal removal of the secular trends in the proper rotation angle. The discrepancies of the comparison do not surpass 10μas over 2000 year time interval. It means a good dynamical consistency of S9000 series with the ephemerides DE404/LE404. The analogous comparison between the numerical solutions and SMART97 revealed the essentially larger discrepancies (Eroshkin *et al.*, 2003, 2004).

The residuals of the comparison between S9000 series and the high-precision numerical integration have to be processed for the determination of the diurnal and sub-diurnal harmonics. It can be expected that the addition of these short-period terms to S9000 series increase the degree of the adequacy of these series to the ephemerides DE404/LE404 and eliminate the secular trend in the residuals in the proper rotation angle.

4. CONCLUSION

The spectral analysis of the discrepancies of the numerical solutions and SMART97 semi-analytical solutions of the rigid Earth rotation problem is carried out for the Kinematical and Dynamical cases over the time interval of 2000 years.

The new high-precision rigid Earth rotation series S9000, which are dynamically adequate to the ephemerides DE404/LE404, are constructed for Dynamical and Kinematical cases of the problem. The S9000 series are presented by 6 files (3 files for the Kinematical case and 3 files for the Dynamical case). Each file includes around 9000 terms and is compiled quite analogous to SMART97 files.

Acknowledgments. Financial support for this investigation was provided by Russian Foundation for Basic Research, Grant No. 02-02-17611. The technical computing support was provided by the Center for Supercomputing Applications at the Institute for High-Performance Computing and Data Bases in St. Petersburg, Russia.

5. REFERENCES

Bretagnon P., Francou G., Rocher P. and Simon J. L.: 1998, A&A , **329**, No.1, pp. 329–338.

V.A.Brumberg and P.Bretagnon, in Proceedings of IAU Colloquium 180, Washington, 2000, pp. 293-302.

Eroshkin G. I., Pashkevich V. V.: 2003, High-precision numerical analysis of the rigid Earth rotation problem with using a high-performance computer, *In: Proc. Journees 2003: Astrometry, Geodynamics and Solar System Dynamics: from milliarcseconds to microarcseconds, (A.Finkelstein and N.Capitaine, eds.)*, St.Petersburg, pp. 138–143.

G.I.Eroshkin, V.V.Pashkevich and A.Brzeziński, ARTIFICIAL SATELLITES, Vol. 39, No. 4, Warszawa, 2004, pp. 291–304.

D.H.Roberts, J.Lehar, J.W.Dreher, Astrophys. J., No. 4, 1987, pp. 968–989.

THE COUPLING EQUATIONS BETWEEN THE NUTATION AND THE GEOMAGNETIC FIELD IN GSH EXPANSION

C.-L. HUANG[1], V. DEHANT[2], X.-H. LIAO[1], O. de VIRON[2], T. V. HOOLST[2]

[1] Shanghai Astronomical Observatory, Chinese Academy of Sciences
80 Nandan Road, Shanghai 200030, P.R.China
e-mail: clhuang@shao.ac.cn

[2] Royal Observatory of Belgium
Ave. Circulaire 3, 1180 Brussels, Belgium
e-mail: v.dehant@oma.be

ABSTRACT. In the studies of Earth nutation involving electro-magnetic coupling at the core boundaries inside the Earth, it is convenient to express the magnetic induction equation and the Lorentz force density, as well as the magnetic field (**B**) itself, in generalized spherical harmonics expansion (GSH). This is especially the case when the ellipticity of the interior structures and boundaries are considered. In this work, the magnetic induction equation and the Lorentz force density in the motion equation are derived to scalar format in GSH. In the resulted induction equation of the perturbed magnetic field **b** caused by nutation, it is shown that the spheroidal and toroidal part of **b** are decoupled with each other, although both of them involve the steady part of **B** and the nutational displacement **s** (or velocity **v**) field. This theoretical result allows one to solve **b** and **s** (or **v**) simultaneously.

1. INTRODUCTION

When interpreting the variation of earth rotation, like the decadal variation of the length-of-day and the nutation, there are four candidates of coupling mechanics between the earth layers interior, they are gravitational coupling, viscous coupling, topography coupling and electromagnetic coupling between the liquid core and the mantle, and/or between the inner core and the liquid core. In the nutation studies, using the angular momentum equation of the different layers of the Earth (*Buffett*, 1992, 1993; *Buffett et al.*, 2002; *Mathews et al.*, 2002), the electromagnetic coupling is regarded as a very good interpretation to the gap between the observed retrograde annual nutation and its theoretical value obtained by previous works without considering the contribution of the geomagnetic field. This paper discusses the coupling between the geomagnetic field and the nutational motion in numerical integration approach in which generalized spherical harmonics expansion (GSH) is used to provide a group of natural basis for the representation of tensor of any order.

The magnetic field exists throughout the Earth, but the coupling effects may be considered in the regions only near the two boundaries of fluid outer core (FOC) as discussed by *Buffett et al.* for simplicity. When the contribution of the magnetic field is considered, the Lorentz force density, $\mathbf{L}$, is to be added to the right hand of the motion equation. Meanwhile, the nutational motion of the fluid interior will also cause an incremental magnetic field (as will be seen in the induction equation) (*Huang et al.*, 2004). Both the nutational motion and the incremental magnetic field are time-varying. Consequently, the magnetic field and the velocity field are coupled in both equations. It is therefore necessary to calculate the induced magnetic field and the velocity field together.

The traditional motion equation for nutation without the contribution of magnetic field has been given in integrable format in generalized spherical harmonics expansion (GSH), which is used to provide a group of natural basis for the representation of tensor of any order, by *Smith*(1974) and are used in the numerical integration approach for nutation (e.g., *Huang et al.*, 2001). Accordingly, it is needed to represent both the additional term ($\mathbf{L}$) and the induction equation by GSH too.

In the next section, after having introduced the vectorial induction equation in frequency domain, we represent it and all the related variables in GSH, and the induction equation for the toroidal and spheroidal parts of the perturbed magnetic field $\mathbf{b}$ is derived to a scale form which is explicit and integrable; the new Lorentz force density in the motion equation is also developed by the scalars of the magnetic field in Section 3. Then, the two equations, induction equation and motion equation, are theoretically solvable for $\mathbf{b}$ and the displacement field $\mathbf{s}$.

2. ON THE VECTORIAL MAGNETIC INDUCTION EQUATION

2.1. In frequency domain

The induction equation links the changes in the magnetic field to existing magnetic field in the presence of flux velocities (enhancing) and of diffusion which tends to decrease the field. This equation is often simplified in the frozen flux hypothesis when diffusion is ignored. This approximation is perfectly valid at diurnal timescale. The general form of this equation, without the pre-hypothesis of frozen flux (see for instance *Moffatt*, 1978) can be written as:

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B}), \tag{1}$$

where $\mathbf{B}$ is the magnetic field and $\mathbf{v}$ is the differential flux velocity.

In Earth nutation study, the flow relative to the mantle is assumed to be mainly a small rigid rotation about an axis in the equatorial plane due to the free slip nutational motion of the mantle.

When discussing the coupling between $\mathbf{B}$ and nutational velocity $\mathbf{v}$, one can decompose $\mathbf{B}$ into initial main part $\mathbf{B}_0$ and time-varying part $\mathbf{b}$:

$$\mathbf{B}(\mathbf{r}, t) = \mathbf{B}_0(\mathbf{r}, t) + \mathbf{b}(\mathbf{r}, t), \tag{2}$$

where $\mathbf{B}_0$ varies very slowly in comparison with the nutation periods (in diurnal band) and can be regarded as a steady part, while $\mathbf{b}$ is induced by $\mathbf{v}$ (or by the nutational deformation, $\mathbf{s}$). $\mathbf{b}$ can, in turn, perturb $\mathbf{v}$ and $\mathbf{s}$. $\mathbf{b}$ can be expressed by a sum of Fourier series.

$$\mathbf{B}(\mathbf{r}, t) = \mathbf{B}_0(\mathbf{r}) + \sum_{\omega} \mathbf{b}(\mathbf{r}, \omega) e^{i\omega t}, \tag{3}$$

$$\partial_t \mathbf{B}(\mathbf{r}, t) = \partial_t \mathbf{b}(\mathbf{r}, t) = \sum_{\omega} i\omega \mathbf{b}(\mathbf{r}, \omega) e^{i\omega t}, \tag{4}$$

Without lost of generality, the flow velocity field $\mathbf{v}(\mathbf{r}, t)$ (or $\mathbf{s}(\mathbf{r}, t)$) is also composed of a steady flow part and a time dependent part. We also use the Fourier series of $\mathbf{s}(\mathbf{r}, t)$ with the same frequency dependence as $\mathbf{B}$, but allow for a time lag with respect to $\mathbf{B}(\mathbf{r},t)$, i.e., the velocity is proportional to $e^{i\omega(t-t_0)}$.

$$\mathbf{s}(\mathbf{r},t) = \sum_{\omega} \mathbf{s}(\mathbf{r},\omega)e^{i\omega t}, \tag{5}$$

$$\mathbf{v}(\mathbf{r},t) = \partial_t \mathbf{s}(\mathbf{r},t) = i\omega\mathbf{s}(\mathbf{r},t) = \sum_{\omega} i\omega\mathbf{s}(\mathbf{r},\omega)e^{i\omega t}. \tag{6}$$

where $\mathbf{b}(\mathbf{r},\omega)$ and $\mathbf{s}(\mathbf{r},\omega)$ (or $\mathbf{v}(\mathbf{r},\omega)$) are complex vectors, which allows us to deal with a phase lag between $\mathbf{s}$ (or $\mathbf{v}$) and $\mathbf{b}$.

The induction equation (1) can then be simplified to

$$\partial_t \mathbf{b}(\mathbf{r},t) = \nabla\times(\mathbf{v}(\mathbf{r},t)\times\mathbf{B}_0(\mathbf{r})) - \nabla\times(\eta(r)\nabla\times\mathbf{b}(\mathbf{r},t)), \tag{7}$$

or in frequency domain

$$i\omega\mathbf{b}(\mathbf{r},\omega) = i\omega\nabla\times(\mathbf{s}(\mathbf{r},\omega)\times\mathbf{B}_0(\mathbf{r})) - \nabla\times(\eta(r)\nabla\times\mathbf{b}(\mathbf{r},\omega)), \tag{8}$$

2.2. Representation in GSH

All the vectors in the equation above, $\mathbf{B_0}(\mathbf{r},\omega)$, $\mathbf{b}(\mathbf{r},\omega)$ and $\mathbf{s}(\mathbf{r},\omega)$ (as well as $\mathbf{v}(\mathbf{r},\omega)$) can be represented by GSH (rather than the ordinary spherical harmonics) as:

$$\mathbf{B}_0(\mathbf{r}) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} B_{lm}^{\alpha}(r)Y_{lm}^{\alpha}(\theta,\phi)\hat{e}_{\alpha}, \tag{9}$$

$$\mathbf{b}(\mathbf{r},\omega) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} b_{lm}^{\alpha}(r,\omega)Y_{lm}^{\alpha}(\theta,\phi)\hat{e}_{\alpha}, \tag{10}$$

$$\mathbf{s}(\mathbf{r},\omega) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} s_{lm}^{\alpha}(r,\omega)Y_{lm}^{\alpha}(\theta,\phi)\hat{e}_{\alpha}, \tag{11}$$

where $Y_{lm}^{\alpha}(\theta,\phi)$ are the GSH, and $\hat{e}_{\alpha}$ are the corresponding canonical unit basis vector (*Dahlen & Tromp*, 1998; *Phinney & Burridge*, 1973; *Huang & Liao*, 2003).

B_{lm}^{α} is for $\mathbf{B}_0$ rather than $\mathbf{B}$ and assumed independent with time (or frequency), while all other terms have been expressed in the nutational frequency domain by Fourier expansion. So these terms depend on $(\mathbf{r},\omega)$ (or (r,ω)). In the following text, for simplifying the writing, we express the variables in the frequency domain and we only discuss their amplitudes, i.e. we speak about functions of $(r,\theta,\phi,\,\omega)$ and ignore the $e^{i\omega t}$ part.

2.3. The explicit scalar form

We define

$$\begin{cases} U_{lm} = s_{lm}^0 \\ V_{lm} = s_{lm}^+ + s_{lm}^- \\ W_{lm} = s_{lm}^+ - s_{lm}^- \end{cases}, \quad \begin{cases} F_{lm} = B_{lm}^0 \\ G_{lm} = B_{lm}^+ + B_{lm}^- \\ H_{lm} = B_{lm}^+ - B_{lm}^- \end{cases}, \quad \begin{cases} f_{lm} = b_{lm}^0 \\ g_{lm} = b_{lm}^+ + b_{lm}^- \\ h_{lm} = b_{lm}^+ - b_{lm}^- \end{cases}. \tag{12}$$

where (U,V,W), (F,G,H) and (f,g,h) are the so-called radial, poloidal and toroidal scalars of $\mathbf{s}$, $\mathbf{B}_0$ (rather than the total field $\mathbf{B}$) and $\mathbf{b}$.

Using the properties of the GSH, the magnetic induction equation (8) then can be derived to following explicit scalar form at diurnal timescale in terms of spheroidal and toroidal solutions as:

$$\begin{aligned} 0 = \;& -\eta\frac{\Omega_l^0}{r}\left[\partial_r g_{lm} + \frac{1}{r}g_{lm} - \frac{2\Omega_l^0}{r}f_{lm}\right] \\ & +i\omega\left\{f_{lm} + \frac{\Omega_l^0}{r}\sum_{k=0}^{\infty}\sum_{n=-k}^{k}\sum_{l'=|l-k|}^{l+k} f_l^{l'k}\times\tilde{h}_{lm}^0\right\}. \end{aligned} \tag{13}$$

$$
\begin{aligned}
0 = \quad & -\eta\left[\partial_r^2 g_{lm} + \tfrac{2}{r}\partial_r g_{lm} - \tfrac{2\Omega_l^0}{r}\partial_r f_{lm}\right] \\
& -\partial_r\eta\left[\partial_r g_{lm} + \tfrac{1}{r}g_{lm} - \tfrac{2\Omega_l^0}{r}f_{lm}^0\right] \\
& +i\omega\left\{g_{lm} + \sum_{k=0}^{\infty}\sum_{n=-k}^{k}\sum_{l'=|l-k|}^{l+k} f_l^{l'k}\times\tilde{h}_{lm}^P\right\}.
\end{aligned} \tag{14}
$$

$$
\begin{aligned}
0 = \quad & -\eta\left[\partial_r^2 h_{lm} + \tfrac{2}{r}\partial_r h_{lm} - 2(\tfrac{\Omega_l^0}{r})^2 h_{lm}\right] \\
& -\partial_r\eta\left[\partial_r h_{lm} + \tfrac{1}{r}h_{lm}\right] \\
& +i\omega\left\{h_{lm} + \sum_{k=0}^{\infty}\sum_{n=-k}^{k}\sum_{l'=|l-k|}^{l+k} f_l^{l'k}\times\tilde{h}_{lm}^T\right\}.
\end{aligned} \tag{15}
$$

where,

$$
\begin{aligned}
\tilde{h}_{lm}^0 \quad = & \begin{pmatrix} l & l' & k \\ + & 0 & + \\ m & m-n & n \end{pmatrix} U_{l'm-n}\left\{\begin{array}{c} G_{kn} \\ H_{kn} \end{array}\right\} \\
- & \begin{pmatrix} l & l' & k \\ + & + & 0 \\ m & m-n & n \end{pmatrix} F_{l'm-n}\left\{\begin{array}{c} V_{kn} \\ W_{kn} \end{array}\right\} \begin{array}{l} \text{if } l+l'+k \text{ even} \\ \text{if } l+l'+k \text{ odd} \end{array},
\end{aligned} \tag{16}
$$

$$
\begin{aligned}
\tilde{h}_{lm}^P \quad & \equiv \tilde{h}_{lm}^+ + \tilde{h}_{lm}^- \\
& = \begin{pmatrix} l & l' & k \\ + & 0 & + \\ m & m-n & n \end{pmatrix}\left\{\begin{array}{l} U_{l'm-n}\partial_r G_{kn} + G_{kn}\partial_r U_{l'm-n} + \frac{1}{r}U_{l'm-n}G_{kn} \\ U_{l'm-n}\partial_r H_{kn} + H_{kn}\partial_r U_{l'm-n} + \frac{1}{r}U_{l'm-n}H_{kn} \end{array}\right\} \\
& - \begin{pmatrix} l & l' & k \\ + & + & 0 \\ m & m-n & n \end{pmatrix}\left\{\begin{array}{l} V_{l'm-n}\partial_r F_{kn} + F_{kn}\partial_r V_{l'm-n} + \frac{1}{r}V_{l'm-n}F_{kn} \\ W_{l'm-n}\partial_r F_{kn} + F_{kn}\partial_r W_{l'm-n} + \frac{1}{r}W_{l'm-n}F_{kn} \end{array}\right\}.
\end{aligned} \tag{17}
$$

$$
\begin{aligned}
\tilde{h}_{lm}^T \quad & \equiv \tilde{h}_{lm}^+ - \tilde{h}_{lm}^- \\
& = \begin{pmatrix} l & l' & k \\ + & 0 & + \\ m & m-n & n \end{pmatrix}\left\{\begin{array}{l} U_{l'm-n}\partial_r H_{kn} + H_{kn}\partial_r U_{l'm-n} + \frac{1}{r}U_{l'm-n}H_{kn} \\ U_{l'm-n}\partial_r G_{kn} + G_{kn}\partial_r U_{l'm-n} + \frac{1}{r}U_{l'm-n}G_{kn} \end{array}\right\} \\
& - \begin{pmatrix} l & l' & k \\ + & + & 0 \\ m & m-n & n \end{pmatrix}\left\{\begin{array}{l} W_{l'm-n}\partial_r F_{kn} + F_{kn}\partial_r W_{l'm-n} + \frac{1}{r}W_{l'm-n}F_{kn} \\ V_{l'm-n}\partial_r F_{kn} + F_{kn}\partial_r V_{l'm-n} + \frac{1}{r}V_{l'm-n}F_{kn} \end{array}\right\} \\
& + \frac{\Omega_l^0}{r}\begin{pmatrix} l & l' & k \\ 0 & + & - \\ m & m-n & n \end{pmatrix}\left\{\begin{array}{l} W_{l'm-n}G_{kn} - V_{l'm-n}H_{kn} \\ V_{l'm-n}G_{kn} - W_{l'm-n}H_{kn} \end{array}\right\}.
\end{aligned} \tag{18}
$$

where the coefficients in the two braces above, as well as in the following text, take the upper (or lower) values if $l+l'+k$ is even (or odd); the 3×3 matrix symbol, named J-square, is a compact form of the product of two Wigner 3-j symbols, arising from the product of two GSHs, and its nine indices subject to some selection rules (see *Smith* (1974) for detail); and

$$
\Omega_l^n \equiv \sqrt{(l+n)(l-n+1)/2}. \tag{19}
$$

$$
f_l^{l'k} \equiv \sqrt{\frac{(2l'+1)(2k+1)}{4\pi(2l+1)}}. \tag{20}
$$

3. THE LORENTZ FORCE DENSITY IN THE MOTION EQUATION

As mentioned above, when the contribution of the magnetic field is considered, the Lorentz force density $\mathbf{L}$ is added to the right hand of the motion equation, i.e.,

$$\begin{aligned}\rho D_t^2\mathbf{s} + 2\rho\mathbf{\Omega_0}\times D_t\mathbf{s} = \; & -\rho\mathbf{\Omega_0}\times(\mathbf{\Omega_0}\times\mathbf{s}) + \nabla\cdot\mathbf{T}^e - \nabla(\gamma\nabla\cdot\mathbf{s}) \\ & -\rho\nabla\phi_1 - \rho\mathbf{s}\cdot\nabla\nabla\phi + \nabla\cdot[\gamma(\nabla\mathbf{s})^T] + \mathbf{L},\end{aligned} \tag{21}$$

where all the notations are the same as in *Smith* (1974), and $\mathbf{L}$ is defined as

$$\mathbf{L} \equiv \mathbf{J}\times B = \frac{1}{\mu}\mathbf{B}\cdot\nabla\mathbf{B} = \frac{1}{\mu}\nabla\cdot\mathbf{BB} \equiv \frac{1}{\mu}\nabla\cdot\mathbf{M}, \tag{22}$$

where, μ is the magnetic permeability (rather than rigidity μ in the motion equation for nutation), $\mathbf{J}$ is the induced current, the dyad (or co-vector) $\mathbf{BB}$ is the Maxwell magnetic stress tensor $\mathbf{M}$, and the solenoidal condition about the magnetic field, $\nabla\cdot\mathbf{B}=0$, is used in the Equation above.

From the decomposition (eq.(2)),

$$\mathbf{M} = \mathbf{B}_0\mathbf{B}_0 + \mathbf{B}_0\mathbf{b} + \mathbf{b}\mathbf{B}_0 + \mathbf{bb}, \tag{23}$$

the first term $\mathbf{B}_0\mathbf{B}_0$ does not contribute to nutation; moreover, the perturbed field is far smaller than the main field ($\mathbf{b} \ll \mathbf{B}_0$), then $\mathbf{bb}$ or equivalently $\mathbf{b}\cdot\nabla\mathbf{b}$ can be ignored in comparison with the other terms. Therefore, the terms in $\mathbf{L}$ kept in the motion equation for nutation are

$$\mathbf{L} \cong \frac{1}{\mu}(\mathbf{B}_0\cdot\nabla\mathbf{b} + \mathbf{b}\cdot\nabla\mathbf{B}_0). \tag{24}$$

The solenoidal condition for both $\mathbf{B}_0$ and $\mathbf{b}$ have been used again.

As the gradient of the incremental magnetic field is important and from the dimensional analysis (*Huang et al., 2005, in preparation*), the second term can be ignored in comparison with the first one. The horizontal derivatives in $\mathbf{b}$ is further assumed to be negligible in comparison with the radial derivative ($\nabla_1\mathbf{b} \ll \partial_r\mathbf{b}$) in the boundary layer (this assumption maybe too strong. In fact, what we need is only that $\nabla_r\mathbf{b} \equiv \frac{1}{r}\nabla_1\mathbf{b} \ll \partial_r\mathbf{b}$, this requirement, involving further more a division by r for the horizontal gradient part, is more loose and more reasonable than the first one). The Lorentz force is then written:

$$\mathbf{L} \cong \frac{1}{\mu}B_0^r\partial_r\mathbf{b}. \tag{25}$$

Analogously to the magnetic induction equation and the motion equation, $\mathbf{L}$ can then be also expanded in GSH as

$$\begin{aligned}
L_{lm}^R \equiv \quad [\mathbf{L}]_{lm}^0 \quad &= \frac{1}{\mu}\sum_{k=0}^{\infty}\sum_{n=-k}^{k}\sum_{l'=|l-k|}^{l+k} f_l^{l'k}\begin{pmatrix} l & l' & k \\ 0 & 0 & 0 \\ m & m-n & n\end{pmatrix} F_{l'm-n}\partial_r f_{kn} \\
L_{lm}^P \equiv [\mathbf{L}]_{lm}^+ + [\mathbf{L}]_{lm}^- &= \frac{1}{\mu}\sum_{k=0}^{\infty}\sum_{n=-k}^{k}\sum_{l'=|l-k|}^{l+k} f_l^{l'k}\begin{pmatrix} l & l' & k \\ + & 0 & + \\ m & m-n & n\end{pmatrix} \begin{Bmatrix} F_{l'm-n}\partial_r g_{kn} \\ F_{l'm-n}\partial_r h_{kn}\end{Bmatrix}, \\
L_{lm}^T \equiv [\mathbf{L}]_{lm}^+ - [\mathbf{L}]_{lm}^- &= \frac{1}{\mu}\sum_{k=0}^{\infty}\sum_{n=-k}^{k}\sum_{l'=|l-k|}^{l+k} f_l^{l'k}\begin{pmatrix} l & l' & k \\ + & 0 & + \\ m & m-n & n\end{pmatrix} \begin{Bmatrix} F_{l'm-n}\partial_r h_{kn} \\ F_{l'm-n}\partial_r g_{kn}\end{Bmatrix}
\end{aligned} \tag{26}$$

These three scalars of $\mathbf{L}$ can then be used directly in the new motion equation as in *Smith*(1974).

4. SHORT REMARKS

In section 2, we present the induction equation about the perturbed magnetic field **b** as three scalar ordinary differential equations by GSH, they depends on the initial main magnetic field $\mathbf{B}_0$ and the nutational displacement field **s**; meanwhile, in the new motion equation about **s**, the Lorentz force density **L** is also related to $\mathbf{B}_0$ and **b**; and $\mathbf{B}_0$ can be obtained beforehand from any geodynamo model (so $\tilde{h}^0_{lm}, \tilde{h}^P_{lm}$ and $\tilde{h}^T_{lm}$ are known), therefore **b** and **s** can be theoretically solved from these two equations. In practice, all the upper limits of the sum over l, l' (and/or k, n) are set to a definite number (10, for example), because, the magnetic field is given in the harmonic series up to that fixed degree.

Moreover, in the resulted induction equations, the spheroidal part (eq.(13) and (14)) and the toroidal part (eq.(15)) of **b** are decoupled with each other, although both of them involve $\mathbf{B}_0$ and **s**. This result makes the equations solvable more easily.

Acknowledgement: This work was performed mainly during the 6 month residence of CLH at ROB. and partly supported by the Projects NSFC 10373021/10133010.

5. REFERENCES

Buffett B.A., 1992, Constraints on magnetic energy and mantle conductivity from the forced nutations of the Earth, *J. Geophys. Res.*, **97(B13)**: 19581-19597.

Buffett B.A., 1993, Influence of a toroidal magnetic field on the nutation of Earth, *J. Geophys. Res.*, **98(B2)**: 2105-2117.

Buffett B.A., Mathews P.M., and Herring T.A., 2002, Modeling of nutation and precession: Effects of electromagnetic coupling, *J. Geophys. Res.*, **107(B4)**: 101029/2000JB000056.

Dahlen F.A., and Tromp J., 1998, Theoretical global seismology, Princeton University Press, Princeton, New Jewsey.

Huang C.L., Jin W.J., Liao X.H., 2001, A new nutation model of a non-rigid Earth with ocean and atmosphere, *Geophys. J. Int.*, **146**, 126-133

Huang C.L., Dehant V., Liao X.H., 2004, The explicit scalar equations of infinitesimal elastic-gravitational motion in the rotating, slightly elliptical fluid outer core of the Earth, *Geophys. J. Int.*, **157**, 831-837.

Huang C.L., Liao X.H., 2003, Comment on "Representation of the elastic-gravitational excitation of a spherical Earth model by generalized spherical harmonics" by Phinney and Burridge, *Geophys. J. Int.*, **155**, 669-678.

Mathews P.M., Herring T.A., and Buffett B.A., 2002, Modeling of nutation and precession: New nutation series for nonrigid Earth and insights into the Earth's interior. *J. Geophys. Res.*, **107(B4)**: 10.1029/2001JB000390.

Moffatt H.K., and Dillon R.F., 1976, The correlation between gravitational and geomagnetic fields caused by interaction of the core fluid motion with a bumpy core-mantle interface, *Phys. Earth Planet. Inter.*, **13**: 67–78.

Phinney R.A., and Burridge R., 1973, Representation of the elastic-gravitational excitation of a spherical Earth model by generalized spherical harmonics, *Geophys. J. R. astr. Soc.*, **34**, 451-487.

Smith M.L., 1974, The scalar equations of infinitesimal elastic-gravitational motion for a rotating, slightly elliptical Earth, *Geophys. J. R. astr. Soc.*, **37**, 491-526.

FORMULATION OF THE RELATION BETWEEN EARTH'S ROTATIONAL VARIATION EXCITATION AND TIME-VARIABLE GRAVITY

B.F. CHAO
Space Geodesy Branch, NASA Goddard Space Flight Center
Greenbelt, Maryland 20771, USA
email: Benjamin.F.Chao@nasa.gov

1. INTRODUCTION

Slight temporal variations in both Earth's rotation and gravity field constantly take place as a result of mass transport in the Earth system, as governed by the conservation of angular momentum and Newton's gravitational law, respectively [e.g., *Chao et al.*, 2000]. These signals are observed on a routine basis by means of space geodetic techniques [e.g., *AGU*, 1993]. As geophysical observables, they can reveal insights about global climatic and geophysical processes and changes.

The gravity field is customarily and conveniently decomposed into its spherical harmonic components, or density multipoles of the gravitating body. For over two decades the satellite laser ranging technique has yielded the low-degree time-variable gravity (TVG) signals, as is the space mission GRACE in the last few years [*Tapley et al.*, 2004]. Among them, the lowest degree, i.e. degree-2, harmonic components of TVG are intimately related to the excitations of Earth's rotational variations (ERV), in the following sense:

The mass transports (besides external torques) that cause the Earth rotation to vary are referred to as geophysical excitations of the Earth rotation variations (ERV). As derived in *Munk and MacDonald* [1960], the excitation functions of ERV are the sum of two terms—the mass term and the motion term of angular momentum variation. While the motion term has no direct connection with gravity, the mass term does. As a vector, the ERV can be conveniently separated into two components: the (1-D) length-of-day variation (ΔLOD) and the (2-D) polar motion (PM). The mass term of the excitation of ΔLOD, under the conservation of the trace of Earth's inertia tensor, is directly proportional to the (degree, order) = (2,0) component of TVG, whereas the mass term of the PM excitation is directly proportional to the two (2,1) components of TVG.

The motion and mass terms (of angular momentum) are functionals of the mass transport. Combining the two independent measurements of ERV and TVG can thus reveal information about the separation of mass and motion terms in their contribution to the ERV excitation. Such information can be further compared to yet other independent sources of angular momentum estimation for the geophysical fluids, for example atmospheric and oceanic angular momenta, to provide constraints on the modeling of the latter.

Equally important, and perhaps geophysically more interesting, is the following: The gravity in general, and hence the TVG signal, comes from the whole Earth composed of both the mantle (including the crust) and the core (including outer and inner cores), whereas the excitation functions of ERV involve “mantle only” where the core are decoupled or only partially coupled to the mantle depending on the timescale and the type of coupling in question. This subtle difference, if detectable by exploiting the two independent measurements of ERV and TVG, can lead to insight into the Earth’s dynamical processes as influenced by the strength and spectral dependence of the core-mantle coupling.

In this paper we shall develop the theoretical formulations that are relevant to conduct the study, and discuss their geophysical significance.

2. FORMULATION

In this section we build the complete formulation, by assembling elements already existing in the literature. The development consists of: (i) the relation between the Earth’s gravitational harmonic components (in terms of the Stokes coefficients) and the mass distribution (in terms of multipole moments) [*Chao and Gross*, 1987, see also *Chao*, 1994; 2005]; (ii) as a special case of (i) the relation of the degree-2 Stokes coefficients with the quadrupole moments or the inertia tensor of the Earth, known as the generalized MacCullaugh formula [*Chao and Gross*, 1987]; (iii) the corresponding relation with respect to the temporal variations of (ii) [*Chao and Gross*, 1987; *Chao et al.*, 1987; *Chao*, 1994]; and (iv) the relation, following (iii), between the degree-2 Stokes coefficients of TVG and the excitation function of ERV [*Chao and Gross*, 1987]. It should be noted that the formulas for (i) – (iii) are exact, while those for (iv) are approximations. For the latter, the basic linearized theory for the excitation of ERV was developed by *Munk and MacDonald* [1960], and later specialized to exclude the core’s participation by *Barnes et al.* [1983]. The relevant references from the literature are given as above, and will not be repeated below.

2.1 Degree-2 Stokes Coefficients and Inertia Tensor

Satisfying the Laplace equation, the external gravity potential field U produced by an arbitrary gravitating body (say the Earth) has a closed-form solution customarily expressed as a sum of spherical harmonic components in the spherical coordinates $\mathbf{r}$ = (radius r, co-latitude θ, longitude λ):

$$U(\mathbf{r}) = \frac{GM}{a}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1} P_{nm}(\cos\theta)\ \left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right) \tag{1}$$

[e.g., *Kaula*, 1966], where G is the gravitational constant, P_{nm} is the 4π-normalized Legedre function of degree n (= 0,1,2,...,∞) and order m(= 0,1,2,...,n), M is the mass of the gravitating body (which will be specified as the whole Earth or the mantle only, as the case may be, in the below). Referring to a, a length parameter conveniently chosen to be the mean equatorial radius of the Earth, the dimensionless coefficients C_{nm} and S_{nm} are known as the (normalized) Stokes coefficient of degree n and order m. The set of Stokes coefficients constitutes quantitatively what is a gravity field model.

Comparing Equation (1) with the multipole expansion of Uaccording to Newton’s gravitational law [e.g., *Jackson*, 1975], one sees that the Stokes coefficients are simply normalized multipoles of the body with internal density distribution $\rho(\mathbf{r})$:

$$C_{nm} + iS_{nm} = \frac{1}{(2n+1)\,Ma^n}\iiint \rho(\mathbf{r})\ r^n\ P_{nm}(\cos\theta\ )\ \exp(im\lambda)\ \ dV \tag{2}$$

In particular, for degree n=2, as the right-side quadrupole moments are closely related to the inertia tensor $\mathbf{I}$ of the body, Equation (2) amounts to the generalized MacCullaugh formula:

$$
\begin{aligned}
C_{20} &= (I_{xx} + I_{yy} - 2I_{zz})/(2\sqrt{5}Ma^2) \\
C_{21} &= -\sqrt{3}I_{zx}/(\sqrt{5}Ma^2) \\
S_{21} &= -\sqrt{3}I_{yz}/(\sqrt{5}Ma^2) \\
C_{22} &= \sqrt{3}(I_{yy} - I_{xx})/(2\sqrt{5}Ma^2) \\
S_{22} &= -\sqrt{3}I_{xy}/(\sqrt{5}Ma^2)
\end{aligned} \tag{3}
$$

where expressed in the terrestrial Cartesian coordinates (where z-axis points to the mean North pole, and the x- and y-axes lie on the equatorial plan pointing, respectively, to the Greenwich Meridian and the 90 $^\circ$ E Longitude):

$$
I = \begin{bmatrix} \int (y^2+z^2)\,\rho\, dV = I_{xx} & -\int xy\,\rho\, dV = I_{xy} & -\int zx\,\rho\, dV = I_{zx} \\ I_{xy} & \int (z^2+x^2)\,\rho\, dV = I_{yy} & -\int yz\,\rho\, dV = I_{yz} \\ I_{zx} & I_{yz} & \int (x^2+y^2)\,\rho\, dV = I_{zz} \end{bmatrix} \tag{4}
$$

The integrals are over the volume of the whole Earth or "mantle only", as the case may be. Note that there are 6 elements in **I** whereas only 5 degree-2 Stokes coefficients or quadrupole moments. The knowledge about the latter is insufficient to determine completely the former. This is a manifestation of the well-known non-uniqueness of the gravitational inversion [e.g., *Chao*, 2005]. We mention that the dynamic oblateness of the Earth is defined (for historical reasons) as J_2 = -$\sqrt{5}\ C_{20}$.

When a mass redistribution, or a change in the density function $\rho(\mathbf{r})$ takes place, the Stokes coefficients in (2) will change accordingly, and so will the inertia tensor (4). The changes can be evaluated using either the Lagrangian or Eulerian approaches (depending on the convenience dictated by the form of the data); but however they are evaluated, we now have the following relation:

$$
\begin{aligned}
\Delta C_{20} &= (\Delta I_{xx} + \Delta I_{yy} - 2\Delta I_{zz})/(2\sqrt{5}Ma^2) \\
\Delta C_{21} &= -\sqrt{3}\Delta I_{zx}/(\sqrt{5}Ma^2) \\
\Delta S_{21} &= -\sqrt{3}\Delta I_{yz}/(\sqrt{5}Ma^2) \\
\Delta C_{22} &= \sqrt{3}(\Delta I_{yy} - \Delta I_{xx})/(2\sqrt{5}Ma^2) \\
\Delta S_{22} &= -\sqrt{3}\Delta I_{xy}/(\sqrt{5}Ma^2) \\
\Delta T &= \Delta I_{xx} + \Delta I_{yy} + \Delta I_{zz}
\end{aligned} \tag{5}
$$

where in this paper Δ means "time variation in", so that the quantity following Δ is a function of time. Note here we have appended a formula for the quantity T= Tr(**I**), the trace of the inertia tensor, anticipating its usage later.

2.2 Length-of-Day Change (ΔLOD)

If the body is under rotation, then any change in $\rho(\mathbf{r})$ and hence in **I** will induce changes in the rotation, as governed by the conservation of angular momentum. The conservation of the z-component of the angular momentum vector dictates that the z-component of the rotation vector, or consequently the ΔLOD if the timescale under consideration is longer than a day, obeys the equation:

$$
\Psi_{z[mass]} = \frac{\Delta\Omega_{mass}}{\Omega} = -\frac{\Delta \mathrm{LOD}_{mass}}{\mathrm{LOD}} = -\frac{\Delta I_{zz}}{I_{zz}} = \frac{2\sqrt{5}Ma^2\Delta C_{20}\ -\ \Delta T}{3I_{zz}} \tag{6}
$$

where Ψ_z is the (dimensionless) excitation function of ΔLOD, and the last equality is readily derivable from Equation (5). The subscript "mass" denotes "the part due to the mass term".

Apart from external torques, two parts of excitation contribute to the observed ΔLOD: a "mass" term due to mass redistribution as described here, and a "motion" term arising from relative angular momentum exchange with other parts of the Earth (via internal torques). For example, in the atmosphere or the oceans under the Eulerian approach, the mass term (which can be readily derived from above) and the motion term are given approximately by [*Barnes et al.*, 1983]:

$$\Psi_{z[mass]} = -\frac{0.70\, a^4}{g\, I_{zz}} \iint p \sin^3\theta d\theta d\lambda \tag{7}$$

$$\Psi_{z[motion]} = -\frac{1.00\, a^3}{\Omega\, g\, I_{zz}} \iiint u \ \sin^2\theta \ d\theta d\lambda \ dp \tag{8}$$

where $g = GM/a^2$ is the mean gravitational acceleration of the Earth, p is the surface pressure field, and u is the east-velocity field of mass transport (for example, of atmospheric winds or oceanic currents). The numerical coefficient $0.70 = 1{+}k_2$' accounts for the elastic yielding of the Earth as a result of the mass loading on the solid Earth, where k_2' is Earth's load Love number of degree 2. The mass term is related to TVG; the motion term has no direct relationship with gravity.

2.3 Polar Motion (PM) Excitation

Similarly, the conservation of the (equatorial) x-y components of the angular momentum vector results in:

$$\Psi_{mass} = 1.43\frac{\Delta I_{zx} + i\Delta I_{yz}}{I_{zz} - I_{xx}} = -1.43\frac{\sqrt{5}\, Ma^2(\Delta C_{21} + i\Delta S_{21})}{\sqrt{3}\,(I_{zz} - I_{xx})} \tag{9}$$

Here the complex-valued $\Psi = \Psi_x{+}i\Psi_y$ is an abbreviation for the (non-dimensional) polar motion excitation function whose real part is the x-component and the imaginary part the y-component. The factor 1.43 accounts for the dynamic feedback of the elastic rotational deformation itself that lengthens the period of the Chandler wobble from the rigid-Earth value of about 10 months to the observed 14 months.

Similarly as above, in the Eulerian approach for the atmosphere and oceans, we have approximately [*Barnes et al.*, 1983]:

$$\Psi_{mass} = -\frac{1.00\, a^4}{(I_{zz} - I_{xx})\, g} \iint p \ \cos\theta \ \sin^2\theta \ e^{i\lambda} d\theta d\lambda \tag{10}$$

$$\Psi_{motion} = -\frac{1.43\ a^3}{(I_{zz} - I_{xx})\Omega\, g} \iiint (u\cos\theta \ + iv) \ e^{i\lambda} \ \sin\theta d\theta d\lambda\, dp \tag{11}$$

where v is the north-velocity field of the mass transport, and an axial symmetric approximation of $I_{xx} = I_{yy}$ has been made. Here the numerical coefficients 1.00 results from the product of 1.43 with $1{+}k_2$' arising from the mass loading effect.

The "observed" PM excitation Ψ is related to the observed PM P via:

$$\Psi = P - (1/i\omega_c) \ \ \partial_t P \tag{12}$$

where ω_c is the resonance Chandler wobble frequency of the Earth.
Equation (12) constitutes a deconvolution relation, because, when solved, it states that P is the temporal convolution of Ψ with the free Chandler wobble.

2.4 Rotation-Derived and the Gravity-Derived Quantities

Equations (6) and (9) can be re-written respectively as

$$\text{rotation}-\text{derived }\Delta C_{20} \quad = \quad \frac{3\ I_{zz}\,\Psi_{z[mass]}\ +\ \Delta T}{2\sqrt{5}Ma^2} \tag{13}$$

$$\text{rotation}-\text{derived }(\Delta C_{21}\ +\ i\,\Delta S_{21}) \quad = \quad \frac{-\sqrt{3}\,(I_{zz}\ -\ I_{xx})}{1.43\sqrt{5}\,Ma^2}\Psi_{mass} \tag{14}$$

The goal of this research is then to compare the rotation-derived quantities (13) and (14) with the independent, corresponding gravity-derived counterparts, and to extract geophysical information and insights in the process. A complete study would require extensive data analysis, which will await future effort. In the next section we will discuss the geophysical significances.

3. GEOPHYSICAL DISCUSSIONS

3.1 Mass term of ERV excitation function

For the last quarter century the space geodetic techniques of satellite-laser-ranging (SLR) and very-long-baseline interferometry (VLBI), and the more recent addition of the Global Positioning System (GPS), have been obtaining precise measurements of ERV, in both ΔLOD and PM. The total excitation function derived from the ERV observations contains both mass and motion terms: $\Psi_z = \Psi_{z[mass]} + \Psi_{z[motion]}$, and $\Psi = \Psi_{mass} + \Psi_{motion}$ (where Ψ is derived by means of Equation 12). They must be stripped of the motion-term contribution to become comparable with the corresponding gravity-derived quantities which are related to the mass term only.

This can in principle be accomplished by introducing, and subtracting off, independent estimates for the motion terms for the geophysical fluids, including atmosphere, oceans, land hydrology, core, etc. [e.g., *Chao et al.*, 2000]. It is well known that the (zonal) motion terms contribute dominantly in the case of ΔLOD or Ψ_z excitation. On interannual to weekly timescales including the seasonal periodicities, the motion term of the atmospheric angular momentum (AAM) accounts for the majority of ΔLOD [e.g., *Salstein et al.*, 1993], while some secondary contributions come from the motion term of the non-tidal oceanic angular momentum (OAM) [e.g., *Marcus et al*, 1998; *Johnson et al.*, 1999; *Gross*, 2003]. The large decadal fluctuation in ΔLOD arises from the motion term in the core angular momentum (CAM) [e.g., *Holme and Whaler*, 2001]. The strong motion terms of the ocean tidal angular momentum are of much shorter periods than of interest here. The hydrological angular momentum and the solid-Earth bodily tides have negligible motion terms. The similar is true with respect to the PM excitation, although the contribution of the motion terms is no longer dominant, but rather comparable or smaller relative to the mass terms.

It should be noted that subtracting the motion-term contributions of the geophysical fluids from the observed total ERV excitation function has the undesirable consequence of magnifying the noise to signal ratio in the residual mass term. Furthermore, any remnant motion-term contributions that are not removed completely become sources of error.

The end products of the removal of motion terms are thus the $\Psi_{z[mass]}$ and Ψ_{mass} needed in Equations (13) and (14).

3.2 Does ΔT vanish?

We note in Equation (13) the inclusion of the "extra" term ΔT (defined in Equation 5). Unless ΔT vanishes, its existence becomes troublesome when we try to relate ΔC_{20} with ΔLOD, because neither rotation nor gravity would observe it directly. Although an invariant under coordinate transformation, T can definitely vary with respect to time. An example is co-seismic dislocation [*Chao and Gross*, 1987].

However, for all practical purposes many Earth processes of mass transport do preserve T, rendering true $\Delta T \approx 0$. Possible examples include glacial isostatic adjustment [R. Peltier, personal communication, 2002] and mantle convection. More significantly, ΔT indeed vanishes on timescales that are dominated by an important class of mass redistribution processes – those taking place on the surface of the Earth, most notably in the form of air and water mass transports: It is easy to show that $\Delta T = 0$ under the conservation of the total surface mass, as long as the surface is (assumed) spherical [e.g., *Chao et al.*, 1987].

Thus, while there is no a priori reason why ΔT should vanish, one can enforce the simplification $\Delta T = 0$, so that Equation (11) becomes

$$\text{rotation}-\text{derived } \Delta C_{20} \approx \frac{3\, I_{zz}}{2\sqrt{5}Ma^2}\, \Psi_{z[mass]} \tag{15}$$

Any ΔLOD signal coming from sources for which $\Delta T \neq 0$ will thus contain such "contamination" when converted into the equivalent ΔC_{20}.

3.3 "Mantle Only" versus "Whole Earth"

Finally, we should consider a fundamental question pertaining to the exact meaning behind Equations (13-15) – whether they apply to the case of the "Whole Earth" or the "Mantle Only". These are dynamical scenarios that represent two extremes: The "Whole Earth" corresponds to 100% coupling of the core with the mantle in the ERV excitation process, and the "Mantle Only" corresponds to zero core-mantle coupling in the ERV excitation process. The reality presumably lies somewhere in between the extreme cases, but is a strong function of the timescale and the mechanisms at work, which may even distinguish between the axial and equatorial components. For example, it appears that the "Mantle Only" scenario is a reasonable approximation on timescales shorter than several years, longer than which it has been demonstrated that the CAM strongly affects ΔLOD [e.g., *Holme and Whaler*, 2001] – the transition from non-coupling to strong-coupling is thus around several years. Similar arguments apply to the PM excitation.

On the other hand, the gravity-derived quantities refers only to the "Whole Earth", as no mass can be "shielded" and not be observed gravitationally from outside. Therefore the corresponding rotation-derived and gravity-derived values of ΔC_{20} and $\Delta C_{21} + i\Delta S_{21}$ differ by the contribution of the core, the amount of which depends on the strength of the core-mantle coupling in the ERV excitation processes [e.g., *Dickman*, 2003].

Suppose we take, say, "Mantle Only" as the baseline case by letting all the quantities in Equations (13-15) assume mantle-only values (except that Ma^2 is the whole-Earth parameter merely serving as normalization factors). Then any observed departure of the gravity-derived quantities from the baseline rotation-derived quantities evaluated accordingly will in principle signify the departure of the reality from the underlying "Mantle Only" assumption for the ERV excitation processes. Such extraction of geophysical information awaits further investigations.

Acknowledgements. This work is supported by NASA's Solid Earth and Natural Hazard Program. I thank G. Bourda and C. Cox for discussions.

4. REFERENCES

AGU, *Contributions of Space Geodesy to Geodynamics: Technology*, Geodynamics Series 25, ed. D. E. Smith and D. L. Turcotte, Amer. Geophys. Union, Washington DC, 1993.

Barnes, R.T.H., R. Hide, A.A. White, and C.A. Wilson, Atmospheric angular momentum fluctuations, length-of-day changes and polar motion. *Proc. Roy. Soc. Lond. A, 387*, 31-73, 1983.

Chao, B. F., and R. S. Gross, Changes in the Earth's rotation and lowdegree gravitational field induced by earthquakes, *Geophys. J. Roy. Astron. Soc., 91,* 569596, 1987.

Chao, B. F., W. P. O'Connor, A. T. C. Chang, D. K. Hall, and J. L. Foster, Snowload effect on the Earth's rotation and gravitational field, 1979-1985, *J. Geophys. Res., 92,* 94159422, 1987.

Chao, B. F., The Geoid and Earth Rotation, in *Geophysical Interpretations of Geoid*, ed. P. Vanicek and N. Christou, CRC Press, Boca Raton, 1994.

Chao, B. F., V. Dehant, R. S. Gross, R. D. Ray, D. A. Salstein, M. M. Watkins, and C. R. Wilson, Space geodesy monitors mass transports in global geophysical fluids, *EOS, Trans. Amer. Geophys. Union, 81,* 247-250, 2000.

Chao, B. F., On inversion for mass distribution from global (time-variable) gravity field, in press, *J. Geodynamics*, 2005.

Dickman S. R., Evaluation of "effective angular momentum function" formulations with respect to core-mantle coupling, *J. Geophys. Res., 108* (B3), 2150, doi:10.1029/2001JB001603, 2003.

Gross, R. S., I. Fukumori, and D. Menemenlis, Atmospheric and oceanic excitation of the Earth's wobbles during 1980-2000, *J. Geophys. Res.,* 108 (B8), 2370, 10.1029/2002JB002143, 2003.

Holme, R., and K. Whaler, Steady core flow in an azimuthally drifting reference frame, *Geophys. J. Int., 145*, 560-569, 2001.

Jackson, J. D., *Classical Electrodynamics*, 2nd ed., Wiley, New York, 1975.

Johnson, T. J., C. R. Wilson, and B. F. Chao, Oceanic angular momentum variability estimated from the Parallel Ocean Climate Model, 1988-1998, *J. Geophys. Res., 104*, 25183-25196, 1999.

Kaula, W. M., *Theory of satellite geodesy*, Blaisdell Publishing Co., Waltham, 1966.

Marcus, S. L., Y. Chao, J. O. Dickey, and P. Gegout, Detection and modeling of nontidal oceanic effects on Earth's rotation rate, *Science*, 281, 1656–1659, 1998.

Munk W. H., and G. J. F. MacDonald, *The Rotation of the Earth*, Cambridge Univ. Press, New York, 1960.

Salstein, D.A., D.M. Kann, A.J. Miller, and R.D. Rosen, The sub-bureau for Atmospheric Angular Momentum of the International Earth Rotation Service (IERS): A meteorological data center with geodetic applications, *Bull. Am. Met. Soc.*, 74, 67-80, 1993.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins, GRACE measurements of mass variability in the Earth system, *Science, 305*, 503-505, 2004.

THE FREE CORE NUTATION

D.D. MCCARTHY
U. S. Naval Observatory
Washington, DC 20392 USA
e-mail: dmc@maia.usno.navy.mil

ABSTRACT. The International Earth rotation and Reference system Service (IERS) provides observational determinations of the celestial pole offsets that describe quantitatively the difference between the observed direction of the Celestial Intermediate Pole in the celestial reference frame and the direction predicted by the conventional precession-nutation model. The free core nutation is the most significant component of that time series. This motion is due to the fact that the rotation axes of the core and mantle are not aligned, and it is seen in the observations as a periodic variation with a period of 432 days with time-variable amplitude and phase. The IERS is tasked with providing a numerical model for this motion. The current status of the free-core nutation models is reviewed and their accuracy is assessed.

1. INTRODUCTION

Beginning on 1 January 2003, the IAU 2000 Precession-Nutation model and associated celestial pole offsets replaced the IAU 1976 Precession and IAU 1980 Nutation as the IAU-recommended model to be used in the transformation between celestial and terrestrial reference systems. Information regarding these procedures is available in Chapter 5 of the *IERS Conventions 2003* (McCarthy and Petit 2004) available at http://maia.usno.navy.mil/conv2003.html. The nutation in longitude and obliquity is based on the adopted MHB2000 (Mathews, *et al.* 2002) model with the exception of the Free Core Nutation (FCN). Data to model the FCN are to be provided by the International Earth rotation and Reference system Service (IERS).

The IAU 2000 model can be implemented through the use of the IAU2000A model, which is available at ftp://maia.usno.navy.mil/conv2000/chapter5/IAU2000A.f. For those users requiring precision at only the milliarcsecond level, the IAU2000B subroutine is available at ftp://maia.usno.navy.mil/conv2000/chapter5/IAU2000B.f. The IAU has also recommended that VLBI observations be continued in order to improve future nutation models and to measure the unpredictable FCN.

Beginning on 1 January 2003, IERS Bulletins A and B have provided new products in addition to those previously published. These products include the celestial pole offsets $X_{obs} - X_{IAU2000A}$ and $Y_{obs} - Y_{IAU2000A}$ where X_{obs} and Y_{obs} are the observed X, Y coordinates of the Celestial Intermediate Pole in the Geocentric Celestial Reference System, and $X_{IAU2000A}$ and $Y_{IAU2000A}$ are the celestial pole coordinates provided by using the IAU 2000A Precession-Nutation theory. It is expected that celestial pole offsets related to the IAU 1980 Nutation Theory will continue to be published indefinitely. The celestial pole offsets related to the IAU 2000A Precession-Nutation theory are in a separate data file.

The IAU 2000 precession-nutation very adequately models the precession-nutation as observed by very long baseline interferometry, accounting for nearly all of the signal in the celestial pole offsets with respect to the IAU 1980 nutation series. As a result, the celestial pole offsets with respect to the IAU 2000 Precession-Nutation are very much smaller than those calculated with respect to the IAU 1980 mode. The FCN, however, is not accounted for by a model in either the IAU 1980 or the IAU 2000 models. For those users who might want to model the FCN, the IERS currently recommends a model that provides corrections to the expression for the longitude of the equinox and the obliquity (dψ and dϵ).

The relationship between variations in the X, Y coordinates of the Celestial Intermediate Pole in the Geocentric Celestial Reference System and dψ and dϵ are given by

$$\begin{aligned} dX &= d\psi \sin\epsilon_A + (\psi_A \cos\epsilon_0 - \chi_A) d\epsilon, \\ dY &= d\epsilon(\psi_A \cos\epsilon_0 - \chi_A) d\psi \sin\epsilon_A, \end{aligned}$$

where ϵ_A is the obliquity referred to the ecliptic of date, ψ_A is the precession in longitude (Lieske, *et al.* 1977) referred to the ecliptic of epoch, and χ_a is the precession quantity for planetary precession along the equator (Lieske, *et al.* 1977).

2. PHYSICAL NATURE OF THE FCN

The FCN is the most significant periodic component seen in the observations of the celestial pole offsets and is due to the free nutation of the Earth's core. This motion is the result of the fact that the rotation axes of the core and mantle of the Earth are not precisely aligned (Brzezinski and Petrov 1999). In the celestial frame it appears as a retrograde motion of the celestial pole with a period of approximately 430 days (Roosbeek, *et al.* 1999). The exact nature of the FCN is influenced by the flattening of the core-mantle boundary and by any deformations on the surface of that boundary (Mathews, *et al.* 1991). In the terrestrial reference frame this phenomenon would be seen as a diurnal motion, and it may be referred to as the Nearly Diurnal Free Wobble.

3. CURRENT IERS MODEL

The model for the FCN currently provided by the IERS on its web site (see http://www.iers.org/iers/earth/rotation/precnut/table1.html) is that found in the *IERS Conventions (1996)* (McCarthy, 1996) based on the KSV 1996 3 nutation series provided by T. Herring. That model provides corrections to the expression for the longitude of the equinox and the obliquity (dψ and dϵ) calculated using the IAU 1980 nutation model in the form

$$\begin{aligned} d\psi_{FCN} &= a_\psi \sin\nu + b_\psi \cos\nu, \\ d\epsilon_{FCN} &= a_\epsilon \sin\nu + b_\epsilon \cos\nu, \\ \nu &= -2\pi/P \times (JD - 2451545.0), \end{aligned}$$

where a_ψ, b_ψ, a_ϵ, and b_ϵ are tabular values for the epoch of interest, and $P=$ period of the FCN $=$ 433 days.

4. MHB 2000 MODEL

The MHB (Mathews, *et al.* 2002) model provides corrections to the expression for the longitude of the equinox and the obliquity (dψ and dϵ) calculated using the IAU 1980 model in the form

Beginning JD	Year	Month	Day	a	b
2443874.5	1979	1	1	-0.0620	-0.1346
2445700.5	1984	1	1	0.0447	-0.1679
2446431.5	1986	1	1	0.2406	-0.2759
2447161.5	1988	1	1	0.1183	-0.2163
2447892.5	1990	1	1	0.0479	-0.1965
2448622.5	1992	1	1	-0.0796	-0.1321
2449353.5	1994	1	1	-0.0075	-0.1150
2450083.5	1996	1	1	-0.0128	-0.0998
2450814.5	1998	1	1	-0.0263	-0.1122
2451544.5	2000	1	1	0.0519	0.0081
2452061.5	2001	6	1	0.2100	0.1401

Table 1: MHB2000 model parameters.

$$
\begin{aligned}
d\psi_{FCN} \sin\epsilon &= -A\sin\nu + B\cos\nu, \\
d\epsilon_{FCN} &= -A\cos\nu - B\sin\nu, \\
\nu &= -2\pi(1 + f_{FCN})r(JD - 2451545.0)
\end{aligned}
$$

where A and B are linearly interpolated values for the epoch of interest derived from tabular values shown in Table 1, r = solar to sidereal ratio (1.002737909), and f_{FCN} is the frequency of the FCN (-1.002318109 sidereal days^{-1}).

5. MALKIN MODEL

Malkin (2004) has published another model in the form

$$
\begin{aligned}
dX &= A(t)\sin[\phi(t - t_0)], \\
dY &= A(t)\cos[\phi(t - t_0)],
\end{aligned}
$$

where

$$\phi(t) = \int_{t_0}^{t} \frac{2\pi}{P(t)} dt + \phi_0.$$

Numerical values for the model components were not published but a visual comparison of the model with observations is provided in the publication.

6. LAMBERT MODEL

S. Lambert (2004) has also provided a FCN model based on an analysis of the VLBI observations. This model is given in the form

$$
\begin{aligned}
dX &= A\sin 2\pi\sigma(t - t_0) + B\cos 2\pi\sigma(t - t_0), \\
dY &= -B\sin 2\pi\sigma(t - t_0) + A\cos 2\pi\sigma(t - t_0),
\end{aligned}
$$

where A and B are linearly interpolated values for the epoch of interest derived from tabular values of a and b, $\sigma = 1/430.21$ days, t is the date (MJD), and $t_0 = 51544.5$. Table 2 provides the numerical values needed to calculate A and B.

Year	a	b
1984	-0.0179	-0.0809
1985	-0.1569	-0.2253
1986	-0.1650	-0.2143
1987	-0.1104	-0.2214
1988	-0.0357	-0.2687
1989	-0.0899	-0.1557
1990	0.0084	-0.1593
1991	0.0418	-0.1277
1992	0.0331	-0.1196
1993	0.0529	-0.0973
1994	0.0154	-0.0692
1995	-0.0189	-0.0748
1996	0.0367	-0.1137
1997	0.0801	-0.0983
1998	0.0249	-0.0622
1999	-0.0595	-0.0442
2000	-0.1043	-0.0017
2001	-0.2024	0.0787
2002	-0.0785	0.1092
2003	0.0036	0.1302

Table 2: Lambert model parameters.

	DX	DY
IERS Web Site	0.000329	0.000296
MHB 2000	0.000253	0.000294
Lambert	0.000247	0.000292

Table 3: Standard deviation of the residuals of FCN Models with respect to observations from January 1984 through August 2004. Entries are standard deviations in seconds of arc.

7. COMPARISON OF MODELS

The three models that provide numerical values for evaluation were compared with VLBI observations of the celestial pole offsets. Figures 1 and 2 show the residuals of each model with respect to the observations. Table 3 provides a comparison of the standard deviations of the differences between the model and the observations. This comparison shows that the Lambert model provides the smallest residuals.

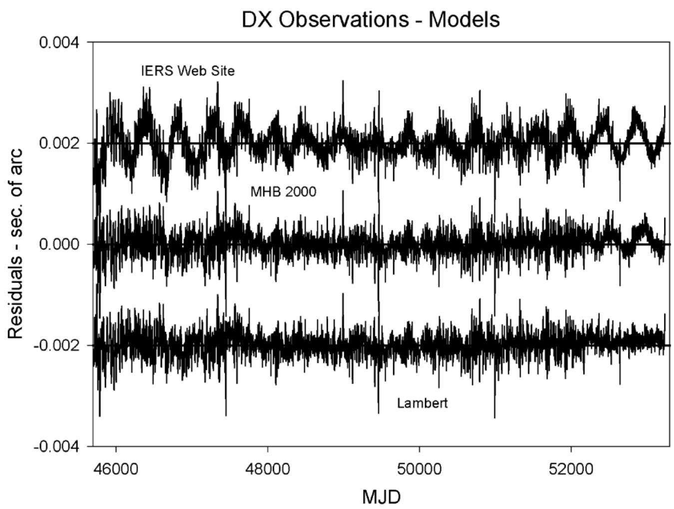

Figure 1: Comparison of FCN models with observations of dX.

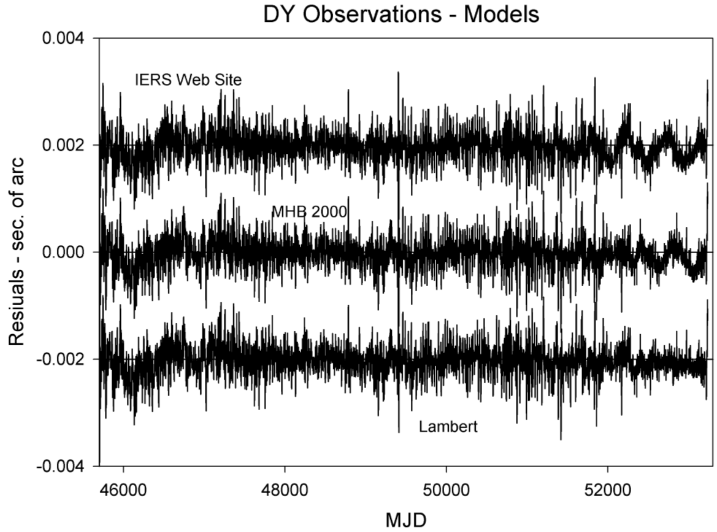

Figure 2: Comparison of FCN models with observations of dY.

8. CONCLUSION

Users that require the most accurate data to transform between the celestial and terrestrial reference systems can make use of the observed values of the celestial pole offsets provided by the IERS. The most significant component of the celestial pole offsets that remains unmodeled by the IAU 2000 precession-nutation model is the FCN. This free motion can be modeled empirically, and the IERS provides a conventional model for this purpose. This conventional model can be improved significantly with the adoption of the Lambert (2004) model.

9. REFERENCES

Brzezinski, A. and Petrov, S. D., 1999, “Observational evidence of the free core nutation and its geophysical excitation,” in *Proceedings of the Journées 1998 Systèmes de Référence Spatio-Temporels 1998*, (Paris, Sept. 1998), N. Capitaine (ed.), Observatoire de Paris, 169.

Lambert, S., 2004, private communication.

Lieske, J. H., Lederle, T., Fricke, W., and Morando, B., 1977, “Expressions for the Precession Quantities Based upon the IAU(1976) System of Astronomical Constants,” A&A , 58, 1.

Malkin, Z., 2004, “A New Free Core Nutation Model with Variable Amplitude and Period,” in *IVS 2004 General Meeting Proc.*, 388-392.

Mathews, P. M., B. A. Buffett, T. A. Herring, and I. I. Shapiro, 1991, “Forced nutations of the Earth: Influence of the inner core dynamics, 1, Theory,” J. Geophys. Res. , 96, 8219.

Mathews, P. M., Herring, T. A., and Buffett B. A., 2002, “Modeling of nutation-precession: New nutation series for nonrigid Earth, and insights into the Earth’s Interior,” J. Geophys. Res. , 107, B4, 10.1029/2001JB000390.

McCarthy, D. D., 1996, *IERS Conventions (1996)*, IERS Technical Note 21, Observatoire de Paris, Paris.

McCarthy, D. D., Petit, G. 2004, *IERS Conventions (2003)*, IERS Technical Note 32, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am main.

Roosbeek, F., Defraigne, P., Feissel, M., and Dehant, V, 1999, “The free core nutation period stays between 431 and 434 sidereal days”, Geophys. Res. Lett.,26, 131.

MODEL OF THE FREE CORE NUTATION FOR IMPROVEMENT OF THE EARTH NUTATION SERIES

V.E. ZHAROV
Sternberg State Astronomical Institute
119992, Universitetskij pr.,13,Moscow,Russia
e-mail: zharov@sai.msu.ru

ABSTRACT. The Free Core Nutation (FCN) is one of a normal mode of the Earth. It is observed as retrograde oscillation with period of 430 days and variable amplitude. The FCN contribution in difference between the model and observed nutation is significant and has to be explaned for further improvement of the nutation theory. In order to model and predict the FCN signal the theory of the atmospheric tides is suggested to use.

1. INTRODUCTION

New model MHB2000 (Mathews et al., 2002) of nutation and precession was adopted as official IAU model. It does not include the FCN because its contribution can not be predicted rigorously. The FCN signal is observed as an oscillation with retrograde period of 430 days and amplitude between 0.1 and 0.3 milliarcseconds.

Several models are proposed for the FCN signal. Herring et al. (2002), assumed the constant frequency of the FCN, determined empirical sine and cosine amplitudes for two-year intervals. Mathematical model for the FCN with variable period and amplitude was developed by Malkin (2003). Other model was proposed by Shirai and Fukushima (2001), in which the FCN is considered as damped sinusoidal oscillation. This physical model is based on the hypothesis of excitation of the FCN by strong earthquakes.

In all models the parameters of the FCN signal are estimated from differences between theoretical and observed nutation. Strictly speaking, this models represent the estimation of the FCN signal from the VLBI data. In this paper, I will try to use the theory of the atmospheric tides to predict the FCN. It was shown (Gegout et al., 1998) that the atmosphere excitation sources are powerful enough to excite the FCN to its mean 0.2 mas observed level in VLBI series. The theory of the atmospheric tides allows to predict the amplitude of the ψ_1 tide, corresponding the retrograde annual oscillation. So frequency of the ψ_1 tide is close to the frequency of the FCN, and this tide can be one of the sources of excitation the FCN.

2. METHOD

In our approach the ψ_1 atmospheric tide is result of semi-annual modulation of the thermal tide S_1. This conclusion is confirmed by Fig.1 on which amplitudes of the tides ψ_1 and π_1 depending on time are shown (uncertainties of each point are of order of 0.07 mas). If these tides are result of semi-annual modulation of the tide S_1 then their amplitudes have to be equal. Amplitudes were estimated be least square method on three-year intervals using the pressure term of the atmosphere angular momentum series (Kalnay et al., 1996).

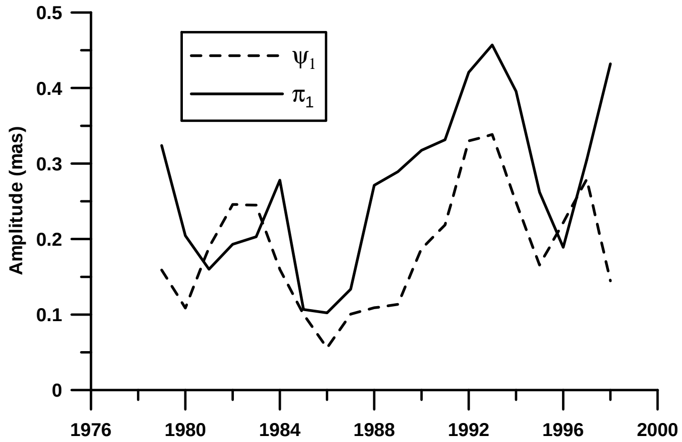

Figure 1: Amplitudes of the atmospheric tides ψ_1 and π_1

Figure 2 shows the spectrum of the pressure term in retrograde diurnal frequency band.

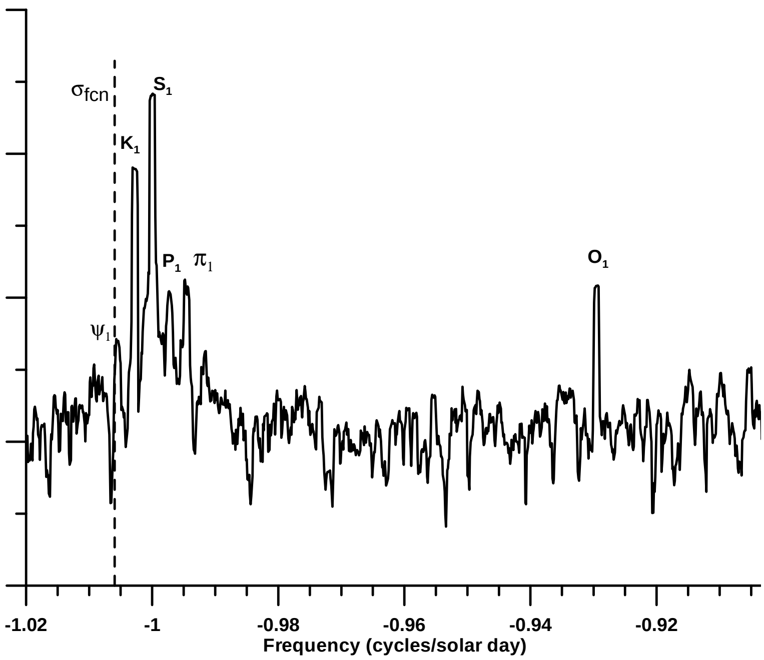

Figure 2: Spectrum of the pressure term

As shown in Zharov (1997) annual modulation of S_1 and appearance of the K_1 and P_1 tides can be explained by the annual variation of water vapour distribution in the atmosphere. Semi-annual modulation can be obtained by application of more complicated model of seasonal variations of water vapour.

The different nutation series MHB2000, GF99 (Getino, Ferrandiz, 2000), ZP2003 (Zharov, Pasynok, 2002) were used to estimate the parameters of the FCN. As was shown by Pasynok (2003) the FCN terms are different for these theories. The OCCAM software (Titov and Zarraoa,

2001) was used for calculation of corrections for $\Delta\psi \sin \varepsilon_0$ and $\Delta\varepsilon$ for each nutation series. In spectra of residuals between the theoretical and observed nutation the strong peak around -430 days is clearly determined but amplitudes of the FCN are different (Fig.3).

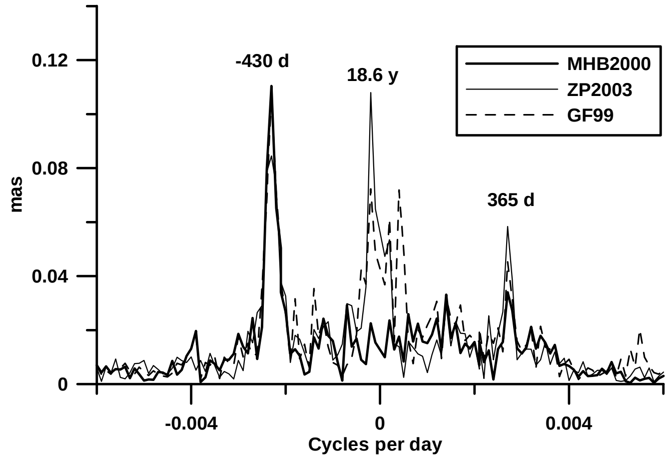

Figure 3: Spectra of complex residuals for different nutation series

Variations of the FCN amplitudes are shown in Fig.4. They were calculated together with the period and quality factor by weighted non-linear least square fitting on two-year intervals. One can see that theories MHB2000 and ZP2003 show similar behavior of the FCN amplitude but theory GF99 differs significantly. The time variations of the FCN period are small ($\sim$ 3 days) and less then formal errors from least square solution, but the quality factor vary significantly.

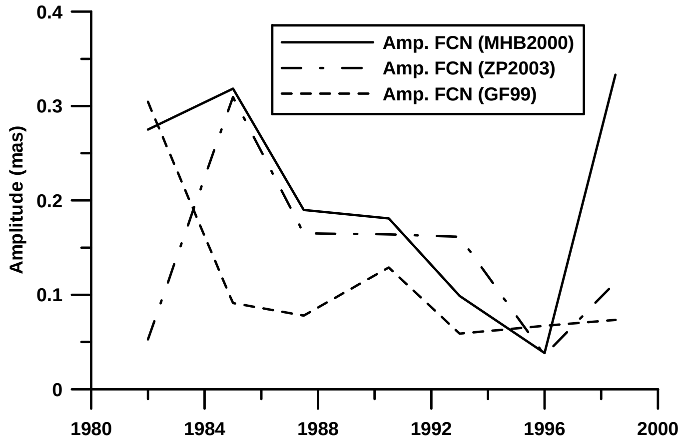

Figure 4: The FCN amplitude

3. CONCLUSIONS

The general conclusion from analysis is that the time variation of the FCN amplitude most probably excited by the atmospheric tides. The time variation of the ψ_1 tide can be connected with the seasonal distribution of water vapour that can be modeled. This approach may be useful for prediction of the FCN amplitude but we suffer failure in explanation of variabilities of the FCN period and quality factor.

Acknowledgments. This work was supported by the Russian Foundation for Basic Research (grant 02-05-39004).

4. REFERENCES

Gegout, P., J. Hinderer, H. Legros, M. Greff, V. Dehant, 1998. Influence of atmospheric pressure on the free and forced nutational motions of the Earth. Phys. Earth Planet. Inter. **106**, 337-351.

Getino, J., J.M. Ferrándiz, 2000. *Proc. of IAU Coll. 180*, eds. K.J.Johnston, D.D.McCarthy, B.J.Luzum, and G.H. Kaplan, U.S. Naval Obs., 236-241.

Herring, T.A., P.M. Mathews, B.A. Buffet, 2002. Modeling of nutation and precession: Very long baseline interferometry results. J. Geophys. Res. , **107**, No. B4, 10.1029/2001JB000165.

Kalnay, E. et al., 1996. The NCEP/NCAR 40-year Reanalysis Project, Bull. Amer. Meteor. Soc., 77, 437-471.

Malkin, Z.M., 2003. Comparison of VLBI nutation series with the IAU2000A model. *Proc. Journeés Systemes de Référence Spatio-Temporels 2003*, ed. by A.Finkelstein and N.Capitaine, IAA RAS, 24-31.

Mathews, P.M., T.A. Herring, B.A. Buffet, 2002. Modeling of nutation and precession: New nutation series for nonrigid Earth and insight into the Earth's interior. J. Geophys. Res. , **107**, No. B4, 10.1029/2001JB000390.

Pasynok, S.L., 2003. IAU2000: Comparison with the VLBI observations and other nutation theories. *Proc. Journeés Systemes de Référence Spatio-Temporels 2003*, ed. by A.Finkelstein and N.Capitaine, IAA RAS, 176-181.

Shirai, T., T. Fukushima, 2001. Construction of a New Forced Nutation Theory of the Nonrigid Earth. AJ , **121**, 3270-3283.

Zharov, V.E., S.L. Pasynok, 2002. Theory of nutation of the non-rigid Earth with the atmosphere. *Proc. Journeés Systemes de Référence Spatio-Temporels 2002*, ed. by N.Capitaine and M.Ctavinschi, Astron. Inst. Romanian Academy, 140-145.

Zharov, V.E., 1997. Rotation of the Earth and atmospheric tides (in Russian). Astron. Vestnik, **31**, 558-565.

A PRECESSION STUDY BASED ON THE ASTROMETRIC SERIES AND THE COMBINED ASTROMETRIC CATALOGUE EOC-2

C. RON[1], N. CAPITAINE[2], J. VONDRÁK[1]

[1] Astronomical Institute, Academy of Sciences of the Czech Republic
Boční II, 141 31 Prague 4, Czech Republic
e-mail: ron@ig.cas.cz, vondrak@ig.cas.cz

[2] SYRTE/UMR8630 – CNRS, Observatoire de Paris
61, avenue de l'Observatoire, 75014 Paris, France
e-mail: capitain@syrte.obspm.fr

ABSTRACT. The new star catalogue EOC-2 has been used for the new solution of Earth Orientation Parameters (EOP) from optical astrometry over the interval 1899.7-1992.0. The same procedures as in the preceding solutions (c.f. Vondrák & Ron 2000) were followed, with two exceptions: 1. The IAU 2000 model of nutation and the improved P03 model of precession (Capitaine et al. 2003) were used which led to much smaller values of the celestial pole offsets (CPO), 2. the CPO in longitude and obliquity were represented by a constant, linear and quadratic terms instead of the 5-day individual values as before. The values obtained for the linear and quadratic terms of the CPO are compared and discussed in view of a possible validation of the P03 precession model.

1. MOTIVATION

After the 2003 implementation of the new IAU 2000A precession-nutation model, a considerable effort has been devoted to improving the precession quantities. The improved P03 precession model of Capitaine et al. (2003, 2004) that is consistent with the IAU 2000A model, but with revised linear and quadratic terms, has appeared recently. The analysis of the celestial pole offsets (CPO) obtained from VLBI can be used for improving the linear terms of precession but the too short time span of VLBI data (20 years) does not allow reliable quadratic fit in the residuals between the models and observations.

On the other hand, the work on the new astrometric catalogue EOC-2 (Vondrák & Ron, 2005) culminated in providing an improved solution of Earth orientation parameters from optical astrometry over the interval 1900-1992 (Ron & Vondrák, 2004). The length of the optical observations as compared with that of VLBI incited us to use the optical astrometry data for fitting the quadratic terms to the observed celestial pole offsets. Moreover, as the correction $\delta\dot{\psi}_A$ for the rate of the IAU 1976 precession model obtained from previous solutions of Earth orientation parameters from optical astrometry was in good agreement with that derived from VLBI (Vondrák & Ron, 2000), these data appear as being appropriate for determining precession.

2. SOLUTION FOR EARTH ORIENTATION PARAMETERS REFERRED TO EOC-2

The new catalogue EOC-2 is based on the recent catalogues ARIHIP, Tycho2, and Hipparcos combined with the observations of optical astrometry. The detailed description of its construction is presented in Vondrák & Ron (2005). The reference frame of EOC-2 has no motion with respect to the so-called "astronomically excellent" stars in ARIHIP, i.e. with respect to the optical representation of International Celestial Reference System (ICRS). The new catalogue is more accurate in the long-periodic sense (namely in proper motions) than the original catalogues. The procedure followed in this study is the same as that followed in the preceding solutions of Earth orientation parameters (see Vondrák & Ron 2000), but all observations were transformed using the IAU 2000A model of nutation (Mathews et al., 2002) and the P03 model of precession (Capitaine et al., 2003). Celestial pole offsets were represented by a constant, linear and quadratic term. The following parameters were derived:

- for each 5-day interval:
  - $x\,, y$ coordinates of the pole in the terrestrial reference frame,
  - Universal time differences UT1–TAI (after 1956),
- for each instrument and the whole interval:
  - constant, linear, annual and semi-annual deviation in latitude A, A_1, B, C, D, E,
  - constant, linear, annual and semi-annual deviation in universal time A', A'_1, B', C', D', E',
  - rheological parameter $\Lambda = 1 + k - l$ governing the tidal variations of the local vertical,
- for the whole interval:
  - celestial pole offsets $\Delta\varepsilon, \Delta\psi \sin\varepsilon$, each represented by a constant, linear and quadratic term.

All observations were recalculated to be related to the EOC-2 catalogue, and in this way also to the ICRS. The observation equations lead to the system of normal equations that are singular with defect of matrix equal to 18. Therefore it is necessary to add 18 constraints tying together the parameters $A, \ldots, E'$, fixing thus the terrestrial reference frame defined by the conventional coordinates of the individual instruments (see Tab. 1) and assuring that projection of seasonal deviations to axes x, y is minimized. The solution is described in details by Vondrák et al. (1998). We used the observations of the instruments listed in Tab. 1 where the coordinates defining the terrestrial system and the secular drifts of the stations caused by the movements of the lithospheric plates derived from the model NUVEL-1 NNR (DeMets et al., 1994), are shown.

The new solution of Earth orientation parameters (called OA04a), based on 4541385 of individual star/star pair observations made with 47 instruments (merged into 40 series), yielded 16462 estimated parameters. These comprises 6702 5-day values of x and y and 2628 5-day values of UT1–TAI, that are shown in Fig. 1, 393 station parameters, 6 parameters for the celestial pole offsets and 18 Lagrange multipliers for the constraints. The average standard error of one observation is $\sigma_0 = \pm 0.191''$ and the formal errors of the estimated parameters $\sigma_x = \pm 0.017''$, $\sigma_y = \pm 0.016''$, $\sigma_{UT} = \pm 0.72$ms.

The celestial pole offsets of the solution OA04a are referred to the IAU 2000A nutation and the P03 precession; they are expressed in mas by Eq. (1) for obliquity $\Delta\varepsilon$, and Eq. (2) for longitude $\Delta\psi \sin\ \varepsilon$:

$$\Delta\varepsilon = -6.1_{\pm 0.4} + 8.2_{\pm 1.1} \times T + 2.9_{\pm 3.5} \times T^2, \tag{1}$$

$$\text{correlation coefficients} \quad \begin{array}{ccc} 1.00 & & \\ -0.56 & 1.00 & \\ -0.61 & 0.25 & 1.00 \end{array}$$

$$\Delta\psi \sin\varepsilon = -7.1_{\pm 0.4} + 27.7_{\pm 1.1} \times T + 32.3_{\pm 3.5} \times T^2 \tag{2}$$

$$\begin{array}{ccc} 1.00 & & \\ -0.58 & 1.00 & \\ -0.62 & 0.29 & 1.00. \end{array}$$

The formal errors of the estimated parameters are shown in the subscripts, T is the time elapsed since 1956 in Julian centuries. The celestial pole offsets with the confidence interval are drawn in Fig. 2.

Code	latitude φ_0	$\dot{\varphi}$	longitude λ_0	dλ	$\dot{\lambda}$	weights	
	° ' "	["/cy]	° ' "	[s]	[s/cy]	v_φ	v_T
Visual zenith telescopes							
CA	39 08 09.149	+0.061	8 18 44.0			1.32	
CI	39 08 19.438	+0.002	−84 25 00.0			1.19	
GT	39 08 13.282	+0.012	−77 11 57.0			0.93	
KZ	39 08 02.093	+0.001	66 52 51.0			0.77	
MZZ,MZL	39 08 03.706	−0.045	141 07 51.0			0.98	
TS	39 08 10.937	+0.004	63 29 00.0			0.94	
	39 08 11.301	+0.004	63 29 00.0			MJD>18512	
UK	39 08 12.141	+0.025	−123 12 35.0			0.99	
BLZ	44 48 10.456	+0.041	20 30 50.0			0.94	
BK	50 19 09.620	−0.048	127 30 00.0			1.79	
IRZ	52 16 44.381	−0.033	104 20 42.7			0.89	
POL	49 36 13.085	+0.031	34 32 52.0			0.89	
PU,PUZ	59 46 15.641	+0.034	30 19 39.0			1.10	
TT	60 24 57.517	+0.040	22 27 00.0			2.17	
VJZ	52 05 56.206	+0.041	21 00 00.0			0.70	
Photoelectric transit instruments							
IRF	52 16 44.0		104 20 42.0	−0.0086	+0.0084		0.89
KHF	50 00 00.0		36 13 58.0	+0.0054	+0.0083		0.94
NK	46 58 18.0		31 58 28.0	+0.0100	+0.0078		1.04
PUF/G/H	59 46 18.0		30 19 38.0	+0.0048	+0.0096		1.34
WHF	30 32 28.9		114 20 41.4	+0.0132	+0.0060		0.81
Photographic zenith tubes							
MZP,MZQ	39 08 02.795	−0.045	141 07 52.0	−0.0053	−0.0005	0.76	0.76
OJP	49 54 55.107	+0.044	14 47 09.0	+0.0121	+0.0072	1.30	1.45
PIP	−35 20 40.635	+0.036	−57 17 09.0	+0.0360	−0.0005	2.14	1.74
RCP,RCQ	25 36 47.038	+0.008	−80 22 56.0	+0.0020	−0.0027	1.31	1.14
WA,W,WGQ	38 55 17.224	+0.012	−77 03 56.0	+0.0014	−0.0044	1.15	0.92
MS	−35 19 17.443	+0.182	149 00 19.0	+0.0322	+0.0049	1.09	0.93
Astrolabes, Photoelectric astrolabes, Circumzenithals							$v_{\delta h}$
BJB	40 06 03.980	−0.042	116 19 40.9	+0.0038	+0.0066		0.96
BRC	48 09 17.757	+0.044	17 07 11.5	+0.0241	+0.0072		0.50
GRD	43 44 55.359	+0.049	6 55 36.0	+0.0767	+0.0063		1.19
PA	48 50 09.254	+0.051	2 20 15.7	−0.0145	+0.0063		0.89
PRE	50 04 40.030	+0.044	14 42 00.3	+0.0375	+0.0072		0.92
PRD	50 06 20.386	+0.044	14 23 20.3	+0.0368	+0.0072		0.67
PYD	49 54 55.590	+0.044	14 47 20.2	−0.0043	+0.0072		0.60
SC	−33 23 57.101	+0.058	−70 32 42.7	+0.0050	+0.0045		0.64
SIA	44 24 12.368	+0.031	33 59 48.6	+0.0113	+0.0076		0.50
SXA	34 56 43.585	−0.037	109 33 04.9	−0.0080	+0.0065		0.90
SXB	34 20 35.792	−0.037	109 08 05.0	+0.0201	+0.0065		0.65
WHA	30 32 29.152	−0.041	114 20 42.2	−0.0116	+0.0060		0.65
YUB	25 01 45.347	−0.032	102 47 41.2	−0.0536	+0.0060		1.65
ZIA	31 11 25.148	−0.045	121 25 37.6	−0.0024	+0.0059		0.79
ZIB	31 11 26.187	−0.045	121 25 39.2	+0.0003	+0.0059		1.22

Table 1: The coordinates φ_0 and λ_0 of the instruments used in the solution OA04a, referred to the mean epoch $\mathrm{MJD}_0 = 32000$ for the latitude and 43000 for the time and equal altitude observations; $\dot{\varphi}$ and $\dot{\lambda}$ are the secular drifts of the stations and v are the weights of observations used in the solution.

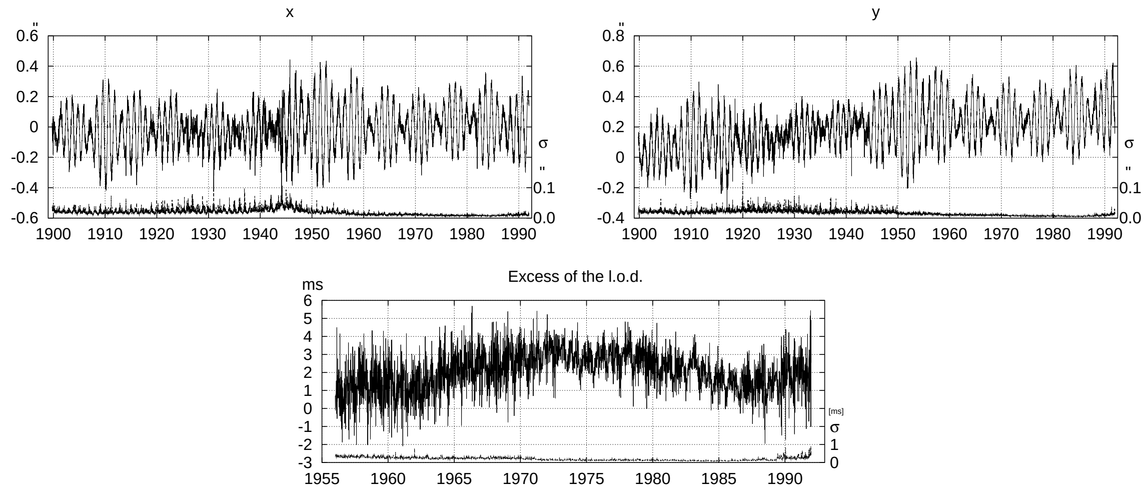

Figure 1: Solution OA04a: Polar motion x, y and excess of the l.o.d. over the nominal value 86400 s at 5-day intervals, and their standard errors. The short-periodic tidal variations in l.o.d. ($P < 35$ days) after Yoder et al. (1981) are removed.

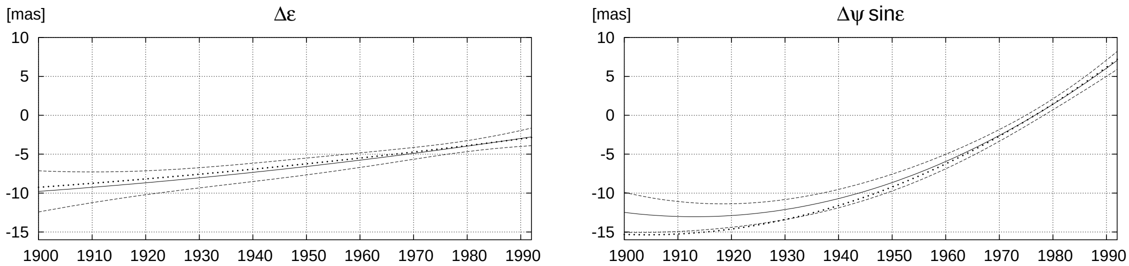

Figure 2: Solution OA04a: Celestial pole offsets in obliquity and longitude, referred to the IAU 2000A nutation and P03 precession models. The dashed curves define the 99% confidence interval. The dotted line shows the celestial pole offsets referred to the IAU 2000 precession.

We also estimated a solution referred to the IAU 2000 precession in order to check the implementation of the P03 precession into the solution OA04a. We used the same procedure and the same data with the exception of the P03 precession. The formal errors and the correlation coefficients are the same as in the solution OA04a. The values of the celestial pole offset referred to the IAU 2000 precession, drawn by the dotted line in Fig. 2, are the following

$$\begin{aligned} \Delta\varepsilon &= -5.8_{\pm 0.4} + 7.4_{\pm 1.1} \times T + 2.2_{\pm 3.5} \times T^2, \\ \Delta\psi \sin\varepsilon &= -7.5_{\pm 0.4} + 30.3_{\pm 1.1} \times T + 29.2_{\pm 3.5}. \times T^2 \end{aligned} \tag{3}$$

3. DISCUSSION

The improved P03 precession model of Capitaine et al. (2003) contains improved expressions for the motion of the ecliptic and for the contributions to precession and obliquity rates of the equator with respect to a fixed frame. The quadratic terms have been revised, due to the consideration of the secular change of the Earth's dynamical ellipticity. But the short time span of VLBI observations does not allow a reliable quadratic fit in the residuals between the models and the observations.

The celestial pole offsets from optical astrometry referred to the P03 precession and derived from the 92-year interval was at hand to determine the correction for the quadratic term of precession. The celestial pole offsets contain the inaccuracies in the P03 precession, but we have to pay attention to the inaccuracy of the link between the Hipparcos reference frame and ICRS of the order of ±0.25mas/y (Kovalevsky et al., 1997). The Hipparcos catalogue is a representation of the ICRS in the visible light range. The value of the linear term of the celestial pole offsets obtained from the optical astrometry is comparable to this inaccuracy (+0.08mas/y in case of obliquity, +0.27mas/y in case of longitude, see Eqs. (1, 2)). For that reason, it is not possible to distinguish between the real error of precession rate and a possible slow rotation of EOC-2 with respect to ICRS. Thus we cannot use the linear term for deriving the correction of the precession rate. The quadratic term in longitude from optical astrometry is improbably too big and cannot be used either for confirmation or refutation of the P03 model. The linear term could be explained by the rotation of the Hipparcos reference frame with respect to distant extragalactic objects, but the big quadratic term in longitude remains unexplained and deserves further study.

Acknowledgements. This study was supported by the grant No. IAA3003205, awarded by the Grant Agency of the Academy of Sciences of the Czech Republic (AS CR) and by the CNRS-ASRT project No. 14670 of SYRTE/Observatoire de Paris and Astronomical Institute, Prague.

4. REFERENCES

Capitaine N., Wallace P.T., Chapront J., 2003, Expressions for IAU 2000 precession quantities, A&A 412, 567–586.

Capitaine N., Wallace P.T., Chapront J., 2004, Comparison between high precision precession models for the ecliptic and equator, A&A 421, 365–379.

DeMets C., Gordon R.G., Argus D.F., Stein S. (1994) Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, Geophys. Res. Let. 21, 2191-2194.

Kovalevsky J., Lindegren L., Perryman M.A.C, et al., 1997, The Hipparcos Catalogue as a realization of the extragalactic reference system, A&A 323, 620–633.

Mathews P.M., Herring T.A., Buffet B.A., 2002, Modeling of nutation-precession: New nutation series for nonrigid Earth, and insights into Earth's interior, J. Geophys. Res. 107 (B4), 10.1029/2001JB00390.

Ron C., Vondrák J., 2004, Earth orientation parameters in 1899-1992 based on the new Earth Orientation Catalogue, In: N. Capitaine and Finkelstein (eds.) *Proc. Journées 2003*, St. Petersburg, 144–149.

Vondrák J., Pešek I., Ron C., Čepek A. (1998) Earth orientation parameters 1899.7–1992.0 in the ICRS based on the Hipparcos reference frame. Publ. Astron. Inst. Acad. Sci. Czech R. 87, 56 pp.

Vondrák J., Ron C., 2000, Precession-nutation estimates from optical astrometry 1899.7–1992.0 and comparison with VLBI results, In: K.J. Johnston, D.D. McCarthy, B.J. Luzum and G.H. Kaplan (eds.) *Towards Models and Constants for Sub-Microarcsecond Astrometry, Proc. IAU Coll. 180*, USNO, Washington, 248–253.

Vondrák J., Ron C., 2005, Combined astrometric catalogue EOC-2 – an improved reference frame for long-term Earth rotation studies, this volume.

Yoder C.F., Williams J.G., Parke M.E., 1981, Tidal variations of earth rotation, J. Geophys. Res. 86, 881–891.

THE RELATIONSHIP BETWEEN THE GLOBAL SEISMICITY AND THE ROTATION OF THE EARTH

P. VARGA[1], D. GAMBIS[2], Z. BUS[1], Ch. BIZOUARD[2]

[1] Geodetic and Geophysical Research Institute, Seismological Observatory
Budapest, Meredek u. 18. H-1112, Hungary
e-mail: varga@seismology.hu, bus@seismology.hu

[2] IERS EOP Product Center
SYRTE/UMR8630-CNRS, Observatoire de Paris
61 Avenue de l'Observatoire, 75014 Paris, France
e-mail: daniel.gambis@obspm.fr, christian.bizouard@obspm.fr

ABSTRACT. Possible relationship between seismicity and the length of day (LOD) variation was investigated for a single seismic event and in global case.

1. On the basis of a theoretical model investigation it was found, that even in case of the largest instrumentally recorded earthquakes, the amplitude of the generated LOD variation is below the associated accuracy of the observations.

2. The latitude distribution of the seismic energy and the number of the earthquakes of magnitude (M) equal or greater than seven are maximal for latitudes around 48.2°. It was shown by model calculations that this phenomenon takes place when the variation of geometric flattening of the Earth, due to the changes in rotation speed, occurs. Significant correlation was found in the course of the XXth century between the changes in LOD and the annual number of M*geqslant*7 seismic events. It is therefore likely, that the variations of LOD have some significant influence on seismic activity.

1. INTRODUCTION

The connection of the Earth rotation vector and the earthquakes up to now were firstly discussed in relation of polar motion (PM). For a review see Lambeck (1980). May 22, 1960, occurred a giant earthquake in Chile (M=9.5) from far the largest seismic event in terms of magnitude for which records exist. Study of the PM excitation caused by this event was based initially on polar motion derived from International Latitude Service (ILS) database (e.g. Slade & Yoder, 1989). For later seismic events different attempts were carried out to use space-based techniques, unfortunately for time-intervals where there was no earthquakes able of significant effects in Earth rotation, even using these most sophisticated techniques (e.g. Souriau and Cazenave, 1985; Gross 1986; Chao and Gross 1987). The second largest recorded earthquake, the Alaskan event of 1964 produced only (20-30) % of energy of the Chilean one. All earthquakes after the earthquake in Alaska produced only ∼1 % of the energy of the Chilean event. The length of day (LOD) is less affected by seismic influences. This is so first of all because the rotation energy is far the biggest component of energetic household of our planet and its yearly variation is somewhat bigger than the seismic energy annually released (Table 1). In spite of this circumstance, Chao and Gross (1995) has shown the connection of changes in the Earth's rotational energy and seismic activity. They arrived to the conclusion that the seismic activity has a tendency to increase the Earth's spin energy.

Annual variations		**Energies**	
Solar energy received	$\approx 2.1 \times 10^{24}$ J/a	Rotation energy	$\approx 2 \times 10^{29}$ J
Atmospheric circulations	$\approx 6.3 \times 10^{22}$ J/a	Earth core rotation energy	$\approx 3 \times 10^{24}$ J
Loss by heat flow	$\approx 1.0 \times 10^{21}$ J/a	Magnetic field of the core	$\approx 8 \times 10^{22}$ J
Oceanic circulations	$\approx 3.2 \times 10^{19}$ J/a	Mantle magnetic field	$\approx 4 \times 10^{18}$ J
Rotational energy	$\approx 1.6 \times 10^{19}$ J/a		
Energy of earthquakes	$\approx 9.5 \times 10^{18}$ J/a		
Vulcanic energy	$\approx 2.0 \times 10^{18}$ J/a		
Geomagnetic storms	$\approx 3.2 \times 10^{13}$ J/a		

Table 1: Energetic budget of the Earth

2. SOME BASIC INFORMATION ON THE SEISMICITY OF THE EARTH

The energy released during the unique Chilean seismic event was $1.1{\cdot}10^6$ TJ. The second and third largest earthquakes happened in Alaska (Prince William Sound 1964.03.28., M=9.2 and Andrean of Islands, 1957.03.09., M=9.1) which produced energy $4{\cdot}10^5$ TJ and 2.8·10 TJ respectively. During the history of instrumental seismology, what means practically during the XXth century, there were only 10 seismic events, which had M⩾8.5. As far as the annual distribution of the seismic events is concerned annually there is on the average one seismic event with M⩾8. The order of seismic events during a year with magnitudes 7⩽M⩽8 is 10^1, 6⩽M⩽7 10^2, 5⩽M⩽6 10^3, 4⩽M⩽5 10^4 etc. It is important to notice here that if M is increased by 1.0 the energy of the earthquake is magnified by a factor of $10^{1.5}$, i.e. approximately 32 times. The annual seismic energy release is of the order of 10^6 TJ (see Table 1). From energetic point of view it can be concluded that earthquakes with M⩾8 are responsible for the 49 % of the annual seismic energy, the events 7<M⩽7.9 for 43 % and 6<M⩽6.9 for 4 % respectively. This means that seismic events M⩾7 represents 92 % of the annual seismic energy budget.

With the use of empirical equation (Kasahara, 1981) the after shock area (A) is

$$\log A\ (\mathrm{km}^2) = 1 + 1.02 \cdot M$$

This way for

$$M = 9 \quad A = 1.5 \cdot 10^5\ \mathrm{km}^2$$

$$M = 8 \quad A = 1.4 \cdot 10^4\ \mathrm{km}^2$$

$$M = 7 \quad A = 1.4 \cdot 10^3\ \mathrm{km}^2$$

$$M = 6 \quad A = 1.3 \cdot 10^2\ \mathrm{km}^2$$

It is generally accepted in seismology that the area of aftershocks coincides with the source area.

3. SEISMOLOGICAL AND LENGTH OF DAY DATA BASES

Earthquake catalogs are primary data sources for the characterization of seismicity behaviour and testing hypotheses. The completeness and accuracy of earthquake catalogues vary in time and depend on earthquake depth and tectonic, but first of all due to density and resolution of worldwide seismograph network. One can observe monotone increase of global annual number of seismic events if the catalog consists earthquake 4.0⩽M⩽9.5 since the beginning of XXth century up to present. The list of seismic events consists in different sudden jumps of annual number of observed earthquakes. The most "dramatic" one reflects the starting of the World Wide Seismic Standard Seismograph Network in 1963. From statistical viewpoint, since about that time the list of worldwide seismic events is complete for M⩾(6.0-5.5). Recently the best catalogues are reasonably complete with the magnitude M⩾5.4. The global catalog of shallow (depth <70 km) and large M⩾7 earthquakes shown to be complete during the whole XXth century (Kagan, 2003). The seismic moment and consequently the energy release are predominantly connected to subduction zones of convergent tectonic plates. The (80-90) % of seismic moment release is connected to large shallow earthquakes. To Chile event of 1960 belong (30-45) % of the total seismic moment observed during the XXth century (Pacheco & Sykes, 1992). Due to above described situation for the purposes of present study the M⩾7 events were collected from the data base of National Oceanic and Atmospheric Administration (NOAA) almost for the whole XXth century.

The LOD data were taken form the IERS EOP CO4 record, which is given at one-day intervals. CO4 is free from tidal effects. The oscillations in UT and duration of the days due to zonal tides for periods under 35 days, as well as the fortnightly terms are present in full size in the series. The EOP (IERS) CO4 is slightly smoothed by Vondrak (1977) algorithm in order to remove the high frequency noise.

4. POSSIBLE INFLUENCE OF A SINGLE EARTHQUAKE ON THE LOD

The influence of the elastic stress accumulation or release on the LOD can be described with the use of Love-Shida theory. For our calculations it was supposed that at the surface of the Earth or at certain depth a normal stress builds up strains, which generates surface vertical displacements. For the modeling it was supposed that the Earth's mantle is elastic and has radial symmetry. The loaded spherical surface can be characterised by an angle $\Delta\alpha = \sqrt{\frac{\Delta\phi+\Delta\lambda}{\pi}}$ (ϕ and λ are the geographical coordinates) and the vertical surface displacements (D)are given in function of ψ angular distance measured from the centre of the loaded area. The theoretical details of the calculations carried out are given in Varga (1987), Varga & Grafarend (1996). For model calculations it was supposed that an anomalic normal stress with a magnitude of 10^7 N $\cdot$ m^2 (which is of the order of maximal stress drops in the case of largest seismic events) acts on spherical surfaces $10^\circ \times 10^\circ$ ($\sim 10^6$ km^2), $1^\circ \times 1^\circ$ ($\sim 10^4$ km^2) and $0.1^\circ \times 0.1^\circ$ (10^4 km^2) Calculations were performed for the surface of the Earth and for the relative depths $r/a = 0.99$, 0,98, and 0.96 (a - is the Earth's radius, r is the radial distance from the Earth's centre). It was found that the vertical displacements are occurring on areas six times bigger than the area of stress accumulation. If $\rho(r)$ is the density function the variation of the polar momentum of inertia due to the layer occupying a spherical layer of thickness D is

$$\Delta C = \int_r^{r+D} \int_{\phi_1}^{\phi_2} \int_{\lambda_1}^{\lambda_2} \rho(r) r^4 \cos^3\phi \; dr \; d\phi \; d\lambda =$$

$$= \frac{(r+D)^5 - r^5}{5} \rho(r) \Delta\lambda [(\sin\phi_2 - \sin\phi_1) - \frac{1}{3}(\sin^3\phi_2 - \sin^3\phi_1)]$$

Since $(r+D)^5 - r^5 = r^5\left[\left(1+\frac{D}{r}\right)^5 - 1\right] \approx 5r^4 D$, the ΔC can be written in the following form

$$\Delta C \approx r^4 D \rho(r) \Delta\lambda [(\sin\phi_2 - \sin\phi_1) - \frac{1}{3}(\sin^3\phi_2 - \sin^3\phi_1)]$$

If an extreme case of the load is considered (the loaded area is $1^\circ \times 1^\circ \approx 10^4$ km^2 and the vertical displacement is $D = 1.0$ cm over an area $6^\circ \times 6^\circ \approx 3.6 \cdot 10^5$ km^2) the anomaly $\Delta C = 7.80 \cdot 10^{27}$ kgm^2 gives with $C = 8.04 \cdot 10^{37}$ kgm^2

$$\Delta LOD = LOD \cdot \frac{\Delta C}{C} \approx 8 \text{ microseconds}$$

Due to the fact that the accuracy of the ΔLOD observations is ~ 10 microseconds it can be concluded that the seismic events are not able to produce any realistic, observable changes in LOD. To similar conclusion arrived, on the basis of modeling viscoelastic Earth, in case of PM Soldati & Spada (1999) and Soldati et al (2001).

5. TEMPORAL DISTRIBUTION OF PLANETARY SEISMICITY AND VARIATIONS OF LOD

The despinning of the acceleration of the angular rotation of the Earth modifies the flattening of the Earth. Amalvict and Legros (1996) have derived sets of formulae for incremental lithospheric stresses. Their results confirm and extend earlier results of Melosh (1977) and express the variation of stress tensor components due to angular speed induced geometrical flattening variations Δf:

Meridional stress	$\sigma_{\phi\phi} = -\frac{\mu \Delta f}{11}(5 - 3\,cos\,2\phi)$	
Azimuthal stress	$\sigma_{\lambda\lambda} = \frac{\mu \Delta f}{11}(1 + 9\,cos\,2\phi)$	(μ is the sheer modulus)
Stress difference	$\Delta\sigma = \sigma_{\phi\phi} - \sigma_{\lambda\lambda} = -\frac{\mu \Delta f}{11}(6 + 6\,cos\,2\phi)$	

It is important to mention that the stress pattern described by above equations is symmetric to the equator and has inflection points around $\phi = 45^\circ$ (the critical latitude is 48.2°), where the stress derivatives along ϕ - which are proportional to the corresponding force components F_ϕ and F_λ - have their maxima. This phenomenon - related to ΔLOD - should be expressed in the seismicity of the Earth. The latitude distribution of the number of M⩾7 earthquakes (Fig.1) have maxima close to the critical latitudes 48.2°. (In the southern hemisphere the maximum is missing because the most of the significant seismic regions of the world are in the northern hemisphere).

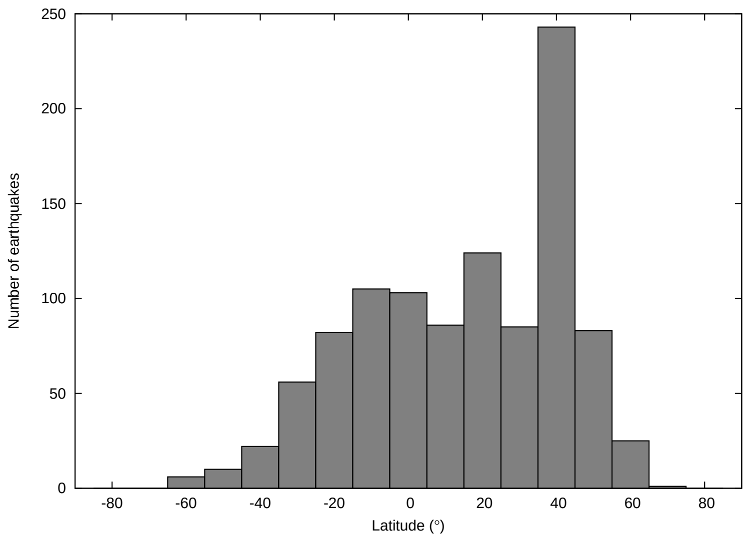

Figure 1: Distribution of M⩾7 earthquakes along the latitude.

Table 2. shows latitude dependence of seismic energy calculated from surface wave magnitudes (M⩾7.5) for the time interval 1950-2000. It can be concluded that the seismic energy is predominantly connected with shallow focus events.

Latitude - $\phi(°)$	Total seismic energy (in 10^{18} Joule)	Events with intermediate[1] and deep[2] focus (in 10^{18} Joule)	Events with shallow[3] focus (in 10^{18} Joule)
0	2.40	0.41	1.99
15	2.16	0.42	1.74
30	2.29	0.68	1.61
45	2.74	0.27	2.47
60	1.64	0.09	1.55
75	0.00	0.00	0.00
Total	11.230 (100%)	1.87 (16.7%)	9.36 (83.3%)

Table 2: Distribution of seismic energy along latitude for 1950-2000 (earthquakes M⩾7.5).

Practically no seismic events M>7.5 occurs above the latitudes $\phi > 65°$. Between $\phi = \pm 50°$ and the poles only shallow focus great seismic events were observed. And - what is the most important for the research described in present study - the earthquake energy release has maximum at the critical latitudes $\phi = \pm 48.2°$. This way it can be concluded that the seismicity of the Earth- through the stress variations caused by changes in rotation speed- is related to the ΔLOD. Fig.2. shows the LOD variations and the yearly number of the earthquakes with M⩾7.0 on the basis of the NOAA earthquake catalogue.

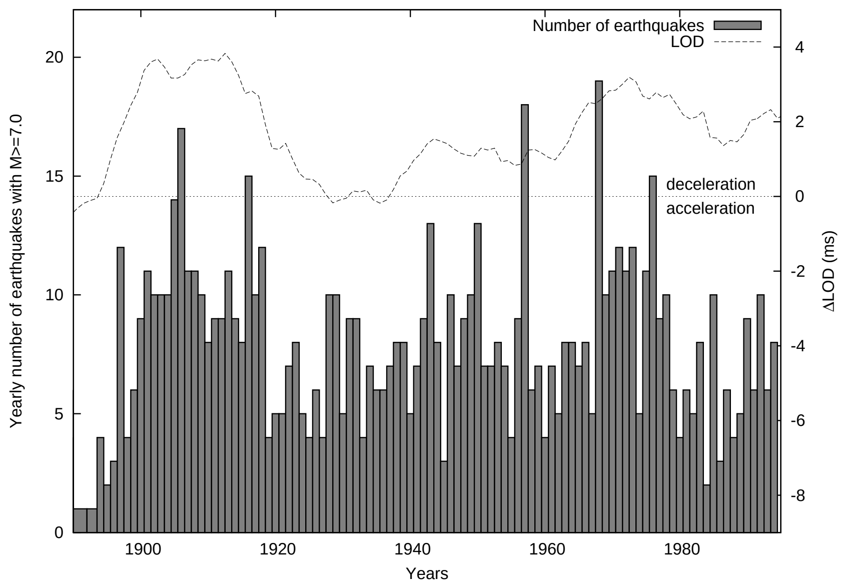

Figure 2: Annual number of seismic events M⩾7 and the LOD variations during the XXth century.

The correlation during the XXth century between these two phenomena was well expressed:

[1]Intermediate earthquakes (hypocentral depth between 70 and 300 km).
[2]Deep earthquakes (depth>300 km).
[3]Shallow earthquakes (depth<70 km).

when the axial rotation decelerates the annual number of M$\geqslant$7 earthquakes has its maximum.

6. CONCLUSIONS

With the use of model calculations, it was found that a seismic event (even the biggest one) is not able to influence the rotation speed of the Earth. The variation of rotation speed through stress caused by the corresponding flattening variations is related to the longitudinal distribution of seismicity and seismic energy. It is likely that the seismicity does not generate ΔLOD anomalies. On contrary: the variations of LOD have influence on seismic activity. This fact is expressed by the correlation between the annual number of the earthquakes with M$\geqslant$7 and LOD.

Acknowledgments. This research was completed in the frame of French-Hungarian bilateral project "Relationship between seismicity and variations in Earth rotation". The Hungarian co-authors enjoyed support of the Hungarian Scientific Research Found in the frame of the project OTKA 038123 "Complex study of the Earth rotation".

7. REFERENCES

Amalvict M., Legros H., 1996: Stresses in the lithosphere induced by geophysical processes of degree two. Manuscripta Geodaetica, 16, 333-352.

Chao B.F., Gross R.S., 1987: Changes in the Earth's rotation and low-degree gravitational field induced by earthquakes. Geophysical Journal of the Royal Astronomical Society, 91, 569-596.

Chao B.F., Gross R.S., 1995: Changes in the Earth's rotational energy induced by earthquakes, Geophysical Journal International, 122, 776-783.

Gross R.S., 1986: The influence of earthquakes on the Chandler wobble during 1977-1983. Geophysical Journal of the Royal Astronomical Society, 85, 161-177.

Kagan Y.Y., 2003: Accuracy of modern global earthquake catalogs. Physics of the Earth and Planetary Interiors, 135, 2-3, 173-209.

Kasahara, K., 1981: Earthquake mechanics, Cambridge University Press.

Lambeck K., 1980: The Earth's variable rotation: geophysical causes and consequences. Cambridge University Press.

Melosh H.J., 1977: Global tectonics of a despin planet. Icarus, 31, 221-243.

Pacheco J.F., Sykes L.R., 1992: Seismic moment catalog of large shallow earthquakes, 1900 to 1989. Bulletin of the Seismological Society of America, 83, 3, 1306-1349.

Slade M.A., Yoder C.F., 1989: 1960: Chile: new estimate of polar motion excitation, Geophysical Research Letters, 16, 10, 1193-1196.

Soldati, G., Boschi L., Piersanti A., Spada G., 2001: The effect of global seismicity of the polar motion of a viscoelastic Earth. Journal of Geophysical Research, 106, B4, 6761-6767.

Soldati G., Spada G., 1999: Large earthquakes and Earth rotations the role of mantle relaxation. Geophysical Research Letters, 26,7, 911-914.

Souriau A., Cazenave A., 1985: Reevaluation of the Chandler wobble seismic excitation from recent data. Earth and Planetary Science Letters, 75, 410-416.

Varga P., 1987: Influence of the elastic stress accumulation on the Earth's pole position. Proceedings of the International symposium, "Figure and Dynamics of the Earth, Moon and Planets, Prague, 513-524.

Varga P., Grafarend E., 1996: Distribution of the lunisolar tidal elastic stress tensor components within the Earth's mantle. Physics of the Earth and Planetary Interiors, 96, 285-297.

Vondrak J.: 1977: Problem of smoothing of observational data. Bulletin of the Astronomical Institute of Czechoslovakia, 28, 84.

EARTH ROTATION AND GLOBAL DYNAMIC PROCESSES - JOINT RESEARCH ACTIVITIES IN GERMANY

J. MÜLLER[1], H. KUTTERER[2], M. SOFFEL[3]

[1] Institut für Erdmessung
University of Hannover, Schneiderberg 50, 30167 Hannover, Germany
e-mail: mueller@ife.uni-hannover.de

[2] Geodätisches Instiut
University of Hannover, Nienburger Str. 1, 30167 Hannover, Germany
e-mail: kutterer@gih.uni-hannover.de

[3] Lohrmann observatory, Institute for Planetary Geodesy
Dresden University of Technology, 01062 Dresden, Germany
e-mail: soffel@rcs.urz.tu-dresden.de

ABSTRACT. An extended project has been defined and proposed to the German Research Foundation (DFG), in order to organize joint research in "Earth rotation and global dynamic processes" in Germany. Funding for about 10 related sub-projects (with 12 co-workers) is envisaged. The main objective of this coordinated project is to describe and explain the physical phenomena which contribute to the variations of Earth rotation. Interactions and couplings of the various sub-systems shall be taken into account to a much higher extent than in previous studies. The contributions of various groups and scientific disciplines enable a comprehensive and integral treatment of Earth rotation as well as a dedicated study and analysis of the dynamic processes involved. This paper gives an overview about the planned research activities and the actual status of the project.

1. INTRODUCTION

For Earth rotation research, the Earth is considered as a complex system of interacting dynamic components. The variations of Earth rotation are global and integral indicators of ongoing changes in the dynamics of the Earth, both for the redistribution of masses inside and outside the Earth and for mass motions like wind and ocean currents. The most important interactions and interrelations are shown in Figure 1. A variety of relevant dynamic processes has direct or indirect effects. The interactions between the individual processes are highly complex. As the research area is rather wide, relevant scientific improvements can only be expected by the collaboration of different scientific fields such as geodesy, geophysics, meteorology and oceanography, and through close clustering of modelling, observation and data processing techniques. For this reason the existing competences in Germany are brought together. They are coordinated with further national and international research activities in neighbouring fields in an optimal way.

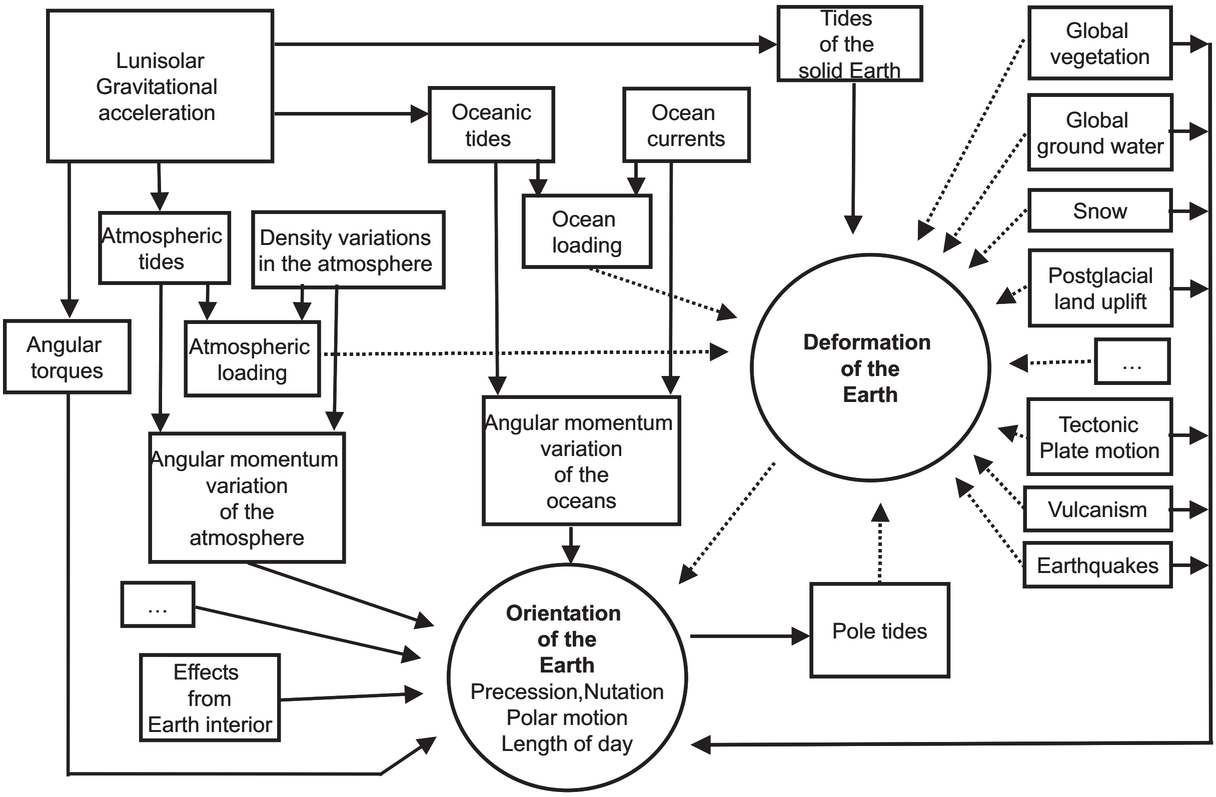

Figure 1: Components und influences in the Earth system with relevance to Earth rotation (Source: Schuh et al., 2003). Direct influences of dynamic processes on the Earth rotation are indicated by solid lines, indirect influences which are affected by the deformation of the Earth by dashed lines.

2. OBJECTIVES AND SPECIAL INTERESTS OF THE RESEARCH PROJECT

The particular importance of this research project is the integral treatment of Earth rotation based on existing or new observation data. Herein the interaction of modelling and data processing plays an important role. This integral treatment is only possible within the envisaged research unit using the demonstrated spectrum of competences. Comprehensive consistency is the key issue. The components of the Earth system which are relevant for Earth rotation as well as their coupling and interaction will be modelled consistently, covering time scales of some hours up to decades and longer. Furthermore, a new net-based information and communication system (ERIS) will be established which shall be used as a research tool. Standards and interfaces required for the research work will also be defined here.

The scheduled projects will provide significant contributions to outstanding international activities such as the project GGOS (Global Geodetic Observing System) which has been established and coordinated by the International Association of Geodesy (IAG). GGOS will support the analysis and interpretation of all geodetic methods for observing the Earth system. The consistent modelling as well as the combination and integration of the various observation methods therefore present important efforts to global geodesy.

3. THE RESEARCH UNIT

The research unit consists of highly competent scientists and institutions from geodesy, geophysics, meteorology and oceanography. The group comprises experts of observation techniques, data processing/analysis and in particular modelling, the central aspect of the scheduled project. Some of them have already contributed to bundle projects in the field of Earth rotation. On the side of the observation techniques, the modelling of those methods has to be improved which have not reached the required sub-cm level of accuracy (mostly LLR). In modelling it is important to cover all components which are relevant for the description of the Earth system with respect to Earth rotation and for a better understanding of global dynamic processes. Considering the German research institutions, a number of university groups and several non-university institutions have to work together in order to achieve the aspired objectives (see Table 1). Furthermore, there exist cooperations with external partners as well as personal and institutional engagements in national and international scientific projects, programs and services like, e.g., the IERS, IGS, IVS, ILRS and others.

Institutions	Contributing Scientists
Geodesy	
Bundesamt für Kartographie und Geodäsie BKG Frankfurt	B. Richter, T. Klügel
Deutsches Geodätisches Forschungsinstitut DGFI, München	H. Drewes, D. Angermann
Forschungseinrichtung Satellitengeodäsie FESG, TU München	M. Rothacher, U. Schreiber
Geodätisches Institut GIUB, Universität Bonn	A. Nothnagel
Geodätisches Institut GIH, Universität Hannover	H. Kutterer
Institut für Erdmessung IfE, Universität Hannover	J. Müller
Institut für Geodäsie und Geophysik IGG, TU Wien	H. Schuh, R. Weber
Institut für Planetare Geodäsie IPG, TU Dresden	M. Soffel, S. Klioner
Meteorology	
Institut für Meteorologie IfM, Freie Universität Berlin	U. Ulbrich, P. Nevir, G. Leckebusch
Oceanography	
Alfred-Wegener-Institut für Polar- und Meeresforschung AWI, Bremerhaven	J. Schröter
Institut für Planetare Geodäsie IPG, TU Dresden	M. Thomas
Geophysics	
GeoForschungsZentrum GFZ, Potsdam	H. Greiner-Mai

Table 1: Participating scientists and institutions, divided into the respective disciplines

The expected benefit of the research unit is manifold. The individual sub-groups contribute with their corresponding competences. The cooperation within the envisaged research unit furthermore enables numerous synergetic effects through exchange of results and products as well as their mutual check through analyses and validations, respectively. The individual projects cover the following topics:

1. Earth Rotation Information System: Development of a virtual Earth rotation system for geodetic and geoscience applications (ERIS) (BKG, IPG);
2. Earth rotation and the ocean's circulation (AWI, IPG);
3. Consistent post-Newtonian nutation series of a "rigid" Earth model (IPG);
4. Mass motions in the Earth's core and mantle and their influence on polar motion and the gravity field (GFZ);

5. Lunar Laser Ranging: Consistent modelling for geodetic and scientific applications (IfE, FESG);

6. Integration of Earth rotation, gravity field and geometry using space geodetic observations (DGFI, FESG);

7. Modelling of episodic-transient signals in measurements of large ring lasers (FESG, BKG);

8. Investigation of sub-daily and episodic variations of Earth rotation (IGG, FESG, GIUB);

9. Usability of time-variable Earth orientation parameters and gravity field coefficients from satellite missions for mutual validation and combined analysis (GIH, IfE);

10. Long-term ERP time series as indicator for global climate variability and climate change (IfM, IPG).

The network of the individual projects is shown in Figure 2. There exists a close relationship and interaction between almost all projects, where ERIS serves as structural and scientific interface. Further details about the individual projects or the whole research unit can be obtained from the authors.

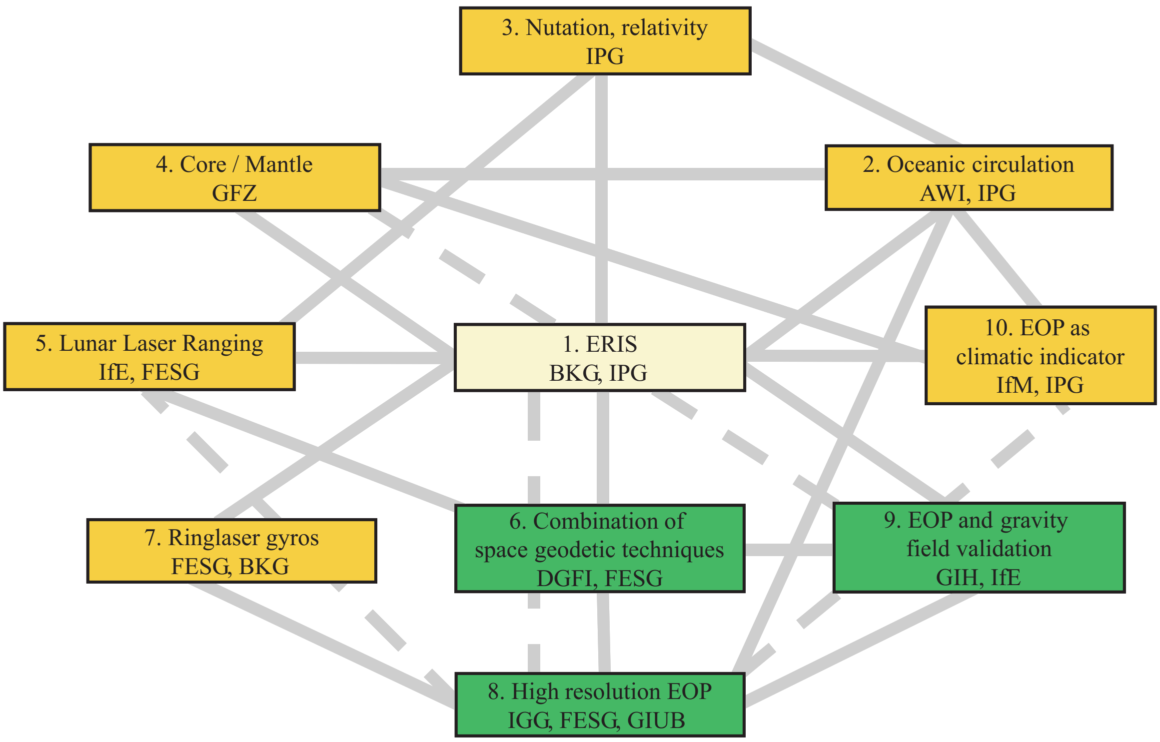

Figure 2: Network of individual sub-projects. The colours indicate the contributions of the projects to the fields of modelling (brown) and data processing/analysis (green). The information and communication system ERIS serves as a structured interface for all sub-projects.

4. EXPECTED RESULTS

The results can widely be discussed and analysed by means of comprehensive scientific exchange through several communication channels. Thus, a management system of high quality can be set up and consequently be realized.

In the same way as the overall goals (section 2), the expected results contribute to modelling as well as data processing and analysis. The main scientific results, which are expected within a medium time interval and which will be of high international interest, will briefly be outlined. It is expected to achieve improvements in modelling, both for the individual sub-systems of the Earth system (hydrosphere, atmosphere, ...) and for the description of the interaction between them. Thereby the interpretation of EOP data becomes more transparent, e.g. of the sub-daily, but also of the long-term parts of the signals. Modelling will be extended, e.g. with respect to the anthropogenic induced climate variations or climate prognoses. Especially in these fields, a lot of scientific results can be transferred to the service sector and support the monitoring systems of global Earth observation programs like GMES (Global Monitoring for Environment and Security). Furthermore, the Earth rotation models will be embedded in a more consistent manner into Einstein's theory of gravity.

5. STATUS AND OUTLOOK

A joint research activity covering "Earth rotation and global dynamic processes" has been set up. The overall goal of this research project is the integral and inter-disciplinary treatment of Earth rotation, where the interaction of modelling and data processing, based on existing or new observation data, plays an important role. All dynamic processes affecting Earth rotation, including their interactions, shall be considered. Time scales of some hours up to decades and longer will be covered.

The project has been proposed as a so-called 'research unit' to the German Research Foundation (DFG) for funding. The pre-evaluation in 2004 was positive, so that full proposals were prepared and submitted to the DFG at the end of 2004. If the research unit will now be evaluated sucessfully, the start of the work in the projects is planned for the mid of 2005.

6. REFERENCES

Schuh, H., R. Dill, H. Greiner-Mai, H. Kutterer, J. Müller, A. Nothnagel, B. Richter, M. Rothacher, U. Schreiber und M. Soffel (2003): Erdrotation und globale dynamische Prozesse. Stand und Ziele der Modellbildung, der Mess- und der Auswerteverfahren. Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Band 32, Frankfurt/Main.

A MODEL AND PREDICTION OF EARTH'S POLE MOTION

L.D. AKULENKO[1], S.A. KUMAKSHEV[1], Y.G. MARKOV[2]

[1] Institute for Problems in Mechanics
pr. Vernadskogo 101-1, Moscow, 119526, Russia
e-mail: kumak@ipmnet.ru

[2] Moscow Aviation Institute
Volokolamskoe sh. 4, Moscow, 125872, Russia

Perturbed rotatory/oscillatory motions of Earth under the action of the gravitational forces due to Sun and Moon are studied. In this study, Earth is regarded as a linear viscoelastic body. It has been established that the excitation of oscillations of the poles (more precisely, the vector of angular velocity of Earth in the Earth-fixed reference frame) has a tidal nature and can be accounted for by the rotatory/translatory motion of the Earth-Moon baricenter about Sun [1, 2]. It is shown that basic characteristics of these oscillations are rather stable and do not change during time intervals that substantially exceed the precession period of Earth's axis. Using methods of celestial mechanics, we construct a simple mathematical model governing these oscillations. This model involves two frequencies (natural (Chandler's) frequency and yearly frequency) and provides predictions that agree with IERS astrometric data. The parameters of this model were identified on the basis of the spectral analysis of the IERS data and least squares method. Using this model, we obtained statistically reliable interpolation data for time intervals from several months to 15–20 years. For the first time, a high-precision prediction of the motion of the poles for a term of 0.5 to 1 year and a fairly reliable 1 to 3 year prediction are presented. These predictions have been validated by observations during several recent years. The results obtained are of great importance for geodynamics and celestial mechanics, as well as for applications in astrometry, navigation, and geophysics.

Analysis of the power spectrum density of the oscillations shows that the Chandler and annual components are the basic ones. The motion of the pole on considerable time intervals ($\tau \sim 10 - 15$ years) can be represented by the expressions

$$x(\tau) = c_x - a_x^c \cos 2\pi N\tau + a_x^s \sin 2\pi N\tau - N d_x^c \cos 2\pi\tau - d_x^s \sin 2\pi\tau \equiv (\xi, f_\xi),$$

$$y(\tau) = c_y + a_y^c \cos 2\pi N\tau + a_y^s \sin 2\pi N\tau - N d_y^c \cos 2\pi\tau + d_y^s \sin 2\pi\tau \equiv (\eta, f_\eta),$$

$$N = 0.845 - 0.850, \quad c_{x,y} = c_{x,y}^0 + c_{x,y}^1\tau + \ldots; \quad \tau = \tau_i, \quad i = 1, 2, \ldots, i^*,$$

where the term $c_{x,y}$ account for slow trend. On short time intervals ($\tau \leq 6$ years), these coefficients can be considered constant ($c_x \approx 0.03''$, $c_y \approx 0.33''$) or linearly dependent on τ. The unknown parameters c^0, c^1, $a^{c,s}$, $d^{c,s}$ for x and y, i.e., the vectors ξ and η and the Chandler frequency N can be identified on the basis of the dispersion analysis by means of least squares. The basis functions f_ξ and f_η involve polynomial and trigonometric components. The choice of these function depends on the purpose of the utilization of the model, specifically, whether this model is utilized for the interpolation or prediction of the motion on short, medium or long

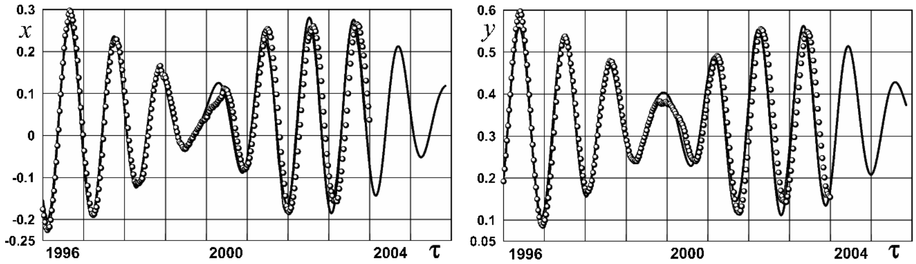

Figure 1: Eight-year (1996–2003) interpolation and 2-year (2004–2005) prediction; the dots correspond to IERS data

time intervals. It should be noted that the coefficients $a_{x,y}^{c,s}$ and $d_{x,y}^{c,s}$ are not independent. The relationship between these coefficients is determined by the structural properties of the model. In the beginning of 2004, we constructed a 6-parameter interpolation of the pole motion ($x(\tau)$ and $y(\tau)$) for an 8-year time interval (1996–2003). On the basis of this interpolation, we gave a 2-year prediction (up to the end of 2005). These results are shown in Fig. 1, where the dots correspond to IERS data. Note that during a period of 1999–2000, abnormal oscillations of the pole accounted for by the parade of planets were observed. This perturbation affected the accuracy of the prediction. Figure 2 presents a segment of the prediction for 2004 (smooth curve)

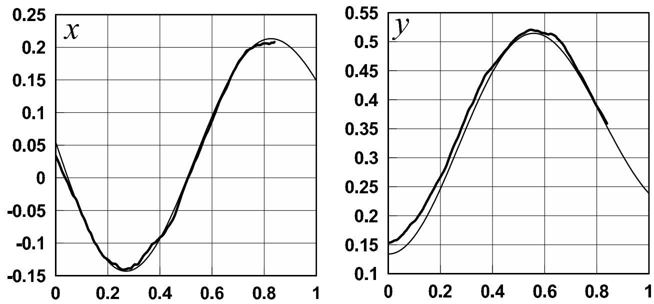

Figure 2: Comparison of the prediction for 2004 with the measurements from January 1 to November 2, 2004.

and the actual motion of the pole on the interval from January 1 to November 2, 2004 (thin irregular curves). A comparison of these curves shows that the prediction provides acceptable degree of accuracy (the maximum error does not exceed $0.02''$ or 60 cm).

A short-term prediction (≤ 0.5 year) with an appropriate interpolation depth enables one to attain higher accuracy ($0.005''$ or 15 cm) on the basis of the 5-parameter model in which c_x^1 and c_1^y are equal to zero. The prediction error in this case coincides in order of magnitude with the perturbing influence of the Moon and some other tidal torques the frequency of which is higher than those taken into account in the model. The further increase of the accuracy of the theoretical and computational models requires a broader frequency spectrum and more precise IERS data to be utilized.

REFERENCES

Akulenko L.D., Kumakshev S.A., Markov Yu.G., 2002, Motion of the Earth's Pole, *Doklady Physics*, **47**, N 1, 78-84.

Akulenko L.D., Kumakshev S.A., Markov Yu.G., and Ryhlova L.V., 2002, Forecasting the Polar Motions of the Deformable Earth, *Astronomy Reports*, **46**, N 10, 858-865.

A METHOD FOR ACCURACY AND EFFICIENCY'S INCREASE OF GEODETIC-ASTRONOMICAL DETERMINATION OF THE VERTICAL'S DEVIATION

O. BĂDESCU[1,2], P. POPESCU[2], R. POPESCU[2]

[1] Technical University of Civil Engineering, Faculty of Geodesy
B-dul. Lacul Tei, no.124, sect.2, Bucharest, Romania
e-mail: octavian@aira.astro.ro

[2] Astronomical Institute of the Romanian Academy
Str. Cuţitul de Argint, no. 5, sect. 4, RO-040558 , Bucharest, Romania
e-mail: petre@aira.astro.ro, pradu@aira.astro.ro

ABSTRACT. In this paper an algorithm for the simultaneous and at the same time rigorous determination of the astronomical coordinates is described: the latitude, longitude and astronomical azimuth, by means of an universal device (total electronical station). We have taken as a basis the azimuthal and zenithal angular observations for a large number of stars, uniformly distributed on the celestial sphere, without using observation ephemeredes. Through the introduction of an adequate matrix of weights, the unequal weights of all direct measurements are taken into account: the angular measurements and times at the chronometer. By applying the theory of conditional measurements with unknowns, we obtain one rigorous algorithm for the determination with maximum efficiency of all three fundamental elements of astronomical geodesy. This is the typical case of different accuracy measurements, in which the weights provide uniformity to the final accuracy of the results and to their coherence. It is important to remark that the determination of the three fundamentals elements of the astronomical geodesy, with accuracy and rapidity, is a present problem in the context of GPS technology, as a method of detail studying of both the geoid and the deviation of the geoid from the adopted reference ellipsoid.

1. EQUATION OF OBSERVATION AND THE PROCESSING

The azimuthal observation equation of the star, results from the star's positional triangle, is a conditional equation of the following form:

$$\underline{\mathrm{F}} = \sin \mathrm{H} \cot \mathrm{A} + \cos\varphi \tan\delta - \sin\varphi \cos \mathrm{H} = 0 \tag{1}$$

The unknowns are $d\varphi$, $d\lambda$, du, corrections of initial values (approximate values) φ°, λ°, u°, respectively the astronomical latitude, astronomical longitude and south azimuth of the zero direction of the azimuthal circle. The observed zenithal equation of the star results from the star's positional triangle and it is a conditional equation too, of the following form:

$$\overline{\mathrm{F}} = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos \mathrm{H} - \cos \mathrm{z} = 0 \tag{2}$$

The unknowns are dφ, dλ, corrections of initial values $\varphi°$, $\lambda°$, respectively the astronomical latitude and astronomical longitude. In the above relations, H is the hour angle of the star at the moment t of azimuthal or zenithal observation. α and δ are the computed right ascension and declination of the star at the time of observation. A right rigorous mathematically process of both types of observations (azimuthal and zenithal) is obtained by including them into a single relations system conditional measurements with unknowns from which an unique vector **X** of the three unknowns (dφ, dλ, du) results, under the condition of the minimum [PVV] = min. (P represents the weights of direct measurements, V is the corrections of the measured values). Briefly, one star azimuthally observed, provides one conditional equation of form (1). Next, the same star zenithally observed, provides one conditional equation of form (2). It can be noticed that each observed star generates two conditional equations.

Astronomical vertical deviation reported to WGS 84	Number of observations (nights)					
	I	II	III	IV	V	VI
ξ''	9.985	10.934	10.081	10.216	10.383	10.547
s_ξ	1.008	0.693	0.931	0.945	0.769	0.302
η''	4.981	4.848	5.604	4.924	4.824	4.736
s_η	1.008	0.693	0.941	0.874	0.801	0.329
$\theta'' = (\xi^2 + \eta^2)^2$	11.158	11.961	11.534	11.341	11.448	11.561
s_θ	1.008	0.693	0.933	0.946	0.793	0.307

Table 1: Notations: ξ - component in meridian of the astronomical vertical deviation; s_ξ - standard deviation of ξ; η - component in the prime vertical of the astronomical vertical deviation; s_η - standard deviation of η; θ - total astronomical vertical deviation; s_θ - standard deviation of θ.

2. RESULTS

Table 1 gives the values of the astronomical vertical deviation referred to the WGS ellipsoid. Further, we intend to improve this method by using a CCD camera adapted to the optical system of LEICA TC2002, a GPS time receiver and eventually another set of weights. We will also try to fully automate the method by writing a software (under the Linux operating system) that provides the value of the vertical astronomical deviation in real time.

This method was tested at Bucharest Technical University of Civil Engineering, by means of a LEICA TC2002 total electronically station. The astronomical pilaster situated on the roof of the Faculty of Geodesy was stationed, and 6 nights of observations were made.

3. REFERENCES

Archinal B.A., Explanatory Supplement to the Astronomical Almanac, Chapter 4 Terestrial coordinates and the rotation of the Earth, University Science Books, Mill Valley, California, USA, 1992

Popescu R., Paraschiv P., "Processing of CCD Astrometric observations with the Bucharest Astrolabe", Publications of the Astronomical Observatory of Belgrade, No.60, 110-113, 1998

WILD TC2002 - Mode d'emploi, Leica AG, CH 9435 Heerbrugg, Suisse, 1993

IMPLEMENTATION OF NEW MODELS FOR EARTH ROTATION IN DATA ANALYSIS AT THE UKRAINIAN CENTRE OF DETERMINATION OF THE EOP

O.V. BOLOTINA
Main Astronomical Observatory NASU
Akad. Zabolotnoho Str. 27, Kiev, Ukraine, 03680
e-mail: olga@mao.kiev.ua

ABSTRACT. In our paper new realization of the Ukrainian Centre of Determination of the Earth Orientation Parameters (UCEOP) is presented. History and purpose of the creation of the UCEOP are given. Structure of Ukrainian Centre of Determination of the Earth Orientation Parameters is described. Ukrainian Space Geodynamics Networks are presented. Analytical Centre of the UCEOP is described.

1. HISTORY AND PURPOSES

Ukrainian Centre of Determination of the Earth Orientation Parameters (UCEOP) was founded in 1998 in the Main Astronomical Observatory of the National Academy of Sciences of Ukraine, Kiev, Ukraine. It was created under support of the State Program 1995-1999/2000-2003. Prof. Yaroslav Yatskiv was the founder and Senior Research Scientist Alla Korsun' was the first leader of the UCEOP (1995 - 2003). Since 2003 Senior Research Scientist Olga Bolotina is the manager of the UCEOP.

The purposes of the creation of the Ukrainian Centre of Determination of the Earth Orientation Parameters are coordination and technical support of activities of the Ukrainian Space Geodynamics Networks, creation of the geodynamics information databases, analysis of the geodynamical information for solving the problem of the basis coordinate-time provision of Ukraine.

2. STRUCTURE OF THE UCEOP

UCEOP coordinates the activities of GPS, SLR and VLBI Ukrainian Space Geodynamics Networks.

Ukrainian GPS Network is presented by nine permanent GPS stations. Five of them, Kiev/Golosiiv, Uzhgorod, Lviv, Poltava, Mykolaiv are members of International GPS Service (IGS) Network and EUREF Permanent GPS Network (EPN). Two stations, Kharkiv and Evpatoria, are candidates to the members of EPN. Permanent GPS station Simeiz is a member of Mediterranean GPS Network. Permanent GPS station Alchevsk is a new station of the Ukrainian GPS Network.

Ukrainian SLR Network includes four permanent SLR stations Golosiiv-Kiev, Lviv, Simeiz, Katzively. All of them are registered in International SLR Service (ILRS).

Ukrainian VLBI Network is presented by only one active station CRIMEA. Station is a member of the International VLBI Service (IVS).

Analyzing of geodynamical is performed in the frame of the UCEOP. The Analytical Centre of the UCEOP includs GPS, SLR and VLBI Data Analysis Centres.

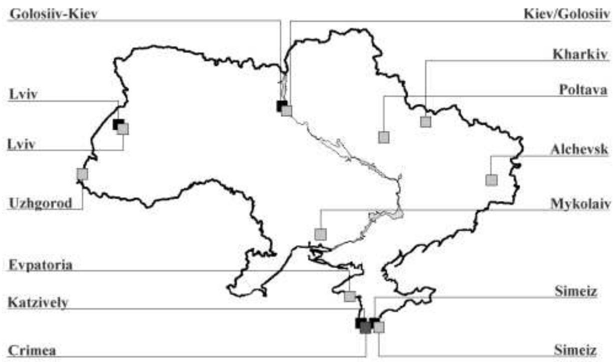

Figure 1: Ukrainian Space Geodynamics Networks

The primary interests of UCEOP Data Analysis Centres are softwares developing, data analysis of the GPS, SLR and VLBI observations, archiving the observations for local needs, controlling of the Ukrainian permanent GPS, SLR and VLBI Networks, management of local GPS campaigns in Ukraine.

The GPS Data Analysis Centre controls and supports the Ukrainian permanent GPS stations Kiev/Golosiiv, Uzhgorod, Kharkov, Evpatoria, as well as supports Operational Data Centre for providing data management for Ukrainian permanent GPS stations (expect stations Lviv and Simeiz), Local GPS Data Centre, and management and analysis of local GPS campaigns in Ukraine. Data from Ukrainian permanent GPS stations are sending automatically to the GPS Data Analysis Centre for archiving and analysis. Softwares BERNESE ver. 4.2 and GAMIT/GLOBK ver.10.1 are used for GPS data analysis in the UCEOP. Since December 16, 2003 regular weekly GPS data processing have been started.

The SLR Data Analysis Centre controls and supports of the Ukrainian SLR Network. This one controls quality of the observation data as well as provides analysis data to the Ukrainian SLR stations. Data from Ukrainian SLR stations are sent to the SLR Data Analysis Centre for archiving and analysis. Unique Kiev-Geodynamics software is used for SLR data analysis. Models and methods recommended by IERS Conventions 1996 and 2000 are realized in the Kiev-Geodynamics software.

The primary interests of the VLBI Data Analysis Centre is software developing. The unique SteelBreeze ver.2 software is used for geodetic VLBI data analysis. SteelBreeze software makes Least Square estimation of different geodynamical parameters with the Square Root Information Filter (SRIF) algorithm. The SRIF uses the Householder's transformation for matrix triangularization that makes it fast and insensitive for computer roundoff. The SRIF also makes possible to introduce the stochastic model for parameter estimation. The SteelBreeze software analyses the VLBI data of single and multiple set of sessions. The time delay is modelled according to the IERS Conventions 2003. Additional models can be used also. Various investigations on the stability of the Celestial Reference Frame have been carried out. Studies of variations of tropospheric zenith delays and comparing of GPS- and VLBI-derived zenith delays have been performed. Now, an analysis of time variations of Love and Shida numbers is conducted. Since November 2003 regular weekly EOP determinations from VLBI data processing have been started. A collection of all available VLBI observations are kept in the local archives.

Acknowledgments. The work was supported by the INTAS Infrastructure Actions Autumn 2003 Ref. Nr 03-59-11 and UNESCO-ROSTE grants Nr #8756974, 2003. Author gratitudes to Dr. Sergei Bolotin and Dr. Oleg Khoda for attention and support. Author gratitudes to Journees2004 Organizing Committee for financial support.

EARTH ROTATION AND VARIATIONS OF THE GRAVITY FIELD, IN THE FRAMEWORK OF THE “DESCARTES-NUTATION” PROJECT

G. BOURDA
SYRTE - UMR8630/CNRS, Observatoire de Paris
61 avenue de l’Observatoire - 75014 Paris, FRANCE
e-mail: Geraldine.Bourda@obspm.fr

1. INTRODUCTION

In this study, we investigate the links between Earth Orientation and Gravity Field Variations, on the basis of real gravity field data. The masses distributions inside the Earth govern the behaviour of the rotation axis in space (precession-nutation) and in the Earth (polar motion), as well as the Earth rotation rate (or equivalently, length of day). These distributions of masses can be measured by space owing to artificial satellites, the orbitography of which provides the Earth gravity field determination. Then, the temporal variations of the Earth gravity field can be related to the variations of the Earth Orientation Parameters (EOP) (with the Inertia Tensor).

Nowadays, the Earth orientation measurements in space, obtained with Very Long Baseline Interferometry (VLBI), have a precision better than the milliarcsecond level. It is then necessary to consider all the geophysical sources that can improve the models precision. The goal of my PhD Thesis was to use the Earth gravity field measurements, as well as its variations, as a tool to improve the Earth orientation modelisation. We present here the theoretical point of view for such studies, as well as some results obtained.

2. LINKS BETWEEN EARTH ORIENTATION PARAMETERS AND TEMPORAL VARIATIONS OF THE GRAVITY FIELD

The exces of length of day $\Delta(LOD)$ with respect to the nominal duration of 86400 s (LOD_{mean} = 86400 s) can be related to the temporal variations of C_{20} (i.e. ΔC_{20}), coefficient of degree 2 and order 0 of the geopotential development into spherical harmonics. We obtain (see for example Gross 2000, Bourda 2003):

$$\frac{\Delta(LOD)}{LOD_{\mathrm{mean}}} = -\frac{2}{3\ C_m}\ M\ {R_e}^2\ \sqrt{5}\ \Delta\bar{C}_{20} + \frac{h_3}{C_m\ \Omega} \tag{1}$$

where C_m is the axial moment of inertia of the Earth mantle, M and R_e are respectively the mass and the equatorial radius of the Earth, h_3 is the axial relative angular momentum of the Earth, and Ω is the mean angular velocity of the Earth. The loading coefficient of 0.7 (Barnes et al. 1983), multiplying classically $\Delta\bar{C}_{20}$, is here a priori already considered into the C_{20} real data. Figure 2 shows the $\Delta(LOD)$ coming from the ΔC_{20} data of Biancale & Lemoine (2004), compared to the one of Fig. 1 coming from the C04 series of IERS where the “movement” effects and long terms have been removed.

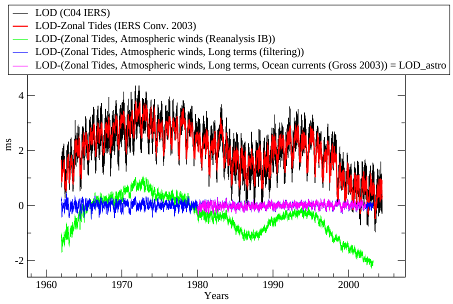

Figure 1: Exces in the length of day: various components of the $\Delta(LOD)$ are removed.

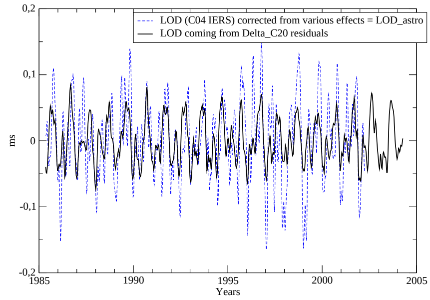

Figure 2: $\Delta(LOD)$ obtained with observed ΔC_{20} data, and compared with $\Delta(LOD)_{astro}$ (see Fig. 1).

The polar motion ($p = x_p - i\ y_p$) excitation can be related to the geopotential coefficients of degree 2 and order 1 (C_{21} and S_{21}), as following (see for example Gross 2000, Bourda 2003):

$$p + \frac{i}{\sigma_0}\ \dot{p} = \frac{k_0}{k_0 - k_2}\ \frac{1}{C_m - A_m} \left[\frac{h}{\Omega} - \sqrt{\frac{5}{3}}\ M\ {R_e}^2\ (\bar{C}_{21} + i\ \bar{S}_{21}) \right] \tag{2}$$

where σ_0 is the Chandler frequency, $k_0/(k_0 - k_2) = 1.43$ (Barnes et al. 1983), A_m is the equatorial moment of inertia of the mantle, and h is the equatorial relative angular momentum of the Earth. We can notice that the loading coefficient of $(1 + k_2')$ (Barnes et al. 1983), multiplying classically $\bar{C}_{21}$ and $\bar{S}_{21}$, is here a priori already considered into the C_{21} and S_{21} real data.

An article about the link between the precession of the equator and the temporal variations of the C_{20} geopotential coefficient have been publihed into A&A by Bourda & Capitaine (2004), on the basis of Williams (1994) and Capitaine et al. (2003). The J_2 rate influence onto the precession acceleration have been studied, as well as the C_{20} periodic influence (annual and semi-annual terms), on the basis of the ΔC_{20} data of Biancale et al. (2002).

3. REFERENCES

Barnes, R. T. H., Hide, R., White, A. A., and Wilson, C. A., 1983, *Proc. R. Soc. Lond.*, **A 387**, pp. 31–73.

Biancale, R., Lemoine, J.-M., Loyer, S., Marty, J.-C., and Perosanz, F., 2002, private communication for the C_{20} data coming from GRIM5.

Biancale, R., and Lemoine, J.-M., 2004, private communication for the C_{20}, C_{21} and S_{21} data coming from the redetermination of the gravity field with Lageos I and II measurements.

Bourda, G., 2003, *Proceedings Journées 2002 Systèmes de référence spatio-temporels*, edited by N. Capitaine and M. Stavinschi, Bucharest: Astronomical Institute of the Romanian Academy, Paris: Observatoire de Paris, p. 150-151.

Bourda, G., and Capitaine, N., 2004, A&A , **428**, pp. 691-702.

Capitaine, N., Wallace, P. T., and Chapront, J., 2003, A&A , **412**, pp. 567-586.

Gross, R. S., 2000, *Gravity, Geoid and Geodynamics 2000*, IAG Symposium 123, Sideris (eds.), Springer Verlag Berlin Heidelberg, pp. 153-158.

Williams, J. G., 1994, AJ , **108(2)**, pp. 711-724.

COMBINATION OF SPACE GEODESY TECHNIQUES FOR MONITORING THE KINEMATICS OF THE EARTH

D. COULOT[1,2], P. BERIO[2], R. BIANCALE[3] et al.

[1] IGN/LAREG
6 et 8 Av. B. Pascal Champs-sur-Marne 77455 Marne-la-Vallée France
e-mail: david.coulot@obs-azur.fr

[2] OCA/GEMINI
Av. N. Copernic 06130 Grasse France
e-mail: philippe.berio@obs-azur.fr

[3] CNES/OMP
14 Av. E. Belin 31400 Toulouse France
e-mail: richard.biancale@cnes.fr

ABSTRACT. In the framework of activities of the International Earth Rotation and Reference Systems Service (IERS) Combination Research Centres (CRC), the french *Groupe de Recherche en Géodésie Spatiale (GRGS)* studies the benefit of combining four geodetic techniques (SLR, VLBI, GPS and DORIS) at the measurement level in order to obtain a global and consistent solution for Earth Orientation Parameters (EOPs): polar motion xp and yp, universal time UT and celestial pole offsets in longitude and obliquity $d\psi$ and $d\epsilon$ with a six-hour sampling, as well as weekly station positions. A one-year test period (the year 2002) has been chosen to prove the power of such a combination moreover worked out in a homogeneous global terrestrial reference frame. All techniques were processed in the same computational framework (GINS/DYNAMO) so with the same *a priori* models and *a priori* values for parameters. The optimal relative weights between each geodetic technique were obtained with an optimal variance component estimation method.

1. METHOD OF COMBINATION

The test period chosen for the combination is the year 2002. More precisely, this period begins on December 30, 2001 (Julian Date 2 452 273,5) and ends on January 01, 2003 (Julian Date 2 452 643,5). The GINS software provides the sensitivity of measurements with respect to parameters of interest, through weekly normal matrices per technique. In our case, these parameters are EOPs and positions of GPS, SLR, DORIS and VLBI stations. Each week, normal matrices of the four techniques are used to obtain a "four-technique" normal matrix. This processing is carried out in two steps. In the first step, the four matrices are used to compute the relative weights between techniques with an optimal variance component estimation method [5]. These four relative weights are used in the second step to gather the four individual normal matrices in a global weekly normal matrix taking into account the quality of each technique.

The weekly normal system so obtained can not be solved for without any additional information on parameters (EOPs every six hours and station positions every week). We so give these supplementary informations as constraints on parameters ("continuity constraints" on EOPs and minimum constraints for station positions [6]) which allow us to invert the normal system and to obtain the final solutions. The EOP offsets are computed with respect to the IERS time series *EOPC04* [2] corrected with the diurnal and sub-diurnal model of [4]. The station position offsets are computed with respect to ITRF2000 positions [1] corrected with models of IERS conventions [3].

2. RESULTS FOR EOPS

There is no absolute method to evaluate the quality of EOP time series. Usually, the quality assessment of time series is done through comparisons with other series and/or with theoretical models. In our case, we choose to compare the one-day and six-hour sampling combined time series with each individual series through the weighted RMS of the estimated offsets (Table 1).

	dx_p	dy_p	dUT		dx_p	dy_p	dUT
GPS	0.079	0.083	0.009	SLR	0.146	0.131	0.019
DORIS	0.706	0.551	0.122	VLBI	0.363	0.363	0.009
C_{1D}	0.075	0.070	0.010	C_{6H}	0.442	0.433	0.013

Table 1: Weighted Root Mean Squares of the individual and combined EOP time series. Units are mas for x_p and y_p and ms for UT. The names C_{1D} and C_{6H} correspond respectively to the combined series with a one-day and a six-hour sampling.

The RMS of the individual series are in good agreement with those usually obtained by the IERS analysis data centres. The C_{1D} series present a RMS of $0,07/0,08$ *mas* for the pole coordinate offsets in agreement with the GPS series. The RMS of dUT for the C_{6H} series is really small. This shows that our combination process takes advantage of the characteristics of each technique. So the dUT series seem to be mainly influenced by the VLBI technique which is known as the best one for this parameter.

The analysis of the combined series of EOPs with a six-hour sampling shows that our method of combination at the measurement level is working. Furthermore this method provides a global and consistent solution of EOPs and station positions simultaneously with a satisfactory sampling. This kind of computation seems to be the future for Reference System realization and maintenance.

3. REFERENCES

[1] Altamimi, Z., Sillard, P., and Boucher, C. 2002, J.G.R., 107, B10, 2214
[2] EOP Product Center website, http://hpiers.obspm.fr/eop-pc/
[3] McCarthy, D. D. 1996, IERS Conventions, IERS Technical Note 21
[4] Ray, R. D., Steinberg, D. J., Chao, B. F. et al. 1994, Science, 264, 830
[5] Sahin, M., Cross, P. A. and Sellers P. C. 1992, Bull. Géod., 66, 284
[6] Sillard, P. and Boucher, C. 2001, J. of Geod., 75, 63
[7] Yaya, P., thse de doctorat, Observatoire de Paris, 1^{er} juillet 2002

THE EQUATIONS OF THE EARTH'S ROTATION IN THE FRAMEWORK OF THE IAU 2000 RESOLUTIONS

M. FOLGUEIRA[1,2] N. CAPITAINE[2], J. SOUCHAY[2]

[1] Instituto de Astronomía y Geodesia (UCM-CSIC),
Facultad de CC. Matemáticas. Universidad Complutense de Madrid.
Plaza de Ciencias, 3. Ciudad Universitaria. 28040 Madrid. Spain.
E-mail: martafl@mat.ucm.es

[2] SYRTE/UMR8630-CNRS, Observatoire de Paris
61 avenue de l'Observatoire, 75014 Paris. France.
E-mail: capitain@danof.obspm.fr; Jean.Souchay@obspm.fr

ABSTRACT. This paper describes the objectives of the European DESCARTES sub-project entitled "Advances in the integration of the equations of the Earth's rotation in the framework of the new parameters adopted by the IAU 2000 Resolutions" and reports on preliminary results.

1. THE EUROPEAN DESCARTES SUB-PROJECT

For many applications in Celestial Mechanics and Astrometry, the x, y-coordinates (denoted X, Y) of the Celestial Intermediate Pole (CIP) unit vector in the Geocentric Celestial Reference System (GCRS), are extremely useful. They are for example the parameters to which the VLBI observations are directly sensitive. It is therefore important to obtain the equations of the Earth's rotation as function of these parameters. This would allow us to provide a precession-nutation model directly in the form recommended by the IAU 2000 Resolutions. With these considerations in mind, the European DESCARTES sub-project entitled: "Advances in the integration of the equations of the Earth's rotation in the framework of the new parameters adopted by the IAU 2000 Resolutions" has been undertaken.

The main objectives of the project can be summarized as follows:

1. discussing the most suitable sets of variables to be used for integrating the equations of the Earth rotation,
2. obtening the equations of the Earth rotation explicitly expressed with the Earth Orientation Parameters (EOP) that are recommended by the IAU 2000 Resolutions,
3. integrating these equations in order to provide the results with an accuracy compliant with that required by the IAU 2000 Resolutions,
4. comparing the new solutions for X and Y with those derived indirectly from the IAU 2000 solutions for the classical $\Delta\psi$ and $\Delta\varepsilon$ variables,
5. transforming the solution for a rigid Earth to the non-rigid Earth,
6. comparing the solution obtained analytically with the observed parameters.

2. VARIATIONAL EQUATIONS IN TERMS OF THE COORDINATES $(X,\ Y)$ OF THE CIP IN THE GCRS

The differential equations of the rotational motion of a rigid Earth in the framework of the IAU 2000 Resolutions have been derived from a direct application of the Euler's dynamical equations. The developments have led to equations which can be written in a compact form as:

$$\begin{cases} F_1\,\ddot{X} + F_2\,\ddot{Y} + F_3\,\dot{X}^2 + F_4\,\dot{Y}^2 + F_5\,\dot{X}\dot{Y} + F_6\,\dot{X} + F_7\,\dot{Y} = \frac{L}{\bar{A}} \\ G_1\,\ddot{X} + G_2\,\ddot{Y} + G_3\,\dot{X}^2 + G_4\,\dot{Y}^2 + G_5\,\dot{X}\dot{Y} + G_6\,\dot{X} + G_7\,\dot{Y} = \frac{M}{\bar{A}} \end{cases} \tag{1}$$

where F_i and G_i are functions of X and Y, L and M are the components of the external torque in the GCRS and $\bar{A}$ is for $\frac{A+B}{2}$, A and B being the principal moments of inertia of the rigid Earth.

From a numerical evaluation of the order of magnitude of the terms in (1), it can be seen that the prominent terms are $F_2\,\ddot{Y}$ and $F_6\,\dot{X}$ in the first equation and $G_1\,\ddot{X}$ and $G_7\,\dot{Y}$ in the second one. The expressions of F_2, F_6, G_1 and G_7 as functions of the X and Y variables, are:

$$\begin{aligned} F_2 &= -1 - \frac{1}{2}Y^2 - \frac{3}{8}X^2Y^2 \\ F_6 &= \frac{C\Omega}{\bar{A}}\left\{1 + \frac{1}{2}X^2 + \frac{3}{8}X^4 + \frac{3}{8}X^2Y^2\right\} \\ G_1 &= 1 + \frac{1}{2}X^2 + \frac{3}{8}X^4 + \frac{3}{8}X^2Y^2 \\ G_7 &= \frac{C\Omega}{\bar{A}}\left\{1 + \frac{1}{2}Y^2 + \frac{3}{8}X^2Y^2\right\} \end{aligned} \tag{2}$$

The variational equations (1) can then be integrated by either an analytical or a numerical method in order to obtain the solutions for X and Y in the absence of external forces. These solutions will be used as approximations for the study of the perturbed problem in terms of X and Y, which is under development in the frame of this project.

Acknowledgments. The research was carried out in the Department SYRTE (*Systèmes de Référence Temps Espace*) at Observatoire de Paris and received a financial support from Descartes Prize Allowance (2004) (M. Folgueira), for which we express our sincere appreciation.

3. REFERENCES

Capitaine, N., Guinot, B. and Souchay, J., 1986, Celest. Mech. 39, 283–307.

Capitaine, N., 1990, Celest. Mech. 48, 127–143.

IERS Conventions (2003), D.D. McCarthy & G. Petit (eds.), (IERS Technical Note 32), Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2004. 127 pp.

ATMOSPHERIC ANGULAR MOMENTUM TIME SERIES: CHARACTERIZATION OF THEIR INTERNAL NOISE AND CREATION OF A COMBINED SERIES

L. KOOT, O. DE VIRON, V. DEHANT
Royal Observatory of Belgium
avenue circulaire,3, B-1180 Brussels, Belgium
e-mail: laurence.koot@oma.be

ABSTRACT. The effects of the atmosphere on the Earth rotation are classically computed using the angular momentum approach. In this method, the variations in the rotation of the Earth are estimated from the variations in the atmospheric angular momentum (AAM). Several AAM time series are available, from different meteorological centers. However, the estimation of atmospheric effects on Earth rotation differs when using one atmospheric model or the other. The purpose of our work is to build an objective criterion which justifies the use of one series in particular. We determine the quality of each series by making an estimation of their noise level, using a generalized formulation of the "three-cornered hat method". As the quality of the series varies in time, we construct a combined AAM series, using time dependent weights chosen so that the noise level of the combined series, estimated using the three-cornered hat method, is minimal.

1. INTRODUCTION

The angular momentum approach considers that the total system Earth and atmosphere is isolated so that variations in the Earth angular momentum are associated with opposite variations in the atmospheric angular momentum (AAM). The atmospheric angular momentum data are obtained from meteorological models of global atmospheric circulation. The International Earth Rotation Service (IERS) Special Bureau for the Atmosphere (Salstein *et al.* 1993) provides the data coming from five meteorological centers: the ECMWF (European Center for Medium-Range Weather Forecast), the UKMO (United Kingdom Meteorological Office), the JMA (Japanese Meteorological Agency), the NCEP (National Center for Environmental Prediction) and the NCEP/NCAR (National Center for Environmental Prediction/ National Center for Atmospheric Research) which makes a 'reanalysis' series. When the correlation between the atmospheric excitation and geodesic data is computed, we show that the results differ from one atmospheric model to another: the estimation of atmospheric effects on Earth rotation depends on the atmospheric series chosen.

2. THE THREE-CORNERED HAT METHOD AND NOISE LEVEL ESTIMATION

We determined the quality of the AAM series by making a comparison of the series with each other with a generalized formulation of the "three-cornered hat" method (Premoli and Tavella

1993, Galindo *et al.* 2001). This method relies on the hypothesis that the signal is the part of the series common to all of them and that the noise is the remaining part of it. The method allows then an estimation of the variance of the noise, which reflects its noise level. We show that the noise level of the series is varying in time and that none of them has at each time the lowest noise level (Koot *et al.* 2005).

3. A COMBINED AAM TIME SERIES

This provides the motivation to generate a series by combination of the five time series available, which would present at each time an estimated noise level as low as possible. The combined series allows to take advantage of the information included in each series, its weight in the combination depending on its noise level.

To check the combination, we computed the correlation as a function of time between the combined AAM series and Earth rotation data (COMB2002 of Gross 2003). We show that our combined series is always amongst the best correlated series. For example, the correlation between the Z component of the AAM and the Length-of-Day lies between 95.40 % (NCEP model) and 97.88% (NCEP/NCAR reanalysis) for the 5 existing models while the combined series gives a correlation of 98.02%.

4. CONCLUSION

We showed that the combination of the atmospheric angular momentum time series allow to create less noisy data series which offer at each time a good correlation with Earth rotation. The creation of combined series seems thus to be a promising tool to improve the evaluation of atmospheric effects on Earth rotation.

5. REFERENCES

Barnes, R.T.H., R. Hide, A.A. White, and C.A. Wilson, Atmospheric angular momentum fluctuations, length-of-day changes and polar motion, *Proc. R. Soc. London, Ser. A, 387*, 31-73, 1983.

Galindo, F.J., J.J. Ruiz, E. Giachino, A. Premoli and P. Tavella, Estimation of the covariance matrix of individual standards by means of comparison measurements, *"Advanced Mathematical and Computational Tools in Metrology, vol.5", Series on Advances in Mathematics for Applied Sciences vol. 57, World Scientific, Singapore*, pp. 179-183, 2001.

Gross, R. S., Combinations of Earth orientation measurements: SPACE2002, COMB2002, and POLE2002, *JPL Publ., 03-11*, 28 pp., 2003.

Koot, L., O. de Viron and V. Dehant, Atmospheric angular momentum time series: a characterization of their internal noise and creation of a combined series, in preparation.

Premoli, A. and P. Tavella, A Revisited Three-Cornered Hat Method for Estimating Frequency Standard Instability, *IEEE Transactions on Instrumentation and Measurement, Vol. 42, No. 1*, pp. 7-13, 1993.

Salstein, D.A., Kann, D.M., Miller, A.J., and Rosen, R.D., The sub-bureau for atmospheric angular momentum of the international Earth rotation service: A meteorological data center with geodetic applications, *Bull. Am. Meteorol. Soc. 74*, 67-80, 1993.

A COMPARISON OF UT1-UTC FORECASTS BY DIFFERENT PREDICTION TECHNIQUES

W. KOSEK[1], M. KALARUS[1], T.J. JOHNSON[2], W.H. WOODEN[2], D.D. McCARTHY[2], W. POPIŃSKI[3]

[1] Space Research Centre, Polish Academy of Sciences, Warsaw, Poland

[2] US Naval Observatory, Washington DC, USA

[3] Central Statistical Office, Warsaw, Poland

E-mail: kosek@cbk.waw.pl

1. INTRODUCTION

The mean observational error of UT1-UTC is now of the order of 0.006 ms, which corresponds to about 2.8 mm on the Earth's surface. Usually the prediction error even for a few days in the future is several times greater than the observational error. In this paper different stochastic prediction techniques including autocovariance, autoregressive, autoregressive moving average, and neural networks were applied to predict UT1-UTC IERS EOPC04 data (IERS 2004). All known effects such as leap seconds and solid Earth zonal tides (McCarthy and Petit 2003) were first removed from the observed values of UT1-UTC. To predict the LODR time series the combination of the least-squares (LS) extrapolation with different stochastic prediction methods was applied. The results of the combination of the LS extrapolation with different stochastic prediction techniques were compared with the results of the UT1-UTC prediction method currently used by the IERS Rapid Service/Prediction Centre.

2. PREDICTION TECHNIQUES APPLIED AND THEIR RESULTS

In the autocovariance prediction (AC) the first predicted value is determined by the principle that the autocovariance of the extended time series coincide as closely as possible with the autocovariance estimated from the given series (Kosek 2002). In the autoregressive prediction (AR) the estimations of the autoregressive coefficients were derived from the modified Yule-Walker equations using the Friedlander and Porat (1984) algorithm. In the autoregressive moving average prediction (ARMA) the estimates of the autoregressive and moving average parameters were estimated using the algorithm described by Marple (1987). In the Neural Network prediction (NN) the Toolbox of Matlab 5.3, in which the topology of the network consisted of two layers, was used (Kalarus and Kosek 2004).

USNO combines different observational and modeling data sets using a cubic spline approach in its combination procedure. The UT1-UTC predictions are computed using an autoregressive integrated moving average (ARIMA) technique (Luzum *et al.* 2001). To improve USNO's estimate of the UT1-UTC value at the solution epoch a UT1-like quantity derived from IGS rapid solutions of GPS satellites is used (Kammeyer 2000). The recent addition of atmospheric angular momentum (AAM) forecast data into the combination has resulted in a greater than

50% reduction in the prediction error at 10 days into the future (Johnson *et al.* 2004).

In the combination of the LS extrapolation with the AR, ARMA, AC and NN stochastic prediction methods called as LS+AR, LS+ARMA, LS+AC and LS+NN, respectively, the LS extrapolation residuals of LODR were determined as the difference between LODR data and their LS models. The seasonal effects of LODR were determined by the LS method. Next, the stochastic prediction method was applied to the LS extrapolation residuals of LODR. The final prediction of LODR is the sum of the LS extrapolation model and the prediction of the LS extrapolation residuals. The UT1R-TAI forecasts were computed by summing the LODR predictions. The mean prediction errors of the UT1-UTC data from 1984 to 2004.6 for the USNO, LS+AR, LS+ARMA and LS+NN prediction methods are shown in Figure 1.

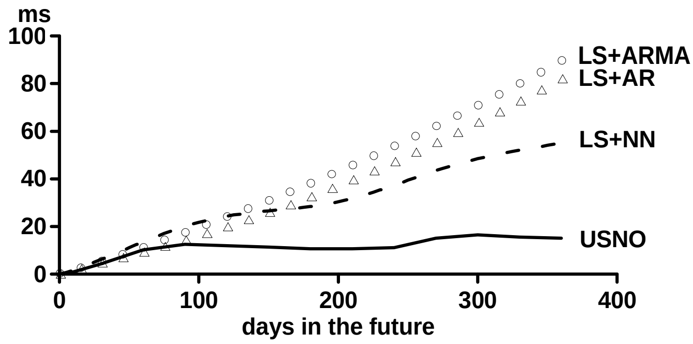

Figure 1: The mean prediction errors of the LOD and UT1-UTC EOPC04 data computed by the combination of the LS extrapolation with the ARMA (circles), AR (triangles), NN (dashed line) from 1984 year to the present and the standard deviation of UT1-UTC prediction for Bulletin A for year of prediction from August 2002 to August 2003 (USNO)(thin line).

3. CONCLUSIONS

The mean prediction errors for 1 to about 70 days in the future are of the same order as those of the method used by the IERS Rapid Service/Prediction Centre. The USNO approach has better prediction capabilities at 1 year into the future.

4. REFERENCES

Friedlander B. and Porat B., 1984, The modified Yule-Walker method of ARMA spectral estimation, *IEEE Trans. on Aerospace and Electronic Systems*, **AES-20**, No 2, 158-172.

IERS, 2004, The Earth Orientation Parameters, http://hpiers.obspm.fr/eop-pc/.

Johnson T.J., Luzum B.J. and Ray J.R., 2004, Improved near-term Earth Rotation predictions using forecast of atmospheric angular momentum. *J. Geodynamics*, in press.

Kammeyer, Peter, 2000. A UT1-Like quantity from Analysis of GPS Orbit Planes, *Celest. Mech. And Dynam. Astr.*, **2044**, 1-32.

Kalarus M. and Kosek W., 2004, Prediction of Earth orientation parameters by artificial neural networks. *Artificial Satellites - Journal of Planetary Geodesy* Vol. **39**, No. 2. 175-184.

Kosek W., 2002, Autocovariance prediction of complex-valued polar motion time series, *Advances of Space Research*, **30**, 375-380.

Luzum, B.J., J.R. Ray, Merri S. Carter, and F.J. Josties, 2001. Recent improvements to IERS Bulletin A combination and prediction, *GPS Solutions*, 4, 3, 34-40.

Marple S.L., Jr., 1987, *Digital Spectral Analysis*, Prentice-Hall, 1987.

McCarthy D.D. and Petit G. (ed.) 2003, IERS Conventions, IERS Technical Note 32.

KSM03 HARMONIC DEVELOPMENT OF THE EARTH TIDE-GENERATING POTENTIAL IN TERRESTRIAL REFERENCE FRAME

S.M. KUDRYAVTSEV
Sternberg Astronomical Institute of Moscow State University
Universitetsky Pr., 13, Moscow, 119992, Russia
e-mail: ksm@sai.msu.ru

ABSTRACT. The KSM03 harmonic development of the Earth tide-generating potential of Kudryavtsev (2004) is re-calculated into the Terrestrial reference frame and presented in the standard HW95 (Hartmann and Wenzel 1995) normalization and format.

The original KSM03 harmonic development of the Earth tide-generating potential (TGP) by Kudryavtsev (2004) is made in a reference frame defined by the true geoequator of date with an origin at a point A - that being the projection of the mean equinox of date. The development is based on the latest NASA/JPL ephemerides DE/LE-405,-406 (Standish 1998) and valid over two thousands years, 1000-3000.

The value $V(t)$ of the TGP at an arbitrary point P on the Earth's surface at epoch t is expressed in the KSM03 as

$$V(t) = \sum_{n=1}^{6} \sum_{m=0}^{n} \left(\frac{r}{R_E}\right)^n \bar{P}_{nm}\left(\sin\varphi'\right) \left[C_{nm}(t)\cos m\theta^{(A)}(t) + S_{nm}(t)\sin m\theta^{(A)}(t)\right] \tag{1}$$

where R_E is the mean Earth equatorial radius; $\bar{P}_{nm}$ are the normalized associated Legendre functions; r and φ' are, respectively, the geocentric distance and latitude of the point P; $\theta^{(A)}(t)$ is the local mean sidereal time at P reckoned from the same origin point A - so that it is related to the Earth fixed east longitude (from Greenwich) λ of P simply as

$$\theta^{(A)}(t) = \lambda + GMST \tag{2}$$

($GMST$ is Greenwich Mean Sidereal Time defined by a well-known expression by Aoki et al. 1982).

The KSM03 provides development of the coefficients $C_{nm}(t)$, $S_{nm}(t)$ to Poisson series of the following form

$$C[S]_{nm}(t) = \sum_{k=1}^{N} \left[\left(A^c_{k0} + A^c_{k1}t + A^c_{k2}t^2\right)\cos\omega_k(t) + \left(A^s_{k0} + A^s_{k1}t + A^s_{k2}t^2\right)\sin\omega_k(t)\right] \tag{3}$$

where A^c_{k0}, A^c_{k1},$\cdots$, A^s_{k2} are constants and the arguments $\omega_k(t)$ are the forth-degree polynomials of time t

$$\omega_k(t) = \nu_k t + \nu_{k2}t^2 + \nu_{k3}t^3 + \nu_{k4}t^4. \tag{4}$$

In total the KSM03 development of the Earth TGP includes 26,753 Poisson series [for all the coefficients $C_{nm}(t)$, $S_{nm}(t)$]. The minimum amplitude of the leading terms of the series (A^c_{k0} and A^s_{k0}) is 1×10^{-8} m^2/s^2; the same limit is set for the minimum values of $A^c_{k1}t$, $A^s_{k1}t$, $A^c_{k2}t^2$ and $A^s_{k2}t^2$ over 1000 years from the epoch J2000. The accuracy of calculation of the gravity tides at a mid-latitude station (Black Forest Observatory, Germany) made with use of the KSM03 series is 0.025/0.39 nGal (the r.m.s./maximum error) over 1600-2200 (Kudryavtsev 2004). It exceeds the accuracy of any previously made harmonic development of the Earth TGP in time domain by a factor of least three.

The series composing the original KSM03 harmonic development of the Earth TGP have TDB time argument and do not include a much less stable UT1 time argument which is necessary to calculate the TGP in the Terrestrial reference frame (TRF). Such an approach makes the KSM03 series valid over a long-term interval of time, 1000-3000, and helps to increase the development accuracy. However, for practical applications it is valuable to develop the TGP in the Earth-fixed TRF. Therefore coefficients of the KSM03 series in the TRF are re-calculated and transformed into the standard HW95 (Hartmann and Wenzel 1995) normalization and format. The KSM03 series represented in such a format include 28806 terms and can be directly used in development of nutation theories and precise calculations of tidal effects observed in the TRF.

The KSM03 harmonic development of the Earth TGP in the standard HW95 normalization and format is available at **http://lnfm1.sai.msu.ru/neb/ksm/tgp/ksm03.dat**.

Acknowledgments. A travel grant provided to the author from the Journées 2004 Organizing Committee in the framework of the EU Project 'Descartes-Nutation' is sincerely acknowledged. The work was supported in part by grant 02-02-16887 from the Russian Foundation for Basic Research.

REFERENCES

Aoki, S., Guinot, B., Kaplan, G. H., Kinoshita, H., McCarthy, D. D., Seidelmann, P. K. (1982) The new definition of Universal Time, A&A , **105**, 359-361.

Hartmann, T. and Wenzel, H.-G. (1995) The HW95 tidal potential catalogue, Geophys. Res. Lett., **22**, 3553-3556.

Kudryavtsev, S.M. (2004) Improved harmonic development of the Earth tide-generating potential, J. Geodesy, **77**, 829-838.

Standish, E.M. (1998) JPL Planetary and Lunar Ephemerides DE405/LE405, JPL IOM 312.F-98-048, Pasadena.

SECOND-ORDER TERMS IN THE EARTH'S NUTATION

S. LAMBERT
US Naval Observatory, Earth Orientation Department
3450 Massachusetts Avenue NW, Washington DC 20392, USA
e-mail: sbl@usno.navy.mil

ABSTRACT. Given the accuracy of the observations, the effects of the second-order terms in the equations of the Earth's rotation have now to be considered. The effects of the zonal deformations have been considered by several authors (Souchay & Folgueira 1999, Mathews et al. 2002, Lambert & Capitaine 2004) but they are only one effect among several second-order effects. This study investigates these second-order terms. The computation yields an almost complete cancellation of the different contributions so that the net effect of the second-order terms is no more than a few tens of microarcseconds.

1. DYNAMICAL EQUATIONS AND SECOND-ORDER TORQUE

The motion of the rotation axis $\vec{\omega} = \Omega(m_1, m_2, 1 + m_3)$, of a stratified Earth with fluid core is given by the angular momentum conservation law, written in the rotating frame :

$$\begin{aligned} \dot{m} - i\sigma_{\mathrm{r}} m + \frac{\dot{c} + i\Omega c}{A} + \frac{A_{\mathrm{f}}}{A}(\dot{m}_{\mathrm{f}} + i\Omega m_{\mathrm{f}}) &= \frac{\Gamma}{A\Omega} \\ \dot{m} + \dot{m}_{\mathrm{f}} - i\sigma_{\mathrm{f}} m_{\mathrm{f}} + i\Omega m_{\mathrm{f}} + \frac{\dot{c}_{\mathrm{f}}}{A_{\mathrm{f}}} &= 0 \end{aligned} \tag{5}$$

with $m = m_1 + im_2$, $c = c_{13} + ic_{23}$, A is the equatorial mean moment of inertia and σ_r the Euler frequency. Quantities relevant to the core are subscripted by f. The lunisolar potential is :

$$V_{lm} = \frac{1}{3}\Omega^2 r^2 \mathrm{Re}(\phi_{lm} Y_{lm}) \tag{6}$$

where $Y_{lm} = P_{lm}(\cos\theta)\exp(-im\lambda)$ for any point within the Earth at geocentric distance r, terrestrial longitude λ and colatitude θ. The second-order torque on the Earth can be written, using the definition of the moments of inertia c_{ij} :

$$\begin{aligned} \Gamma_{20} &= -i\Omega^2\phi_{20} c \\ \Gamma_{21} &= \Omega^2\phi^{\star}_{21} c_{12} + i\Omega^2\phi^{\mathrm{re}}_{21}(c_{33} - c_{11}) - \Omega^2\phi^{\mathrm{im}}_{21}(c_{33} - c_{22}) \\ \Gamma_{22} &= 2i\Omega^2\phi_{22} c^{\star} \end{aligned} \tag{7}$$

The deformability of the Earth is taken into account using McCullagh's theorem. One gets :

$$\begin{aligned} c_{11} + c_{22} - 2c_{33} &= -2\kappa A \phi_{20} \\ c_{13} + ic_{23} &= \kappa A \phi_{21} \\ c_{22} - c_{11} + ic_{12} &= -4\kappa A \phi_{22}^{\mathrm{re}} + 2i\kappa A \phi_{22}^{\mathrm{im}} \\ c_{11} + c_{22} + c_{33} &= 0 \end{aligned} \tag{8}$$

where $\kappa = ka^5\Omega^2/3GA$ is the secular Love number, a is the mean equatorial radius of the Earth and k is the static Love number. The zonal deformations are taken into accound accurately through their effects on the length-of-day (see Lambert & Capitaine 2004 for this part of the computation). The Love number k is obviously depending upon the frequency and includes a small imaginary part accounting for the anelasticity.

Introducing these relationships into (7), one gets, for an homogeneous Earth :

$$\begin{aligned} \Gamma_{20} &= iA\Omega^2\kappa\phi_{20}m - iA\Omega^2\kappa\phi_{20}\phi_{21} \\ \Gamma_{21} &= iA\Omega^2\kappa\phi_{20}\phi_{21} - 2iA\Omega^2\kappa\phi_{22}\phi_{21}^{\star} \\ \Gamma_{22} &= -2iA\Omega^2\kappa\phi_{22}m^{\star} + 2iA\Omega^2\kappa\phi_{22}\phi_{21}^{\star} \end{aligned} \tag{9}$$

A numerical evaluation shows that the terms containing quantities m and m_{f} are very small (order of magnitude of 1 μas). The remaining terms cancel out so that the net effect is close to zero (not completely zero because of the frequency dependence of κ). For an anelastic Earth with fluid core, one has, with $C_{\mathrm{eff}} = C_{\mathrm{m}}/(1 - \gamma C_{\mathrm{f}}/\kappa C)$:

$$\begin{aligned} \Gamma_{20} &= iA\Omega^2\kappa\phi_{20}m - iA\Omega^2\kappa\phi_{20}\phi_{21} + iA\Omega^2\xi\phi_{20}m_{\mathrm{f}} \\ \Gamma_{21} &= -\frac{3}{2}i\Omega^2 C_{\mathrm{eff}} m_3^{z}\phi_{21} - 2iA\Omega^2\kappa\phi_{22}\phi_{21}^{\star} \\ \Gamma_{22} &= -2iA\Omega^2\kappa\phi_{22}m^{\star} + 2iA\Omega^2\kappa\phi_{22}\phi_{21}^{\star} - 2iA\Omega^2\xi\phi_{22}m_{\mathrm{f}}^{\star} \end{aligned} \tag{10}$$

2. RESULTS

The zonal tides effects on the nutation investigated in previous studies (Souchay & Folgueira 1999, Mathews et al. 2002, Lambert & Capitaine 2004) are not the only second-order effects. Mathews (2003) pointed out that reciprocal effects should cancel out one each other so that the net effect is considerably lowered.

Indeed, in this study, we establish that the remainder is due to the rotational effects, to the frequency dependence of κ, to the anelasticity and to the fluid core. The only effect above 1 μas is on the 18.6-y nutation (37 μas in longitude and -1 μas in obliquity). The precession in longitude is changed by -518 μas/c.

This computation was revised after discussions which occured during the meeting with A. Escapa. The sign of one contribution was erroneous, leading to wrong values of the final amplitudes. These results agree with those of Mathews (2003) and Escapa et al. (2004), the latter work using a Hamiltonian approach.

3. REFERENCES

Lambert, S., & Capitaine, N. 2004, A&A, 428, 255

Escapa, A., Getino, J., & Ferrandiz, J. M. 2004, Proc. Journées Syst. Ref., ed. N. Capitaine, Paris, this issue

Mathews, P. M., Herring, T. A., & Buffett, B. A. 2002, J. Geophys. Res., 107, B4, 10.1029/2001JB000390

Mathews, P. M. 2003, AGU Fall Meeting

Souchay, J., & Folgueira, M. 1999, EM&P, 81, 201

STUDIES OF REGIONAL ATMOSPHERIC PRESSURE EXCITATION FUNCTION OF POLAR MOTION

J. NASTULA, B. KOLACZEK
Space Research Center of the PAS
Bartycka 18a, Warsaw 01-871, Poland
e-mail: nastula@cbk.waw.pl
e-mail: kolaczek@cbk.waw.pl

EXTENDED ABSTRACT. It is known from earlier studies such as Salstein and Rosen (1989), Nastula and Salstein (1999) and Nastula et al. 2003, that isolated regions such as North Eurasia are very important in driving polar motion on seasonal and subseasonal time scales. The paper presents correlations and covariances between the regional atmospheric pressure excitation functions of polar motion and global geodetic excitation function of polar motion computed in two spectral bands, annual and semi-annual ones in two sets of geographic regions of different sizes. In the paper the following two sets of regional atmospheric data are used:

- The regional atmospheric excitation functions chi1 and chi2 computed by Nastula and Salstein (Nastula et al. 2003) in 828 equal-area sectors for the period January 1983 to December 2000 from meteorological fields on $2.5^o \times 2.5^o$ latitude-longitude grid. This network sector has an area of $6.16 \times 10^5 km^2$.
- The regional atmospheric excitation chi1 and chi2 computed by Nastula during visit at the Atmospheric and Environmental Research Inc. USA Lexington in 3312 equal-area sectors for the period January 1983 to December 2000 from meteorological fields on $2.5^o \times 2.5^o$ latitude-longitude grid. This network sector has an area of 1/4 of the previous one.

The excitation function of polar motion referred to as geodetic (GEOD) excitation was computed from the COMB02 series of polar motion (Gross, 2003), filtering by the Kalman filter developed by Brzeziński (Brzeziński, 1992; Brzeziński et al., 2004). The input polar motion series covers the period from 1962 to 2003 with 12-hour sampling. The computations were performed for seasonal, annual and semi-annual, bands obtained by filtering with Butterworth filter for periods 230-500 days and 150-230 days respectively. Covariations between regional atmospheric pressure and global geodetic excitation functions of polar motion computed in two mentioned above regions of different sizes show that the covariances diminishes with the size of region but the geographic patterns are not very sensitive on the size of regions. In the smaller regions more fine details are seen. The covariances for the semi-annual are ten time smaller than in the case of annual band. Comparison of covariances between regional atmospheric pressure and global geodetic excitation functions computed for annual and semiannual bands for considered two regions of chosen sizes are shown in Fig. 1. Correlation coefficients between regional atmospheric pressure and global geodetic excitation functions of polar motion were computed for larger and finer (only for the Northern Hemisphere) sectors. They are comparable although they are not shown here. Even

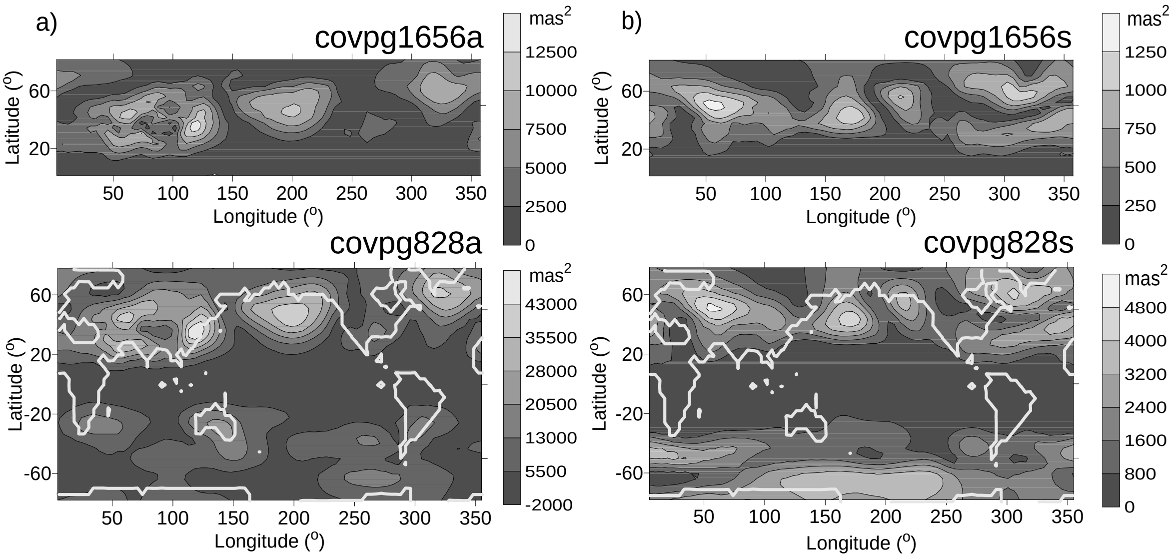

Figure 1: Maps of the covariance between values of excitation functions of polar motion of global geodetic and regional atmospheric pressure computed for a) annual band (230–500 days) for 1656 and 828 regions, and for b) semiannual band (150–230 days) for 1656 and 828 regions.

for such small regions, are quite high and reaching in maximum 0.7–0.8 for the annual band and about 0.6 for the semiannual band.

Acknowledgments. The work has been supported partly by The Polish State Commit tee for Scientific Research through the project 0001/T12/2004/26.

REFERENCES

Brzeziński, A., (1992): Polar motion excitation by variations of the effective angular momentum functions: considerations concerning deconvlution problem, Manuscr. Geodet, 17, 3-20.

Brzeziński A., J. Nastula, B. Kolaczek (2004): Oceanic excitation of polar motion from intraseasonal to decadal periods. Proceedings of the Meeting of the IAG Sections III + V on "Insight into Earth System Science: Variations in the Earth's Rotation and its Gravity Field" held at the IUGG General Assembly, Sapporo,Japan, June 30 - July 11, 2003, (in print).

Gross, R.S. (2003): Combinations of Earth orientation measurements: SPACE2002, COMB2002 and POLE2002, Jet Propulsion Laboratory Publ. 03-11, 28pp., Pasadena, Calif., USA.

Nastula, J., D.A. Salstein (1999): Regional atmospheric momentum contributions to polar motion. J. Geophys. Res., 104, 7347-7358.

Nastula, J., D.A. Salstein, R.M. Ponte (2003): Empirical patterns of variability in atmospheric and oceanic excitation of polar motion. Journal of Geodynamics, Special Issue: Earth rotation and episodic processes, Vol. 36, pp. 383-396.

Salstein, D.A., R.D. Rosen (1989): Regional contributions to the atmospheric excitation of rapid polar motions. J. Geophys. Res., 94, 9971-9978.

EXCITATION OF POLAR MOTION BY ATMOSPHERIC AND OCEANIC VARIABILITIES

J. NASTULA[1], D.GAMBIS[2]

[1] Space Research Center of the PAS
Bartycka 18a, Warsaw 01-871, Poland
e-mail: nastula@cbk.waw.pl

[2] IERS EOP Product Center
SYRTE/UMR8630-CNRS, Observatoire de Paris
61 Avenue de l'Observatoire, 75014 Paris, France
e-mail: daniel.gambis@obspm.fr, christian.bizouard@obspm.fr

ABSTRACT. It is widely accepted that atmospheric and oceanic variabilities play a major role in the excitation of polar motion at period longer than 10 days. However for shorter periods the effect is not clear. We have reanalysed the role of Atmospheric Angular Momentum (AAM) and Oceanic Angular Momentum (OAM) variabilities on the excitation of high frequency polar motion variations taking advantage of a recent Oceanic Angular Momentum (OAM) series derived by Ponte and Ali. We show that the correlation significant at periods between 2 and 10 days.

1. DATA

The oceanic influence on polar motion is investigated by using three different series of OAM time series considered as the sum of the signals resulting from changes in the oceanic mass and velocity fields. The input OAM series assumes an oceanic inverted barometer correction (IB) response to surface atmospheric pressure signals. The following three OAM series are used in the present analyses: G03 (Gross et al. 2003); ocean model: ECCO-JPL time span 1980 - 2002.2; PO - (Ponte and Ali, 2002) ocean barotropic mode, sampling interval 1 hour, time span 1993 - 2002; PN - (Ponte and Ali, 2003 - private communication) ocean barotropic model from 4 times daily series sampling interval 1 hour, time span 1993 - 2002.

The atmospheric excitation series AAM is derived from six-hour series (Salstein et. al, 1993) based on products obtained from the US NCEP/NCAR reanalysis project. We used here a sum of the wind and the pressure terms with the Inverted Barometer (IB) correction for the ocean response.

The excitation function of polar motion referred as geodetic (GEOD) excitation was inferred from the polar motion observations by applying the Barnes formaliam to the following polar motion series: 9070, Combined GPS series derived by the EOP Product Center of the IERS, 9083 Combined analysis GPS series derived by the IGS, 5522 Operational GPS series derived by JPL analysis center, 5422 Operational GPS series derived by CODE analysis center, NEOS Combined multi-technique solution of the USNO rapid service center and SPACE Combined multi-technique solution of the JPL.

2. ANALYSES

The amplitude coherence and phase spectra are computed using either one selected geodetic series and one of the tree oceanic-atmospheric series or using one selected oceanic-atmospheric series and one of four geodetic series.

All AAM+OAM models show similar coherences with the IGS combined solution (9083) for periods greater than 6 days (Fig.1a). For shorter periods, the best agreement is obtained for PN, (Ponte and Ali) model. This is clearly evident in the case of the power spectra where only AAM+PN series have power almost equal to the geodetic series power. There is a significant drop of the coherence level in the spectral range below 4 days in all cases, still the coherence values remain significant. It is also clear that there are differences in the coherence, amplitude spectra, and phases between geodetic series and AAM+PN, in the spectral range below 3.5 days (Fig. 1b). Here the best result was obtained when the 9083 was used for comparisons. It is unexpected that results obtained from the CODE data are slightly worst to those concerning the 9083 series. Analyses of correlation and variance relation between the chosen AAM+PN and different geodetic series in the two spectral bands spectral bands (2 - 8 days; 2-4 days, performed in sliding window confirmed the results mentioned above. The best correlation and values of variance ratio (near 1) is obtained for the series 9083.

3. CONCLUSION

The origin of polar motion variations in spectral band below 4 days needs more investigation and also more accurate geodetic, atmospheric and oceanic series. Since oceanic series are based on models, it is not clear whether comparison between geodetic on one hand and atmospheric + oceanic series on the other hand may serve as estimation of accuracy of the geodetic solutions to allow discrimation between various independant EOP solutions.

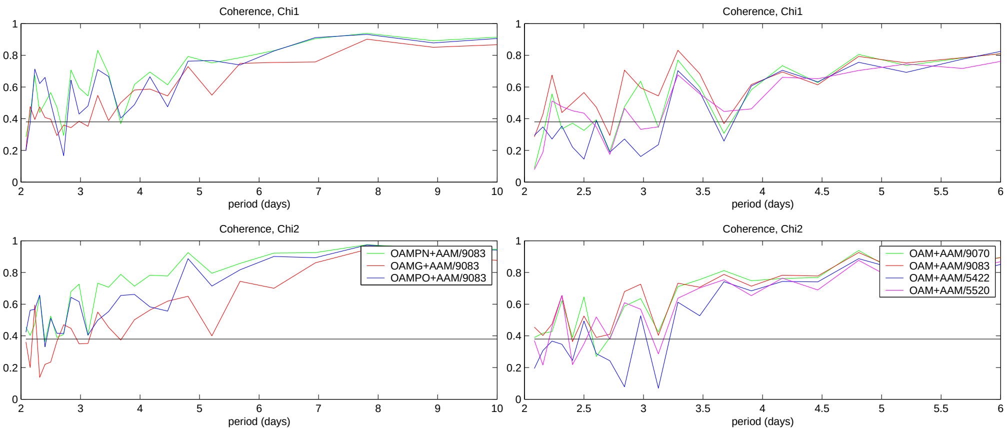

Figure 1: a -left panels) Coherence spectra between the three joint atmosphere+ocean series and the geodetic series(9083), b - right panels) coherence spectra between the chosen joint atmosphere ocean spectra (PN + AAM) and different geodetic series.

4. REFERENCES

Gross, R. S., I. Fukumori, and D. Menemenlis, (2003): Atmospheric and oceanic excitation of the Eath's wobble during 1980-2000, J. Geophys. Res., in press.

Ponte, R.M., and A.H. Ali, (2002): Rapid ocean signals in polar motion and the length of day. Geophys. Res. Lett., Vol. 29, 10.10129/2002GL015312.

Salstein, D. A., D. M. Kann, A. J. Miller, and R. D. Rosen, (1993):The Sub-Bureau for Atmospheric Angular Momentum of the International Earth Rotation Service: a meteorological data center with geodetic applications, Bull. Amer. Meteor. Soc., 74, 67-80.

EARTH LIBRATIONS DUE TO CORE-MANTLE COUPLINGS

N. RAMBAUX[1,2], T. VAN HOOLST[1], V. DEHANT[1], E. BOIS[3]

[1] Royal Observatory of Belgium, 3, avenue circulaire, 1180 Bruxelles

[2] Facultés Universitaires Notre-Dame de la Paix, 8 rue des remparts, 81000 Namur

[3] Observatoire de la Côte d'Azur, B.P. 4229, F-06304 NICE Cedex 4

e-mail: Nicolas.Rambaux@oma.be

ABSTRACT. We present a study of the dynamical behavior of the liquid core inside the Earth related to the mantle by inertial coupling. In order to integrate the terrestrial core-mantle interaction in a realistic model of the Earth's rotation, we have used our SONYR model (Spin-Orbit N-bodY Relativistic model) of the solar System including the Earth's spin-orbit motion. We obtain the dynamical behavior of the rotational motion of the Earth considered as a homogeneous body and as a model with two layers. The comparison of the dynamical evolution of these two models of internal structure permits to clarify the impact of the core's motion on the librations/nutations. We estimate the proper frequencies, the Free Core Nutation and the Chandler Wobble, of the two-layer Earth model. Moreover, we compute the dynamical motion of the core itself, and find that it has a larger amplitude than the dynamical motion of the mantle.

1. TWO-LAYER MODEL OF THE EARTH

In order to perform the terrestrial core-mantle interaction in a realistic model of the Earth's rotation, we have used the SONYR model of the Solar System including the Earth's spin-orbit motion. The SONYR model is a numerical approach to integrate the spin-orbit N-body problem,

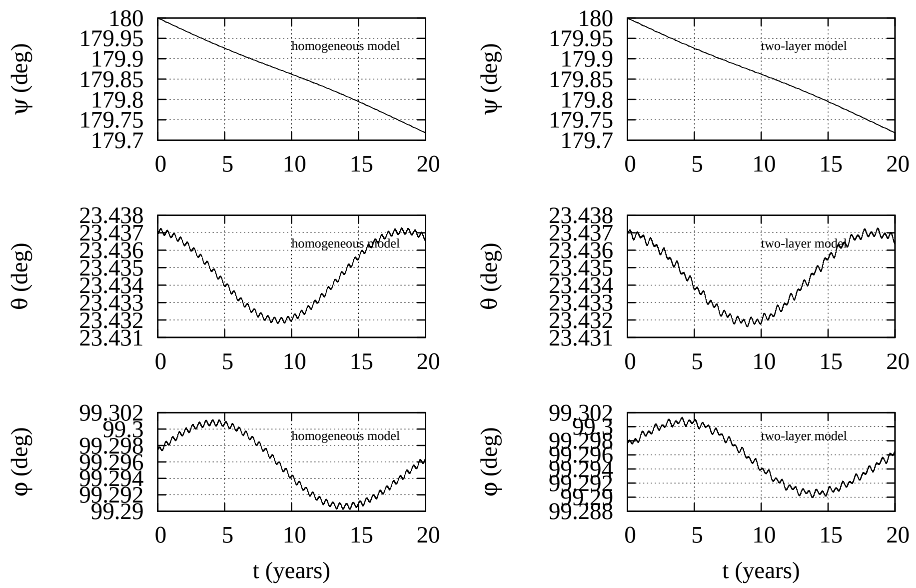

Figure 1: The rotational motion of the Earth's mantle in an homogenous and a two layer model expressed by the classical 3-1-3 Eulerian sequence (ψ, θ, ϕ) with respect to the ecliptic reference frame.

and to identify the different families of libration, of the terrestrial planets, with special emphasis for this paper on the Earth's spin-orbit motion (for details see Bois 2000; Bois and Vokrouhlicky 1995; Rambaux and Bois 2004). We obtain the dynamical behavior of the rotational motion of the Earth considered as a homogeneous body and as a model with two layers. In order to perform the core-mantle coupling, we have included the Poincaré model (see, e.g., Poincaré 1910; Moritz, 1980). The coupling between the mantle and core in this model is called inertial coupling, and is due to the pressure of the fluid on the core-mantle boundary. Figure 1 presents the comparison of the two models in the classical 3-1-3 Eulerian angles . The curves characterize the dynamical motion of the Earth considered as a homogeneous body and for the two-layer model.

In the case of the Earth composed of two layers, we have estimated the periods of two rotational normal modes, the Free Core Nutation (FCN, this period is defined with respect to an inertial reference frame) and the Chandler Wobble (CW, this period is expressed with respect to an Earth-fixed, co-rotating reference frame) at 333.5 and 275.2 days, respectively. Analytical models give 334.8 days for the FCN in the Poincaré case (Dehant *et. al.* 1999) and 274.1 days for the CW (Legros and Amalvict, 1985), these values are in a very good agreement with our model. Note that in contrast to the analytical expressions, SONYR also takes into account non-linear interactions and couplings between the three Euler angles, thus allowing to estimate the impact of these terms on the rotational behavior of the planet.

2. MOTION OF THE CORE INSIDE THE EARTH

We also investigated the dynamical behavior of the core itself. Generally speaking, the mean motion of the core follows the motion of the mantle. However, the dynamical motion of the core has a larger amplitude, the amplitude of the CW normal mode is of the order of 9 arcseconds, than the dynamical motion of the mantle for periods smaller than one year. The core performes oscillations, with amplitudes of the order of 230 meters at the core-mantle boundary. Due to this large motion of the core, it is possible to detect a signature of its presence in the nutation observations as already done by Herring et al. (1986).

We have included the presence of a core acting by inertial coupling on the rotational motion of the planet in the SONYR model. SONYR then becomes a model at the intersection between Celestial Mechanics and Geophysics. We have studied the impact of the core on the well-known rotational motion of the Earth. We clarified the signature of the core in the librations/nutations of the Earth, and we investigated in detail the motion of the core inside the mantle in the framework of the Poincaré model. Our approach allows coupling between spin-orbit in that framework, which has never been done before. Let us note that the SONYR model not only permits to study the rotation of Earth with different layers but can also be used for the Mercury, the Moon, Venus and Mars.

N. Rambaux acknowledges the support of a External Fellowship from the European Space Agency at the ROB and FUNDP.

3. REFERENCES

Bois, 1995, Astron. Astrophys., 296, 850-857

Bois 2000, CRAS, tome 1, Srie IV, 809-823

Bois and Vockrouhlicky, 1995, Astron. Astrophys., 300, 559-567

Dehant *et. al.*, 1999, Celestial Mechanics and Dynamical Astronomy, 72, p.245-310

Herring, T., C. Gwinn, and I Shapiro, 1986, J. Geophys. Res., 91, 4745-4755.

Legros and Almavict, 1985, Annale Geophysicae, 3, 5, 655-670

Moritz, 1980, report III No 342, eds. The Ohio State University, 109

Poincaré, 1910, Bull. Astron., 27, 321

Rambaux and Bois, 2004, Astron. Astrophys., 413, 381-393.

3D NORMAL MODE THEORY OF A ROTATING EARTH MODEL USING A LAGRANGIAN PERTURBATION OF A SPHERICAL MODEL OF REFERENCE

Y. ROGISTER[1], M.G. ROCHESTER[2]

[1] Ecole et Observatoire des Sciences de la Terre Strasbourg
5, rue Ren Descartes, F-67084, Strasbourg Cedex, France
e-mail: Yves.Rogister@eost-u.strasbg.fr

[2] Department of Earth Sciences, Memorial University of Newfoundland,
St. John's, Newfoundland, A1B 3X5, Canada

ABSTRACT. The normal mode theory of a rotating Earth model is based on the superposition of two perturbations. The first one is the perturbation of a spherically-averaged model of reference by rotation; it provides the rotating Earth model. The second one is a perturbation of the rotating model; it is a normal mode. In both cases, we consider Lagrangian perturbations. This implies that we define first a new coordinate system in the spherical configuration of reference. These coordinates, which are non-orthogonal, are such that the parameters of the spherical model depend on one of the coordinates only. The relation between the physical spherical coordinates in the rotating configuration and the new coordinates involves the radial discrepancy h between the spherical model of reference and the rotating model. We assume that, prior to being perturbed, the rotating model is in hydrostatic equilibrium. We determine the shape of the rotating configuration to the second order in h, using the theory of hydrostatic equilibrium figures. Next, we write the equations of motion of the rotating model in the new coordinate system. We suppose that the stress-strain relation is linearly elastic and isotropic. By inserting the analytical solution for the tilt-over mode in the equations of motion, we show that the terms containing the initial equilibrium gravity must be computed to the second order in h. Finally, we separate the variables in the equations of motion by expanding the unknown functions on the basis of surface spherical harmonics. We obtain an infinite set of coupled first-order ordinary differential equations that, if truncated, is suitable for numerical integration.

Rogister & Rochester GJI 159, 3, pp 874-908

THE DECADE FLUCTUATIONS OF THE EARTH ROTATION VELOCITY AND OF THE SECULAR POLAR MOTION

N. SIDORENKOV
Hydrometcentre of RF
B.Predtechensky pereulok, 11-13, Moscow 123242, RUSSIA
e-mail: sidorenkov@rhmc.mecom.ru

The decade fluctuations of the Earth rotation velocity and the secular polar motion (DFER) are usually explained by the interactions of the Earth's core and mantle. This hypothesis well explains a close correlation between DFER and the variations in the rate of the westward drift of the geomagnetic eccentric dipole; it corresponds quite reasonably to the possible redistribution of the angular momentum between the fluid core and the mantle of the Earth. However, the hypothesis cannot explain the close correlations of DFER with the observable variations in the masses of the Antarctic and Greenland ice sheets, with the decade oscillations of the types of synoptic processes (the epochs of the atmospheric circulation), with the global anomalies of the atmospheric pressure and temperature, regional anomalies of the cloudiness, precipitation, and other climatic characteristics.

A new hypothesis is proposed. It supposes that DFER are the fluctuations of the velocity of the lithosphere drift along the asthenosphere. These fluctuations are due to the lithosphere moments of the inertia variations owing to the redistribution of the water masses between the World Ocean and the Antarctic and Greenland ice sheets. The atmospheric and oceanic circulations are responsible for the redistribution of water on the Earth's surface and govern the global climate. The initial cause of the decade oscillations of the atmospheric and oceanic circulations are, probably, the gravitational interaction between the Earth's non-spherical and eccentrical envelopes and the Moon, Sun, and planets (J.V.Barkin, 2002). The astrometrical consequences following from this hypothesis are discussed. See Figures and References below.

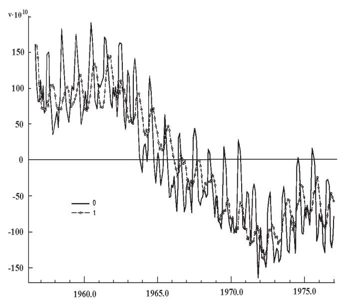

Figure 1: Monthly mean of the Earth angular velocity in 1957-1977:
0 - by the astronomical data; 1 - theoretical value (Sidorenkov, 1979, 2002).

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (project code 02-02-16178) and the Local Organizing Committee of the "Journées Systèmes de Référence Spatio-temporels 2004".

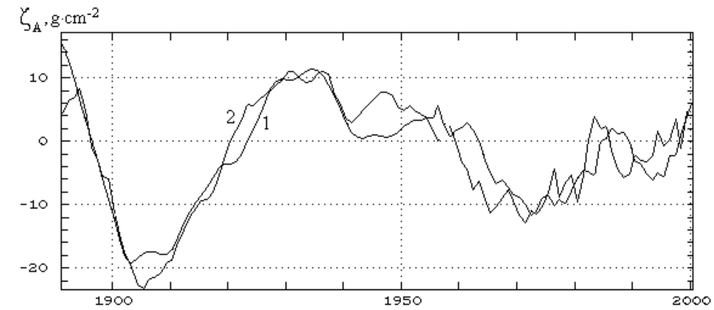

Figure 2: Temporal variations of the specific mass of ice ζ_A in Antarctica, gcm^{-2}.
1 - the theoretical value ζ_A; 2 - the empirical value ζ'_A (Petrov, 1975; Bryazgin, 1990).

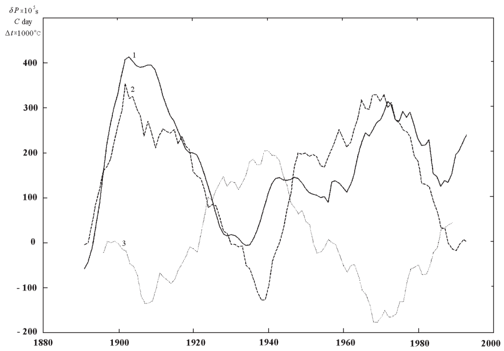

Figure 3: Synchronous changes in the length of day δP (1), the cumulative sums of anomalies of the circulation form C (2), and of the ten year running anomalies of the Northern Hemisphere air temperature Δt (after elimination of a trend and a thousandfold magnification (3).

REFERENCES

Barkin, Yu.V., 2000: A mechanism of variations of the Earth rotation at different timescales. In: Polar Motion: Historical and Scientific Problems (Eds. Steven Dick, Dennis McCarthy, and Brian Luzum)/Proceedings of IAU Colloquium 178 (Cagliari, 27-30 September 1999). Astronomical Society of the Pacific conference series, V. 208. Sheridan Books, Chelsia, Michigan. P. 373-379.

Lambeck, K., 1980: The Earth's Variable Rotation, Cambridge University Press, New York, p. 449.

Munk, W.H. and MacDonald, G.T.F., 1960:The Rotation of the Earth, Cambridge University Press, London, p. 323.

Sidorenkov, N.S., 1979: Astronomicheskii Zhurnal, 56, N 1, p. 187-199. /Soviet Astronomy-AJ, vol. 23, No. 1, P. 102-109/.

Sidorenkov, N.S., 1980: Meteorologiya i gidrologiya /Soviet Meteorology and Hydrology, No. 1, P. 39-45.

Sidorenkov, N.S., 1982: Vodnye Resursy /Water Resources/, N 3, P. 39-46.

Sidorenkov, N.S. 2002: Fizika nestabilnostey vrashenija Zemli [Physics of the Earth's rotation instabilities.]. Moscow, Nauka, Publishing Company Fizmatlit. p. 384 [In Russian with English summary and contents.]

Sidorenkov N.S., 2003: Influence of the atmospheric and oceanic circulation on the plate tectonics. In: Journees 2003. Astrometry, Geodynamics and Solar System Dynamics: from Milliarcseconds to Microarcseconds, St. Petersburg, September 22-25, Ed. A. Finkelstein and N. Capitaine, P. 225-230.

Vangengeim G.Ja., 1935: Opyt primenenija sinopticheskogo metoda k izucheniju i characteristike climata. [The experience of application of synoptic methods for studing and characterizing the climate.] Publishing house TSUEGMS, Moscow. p. 112. [In Russian].

ASTRONOMICAL RESEARCHES IN POINCARÉ'S AND ROMANIAN WORKS

M. STAVINSCHI, V. MIOC
Astronomical Institute of the Romanian Academy
Str. Cuţitul de Argint 5, RO-040557, Bucharest, Romania
e-mail: [magda, vmioc]@aira.astro.ro

ABSTRACT. Henri Poincaré was not only a honorary member of the Romanian Academy, but also an important collaborator of many Romanian mathematicians and astronomers. It is sufficient to mention Spiru Haret, the first doctor in mathematics at Sorbonne, or Nicolae Coculescu, the first director of the Astronomical Observatory of Bucharest. The 150th anniversary of the birth of the illustrious French personality offered us a good opportunity to study the relations he and two other Poincaré, Raymond and Lucien, had with Romania.

150 years ago, Jules Henri Poincaré, the one who was to become the glory of France and of universal mathematics, was born at Nancy. In 1860 Raymond Poincaré, future prime minister and president of France (1913-1920) was born. Finally, two years later, his brother, Lucien, an important physicist who was to become the rector of Paris Academy, was born.

The extremely close collaborations between the Romanians and the French, especially in the second part of the 19th century, made each of these illustrious names of the Poincarés play a not at all negligible part in the emancipation of the young Romanian state, which had just been set up, first through the union of the two principalities, Moldavia and Wallachia in 1859, and then through the union of these two with Transylvania, Bassarabia and Bucovina on 1 December 1918, when the Great Romania was born. We shall try to sketch at least a part of the connections of the three Poincarés with the Romanians.

Immediately after the Union of the Romanian Principalities in 1859 the first modern universities of Romania were set up. From among the first students sent to Paris for doctor thesis, three approached subjects of celestial mechanics, namely the theses of Spiru C. Haret, Constantin Gogu and Nicolae Coculescu.

One of the most outstanding performances of Henri Poincaré in the realm of mathematics is subtly and closely related to Spiru Haret. Both got resounding results in maybe the most celebrated problem of dynamics: the n-body problem, initially aimed at modeling the planetary motions in our Solar System. Even if not decisive, Haret's results helped and determined Poincaré to search for, to find, and to offer new fundamental methods, primarily intended to tackle this problem, but revolutionary and useful for most domains of science. Haret's and Poincaré's achievements marked, respectively, the end of a old era and the beginning of a new era in celestial mechanics and, in general, in mathematics.

Which is the link between Haret's and Poincaré's achievements from the narrow standpoint of the concrete problem they studied? Haret proved instability of the model of the n-body problem, but considering frequencies (mean motions) to be incommensurable. Taking also into account commensurabilities, and using generalized Fourier series (which generate quasiperiodic solutions), Poincaré proved the divergence of these series, which means instability, confirming in this way Haret's result. Haret's and Poincaré's results show that the question of the Solar system's stability remains still unsolved. Haret's work marked the beginning of the end of an era, that of exclusively quantitative endeavors in mathematics. 12 years younger than Henri Poincaré, Nicolae Coculescu was the third Romanian who presented a thesis of celestial mechanics in Paris, Sur les expressions approchées des termes d'ordre élevé dans le développement de la fonction perturbatrice, published in Journal de mathématiques pures et appliquées. Henri Poincaré was one of the members of the jury.

It is certain that Nicolae Coculescu asked many times the advice of his illustrious predecessor, the only evidence that we know of about this being the letter H. Poincaré received from his "élève bien dévoué" on 29 May 1899 (which is today in the archives of Nancy University). Naturally, H. Poincaré had other Romanian students as well. We should like to mention here one of the most brilliant ones, namely the physicist Dragomir Hurmuzescu, collaborator of Curies, author of important contributions to electricity and X-ray physics. He was one of the redactors of the two volumes of Poincaré, *Théorie mathématique de la lumière* (1889-1892).

Another volume of H. Poincaré, *Électricité et Optique de la lumière et les théories électrodynamiques* was published by Jules Blondin and Eugen Neculce, another physicist, professor at Bucharest University.

But H. Poincaré himself was in Romania. Finishing "École des Mines", he spend a lot of time for studying in Resita, a Romanian city situated at the epoch in the Austro-Hungarian Empire. His Mémoire sur la fabrication de l'acier dans le Banat has 213 pages.

Several famous universities, scientific societies and acadmies awarded Henri Poincaré. Between them, he was nominated "docteur honoraire en philosophie" of Cluj University (at the epoch Kolozsvar) and in 1909 "membre d'honneur" of the Romanian Academy.

Because the relations between the Romanians and the French are entirely special, being difficult to decipher all the threads that connect them, it is natural that in the most difficult moments of the two peoples' destinies there should be important moments of approach. Thus, in March 1919, Queen Mary visited France. The President of the Republic, Raymond Poincaré, felt obliged to receive the Queen of Romania at Elysée, with military honors, which was an unusual thing as the Queen was not a chief of state but only consort sovereign.

At the end of the First World War, France consolidated alliances in the East. It was a period of important exchanges of delegations between the two countries. Lucien Poincaré, the rector of Paris Academy and brother of the President of the Republic led one of the most important French missions in Romania. We still keep the photo of the delegation at the Astronomical Observatory in Bucharest. This has been only a short review of the most important relations established between Poincaré and the Romanians, unfortunately still very little studied.

REFERENCES

Diacu, F., Holmes, P.: 1996, Celestial Encounters. The Origins of Chaos and Stability, Princeton University Press, Princeton, NJ.

Diacu, F., Raţiu, T.: 2001, Rom. Astron. J. 11, 85.

Mioc, V., Stavinschi, M.: 2001, Rom. Astron. J. 11, 93.

Poincaré, H.: 1905, Leçons de Mécanique céleste, Gauthier-Villars, Paris.

Stavinschi, M.: 2004, L'Astronomie 118, 424.

SOLUTION OF HIGH FREQUENCY VARIATIONS OF ERP FROM VLBI OBSERVATIONS

B. ZHANG, J.L. LI, G.L. WANG, M. ZHAO
Shanghai Astronomical Observatory
80 Nandan Road, Shanghai 200030, China
e-mail: zb@shao.ac.cn

In the astrometric and geodetic VLBI data analysis software CALC/SOLVE (Ma et al., 1990), the high frequency variations of the Earth Rotation Parameters (ERP) are determined by a constrained continuous piecewise linear model, that is, the ERP rate within two epoch nodes is constrained to be smaller than a limitation setting, and the ERP is forced to be continuous at epoch nodes. Observation analysis shows that when the data points are not very dense the constraint and the continuation requirement are helpful to the improvement in the stability of the solution, but degrade the independence of ERP solutions at epoch nodes as well. By using the Userpartial entry of CALC/SOLVE a direct solution module (referred as ERPPART) of the high frequency variations of ERP is realized without any constraint on the rate nor the requirement of continuation at nodes. It is shown from real observation reduction that the direct solution mode is feasible.

According to Richter (2001) & Weber et al. (2000), the celestial pole offsets could not be solved together with the hourly resolution polar motion because the errors in the nutation model will expressed as retrograde nearly diurnal polar motions after coupling with the Earth rotation and so correlated with the solution of the hourly resolution polar motion. However, in the data analysis of long time span, the errors in the nutation model could not be neglected. There are generally two ways to deal with this case. One is to take the nutation series (could be fitted series from observations) directly as *a priori* inputs. The other is to take the corrections to nutation terms as global parameters in order to pick up the effects of nutation model errors. In CALC /SOLVE system the global and the arc parameters are solved for separately. The global parameters are solved firstly and by substituting back into the observation equations the arc parameters are solved secondly. Therefore by taking corrections to nutation terms as global parameters the correlation between the hourly resolution ERP and the nutation model errors could be resolved. In CALC/SOLVE the first way is already realized. For the second way, by using the User-Partial feature a new solution module (EOPPTWG) is compiled.

Global solutions of thousands astrometric and geodetic VLBI sessions are performed by using the original solution mode of SOLVE (referred as NORMAL) and the newly developed mode ERPPART and EOPPTWG. The ERP series within CONT02 (October of 2002) with two hours resolution were extracted. Fig.1 shows the adjustments (high frequency variation) and formal errors of the x component of polar motion. The curve in Fig.1 represents the model prediction given by Gipson (1996). From Fig.1 it is clear that the stability and the precision of the solution are becoming better from NORMAL, ERPPART to EOPPTWG.

In conclusion, when the data points are sufficient the constraint as well as the requirement of continuation of ERP at epoch nodes is not necessarily used. When observations with long time span are analyzed the possible errors in nutation model should be taken into consideration.

Compared with the NORMAL mode, solutions of the high frequency variation of ERP from ERPPART and EOPPTWG at different epoch nodes are more independent and so are more reasonable to use.

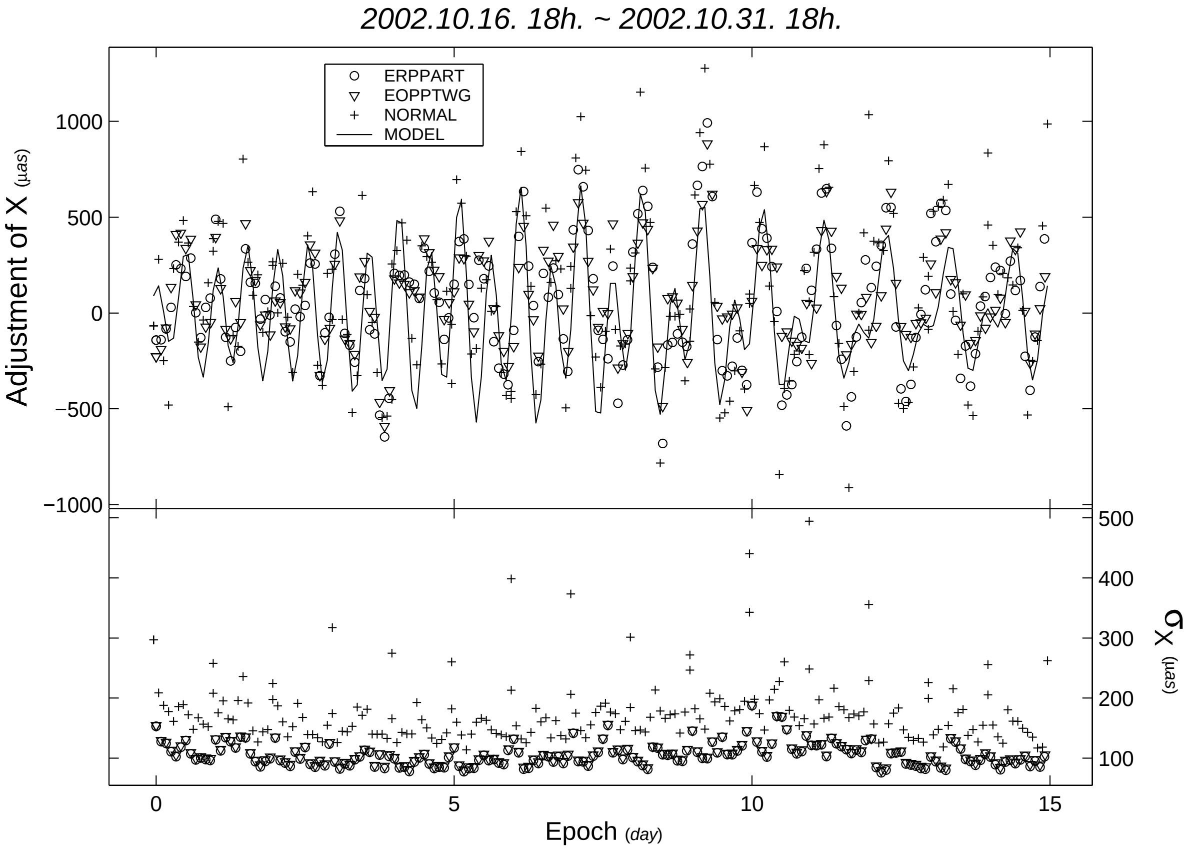

Figure 1: Solution comparison of X component of polar motion by ERPPART, EOPPTWG and NORMAL (see the text) mode (CONT02)

REFERENCES

[1]Gipson, J.M.: 1996, 'VLBI determination of neglected tidal terms in high-frequency Earth orientation variation'. J. Geophys. Res. 101:28051-28064

[2]Ma, C., Sauber, J., Bell, L., Clark, T., Gordon, D., Himwich, W. and Ryan, J.: 1990, 'Measurement of horizontal motions in Alaska using very long baseline interferometry'. J. Geophys. Res. 95: 21991–22013

[3]Richter, B.: 2001, 'Simultaneous estimation of polar motion and nutation parameters', IAG 2001 Scientific Assembly, Budapest, Sept 2-8, 2001

[4]Weber, R., Rothacher, M., Beutler, G.: 2000, 'Contribution of the GPS to monitor Earth Orientation Parameters', High frequency to subseasonal variations in Earth rotation, IERS technical note 28, Observatoire de Paris, 2000, 43-51

Session III

NOMENCLATURE IN FUNDAMENTAL ASTRONOMY

NOMENCLATURE EN ASTRONOMIE FONDAMENTALE

REPORT OF THE IAU DIVISION 1 WORKING GROUP ON "NOMENCLATURE FOR FUNDAMENTAL ASTRONOMY" (NFA)

N. CAPITAINE, Observatoire de Paris, France
and
C. HOHENKERK, HMNAO, UK; A.H. ANDREI, Observatorio Nacional, Brazil; M. CALABRETTA, ATNF, Australia; V. DEHANT, ROB, Belgium; T. FUKUSHIMA, NAO, Japan; B. GUINOT, Observatoire de Paris, France; G. KAPLAN, USNO, USA; S. KLIONER, Lohrmann Observatory, Germany; J. KOVALEVSKY, OCA, France; I. KUMKOVA, IAA, Russia; C. MA, GSFC, USA; D.D. MCCARTHY, USNO, USA; K. SEIDELMANN, Virginia University, USA; P. WALLACE, HMNAO, UK

ABSTRACT. A Division 1 Working Group on "Nomenclature for Fundamental Astronomy" (NFA) was formed at the 25th IAU GA in 2003 in order to provide proposals for new nomenclature associated with the implementation of the IAU 2000 Resolutions. This WG is also intended to make related educational efforts for addressing the issue to the large community of scientists. Five Newsletters were issued from October 2003 to July 2004 and posted on the NFA webpage (`http://syrte.obspm.fr/iauWGnfa/`). One important step has been the preparation of a questionnaire including a part on 'terminology choices' and a part for the Almanac Offices and related organizations. The summary of the responses and comments to this questionnaire and further questions have led to draft WG recommendations and guidelines on terminology together with a Resolution proposal to the IAU 2006 GA which are supported by explanatory documents. This paper reports on the WG activities, draft recommendations and future actions.

1. INTRODUCTION

The IAU Working Group on "Nomenclature for Fundamental Astronomy" (NFA) was created by Division I at the 25th IAU General Assembly in July 2003 and officially installed by the IAU in November 2003. The general task of this WG is to provide proposals for new nomenclature associated with the implementation of the IAU 2000 Resolutions and to make related educational efforts for addressing the issue to the large community of scientists.

2. BACKGROUND ON IAU RESOLUTIONS ON THE REFERENCE SYSTEMS

At its 23rd General Assembly in 1997, the IAU adopted the International Celestial Reference System (ICRS) as specified by IAU Resolution A4, 1991 and the International Celestial Reference Frame (ICRF) (Ma et al. 1998) that realizes the ICRS. At the 24th IAU GA in 2000, a number of resolutions were passed that concern the definitions of astronomical reference systems and transformations between them:

- Resolution B1.3 specifies that the systems of space-time coordinates as defined by IAU Resolution A4 (1991) for the solar system and the Earth within the framework of General Relativity are named the Barycentric Celestial Reference System (BCRS) and the Geocentric Celestial Reference System (GCRS), respectively. It also provides a general framework for expressing the metric tensor and defining coordinate transformations at the first post-Newtonian level (see Soffel et al. 2003).

- Resolution B1.6 recommends the adoption of the new precession-nutation model (see Dehant et al. 1999) that came into force on 1 January 2003 and is designated IAU 2000 (version A corresponding to the complete model of Mathews et al. (2002), of 0.2 mas accuracy and version B corresponding to its shorter version (McCarthy and Luzum 2002) with an accuracy of 1 mas).

- Resolution B1.7, specifies the definition of the CIP as an intermediate pole separating, by convention, the motion of the pole of the ITRS in the GCRS into two parts:

  - the celestial motion of the CIP (precession/nutation), including all the terms with periods greater than 2 days in the GCRS (i.e. frequencies between -0.5 cycles per sidereal day (cpsd) and $+0.5$ cpsd),

  - the terrestrial motion of the CIP (polar motion), including all the terms outside the retrograde diurnal band in the ITRS (i.e. frequencies less than -1.5 cpsd or greater than -0.5 cpsd).

```
frequency in ITRS  - - - - |-------- |-------- |-------- |-------- |-------- |-------- |- - - -
                          −3.5     −2.5     −1.5     −0.5     +0.5     +1.5    (cpsd)
                          ----- polar motion|          |polar motion -----
frequency in GCRS  - - - |-------- |-------- |-------- |-------- |-------- |-------- |- - - -
                          −2.5     −1.5     −0.5     +0.5     +1.5     +2.5    (cpsd)
                                             |nutation|
```

- Resolution B1.8 recommends using the "non-rotating origin" (Guinot, 1979), designated CEO (Celestial Ephemeris Origin) and TEO (Terrestrial Ephemeris Origin), as origins on the moving equator in the celestial and terrestrial reference systems, respectively, and defines UT1 as linearly proportional to the Earth Rotation Angle (ERA) between the CEO and TEO on the moving equator (Capitaine et al. 2000).

Note that the CEO and TEO have now been renamed "Celestial intermediate origin" (CIO) and "Terrestrial intermediate origin" (TIO), respectively by the NFA Working Group (see Section 3).

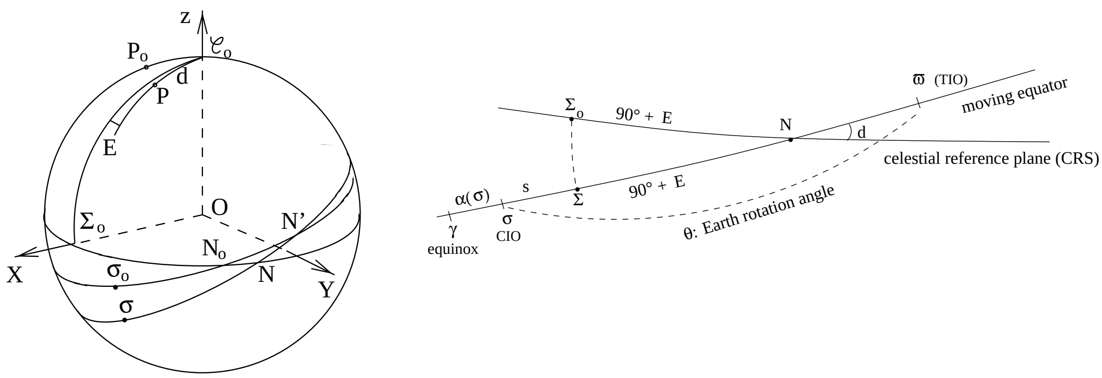

Figure 1: left: Definition of the CIP (P) and CIO (σ); right: Definition of the ERA

This resolution recommends that the transformation between the International Terrestrial Reference System (ITRS) and the GCRS be specified by the position of the Celestial Intermediate Pole, CIP, (defined by Resolution B1.7) in the GCRS, the position of the CIP in the ITRS, and the ERA (i.e. referred to CIO and TIO).

This resolution also recommends that the IERS continue to provide users with data and algorithms for the classical transformations (i.e. referred to the equinox).

- Resolution B1.9 provides the conventional linear relation between TT and TCG.

The IAU 2000 Resolutions have been implemented in IERS 2003 Conventions that include expressions, tables and routines based on either the classical or the new transformation.

3. ACTIVITIES OF THE NFA WORKING GROUP

The implementation of the IAU 2000 Resolutions (especially B1.3, B1.7 and B1.8) for various astronomical applications requires that a consistent and well defined terminology be recognized and adopted by the astronomical community for all the quantities based on the new concepts. The terminology issue began to be discussed within the ICRS Working Group in 2003 and in recent papers (Seidelmann and Kovalevsky 2002, Capitaine et al. 2003 a, b) and was identified during the 2003 IAU General Assembly as being an important and urgent issue. The Division 1 Working Group on "Nomenclature for Fundamental Astronomy" (NFA) was established by the 2003 IAU GA with the task of preparing a consistent and well defined terminology for fundamental astronomy.

Starting from October 2003, the activities of the NFA WG has consisted of newsletters, questionnaires, e-mail discussion and the preparation of WG recommendations and guidelines as well as a draft resolution to be submitted to the IAU 2006 GA. They have also included the preparation of explanatory documents that are intended to support the NFA recommendations. All the NFA material has been made available on the NFA web site.

The NFA WG Newsletters

Five newsletters were issued by the NFA WG from October 2003 to July 2004 to discuss the different steps to be followed by the WG in order to select the proposed terminology. One important step has been the preparation of a NFA questionnaire, a preliminary version of which was submitted to the WG (November 2003) with Newsletter 2. Suggestions of the WG were incorporated including splitting the Questionnaire into two parts; Questionnaire NFA/A on 'terminology choices' which was at first intended for the astronomical community, and Questionnaire NFA/B, for the Almanac Offices and related organizations. All the WG members responded to QA and the main Almanac Offices responded to QA and QB (issued on 13 January 2004). Newsletter 4 (15 March 2004) included a short summary of the questionnaire responses together with some further questions to the WG. The documents collecting the responses and comments to both questionnaires have been the basis for the preparation of WG recommendations and explanatory documents. These documents are more appropriate to be submitted for comments to the astronomical community instead of the questionnaire itself. Newsletter 5 (16 July 2004) included draft1 WG Recommendations and Resolution proposal.

The NFA WG web site

All the documents regarding the WG discussion and the Newsletters are posted on the webpage of the NFA WG at: `http://syrte.obspm.fr/iauWGnfa/`; the page also includes links to sites of interest for the WG activities. The NFA webpage contains, at the time of the Journées 2004, the following items: Membership, Working Group objectives and methods, Newsletters 1 to 5 with the NFA Questionnaire, NFA explanatory documents, Related documents, Questionnaire responses, Educational documents, IAU Resolutions and Links (to IAU, Div 1, IERS, IERS Conventions 2003, IERS FAQs, IVS, IAU Resolutions, Division 1 Working Groups).

The NFA WG e-mail discussion

There has been active WG e-mail discussion about the following points:

- the naming of the old and new paradigms (e.g. "equinoctial" and "orthogenic", respectively, or "equinox based" and "CIO based", respectively),

- the naming of the system defined by the CIP equator and the CIO (e.g. "intermediate"),

- the naming and order of certain steps in the transformation from ICRS to observer (e.g. 'apparent intermediate places'),

- the naming of the distance between the equinox and the CIO along the equator,

- whether to use capitals for names for origins, poles and systems,

- whether to improve the consistency of the nomenclature in using the designation "intermediate" to refer both to the pole and the origin of the new systems linked to the CIP and the CIO or TIO,

- whether to refer to catalogue coordinates as ICRF or ICRS coordinates,

- whether to use "system" or "frame" for the "intermediate frame/system",

- whether "right ascension" could legitimately be used in an extended way,

- the meaning of the term and concept of the ICRS (including orientation),

- the meaning of the term and concept of TCB/TDB,

- the relationship between the spatial axes of the BCRS and the ICRS,

- the need for a new name for the GCRS having its axes aligned to those of the ICRS.

The agreement reached by the WG on some of the above points has been reflected into the draft WG Recommendations; in contrast, there are still some weak points (e.g. the use of capitals) and some issues to be further discussed (e.g. the spatial axes of the BCRS/GCRS).

The NFA WG explanatory documents

This includes:

NFA/A documents providing the basis for the IAU Resolutions and their implementation,

NFA/B documents providing detailed implementation of the proposed terminology:

- B1: Chart from transformation from ICRS to observed places (20 July 2004),
- B2: Summary of terms and definitions (20 July 2004),
- B3: Terminology list (20 July 2004)

The educational activities

A special page of the NFA web site makes available documents (pdf files) with educational purpose relevant to the NFA issue; this includes:

(i) presentations at different meetings on the IAU Recommendations on Reference Systems and their applications (e.g. at Journées 2001, 2004, IVS Meeting 2004, AAS Meeting 2004, etc.),

(ii) one example transformation (from P. Wallace) which is an application of the IAU 2000 resolutions concerning Earth orientation and rotation in order to predict the topocentric apparent direction of a star.

4. NFA WG RECOMMENDATIONS AND GUIDELINES ON TERMINOLOGY

The summary of the responses and comments to the NFA questionnaire provided in the NFA Newsletter 4 and the responses to the questions of this Newsletter have led to draft Working Group recommendations and guidelines on terminology circulated to the WG with Newsletter 5. These guidelines have been discussed in July and August 2004 by the WG and they now need to be discussed by a larger community before being submitted to the IAU together with a Resolution proposal to the IAU 2006 GA (See the Annex of the NFA discussion, this Volume). The explanatory documents are updated according to the discussion.

5. REFERENCES

Capitaine, N., Guinot, B., McCarthy, D.D., 2000, "Definition of the Celestial Ephemeris Origin and of UT1 in the International Celestial Reference Frame", A&A 355, pp. 398–405.

Capitaine, N., Chapront, J., Lambert, S., and Wallace, P.T. 2003a, "Expressions for the Celestial Intermediate Pole and Celestial Ephemeris origin consistent with the IAU 2000A precession-nutation model", A&A 400, pp. 1145–1154.

Capitaine, N., Wallace, P.T., and McCarthy, D.D. 2003b, "Expressions to implement the IAU 2000 definition of UT1", A&A 406, pp. 1135–1149.

Dehant, V., Arias, F., Bizouard, Ch., Bretagnon, P., Brzezinski, et al. 1999, Considerations concerning the non-rigid Earth nutation theory, Celest. Mech. Dyn. Astr., 72, pp. 245-310.

Guinot, B., 1979, "Basic Problems in the Kinematics of the Rotation of the Earth," in *Time and the Earth's Rotation*, D. D. McCarthy and J. D. Pilkington (eds), D. Reidel Publishing Company, pp. 7–18.

Hohenkerk C., 2003, "Draft of Nomenclature and Terminology for the IAU WG" (Annex 6 of NFA Newsletter 1, October 2003).

IERS Conventions 2003, IERS Technical Note 32, D.D. McCarthy and G. Petit (eds), Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2004.

Ma, C., Arias, E. F., Eubanks, T. M., Fey, A., Gontier, A.-M., et al. 1998, "The International Celestial Reference Frame as realized by Very Long Baseline Interferometry", AJ 116, pp. 516–546.

Mathews, P. M., Herring, T. A., and Buffett B. A., 2002, "Modeling of nutation-precession: New nutation series for nonrigid Earth, and insights into the Earth's Interior", J. Geophys. Res. 107, B4, 10.1029/2001JB000390.

McCarthy, D. D. and Luzum, B. J., 2002, "An Abridged Model of the Precession-Nutation of the Celestial Pole," Celest. Mech. Dyn. Astr. 85, pp. 37–49.

Seidelmann, P.K. and Kovalevsky, J. 2002, "Application of the new concepts and definitions (ICRS, CIP, and CEO) in fundamental astronomy", A&A 392, pp. 341-351.

Soffel,M., Klioner, S., Petit, G., Bretagnon, P., Capitaine, N., et al. 2003, "Explanatory supplement for the IAU 2000 resolutions on relativity", AJ 126, pp. 2687–2705.

3D REPRESENTATION OF THE NON-ROTATING ORIGIN

O. DE VIRON, V. DEHANT
Royal Observatory of Belgium
Avenue Circulaire, 3, B-1180, Brussels Belgium
e-mail: v.dehant@oma.be

ABSTRACT. In the frame of the IAU working group of Nomenclature in Fundamental Astronomy (of which one of the objectives is to make educational efforts for addressing the implementation of the IAU 2000 Resolutions for a large community of scientists), we have developed a set of didactic animation in order to give a physical understanding to the concept of non-rotating origin (NRO). In this paper, we give a short explanation on the existing animations, in order to encourage their use. A complete zip file with all the material is available on : http://danof.obspm.fr/iauWGnfa/Educational.html.

1. ROTATION OF THE EARTH

The first movie shows that the Earth rotation is not constant. At first, it was used to define the timescale, but with the increasing precision of the measurement techniques, it became, at the end of the 18th century, rather obvious that the Earth rotation presents 3 types of variation:

- the Earth angular velocity is not constant, nor is the length-of-day,
- the Earth rotation axis moves in space,
- the Earth moves around its rotation axis.

Of course, in the real world, those three motions are mixed, and the Earth rotation is quite complicated.

This movie can be found on: http://www.observatoire.be/D1/DIDAC/rotationterre.htm

2. THE EARTH REFERENCE SYSTEM

In some applications, the Earth reference system was defined from the rotation axis (Z axis) and the Greenwich meridian (X axis). For reference frame purposes, the use of the Tisserand axis of the Earth was the most common approach (i.e. the axis attached to the mantle and defining a reference frame where the positions of points attached to the solid surface of the Earth have coordinates which undergo only small variations with time, see McCarthy, 2003). Nevertheless, this definition generates practical issues when it came to the realization of the reference system. The definition is based on the position at the Earth surface of a set of well known reference station.

This movie can be found on: http://www.observatoire.be/D1/DIDAC/systemeterrestre.htm

3. THE CELESTIAL REFERENCE SYSTEM

Originally, the Celestial reference system was defined from the positions of stars of which the proper motion was corrected. The Z axis was very close to the rotation axis and the X axis was defined in the direction of the vernal point, which is the intersection between the ecliptic plane and the equatorial plane. Nevertheless, this definition generates practical issues when it came to the realization of the reference system. Now, the reference system is based on a kinematical definition, making the axis directions fixed with respect to the distant matter of the universe (see McCarthy, IERS convention, 2003). The system is materialized by a celestial reference frame defined by the precise coordinates of extragalactic objects, such as quasars, BL on the grounds that these sources are so far away that their expected proper motions should be negligibly small.

This movie can be found on: http://www.observatoire.be/D1/DIDAC/systemeterrestre.htm

4. REFERENCE SYSTEM TRANSFORMATION USING EULER ANGLE

In this movie, we show the Euler angle method to change from one reference frame to another, allowing to only rotate around the axes of a given reference frame. This method is used in the next section.

This movie can be found on: http://www.observatoire.be/D1/DIDAC/anglesdeuler.htm

5. THE REFERENCE SYSTEM TRANSFORMATION

This set of two movies shows how it is possible to change from the terrestrial reference system to the celestial reference system. The first movie shows how it was done before the new conventions

This movie can be found on: http://www.observatoire.be/D1/DIDAC/anciennetransformationstsc.htm

The second movie shows how the new conventions allow to change reference frame.

This movie can be found on: http://www.observatoire.be/D1/DIDAC/nouvelletransformationstsc

6. THE MOTION OF SOME PARTICULAR POINTS

It is important to note that any point of the celestial sphere can qualify for a possible Non-rotating origin (NRO), as it is not so much the point which is important, but its motion. In this movie, we consider some particular points of the celestial sphere, of which the motion is imposed by their definition, and we show that none of them can qualify for being an NRO, as their motions is inappropriate. In addition, we show what would be the motion of a NRO. The advantage of the use of the NRO is that there is no component of the motion along the Z-axis, allowing for a description of the Earth rotation as a pure Earth rotation angle (the Earth Rotation Angle, ERA, or stellar angle) independent of the changes in the orientation of the Earth and of the definitions of the reference frames.

This movie can be found on: http://www.observatoire.be/D1/DIDAC/originenontournante.htm

IMPLEMENTATION OF THE NEW NOMENCLATURE IN THE ASTRONOMICAL ALMANAC

C. HOHENKERK
H.M. Nautical Almanac Office
Rutherford Appleton Laboratory
Chilton, Didcot, OX11 0QX, United Kingdom
e-mail: cyh@nao.rl.ac.uk

ABSTRACT. Following the resolutions of the 24th International Astronomical Union in 2000 (IAU 2000) together with the implementation and availability of the various software routines, it became imperative that *The Astronomical Almanac* (AsA) included the IAU recommended techniques for applying precession-nutation. This involves introducing the Earth rotation angle (ERA), the adopted relationship between Universal Time (UT1) and the rotation of the Earth, together with the celestial intermediate origin (CIO), the corresponding origin for right ascension. The introduction of the CIO has been complicated by the fact that new nomenclature is required, which is in the process of being discussed and agreed by the IAU Working Group on Nomenclature for Fundamental Astronomy. However, an attempt has been made in the 2006 edition to incorporate the new nomenclature (which is also used here) and describe the process in a straight forward way with the intention of helping the diverse user community.

1. THE ASTRONOMICAL ALMANAC AND THE NEW NOMENCLATURE

The *Astronomical Almanac* (AsA) is a joint publication with the Nautical Almanac Office of the US Naval Observatory. However, HM Nautical Almanac Office (HMNAO) is responsible for Section B - Time-scales and Coordinate Systems, and so it became our goal to include the IAU 2000 resolutions and in particular to explain how to calculate positions using the celestial intermediate origin (CIO) and the Earth rotation angle (ERA). This report is about the changes to Section B of the AsA, and not about the almanac as a whole.

It must be stressed that the whole almanac will include the IAU 2000 precession-nutation and all the updated constants, wherever relevant. This enhancement is a continuing process, and over the last few years there have been many improvements, particularly to incorporate the IAU requirements, e.g. use of the ICRS, the JPL DE405 ephemeris, and incorporation of the Hipparcos and Tycho-2 data. Also, equally importantly, the AsA continues to provide its users with all the equinox-based data, tables, formulae and explanation that are printed each year.

The adoption of the 2000 IAU resolution B1.8 means that the IAU is asking astronomers to adopt a new method for calculating "of date" positions. This is complicated by the fact that not only is a new nomenclature required, but it has also been proposed that the name of two of the fundamental quantities (the origins) that are specifically mentioned are changed, to make things more consistent. In particular, the resolution recommends the use of the "non-rotating" origin on the equator of the celestial intermediate pole (CIP) and names these origins the Celestial Ephemeris Origin (CEO) in the Geocentric Celestial Reference System and the

Terrestrial Ephemeris Origin (TEO), in the terrestrial system. These topics are in the process

UNIVERSAL TIME AND EARTH ROTATION ANGLE, 2006

Date 0^h UT1	Julian Date	Earth Rotation Angle	Equation of the Origins	Date 0^h UT1	Julian Date	Earth Rotation Angle	Equation of the Origins
	245	° ′ ″	′ ″		**245**	° ′ ″	′ ″
Jan. 0	**3735·5**	99 26 39·6076	− 4 34·6091	Feb. 15	**3781·5**	144 46 57·0025	− 4 41·9679
1	**3736·5**	100 25 47·8118	− 4 34·9270	16	**3782·5**	145 46 05·2067	− 4 41·9872
2	**3737·5**	101 24 56·0160	− 4 35·2004	17	**3783·5**	146 45 13·4109	− 4 42·0010
3	**3738·5**	102 24 04·2203	− 4 35·4072	18	**3784·5**	147 44 21·6152	− 4 42·0258
4	**3739·5**	103 23 12·4245	− 4 35·5460	19	**3785·5**	148 43 29·8194	− 4 42·0771

GHA = Earth rotation angle − α_i, $\alpha_i = \alpha_e +$ equation of the origins

α_i, α_e are the right ascensions with respect to the CIO and the true equinox of date, respectively.

Figure 1: Table of Universal Time and Earth Rotation Angle

of being discussed and proposed by the IAU Working Group on Nomenclature for Fundamental Astronomy, and it is thought that they will recommend that the names be changed to the celestial intermediate origin (CIO), and terrestrial intermediate origin (TIO). Thus the new fundamental quantities of the Celestial and Terrestrial Intermediate Reference Systems are the X, Y of the CIP, the angle s that positions the CIO on the equator of the CIP, and the ERA, which relates the CIO with the TIO.

An attempt has been made in Section B of the 2006 edition of the AsA to incorporate the new quantities and describe the process in a straight forward way using the new nomenclature, with the intention of helping the diverse user community.

When undertaking such a revision, the following points were considered. The AsA is a reference product for the year, it must be useful to the people who need the information, and it must maintain standards, be up-to-date and reliable. On the other hand, it is not an educational product, nor is it at the forefront of research in fundamental astronomy. Such material is changing quickly and is not yet a standard; users require continuity. One must also consider the production process with deadlines, funding, and having access to the necessary personnel to incorporate, produce and check the new material.

One of the most difficult in this case is that the AsA is not a text book. Of course, the AsA may be used in education. In general, the style and content assumes some level of knowledge and a balance is required between explanation and information.

NUTATION, OBLIQUITY & INTERMEDIATE SYSTEM, 2006
FOR 0^h TERRESTRIAL TIME

Date	NUTATION		True Obl. of	**Julian**	CELESTIAL INTERMEDIATE SYSTEM		
	in Long.	in Obl.	Ecliptic	**Date**	Pole		Origin
0^h TT	$\Delta\psi$	$\Delta\epsilon$	ϵ 23° 26′	0^h TT	$\mathcal{X}$	$\mathcal{Y}$	s
	″	″	″		″	″	″
Jan. 0	− 2·1954	+ 8·3424	26·9813	**3735·5**	+ 119·3163	+ 8·2546	− 0·0025
1	− 1·9865	+ 8·3810	27·0186	**3736·5**	+ 119·4543	+ 8·2931	− 0·0025
2	− 1·8262	+ 8·4452	27·0815	**3737·5**	+ 119·5731	+ 8·3570	− 0·0025
3	− 1·7383	+ 8·5198	27·1548	**3738·5**	+ 119·6630	+ 8·4316	− 0·0026
4	− 1·7246	+ 8·5872	27·2209	**3739·5**	+ 119·7234	+ 8·4989	− 0·0026

Figure 2: Table of Nutation, Obliquity and Celestial Intermediate Reference System

After due consideration, it was decided that time and manpower would not allow a complete re-write of the whole of Section B. No change would be made to the methods and algorithms, nor would the precision of any of the tables change. The new quantities and methods would be incorporated, remembering that all existing material is still required. For HMNAO, the problem of updating our software was greatly helped by using the IAU SOFA[1] Fortran library. All the basic quantities were also successfully compared with NOVAS[2], USNO's independent implementation. The assistance of the staffs of USNO's AA Department, HMNAO, and Dr. N. Capitaine are gratefully acknowledged.

Nomenclature is all pervasive but not everything is specified in the IAU resolutions. First one must consider the quantities that need tabulating and then the explanation.

ICRS FRAME BIAS, PRECESSION AND NUTATION, 2006

MATRIX ELEMENTS FOR CONVERSION FROM

ICRS TO TRUE EQUATOR AND EQUINOX OF DATE

Date 0^h TT	$\mathbf{NPB}_{11}-1$	$\mathbf{NPB}_{12}$	$\mathbf{NPB}_{13}$	$\mathbf{NPB}_{21}$	$\mathbf{NPB}_{22}-1$	$\mathbf{NPB}_{23}$	$\mathbf{NPB}_{31}$	$\mathbf{NPB}_{32}$	$\mathbf{NPB}_{33}-1$
Jan. 0	−105	−133 134	− 57 841	+133 132	− 89	−4079	+ 57 846	+4002	− 17
1	−106	−133 288	− 57 908	+133 286	− 89	−4098	+ 57 913	+4021	− 17
2	−106	−133 421	− 57 965	+133 418	− 89	−4129	+ 57 971	+4052	− 17
3	−106	−133 521	− 58 009	+133 519	− 89	−4165	+ 58 014	+4088	− 17
4	−106	−133 588	− 58 038	+133 586	− 89	−4198	+ 58 044	+4120	− 17

Values are in units of 10^{-8}. Matrix used with GAST (B12-B19). CIP is $\mathcal{X} = \mathbf{NPB}_{31}$, $\mathcal{Y} = \mathbf{NPB}_{32}$.

Figure 3: Matrix elements for conversion from ICRS to True Equinox and Equator of Date

There is a new table (see Figure 1) with ERA tabulated daily at 0^h UT1 with the Equation of the Origins, the difference between ERA and Greenwich apparent sidereal time (GAST). There is the X, Y of the CIP, and s, the angle that defines the position of the CIO on the equator of date (see Figure 2). These quantities are tabulated on the same pages as the nutations in longitude and obliquity, and the true obliquity of the ecliptic.

ICRS TO CELESTIAL INTERMEDIATE SYSTEM, 2006

MATRIX ELEMENTS FOR CONVERSION FROM

ICRS TO CELESTIAL INTERMEDIATE ORIGIN AND TRUE EQUATOR OF DATE

Julian Date	$\mathbf{C}_{11}-1$	$\mathbf{C}_{12}$	$\mathbf{C}_{13}$	$\mathbf{C}_{21}$	$\mathbf{C}_{22}-1$	$\mathbf{C}_{23}$	$\mathbf{C}_{31}$	$\mathbf{C}_{32}$	$\mathbf{C}_{33}-1$
245									
3735·5	− 1673	+ 6	− 578 4616	−237	− 8	−40 0195	+ 578 4616	+40 0195	− 1681
3736·5	− 1677	+ 6	− 579 1308	−238	− 8	−40 2059	+ 579 1308	+40 2060	− 1685
3737·5	− 1680	+ 5	− 579 7065	−240	− 8	−40 5160	+ 579 7065	+40 5161	− 1689
3738·5	− 1683	+ 5	− 580 1425	−242	− 8	−40 8775	+ 580 1425	+40 8775	− 1691
3739·5	− 1685	+ 5	− 580 4354	−244	− 8	−41 2038	+ 580 4354	+41 2038	− 1693

Values are in units of 10^{-10}. Matrix used with ERA (B20-B23).

Figure 4: Matrix elements for conversion from ICRS to the CIO and True Equator of Date

Finally there are the "precession-nutation" matrices, which are tabulated on an open pair of pages. The equinox-based bias, precession and nutation matrix is tabulated on the left-hand pages (see Figure 3) and the equivalent CIO-based matrix on the right-hand pages (see Figure 4). Shading has been used to highlight the CIO-based quantities.

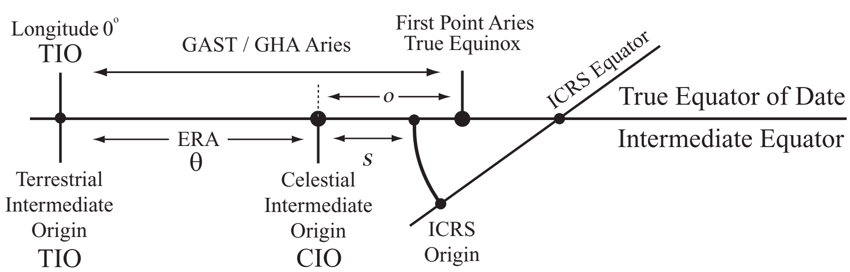

Figure 5: Schematic diagram showing the Equator, the Equinox, the CIO and the TIO

The explanation, which is the more difficult part, has been revised and extended. Apart from giving the various formulae for ERA, X, Y and s, a simple schematic diagram (see Figure 5) has been included that shows the relationships between the old and new quantities. This shows that both methods use the same equator (and pole), and that the resulting hour angles are identical.

Equinox Method	*CIO Method*
5. Apply frame bias, precession and nutation to convert from the ICRS to the system defined by the true equator and equinox of date.	**5.** Rotate the ICRS to the intermediate system using $\mathcal{X}, \mathcal{Y}$ and s to apply frame bias, precession-nutation.
6. Convert to spherical coordinates, giving the geocentric apparent right ascension and declination with respect to the true equinox and equator of date.	**6.** Convert to spherical coordinates, giving the geocentric intermediate right ascension and declination with respect to the CIO and the true equator of date.
7. Calculate Greenwich apparent sidereal time and form the Greenwich hour angle for the given UT1.	**7.** Calculate the Earth Rotation Angle and form the Greenwich hour angle for the given UT1.

Figure 6: Extract from the Planetary Reduction section showing the Equinox and CIO Methods

The planetary reduction has been extended to include the calculation of Greenwich hour angle, involving GAST or ERA, as appropriate, which allows users to see that both methods produce the same result. The description of both methods is done in parallel (see Figure 6). The left-hand column gives the familiar equinox-based method, and the right-hand column gives the new CIO-based method. Shaded heading and step numbers highlight the CIO-based material.

A new example has been included that takes the ICRS star position and calculates its approximate ($1''$) altitude and azimuth at a given UT1. The purpose of the example is to show how easy it is to use the new CIO method (see Figure 7) particularly for approximate work.

Step B. Apply aberration (from $\dot{\mathbf{e}}$) and precession-nutation (using $\mathcal{X}$, $\mathcal{Y}$) to form

$$\begin{aligned} x_i &= (1 - \mathcal{X}^2/2)\, p_x - \mathcal{X}\, p_z + \dot{e}_x/c &&= -0{\cdot}373\,494 \\ y_i &= p_y - \mathcal{Y}\, p_z + \dot{e}_y/c &&= -0{\cdot}312\,495 \\ z_i &= \mathcal{X}\, p_x + \mathcal{Y}\, p_y + (1 - \mathcal{X}^2/2)\, p_z + \dot{e}_z/c &&= -0{\cdot}873\,355 \end{aligned}$$

Figure 7: Extract from the altitude, azimuth example applying approximate precession-nutation

2. SUMMARY

The following table summarizes some of the terms. The left-hand column gives the familiar equinox-based nomenclature while right-hand column gives the new terms that are thought likely to be recommended by the IAU Working Group on Nomenclature for Fundamental Astronomy.

Equinox Based		**CIO Based**
True equator and equinox of date		Celestial Intermediate Reference System
Celestial Intermediate Pole (CIP), (X, Y)	=	CIP, (X, Y)
True equator of date	=	Celestial Intermediate equator
True equinox of date		Celestial Intermediate origin (CIO)
Apparent place		Intermediate place
Apparent right ascension		Intermediate right ascension
Declination	=	Declination
Greenwich apparent sidereal time (GAST)		Earth rotation angle (ERA)

3. REFERENCES

1. Wallace P., 2002, Update to SOFA report, in: *Highlights of Astronomy*, **12**, as presented at the XXIVth General Assembly of the IAU - 2000. Edited by H. Rickman. San Francisco, CA: *Astronomical Society of the Pacific*, **12**, 128. (http://www.iau-sofa.rl.ac.uk).
2. Kaplan (1990), Bull AAS **22**, pp. 930-931. For the IAU2000 version used for AsA 2006 see web site http://aa.usno.navy.mil/software/novas/new_ novas_ f/.

POST-IAU-2000 NOMENCLATURE FOR THE TELESCOPE POINTING APPLICATION

Patrick WALLACE
Rutherford Appleton Laboratory
Chilton, Didcot, Oxon OX11 0QX, UK
e-mail: ptw@star.rl.ac.uk

ABSTRACT. Pointing a telescope (or radio antenna) at celestial sources is, by the usual fundamental-astronomy standards, a rather low-accuracy application. Predictions of only 100 mas accuracy would in most respects be adequate, and this is well within the capabilities of even the pre-2000 models and procedures. However, the positional-astronomy part of the pointing application involves a long chain of transformations and corrections that has to be understood both by the astrophysicists who will use the telescope and by the engineers who will develop the control systems. These users, as well as being non-specialists in positional astronomy, have, with few exceptions, encountered only the old equinox-based methods. In addition, considerations of real-time computing efficiency usually make it necessary to calculate different effects and coordinates at different rates, rather than a straightforward end-to-end transformation for a given moment in time, introducing the need to label various "in-between" coordinates. All of these factors make telescope pointing a good test case for the post-IAU-2000 nomenclature. How easy is it to describe to a non-specialist how to point a telescope, and does the introduction of the new paradigm help or hinder this elementary task?

1. INTRODUCTION

Typical astronomical telescopes and antennas have mountings that consist of two rotating axes (generically *roll* and *pitch*) at right angles to one another, with the telescope or radio dish fixed to the pitch axis and at right angles to it. The most common configurations are *equatorial,* where the roll axis is parallel to the Earth's axis, and *altazimuth,* where the roll axis is vertical.

In essence, "pointing" means choosing roll and pitch angles—hour angle and declination in the case of an equatorial, azimuth and altitude in the case of an altazimuth—that bring the telescope or antenna into alignment with a specified celestial target. The process begins with *acquisition;* maintaining alignment as the Earth rotates is called *tracking.* Various techniques exist for high-accuracy acquisition and tracking, including dead reckoning, the use of finding charts, offsetting from an astrometric reference star, and autoguiding. The telescope's pointing control software also has to support the data acquisition system, by recording what part of the sky was being observed. This topic is called *world coordinate systems* (WCS), and in particular enables pixel coordinates (i, j) to be transformed into (α, δ) during subsequent data analysis. The accuracy requirements for WCS can be quite stringent, for identifying sources and overlaying pictures taken by different telescopes.

Telescope pointing is a good test case for positional-astronomy nomenclature schemes, for several reasons:

- The accuracy requirements, and hence the demands on the nomenclature scheme, are reasonable.
- On the other hand the application spans a wide range of transformations, with exposed intermediate stages.
- Typical users are not fundamental-astronomy experts.

2. THE APPLICATION AND ITS USERS

No existing groundbased telescope achieves dead-reckoning pointing better than about 2 arcseconds operationally, though some do considerably better than this in an *a posteriori* sense for the 1-2 hours it takes to perform an all-sky pointing test. Thus the control system's calculation of pointing direction could neglect effects below, say, 0.5 arcsec without much damage. However, relative accuracy needs to be better, say 1 mas, for reliable blind offsetting and to avoid digital noise when calculating tracking rates etc. In practice, there is a lot to be said for implementing the astrometric side of a telescope control system rigorously and completely. Validation is easier, there is more headroom and the application is future-proofed; moreover, with careful software design and modern computer hardware the extra computation is not an issue. However, for operational simplicity, most telescope control systems neglect polar motion (let alone IERS corrections to nutation); however, UT1−UTC is essential unless, for an equatorial mount, the old-fashioned "clock star" approach is taken to introduce an *ad hoc* hour-angle zero-point correction at start-up.

The target audience for the nomenclature scheme comprises:

- The telescope users themselves, typically astrophysicists but increasingly service observers. For the most part, the only celestial coordinates they use are ICRS, synonymous with FK5 and/or J2000 to the required accuracy. They also need to know in broad terms where their targets are, in particular the zenith distance (or air mass), so that scheduling decisions can be made in real time.
- The engineers and programmers who create and maintain the telescope control systems. They need to understand all the steps that lie between ICRS (α, δ) and telescope axis encoder readings.

Few of these people are will have heard of the IAU 2000 resolutions. They will have encountered only equinox/ST methods, even then with only a rudimentary grasp of the general principles, and will need to be persuaded that there are benefits in changing to a new scheme.

3. HOW TO POINT A TELESCOPE

Figure 1 shows the main components of a telescope pointing algorithm. The starting point is the catalog position of the science target, for example a star. Through a series of astrometric transformations, the *observed* azimuth and altitude (az,alt) are predicted, i.e. where a perfect theodolite would have to be pointed to see the star. The inputs to the transformation process include the time, UT1−UTC, the site location and the ambient air conditions (for refraction; for optical/IR the color is also needed). Once the observed (az,alt) is known, the mechanical properties of the telescope and mount can be allowed for—zero points, misalignments, flexures etc.—plus in more sophisticated control systems the desired focal-plane coordinates of the image.

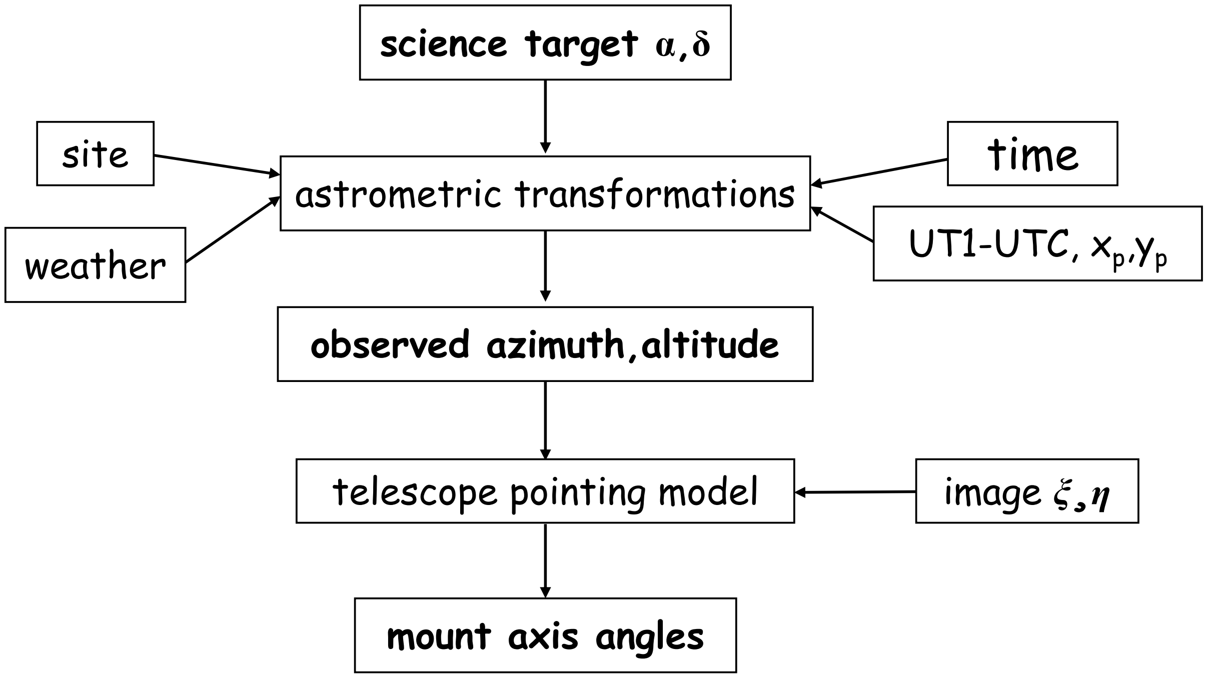

Figure 1: Telescope pointing algorithm.

The result is the mount-axis encoder readings required to acquire the image of the target. Final setting, and guiding, involves small *ad hoc* manual corrections either to the target (α, δ) or (usually more appropriate) to selected terms in the pointing model.

The entire transformation scheme has to be executed sufficiently often to keep the telescope tracking smoothly and responsive to guiding inputs, typically 10-20 times per second. Modern computers are so fast that the entire pointing calculation could be done at the full rate. But it is still usual to re-compute precession and nutation only occasionally, for example for each new target. In general, star-independent quantities—Earth ephemeris, precession, refraction etc.—can be refreshed infrequently; only Earth rotation is time-critical. All of this means that various sorts of interim coordinates are present in the software and must be clearly labelled.

4. ASTROMETRIC TRANSFORMATIONS

Figure 2 shows the sequence of transformations that take a star catalog entry and predict the where in the sky to point the telescope. Apart from certain preliminaries, the sequence corresponds to the box in Figure 1 labeled "astrometric transformations".

The starting point, **CATALOG** $(\boldsymbol{\alpha}, \boldsymbol{\delta})$, may include proper motion and parallax (and radial velocity) in addition to the star's coordinates at the catalog epoch[1]. The first step in the sequence of transformations is needed only for the case where the catalog epoch is not already J2000, and allows for space motion from the catalog epoch to J2000, to give the **INTERNATIONAL CELESTIAL REFERENCE SYSTEM** $(\boldsymbol{\alpha}, \boldsymbol{\delta})$**, epoch J2000**. A position from, say, the Tycho-2 catalog is already in this form. This step would be part of the preparation for acquiring

[1]ICRS is assumed here; demand by observers for FK4, FK5, and equinoxes other than 2000.0 has in practice all but disappeared and can in any case be dealt with pre-observation. Catalog epoch is normally J2000.0, but the Hipparcos catalog and the original Tycho catalog are epoch J1991.25, a fruitful source of mistakes. Proper motions are another minefield: both annual and centennial values are found, while RA proper motions may use time or arc measure and can either be $\dot{\alpha}$ or $\dot{\alpha} \cos \delta$.

CATALOG [α,δ]
proper motion, catalog epoch to J2000
INTERNATIONAL CELESTIAL REFERENCE SYSTEM [α,δ], epoch J2000
proper motion, J2000 to date
(barycentric) ICRS [α,δ] of date
annual parallax
ASTROMETRIC [α,δ]
light deflection
annual aberration
GEOCENTRIC ICRS [α,δ]
frame bias
precession
nutation
CELESTIAL INTERMEDIATE REFERENCE SYSTEM [α,δ]
Earth rotation
TERRESTRIAL INTERMEDIATE REFERENCE SYSTEM [λ,φ]
polar motion
ITRS / GREENWICH [h,δ]
site longitude
diurnal aberration and parallax
TOPOCENTRIC [h,δ]
h,δ to az,alt
TOPOCENTRIC [az,alt]
refraction
OBSERVED [az,alt]

Figure 2: The ICRS-to-observed transformation sequence.

a new target and would be performed just once. The same is in practice true for the second step, where proper motion from J2000 to date is applied, though on some telescopes it is part of the tracking loop for the sake of rigor. In Figure 2, the resulting coordinates are called the **(barycentric) ICRS ($\boldsymbol{\alpha}, \boldsymbol{\delta}$) of date**. There is at the time of writing some disagreement about whether such coordinates can be labeled "BCRS". I have taken the view here that it is unwise to use this term outside its metric tensor meaning, and to recognize that there is no preferred spatial axis directions in BCRS (Soffel et al., 2003). Using the ICRS label also has the advantage that telescope users and engineers will recognize the term, whereas BCRS (and GCRS) will be new to them. The next step is to allow for annual parallax, thereby changing the viewpoint to the geocenter and producing the *coordinate direction* of the target. Note that this step has eliminated the final distinction between the star and any other source outside the solar system. It is useful to label the result the **ASTROMETRIC ($\boldsymbol{\alpha}, \boldsymbol{\delta}$)**. even though this has a tautological flavor.

The coordinate direction is next transformed into the *natural direction* by allowing for the path of the light ray through the solar system. For telescope pointing applications, only the Sun's gravitational field need be included, and even then the effect becomes appreciable only very close to the Sun. Finally, the star's direction as seen by a geocentric observer is obtained by allowing for annual aberration. In Figure 2, the resulting *proper direction* is labeled **GEOCENTRIC ICRS ($\boldsymbol{\alpha}, \boldsymbol{\delta}$) of date**. The alternative would be to say "GCRS", but the same arguments apply as for BCRS (see above). The adopted term *geocentric ICRS* may not be destined to receive official recognition but is at least self-explanatory: compared with plain ICRS, the orientation of the coordinate triad has not changed, but the viewpoint has.

We now reach the set of transformations that reflect the attitude and orientation of the Earth in space. The first step is to rotate the coordinate triad so that it aligns with the celestial intermediate pole (CIP) of date and the celestial intermediate origin (CIO) of date[2]. The components of this transformation are the frame bias, precession and nutation, and there are various ways of computing it (Capitaine et al. 2004). The result is the **CELESTIAL INTERMEDIATE REFERENCE SYSTEM $(\boldsymbol{\alpha}, \boldsymbol{\delta})$** of date.

The transition from slowly-changing celestial coordinates to rapidly-changing terrestrial coordinates occurs when the coordinate triad is turned about its z-axis through the Earth rotation angle (ERA) to produce the **TERRESTRIAL INTERMEDIATE REFERENCE SYSTEM $(\boldsymbol{\lambda}, \boldsymbol{\phi})$**. After the small supplementary re-orientation to take into account the tiny quantity s' and the polar motion, the resulting vector is in the **INTERNATIONAL TERRESTRIAL REFERENCE SYSTEM** and corresponds to the point on the Earth at which the star is in the zenith or, equally well, the **GREENWICH $(\boldsymbol{h}, \boldsymbol{\delta})$**, with due regard to the hour angle sign convention. By rotating the triad about z through the site longitude, and, depending on accuracy objectives, the diurnal aberration,[3] we reach the **TOPOCENTRIC $(\boldsymbol{h}, \boldsymbol{\delta})$**. Transformation from equatorial coordinates to azimuth and altitude requires the site latitude, ϕ, to give **TOPOCENTRIC $(\boldsymbol{az}, \boldsymbol{alt})$**. and finally atmospheric refraction (a function of pressure, temperature and humidity at the telescope and, in the optical/IR case, color) is applied to give the **OBSERVED $(\boldsymbol{az}, \boldsymbol{alt})$**. This is the direction in which the telescope or antenna must be pointed. It differs from the actual settings of the mount because of mechanical misalignments and distortions, and the location in the focal plane to which the image is to be delivered. These corrections are typically some tens or hundreds of arcseconds in size. See Wallace (2002) for details.

5. CONCLUDING REMARKS

The scheme outlined above complies for the most part with the latest nomenclature recommendations, is as complete as the application requires and is no harder to grasp than its classical predecessors. But there are a few reservations:

- At the time of writing, opinion is moving towards adopting "BCRS" and "GCRS" as labels for the respective spatial coordinates. These names really apply to metric tensors and are about the computation of intervals in spacetime: applying them to spatial coordinates is at best informal and at worst misleading.

- The term "astrometric place" is used here in a way which corresponds to a plain-English meaning but not to published definitions, which mention aberration but not light deflection. There is a need to change the official definition so that future astrometric places include stellar light deflection, even for nearby objects such as minor planets. The concept is that the astrometric place is the point on the distant background occulted by the nearby object.

- In "CIRS", the word "intermediate" is weak. Although it identifies the link to the CIP and CIO, it fails to highlight the most noteworthy aspect of these coordinates, namely that

[2]It is equally valid to use the true equinox instead of the CIO, in which case apparent sidereal time will replace Earth rotation angle later on.

[3]. . . and in principle the diurnal parallax. Note that transforming from barycentric to topocentric with no intermediate geocentric stage would remove the need for a diurnal aberration step; however, from some points of view, general-purpose software and almanac tabulations for example, working via the geocenter has advantages.

they are moving because of precession-nutation. Some form of words such as “the CIRS place, i.e. the RA,Dec of date” can be employed to augment the bald label. Or perhaps the word “instantaneous” could be revisited, by a happy coincidence also beginning with “I”.

- In the scheme presented, “geocentric ICRS” is taken to mean that the effects of parallax, light deflection and aberration have been included (similarly GCRS versus BCRS if these labels are eventually adopted). Is this acceptable given that the spatial axes and the path of a light ray are really quite separate matters? Would it perhaps be better to label the triad (ICRS) and then identify the light direction (coordinate, natural, proper) separately?

However, it should not be forgotten that the classical names, though familiar, are baffling to beginners. Are “mean place”, “true place”, “apparent place” really self-explanatory, and how many practising astronomers could give a convincing definition of each of them? What about “virtual place”? How frequently is “epoch” used when “equinox” is meant? What do students make of the “equation of the equinoxes”. Or “uniform equinox”?

Whatever the relative merits of the classical and new paradigms, there is no doubt that “selling” will be needed before the new paradigm becomes properly established. Existing descriptions of the new paradigm tend to focus on the CIO, which because it is kinematically defined is a subtle and confusing change to existing approaches. A better idea is to start instead with Earth rotation angle. The superiority of the two-coefficient ERA(UT1) formula over the complicated and messy GAST(UT1,TDB) expressions is quite obvious; the fact that adopting ERA requires a change in the definition of the RA zero-point no surprise; and the actual location of the CIO, for telescope pointing purposes (in fact to better than 0.1 arcsec for another century) where the ICRS prime meridian crosses the equator of date, easy to remember.

Further reassurance comes from realizing that if the observatory's sidereal clock is set to local ERA, and CIRS coordinates are used instead of apparent places, everything still works as expected. Moreover, whereas observers at present can get a rough estimate of the hour angle from $h \simeq LST - \alpha_{J2000}$, they will in fact get a slightly better result from the new-paradigm equivalent, $h \simeq LERA - \alpha_{ICRS}$.

6. REFERENCES

Capitaine, N., Wallace, P.T., Chapront, J., 2004, A&A 421, 365

Soffel, M., Klioner, S.A., Petit, G., Wolf, P., Kopeikin, S.M., Bretagnon, P., Brumberg, V.A., Capitaine, N., Damour, T., Fukushima, T., Guinot, B., Huang, T.-Y., Lindegren, L., Ma, C., Nordtvedt, K., Ries, J.C., Seidelmann, P.K., Vokrouhlický, D., Will, C.M & Xu, C., 2003, AJ, 126 (6), 2687-2706

Wallace, P.T., 2002, Advanced Telescope and Instrumentation Control Software II, edited by Lewis, H., Proc. SPIE, 4848, 125

THOUGHTS ABOUT ASTRONOMICAL REFERENCE SYSTEMS AND FRAMES

M. SOFFEL
Lohrmann Observatory,
Dresden Technical University,
01062 Dresden, Germany

ABSTRACT. The various theoretical and practical structures necessary for a definition of the astronomical reference systems (BCRS, GCRS, ICRS) and frames (ICRF) are discussed. It is argued that with increasing accuracy the distiction between astronomical reference systems and corresponding frames becomes increasingly problematic.

For the description of precise astronomical observations various astronomical reference systems have been introduced: the BCRS, GCRS, ICRS and ITRS. At least for the ICRS and the ITRS corresponding frames, the ICRF and ITRF have been realized. This article tries to sketch the various constructive elements related with the definition of these systems and frames. Naively speaking a coordinate system is defined by a set of formal rules about mathematical structures and how to interact with the universe to produce a corresponding frame. A frame is thought to be the practical realization of the corresponding system by means of observations and by attributing coordinates to certain material elements. In Table 1 I have tried to keep this distinction between systems and frames. In the left column I have listed theoretical concepts whereas observations, experiments or tests appear in the right column.

It is obvious that due to the high precision needed, e.g., for future astrometric measurements or spacecraft navigation the definitions of these systems and frames is necessarily very complex. Here I will start from simple elementary concepts and then will work my way to higher and higher complexity. I have devided this complexification into various levels simply for didactical purposes.

A reference system is a coordinate system or a chart in a manifold $\mathcal{M}$ giving n numbers to a set of points in an n-dimensional manifold endowed with some abstract metric tensor. Hence we start with a purely mathematical construction (Level 1).

In the next Level we relate the manifold picture with time and space of our universe, i.e., we consider 4-dimensional space manifold and a metric tensor with (non degenerate) metric tensor g obeying Einstein's field equations. To have a natural relation with nature physical time and space should have a variety of properties and the gravitational interaction should be described by Einstein's theory of gravity. This already is related with a huge complex of experiences with nature based upon the usual scientific interactions of observers with the universe including simplifications of various kinds. E.g., the 3 dimensionality of physical space can be experienced by simple observations; the local Euclidean topology certainly is an useful idealization since the treatment of differential equations is simpler than that of difference equations. In any case for distances smaller then about 10^{-33} cm (the Plack length) one expects the classical manifold picture to break down and a quantum mechanical picture will become necessary. Tests of Special Relativity and Einstein's theory of gravity (General Relativity Theory, GRT) present a huge subject for itself and will not be discussed further here (see e.g., Will 1993).

On the next Level we will come to the definition of the BCRS and the GCRS. First we will use a certain approximation to Einstein's theory of gravity, the first post-Newtonian approximation. On the experimental side we face the various tests of metric theories related with the first post-Newtonian approximation. Here the so-called paramatrized post-Newtonian framework where a set of formal PPN-parameters is introduced is of great value since measurements of them provide not only tests of GRT (where the most important parameters β and γ both take the value 1) but also serve is indicator for the measurement accuracy.

One may wonder why the reduction of Einstein's theory of gravity to its first post-Newtonian approximation is so important. The answer lies in the complexity of GRT that would not even allow for a reasonable definition of the mass of a body. For present accuracies the first post-Newtonian approximation is sufficient for the definition of astronomical reference system. Actually the first post-Newtonian framework is much simpler than the full GRT and the equations for the gravitational potentials are not more complex than Maxwell's equations of electromagnetism. In this approximation relativistic masses and higher multipole-moments (potential coefficients) of the various bodies in the gravitational N-body problem can be defined (Damour et al., 1991). This is by non means trivial; e.g., the post-Newtonian center of mass of some matter distribution like the solar system is based upon the vanishing of the corresponding mass dipole-moment $M_i = \int d^3x\, x^i \sigma + (1/10c^2)(d^2/dt^2) \int d^3x\, x^i \mathbf{x}^2 \sigma - (12/10c^2)(d/dt) \int d^3x\, \hat{x}_{ij} \sigma^j$ where $\hat{x}_{ij} = x^i x^j - (1/3)\mathbf{x}^2 \delta_{ij}$ and the gravitational mass density σ and mass-current density σ^i are determined from the components of the energy-momentum tensor by $\sigma = (T^{00} + T^{ss})/c^2$ and $\sigma^i = T^{0i}/c$.

In a next step we consider an idealization of our solar system as an isolated N-body problem. Locally that means that we consider only N bodies, the Sun, Moon, planets, certain asteroids etc., of constant post-Newtonian mass subject to their mutual gravitational action and nothing else. Nongravitational forces, mass losses etc. are neglected. Similarly we neglect all matter outside the solar system such as neighbouring stars other matter in our Milky Way or other galaxies. In addition to that we assume to be asymptotically flat, i.e., the metric potentials w and w^i to vanish asymptotically for $|\mathbf{x}| \to \infty$ and $t = \text{const.}$ ('spacelike infinity').

Next we choose special conditions for our coordinates by assuming a special form of the metric tensor. If we denote the flat space Minkowski metric tensor in inertial Cartesian coordinates by η ($\eta_{\mu\nu} = \text{diag}(-1, +1, +1, +1)$) we require *local* conditions: at the origin of our Barycentric Celestial Reference System we require that $g = \eta$ in the limit $T^{\mu\nu} = 0$, that is for vanishing masses in our N-body problem. Next we require an *asymptotic* condition that $g \to \eta$ if we approach spacelike infinity. Finally we relate the local with the asymptotic conditions by choosing the harmonic gauge for the BCRS metric tensor.

This finally defines the BCRS by the corresponding choice of the metric tensor that fixes the space-time coordinates up to certain symmetry transformations. Especially the orientation of spatial coordinates is not fixed and it can be done in many different ways, e.g., by observations of solar-system bodies or remote astronomical objects such as quasars.

A special coordinate transformation from barycentric coordinates (t, x^i) to suitably chosen geocentric coordinates (T, X^a) then defines the GCRS. Here one requires local conditions for the GCRS metric tensor: if we neglect the matter from the Earth itself then $G \to \eta$ at the geocenter. The gravitational action of other bodies appears only in form of tidal terms in the GCRS metric tensor. Moreover, we require the GCRS coordinates to be harmonic. Since the geocenter is accelerated one can show that such geocentric coordinates loose their meaning far from the geocenter (typically at distances of order c^2/a, where a is the acceleration of the geocenter; see, e.g., Misner et al., 1972). This implies that without the BCRS the GCRS cannot be defined. The orientation of spatial GCRS coordinates is fixed by choosing them to be kinematically non-rotating with respect to the spatial BCRS coordinates.

These constructions can be introduced theoretically in the frame of a post-Newtonian formalism. However, we want the BCRS to be related with the astronomical bodies of our solar system. This relation requires solar-system data with hight precision. Theoretically the dynamical equations of motion for a system of mass monopoles ('point masses') are the well known relativistic Einstein-Infeld-Hoffmann equations of motion that form the basis of the JPL DE-ephemerides. The theoretical framework features several parameters such as masses and initial conditions for positions and velocities that have to be fitted to observational data. Here a whole complex of practical problems how to deal with observational solar system data comes into play. For each specific kind of observations or measurements, e.g., optical observations on CCD-frames, radar ranging to spacecrafts or planets, LLR etc. a whole set of rules, recipies or models exist that tells the observer how to proceed.

In the next Level we want to approach the ICRS and the ICRF. Naively we might consider the ICRS as a special version of the BCRS with spatial orientations fixed by VLBI observations of quasars. This standpoint ignores the actual large scale structure of our universe including its global expansion. Since the redshifts observed in spectral lines of quasars usually are significant this cosmic expansion should not be neglected and the BCRS should be modified to account for that. Present work in that direction is described e.g., in Klioner and Soffel, 2004.

Obviously there is a basic concept related with the idea for the ICRS. The ICRS should represent some sort of cosmic global quasi-inertial coordinate system with respect to rotational motion defined by means of observations of very remote cosmic objects showing almost no proper motions. This is the vague concept behind the ICRS and the real problem is if or how it can be realized in our actual universe. In GRT a coordinate system is determined by the choice of the metric tensor that itself is related with the cosmic distribution of energy and momentum in the universe by Einstein's field equations. The ICRS concept in that manner is related with *cosmic assumptions* on the distribution of matter on very large distance scales and the corresponding world model. In our approach to the BCRS we neglected all cosmic matter outside the solar system and the field equations then imply that a corresponding 'world model' is asymptotically flat. In addition we could then assume that the distribution of quasars is such that apart from small random proper motions they are at rest with respect to our asymptotically Minkowskian coordinate system.

In our real world we might proceed with the Cosmological Principle saying that on very large scales of several billion lightyears the universe is homogeneous and isotropic, a picture that is supported by the latest data on the Cosmic Microwave Background Radiation (CMBR). In such a world-model asymptotically the metric would reduce to the Robertson-Walker metric and we might assume the set of quasars to be approximately at rest in suitably chosen Robertson-Walker coordinates.

Clearly any reasonable world-model should be supported by cosmological observations, deep redshift surveys, studies of the CMBR, etc. As solar system observations they present an art for itself related with expert knowledge and know-how.

After having chosen a suitable world-model we idealize again by neglecting e.g., the gravitational action of certain galaxies (i.e., certain gravitational lensing effects) or gravity waves. On the observational side we now study the properties of quasars in detail by means of VLBI observations and corresponding software such as CALC-SOLVE. We study the structures of quasars, variablities, identify fiducial points for coordinization etc. At this level of accuracy all the details of the software enter. How plate tectonics, the topospheric delay, loading effects etc. are modelled might influence the fitting of parameters related with the reference system.

Formally we might then require additional conditions for the spherical angles (α, δ) to fix the origin of coordinates and to ensure historical continuity. We then end up with the ICRS and VLBI observations of certain structural elements of quasars finally yield the ICRF in form of a quasar catalogue.

Considering these various aspects in the construction of astronomical reference systems and frames I would like to point out the following.

1 With increasing accuracy the precise definition of a reference system requires more and more observations. The distinction between a system and its frame becomes increasingly problematic. People frequently have asked: what is the ICRS? The answer might be related to very different possible standpoints between two extremes. Someone preferring the idea of a system to be defined by formal rules might argue that the ICRS is given by the BCRS plus cosmic assumptions. For most astronomers, however, that definition would not be broad enough and fail to characterize what commonly is thought to be the ICRS.

   For someone else the ICRS is defined by the complete set of rules (mathematical and others) for its construction including the treatment of atmospheric delays or the solar-system ephemeris. This other extreme standpoint implies that we devide the set of all observations, experiments and tests related with ICRS and described above into two parts: 1. into those that are related with the definition, that e.g., is based upon Einstein's theory of gravity, and 2. those very dedicated observations necessary for the realization of the corresponding frame.

   For all of that reasons one might suggest to speak about astronomical reference systems only. For a mechanical structure servoing for spatial reference such as a telescope mounting or a wall inside a spacecraft used for the orientation of spatial coordinates the word frame ic clearly appropriate.

2 The ICRS and the BCRS appear at different levels of abstraction. In principle the orientation of spatial axes of the BCRS could be fixed by different techniques. Presently it is determined by the ICRS and as long as this is clear the nomenclature must not necessarily point this out explicitly. However, in case several techniques compete in that respect the nomenclature should account for that and one should write e.g., $BCRS_{[\mathrm{QSO}]}$, $BCRS_{[\mathrm{dyn}]}$ etc.

REFERENCES

Damour, T., Soffel, M., Xu, C., 1991, Phys.Rev.D 43, 3273

Klioner, S., Soffel., M., 2004, Proceedings of the GAIA meeting 2004,Paris

Misner, C., Thorne, K., Wheeler, J., 1973, Gravitation, Freeman

Will, C., 1993, Theory and experiment in gravitational physics, Cambridge University Press

Theoretical concepts	**Observations, experiments, tests**
coordinates in manifolds with metric tensor g	
Level 1	
space-time manifolds (dim = 4, sign(g))	general properties of space and time
g satisfies Einstein's GRT	tests of GRT
Level 2	
post-Newtonian framework	specific tests
definitions, e.g., for centers of mass (barycenter)	
idealization, e.g., solar-system as isolated N-body problem	solar-system observations, tests of idealizations (e.g., external tidal forces)
special coordinate conditions	
BCRS [$(x^\mu = (ct, \mathbf{x}))$; g]	
orientation of spatial coordinates not fixed; can principally be done in many ways	
special coordinate transformation leads to **GCRS**, only a local system	solar-system ephemerides
Level 3	
ICRS concept	cosmological observations tests of Cosmol.Principle and world models
cosmic idealizations	
	detailed QSO observations identify fiducial marks
auxiliary conditions for (α, δ)	
	observe (relative) positions
ICRS	**ICRF**
Level 4	

Table 1: Various steps necessary for the definition of the BCRS, GCRS, ICRS and ICRF

SUMMARY OF THE DISCUSSION ON "NOMENCLATURE IN FUNDAMENTAL ASTRONOMY" DURING THE JOURNÉES 2004

N.CAPITAINE
Chair of the IAU Working Group on "Nomenclature for Fundamental astronomy"

This discussion took place on Tuesday 21 September 2004 (1700-1830), during the Journées 2004 in Paris, after Session III "Nomenclature in fundamental astronomy" chaired by D.D. McCarthy and including the following contributions:

"Report of the NFA Working Group" by N. Capitaine,

"3D representation of the Non-Rotating Origin" by O. de Viron and V. Dehant,

"Implementation of the new nomenclature in the Astronomical Almanac" by C. Hohenkerk,

"Post-IAU-2000 nomenclature for the telescope pointing application" by P. Wallace,

"The ICRS, BCRS and GCRS: astronomical reference-systems and frames in the framework of Relativity, problems of nomenclature" by M. Soffel M., S. Klioner.

The following points were introduced by the panel, composed of N.Capitaine, C.Hohenkerk, C.Ma, D.McCarthy, M.Soffel and P.Wallace, and were submitted to the audience for comments and discussion:

(1) The draft NFA WG recommendations,

(2) The draft Resolution proposal to the IAU 2006 GA,

(3) The WG explanatory documents,

(4) Future actions of the NFA Working Group.

The discussion on these points is summarized below.

(1) The draft NFA Working Group recommendations (see Annex to this summary)

The discussion concluded by supporting Recommendations 1 to 12, except for, in Recommendation 9, the comment on the use of Greenwich meridian which was considered unnecessary by a number of participants.

The most contentious points in the other recommendations were:

- in Recommendation 3, whether "intermediate" was the best term for the CIP/CIO triad,

- in Recommendations 5 and 6, whether to use "system" or "frame"; this was debated not only for the "intermediate frame/system" itself, which is quoted in this recommendation, but also for the ICRS/ICRF,

- in Recommendation 8, whether "right ascension" could legitimately be used for CIO based positions,

but the final conclusion was to support these Recommendations.

The conclusion on the system/frame question was using "system" in the broadest sense as possible (especially in the case of the intermediate system), but keeping "frame" for the set of coordinates as with the ICRF; a suggestion by M. Soffel to suppress the use of "frame" was debated but not supported, especially because of the necessity of having ITRF in the terrestrial case. Using special designations for particular realizations of the "intermediate celestial system" was supported, but not for the ICRS or ITRS which are considered as being theoretical ideal versions of the ICRF and ITRF, respectively, although a certain asymmetry was recognized between the celestial and terrestrial cases (e.g. special designations exist for the ITRF, such as ITRF2000, but not for the ICRF).

In Recommendation 12, there was the requirement that "ITRF prime meridian" be replaced by "ITRF zero-meridian" which was to be verified, and agreed afterwards, by the ITRS IERS Product Center (C. Boucher).

(2) The draft Resolution proposal to the IAU 2006 GA (see Annex to this summary)

This proposal was supported, except by one participant who was strongly against.

(3) The NFA Working Group explanatory documents (see the NFA website)

- B1 NFA document (Chart)
  There have been some criticisms of showing all the successive steps and giving them names: a suggestion to leave the chart as it is, simply adding an introductory sentence explaining that these steps are set out "as supplementary information for the general user community", was agreed. Some warning should also be given regarding the step from the intermediate terrestrial system to the local system that in fact it would require a more complicated process in the General Relativity framework in order to achieve a microarcsecond accuracy.
- B2 NFA document (summary of terms and definitions)
  There was a consensus that a more complete list of acronyms and abbreviations was needed to be added to the Chart.
- B3 NFA document (terminology list)
  This document will be revised when the ICRS/BCRS/CRS issue is clarified.
- The ICRS/BCRS/GCRS issue
  The recent WG question on how the GCRS is defined from ICRS was discussed in detail; the conclusion was that regarding the WG documents and recommendations, it may be simply necessary to specify at the start that the BCRS is considered together with the cosmological hypothesis of non-rotation of the directions of quasars [1]; introducing a new name for the GCRS that has its axes aligned to those of the ICRS was debated but without any definitive conclusion.

(4) Future actions of the NFA Working Group

Further educational efforts were strongly recommended. Part A of the NFA explanatory document is considered as being a key document to be realized by the WG. The 3D representation of the Non-Rotating Origin presented by O. de Viron will be made available (through a link to the appropriate URL) after some improvements on the NFA web page.

[1]More recent discussions with Sergei Klioner leads me to think, that in this case, we can assume in addition, that the BCRS considered here, has its spatial axes fixed to those of the ICRS; this would avoid having to introduce a new name for the GCRS that has its axes aligned to those of the ICRS.

ANNEX

IAU Division I Working Group on
"Nomenclature for Fundamental Astronomy" (NFA)

NFA Working group recommendations and guidelines on terminology

(Draft 5, 14 December 2004)

Introduction

The WG recommendations on nomenclature are the result of the work of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (NFA) from October 2003 to September 2004 (cf. NFA Newsletters 1 to 5, NFA Questionnaires A and B, and WG comments and answers to the questions of Newsletters 4 and 5). A draft Resolution is proposed to be submitted to the IAU 2006 General Assembly in order to approve the proposed terminology.

This draft of the WG Recommendations and Resolution takes into account the discussion that was organized on 21 September 2004 during the "Journées 2004" in Paris.

Separate NFA explanatory documents provide additional information for supporting the following NFA WG recommendations. Part A of these documents reports on the basis for the IAU Resolutions and their implementation and Part B provides more detailed implementation of the proposed terminology by means of the "Chart for transformation from ICRS to observed places" (Part B1), the "Summary of terms and definitions" (Part B2) and the "Terminology list" (Part B3).

WG Recommendations

1. *Using existing terms (e.g. right ascension) in extended ways for the terminology associated with the new paradigm with a clear specification*, rather than introducing new names,

2. *Using "equinox based" and "CIO based" for referring to the classical and new paradigms, respectively*,

Comment: the "Celestial/Terrestrial Intermediate Origin" with the acronym CIO/TIO is proposed here as the updated terminology to replace the IAU 2000 "Celestial/Terrestrial Ephemeris Origin" with the acronym CEO/TEO (see below items 3. and 4. and the proposed Resolution),

3. *Using "intermediate" to describe (i) the moving geocentric celestial reference system defined in the IAU 2000 Resolutions (i.e. containing the CIP and the CIO), and (ii) the moving terrestrial system containing the CIP and the TIO)*,

Comment: the term "intermediate" has been chosen to specify that these systems are intermediary systems between the geocentric celestial system and the terrestrial system, which are realized by using the models, constants and procedures that are conventionally accepted; it conventionally separates the instantaneous celestial orientation of the Earth into components we label polar motion (in the terrestrial system) and precession-nutation (in the celestial system),

4. *Harmonizing the name of the pole and the origin to "intermediate" and therefore changing CEO/TEO to CIO/TIO*,

5. *Using "system" in a broad sense rather than "frame" in this context of the intermediary system/frame*,

6. *Using special designations for particular realizations of the intermediate celestial system*,

Comment: this applies for example to "the IAU 2000A system" to designate the system which is realized by transforming the geocentric celestial system GCRS to the intermediate system using the IAU 2000A precession-nutation and associated frame biases at J2000 (the GCRS being transformed from the BCRS by using the coordinate transformation specified in the IAU 2000 Resolution B1.3),

7. *Keeping the classical terminology for "true equator and equinox" (or "true equinox based") for the classical equatorial system*,

8. *Choosing "equinox right ascension" and "CIO right ascension", respectively (or "RA with respect to the equinox/or CIO"), for the azimuthal coordinate along the equator in the classical and new paradigms, respectively* (Note that right ascensions and declinations with respect to the ICRS are usually designated by α_{ICRS}, δ_{ICRS}),

Comment: this is to be specified only once in the presentation of a paper if there is some risk of misunderstanding. Afterwards, "right ascension" alone is sufficient,

9. *Giving the name "equation of the origins" to the distance between the CIO and the equinox along the intermediate equator, the sign of this quantity being such that it represents the CIO right ascension of the equinox, or equivalently, the difference between the Earth rotation angle and Greenwich apparent sidereal time*,

10. *Retaining "apparent places" and "mean places" in the equinox based system*,

11. *Not introducing "apparent intermediate places" in the CIO based system, but introducing instead "intermediate places"*,

12. *Using "ITRF zero-meridian" to designate the plane passing through the geocenter, ITRF pole and ITRF x-origin and using, if necessary "TIO meridian" to designate the moving plane passing through the geocenter, the CIP and the TIO.*

Additional points

- *Considering a terminology associated with other types of apparent places, although it can be required for specific use, has not been considered as being essential for common astronomical use and is therefore not part of the NFA WG terminology recommendations*,

- *no WG consensus having been reached for having strict rules for using or not using capitals for names for origins, poles and systems, no recommendation on this issue is proposed by the WG.*

Draft Resolution to be submitted to the IAU GA 2006

Recommendation from the Division I IAU Working Group on "Nomenclature for Fundamental Astronomy" (NFA)

Complementary terminology associated with the IAU 2000 Resolutions

The XXVIth General Assembly of the IAU

NOTING

1) the adoption of resolutions IAU B1.1 through B1.9 by the IAU General Assembly of 2000, and

2) that the International Earth rotation and Reference Systems service (IERS) and the Standards Of Fundamental Astronomy (SOFA) activity have made available the models, procedures, data and software to implement these resolutions operationally, and that the Almanac Offices have begun to implement them beginning with their 2006 editions.

RECOGNISING

1) that using the designation "intermediate" to refer to both the pole and the origin of the new systems linked to the Celestial Intermediate Pole and the Celestial or Terrestrial Ephemeris origins, defined in Resolution B1.7 and B1.8, respectively would improve the consistency of the nomenclature, and

2) that the name "Conventional International Origin" with the potentially conflicting acronym CIO is no longer commonly used to refer to the reference pole for measuring polar motion as it was in the past by the International Latitude Service,

RECOMMENDS

1. that the designation "intermediate" be used to describe the elements of the moving reference system defined in the 2000 IAU Resolutions,

2. that the terminology "Celestial Intermediate Origin" (CIO) and "Terrestrial Intermediate Origin" (TIO) be used in place of the previously introduced "Celestial Ephemeris Origin" (CEO) and "Terrestrial Ephemeris Origin" (TEO), and

3. that authors carefully define acronyms used to designate elements of astronomical reference systems to avoid possible confusion.

Session IV

ASTRONOMICAL REFERENCE SYSTEMS

SYSTÈMES DE RÉFÉRENCE ASTRONOMIQUES

RELATIVITY IN THE PROBLEMS OF EARTH ROTATION AND ASTRONOMICAL REFERENCE SYSTEMS: STATUS AND PROSPECTS

M. SOFFEL, S. KLIONER
Lohrmann Observatory,
Dresden Technical University,
01062 Dresden, Germany

ABSTRACT. Status and prospects of the problems: Earth rotation and astronomical reference systems in the framework of relativity are discussed. Several points where future work is urgently necessary are pointed out.

1. RELATIVITY IN THE PROBLEM OF EARTH'S ROTATION

The description of rotational motion of extended bodies within Einstein's theory of gravity in the general case without approximation can only be achieved by direct numerical integration of Einstein's field equations, that is by methods of numerical relativity. Even the definitions of quantities like total angular-momentum or angular velocity presents a fundamental obstacle. Only in the idealized stationary case of a single uniformly rotating axisymmetric body the scalar quantities of spin, angular velocity Ω and principle moment of inertia are well defined (e.g., Komar 1959). The extremely useful *Newtonian* concept of a rigid body that for many purposes serves as first approximation to the real problem becomes meaningless in relativity where the sound speed is limited to the speed of light. Nevertheless, in a remarkable paper Thorne and Gürsel (1983) have shown that if one restricts to first order terms in Ω rigid bodies can be introduced in general relativity and one finds a Newtonian-like Euler theory apart from the usual MacCullagh relations between the potential coefficients (multipole moments) and the components of the moment of inertia tensor I_{ab}. In mathematical terms, in general

$$M_{ab} \neq -\mathrm{STF}(I_{ab})\,.$$

Here, M_{ab} is the Cartesian Symmetric and Trace Free (STF) mass quadrupole tensor, in the Newtonian limit equivalent to the usual potential coefficients (C_{lm}, S_{lm}) for $l = 2$.

For practical applications in the solar system usually one resorts to the first post-Newtonian approximation to Einstein's theory of gravity. There at least the construction of a post-Newtonian spin vector for one isolated body presents no problem (e.g., Fock 1959). In a series of papers Damour, Soffel and Xu (1991, 1992, 1993) formulated a new and improved approach to celestial mechanical problems within the post-Newtonian framework. Especially they gave a new definition of the spin (total intrinsic angular momentum) of a certain body A that is member of some gravitational N-body problem in the local frame comoving with body A. Also the PN dynamical equations for the evolution of the local spin vector was derived including the expression for the post-Newtonian torque. A Newtonian nutation theory with post-Newtonian torques was considered by Bizouard et al. (1992). For such a 'Newtonian plus a post-Newtonian torque' approach they found that the largest 'post-Newtonian corrections' to nutations in longitude and obliquity are given by

$$\Delta\Psi = 3 \times 10^{-7\prime\prime} \sin\Omega\,; \qquad \Delta\epsilon = 4 \times 10^{-7\prime\prime} \cos\Omega$$

where Ω is the ascending node of the lunar orbit with respect to the ecliptic.

Post-Newtonian Tisserand axes and a post-Newtonian moment of inertia tensor were introduced by Klioner (1996). Finally, Klioner et al. (2001) formulated a useful generalization of the Newtonian Euler theory of a rigid Earth: the rigid multipole formalism. In that framework no assumptions on the local flow of matter are made; instead one assumes the post-Newtonian mass- and spin-multipole moments as well as the components of the moment of inertia tensor to rotate with some common angular velocity vector. If this formalism is actually consistent with Einstein's theory of gravity, however, is not clear. Likely no physical flow of matter obeying causality and the principles from relativity leads to rigidly rotating multipoles. This, however, would not reduce the usefulness of the formalism since it should serve only as intermediate step to model the real deformable Earth consistent with Einstein's theory of gravity.

In a series of papers Xu and coworkers laid the foundation for a relativistic description of elastic deformable rotating astronomical bodies (Xu et al., 2001, 2003, 2004). This work is based upon the introduction of a displacement field in the first post-Newtonian approximation to Einstein's theory of gravity. One starts with an isolated equilibrium configuration for the Earth, described in the GCRS and then considers small perturbations described by the displacement field resulting form the tidal forces and the elastic behaviour of the Earth. The formalism that was developed by Carter and Quintana (1972; Carter 1973) here serves as mathematical basis. In the first of these papers the basic post-Newtonian formalism is presented in Cartesian coordinates (Xu et al., 2001), the second rewrites the fundamental equations in spherical coordinates and discusses junction conditions for the Earth's surface and for internal layers. In the third paper first for the non-rotating ground state the relevant equations are expanded in terms of generalized spherical harmonics (scalar-, vector- and tensor spherical harmonics) so that the original system of partial differential equations reduces to an infinite system of ordinary differential equations for the expansion coefficients. Usually such a system serves as basis for numerical integrations as they were performed in the Newtonian case by Wahr (1982), Schastok (1997) and Dehant and Defraigne (1997). It should be stressed that this line of research is far from being complete and has to be pursued in several directions. An expansion of relevant equations into generalized spherical harmonics is still lacking for a rotating ground state, which is necessary for the description of precession and nutation. Because of the complexity of equations it might be useful to study the orders of magnitude of the various post-Newtonian terms first and to continue the work with the largest relativistic terms only. It might even be possible to understand the origin and meaning of several of the larger post-Newtonian terms.

It must be confessed that this local approach still poses fundamental problems since the relation of the formalism with observed quantities related with Earth's rotation is completely unclear at the moment. Also unclear is the use of the formalism in the frame of a perturbative approach. In the Newtonian framework one usually starts with a theory for a rigid Earth and adds perturbations due to the Earth's elastic behaviour, due to angular momentum exchange between solid Earth and other subsystems such as the atmosphere, the oceans, the hydrosphere etc. by means of a transfer function. A corresponding post-Newtonian generalization without the employment of a transfer function, however, does not exist.

The formulation of a high precision Newtonian nutation theory for a rigid Earth's model has been pursued by several groups: Souchay and Kinoshita (1996; REN2000), Bretagnon et al. (1997, 1998 (SMART97)) and Roosbeek and Dehant (1998; RDAN97). Actually, such Newtonian rigid Earth nutation series serve as basis for more realistic nutation series including the IAU2000 nutation series.

As mentioned above a useful generalization of this approach to the post-Newtonian framework would be the model of rigidly rotating multipoles. Such a model has already been worked out in detail (Klioner et al., 2001) and the derivation of a corresponding nutations series is feasible and highly desirable. The GCRS with its timescale $T = \mathrm{TCS}$ will be the fundamental reference system.

In a first step the problem of constants and initial conditions for the relativistic equations of rotational motion should be investigated. The corresponding Newtonian initial conditions are discussed by Bretagnon et al., (1997, 1998). The following constants are relevant here: H_d: dynamical ellipticity of the Earth; a_E: its equatorial radius; masses of the Earth (M_E), Sun, Moon and planets; (A, B, C): principle moments of inertia of the Earth; (C_{lm}, S_{lm}): potential coefficients (mass multipole moments) of the Earth and the angle α describing the location of the principle axes with respect to the terrestrial $\hat{X}$-axis.

2. RELATIVITY IN THE PROBLEM OF ASTRONOMICAL REFERENCE SYSTEMS

For practical applications in the solar system the Barycentric Celestial Reference System BCRS with coordinates (t, x^i) and a corresponding Geocentric Celestial Reference System GCRS with coordinates (T, X^α) has been introduced. The properties of these two fundamental reference systems have been discussed exhaustively (e.g., Soffel et al., 2003). Still under discussion is the problem of orientation of spatial axes of the BCRS. Usually it is tacitly assumed that this orientation is given by the ICRF. Apart from these discussions it should be noted that the definitions of the BCRS and GCRS (or at least our understanding of these definitions) could be improved in several directions. One direction will be discussed below.

Present definitions of the BCRS assume the solar system to be isolated, i.e, one neglects cosmic matter outside of the solar system. Gravitational effects from neighbouring stars or galaxies can be considered as tidal terms in the same way that the Sun, Moon and planets are taken into account in the GCRS. These tidal terms have been estimated to be negligible for any applications in the solar system with current and foreseeable levels of accuracy, and thus neglected in the BCRS. Going to greater and greater distances at a certain distance scale the global geometry of the universe has to be considered. To include effects from the cosmological background is a more trickier task, and a new approach will be necessary here.

The apparently simple question whether the cosmological expansion happens also locally (that is, if a hydrogen atom or the Solar system also expand) is a very complicated one and presents still an unsolved problem. Starting from Einstein himself different authors got different answers using different arguments (see Bonnor (2000) for a review of recent progress). Certainly, the answer to this question crucially depends on our model of the matter in the universe and especially on the distribution of dark matter and "dark energy".

Recently (Soffel, Klioner, 2003; Klioner, Soffel, 2005), we have introduced the first "toy" version of the BCRS with cosmological terms in g_{00} and g_{ij}:

$$
\begin{aligned}
g_{00} &\approx -1 + \frac{2}{c^2}\, w(t, \mathbf{x}) - \frac{2}{c^4}\, w^2(t, \mathbf{x}) + \frac{1}{c^2}\, A_1\, |\mathbf{x}|^2, \\
g_{0i} &\approx -\frac{4}{c^3}\, w^i(t, \mathbf{x}), \\
g_{ij} &\approx \delta_{ij} \left(1 + \frac{2}{c^2}\, w(t, \mathbf{x}) + \frac{1}{c^2}\, B_1\, |\mathbf{x}|^2 \right),
\end{aligned}
\tag{1}
$$

where $A_1 = -q\, H^2$ and $B_1 = -\frac{1}{2}\left(H^2 + \frac{k\, c^2}{a^2}\right)$, H is the Hubble constant, q is the decelation parameter of the Universe, k is the curvature parameter and a is the current "radius of the universe".

Here we neglected: (1) higher post-Newtonian terms $\mathcal{O}(c^{-5})$ in g_{00} and in g_{0i}, and $\mathcal{O}(c^{-4})$ in g_{ij} due to post-post-Newtonian (and higher order) effects from the solar system matter (they were also neglected in the BCRS adopted by the IAU); (2) higher-order cosmological terms $\mathcal{O}(|\mathbf{x}|^4)$; (3) any terms induced by the interaction of the cosmological fluid (including the cosmological constant) with the solar system matter. To derive the latter kind of terms is still an unsolved problem which appears to be quite tricky. That is why, we call this form of the BCRS with cosmological terms a "toy" version.

Current best estimates of the cosmological parameters give $A_1 \approx 3.2 \times 10^{-36}$ s^{-2} and $B_1 = -2.6 \times 10^{-36}$ s^{-2}. The estimates described in (Klioner, Soffel, 2005) shows that the direct dynamical effects of the cosmological terms in the solar system can be neglected totally. However, for light rays coming from very large distances cosmological effects play obviously an important role.

The BCRS metric with cosmological terms suggested above implies that the cosmological expansion has a certain influence on the properties of space-time within the solar system. This is certainly true for the terms coming from the cosmological constant Λ or vacuum energy since this energy source is present everywhere. Note that recent cosmological observations suggest that about 73% of the energy in the universe comes from that source. The applicability of the suggested BCRS metric to the 4% coming from the luminous matter and the 23% of the dark matter has to be investigated further.

Azimuth and elevation

For some applications a consistent post-Newtonian definition of geometrical horizon angles, azimuth A and elevation angle a might be useful. Note that such a definition does not yet exist and it is not clear if for some application post-Newtonian accuracy will be necessary (for standard applications such as telescope pointing obviously not).

Post-Newtonian horizon angles can be defined by introducing three orthonormal (with respect to the GCRS metric) horizon vectors that we call: horizon-(normal), south- and east-vector. A definition involving a simple geometrical horizon-vector, pointing in radial coordinate direction, could read like this. Start from the GCRS and consider the topocenter at time $T_0 = TCG_0$. Transform the spatial GCRS coordinates X^a to new topocentric coordinates $\hat{X}^a$ only by change of orientation and origin such that the $\hat{Z}$-axis runs through the topocenter, the $\hat{X}$-axis points 'southwards' and the $\hat{Y}$-axis 'eastwards' in a coordinate sense. Next transform to local proper coordinates in the same way that we transformed from BCRS to GCRS coordinates, where the geocenter now is replaced by the topocenter. Such a transformation defines a set of instantaneous tetrad vectors attached to the topocenter and the three spatial vectors are the vectors denoted by 'horizon-(normal), south- and east-vector'. By a suitable projection of the tangent vector to some incident light-ray onto the horizon-vector and the south-vector the two horizon angles, azimuth and elevation can be defined rigorously.

3. REFERENCES

Bizouard C., Schastok, J., Soffel M.H., Souchay J., 1992, In: *Journées 1992*, N. Capitaine (ed.), Observatoire de Paris, Paris, 76–84.

Bonnor, W.B. 2000, Gen. Rel. Grav., 32, 1005

Bretagnon, P., Francou, G., Rocher, P., Simon, J.L., 1997, A&A 319, 305–317.

Bretagnon, P., Francou, G., Rocher, P., Simon, J.L., 1998 A&A 329, 329–338.

Brumberg, V.A., Bretagnon, P., Francou, G., 1991, in: *Métrologie et Astrométrie*, N. Capitaine (ed.), Proceedings of Journées 1991, Observatoire de Paris, Paris, 141–148.

Carter, B., 1973, Commun.Math.Phys., 30, 261

Carter, B., Quintana, H., 1972, Proc.Roy.Soc.Lond., A331, 57
Damour, T., Soffel, M., Xu, C., 1991, Phys.Rev. D 43, 3273.
Damour, T., Soffel, M., Xu, C., 1992, Phys. Rev. D 45, 1017.
Damour, T., Soffel, M., Xu, C., 1993, Phys. Rev. D 47, 3124.
Dehant, V., Defraigne, P., 1997, J.Geophys.Res. 102, 27659
Fock, V.A., 1955, *Teoria Prostranstva, Vremeni i Tyagoteniya*, Fizmatgiz, Moscow (translated into English as *Theory of space, time and gravitation*, Pergamon, Oxford, 1959).
IAU (2001) Information Bulletin No. 88, January 2001 (see also Erratum in Information Bulletin No. 89, June 2001 and the full text of the Resolution at `http://danof.obspm.fr/IAU_resolutions/Resol-UAI.htm`.
Klioner S.A., 1996, In: S.Ferraz-Mello, B.Morando, J.E.Arlot (eds.), Dynamics, ephemerides and astrometry in the solar system, Kluwer, Dordrecht, 309–320.
Klioner, S.A., Xu, Ch., Wu, X., Soffel, M., 2001. In: Influence of geophysics, time and space reference frames on Earth rotation studies (Proceedings of Journées'2001), N. Capitaine (ed.), Paris Observatory, Paris, 232–238.
Klioner, S.A., Soffel, M.H., 2004. Refining the relativistic model for Gaia: cosmological effects in the BCRS. Proceeding of the International Symposium "The three dimensional universe with Gaia", ESA, in press
Komar, A., 1959, Phys.Rev. 113, 334.
Roosbeek, F., Dehant, V., 1998, Celest. Mech. Dyn. Astr. 70, 215.
Schastok, J., 1997, Geophys.J.Int. 130, 137
Soffel, M., 1994, The problem of rotational motion and rigid bodies in the post-Newtonian framework. *unpublished notes.*
Soffel, M., S.A. Klioner, G. Petit, P. Wolf, S.M. Kopeikin, P. Bretagnon, V.A. Brumberg, N. Capitaine, T. Damour, T. Fukushima, B. Guinot, T. Huang, L. Lindegren, C. Ma, K. Nordtvedt, J. Ries, P.K. Seidelmann, D. Vokrouhlický, C. Will, C. Xu, 2003: The IAU2000 resolutions for astrometry, celestial mechanics and metrology in the relativistic framework: explanatory supplement. Astronomical Journal 126, 2687–2706.
Soffel, M., Klioner, S.A. 2004, The BCRS and the large scale structure of the universe. In: Proceedings of Journées'2003, N. Capitaine (ed.), Paris Observatory, Paris, in press
Souchay, J., Kinoshita, H., 1990, Celest. Mech. Dyn. Astr. 48, 187.
Thorne, K.S., Gürsel, Y., 1983, MNRAS , 205, 809–817.
Wahr, J., 1982, in: Geodesy and Geodynamics (H.Moritz and H.Sünkel (eds.), Mitteilungen der Geodätischen Institute der Technischen Universität Graz, No.41), 327
Xu, C., Wu, X., Soffel, M. (2001), Phys.Rev. D 63, 043002.
Xu, C., Wu, X., Soffel, M., Klioner, S. (2003), Phys.Rev. D 68, 064009.
Xu, C., Wu, X., Soffel, M., 2004 General-relativistic perturbation equations for the dynamics of elastic deformable astronomical bodies expanded in terms of generalized spherical harmonics, Phys.Rev.D, in press

THE GAIA REFERENCE FRAME : HOW TO SELECT THE SOURCES

F. MIGNARD

OCA/Cassiopée
Observatoire de la Côte d'Azur, BP. 4229, 06304 NICE CEDEX 4
francois.mignard@obs-nice.fr

ABSTRACT. The European space astrometry mission Gaia is scheduled for a launch in 2011 and aims to produce a complete sky survey down to $V = 20$ with an astrometric accuracy of 10 μas at $V = 15$. During its 5-year mission the satellite will also repeatedly measure the position of $\sim$500,000 quasars in a consistent way, leading to a direct realisation of the primary inertial frame in the visible in the framework the ICRS concepts. At $V = 20$ the sky density of the QSOs is about 1000 times smaller than that of the stars at mid galactic latitude, and given their number and their stellar-like images, this implies the construction an automatic recognition scheme of the non stellar sources with a sensitivity of the order of one part in a thousand. In this paper I present the expected performance for the realisation of the reference frame and discuss the procedure under development to select the primary sources.

1. PRESENTATION

Gaia will provide astrometric and photometric observations for the quasars (QSOs) at $G < 20$ mag over the whole sky, 5 times more than the number expected from the Sloan Digital Sky Survey. This will be the first all-sky, flux-limited survey to $V = 20$ of the extragalactic sources. Although there is no global survey of quasars available at the moment, local surveys indicate that the typical surface density of quasars is about 20 sources $V < 20$ per square degree, much smaller than that of the stars at any galactic latitude. So at the end one may reasonably expect a census of about 500,000 quasars at galactic latitudes $|b| > 20^\circ - 25^\circ$. Closer to galactic plane, Gaia faces two difficulties: (i) the galactic extinction and reddening that will block off the light of these distant and rather faint sources, (ii) the difficulty to discriminate between the stars as their relative density to that of the quasars increases drastically at low galactic latitudes (this ratio is about 10,000 at $b = 10^\circ$ and $G = 19$).

The extensive zero-proper motion survey will provide a direct realization of the quasi-inertial celestial reference frame with a residual rotation less than 0.5 $\mu\mathrm{as\,yr}^{-1}$ (Fig. 1) and a space density at least hundred time larger than that achieved by the radio version of the ICRF. Many more secondary sources (stellar or extragalactic) will also facilitate the access to this frame. The random instability of the sources puts a serious limitation in the ultimate precision of the inertial frame and imposes a strict selection of the primary sources, among a population of quasars already free of stellar contaminants. I discuss in the following sections the basic properties of the methods that has been considered for Gaia.

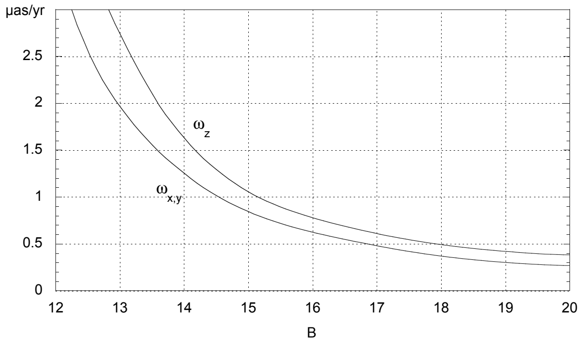

Figure 1: Precision of the spin rate of the inertial frame achievable with Gaia from the observations of the quasars. This is based on a simulation of 42,000 known sources (10,000 with $B < 18$) whose distribution with galactic latitude to that expected from Gaia. The precision read for a B magnitude is computed with only sources brighter than B selected. Here galactic coordinates have been used and the random instability has been taken equal to 20 μas yr^{-1}. Though there are many more faint objects than bright ones, the frame is primarily determined by the brightest sources, because of their astrometric precision. A similar situation should prevail in the real mission.

2. SELECTION OF KNOWN SOURCES

The way extragalactic sources are selected with Gaia depends on the science objective : to realise the survey one aims to generate a set of sources including most of the QSOs, accepting that the set may contain a significant number of stellar contaminants, to be removed later. Regarding the reference frame it is obvious that the selection must end with a very clean sample, probably much smaller, but without contaminant. In addition even among the well selected sources, many of them will not pass subsequent tests to be included in the list of primary sources to build the inertial frame, in case unaccounted proper motions are found or when a strong photometric instability will make the astrometric stability of the same sources questionable.

There are several possibilities available to create this clean sample where "clean" means that the sources are all extragalactic without contaminant. Hereafter the final selection of the most suitable sources for the reference frame is not considered and deferred to a further investigation. The number of sources is an important criteria, but not critical as long as $\sim$ 5000–10000 are available. However the space distribution is a key factor : we have many new sources with the SDSS, but primarily located around the galactic cap, definitely an undesirable feature to build a rigid reference frame. Thus one can :

- use the ICRF sources brighter than $G = 20$;
- take the sources found in ground-based surveys of QSOs;
- rely on the Gaia internal recognition scheme.

These three means will correspond to different size of the sample, and also to different risks of introducing stellar contaminants. Using the ICRF sources (primary sources and the others) is an obvious starting solution and in practice a requirement. Out of the $\sim$ 700 sources, there are $\sim$ 400 (resp. 150 primaries) off from the galactic plane by more than 20° and with V magnitude < 20 (Fig. 2) that will be well detected by Gaia.

Most of these sources are quasars, and a good 50% are brighter than $V = 18$ and will be observed with an astrometric accuracy of about 50 μas. The ICRS paradigm will be applied to eliminate any global rotation from the preliminary frame and then correct all the observations

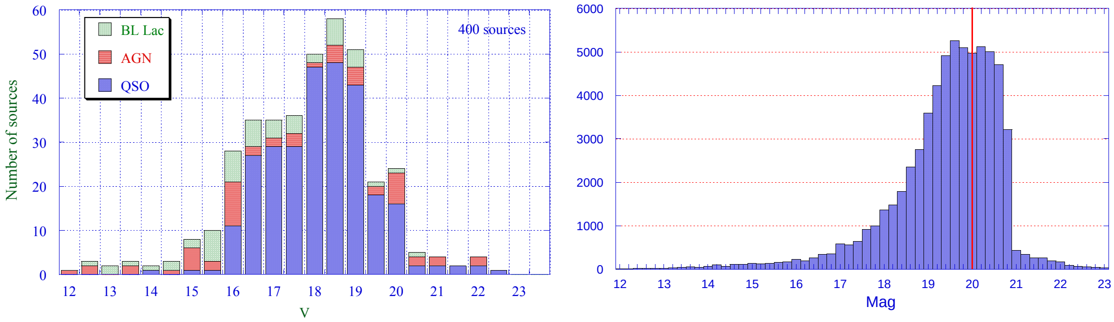

Figure 2: Magnitude distribution of the ICRF sources (left) and of the extragalactic sources in the Véron-Cetty & Véron Catalogue. Only the sources outside the galactic plane and brighter than $V = 20$ have been considered.

for this spin. It must be clear that the Gaia solution will be autonomous and not linked in any way to the ICRF, unlike what has been done for Hipparcos. The primary sources of the ICRF will be used as control : the residual rotation exhibited by these sources should be compatible with the ICRF uncertainty, that is to say less than 10 μas yr^{-1}. The origin of the right ascension is totally arbitrary and will be ascertained by constraining the orientation of the frame to be similar to that of the current ICRF, ensuring in this way the continuity between old and new standards. A global rotation will be fitted to the positional differences for the $\sim$ 150 primary sources observable with Gaia to determine the three angles $\epsilon_x, \epsilon_y, \epsilon_z$. The final uncertainty will come from the $\sim 0.3 - 0.4$ mas positional error in the radio ICRF, much larger than Gaia's. Eventually the orientation should be the same as the ICRF axes within $\sim$ 50 μas.

The second source of QSOs that Gaia could use, even if the internal recognition scheme fails, will come from the ground-based observations. At the moment the systematic compilation of QSO is available with the 11th edition of the Catalog of Quasars and Active Galactic Nuclei by Véron-Cetty and Véron [1]. It includes 49,000 quasars brighter than $M_B = -23$ and 15,000 AGNs fainter than $M_B = -23$, although this distinction is purely historical and no longer relevant. In total one finds 42,000 sources brighter than 20th magnitude (Fig. 2, right) and potentially measurable with Gaia.. However, given the nature of the compilation, a fraction of theses sources will be eliminated as not being really extragalactic, either from the astrometry or from the internal photometric detection. Once the Catalogue is cleaned of its contaminants, a more severe selection will be applied to the remaining sources to qualify them to become primary sources. By the time Gaia will fly, new versions of this Catalogue will be issued to incorporate the results of the SDSS, whose 3rd data release has produced more than 50,000 quasars identified with spectroscopy [2]. Virtually all these sources are brighter than $g = 20.2$ and will be seen by Gaia. This again will constitute a excellent subset to calibrate the Gaia classification procedure together with the photometric determination of the redshift.

3. RECOGNITION OF NEW SOURCES

The major problem in any QSO survey is the recognition among many starlike sources of the rare quasars. The ratio between the number of stars and of quasars per square degree is a function of the magnitude and of the galactic latitude. The quasars being very distant extragalactic objects are basically uniformly distributed on the sky in contrast with the stars primarily concentrated in the galactic plane and in the direction of the galactic center. As can be seen in Table 1 the extent of the problem is not the same outside the galactic plane as very close to this plane. Fortunately the quasar population grows faster than that of the stars toward faint magnitudes, hence the proportion of quasars increases with fainter sources. Find a quasar out of 100 stellar contaminants at high galactic latitude does not imply too powerful tests, while doing the same for 100 times more stars at low galactic latitude is very challenging and not yet fully solved.

Table 1: Relative surface density of stars and quasars for different magnitude and galactic latitude. The numbers are $N_{\star}/N_{\rm QSO}$

b(°)	G=18	G=19	G=20
90	725	125	75
60	1150	280	120
30	3075	765	330
10	33,000	10,500	5600

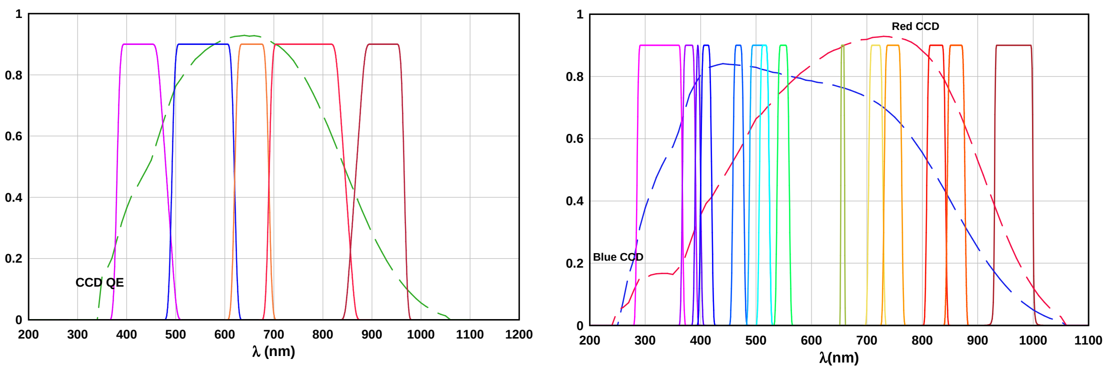

Figure 3: The two photometric systems to be used by Gaia. The left panel shows the five filters of the broad band photometre placed on fours strips of CCD at the edge of the astrometric fields. The right panel corresponds to the filters of the medium band photometre working with an independent telescope and different detector.

There are several indicators that will help make the decision, like the absence of parallax, the negligible proper motion (in an inertial frame), the short term variability and, before all, the spectral signature summarised in a set of color indices. Given the astrometric capabilities of Gaia it is highly advisable that the parallaxes and proper motions should be taken as good indicators only to exclude an object when its distance or motion are definitely not compatible with that expected for an extragalactic source : no quasar will have a significant parallax or a large proper motion. However some stars will have a negligible parallax or proper motion making this criteria not powerful to discriminate between the two populations. In addition with the astrometric accuracy of Gaia there are important science issues in trying to detect quasars with non-zero proper motion, for example to determine the acceleration induced by the galactic rotation or the accelerated motion of the Local group with respect to the distant Universe. Variable macro lensing on quasars may also be a source of spurious proper motions, that will deserve specific treatment. So these tests should only be used as confirmation tool, when the photometric testing has concluded positively that a particular source is likely to be a QSO. Objects selected as quasars from their photometric signature and not passing the final astrometric tests, will be looked at carefully for possible multi-images quasars, with relevant cosmological implications.

The photometric testing with Gaia rests upon the measurements to be carried out with the BBP (broad-band photometre) and MBP (medium-band photometre). The current photometric system is shown in Fig. 3. The choice is the result of many optimisations, primarily based on stellar physics to retrieve the fundamental stellar parameters for every kind of stars. For the QSO photometric testing, the most important point was to avoid large gaps between filters. The standard energy distribution of a quasar is markedly different for that of a star, having a large UV flux and a regular decrease in the continuum (in the rest frame). There are strong and broad emission lines like Lyα, SI IV, O IV, CIV, not seen in normal stars. Due to the redshift the spectrum will be quite often displaced in the visible and strongly squeezed. Gaia will observe repeatedly each quasar and determine its location in the multi-dimensional color space. In this space they should occupy a different location from that of the stars, including white dwarfs. The difficult cases appear with very reddened stars : but this will mean strong absorption in the vicinity of the galactic plane, where QSOs are also reddened and difficult to observe and distinguish among the star filled regions.

Claeskens and collaborators [3] have generated a large library of synthetic spectra for the quasars, covering a wide range of redshifts, reddening and line strengths. Using in parallel spectral libraries for stars of every spectral class and type, binaries stars and white dwarfs, they have correlated all these energy distributions with the different filters proposed for Gaia. Tests were conducted with a set of templates to simulate the observations with realistic noises. From the location of each source in the colour space they have shown conclusively that the combination of the broad band and medium band filters permits a photometric identification of quasars from virtually any type of stars. The photometric redshift ($\sim$ redshift seen in the continuum) can be retrieved as well with an accuracy of few percents, even if the actual spectral index differs significantly from that of the template used for the analysis.

The Gaia internal autonomous multi-color detection will be very efficient to get rid of the traditional contaminants like the white dwarfs and the very reddened stars and will permit the selection of a 99.6% star-free sample of QSOs. At $G = 19$, 85% of the QSOs are correctly identified with a level of stellar contaminants $< 0.01\%$ (0.4% at $G = 20$) [3]. These contaminants are not uniformly distributed in the colour space, but are associated to extreme reddening or low metallicity. By reducing the level of completeness of the QSO sample it is possible to virtually eliminate any contaminants. Such a clean sample should contain about 15% of the QSO population, nonetheless amounting to more than 50,000 sources, largely enough to tie the Gaia astrometric solution to the non-rotating Universe.

4. TESTING

As I have mentioned earlier in each range of magnitude the field stars outnumber the QSOs making the recognition of the latter difficult. Any recognition criterion will be probabilistic with a risk of ending with a wrong conclusion as to the true nature of the object examined. In this kind of testing, like in medical testing of the efficiency of a treatment, one has two different kinds of errors, each quantified by a probability :

- A QSO may be classified as a star, that is to say be unrecognized by the test. As a result, if the test is not sensitive enough, the survey will be incomplete and many QSOs will be left out. Quantitatively this is determined by the risk of the test α or equivalently by its significance level $1 - \alpha$. The risk of rejecting genuine QSOs from the sample can be made very small by decreasing α, but this will increase the fraction of stars in the samples.

- On the opposite a star may be wrongly taken as a QSO and flagged as such. In this case the sample of supposed QSOs will be contaminated by genuine stars. This is represented by the risk of contamination β and its complement $1-\beta$ is called the power of the test. Since the stars are much more frequent than the QSO, even if this risk has a low probability, this may end up with a large number of contaminants in the selected sample.

The overall performance is easily modelled by introducing the frequency f of QSOs among the celestial sources detectable by Gaia in a given region of the sky. The meaning of the risks is summarized in Table 2 where the columns refer to the true nature of the source and the lines to the conclusions produced by the tests.

Table 2: Probabilities of wrongly labelling a star or a QSO with the recognition tests.

		The object is a :	
		QSO	star
Found as :	QSO	$1-\alpha$	β
	star	α	$1-\beta$

What matters now is the probability of making a correct decision : if a source has been found as being a QSO, what is the probability that this conclusion is correct. Application of the elementary laws of probability yields the a posteriori probability that a source being found as a QSO is in fact a QSO (right) or a star (wrong decision) (FQ : means found to be a QSO) :

$$P(Q/FQ) = \frac{f(1-\alpha)}{f(1-\alpha)+(1-f)\beta} \sim \frac{f}{f+\beta} \quad (1)$$

$$P(S/FQ) = \frac{(1-f)\beta}{f(1-\alpha)+(1-f)\beta} \sim \frac{\beta}{f+\beta} \quad (2)$$

Therefore, as expected, if $f \ll \beta$ then $P(S/FQ) \sim 1$ and most purported to be quasars are in fact ordinary stars. So the testing must be such that the risk β to misclassify a star should be much less than the frequency of QSO among the stars. The efficiency parameter (proportion of QSO in the selected sample) is given approximately by $f/(f+\beta)$. For the sake of illustration consider a sample of 10,000 sources with a 0.1 percent error selection ($\beta = 0.001$) down to the Gaia limiting magnitude $G = 20$. When these sources are classified as QSOs the actual number of quasars and stars in this set is shown in Table 3 as a function of the galactic latitude, where f has been taken from Table 1. Therefore, with the typical quasar density of 20 QSOs per square degree brighter than $B = 20$, the realisation of a clean sample of sources needed for the reference system, just based on the Gaia internal detection system, is very challenging at low galactic latitude. Combined with the absorbtion and the reddening of the sources this makes very likely that the Gaia inertial frame will show a deficiency of sources around the galactic plane.

5. PARALLAXES AND PROPER MOTIONS

So far I have shown that the Gaia photometric detection alone will bring a large number of QSOs without stellar contaminants. The astrometry will be used to reject obvious non stellar object from this sample, but also from the larger sample planned for the QSO survey. While the selected power of the photometric tests for the clean sample implies that very few sources will not be QSOs this is not the case for the survey sample, which will contain most of the

Table 3: Number of quasars and stars in a set of 10,000 sources categorised as quasars with a test having a risk $\beta = 0.001$. b is the galactic latitude in degrees.

b (°)	QSOs	Stars
90	9300	700
60	8900	1100
30	7500	2500
10	1500	8500

QSOs, but also many contaminants. So additional testing based on the proper motions and parallaxes will be useful to eliminate the most conspicuous contaminants. For example late type red stars or white dwarfs will show up with large parallaxes and proper motions ruling out the QSO identification.

The testing is based on the null hypothesis H_0 that extragalactic sources have zero parallax and zero proper motion, or at least $\mu \ll 1\mu\mathrm{as\,yr}^{-1}$. If the measurement error is σ_μ on each component $\mu_\alpha^\star$ and μ_δ, with a gaussian distribution, one has under H_0 the probability distribution of the magnitude μ of the proper motion,

$$P(\mu/\sigma_\mu) < x = \exp(-x^2/2) \tag{3}$$

and then with the risk α one can reject the null hypothesis whenever

$$\mu > (-2\log\alpha)^{1/2}\,\sigma_\mu \tag{4}$$

and similarly for the parallax, one would have a rejection if,

$$\pi > \Phi^{-1}(1-\alpha)\,\sigma_\pi \tag{5}$$

where $\Phi(x)$ is the cumulative probability function of the normal law. The test is one-sided because all the alternative hypotheses have positive parallaxes or proper motions. For faint objects the threshold of rejection is given in Table 4 as a function of magnitude and risk. For example the test will reject with a risk 0.1% photometrically selected quasars of magnitude 19 if the proper motion measured by Gaia is larger than 223 $\mu\mathrm{as\,yr}^{-1}$.

The power of the test $(1-\beta)$ can be established only if we know something about the alternative possibilities, that is to say the distribution of proper motions and parallaxes for every other sources which are not quasars. From the values in Table 4 the prospect of testing does not appear very good : if stars with parallax $< 600\,\mu$as or proper motion $< 400\,\mu\mathrm{as\,yr}^{-1}$ are common among the field stars, the test will be very poor to select QSOs, but at the level of significance $1-\alpha$ good to reject nearby white dwarfs or very red stars. Consider in more detail separately the case of a test built on the parallaxes from that on the proper motions.

- Gaia will observe stars in the Milky way all the way through the disk and the halo and in few external galaxies like the Magellanic clouds and Andromeda. Unless a quasar is precisely observed in the same direction as the LMC or M31 the largest distance of the field stars will be less than 20 kpc, yielding a parallax of 50 μas. Most of the stars will have a parallax larger than this level, but the important point is that a non negligible population will have a parallax of this order of magnitude. It is clear that the probability

Table 4: Threshold of rejection for the proper motion or parallax of photometrically selected quasars as a function of their magnitude and of the risk α.

	Proper Motions				Parallaxes			
V	σ_μ	α			σ_π	α		
mag	μas yr^{-1}	0.01	0.005	0.001	μas	0.01	0.005	0.001
		μas yr^{-1}				μas		
18	35	106	115	130	65	151	168	201
19	60	182	195	223	125	292	323	386
20	115	350	375	430	230	536	592	711

distributions of the measured parallaxes under H_0 and that of the possible alternative hypotheses overlap significantly, meaning that the parallax test is virtually powerless to reject non-QSO sources from the sample. It is just efficient to reject non-QSO sources with totally anomalous parallaxes, as it can be seen in the last three columns of Table 4, corresponding to stellar sources at distances of 2 to 5 kpc.

- For the proper motions the situation is much more promising. Excluding again isolate stars in external galaxies which will be limited in number, one restricts to the field stars of the Milky Way. The proper motions follow from the combination of the relative motion due to the galactic rotation and that of the proper velocity–with magnitude equal to the velocity dispersion– of each star in its own local standard of rest. There are essentially three categories : (i) very nearby stars at less than 1 kpc, with typical velocity of 20 km s^{-1}, giving $\mu \sim 5\,\mathrm{mas\,yr^{-1}}$; (ii) then the stars up to 3 to 5 kpc, where the shear motion of the Galaxy is the dominant factor, with the kinematics well described by the Oort constants. With $A = 15$ km s^{-1} kpc^{-1}, this give $\mu \sim 3\,\mathrm{mas\,yr^{-1}}$. (iii) The very distant stars are in the last group with $d \geq 10$ kpc and a relative velocity comparable to that of the Sun around the galactic center, $V \sim 200$ km s^{-1}, yielding $\mu \sim V/d \sim 4$ mas yr^{-1}. Therefore the range of proper motions for stars not rejected by the parallax test is rather limited and in fact fairly constant for the field stars. No need to use sophisticated probabilistic argument to notice that the two probability distributions have virtually no overlapping, or equivalently that the power of the test will be very high (provided the assumption about the stellar proper motions is correct).

A the time of writing the principles laid out above for the astrometric tests have not yet been implemented in the simulation. This should be done in 2005 in complement to the photometric selection, in order to assess the efficiency and to identify potential problems.

6. REFERENCES

[1] Véron-Cetty, M.P., Véron, P., 2003, A&A 412, 399-403.

[2] Abazajian, K. et al., 2004, AJ in press.

[3] J.-F. Claeskens, A. Smette, J.Surdej, 2005, “Quasars with Gaia: Identification and Astrophysical Parameters” in: Proceedings of the Symposium “The Three-Dimensional Universe with Gaia”, ESA SP-576, in press.

INFLUENCE OF THE MULTIPOLE MOMENTS OF A GIANT PLANET ON THE PROPAGATION OF LIGHT : APPLICATION TO GAIA

C. LE PONCIN-LAFITTE, P. TEYSSANDIER
SYRTE, CNRS/UMR 8630, Observatoire de Paris
61 Av. de l'Observatoire, 75014 Paris, France
e-mail: leponcin@danof.obspm.fr
e-mail: pierre.teyssandier@obspm.fr

ABSTRACT. Approved space astrometry missions, like GAIA and SIM, are aimed to measure positions and/or parallaxes of celestial objects with an accuracy of 1-10 microarcseconds (μas). At such a level of accuracy, it will be indispensable to take into account the influence of the multipole structure of the giant planets (mainly Jupiter and Saturn) on the gravitational light deflection. Using the Nordtvedt-Will parametrized post-Newtonian formalism, we present an algorithmic procedure enabling to determine this influence on a light ray connecting two points located at a finite distance.

1. INTRODUCTION

Two major space astrometry missions, GAIA and SIM, are planned to be launched in the next years. The accuracy in the measurements of positions and/or parallaxes of celestial objects is expected to attain a level of 1-10 μas. In this context, we have to describe precisely the propagation of light inside and outside Solar System in a fully relativistic framework. By the time of Hipparcos mission, it was sufficient to consider the light deflection due to a static spherically symmetric Sun. Now, at the level of the μas accuracy, it is necessary to take into account the masses of the planets, as well as the higher multipole moments of those among them which are the most massive ones (Jupiter, Saturn, Uranus and Neptune). Table 1 gives the order of magnitude of the different contributions to the bending of a light ray propagating in Solar System. It is seen that for Jupiter, e.g., the effects of the multipole moments J_2 and J_4 may amount to 240 μas and 10 μas for a grazing light ray, respectively. So these effects must be taken into account in GAIA mission.

To take into account these intricate effects, several studies have been performed in the last decade. The first general relativistic model of positional observations at the level of 1 μas in space was proposed by Klioner & Kopeikin (1992), where gravitating bodies are considered as mass monopoles moving with constant velocities. More recently, a complete analytical description of the light propagation in the field of arbitrarily moving spinning mass monopoles bodies has been found by Kopeikin & Schäfer (1999) and Kopeikin & Mashhoon (2002) in the first post-Minkowskian approximation. For treating the particular problem of the multipole structure of celestial bodies, Hellings (1986) recommended to use the post-Newtonian formulas for the light propagation in the field of a motionless body and to introduce the position of each gravitating

Body	δ_{pn}	δ_{J_2}	δ_{J_4}	δ_{J_6}	δ_R	δ_{ppn}
Sun..................	1.752×10^6	1	—	—	0.7	11
Mercury...........	83	—	—	—	—	—
Venus.............	493	—	—	—	—	—
Earth................	574	0.6	—	—	—	—
Moon...............	26	—	—	—	—	—
Mars................	116	0.2	—	—	—	—
Jupiter.............	16270	240	10	$\geq$0.1	0.2	—
Saturn.............	5780	95	6	$\geq$0.1	—	—
Uranus............	2080	8	—	—	—	—
Neptune..........	2533	10	—	—	—	—

Table 1: Gravitational bending of light rays in Solar System. Here δ_{pn} and δ_{ppn} are the post-Newtonian and the post-post-Newtonian effects due to the spherically symmetric field of the body, δ_{J_2}, δ_{J_4} and δ_{J_6} are the effects due to multipole moments J_2, J_4 and J_6, respectively, and δ_R is the gravitomagnetic deflection. Each effect is evaluated for a grazing light ray. Unit is μas.

body at the moment of closest approach of that body by the photon. Klioner & Kopeikin (1992) apply this recommendation to treat the influence of the quadrupole moment of giant planets. Moreover, a rigourous formalism for determining the light propagation in the gravitational field of an isolated axisymmetric body was developped by Kopeikin (1997). However, the procedures given in these works are based on the analytical solution of the geodesic equations and requires cumbersome calculations. For this reason, only the influence of the quadrupole moment seems to be workable by this method.

Quite recently, we have reconsidered the problem of propagation of light between two events located at a finite distance in general spacetime (Linet & Teyssandier (2002) and Le Poncin-Lafitte & *al.* 2004). First of all, we have established a direct relation between the travel time of a photon and the vector tangent to the null geodesic at the emission point and the reception point, respectively. This means that all theoretical problems related to the direction of light rays may be solved as soon as the time transfer functions are determined. In addition, we have developed a procedure enabling to calculate explicitly the time travel of a photon in a general post-Minkowskian expansion, at any order of approximation without integrating the geodesic equations, even if the gravitational field is not stationary. Applying these results, we outline here a general method for determining the influence of the mass multipole moments of a planet on a light ray within the post-Newtonian approximation.

In section 2, we show that the angle between two light rays as measured by an observer can be computed when the time transfer functions are known. Then, we give the expression of this angle up to the order $1/c^3$ in the framework of the post-Newtonian approximation. In section 3, we restrict our attention to the case of an isolated, axisymmetric body. We suppose that the contribution of spin multipole moments are negligible, so that the gravitational field may be considered as a static one. On these assumptions, we give the contributions of the mass multipole moments to the time transfer function and to the direction of a light ray.

In this paper, G is the Newtonian gravitational constant and c is the speed of light in a vacuum. The Lorentzian metric of spacetime is denoted by g. The signature adopted for g is $(+ - - -)$. We suppose that spacetime is covered by a global coordinate system $(x^\mu) = (x^0, \boldsymbol{x})$, where $x^0 = ct$, t being a time coordinate, and $\boldsymbol{x} = (x^i)$, the x^i being quasi-Cartesian coordinates. We assume that the curves of equation $x^i = \ const$ are timelike, which means that $g_{00} > 0$ anywhere. We employ the vector notation $\boldsymbol{a}$ in order to denote either $(a^1, a^2, a^3) = (a^i)$ or $(a_1, a_2, a_3) = (a_i)$. Considering two such quantities $\boldsymbol{a}$ and $\boldsymbol{b}$ with, for instance $\boldsymbol{a} = (a^i)$, we use $\boldsymbol{a}.\boldsymbol{b}$ to denote a^ib^i if $\boldsymbol{b} = (b^i)$ or a^ib_i if $\boldsymbol{b} = (b_i)$ (the Einstein convention on repeated indices is used). The quantity $|\boldsymbol{a}|$ stands for the ordinary Euclidean norm of $\boldsymbol{a}$. In what follows, greek indices run from 0 to 3, and latin indices run from 1 to 3.

2. ASTROMETRIC ANGLE WITHIN THE POST-NEWTONIAN APPROXIMATION

Let Γ_1 and Γ_2 be two light rays emitted at point $x_{A_1} = (ct_{A_1}, \boldsymbol{x}_{A_1})$ and $x_{A_2} = (ct_{A_2}, \boldsymbol{x}_{A_2})$ respectively and simultaneously received by an observer B located at point $x_B = (ct_B, \boldsymbol{x}_B)$. Let u be the unit 4-velocity of this observer. Denote by $l^{(1)}$ and $l^{(2)}$ the vectors tangent at x_B to Γ_1 and Γ_2, respectively. Since $l^{(1)}$ and $l^{(2)}$ are null vectors, the angle ϕ between these rays as measured by the observer B is given by

$$\cos\phi = 1 - \left[\frac{l^{(1)}.l^{(2)}}{(u.l^{(1)})(u.l^{(2)})}\right]_B . \tag{1}$$

This formula holds in any gravitational field. Using the quasi-Cartesian coordinates system (x^α) introduced in section 1, Equation (1) may be explicitly written as

$$\cos\phi = 1 - \left[\frac{g^{00} + g^{0i}\left(\frac{l_i^{(1)}}{l_0^{(1)}} + \frac{l_i^{(2)}}{l_0^{(2)}}\right) + g^{ij}\frac{l_i^{(1)}}{l_0^{(1)}}\frac{l_j^{(2)}}{l_0^{(2)}}}{(u^0)^2\left(1 + \frac{v^i}{c}\frac{l_i^{(1)}}{l_0^{(1)}}\right)\left(1 + \frac{v^i}{c}\frac{l_i^{(2)}}{l_0^{(2)}}\right)}\right]_B , \tag{2}$$

where $v^i = dx^i/dt$ is the coordinate velocity of the observer. In Le Poncin-Lafitte & *al.* (2004), we showed that the ratio l_i/l_0 can be explicitly determined when the time transfer functions are known. Let us recall that in general the travel time $t_B - t_A$ of a photon between an emission point $(ct_A, \boldsymbol{x}_A)$ and a reception point $(ct_B, \boldsymbol{x}_B)$ may be considered as a function of t_A, $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$, or as a function of t_B, $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$, so that we can put

$$t_B - t_A = \mathcal{T}_e(t_A, \boldsymbol{x}_A, \boldsymbol{x}_B) = \mathcal{T}_r(t_B, \boldsymbol{x}_A, \boldsymbol{x}_B) , \tag{3}$$

where $\mathcal{T}_e$ and $\mathcal{T}_r$ may be called the emission and reception time transfer functions, respectively. We proved in the above-mentioned paper that the ratio l_i/l_0 is given at reception point x_B by the relation

$$\left(\frac{l_i}{l_0}\right)_B = -c\frac{\partial\mathcal{T}_e}{\partial x_B^i} = -c\frac{\partial\mathcal{T}_r}{\partial x_B^i}\left[1 - \frac{\partial\mathcal{T}_r}{\partial t_B}\right]^{-1} . \tag{4}$$

In what follows, we use the post-Newtonian approximation, so that the metric tensor may be written as

$$g_{00} = 1 - \frac{2W}{c^2} + O\left(\frac{1}{c^4}\right) , \tag{5}$$

$$\{g_{0i}\} = \{h_{0i}\} = \vec{h} = O\left(\frac{1}{c^3}\right) , \tag{6}$$

$$g_{ij} = \left(1 + 2\gamma\frac{W}{c^2}\right)\eta_{ij} + O\left(\frac{1}{c^4}\right) , \tag{7}$$

where $W = U + O(1/c^2)$, U being the Newtonian-like potential of the body. For a light ray emitted at point x_A and received at point x_B, we may write

$$\frac{l_i}{l_0} = -N^i + \Delta_i , \tag{8}$$

where

$$N^i = \frac{x_B^i - x_A^i}{R_{AB}}\,, \quad R_{AB} = |\boldsymbol{x}_B - \boldsymbol{x}_A|$$

and Δ_i is the relativistic contribution to the light deflection. As a consequence, Eq. (2) becomes

$$\begin{aligned}\cos\phi &= 1 - \frac{1-\frac{v^2}{c^2}}{\left(1-\frac{\vec{v}}{c}.\boldsymbol{N}^{(1)}\right)\left(1-\frac{\vec{v}}{c}.\boldsymbol{N}^{(2)}\right)}\Big\{(1-\boldsymbol{N}^{(1)}.\boldsymbol{N}^{(2)})\Big[1-(\boldsymbol{N}^{(1)}+\boldsymbol{N}^{(2)}).\vec{h} \\ &\quad -\frac{v^i}{c}(\Delta_i^{(1)}+\Delta_i^{(2)})\Big] + [N^{(2)i} - (\boldsymbol{N}^{(1)}.\boldsymbol{N}^{(2)})N^{(1)i}]\Delta_i^{(1)} \\ &\quad +[N^{(1)i} - (\boldsymbol{N}^{(1)}.\boldsymbol{N}^{(2)})N^{(2)i}]\Delta_i^{(2)}\Big\} + 0\left(\frac{1}{c^4}\right)\,, \end{aligned} \tag{9}$$

where

$$N^{(1)i} = \frac{x_B^i - x_{A_1}^i}{|\boldsymbol{x}_B - \boldsymbol{x}_{A_1}|}\,, \quad N^{(2)i} = \frac{x_B^i - x_{A_2}^i}{|\boldsymbol{x}_B - \boldsymbol{x}_{A_2}|}\,, \tag{10}$$

Let us note that Eq. (9) holds even if the gravitational field is not stationary.

3. TIME TRANSFER AND LIGHT DEFLECTION

Let us apply these results to a light ray propagating in the field of an isolated, axisymmetric body. We suppose that the gravitational effects of the internal angular momentum of the body may be neglected. So we consider that the gravitational field is static. The center of mass of the body being taken as the origin O of quasi-Cartesian coordinates $(\boldsymbol{x})$, we choose the axis of symmetry as the x^3-axis. We put $r = |\,\boldsymbol{x}\,|$, $r_A = |\,\boldsymbol{x}_A\,|$ and $r_B = |\,\boldsymbol{x}_A\,|$. We denote by $\boldsymbol{k}$ the unit vector along the x^3-axis and we consider only the case where all points of the segment joining $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$ are outside the body. We denote by r_e the radius of the smallest sphere centered on O and containing the body (for celestial bodies, r_e is the equatorial radius). We assume the convergence of the multipole expansions formally derived below at any point outside the body, such that $r > r_e$. On the above-mentioned assumptions, the two time transfer functions $\mathcal{T}_e$ and $\mathcal{T}_r$ reduce to a single function $\mathcal{T}(\boldsymbol{x}_A, \boldsymbol{x}_B)$ which may be expanded as

$$\mathcal{T}(\boldsymbol{x}_A, \boldsymbol{x}_B) = \frac{1}{c}R_{AB} + (\gamma+1)\frac{GM}{c^3}R_{AB}F(0, \boldsymbol{x}_A, \boldsymbol{x}_B) + \sum_{n=2}^{\infty}\mathcal{T}_{W,J_n}(\boldsymbol{x}_A, \boldsymbol{x}_B) + 0\left(\frac{1}{c^4}\right)\,, \tag{11}$$

where $F(\boldsymbol{x}, \boldsymbol{x}_A, \boldsymbol{x}_B)$ is defined by

$$F(\boldsymbol{x}, \boldsymbol{x}_A, \boldsymbol{x}_B) = \frac{1}{R_{AB}}\ln\left(\frac{|\boldsymbol{x}-\boldsymbol{x}_A| + |\boldsymbol{x}-\boldsymbol{x}_B| + R_{AB}}{|\boldsymbol{x}-\boldsymbol{x}_A| + |\boldsymbol{x}-\boldsymbol{x}_B| - R_{AB}}\right)\,, \tag{12}$$

and $\mathcal{T}_{W,J_n}$ is the contribution of the mass multipole moment J_n, given by

$$\mathcal{T}_{W,J_n}(\boldsymbol{x}_A, \boldsymbol{x}_B) = -(\gamma+1)\frac{GM}{c^3}\frac{1}{n!}J_n r_e^n R_{AB}\frac{\partial^n}{\partial(x^3)^n}F(\boldsymbol{x}, \boldsymbol{x}_A, \boldsymbol{x}_B))|_{\boldsymbol{x}=0}\,. \tag{13}$$

Calculating explicitly the successive derivatives of $F(\boldsymbol{x}, \boldsymbol{x}_A, \boldsymbol{x}_B)$, we find

$$\begin{aligned}\mathcal{T}_{W,J_n}(\boldsymbol{x}_A, \boldsymbol{x}_B) &= -(\gamma+1)\frac{GM}{c^3}J_n r_e^n\sum_{m=1}^{n}(-1)^m\frac{(m-1)!}{2^m} \\ &\quad\times\frac{(r_A+r_B+R_{AB})^m - (r_A+r_B-R_{AB})^m}{(r_Ar_B+\boldsymbol{x}_A.\boldsymbol{x}_B)^m} \\ &\quad\times\sum{}'\left\{\frac{1}{i_1!i_2!\ldots i_{n-m+1}!}\prod_{l=1}^{n-m+1}\left[\frac{1}{r_A^{l-1}}C_l^{(-1/2)}\left(\frac{\boldsymbol{k}.\boldsymbol{x}_A}{r_A}\right) + \frac{1}{r_B^{l-1}}C_l^{(-1/2)}\left(\frac{\boldsymbol{k}.\boldsymbol{x}_B}{r_B}\right)\right]^{i_l}\right\}\,,\end{aligned} \tag{14}$$

where $C_l^{(-1/2)}$ denote the Gegenbauer polynomial of degree l with parameter $-1/2$ (see Abramowitz and Stegun 1970) and $\sum'$ is a summation over all positive integers $i_1, i_2, ..., i_{n-m+1}$, solutions to the linear system

$$i_1 + 2i_2 + ... + (n-m+1)i_{n-m+1} = n\,, \qquad i_1 + i_2 + ... + i_{n-m+1} = m\,.$$

We are now in a position to determine the covariant components of the vector tangent to the light ray emitted at point x_A and received at point x_B. Applying Eqs. (4), (11) and (14), and then noting that one may set $l_0 = 1$ along the ray since the gravitational field is static, we find at point x_B

$$(\boldsymbol{l})_B = -\boldsymbol{N} + (\boldsymbol{l}^W)_B\,, \tag{15}$$

where

$$(\boldsymbol{l}^W)_B = -(\gamma+1)\frac{GM}{c^2}\frac{(r_A + r_B)\boldsymbol{N} - R_{AB}\boldsymbol{n}_B}{r_A r_B + \boldsymbol{x}_A.\boldsymbol{x}_B} + \sum_{n=2}^{\infty}(\boldsymbol{l}^{W,J_n})_B(\boldsymbol{x}_A, \boldsymbol{x}_B)\,, \tag{16}$$

with

$$\begin{aligned}
\left(\boldsymbol{l}^{\,W,J_n}\right)_B(\boldsymbol{x}_A, \boldsymbol{x}_B) &= (\gamma+1)\frac{GM}{c^2}J_n r_e^n \left\{\sum_{m=1}^{n}(-1)^{m+1}m! \right.\\
&\times \left[\frac{\boldsymbol{n}_B - \boldsymbol{N}}{(r_A + r_B - R_{AB})^{m+1}} - \frac{\boldsymbol{n}_B + \boldsymbol{N}}{(r_A + r_B + R_{AB})^{m+1}}\right] \sum{}' \frac{1}{i_1!i_2!...i_{n-m+1}!}\prod_{l=1}^{n-m+1} D_{(l)}^{i_l}\\
&+ \sum_{m=1}^{n}(-1)^m(m-1)!\left[\frac{1}{(r_A + r_B - R_{AB})^m} - \frac{1}{(r_A + r_B + R_{AB})^m}\right]\\
&\qquad \times \sum{}' \left[\frac{1}{i_1!i_2!...i_{n-m+1}!}\sum_{l=1}^{n-m+1}\frac{i_l}{r_B^l}D_{(l)}^{i_l-1}\prod_{p=1\,,\,p\neq l}^{n-m+1} D_{(p)}^{i_p}\right.\\
&\qquad \left.\left.\times \left[\boldsymbol{n}_B P_l\left(\frac{\boldsymbol{k}.\boldsymbol{x}_B}{r_B}\right) - \boldsymbol{k}P_{l-1}\left(\frac{\boldsymbol{k}.\boldsymbol{x}_B}{r_B}\right)\right]\right]\right\}\,,
\end{aligned} \tag{17}$$

P_l being the Legendre polynomial of degree l, and $D_{(l)}$ being defined by

$$D_{(l)} = \frac{1}{r_A^{l-1}}C_l^{(-1/2)}\left(\frac{\boldsymbol{k}.\boldsymbol{x}_A}{r_A}\right) + \frac{1}{r_B^{l-1}}C_l^{(-1/2)}\left(\frac{\boldsymbol{k}.\boldsymbol{x}_B}{r_B}\right)\,.$$

The contributions to angle ϕ due to $\boldsymbol{l}^{\,W,J_n}$ are on current study now.

4. REFERENCES

Abramowitz M. and Stegun I.A., eds. 1970, Handbook of Mathematical Functions, Dover

Bienaymé O. and Turon C., eds. 2002, GAIA: A European Space Project (Les Ulis: EDP Sciences) ESA. 2000 GAIA: Composition, Formation and Evolution of the Galaxy, Concept and Technology Study Report (ESA-SCI[2000]4) (Noordwijk: ESA)

Hellings R. W., 1986, AJ 91, 650

Klioner S. A. and Kopeikin S. M., 1992, AJ 104, 897

Klioner S. A., 2003, AJ 125, 1580

Klioner S. A., 2003, A&A 404, 783

Kopeikin S. M., 1997, J. Math. Phys. 38, 2587

Kopeikin S. M. and Schäfer G., 1999, Phys. Rev. D 60, 124002

Kopeikin S. M. and Mashhoon B., 2002, Phys. Rev. D 65, 064025

Linet B. and Teyssandier P., 2002, Phys. Rev. D 66, 024045
Le Poncin-Lafitte C., Linet B. and Teyssandier P., 2004, Class. Quantum Grav., 21, 4463
Perryman M.A.C. et al., 2001, A&A 369, 339
Shao M., 1998, Proc. SPIE, 3350, 536
Weissman P.R., McFadden L.-A., Johnson T.V., eds. 1999, Encyclopedia of the Solar System (San Diego, Academic Press)
Will C. M., 1993, Theory and Experiment in Gravitational Physics (revised edition ; Cambridge: Cambridge University Press)

COMBINED ASTROMETRIC CATALOGUE EOC-2 – AN IMPROVED REFERENCE FRAME FOR LONG-TERM EARTH ROTATION STUDIES

J. VONDRÁK, C. RON
Astronomical Institute, Academy of Sciences of the Czech Republic
Boční II, 141 31 Prague 4, Czech Republic
e-mail: vondrak@ig.cas.cz, ron@ig.cas.cz

ABSTRACT. We collected the astrometric observations of latitude / universal time variations made worldwide at 33 observatories. These observations, referred to Hipparcos Catalogue, were then used to determine Earth Orientation Parameters (EOP) at 5-day intervals, covering the interval 1899.7-1992.0. Later on, new astrometric catalogues (such as ARIHIP or TYCHO-2) appeared as combination of Hipparcos / Tycho positions with ground-based catalogues. These catalogues yield more accurate proper motions than original Hipparcos Catalogue. Our attempt goes however even further - we use about 4.5 million observations of latitude / universal time variations, and combine them with these catalogues to obtain Earth Orientation Catalogue (EOC). The second version of the catalogue, EOC-2, contains 4418 different objects (stars, components of double stars, photocenters). The improvement of the accuracy of proper motions (especially in declination) over Hipparcos is remarkable - median formal inaccuracies attain 0.70 and 0.35 mas/year in right ascension and declination, respectively.

1. INTRODUCTION

In the past, we produced three solutions of Earth Orientation Parameters (EOP), based on optical observations of latitude / universal time / altitude variations made at 33 observatories in years 1899.7 – 1992.0. These solutions are denoted as OA97 (Vondrák et al. 1998), OA99 (Vondrák et al. 2000) and OA00 (Ron & Vondrák 2001). All these solutions were worked out in the reference frame of Hipparcos Catalogue (ESA 1997), but about 20% of positions / proper motions of Hipparcos stars had to be corrected, because of the systematic deviations in their positions extrapolated from Hipparcos epoch backwards. These corrections reflected the problems mostly connected with double and multiple star systems – real proper motions are not linear, Hipparcos mission was shorter than four years (i.e., much shorter than orbital periods of double stars), and sometimes it was not clear which component was observed by ground-based astrometry. The reference point can even be different for visual and photographic / photoelectric observations, due to better resolution of human eye!

Recently, new catalogues with improved proper motions appeared, as combination of Hipparcos and/or Tycho Catalogues with ground based catalogues. They comprise FK6, Part I and III, as combination of FK5 with Hipparcos (Wielen et al. 1999, 2000), GC+HIP as combination of Boss' General Catalogue with Hipparcos (Wielen et al. 2001a), and TYC2+HIP as combination of Tycho-2 with Hipparcos (Wielen et al. 2001b). The same authors made a selection of the preceding three catalogues and Hipparcos itself, and formed a catalogue called ARIHIP (Wielen et al. 2001c). Wielen et al. in their catalogues introduced a classification of 'astrometric excellency' by assigning a number of asterisks to each star (going from no to three asterisks, the more asterisks the better the star from astrometric point of view). Parallel to these, Høg et al. (2000) derived the catalogue TYCHO-2 as combination of Tycho Catalogue with 144 ground-based catalogues. The latter two, i.e. ARIHIP and TYCHO-2, form the basis of constructing the new Earth Orientation Catalogue (EOC) whose description follows.

2. CONSTRUCTION OF EOC

The idea is to create a new improved reference frame for long-term Earth rotation studies, by using the best available star catalogues and their combination with the rich observation material of measuring Earth orientation in 20th century. To this end, we first inspected all optical data from 47 instruments at 33 observatories, covering the interval 1899.7 – 2002.6. We found that there were 4418 different objects (stars, double star components, their photocenters) observed. They were identified in recent catalogues, and their positions, proper motions, parallaxes and radial velocities taken over from them to form zero version of the new catalogue, EOC-0. In total, 2995 objects are taken over from ARIHIP, 1248 from TYCHO-2, 144 from Hipparcos, 238 from PPM (Roeser & Bastian 1991, Bastian & Roeser 1993), and remaining three were found in none of these, so they are taken over from original 'local' catalogues used by respective observatories. However, only 44% of these stars are 'astrometrically excellent' (i.e., with at least one asterisk), so further improvement is necessary. The rich observational material of Earth orientation programmes (about 4.5 million observations made during a century), in which each object was observed in average a thousand times, makes such improvement feasible.

Next we combine EOC-2 with the observations that can be divided into four groups, according to the type of instruments used and observable obtained:

- 10 PZT's that observe stars near local zenith and determine both latitude and universal time: 2 at Mizusawa (1959.0-1993.1), Japan; 1 at Mount Stromlo (1957.8-1985.7), Australia; 1 at Punta Indio (1971.6-1984.5), Argentina; 1 at Ondřejov (1973.1-2002.6), Czech Republic; 2 at Richmond (1949.8-1989.4) and 3 at Washington DC (1915.8-1992.0), USA;
- 7 photoelectric transit instruments (PTI), observing the transits of stars over local meridian and determining only universal time: 1 at Irkutsk (1979.1-1992.0) and 3 at Pulkovo (1959.7-1994.0), Russia; 1 at Nikolaev (1974.4-1992.4) and 1 at Kharkov (1973.0-1992.0), Ukraine; 1 at Wuhang (1981.9-1987.2), China;
- 16 visual zenith telescopes (ZT) and similar instruments (visual zenith tube - VZT, floating zenith telescope - FZT) that observe small difference of zenith distances of two stars passing over local meridian symmetrically (one in south, one in north), determining only latitude: 7 ZT's at ILS stations – Carloforte, Cincinnati, Gaithersburg, Kitab, Mizusawa, Tschardjui, Ukiah (1899.7-1979.0); 1 ZT at Belgrade (1949.0-1986.0), Yugoslavia; 1 ZT at Blagovestschensk (1959.0-1992.0), 1 ZT at Irkutsk (1958.2-1991.0) and 1 ZT's at Pulkovo (1904.7-1995.0), Russia; 1 ZT at Józefoslaw (1961.8-1996.0), Poland; 1 FZT at Mizusawa (1967.0-1984.8), Japan; 2 ZT's at Poltava (1949.7-1990.4), Ukraine; 1 VZT at Tuorla-Turku (1963.7-1989.1), Finland;
- 14 equal altitude instruments (Danjon astrolabes - AST, photoelectric astrolabes - PAST, and circumzenithals - CZ) that observe transits of stars through an almucantar, determining a combination of latitude/universal time: 1 PAST at Beijing (1979.0-1987.8), 2 PAST's at Shaanxi (1974.0-1992.0), 1 AST + 1 PAST at Shanghai (1962.0-1985.0), 1 AST at Wuhang (1964.0-1986.2) and 1 PAST at Yunnan (1980.7-1991.3), China; 1 CZ at Bratislava (1987.0-1991.9), Slovakia; 1 PAST at Grasse (1983.2-1992.0) and 1 AST at

Paris (1956.5-1983.0), France; 1 AST at Pecný (1970.0-1992.0) and 1 CZ at Prague (1980.2-1992.0), Czech Republic; 1 AST at Santiago de Chile (1965.9-1990.9), Chile; 1 AST at Simeiz (1977.0-1991.0), Ukraine.

A procedure of combining these observations with the catalogue EOC-0 was first applied to only the first three groups above, leading to first version EOC-1 (Vondrák & Ron 2003, 2004), more details on constructing EOC-2 by using all instruments are given in (Vondrák 2004).

The strategy, based on the assumption that the latitude / universal time is constant during a night, was followed; the method is insensitive to any change of the direction of the local vertical (in terrestrial frame) between successive nights. We proceeded by following these steps, for observations by all instruments:

1. All observed quantities (i.e., latitude / universal time / altitude difference) were recalculated with EOC-0 and the model of precession-nutation IAU2000A (Mathews et al. 2002).
2. The deviations of these observables from the mean value of the night (calculated only for astrometrically excellent stars) were computed, and linear regression for these differences for the same star in different epochs was made.
3. Stars with statistically significant deviations were checked for multiplicity, using the information contained in Hipparcos Catalogue. In positive case, the displacement of reference point from EOC-0 was estimated, and the respective position in EOC-0 was corrected. In this case, the procedure above (item 2) was repeated.
4. Combination of these deviations with EOC-0 was made. To this end, each entry of the star of EOC-0 was represented by three virtual observations (both for right ascension and declination) in three different epochs: $t_1 = t_\circ - 90$, $t_2 = t_\circ$, $t_3 = t_\circ + 10$, where $t_\circ$ is the mean epoch of the catalogue in years. The values of these 'observations' were implicitly set to zero, their uncertainties were then calculated from catalogue standard errors of the position $\sigma_\circ$ and proper motion σ_μ as

$$\sigma_1^2 = 9000\sigma_\mu^2, \quad \sigma_2^2 = \sigma_\circ^2/\left[1 - (\sigma_\circ/\sigma_\mu)^2/900\right], \quad \sigma_3^2 = 1000\sigma_\mu^2. \tag{1}$$

   In such case the catalogue entry is reproduced exactly, if the three virtual observations are subject to linear regression. The values from Eq. (1) were then used to calculate the weights $p_i = (200/\sigma_i)^2$, if σ_i are given in milliarcseconds. Real observations (deviations calculated above) were assigned the weights 1. Weighted linear regression through all real and virtual observations was then made to yield the combined position / proper motion. To this end, we used the following observation equations for the three types of observations (deviation in latitude $\delta\varphi$, universal time δUT, altitude δh), respectively:

$$\begin{aligned} v_\varphi &= \Delta\delta + \Delta\mu_\delta(t - t_\circ) - \delta\varphi \\ v_{UT} &= \Delta\alpha^* + \Delta\mu_\alpha^*(t - t_\circ) - 15.041\delta\mathrm{UT}\cos\varphi \\ v_h &= \Delta\alpha^*\sin q + \Delta\mu_\alpha^*(t - t_\circ)\sin q + \Delta\delta\cos q + \Delta\mu_\delta(t - t_\circ)\cos q - \delta h. \end{aligned} \tag{2}$$

   Here $\Delta\alpha^*$, $\Delta\mu_\alpha^*$ stand for $\Delta\alpha\cos\delta$, $\Delta\mu_\alpha\cos\delta$, and q is the parallactic angle of the star. First two of Eqs (2) are used always, for virtual observations of declination and right ascension with their weights, respectively, and they are mixed with any of the three equations for real observations, according to their type.

An illustrative example of combination is given in Figs. 1 and 2. Tycho-2 double star No. 84606 was observed - universal time by four PTI's, latitude by all ILS ZT's. Since the photocenter was observed, its position as given in Tycho-2 was displaced from component A

Table 1: Comparison of accuracies of different catalogues

Catalogue	n_{stars}	Ep_α	σ^*_α	$\sigma^*_{\mu\alpha}$	Ep_δ	σ_δ	$\sigma_{\mu\delta}$
Hipparcos	117995	91.25	0.87	0.72	91.25	1.02	0.85
ARIHIP	90842	91.24	0.81	0.79	91.27	0.62	0.71
TYCHO-2	2.5 mil.	90.74	8.00	1.30	90.54	9.00	1.30
EOC-2	4418	91.16	0.70	0.47	91.03	0.60	0.35

position by a value, estimated from the observations, and the corrected position was adopted in EOC-0. This very position (and original proper motion) was then used to calculate the three virtual observations and combined with real observations.

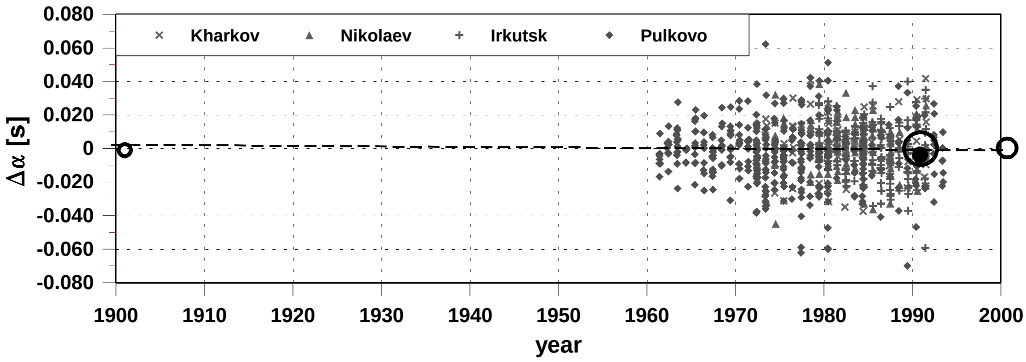

Figure 1: Combination (dashed line) of Tycho-2 right ascension of double star 84606 with PTI observations (gray markers) of its photocenter. Virtual observations (open circles) are displaced from component A (full circle).

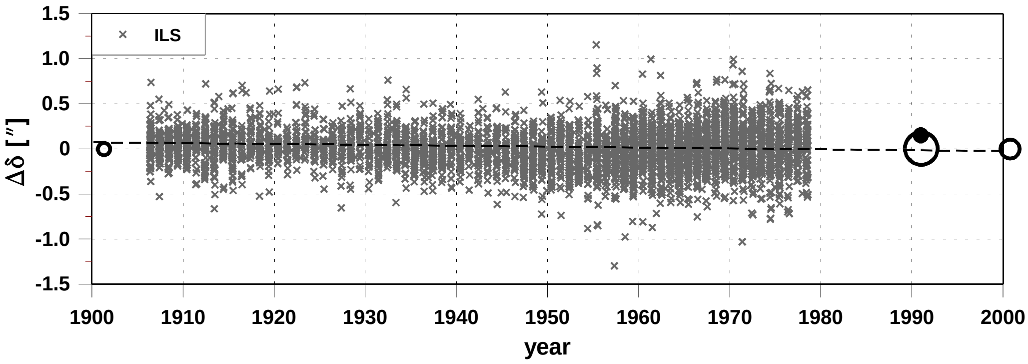

Figure 2: Combination (dashed line) of Tycho-2 declination of double star 84606 with ZT observations (gray markers) of its photocenter. Virtual observations (open circles) are displaced from component A (full circle).

The accuracy of EOC-2 is compared with those of the catalogues Hipparcos, ARIHIP, and Tycho-2 in Table 1, in which median values are displayed. The improved accuracy, especially of proper motions in declination, is evident from the table.

The values from Table 1 are used to calculate the time evolution of accuracies of these catalogues over the twentieth century, shown in Fig. 3. The differences amongst the catalogues grow backwards, towards the beginning of the twentieth century. The ever growing superiority of EOC-2 with respect to the remaining three catalogues is obvious.

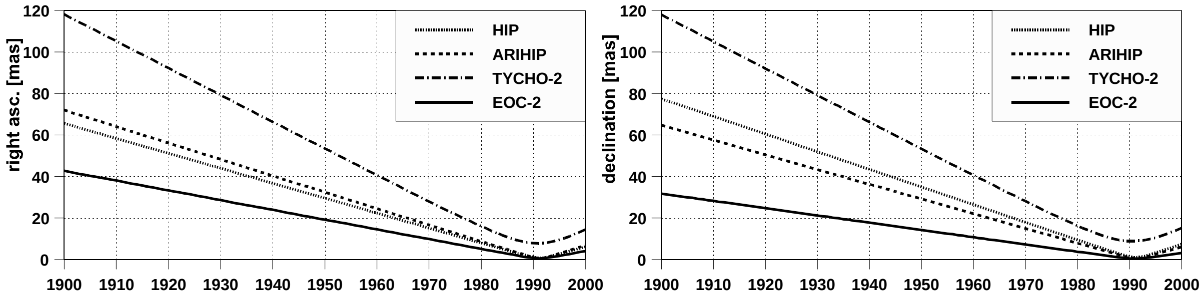

Figure 3: Comparison of accuracies of different catalogues - evolution in time.

3. SOLUTIONS OF EOP BASED ON EOC-2, CONCLUSIONS

The catalogue EOC-2 was used in 2004 to produce new solutions of Earth Orientation Parameters. There were two of them, denoted OA04 and OA04a, both calculated by a method more or less identical with our preceding solutions. They cover the same interval, i.e., 1899.7 – 1992.0, the main differences from the preceding solutions are characterized by the following:

- OA04 uses all 47 instruments merged into 42 series (instruments of the same or similar type, working at the same observatory, were treated as a single instrument). IAU2000A model of precession-nuation was used, and consequently celestial pole offsets were represented by a constant plus linear term, instead of 5-day values used formerly.
- OA04a merged the same observations into only 40 series. IAU2000A model of nutation plus P03 model of precession (Capitaine et al. 2003) were used, celestial pole offsets were represented by a constant, linear and quadratic terms. This solution is described in more detail and used to test precession models by Ron et al. (2005).

These two solutions are supposedly more robust than our preceding solutions, mainly because of the different treatment of celestial pole offsets – the replacement of 5-day points by two or three 'global' parameters for each component decreases the number of parameters estimated from the adjustment by about 45%. Also, the number of observations increased since a better EOC-2 catalogue was used as the celestial reference frame – less observations were rejected due to their large residuals, especially at the beginning of the solution. This is demonstrated in Table 2 that displays a comparison of some statistical data of the last three solutions.

Table 2: Comparison of accuracies of solutions OA00, OA04, OA04a

Solution	$n_{obs.}$	$n_{param.}$	$\sigma_\circ$ ["]	σ_x [mas]	σ_y [mas]	σ_{UT1} [ms]
OA00	4 447 400	29 809	0.188	20.5	18.3	0.78
OA04	4 538 694	16 443	0.190	17.4	15.7	0.72
OA04a	4 541 385	16 444	0.191	17.4	15.9	0.72

The uncertainties shown in the table are median values, and they confirm a higher accuracy of the last two solutions in 5-day values of all three EOP components (σ_x, σ_y and σ_{UT1}), in spite of a slightly larger average uncertainty of a single observation ($\sigma_\circ$).

Acknowledgements. This study was supported by grant No. IAA3003205, awarded by the Grant Agency of the Academy of Sciences of the Czech Republic.

4. REFERENCES

Bastian U., Roeser S., 1993, Positions and Proper Motions – South. *Astron. Rechen-Inst.* Heidelberg.

Capitaine N., Wallace P.T., Chapront J., 2003, Expressions for IAU2000 precession quantities. *A&A* **412**, 567–586.

ESA, 1997, The Hipparcos and Tycho Catalogues. *ESA SP-1200*.

Høg E., Fabricius C., Makarov V.V. et al., 2000, The Tycho-2 Catalogue of the 2.5 million brightest stars. *A&A* **355**, L27–L30.

Mathews P.M., Herring T.A., Buffet B.A., 2002, Modelling of nutation and precession: New nutation series for nonrigid Earth and insights into the Earth's interior. *J. Geophys. Res.* **107**, B4, 10.1029/2001JB00390.

Roeser S., Bastian U., 1991, Positions and Proper Motions – North. *Astron. Rechen-Inst.* Heidelberg.

Ron C., Vondrák J., 2001, On the celestial pole offsets from optical astrometry in 1899–1992. In: N. Capitaine (ed.) *Proc. Journées 2000 Systèmes de référence spatio-temporels*, Paris, 201–202.

Ron C., Capitaine N., Vondrák J., 2005, A precession study based on the astrometric series and the combined astrometric catalogue EOC-2, this volume.

Vondrák J., 2004, Astrometric star catalogues as combination of Hipparcos/Tycho catalogues with ground-based observations. *Serb. Astron. J.* **168**, 1–8.

Vondrák J., Ron C., 2003, An improved reference frame for long-term Earth rotation studies. In: *Journées 2002 Systèmes de référence spatio-temporels*, Observatoire de Paris, 49–55.

Vondrák J., Ron C., 2004, Earth Orientation Catalogue – An improved reference frame. In: R. Gaume, D. McCarthy & J. Souchay (eds.) *IAU XXV, Joint Discussion 16: The ICRS Maintenance and Future Realizations*, in press.

Vondrák J., Pešek I., Ron C., Čepek A., 1998, Earth orientation parameters 1899.7–1992.0 in the ICRS based on the HIPPARCOS reference frame. *Publ. Astron. Inst. Acad. Sci. Czech R.* **87**, 1–56.

Vondrák J., Ron C., Pešek I., 2000, Survey of observational techniques and Hipparcos reanalysis. In: S. Dick, D.D. McCarthy, B. Luzum (eds.) *Polar motion: Historical and Scientific Problems, Proc. IAU Coll. 178*, ASP Conf. Series **208**, 206–213.

Wielen R., Schwan H., Dettbarn C. et al., 1999, Sixth Catalogue of fundamental stars (FK6), Part I Basic fundamental stars with direct solutions. *Veröff. Astron. Rechen-Inst. Heidelberg* No. 35, Kommissions-Verlag G. Braun, Karlsruhe.

Wielen R., Schwan H., Dettbarn C. et al., 2000, Sixth Catalogue of fundamental stars (FK6), Part III Additional fundamental stars with direct solutions. *Veröff. Astron. Rechen-Inst. Heidelberg* No. 37, Kommissions-Verlag G. Braun, Karlsruhe.

Wielen R., Schwan H., Dettbarn C. et al., 2001a, Astrometric Catalogue GC+HIP derived from a combination of Boss' General Catalogue with the HIPPARCOS Catalogue. *Veröff. Astron. Rechen-Inst. Heidelberg* No. 38, Kommissions-Verlag G. Braun, Karlsruhe.

Wielen R., Schwan H., Dettbarn C. et al., 2001b, Astrometric Catalogue TYC2+HIP derived from a combination of the HIPPARCOS Catalogue with the proper motions given in the TYCHO-2 Catalogue. *Veröff. Astron. Rechen-Inst. Heidelberg* No. 39, Kommissions-Verlag G. Braun, Karlsruhe.

Wielen R., Schwan H., Dettbarn C. et al., 2001c, Astrometric Catalogue ARIHIP containing stellar data selected from the combination catalogues FK6, GC+HIP, TYC2+HIP and from the HIPPARCOS Catalogue. *Veröff. Astron. Rechen-Inst. Heidelberg* No. 40, Kommissions-Verlag G. Braun, Karlsruhe.

THE LUNAR LIBRATION: COMPARISONS BETWEEN VARIOUS MODELS- A MODEL FITTED TO LLR OBSERVATIONS

J. CHAPRONT, G. FRANCOU
SYRTE - Observatoire de Paris - UMR 8630/CNRS
61, avenue de l'Observatoire 75014 Paris
e-mail: jean.chapront@obspm.fr

ABSTRACT. We consider 4 libration models : 3 numerical models built by JPL (ephemerides for the libration in DE_{245}, DE_{403} and DE_{405}) and an analytical model improved with numerical complements fitted to recent LLR observations. The analytical solution uses 3 angular variables (p_1, p_2, τ) which represent the deviations with respect to Cassini's laws. After having referred the models to a unique reference frame, we study the differences between the models which depend on gravitational and tidal parameters of the Moon, as well as amplitudes and frequencies of the free librations. It appears that the differences vary widely depending of the above quantities. They correspond to a few meters displacement on the lunar surface, reminding that LLR distances are precise to the centimeter level. Taking advantage of the lunar libration theory built by Moons (1984) and improved by Chapront *et al.* (1999a) we are able to establish 4 solutions and to represent their differences by Fourier series after a numerical substitution of the gravitational constants and free libration parameters. The results are confirmed by frequency analyses performed separately. Using DE_{245} as a basic reference ephemeris, we approximate the differences between the analytical and numerical models with Poisson series. The analytical solution - improved with numerical complements under the form of Poisson series - is valid over several centuries with an internal precision better than 5 centimeters.

1. PRESENTATION OF THE MODELS

• *Cassini's laws.* The lunar libration is characterized by small oscillations around an equilibrium position governed by Cassini's laws: *(i)*, the rotation period of the Moon is identical to its circulation period in the orbital motion; *(ii)*, the inclination of the lunar equator on the ecliptic is a constant; *(iii)*, the secular motions of the nodes N and N' on the ecliptic of the orbital plane and the lunar equator are identical (see Fig. 1).

• *The variables.* A selenodesic system of axes (ξ, η, ζ) along the principal moments of inertia (A, B, C) is connected with the ecliptic system (X, Y, Z) by 3 Euler's angles (ϕ, ψ, θ) as shown on Fig. 1. Three position angles denoted by (p_1, p_2, τ) express the small oscillations around the equilibrium position. They are referred to Euler's angles by the relation:

$p_1 = \sin\phi\sin\theta$; $p_2 = \cos\phi\sin\theta$; $\tau^* = \phi + \psi$ or $\tau = \tau^* - w_1 - 180°$

where w_1 is the mean longitude of the Moon. p_1 and p_2 are the components of the unit vector pointing towards the mean pole of the ecliptic of date on the two lunar equatorial principal axes of inertia; τ is the libration in longitude. In the analytical theory the position variables are (p_1, p_2, τ). In the 3 JPL lunar ephemerides Euler angles are used instead.

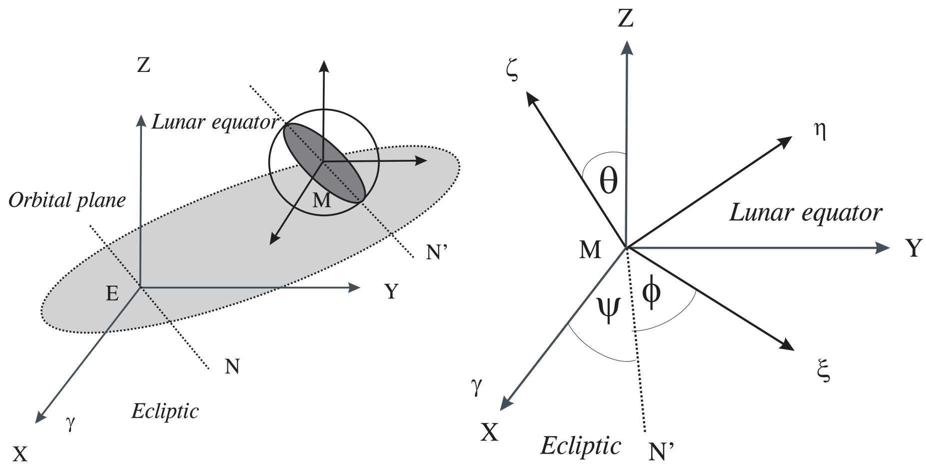

Figure 1: Ecliptic frame, selenodesic system of reference, and Euler's angles

Table 1: Parameters of the various models

Fundamental arguments	DE_{245}	DE_{403}	DE_{405}	$S_{LLR}(ICRS)$
ϕ	-0.07355	-0.05294	-0.05028	-0.05542
$\epsilon - 23°26'21"$	0.40580	0.4092	0.40960	0.41100
$w_1^{(0)} - 218°18'59"$	0.83482	0.87484	0.87267	0.8782
$w_1^{(1)} - 1732559343$ "$/Cy$	0.35614	0.35624	0.32953	0.3328
$w_1^{(2)}$ "$/Cy^2$	-6.7996	-6.7772	-6.8368	-6.8700
Earth figure parameters				
Units of 10^{-4}				
C_{30}	-0.086802	-0.086474	-0.087855	-0.086802
C_{31}	0.307083	0.307083	0.308038	0.307083
C_{32}	0.048737	0.048727	0.048798	0.048737
C_{33}	0.017161	0.017655	0.017702	0.017161
S_{31}	0.046115	0.044875	0.042593	0.046115
S_{32}	0.016975	0.016962	0.016955	0.016975
S_{33}	-0.002844	-0.002744	-0.002710	-0.002844
γ	2.278860	2.278642	2.278583	2.278860
β	6.316191	6.316107	6.316121	6.316191
$\frac{C}{mR^2}$	3948.723999	3950.296917	3952.951990	3948.723999
Free libration				
$\sqrt{2P}$	0.2933	0.2915	0.3047	0.2919
$\sqrt{2Q}$	5.1924	5.2095	5.1860	5.2722
$\sqrt{2R}$	0.0208	0.0218	0.0089	0.0217
p_0 *degree*	224.3029	224.3095	229.5037	224.2277
q_0 *degree*	161.6400	161.7655	160.9133	161.0477
r_0 *degree*	124.3936	109.6807	164.2453	98.7506
ω_p (observed) "$/Cy$	44820553.89	44820553.89	44819747.03	44820417
ω_q (observed) "$/Cy$	1736494.75	1736523.38	1736520.37	1736493.0
ω_r (computed) "$/Cy$	-5364715.23	-5364708.34	-5364600.06	-5364715.23

• *The libration theory.* The analytical theory of the lunar libration that we use is due to Moons (1981, 1982 and 1984). It contains 'forced libration' and 'free libration' series. All the components of the Moons' series are described in (Chapront *et al.*, 1999a) that include also further improvements due to the authors. The literal parameters which enter the 'forced libration' are: $\beta = \frac{C-A}{B}$, $\gamma = \frac{B-A}{C}$, where A, B and C are the lunar principal moments of inertia; and the ratios of the coefficients $C_{i,j}, S_{i,j}$, $(i = 3, 4,\ 0 \leq j \leq i)$ to $\frac{C}{m_L R_L^2}$, where m_L and R_L are the lunar mass and equatorial radius. The corresponding Fourier series are developped with angular variables which are linear combinations of the 4 Delaunay's arguments D, F, l, l', the planetary mean longitudes λ_k $(1 \leq k \leq 8)$ and ζ, the lunar mean longitude referred to the mean equinox of date. The tidal perturbations introduce time-dependant analytical corrections $\Delta C_{i,j}$ and $\Delta S_{i,j}$ to the harmonics $C_{i,j}$ and $S_{i,j}$. The 'free libration' is described by 3 literal parameters $\sqrt{2P}$, $\sqrt{2Q}$, $\sqrt{2R}$ (constants of integration). In the corresponding Fourier series enter the 3 arguments of the free libration denoted by p, q, and r in addition to Delaunay's arguments.

• *Frame and constants.* A comparison between various JPL ephemerides of number n, i.e. $DE_n = DE_{245}, DE_{403}, DE_{405}$, and the analytical solution fitted to LLR observations, supposes that we use in all solutions the same set of constants and the same reference frame. Using the analytical theory ELP for the orbital motion of the Moon, by comparison with the JPL lunar ephemeris, we determine the reference frames of DE_n referred to the ecliptic and the inertial mean equinox for J2000.0, as well as the lunar mean longitude w_1 referred to a fixed equinox. The basic angles are: ϕ, separation between the origin of right ascensions of DE_n and the inertial equinox of J2000.0 along the equator of DE_n, and ϵ, the obliquity of DE_n (Chapront, *et. al.*, 1999b, 2002). Having brought the solutions in the same frame of reference, and using the sets of physical parameters listed in Table 1, a frequency analysis on the residuals between the analytical and the numerical models allows to evaluate the amplitudes of the 'free libration', i.e. the numerical values of literal parameters $\sqrt{2P}$, $\sqrt{2Q}$, $\sqrt{2R}$, as well as the libration frequencies: ω_s, $(s = p, q, r)$, with the following notations: $p = \omega_p t + p_0$, $q = \omega_q t + q_0$, $r = \omega_r t + r_0$; we call these frequencies 'observed values' in the sense that they are obtained by an ajustment to an ephemeris which represents the observations. Besides, the frequencies ω_s can be computed from their literal expressions provided by the theory; we call them 'computed values'.

2. COMPARISONS OF THE MODELS WITH DE_{245} AS REFERENCE

• *A semi-analytic form of the libration series.* On the basis of the analytical series, we have established 4 various solutions S_n $(S_{245}, S_{403}, S_{405}, S_{LLR})$ under the form of Fourier series with numerical coefficients. For each solution S_n, the coefficients have been computed with the numerical values given in Table 1. Hence, we have generated the series p_1^n, p_2^n and τ^n for any of the solutions S_n corresponding to the 3 JPL ephemerides DE_n and to the ephemeris E_{LLR} obtained by the authors with a LLR fit (see description hereafter). The quantities which are retained to adjust the solutions are ϕ, ϵ, $w_1 = w_1^{(0)} + w_1^{(1)} t + w_1^{(2)} t^2$, the free libration parameters (amplitude, phases and frequencies for p, q and r). In all the analytical series S_n, the arguments are linear combinations of Delaunay's arguments, planetary longitudes, ζ, and the angles p, q and r, whose frequencies are 'observed' through harmonic analysis as mentioned above. Nevertheless r cannot be determined with enough accuracy by harmonic analysis. We used the 'computed' value instead. The ephemeris E_{LLR} which corresponds to our fit to LLR observations is derived from DE_{245}. We have first established numerical complements to the analytical solution S_{245}, i.e. ρ_{245}, in order to get $S_{245} + \rho_{245} = DE_{245}$. Next, we have fitted the parameters to the LLR observations covering the period [1974-2002] (Chapront *et al.*, 2002). Using the values of the fitted paramers, we have obtained a new solutions S_{LLR} and a new ephemerides $E_{LLR} = S_{LLR} + \rho_{245}$.

• *A crude comparison of the models.* We choose as a reference DE_{245} which is also the model providing the Earth figure parameters in S_{LLR}. Formely, this solution has been a reference to elaborate the numerical complements to ELP and the libration ephemeris (Chapront *et al.*, 1997). We compute for the 3 variables p_1, p_2 and τ the differences: $\Delta E_n = DE_n - DE_{245}$ for DE_{403} and DE_{405}; in case of the LLR ephemerides, we form the difference: $\Delta E_{LLR} = E_{LLR} - DE_{245}$. Over a short time interval (1968-2010) we illustrate the differences on Fig. 2. For the variable τ, the graphs 'ΔE_{405}' and 'ΔE_{403}' have been shifted as follows: $\tau_{405} - \tau_{245} + 3".9$; $\tau_{403} - \tau_{245} + 2".2$. The differences ΔE_n reach maximum values as large as 0".3. That represents on the lunar surface a displacement of a few meters while the individual LLR observations have an accuracy at the centimeter level. In the process of comparisons and fits to observations, the scatter between the models is reflected on the determinations of the frames, the values of the physical parameters, the positions and velocities of the stations and reflectors.

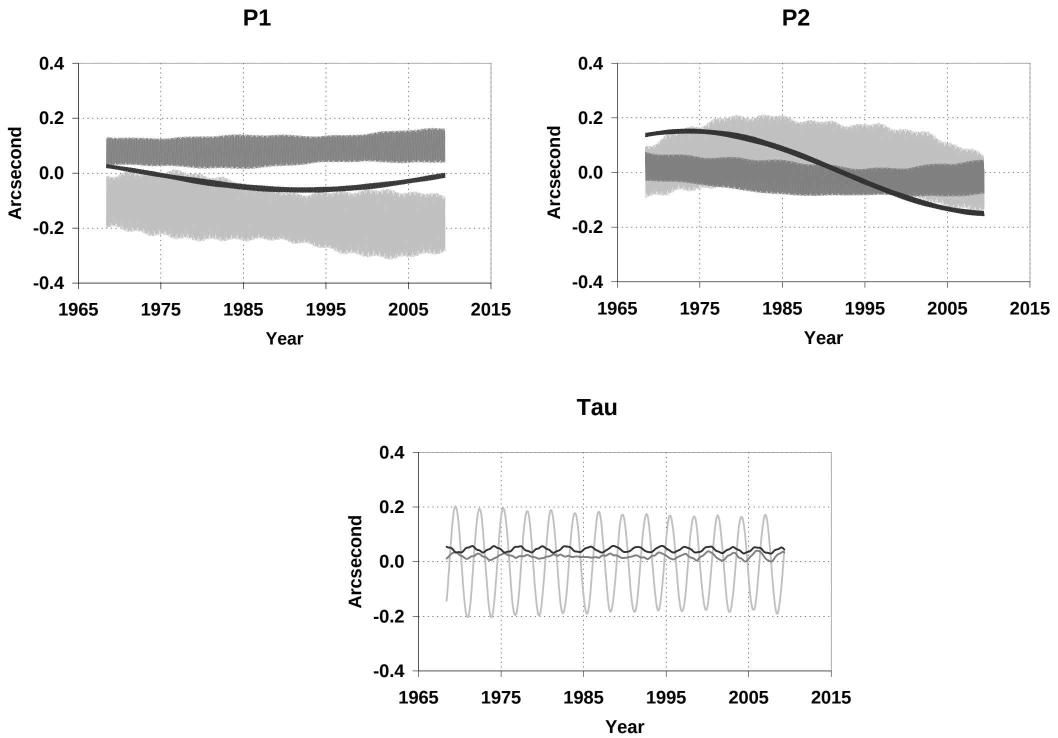

Figure 2: Differences of various models with respect to DE_{245}; (a) light grey: $\Delta E_{405} = DE_{405} - DE_{245}$; (b) dark grey: $\Delta E_{403} = DE_{403} - DE_{245}$; (c) black: $\Delta E_{LLR} = E_{LLR} - DE_{245}$

• *Approximation of the differences.* The solutions although they are far from each others, can be brought closer in a very simple manner with the aid of the analytical solution. In the case of DE_{405} (Standish, 1998), on one side we build the differences on the source ephemerides $\Delta E_{405} = DE_{405} - DE_{245}$; on the other side we build the differences on the analytical solutions $\Delta S_{405} = S_{405} - S_{245}$. An identical work can be performed with DE_{403} with results qualitatively very close. The residuals between ΔE_{405} and ΔS_{405} are shown on Fig. 3. They are explicitely described with short series of about ten terms. The extremum between the residuals are about 0".01 over 3 centuries. Using a sofware due to Mignard (2003), we have performed a frequency analysis of the differences ΔE_{405} and we have obtained ΔE^*_{405}. The related differences $\Delta E_{405} - \Delta E^*_{405}$, which are also represented on Fig. 3, are smaller than above ($\leq$ 0".005) which corresponds to the centimeter level. We note also that this approximation is valid on a very long time interval: [1750-2050]. It is worth noticing that we find in ΔE^*_{405} the main arguments (or frequencies) explicitely given in the analytical differences ΔS_{405}. For the variable τ, the deviation in $\Delta E_{405} - \Delta S_{405}$ is due to 2 periodic terms with close frequencies. Only one exists in S_{405}, the second one has been detected by harmonic analysis.

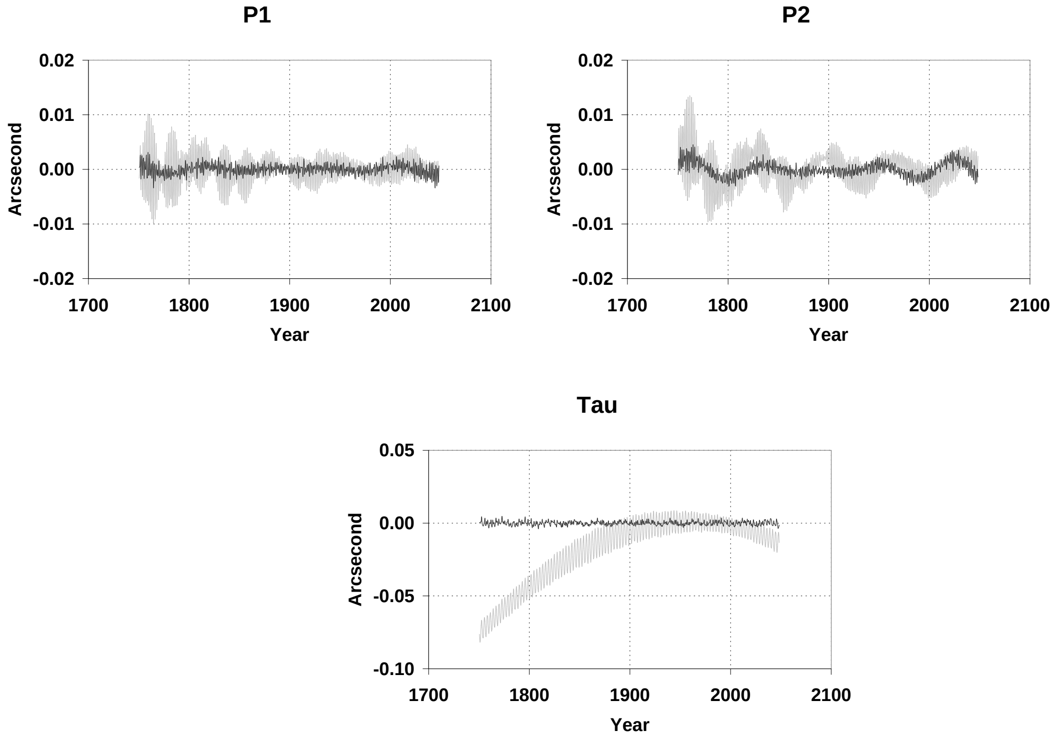

Figure 3: Comparison between numerical and analytical differences for DE_{405}; (a) light grey: Analytical solution, $\Delta E_{405} - \Delta S_{405}$ (b) black: Frequency analysis, $\Delta E_{405} - \Delta E^*_{405}$

3. PSEUDO-ANALYTICAL COMPLEMENTS WITH POISSON SERIES

Since we have at our disposal an analytical representation of the libration series (p_1, p_2, τ), and in particular a list of arguments (or frequencies) corresponding to the Fourier terms , we have completed and improved the analytical series by Poisson series. We have used a method which has been formely elaborated to improve, over a long time span, planetary analytical series (Chapront, 2000). We compute the differences between the numerical ephemeris and give to any variable σ the following form which is called P_n, or Poisson approximation of the difference $E_n - S_n$ related to the ephemeris $E_n = DE_n$ or E_{LLR}:

$$\sigma = \sigma_0 + \sigma_1 t + \sum_{[j]} \sum_k (C_0^{(k)} + C_1^{(k)} t)\cos(j_1\lambda_1 + j_2\lambda_2 + ...) + (S_0^{(k)} + S_1^{(k)} t)\sin(j_1\lambda_1 + j_2\lambda_2 + ...)$$

The numerical coefficients σ_s, $C_s^{(k)}$, $S_s^{(k)}$, $(s = 0, 1)$, are determined by least square fits. On the Fig. 4, in the case of DE_{245}, one represents the differences $E_n - S_n$ between numerical and analytical ephemerides and a comparison to its approximation P_n. The graph '$E_n - S_n$' shows the crude differences between the numerical and the analytical model. The graph '$E_n - (S_n + P_n)$' shows the small-sized residuals after the approximation of the analytical solution with Poisson series. The maximum of the differences is of the order of 0".01.

4. CONCLUSION

This study puts in evidence that it is possible to pass from a model of the lunar libration to another one, with the addition of short Fourier series. Besides, a chosen analytical solution S_n completed by Poisson terms represent the libration variables with a great accuracy over several centuries. Our final choice is the solution fitted to the LLR observations, S_{LRR}. A complete analytical model plus its pseudo-analytical complements, as well as a FORTRAN software to built an ephemeris of the libration variables, can be found on the website : http://syrte.obspm.fr/polac.

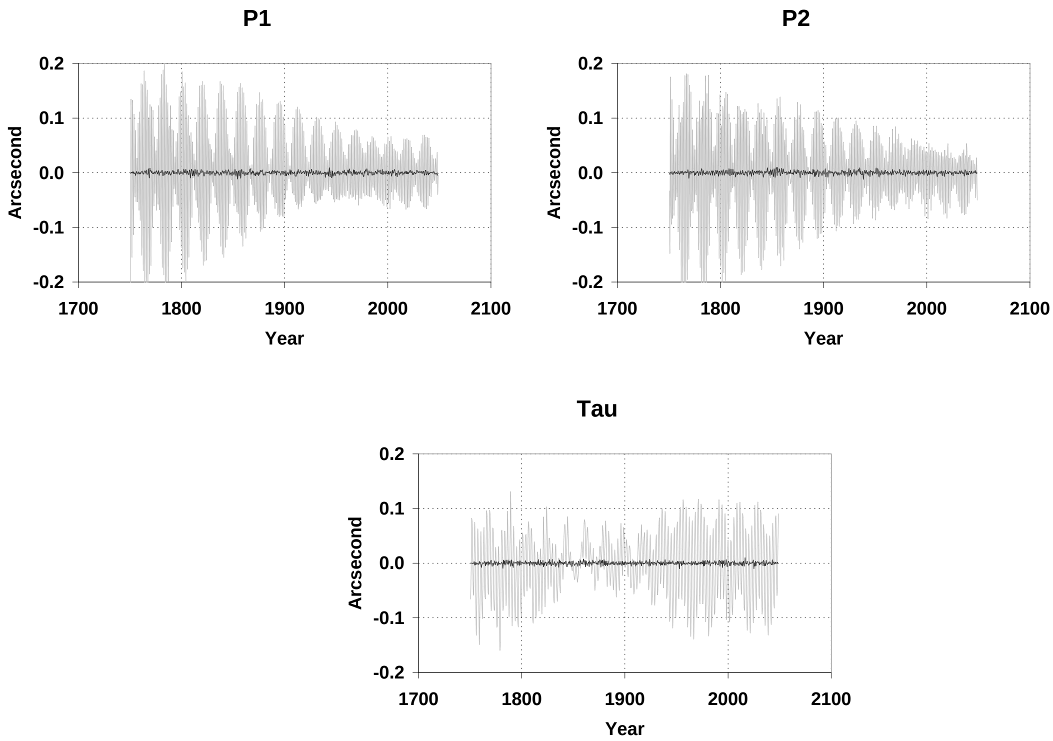

Figure 4: Improvement of the differences $DE_{245} - S_{245}$ with Poisson series; (a) light grey: $DE_{245} - S_{245}$; (b) black: $DE_{245} - (S_{245} + P_{245})$

5. REFERENCES

Chapront, J.: 2000, Celest. Mech. Dyn. Astr. 78, 75.

Chapront, J. and Chapront-Touzé, M.: 1997, Celest. Mech. Dyn. Astr. 66, 31

Chapront, J., Chapront-Touzé, M. and Francou G.: 1999a, Celest. Mech. Dyn. Astr. 73, 317.

Chapront, J., Chapront-Touzé, M. and Francou G.: 1999b, A&A 343, 624.

Chapront, J., Chapront-Touzé, M. and Francou G.: 2002, A&A 387, 700.

Mignard, F.: 2003, FAMOUS (Frequency Analysis Mapping On Unusual Sampling), Software.

Moons, M.: 1981, Libration physique de la Lune, Thesis, Facultés Universitaires de Namur.

Moons, M.: 1982, The Moon and the Planets, 27, 257.

Moons, M.: 1984, Celest. Mech. Dyn. Astr. 34, 263.

Standish, E.M.: 1995, JPL Planetary and Lunar Ephemerides, DE403/LE403, IOM 314-10-127, Pasadena.

Standish, E.M.: 1998, JPL Planetary and Lunar Ephemerides, DE405/LE405, IOM 321.F-98-048, Pasadena.

EFFICIENT ORBIT INTEGRATION BY ORBITAL LONGITUDE METHODS

T. FUKUSHIMA
National Astronomical Observatory of Japan
2-21-1, Ohsawa, Mitaka, Tokyo 181-8588, Japan
e-mail: Toshio.Fukushima@nao.ac.jp

ABSTRACT. Triggered by the desire to investigate numerically the planetary precession through a long-term numerical integration of the solar system, we developed a new formulation of numerical integration of orbital motion named *manifold correction methods* [4, 5, 6, 7, 8, 9]. The main trick is to keep rigorously the consistency of some physical relations such as that of the orbital energy, of the orbital angular momentum, or of the Laplace integral of a binary subsystem. This maintenance is done by applying a sort of correction to the integrated variables at every integration step. Typical methods of correction are certain geometric transformation such as the spatial scaling and the spatial rotation, which are commonly used in the comparison of reference frames, or mathematically-reasonable operations such as the modularization of angle variables into the standard domain $[-\pi, \pi)$. The finally-evolved form of the manifold correction methods is the orbital longitude methods [9, 10, 11, 14], which enable us to conduct an extremely precise integration of orbital motions. In the unperturbed orbits, the integration errors are suppressed at the machine epsilon level for an infinitely long period. In the perturbed cases, on the other hand, the errors initially grow in proportion to the square root of time and then increase more rapidly, the onset time of which depends on the type and the magnitude of perturbations. This feature is also realized for highly eccentric orbits by applying the same idea to the KS-regularization [12, 13, 15]. Especially the introduction of time element greatly enhances the performance of numerical integration of KS-regularized orbits whether the scaling is applied or not.

1. METHODS OF MANIFOLD CORRECTION

In short, the new method is a modern revival of Nacozy's original idea [19] to correct the integrated orbits during the integration process to ensure that they exactly lie on a certain manifold containing the true solution such as an energy-constant hypersurface by a kind of projection operation. It was first named as the methods of *manifold correction* by Murrison [18]. Later Hairer discussed it independently and called it the *projection method* [16].

The simplest example [4] of the manifold correction is to maintain the Kepler energy relation,

$$K = T - U \tag{1}$$

where $T \equiv \vec{v}^2/2$ is the kinetic energy and $U \equiv \mu/r$ is the (negative) gravitational potential energy. The correction is achieved to all the binary subsystems by applying the single spatial scaling,

$$(\vec{x}, \vec{v}) \rightarrow (\sigma\vec{x}, \sigma\vec{v}), \tag{2}$$

at every integration step. This form of correction was motivated by a theoretical examination of the manner of error growth of a circular motion by the simplest integrator, the Euler method [4]. Here the scale factor σ is determined from the solution of an associated cubic equation,

$$T\sigma^3 - K\sigma - U = 0, \tag{3}$$

numerically by means of the Newton method starting from an obvious initial guess $\sigma_0 = 1$.

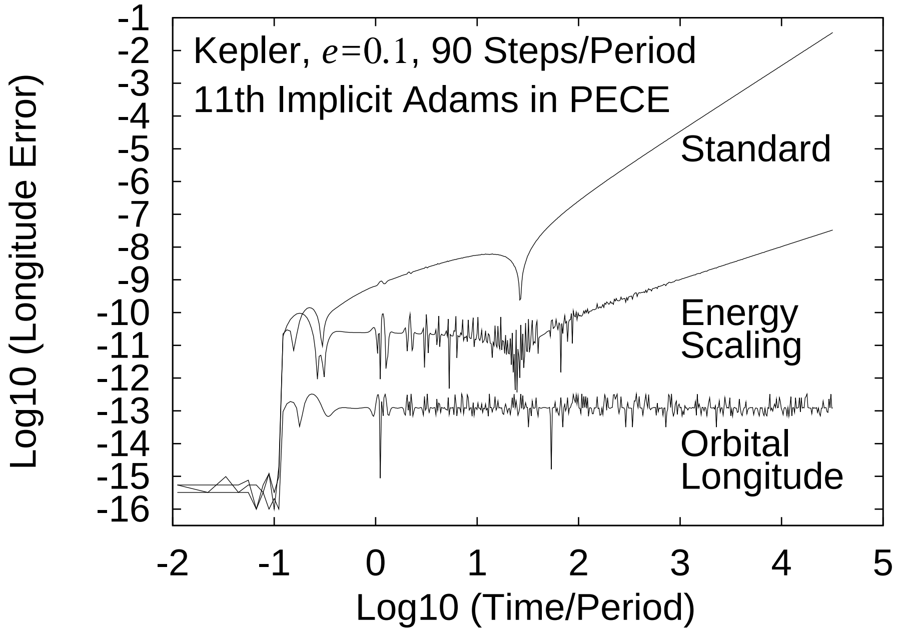

Figure 1: Illustrated are the errors in the mean longitude at epoch as functions of time in a log-log scale. Integrated was a moderately eccentric ($e = 0.1$) Keplerian orbit by (1) the standard method to integrate directly in rectangular coordinates, (2) the scaling method for Kepler energy consistency [4], and (3) the antifocal longitude method [11]. The adopted integrator was the eleventh order implicit Adams method in the PECE mode (predict, evaluate, correct, evaluate), the step size was fixed through the integration and set as 1/90 the orbital period, the starting tables were prepared by Gragg's extrapolation method, and the errors were measured by comparing with the reference solutions obtained by the same method, the same integrator, and the same model parameters but with half the step size. Since the order of the integrators are sufficiently high, halving the step size eliminates almost all the truncation errors.

See Figure 1, which compares the error growth of a Keplerian orbit obtained by the standard method to integrate the equation of motion in rectangular coordinates directly and that with the aforementioned single scaling for the Kepler energy, K, which becomes a constant in this unperturbed case. This figure shows that the well-known quadratic increase of the integration errors is reduced to a linear growth, which has been observed for a limited type of integration scheme; the symplectic integrator and the symmetric linear multistep method. The observed difference in the rate of error growth, which was partially enhanced by the introduction of some Encke-like technique to reduce the effect of round-off error accumulation [3], will lead to a large difference in the magnitude of integration error in the long run.

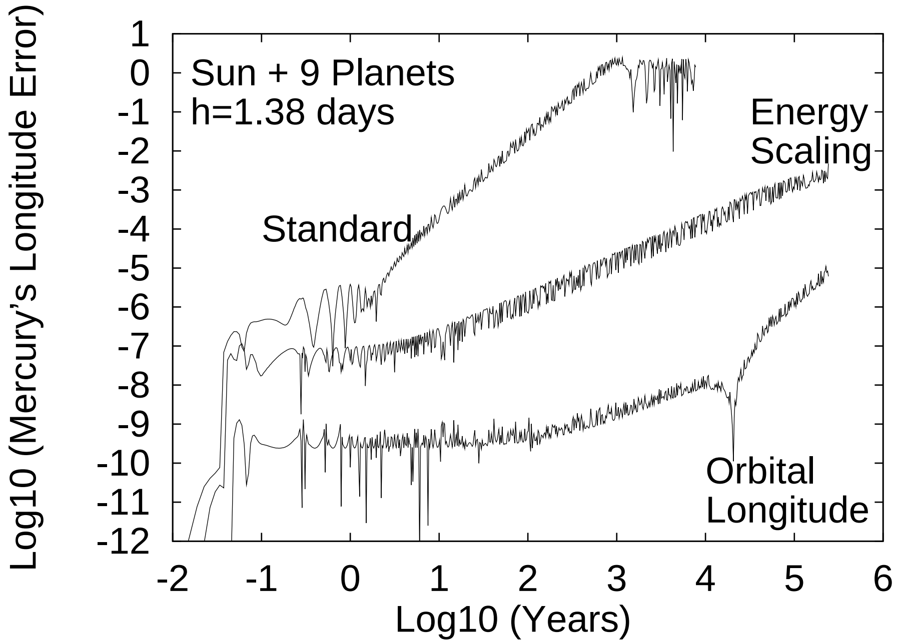

Figure 2: Same as Figure 1 but for the longitude error of Mercury in the simultaneous integration of the Sun and nine major planets for half a million years. The step size was chosen relatively large as around 1.4 days.

In case of perturbed orbits, the Kepler energy is no more a constant. Then we follow its time development by integrating its equation of motion simultaneously with that of the position and velocity. The good performance of the scaling method is unchanged as seen in Figure 2, which illustrates an example of n-body integration; Mercury's error growth in the integration of the Sun and nine major planets.

The effectiveness of manifold correction methods is independent on various aspects of the orbit integration such as the method of integration (Runge-Kutta, extrapolation, or linear multistep), the type of base orbits (elliptic, parabolic, or hyperbolic), the kind of perturbations (autonomous or not, conservative or not, velocity-dependent or not, etc.) [4].

2. ORBTIAL LONGITUDE METHODS

The Kepler energy is not the only quantity suitable to be monitored for the manifold correction. Any quasi-conserved quantity can be used additionally. Then we refined the single scaling method by adding such quantities as (1) a quantity related to the Laplace integral [5], (2) the orbital angular momentum [6], and (3) the full Laplace integral vector [7]. Such extensions enhance the performance but at the cost of increase of computational effort.

Next we developed some simplified version of the last evolved form, the linear transformation method [7], by reducing the complexity of the manifold correction by some sets of variable transformation [8, 9]. Finally we arrived a method requiring *no* manifold correction, which we named the (original) orbital longitude method [9]. The method uses a set of six variables consisting of (1) $\vec{L}$ as the three rectangular components of the orbital angular momentum, (2) g as a true orbital longitude measured from a certain longitude origin solely determined from $\vec{L}$, and (3) P_A and P_B as the two on-the-plane components of the Laplace integral vector.

To our surprise, the application of the modularization of angle g into the standard range

$[-\pi, \pi)$ at every integration step leads to *no* growth of integration error if the integration method is sufficiently precise, say the eleventh order implicit Adams method with the step size as 1/90 the orbital period [10]. The true longitude is not the only orbital longitude to be used. By replacing it with the antifocal longitude, we enhanced its performance further [11]. Here the antifocal longitude is an orbital longitude with the coordinate origin as not the primary focus but the secondary one.

See Figure 1 again which shows the superiority of this antifocal longitude method over the standard and the single scaling method. Note that this slowness of the error increase also means that the accumulation of round-off errors, which is usually expected to grow in the 1.5 power of the time, is also suppressed. As far as the author knows, this is the first exception of Brouwer's law [2]. We think that this exceptional phenomenon was caused by transforming the second-order differential equation in rectangular coordinates to the first-order one in the orbital longitude. Its example is the equation of time development of true anomaly in the Keplerian motion,

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \nu(1 + e\cos f)^2 \quad \text{where} \quad \nu \equiv n\left(1 - e^2\right)^{-3/2}, \tag{4}$$

which is nothing but a rewriting of Kepler's second law or the defining relation of the angular momentum.

In fact, we observed that the presence of the perturbations only enlarges this zero-growth to the square-root-growth as was already observed in Figure 2. This low rate of error growth is understood by the statistical accumulation of zero-mean random errors. Of course, this is only for some initial phases and the actual integration errors will increase more rapidly when the truncation errors become dominant. In any sense, these changes in the manner of error growth has led to a drastic decrease of the overall integration errors as seen in Figures 1 and 2.

Recently, we elaborated these orbital longitude methods by introducing Sundmann's time transformation [14], which enhances the original orbital longitude methods especially in the highly eccentric cases.

3. APPLICATION TO KS-REGULARIZED MOTION

The concept of the manifold correction is not limited to the direct integration in rectangular coordinates. Since the two orbital longitude methods [9, 10, 11] loose their efficiency in highly eccentric cases, we applied the same idea to the KS regularization.

In terms of the KS-regularized orbital motion, the Kepler energy relation reduced to that of, H, the total energy of the four-dimensional harmonic oscillator , $\vec{u}$, associated to the regularization;

$$H = T + V, \tag{5}$$

where $T \equiv \left(\vec{u}'\right)^2/2$ and $V \equiv -(K/2)\vec{u}^2$ are the kinetic and potential energies of the associated four-dimensional harmonic oscillator, and $'$ denotes the differentiation with respect to the fictitious time, s, the independent variable in the KS regularization. Again the correction is done by the single scaling. This time the scale factor is explicitly evaluated as

$$\sigma = \sqrt{\frac{\mu}{4(T+V)}}. \tag{6}$$

In late 1970's, Mikkola invented a similar device to correct the KS variables to maintain the orbital energy (E) and the magnitude of the orbital angular momentum (J) of a binary subsystem. Then Aarseth named it the *EJ scaling* [1]. We confirmed that the single scaling to maintain the Kepler energy consistency in terms of the KS variables is slightly better than the EJ scaling [12]. Next we developed it into the quadruple scaling method, which adjusts all the four components of the harmonic oscillator associated with the KS regularization [13].

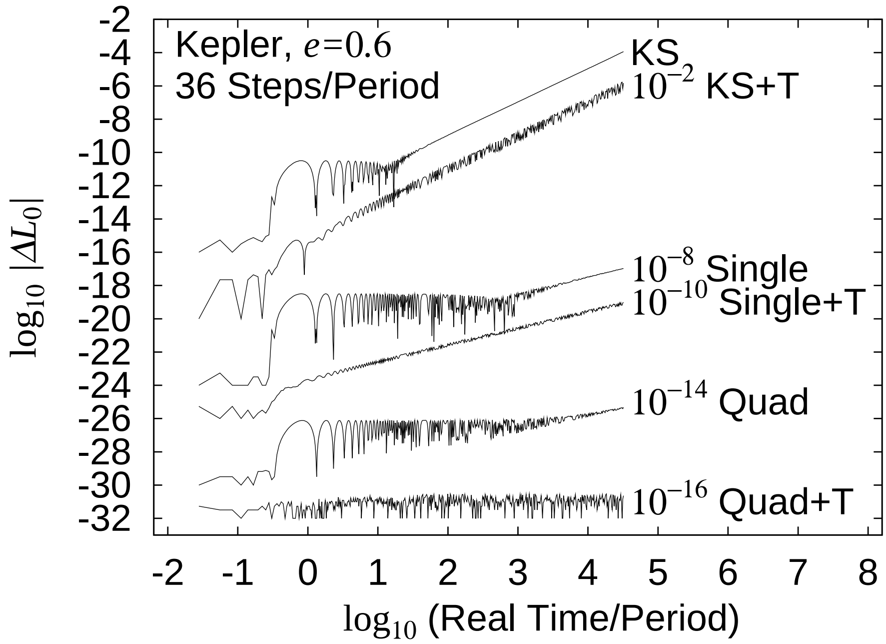

Figure 3: Similar as Figure 1 but for a highly eccentric ($e = 0.6$) orbit integrated by the methods using the KS regularization; (1) the original KS regularization [20], (2) the single scaling method [13], (3) the quadruple scaling method [13], (4) the KS regularization using the time element in a primitive form, (5) the single scaling using the time element [15], and (6) the quadruple scaling using time element [15]. The symbol '+T' denotes the usage of time element. Most of the curves are multiplied with some factors to avoid an overlap with others. The step size in the fictitious time was fixed through the integration and made so large that one orbital period in the real time is covered by only 36 steps. The order of the Adams method was set as that led to the least errors; the 13th for the two methods of quadruple scaling, and the eleventh for the others.

See Figure 3 showing the performance of these two scaling methods. Again the scaling reduces the error growth rate from quadratic to linear in the long run, although the appearance of some amount of periodic errors are unchanged. The quadruple scaling provides the better performance. However, we should note that this is at the cost of increase of variables to be integrated simultaneously from 10 to 13.

Unfortunately, even the quadruple scaling method could not achieve the zero growth of integration error. Therefore we examined the origin of the quadratic and linear error growth in the KS regularization with and without the scaling.

During the course of investigation, we unexpectedly discovered that the integration error of a harmonic oscillator can be reduced to achieve the zero-growth manner if the integrator adopted is sufficiently precise. Also we found that the cause of total error growth lies in integrating the development equation of physical time

$$t' = r \equiv \vec{u}^2. \tag{7}$$

Once Stiefel [20] proposed to integrate not the physical time, t, but its function named the *time element*, τ, defined as

$$\tau \equiv t - \left(\frac{1}{K}\right) \vec{u} \cdot (\vec{u})'. \tag{8}$$

A primitive form of the equation of motion of τ becomes as

$$\tau' = r - \left(\frac{1}{K}\right)\left[(\vec{u})'\right]^2 + \cdots , \tag{9}$$

where we omitted the terms reducing to zero in the case of unperturbed motion. Adoption of this primitive form leads to the supression of periodic part whose appearance is eminent in the initial phases as seen in Figure 3.

On the other hand, if one rewrites the first two terms by using the Kepler energy relation, the above equation of motion is further simplified as

$$\tau' = -\left(\frac{\mu}{2K}\right) + \cdots , \tag{10}$$

where the first term remains to be a constant in the limit of unperturbed case. Namely the motion of the time element reduces to a linear function of the fictitious time in the limit of unperturbed orbits, which can be integrated error-free by any kind of proper integrator. We confirmed that the combination of this elaborated form and the quadruple scaling guides us to the zero growth of unperturbed orbit integration in the KS-regularized formulation as was already shown in Figure 3.

In any case, the magnitude of the periodic error observed commonly in the KS regularization integrating the physical time, t, no longer appears after its replacement by the time element, τ.

References

[1] Aarseth, S.J., 2003, Gravitational N-body simulations, (New York: Cambridge Univ. Press)

[2] Brouwer, D., 1937, AJ , 46, 149

[3] Fukushima, T., 1996, AJ , 112, 1263

[4] Fukushima, T., 2003a, AJ , 126, 1097 (Paper I)

[5] Fukushima, T., 2003b, AJ , 126, 2567 (Paper II)

[6] Fukushima, T., 2003c, AJ , 126, 3138 (Paper III)

[7] Fukushima, T., 2004a, AJ , 127, 3638 (Paper IV)

[8] Fukushima, T., 2004b, AJ , 128, 920 (Paper V)

[9] Fukushima, T., 2004c, AJ , 128, 1446 (Paper VI)

[10] Fukushima, T., 2004d, submitted to Celest. Mech. Dyn. Astr. (Paper VII)

[11] Fukushima, T., 2004e, AJ , 128, 1455 (Paper VIII)

[12] Fukushima, T., 2004f, AJ , 128, No.6 (Paper IX)

[13] Fukushima, T., 2004g, AJ , 128, No.6 (Paper X)

[14] Fukushima, T., 2004h, submitted to AJ (Paper XI)

[15] Fukushima, T., 2004i, submitted to AJ (Paper XII)

[16] Hairer, E., Lubich, C., and Wanner, G. 1999, Geometric Numerical Integration, Springer-Verlag, Berlin

[17] Kustaanheimo, P., and Stiefel, E.L., 1965, J. Reine Angew. Math. 218, 204

[18] Murison, M.A. 1989, AJ , 97, 1496

[19] Nacozy, P.E. 1971, Astrophys. and Space Sci., 14, 40

[20] Stiefel, E.L., and Scheifele, G., 1971, Linear and Regular Celestial Mechanics, (New York: Springer)

VÉRON & VÉRON BASED EXTRAGALACTIC REFERENCE FRAME

A.H. ANDREI[1,2,3], A. FIENGA[1], M. ASSAFIN[3], J.L. PENNA[2], D.N. DA SILVA NETO[3], R. VIEIRA MARTINS[1,2,3]

[1] Institut de Mécanique Céleste et Calcul des Ephémérides-IMCCE/OP
77 Av. Denfert-Rocherau F-75014, Paris, France

[2] Observatório Nacional-ON/MCT (permanent address)
R. Gal. José Cristino 77, Rio de Janeiro, 20921-400, RJ, Brasil

[3] Observatório do Valongo-OV/UFRJ
Ladeira do Pedro Antonio 43, Rio de Janeiro, 20080-090, RJ, Brasil
e-mail: oat1@on.br

ABSTRACT. The Gaia Extragalactic Celestial Reference Frame (GCRF) will be formed by about 500,000 quasars, up to magnitude G=20, to typical precision of 100 μas. It is pivotal for many of the mission objectives, starting with the astrometry catalogue. We present a restricted representation of the GCRF, based on the Véron-Cetty & Véron list of 48,921 quasars. This representation brings the original list to a fully coherent placement on the ICRS. The sources positions have been collected from the USNO B1.0 catalog, which is complete to V=20. Around each source, fields of size as small as 6' were detailed, in which were picked up B1.0 stars and their corresponding positions from catalogs extending the HCRS to dimmer magnitudes. The UCAC2 (48 million stars, to R=16, precise to 50 mas) and the 2MASS (470 million objects, complete to J=16, precise to 100 mas) acted as the astrometric reference catalogs. Taking as paradigm the B1.0 positions corrected by the UCAC2, it is obtained a reference frame containing 37,513 quasars, globally aligned to 1 mas with the ICRF. The optical minus radio standard deviation is at 150 mas, much smaller than the nominal 200 mas B1.0 accuracy (the o-r standard deviation is above 300 mas for the original V&V entries). The extragalactic reference frame so obtained enables to gather insights on the distribution and luminosity of the GCRF. At the same time it provides an useful frame for all purpose observations.

1. METHOD AND RESULTS

To find the B1.0 (Monet et al., 2003) position for the V&V (Véron-Cetty & Véron, 2003) quasars three conditions have been enforced. That the positions would match below 1", which guarantees to be within the combined 2.5σ level. That the corresponding B1.0 entry had proper motions smaller than the proper motions error. And that the B1.0 and V&V magnitudes would not differ by more than 3. The process is fully automated and, in case of more than one candidate fulfilling the criteria, the closest to the V&V position was chosen. Next, B1.0 positions were picked up for UCAC2 stars (Zacharias et al., 2004) around the quasar. For that the UCAC2 positions were placed at the date of the B1.0 original plate containing the quasar. Then the same recognizing criteria of position and magnitude matching were used. Extensive tests have shown that first degree independent complete polynomials suffice, and indeed are more indicated, to obtain the UCAC2 corrections to the B1.0 positions (Andrei et al., 2004). The present status of the extragalactic optical frame is shown in Figure 1. Note the limitation due to the currently incomplete UCAC2 northern stellar coverage. Supplementary, B1.0 corrections by 2MASS (Cutri et al., 2003) stars were also essayed with encouraging results.

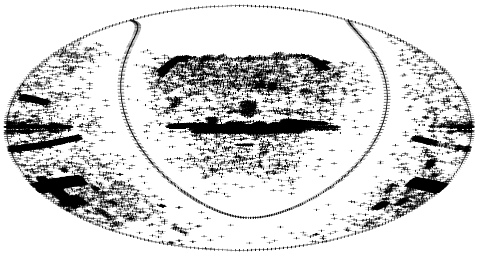

Figure 1: Sky distribution of the 37,513 V&V quasars. The positions were here determined from B1.0 entries as locally corrected on local UCAC2 stars frames.

2. CONCLUSION AND PERSPECTIVES

The combination of the V&V list with the positions from the B1.0 catalog enables to obtain an optical extragalactic reference frame, with one hundred times the number of the ICRF sources. The B1.0 systematic errors can be removed by local corrections using UCAC2 stars. As both the B1.0 and the UCAC2 catalogues are tied to the HCRS, it equally is the so formed extragalactic reference. The UCAC2 local correction mimics a plate reduction, and, due to the smallness of the required fields, it can be performed by independent (X,Y) first degree polynomials.

Presently, the formed extragalactic reference frame contains 37,513 sources. The adherence to the ICRF is -32 ± 10 mas on right ascension and $+8 \pm 9$ mas on declination. The standard deviations of the offsets to the ICRF positions are at the level of 150 mas. No systematic differences to the ICRF are apparent at this level. To compare, the corresponding standard deviation from the direct V&V entries to the ICRF positions is at the level of 320 mas.

The next steps, already being tackled, are to complete the northern part of the V&V list, for which UCAC2 stars are not yet available. A way to do it is by using preliminary UCAC2 positions, provided that a study of proper motion is made. Alternatively, 2MASS stars can be used. At any rate, a thorough reduction using 2MASS stars is planned, for the sake of comparison and study of the 2MASS astrometry. The analysis of residuals is also planned relatively to the sources characteristics, as color, magnitude, and redshift. For the final version of the optical extragalactic reference frame, the adherence to VLBI positions is to be used to furnish harmonic corrections, to tie the optical reference frame directly to the ICRF.

AHA thanks CNRS for contract QAF183803, MA acknowledges FAPERJ grant E-26/170.686/ 2004, DNSN thanks to CNPq grant 303950/2003-0, RVM is thankful to CAPES grant 0449/04-0.

3. REFERENCES

Andrei, A.H., Fienga, A., Assafin, M., Penna, J.L., da Silva Neto, D.N., Vieira Martins, R., Soares Musumeci, P., 2004, in The Three Dimensional Universe with Gaia, Observatoire de Paris, Section de Meudon.

Cutri, R.M., Skrutskie, M.F., Van Dik, S., et al., 2003, IPAC/CalTec - The 2MASS Point Source Catalogue

Monet, D.G., Levine, S.E., Casian, B. et al, 2003, AJ, 125, 984 - The USNO B1.0 Catalogue

Véron-Cetty, M.P., Véron, P., 2003, A&A, 412, 399 - 11^{th} edition

Zacharias, N., Urban, S., Zacharias, M.I., et al., 2004, AJ, 127, 3043 - The UCAC2 Catalogue

IMPROVED PROPER MOTIONS IN DECLINATION OF HIPPARCOS STARS DERIVED FROM OBSERVATIONS OF LATITUDE

G. DAMLJANOVIĆ[1], J. VONDRÁK[2]

[1] Astronomical Observatory
Volgina 7, 11160 Belgrade – 74, Serbia and Montenegro
e-mail: gdamljanovic@aob.bg.ac.yu

[2]Astronomical Institute, Academy of Sciences of the Czech Republic
Boční II, 14131 Prague 4, Czech Republic
e-mail: vondrak@ig.cas.cz

ABSTRACT. At the end of 20th century, the HIPPARCOS Catalogue was finished, and near 4.4 million astrometric optical observations (made at 33 observatories) of near 4.5 thousand HIPPARCOS stars used for the investigations of latitude/universal time UT0 variations were collected. Nowadays, these optical observations are useful for improvement of proper motions of HIPPARCOS data; the long history optical observations (during the interval 1899.7-1992.0) can improve them (at the first place, the long term part). Here, some results of improved proper motions in declination (of some HIPPARCOS stars) are presented; we used the optical observations of latitude variations made with Photographic Zenith Tubes (PZT).

1. INTRODUCTION AND RESULTS

The ICRF started to materialize the ICRS from the beginning of 1998, after decision of the GA of the IAU in Kyoto 1997. The precision of 608 compact radio sources (Ma et al. 1998) is of 0.3 to 0.5 mas (milliarcsecond), and some time ago it was added 59 new sources by the ICRF – Ext.1 (IERS Annual report 1999). The HIPPARCOS Catalogue was started to be the optical counterpart of the ICRF in 1997. The ESA mission (ESA 1997) produced two catalogues: Hipparcos one and Tycho one. Hipparcos Catalogue, as an optical frame, contains 118218 stars, brighter than magnitude 12, with very large number of parameters (precise parallaxes, positions, proper motions, photometry, etc.). The accuracy of the positions is at the order of 1 mas at the epoch of the catalogue 1991.25. The standard error of the proper motions in $\mu_\alpha \cos(\delta)$ and μ_δ is about 1 mas/year. But the mission lasted too short time (less than four years) for the mentioned proper motions accuracy of some stars, mostly double and multiple ones. Nowadays, there are several programmes, based on the long history ground – based data, to remove that problem, and to achieve a better reference frame (more stable in time). Some new catalogues appeared, as the combinations of the ESA mission data with the ground – based ones: FK6(I), FK6(III), ACT, TYCHO – 2, GC+HIP, TYC2+HIP, ARIHIP; the most recent one is the Earth Orientation Catalogue – EOC (Vondrák and Ron 2003). Here, we used few PZTs latitude data (Vondrák et al. 1998) to improve the proper motions in μ_δ of some Hipparcos stars. These

PZTs data (Vondrák and Ron 2002) are: Punta Indio-PIP (Argentina,1971.6-1984.5), Mount Stromlo-MS (Australia,1957.8-1985.7), and Ondřejov-OJP (Czech Republic,1973.1-1992.0).

We made the separate file for each Hipparcos star (with all observations of that star observed at PIP, MS or OJP). There were: 165 Hipparcos stars observed at PIP, 184 stars at MS, 285 stars at OJP, 157 common PIP and MS stars. Because a lot of common PIP/MS stars, the PIP and MS data are very interesting for checking our procedure of calculation. The curve of the component of double/multiple star ($\Delta\delta$ or $\Delta\alpha\cos\delta$ with time) can be very complicated; in this paper we present the results made with the linear model. The polar motion effect $\Delta\varphi_i$ (calculated one) was removed from the data of each star by using x and y coordinates of polar motion from the file EOPOA00.dat (Vondrák 2000) and Kostinski formula (Kulikov 1962). Then, we continued with the residuals r_i (for the moment i) for each star ($r_i = \Delta\varphi_i - \varphi_n$). The value φ_n is the mean value of n observations of latitude (of some Hipparcos star observed during subperiod near one year long). In line with 2.7*σ statistical criterion, we removed some residuals (of some subperiods). For each star, we have got near one point (residual r_i) per year. Each point is with: MJD (the moment i), residual r_i, standard error of r_i, and number of latitudes n.

To determine the free term a, linear one b, and its standard errors, we used the Least – Squares Method (LSM) and the linear model $Y(j) = a + b * (X(j) - 1991.25)$, where: $X(j)$ is the time (MJD transformed into years), $Y(j)$ – mentioned residuals, j is the number of residuals (points). For any mentioned star, our value of b have the correct sign to be added to the proper motion in declination as given in the Hipparcos Catalogue. We calculated the values of a and b of each instrument and removed these values from the values of a and b of each star observed with that instrument. The calculated trend of each instrument was found from the residuals of lot of stars observed by that instrument. Finally, we have got the results (LSM, linear model, no weights); only a few examples are given here:

- PIP, H45995 , $a = +0.''037 \pm 0.''045$, $b = +0.''0023/year \pm 0.''0033/year$,
- MS, H45995 , $a = +0.''069 \pm 0.''025$, $b = +0.''0038/year \pm 0.''0012/year$,
- PIP, H53399 , $a = +0.''048 \pm 0.''044$, $b = +0.''0027/year \pm 0.''0032/year$,
- MS, H53399 , $a = +0.''070 \pm 0.''019$, $b = +0.''0032/year \pm 0.''0009/year$,
- OJP, H83885 , $a = -0.''050 \pm 0.''031$, $b = -0.''0063/year \pm 0.''0030/year$,
- OJP, H90454 , $a = +0.''029 \pm 0.''018$, $b = +0.''0062/year \pm 0.''0018/year$.

The presented results of the stars H45995 and H53399, from PIP and MS data, are in good agreement between each other, and it means that our procedure is relevant for that kind of investigations. It is necessary to be careful with PZT latitude data because of its level of formal errors (much bigger than the Hipparcos ones), and different kinds of systematic ones. These long series of historical data still can give us useful results. It is possible to improve the proper motions in declination of some Hipparcos stars by using the latitude data of PZTs.

2. REFERENCES

ESA: 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200.

IERS Annual Report: 1999, Observatoire de Paris.

Kulikov, A.K.: 1962, Izmenyaemost' sirot i dolgot, Moskva.

Ma, C. et al.: 1998, Astron. J., 116, 516.

Vondrák, J., Pešek, I., Ron, C., Čepek, A.: 1998, Earth orientation parameters 1899.7-1992.0 in the ICRS based on the HIPPARCOS reference frame, Astron. Inst. of the Academy of Sciences of the Czech R., Publ. No. 87.

Vondrák, J.: 2000, priv. comm.

Vondrák, J., Ron, C.: 2002, priv. comm.

Vondrák, J., Ron, C.: 2003, in Journées 2002 Systèmes de Référence Spatio-Temporels, ed. N. Capitaine (Observatoire de Paris), 49.

A NEW METHOD FOR DYNAMICAL ANALYSIS OF ORIENTATION ERRORS FROM NON REGULAR SAMPLES

J.A.LOPEZ[1], F.J.MARCO[2], M.J.MARTINEZ[3]

[1,2] Departamento de Matemáticas. Universidad Jaume I de Castellón.
Campus Riu Sec s/n. 12071 Castellón Spain.
[1] lopez@mat.uji.es , [2]marco@mat.uji.es

[3] Departamento de Matemática Aplicada. Universidad Politécna de Valencia
Camino Vera s/n. Valencia Spain.
[3] mjmartin@mat.upv.es

ABSTRACT. The main aim of this paper is the analysis of the orientation errors of a celestial reference system from the differences between observed and calculated positions for a set of selected minor planets. In this paper a new numerical method not based on the Gauss-Markov will be presented.

1. INTRODUCTION

A traditional method to study the orientation error of the star catalogues is the analysis of the residual observation minus calculus for a set of selected minor planets. Usually, there are two problems: first, the distribution of the minor planet positions is not homogeneous in a band around the equator or the ecliptic, and second, the means in residuals are not null. Traditional methods based on least squares do not run well because the hypotesis of Gauss-Markov theorem is not allowed (López et al. 2005).
In this work we present an alternative numerical method based on a new class of spatial estimators and a reconstruction is proposed. This method is more suitable in this case.

2. FUNCTIONAL MODEL

Let $\{\{(\alpha_i^r, \delta_i^r)\_i = 1^{n_r}\}_{r=1}^{N}\}$ be a set of observed positions of the minor planet r at the epoch t_i^r (Marsden 1999). Let $(\sigma_{r,1}^0, \cdot, \cdot, \cdot, \sigma_{r,6}^0)$ the orbital elements of the asteroid r at the occultation epoch t^0 taked from I.T.A. tables (Batrakov 1997). The topocentric calculated positions can be obtained from the integration of the planetary equations of Lagrange. For the integration, the planetary theory VSOP87 of Bretagnon & Francou (1988) has been used.
To analyse the O-C errors, a previous process of improvement of asteroids elements is necessary. The component due to the errors in the reference frame can be modelized by means of three infinitesimal rotations $\varepsilon_x, \varepsilon_y, \varepsilon_z$ arround the OX, OY, OZ axis.

The residuals O-C can be written from the hypothesis as:

$$\triangle\alpha_{Rot} = \alpha_{Cat} - \alpha_D = \varepsilon_x \tan\delta\cos\alpha + \varepsilon_y \tan\delta\sin\alpha - \varepsilon_z + r_\alpha$$
$$\triangle\delta_{Rot} = \delta_{Cat} - \delta_D = -\varepsilon_x \sin\alpha + \varepsilon_y\cos\alpha + r_\delta$$

where r_α, and r_δ are random variables. The residual function Ψ can be written over a spherical domain D as:

$$\Psi(\varepsilon_x, \varepsilon_y, \varepsilon_z) = \int\int_D \left[r_\alpha^2 \cos^2\delta + r_\delta^2\right] \cos\delta d\alpha d\delta$$

and from them we can obtain $(\varepsilon_x, \varepsilon_y, \varepsilon_z)$ by a minimization proccess. In order to arrange the minimum, it is necessary to evaluate the integrals countaining the functions $r_\alpha(\alpha, \delta), r_\delta(\alpha, \delta)$, but these funtions are know only for the point belonging to D covered with the observations. To evaluate the integral we propose the following method:
1. Take as D the domain defined by a band around the equator (or the ecliptic) defined as: $B = \{(\alpha, \delta | \alpha \in [0, 2\pi], \delta \in [-\delta_{max}, \delta_{max}\}$.
2. Discretize the spatial domain B by means of a rectangular lattice defined as: $B : \{(\alpha_i, \delta_j) \in S_2 | \alpha_i = ih, \quad \delta_j = jk, \quad i = 0, ..., N_\alpha, \quad j = -M, ..., M\}$; $h = \frac{2\pi}{N}$, $k = \frac{\delta_{max}}{M}$.
3. Estimation of a function of $\triangle\alpha(\alpha, \delta)$, $\triangle\delta(\alpha, \delta)$ quantities from the sample done by the set of observations. For this purpose, we define for a generic function g, the quantities:

$$\overline{g_i}(\delta) = \frac{1}{h}\int_{(i-\frac{1}{2})h}^{(i+\frac{1}{2})h} g(\alpha, \delta) d\alpha \qquad \overline{\overline{g_{i,j}}} = \frac{1}{hk}\int_{\alpha_i - \frac{h}{2}}^{\alpha_i + \frac{h}{2}} \int_{\delta_j - \frac{k}{2}}^{\delta_j + \frac{k}{2}} f(\alpha, \delta) d\alpha d\delta = \frac{1}{k}\int_{\delta_j - \frac{k}{2}}^{\delta_j + \frac{k}{2}} \overline{g_i}(\delta) d\delta$$

To give the value $\overline{\overline{f_{i,j}}}$ from the sample, we use an efficient unbiased linear estimator of order s (López et al. 2005) and to take the values of $g(\alpha, \delta)$ from their means values, we use a reconstruction operator of order r (Casper & Atkins 1993).

3. NUMERICAL RESULTS

The numerical results obtained from this methods are: $\triangle\varepsilon_x = -0''003$, $\triangle\varepsilon_y = -0''002$, $\triangle\varepsilon_z = 0''046$ and from them, we obtain the value $\triangle A = 0''.041$ for the zero point of the FK5 calalogue, which is a value compatible with other determinations.

4. REFERENCES

Batrakov, Y.V., Shor V.A., "Ephemerides of Minor Planets for 1998" *Institute of Applied Astronomy Saint Petesburg (Russia).*

Bretagnon P. and Francou G., 1988, 'Variations Séculaires des Orbites Planétaires. Théorie VSOP87', A&A 114, 69-75.

Casper J. Atkins, H.L. 1993, "A Finite Volume Method H Order ENO Scheme for Two-dimensional Hyperbolic Systems", Jounal of Computational Physics 106, 62-76

López, Marco F.J., J.A., Martínez M.J., "Proposal of a new Computational Method for the Analysis of the Systematic Differences in Star Catalogues", Journal of Computational Methods in Science an Engineering, in press.

Marco F.J., López, J.A., Martínez M.J., 2004 "A critical discussion on parametric and nonparametric regression methods applied to Hipparcos-FK5 residuals", A&A 418, 1159-1170

Marsden B.G. 1999 "M.P.C. Electronic Version 1999. Minor Planet Center. S.A.O. Camdbrige MS U.S.A."

INFINITESIMAL VARIATIONS IN THE REFERENCE AND THEIR IMPLICATIONS ON THE MINOR PLANETS ELEMENTS AND MASSES

F.J. MARCO[1], M.J. MARTINEZ[2], J.A. LOPEZ[1]

[1]Universidad Jaume I
Campus de Riu Sec. Dep. Matemáticas. Castellón. Spain
e-mail: marco@mat.uji.es, lopez@mat.uji.es

[2]Universidad Politécnica de Valencia
Camino de Vera. Dep de Matemática Aplicada. E.T.S.I.I. Valencia. Spain
e-mail: mjmartin@mat.upv.es

ABSTRACT. It is well known that the elliptic motion of a body is determined by metrical elements, connected with the size and the shape of the orbit, and the angular elements, connected with the orientation of the orbit. On the other hand, the change of the Reference System could vary the orientation of the orbit including the inclination which, being a metrical element, contributes to determine the orientation of the orbit too. So, a temporal variation of the inclination may indicate a geometrical initial variation or a bad initial determination of any physical parameter, or both things. This is a question that we shall study in our paper, in a first approach.

1. EXPLAINING THE PROBLEM

A variation on the Reference induces also variations on the initial elements $\Delta i_0, \Delta\Omega_0, \Delta\omega_0$ and these initial variations imply variations in all the elements with time. We know that the inclination is related not only with the orbit orientation, but also is a metric element that is related with the size of the orbit. So, the observation of a metric element at a given time, comes from a bad determination of the initial elements, the initial Reference or its mass (or maybe all of them)?

2. EXPERIMENTAL CONFIRMATION OF THE PROBLEM

We take Pallas and we integrate taking null mass for it and with the initial elements varied by means of the infinitesimal rotations between FK5 and Hipparcos from Mignard & Froeschle (2000). We note that at initial time only changes the angles $\Delta i_0, \Delta\Omega_0, \Delta\omega_0$. On the other hand, we take the mass value given by Krasinsky et al. (2001), and the initial elements without the previous mentioned variations. Finally, we compare different shapes of temporal elements variations (35000 days) in order to observe possible relations. It's clear the "a priori" independence of the results. Nevertheless, we have observed many non expected and surprising relations:

a) there is a relationship between the temporal variation in the inclination of Pallas induced by change of its mass and the temporal variation in the semiaxis due to variations in the initial elements (and mass null); b) between the eccentricity and the perihelion argument; c) between the perihelion argument and the eccentricity. Another fewer relations appear between: d) the ascending node and the inclination; e) with semiaxis and the partial derivative of the semiaxis with respect to its initial value; and finally f) with the argument of the ascending node and the partial derivative with respect itself at initial epoch. Summing up, it appears as necessary a correct and global approach to the correction of Systems (with the geometrical and physical aspects and their mutual compatibility relationships). See also Marco et al. (2004) and Mignard & Froeschlé (2000).

Acknowledgments. This work was partially supported by the grant P1 1B2003-12 from the FUNDACIO CAIXA CASTELLO-BANCAIXA

3. REFERENCES

Krasinsky, G.A.; Pitjeva, E.V. et al. (2001) "Estimating masses of asteroids". Russian Academy of Sciences. I.A.A., 139

Marco, F.J.; López, J.A. and Martínez, M.J. (2003) "Monitoring Reference Systems: a try of global approach (Part I)" ACM 2002. Berlin, ESA, SP-500

Marco, F.J.; Martínez,M.J. and López, J.A. (2004) "A critical discussion on parametric and nonparametric regression methods applied to Hipparcos-FK5 residuals". A&A 418

Mignard, F. and Froeschlé, M. (2000) "Global and local bias in the FK5 from the Hipparcos data". A&A 354

TWO INDEPENDENT ESTIMATIONS FOR THE ϵ_z VALUES IN THE HIPPARCOS-FK5 CATALOGUES

M.J. MARTINEZ[1], F.J. MARCO[2], J.A. LOPEZ[2]

[1]Universidad Politécnica de Valencia
Camino de Vera. Dep de Matemática Aplicada. E.T.S.I.I. Valencia. Spain
e-mail: mjmartin@mat.upv.es

[2]Universidad Jaume I
Campus de Riu Sec. Dep. Matemáticas. Castellón. Spain
e-mail: marco@mat.uji.es, lopez@mat.uji.es

ABSTRACT. After the publication of the Hipparcos catalogue and its acceptation as the fundamental reference frame the questions of the homogenization of catalogues reemerged, because the IAU recommended that necessary studies should be arranged in order to obtain as thorough relationships as possible with the rest of catalogues. A first step to arrange the comparative study of two catalogues (in particular Hipparcos and FK5 which are the reference frames of the new and old reference system, respectively) is the application of a global rotation of one catalogue into the other. We employed two different models, including bias (GLAD model) or not (GL model) to obtain the infinitesimal rotations between the different catalogues (namely Hipparcos and other catalogue) They provide different ϵ_z values, which is an important problem to be solved. To this aim, we use two different verification methods based on nonparametrical adjustment employing kernel regression (KNP) and spherical harmonics of order n (SHn). These methods are independent of the previously employed (GL or GLAD) and they give us an idea of the true magnitude order of the parameter.

1. INTEGRAL NUMERICAL ESTIMATIONS OVER THE SPHERE FOR THE ϵ_z VALUES

The difference between the GLAD and the GL model lies in the difference between the corresponding ϵ_z values. The main intrinsecal difference between them rests on whether or not a value for DA and DD is included As a consequence, we need an independent method that gives us an idea of the true magnitude order of this parameter. This will be the KNP method. Nonparametrical adjustments by kernels compute the conditional mean of a certain random variable that depends on other variables. Let X be a random variable ($\Delta\alpha \cos\delta$ or $\Delta\delta$). If D is the spherical domain of X, $f\left(x,\alpha,\delta\right)$ the joint density function and $f_{(\alpha,\delta)}\left(\alpha,\delta\right)$ the marginal density, the method consists of finding:

$$m_X\left(\alpha,\delta\right) = E\left(X|\left(\alpha,\delta\right)\right) = \int_D x \frac{f\left(x,\alpha,\delta\right)}{f_{(\alpha,\delta)}\left(\alpha,\delta\right)} dx$$

In the previous equation it may be necessary to approximate the unknowns and selecting the Kernel, we arrive at an expression similar to the one of Nadaraya-Watson, but in the sphere:

$$m_X(\alpha, \delta) = \sum_{i=1}^{n} w_i x_i, \;\; w_i = \frac{K_\alpha\left(\frac{\alpha-\alpha_i}{h_\alpha}\right) K_\delta\left(\frac{\sin\delta-\sin\delta_i}{h_{\sin\delta}}\right)}{\sum\limits_{j=1}^{n} K_\alpha\left(\frac{\alpha-\alpha_i}{h_\alpha}\right) K_\delta\left(\frac{\sin\delta-\sin\delta_i}{h_{\sin\delta}}\right)}$$

2. CONCLUSION

The models usually employed search for infinitesimal rotations using the least squares method, but they do not remove the bias. The existence of the bias in $\Delta\alpha\cos\delta$ and $\Delta\delta$ makes the introduction of the Δ A and Δ D coefficients in the adjustment, cause a variation in the ϵ_z value. The SH and KNP models do not make any supposition about dependence on right ascension and declination residuals. Therefore, we can use them to see the GL and GLAD coefficients that they imply and to decide the ϵ_z values for two independent methods. The ϵ_z estimations are very different for the corresponding values obtained using the GL (Marco et al. 2004, Mignard & Froeschlé 2000,Schwan, H. 2001) or GLAD [1] and it is very important to reconsider the adopted model regarding further applications

Acknowledgments. This work was partially supported by the grant P1 1B2003-12 from the FUNDACIO CAIXA CASTELLO-BANCAIXA

3. REFERENCES

Marco F.J, Martínez M.J, López J.A. 2004, A critical discussion on parametric and nonparametric regression methods applied to Hipparcos-FK5 residuals. A&A 418. 1159-1170.

Mignard, F. and Froeschlé, M. 2000, A&A 354, 732

Schwan, H. 2001, A&A 373, 1099

RELATIVISTIC MODELING OF THE ORBIT OF GEODETIC SATELLITES EQUIPPED WITH ACCELEROMETERS

S. PIREAUX[1], J-P. BARRIOT[1], P. ROSENBLATT[2]

[1] UMR5562, Observatoire Midi-Pyrénées,
14 avenue Edouard Belin, 31400 Toulouse, FRANCE
e-mail: sophie.pireaux@cnes.fr, jean-pierre.barriot@cnes.fr

[2] Observatoire Royal de Belgique,
3 Avenue Circulaire, 31180 Bruxelles (Uccle), BELGIQUE
e-mail: Pascal.Rosenblatt@oma.be

1. THE CLASSICAL APPROACH: *GINS*

In today's planetary orbitography softwares, as in GINS (Géodésie par Intégrations Numériques Simultanées, developed by CNES [1] and GRGS [2]), the motion of spacecrafts is still described according to the classical Newtonian equations plus the so-called "relativistic corrections", computed with the required precision using the Post-(Post-) Newtonian formalism. Hence, it is the 3-vector acceleration ($i = 1, 2, 3$),

$$\frac{d^2X^i}{dT^2} = \frac{\partial W}{\partial X^i} + \textit{non-gravitational accelerations} + \textit{general relativistic corrections,} \qquad (1)$$

which is numerically integrated with respect to coordinate time T. The gravitational potential W includes not only the central planetary potential model but also the Earth-tide (due to the Sun and Moon, corrected for Love number frequencies, ellipticity and polar tides) potential, ocean-tide potential and Newtonian-perturbation potentials from other solar system bodies. The atmospheric drag, the radiation pressure (solar radiation, Earth albedo, thermal emission) are the non-gravitational perturbations considered. The orbitography software GINS also includes, as relativisitic corrections, the Schwarzschild, geodesic and Lense-Thirring precessions [1].

2. THE (SEMI-CLASSICAL) RELATIVISTIC APPROACH: *(SC)RMI*

The classical Newton plus relativistic corrections method faces three major problems. First of all, it ignores that in General Relativity time and space are intimately related. Secondly, a (complete) review of all the corrections is needed in case of a change in conventions (metric adopted), or if precision is gained in measurements. Today with the increase of tracking precision (32 GHz Ka/Ka-Band Doppler radio tracking at at the level of 1 mm/s with respect to a relative motion Earth/spacecraft of 10 km/s, i.e. with a relative accuracy of 10^{-13}), active interplanetary laser tracking (at the level of 10 cm with respect to a distance of 10^8 km, i.e. with a relative accuracy of 10^{-9}) and clock stabilities (Allan deviation of $\sim$4 $10^{-14}\tau^{-1/2}$ for atomic fountains), the classical method is reaching its limits in terms of complexity. The penalty for not taking relativistic effects into account is the risk of polluting very weak geophysical effects, like the polar motion of Mars ($\sim$ 1 m in amplitude at the planet surface), or the signature on the nutations of the liquid core of Mars ($\sim$ a few cm over an amplitude of $\sim$10 m), by unwanted relativistic effects that are at the same period (typically one planetary year, or 687 days for Mars), and, worse, that can be cumulative (up to or larger than 10 m ranging error coming from relativity

[1] Centre National d'Etudes Spatiales, France
[2] Groupe de Recherche en Géodésie Spatiale, France

over one Mars orbit, ~150 minutes). Thirdly, with such a classical method, one correction can sometimes be counted twice (for example, the reference frequency provided by the GPS satellites is already corrected for the main relativistic effect), if not forgotten. For those reasons, a new approach, called (SC)RMI ((Semi-Classical) Relativistic Motion Integrator) [2], was suggested.

The relativistic equation of motion, when non-gravitational accelerations encoded in a 4-vector K_β [5] are present, is

$$\frac{dU^\alpha}{d\tau} = -\Gamma^\alpha_{\beta\gamma} U^\beta U^\gamma + K_\beta \left(G^{\alpha\beta} - \frac{U^\alpha}{c^2}\frac{U^\beta}{c^2} \right) \quad \text{with } U^\alpha \equiv \frac{dX^\alpha}{d\tau}, \quad U^\alpha U_\alpha = c^2 \tag{2}$$

where $X^{\alpha=0,1,2,3} \equiv \left(c \cdot T,\ X^i \right)$ are the space-time coordinates; $\Gamma^\alpha_{\beta\gamma}$ are the Christoffel symbols, functions of the derivatives of the space-time metric $G^{\alpha\beta}$; and τ is the proper time. In the relativistic approach, it is those 4-dimensional equations (i.e. $\frac{d^2X^\alpha}{d\tau^2}$) which are directly numerically integrated. For the appropriate metric at the required order, they contain all the gravitational effects at the corresponding order. Indeed, computing the above equations for the Geocentric Coordinate Reference System (GCRS) metric [3,4] will take into account gravitational multipole moment contributions from the central planetary gravitational potential, perturbations due to solar system bodies, the Schwarzschild, geodesic and Lense-Thirring precessions. Non-gravitational forces can be treated as perturbations, in the sense that they do not modify the local structure of space-time (the metric). Moreover, K_β being small, one can safely replace $G^{\alpha\beta}$ by its Minkowskian counterpart in the second term of the right-hand-side of equation (2), hence the terminology "Semi-Classical" in SCRMI. When $K_\beta = 0$, equation (2) reduces to the geodesic equation of the local space-time.

3. THE PRINCIPLE OF ACCELEROMETERS

Last we show how to update the classical equation for accelerometers, in other words, how to measure K_β, or consider introducing a non-gravitational force model in the relativistic framework. Let the satellite center of mass (CM) be located at X^μ; while a test-mass is at $X^\mu + \delta X^\mu$, in a cavity inside the satellite, hence shielded from non-gravitational forces. The test-mass motion is described by geodesic equations ((2) with K_β=0) while that of the satellite is described by (2). Evaluating the difference between those two equations at first order in δX^μ gives a general relativistic equation for accelerometers:

$$\frac{d^2\delta X^\alpha}{d\tau^2} = K^{(CM)}_\beta \left(G^{\alpha\beta} - \frac{dX^\alpha}{d\tau}\frac{dX^\beta}{d\tau} \right) - \frac{\partial \Gamma^\alpha_{\beta\gamma}}{\partial X^\mu} \delta X^\mu \frac{dX^\beta}{d\tau}\frac{dX^\gamma}{d\tau} - 2\Gamma^\alpha_{\beta\gamma}\frac{dX^\beta}{d\tau}\frac{d\delta X^\gamma}{d\tau} \tag{3}$$

Equation (3) reduces to geodesic deviation if $K^{(CM)}_\beta$=0.

Acknowledgements. S. Pireaux acknowledges financial support provided through the European Community's Improving Human Potential Program under contract RTN2-2002-00217, MAGE. JP. Barriot is funded by CNES/INSU. P. Rosenblatt is funded under a Belgian ESA/PRODEX contract.

4. REFERENCES

[1] GRGS. Descriptif modèle de forces: logiciel GINS. Note technique du Groupe de Recherche en Géodesie Spatiale (GRGS), (2001).

[2] X. Moisson. Intégration du mouvement des planètes dans le cadre de la relativit générale (thèse). Observatoire de Paris (2000).

[3] IAU 2000 resolutions. IAU Information Bulletin, 88 (2001). Erratum on resolution B1.3. Information Bulletin, 89 (2001).

[4] M. Soffel et al. The IAU 2000 resolutions for astrometry, celestial mechanics and metrology in the relativistic framework: explanatory supplement. astro-ph/0303376v1 (2003).

[5] A. Lichnerowicz. Théories relativistes de la gravitation et de l électromagnétisme. Masson et Cie Editeurs 1955.

ASTROMETRICAL POSITIONS OF NEO INFERRED FROM CCD OBSERVATIONS AT BUCHAREST

R. POPESCU, P. POPESCU, A. NEDELCU
Astronomical Institute of the Romanian Academy
Str. Cuţitul de Argint, no. 5, sect. 4, RO-040558 , Bucharest, Romania
e-mail: [pradu, petre, nedelcu@aira.astro.ro]

ABSTRACT. We show up the capability of the old Prin-Merz astrograph, completely renewed, to perform narrow-field astrometry. A highly accurate metrological system has been conceived in order to monitor, focus, and track the reference stars. Besides, a high quantum efficiency CCD camera based on a back illuminated chip, allows this instrument to "observe" celestial objects up to 18 magnitudes, in less than 30 seconds of exposure. Due to the small FOV of the instrument we use the most dense star catalogue available - USNO B1.0 which can provide us reference stars enough to compute an accurate plate solution. 2 NEO have been observed during the testing phase (3908) Nyx and (85640) 1998OX4 and the results are presented in this paper. All the data have been submitted to the MPC.

1. OBSERVATIONS AND DATA PROCESSING

The old F/15.8 Prin-Merz visual astrograph, completely renewed is now able to perform narrow-field astrometry. The instrument is endowed with an Apogee 47P CCD Camera with a thinned, back illuminated, 1kX1k chip. The field of view is 7.6 x 7.6 arcmins. High quantum efficiency of CCD camera (92% at 650 nm) allow us to observe objects up to 18 magnitudes in 30 second of exposure time. The rather limited field of view leads us to the use of most dense star catalogue available at the moment - USNO B1.0, in order to have enough reference stars to compute an accurate plate solution.

The software used for images reductions and data processing is IRAF [1] in combination with NOVAS routines [2] from USNO. In the first step *daofind* function from Daophot package is used to extract objects positions from CCD frames. The catalog positions of the reference stars are taken via a small script from Vizier Service [3] and used together with the output of *daofind* by *ccxymatch* and *ccmap* to compute the plate solution.

2. RESULTS

During this testing phase of our instrumentation 2 NEO selected from Near Earth Object Program [4] have been observed. CCD Camera was used in 2x2 binned mode and with 20 seconds exposure time to avoid trailing of the faster asteroids and shorten the download time. The image scale was 0.89 arcsec/pixel.

First NEO observed was (3908) Nyx an asteroid with a magnitude of 16.5V and a rate of apparent motion of 0.096°/day at the moment of observation. The second one was (85640)

1998OX4 at a magnitude of 17.5V and rate of apparent motion of 5.765°/day. On average 30 reference stars have been found on each CCD frame. 14 astrometrical positions have been inferred for the first asteroid and 18 for the second.

Data concerning O-C residuals in α and δ for the two NEO are presented in the Table 1.

Asteroid	$(O-C)_\alpha$	$(O-C)_\delta$	$(O-C)_{total}$	No. of observations		
				≤ 0.2	≤ 0.5	≤ 1.0
(3908) Nyx	0.14 ± 0.16	-0.07 ± 0.14	0.23 ± 0.13	7	14	14
(85640) 1998OX4	-0.22 ± 0.28	-0.24 ± 0.27	0.47 ± 0.19	1	9	18

Table 1: Average offset and the corresponding standard deviations of the observed minus computed position. All values are in *arcsec*. Last three columns represents the number of observations within a given residual

The astrometrical positions of NEO inferred from recent CCD observations at Bucharest have been submitted to Minor Planet Center and distributed to Near Earth Objects - Dynamic Site. [5]

3. REFERENCES

1. http//noao.iraf.edu
2. Kaplan, et al. (1989) Astron. J. 97, 1197
3. Ochsenbein F., Bauer P., Marcout J., 2000, A&AS 143, 221
4. http://neo.jpl.nasa.gov
5. http://newton.dm.unipi.it/cgi-bin/neodys/neoibo?sites:073;obs;1;200

A FORTRAN VERSION IMPLEMENTATION OF BLOCK ADJUSTMENT OF CCD FRAMES AND ITS PRELIMINARY APPLICATION

Y. YU, Z.-H. TANG, J.-L. LI, M. ZHAO
Shanghai Astronomical Observatory, Chinese Academy of Sciences
Shanghai 200030, China
e-mail: yuy@shao.ac.cn; zhtang@shao.ac.cn; jll@shao.ac.cn; mzhao@shao.ac.cn

ABSTRACT. A FORTRAN version implementation of the block adjustment (BA) of overlapping CCD frames is developed and its flowchart is shown. The program is preliminarily applied to obtain the optical positions of four extragalactic radio sources. The results show that because of the increase in the number and sky coverage of reference stars the precision of optical positions with BA is improved compared with the single CCD frame adjustment.

1. FLOWCHART OF BA COMPUTER PROGRAM

Since the field of view of a CCD is usually too small to cover enough reference stars, the block adjustment (BA) of overlapping CCD frames was proposed in order to extend the sky coverage of observations, mitigate the effect of the position biases of reference stars, and consequently improve the local reference frame of the observation (Yu et al, 2004). In order to understand the basic principle of BA easily and develop the computer program conveniently, we showed the observation equations of BA in vectorial expressions. A FORTRAN version implementation of BA is developed and its flowchart is shown in Figure 1.

2. DETERMINATION OF OPTICAL POSITIONS OF FOUR EXTRAGALACTIC RADIO SOURCES

The observations of four extragalactic radio sources were carried out with the 2.16 m telescope in Xionglong station of the National Astronomical Observatories of China (NOAC) from June 6 to 10 of 2004. The CCD FOV is $10' \times 10'$ with 2048×2048 pixels, the scale is 0.015 mm/pixel.

UCAC2 (Zacharias et al, 2004) is taken as the reference catalogue in the reduction. The results of optical positions of the four extragalactic radio sources with BA and SPA are listed in Table 1. Column 2 to 4 are for BA and 5 to 7 are for SPA. 'Nref' represents the number of reference stars and 'O-R' means the difference ($\Delta\alpha cos\delta, \Delta\delta$) of the optical position from the radio one. The uncertainties of the deduced positions of objects are depended on those of the model parameters and measured coordinates. Since in BA and SPA the same measured coordinates are used and so the difference in the uncertainties of the deduced positions from BA and SPA are mainly determined by the uncertainty of model parameters. Because of the increase in the number and sky coverage of reference stars, the precision of model parameters is improved by BA compared with SPA, and so as shown by the formal error estimations in Table 1 BA is capable to provide more precise position determinations of objects.

3. REFERENCES

Yu Y, Tang Z H, Li J L, Wang G L & Zhao M., 2004, AJ 128, 911
Zacharias, N. et al. 2004, AJ 127, 3043

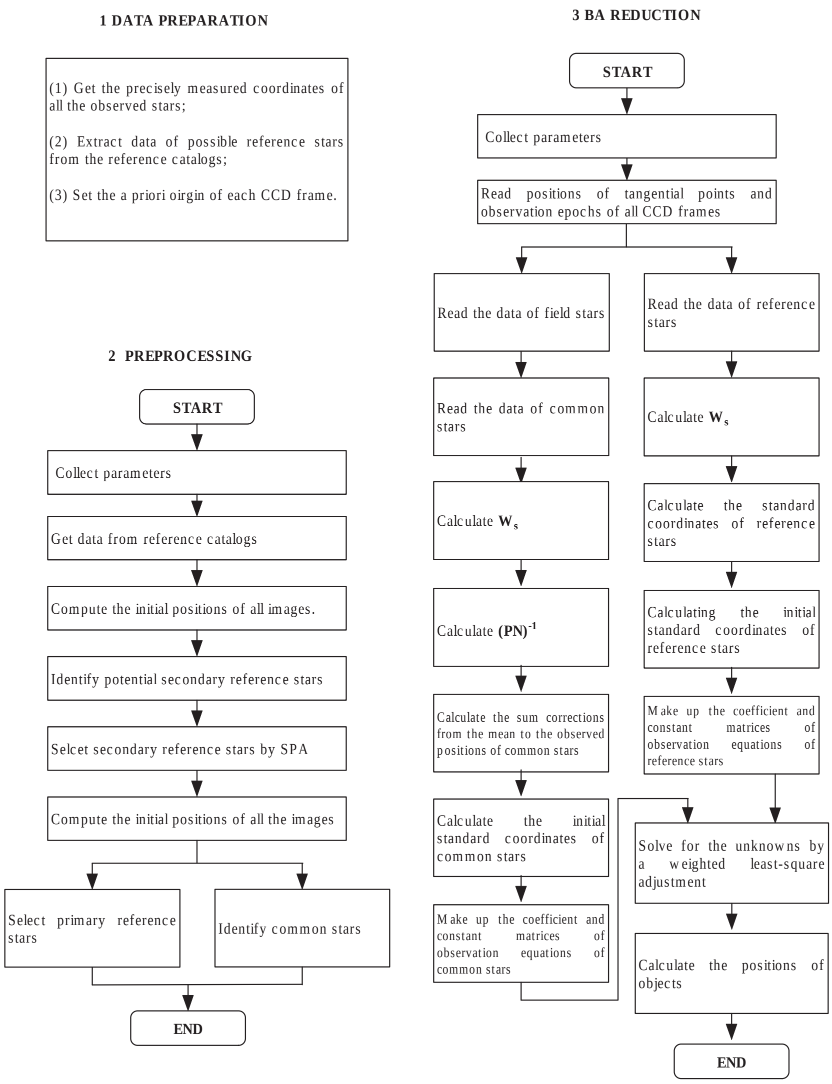

Figure 1.: Flowchart of the FORTRAN version realization of BA reduction of overlapping CCD frames.

	BA			SPA		
Object	α $(h\ m\ s)$ $\pm\sigma_\alpha$ (ms) O-R (ms)	δ $(^\circ\ '\ '')$ $\pm\sigma_\delta(mas)$ O-R (mas)	Nref	α $(h\ m\ s)$ $\pm\sigma_\alpha(ms)$ O-R (ms)	δ $^\circ\ '\ ''$ $\pm\sigma_\delta(mas)$ O-R (mas)	Nref
1252+119	12 54 38.2530	11 41 05.865	14	12 54 38.2582	11 41 05.854	6
	±1.0	±15		±2.5	±28	
	-2.5	-30		2.5	-41	
1307+121	13 09 33.9318	11 54 24.533	20	13 09 33.9328	11 54 24.559	5
	±1.0	±16		±2.5	±45	
	-0.6	-19		2.5	-41	
1743+173	17 45 35.2071	17 20 01.419	127	17 45 35.2043	17 20 01.383	15
	±0.7	±14		±3.0	±46	
	-0.9	-4		-3.7	-40	
1749+096	17 51 32.8166	09 39 00.768	170	17 51 32.8189	09 39 00.760	21
	±0.7	±11		±0.9	±15	
	-2.0	40		0.3	32	

Table 1: OPTICAL POSITIONS OF FOUR EXTRAGALACTIC RADIO SOURCES.

GALACTIC WARPING MOTION FROM HIPPARCOS PROPER MOTIONS AND RADIAL VELOCITIES

Z. ZHU, H. ZHANG
Department of Astronomy, Nanjing University
Nanjing 210093, China
zhuzi@nju.edu.cn, zhangh@nju.edu.cn

ABSTRACT. Based on the Hipparcos proper motions and the available radial velocity data of O-B stars, we have reexamined the local kinematical structure of young disk population of ∼1500 O-B stars other than the Gould-belt stars. A systematic warping motion of stars about the axis pointing to the Galactic center has been reconfirmed. A negative K-term has been detected that is a systematic contraction of stars in the solar vicinity. Two different distance scales have been accepted in order to inspect their impact on the kinematical parameters to be determined. We conclude that the adopted distance scale plays a certain role in characterizing the kinematical parameters at the present level of the measurement uncertainty.

1. INTRODUCTION

Thanks to the small velocity dispersion and low rotational lag relative to the LSR of the young disk population of stars, the analysis of large scale velocity fields of objects that belong to the young Galactic disk is the principal tools used by many investigators. Carrying out a proper motion analysis for Hipparcos O-B5 stars, we found a clear warping motion that is a systematic rotation of stars about the axis pointing to the Galactic center (Miyamoto & Zhu 1998). Using Hipparcos proper motions supplemented with radial velocities, a kinematical study of the classical Cepheids gave a negative K-term in our previous work (Zhu 2000). Comerón et al. (1994) examined the local kinematical structure of the O-B stars, and found that stars within the heliocentric distance $r = 1.5$ kpc exhibit a contraction, while stars within 0.4 kpc behave an expansion which may be dominated by the moving groups. A recent work by Bobylev (2004) confirmed that a negative K-term exists in the distant O-B stars. It is noticed that our following work differs from that by Comerón et al. or by Bobylev, because we have removed Gould-belt stars from our analyzing sample.

In the following work, we select O-B5 stars with all kinds of luminosity classes and B6-A0 stars with Luminosity classes I-II, excluding the Gould-belt stars, to reexamine the local kinematics of stars in a heliocentric distance up to $r = 3.0$ kpc. The astrometric data are taken from the Hipparcos Catalogue. The radial velocity data are obtained from the General Catalog of Mean Radial Velocities. In order to inspect the systematic deviation of the distance scales which might disturb the velocity field for the kinematical analysis, we have compared the Hipparcos distance scale derived from trigonometric parallaxes of stars with the spectroscopic SKYMAP distance scale. Statistically, the Hipparcos distance scale is smaller than that of the SKYMAP by about 5% on average.

2. KINEMATICAL STRUCTURE OF O-B STARS

The kinematical solution is derived from the O-B5 stars, B6-A0 supergiants and bright giants at a distance domain $0.2 \text{ kpc} \leq r \leq 3.0$ kpc. Based on the 3-D model (Zhu 2000), the kinematical parameters are determined via the generalized least-squares method.

The total velocity of the Sun S_0 relative to the LSR defined by stars considered, with the apex towards ℓ_0 and b_0, are derived on the basis of the SKYMAP distance scale

$$S_0 = 20.1 \pm 0.4 \text{ km s}^{-1}, \quad \ell_0 = 51.^\circ 2 \pm 1.^\circ 2, \quad b_0 = +22.^\circ 9 \pm 1.^\circ 1, \tag{1}$$

and based on the Hipparcos distance scale

$$S_0 = 16.9 \pm 0.4 \text{ km s}^{-1}, \quad \ell_0 = 47.^\circ 2 \pm 1.^\circ 3, \quad b_0 = +22.^\circ 2 \pm 1.^\circ 2. \tag{2}$$

Our previous determination of the solar motion gave

$$S_0 = 19.1 \pm 0.5 \text{ km s}^{-1}, \quad \ell_0 = 49.^\circ 2 \pm 1.^\circ 6, \quad b_0 = +21.^\circ 9 \pm 1.^\circ 3, \tag{3}$$

that was obtained from a proper motion analysis of O-B5 stars based on the SKYMAP distance scale (Miyamoto & Zhu 1998). The present determinations coincide with the previous one within the standard errors, except the total solar motion on the Hipparcos distance scale.

The combinations of the Oort constants A and B in a circular stream model give

$$A - B = 29.05 \pm 1.11 \text{ km s}^{-1} \text{ kpc}^{-1}, \quad A + B = \left(\frac{\partial V_\theta}{\partial R}\right)_{R=R_0} = -3.34 \pm 1.11 \text{ km s}^{-1} \text{ kpc}^{-1}, \tag{4}$$

for the SKYMAP distance scale, and

$$A - B = 31.05 \pm 1.22 \text{ km s}^{-1} \text{ kpc}^{-1}, \quad A + B = \left(\frac{\partial V_\theta}{\partial R}\right)_{R=R_0} = 1.58 \pm 1.22 \text{ km s}^{-1} \text{ kpc}^{-1}, \tag{5}$$

for the Hipparcos distance scale. Here, the azimuthal angle θ is pointing to the opposed direction of the Galactic rotation. The combination $(A+B)$ expresses the slope of the rotation curve at the Sun. It indicates that the variation of the distance scale does not only changes the rotational speed of the Galaxy, but also changes its gradient at the Sun.

In our previous work, a clear warping motion $+3.8\pm1.1$ km s^{-1} kpc^{-1} of stars about the axis pointing to the Galactic center has been found (Miyamoto & Zhu 1998). The present analysis gives a value of $+2.6\pm1.1$ km s^{-1} kpc^{-1} for both SKYMAP distance scale and Hipparcos distance scale. The determination of the warping motion is favorably independent of the distance scale adopted. The K-terms are found to be K=-2.2 ± 0.8 km s^{-1} kpc^{-1} from the SKYMAP distance scale, and K=-4.2 ± 0.9 km s^{-1} kpc^{-1} for the Hipparcos distance scale, respectively. The negative K-term means an overall contraction of stars at the solar vicinity.

In general, we conclude that the kinematical structure of O-B stars other than the Gould-belt stars, exhibits an overall rotation around the Galactic gravitation center on the Galactic plane simultaneously with a warping motion and a contraction. The adopted distance scale plays an important role in characterizing the kinematical parameters at the present level of the measurement uncertainty.

Acknowledgments. This work was supported by the National Natural Science Foundation of China (grant No.10333050) and by Nanjing University Talent Development Foundation.

3. REFERENCES

Bobylev, V.V., 2004, Astronomy Letters 30, 159
Comerón, F., Torra, J., & Gómez, A.E., 1994, A&A 286, 289
Miyamoto, M., & Zhu, Z., 1998, AJ 115, 1483
Zhu, Z., 2000, Ap&SS 271, 353

Session V

FUTURE OF UTC: CONSEQUENCES IN ASTRONOMY

FUTUR DE l'UTC: CONSÉQUENCES EN ASTRONOMIE

FUTURE OF UTC: CONSEQUENCES IN ASTRONOMY: REPORT ON THE UTC WORKING GROUP AND THE LATEST DEVELOPMENTS

D.D. MCCARTHY
U. S. Naval Observatory
Washington, DC 20392 USA
e-mail: dmc@maia.usno.navy.mil

ABSTRACT. The International Telecommunications Union Radiocommunications section (ITU-R) Working Party 7A has created a Special Rapporteur Group on the Future of the UTC Time Scale, and it presented its final report in September, 2004. This report suggests potential alternatives to the current relationship between the UTC time scale and the Earth's rotation angle as described by UT1. It is expected that this may lead to formal proposals to re-define this relationship. Possible consequences for the astronomical community are reviewed.

1. BACKGROUND

Coordinated Universal Time (UTC), the basis for worldwide civil timekeeping is an atomic time scale with a rate corresponding to the internationally accepted definition of the length of the second. However, it is adjusted in epoch by the occasional insertion or deletion of an integral second in order to keep it within 0.9s of UT1, the angle, expressed in terms of time, which is used to measure the rotation angle of the Earth in a celestial reference frame. This definition was implemented in 1972, principally to accommodate celestial navigation. The definition of UTC follows recommendation 460 of the International Radio Consultative Committee (CCIR) in 1970.

Stephenson and Morrison (1995), from their study of solar eclipse information, have shown that the average rate of increase in the length of the day is about 1.7ms per century in the long term. Although this might seem insignificant, the integrated effect on the difference between a uniform time scale and one based on the Earth's rotation can be very significant. For example, a time scale based on the Earth's rotation has lost more than three hours with respect to a uniform time scale over the past 2000 years. (Stephenson 1997). This deceleration of the Earth's rotation indicates that leap seconds will be inserted with increasing frequency in the future.

Since 1972 the use of electronic means to navigate has overtaken celestial navigation. This fact along with increasing public dissatisfaction with the possible disruption to modern electronic communications and navigation systems caused by the insertion of a leap second has called into question the current definition of UTC. An extensive review of the background and issues relating to the leap second can be found in Nelson *et al.* (2001).

2. CONSIDERATION OF A POSSIBLE REDEFINITION OF UTC

In 2000 the International Telecommunications Union Radiocommunications Section (ITU-R), the follow-on organization to the CCIR, adopted Question 236/7 "Future of the UTC Timescale" for discussion and possible future action. The issues addressed in this question were:

- What are the requirements for globally-accepted time scales for use both in navigation/telecommunication systems, and for civil time keeping?
- What are the present and future requirements for the tolerance limit between UTC and UT1? and
- Does the current leap second procedure satisfy user needs or should an alternative procedure be developed?

The question stipulated that results of the above studies should be included in recommendation(s), and that the above studies should be completed by 2006. It further required that this question should be brought to the attention of the Bureau international des poids et mesures (BIPM); the International Earth Rotation Service (IERS), now called the International Earth rotation and Reference system Service; Study Group 13 of the Telecommunication Standardization Sector; and ITU-R Study Group 8.

The question was referred to Working Party 7A (WP 7A) (Time Signals and Frequency Standard Emissions) of Study Group 7 (Science Services) for their action. In response WP 7A created a Special Rapporteur Group (SRG) to gather information and prepare a report with possible recommendations. The SRG met in December 2000, March 2001, May 2001, December 2001, and March 2002. A colloquium on the subject was held in Torino, Italy in 2003. During this time independent surveys on the topic were also conducted by the IERS, The International Union of Radio Sciences (URSI), the Communications Research Laboratory of Japan (CRL), and the National Institute of Standards and Technology of the USA (NIST). The SRG presented its report to the ITU-R WP 7A in September, 2004. At that meeting the USA WP 7A members proposed formally a recommendation to change the definition of UTC to modify its definition so that in the future, adjustments would be made to keep the difference between UTC and UT1 within one hour.

The International Astronomical Union (IAU) Working Group on the Definition of Coordinated Universal Time was created in compliance with IAU Resolution B2 of the 24th IAU General Assembly. The members were F. Arias, W. Dick, E. Fedoseev, D. Gambis, W. Klepczynski, S. Leschiutta, J. Luck, Z. Malkin, D. Matsakis, P. Paquet, J. Vondrak, P. Wallace, and S. Ye. D. McCarthy served as Chairman of the Group and as IAU representative to the ITU-R Special Rapporteur Group (SRG) on the Definition of Universal Time.

The IAU Working Group carried on its work by electronic correspondence and occasional meetings of opportunity. It contacted groups using celestial navigation and found no interest in continuing the use of leap seconds. It also identified the possible problems with existing software should a change be made in the current definition of UTC. Some members recommended the greater use of International Atomic Time (TAI) as a uniform time scale, but others argued that TAI would have to become more accessible to be widely used. Its report was submitted to IAU Division 1.

At the next IAU General Assembly it was decided to extend the lifetime of the Working Group to formulate a draft response to the possible recommendation of the ITU-R. The membership was revised at that time, and its new members are F. Arias, W. Dick, D. Gambis, M. Hosokawa, W. Klepczynski, S. Leschiutta, J. Laverty, Z. Malkin, D. Matsakis, R. Nelson, J. Vondrak, P.

Wallace, N. Capitaine (ex officio), and D. McCarthy (chair). Its response to any official action by the ITU is to be submitted through Division 1 to the General Secretary for IAU approval.

3. OPTIONS DISCUSSED

Options that have been discussed for the future of UTC include:

- Maintain the status quo
- Increase the tolerance between UT1 and UTC
- Periodic insertion of leap seconds
- Variable adjustments in frequency
- Redefine the second
- Substitute TAI for UTC
- Discontinue leap seconds in UTC

None of the options beyond (1) has received significant acceptance in discussions and surveys to this point. Also discussed has been the feasibility of establishing a low-cost low-precision UT1 service for any applications that need approximate mean solar time. The Internet would be a possible way to accomplish this and the IERS is taking steps to implement that service.

4. ISSUES

In the time since the ITU-R adopted Question 236/7 it is clear that analyses of Earth rotation lead to the conclusion that, at some future point, multiple leap seconds per year will be required to maintain the currently defined tolerance between UT1 and UTC. While advances in telecommunications, navigation and related fields are moving toward the need for a single, internationally recognized uniform time scale, no overwhelming consensus has emerged regarding maintaining the status quo until change is essential or actively seeking an alternative in anticipation of that change.

Continuation of the current definition has also led to concerns regarding the timing sequence to be followed during the actual implementation of a leap second. The convention is to number the leap second with the label "60" in the minute in which it has been inserted. Unfortunately many timing system do not permit a second to be labeled "60." In the past, this may have resulted in 2 seconds labeled 59 or even a second without a label. A conventional means to resolve this problem has not been adopted.

Yet another concern is that the traditional model of generating internal system time scales for operations could produce multiple *de facto* time scales. These "pseudo time scales" could lead to confusion and potentially serious consequences.

On the other hand some members of the astronomical community have expressed concerns over any change to the current system. These concerns are based on existing software that takes advantage of the current definition and uses UTC as a substitute for UT1. Their requirements for precision are such that the current 0.9-second tolerance is adequate, and their software has been designed accordingly. Should the definition of UTC be modified in any way that would permit this tolerance to be exceeded, they would anticipate substantial cost to make non-trivial changes in existing software. Similarly, the astrodynamic community has similar concerns regarding legacy software used in the determination of orbital parameters of artificial satellites that again utilizes UTC as a substitute for UT1.

However, although UT1 is expressed as a time, it is not used practically as a time scale. It is used as an angle that is related to the rotation angle of the Earth in the celestial reference frame. Knowledge of UT1 is essential in relating celestial and terrestrial reference systems and is obtained observationally for that purpose. The IERS provides daily values and predictions for up to a year in the future. It is conceivable that the systems served by legacy software based on the current UTC definition could benefit from using more realistic values for UT1 as opposed to the UTC approximation.

The reference of UTC to UT1 does provide a means to keep UTC vaguely in synchronization with the position of the Sun in the sky. It is generally agreed that a change in the definition of UTC that would cause legal time to depart from a solar connection would be unacceptable.

5. TORINO COLLOQUIUM

Although there was no overall consensus on this topic, findings from the official report of the Torino Colloquium, held in 2003, were the following.

- The definition of UTC is likely to evolve from the current UTC standard by transitioning to a uniform time scale, perhaps to be called Temps International (TI).
- If a change were to be made, a date suggested to inaugurate that change could be 2022, the 50th anniversary of the institution of the UTC timescale. This date was influenced by the anticipated lifetimes of existing systems that would be expensive to change.
- TI would likely be a continuous atomic time scale, without leap seconds, synchronized with UTC at the time of transition.
- The responsibility for disseminating UT1 information should remain solely with the IERS.

6. SPECIAL RAPPORTEUR REPORT

Following the Torino Colloquium and after further discussion, the SRG prepared a final report outlining a possible transition to a new definition of UTC. The final report of the SRG was submitted to ITU-R Working Party 7A. It contained the following recommendations.

- The creation of a new name was not recommended because it would add significant complications in the process of defining a new time scale. A name change alone could cause great confusion and complications in the ITU-R process and systems attempting to implement the new standards.
- The radio broadcast of DUT1 information should be discontinued since UT1 is available via IERS.
- The redefinition of a new "UTC" is not necessary
- Divergence from solar time, a possible issue in "civil" timekeeping is considered to be insignificant as an error of approximately 1 hour would result in 2600. Subsequent step adjustment could maintain approximate agreement and that advances in time keeping may lead to other solutions.
- The recommended date for change is 2010.

7. RECOMMENDATION PROPOSED TO ITU-R WP-7A

In order to work toward a final decision on the matter, the U. S. Working Party 7A prepared a proposal that was submitted to ITU Working Party 7A in September, 2004. In that proposed recommendation the Operational Rules for the formation of UTC after 0000 UTC December 21, 2007 would be modified so that the difference of UT1 from UTC should not exceed 1 hour. It further proposed that adjustments to the UTC time scale should be made as determined by the IERS to ensure that the time scale remains within the specified tolerances and that the IERS should announce the introduction of an adjustment to the UTC time scale at least five years in advance. At the time of that announcement the IERS should provide directions regarding the details of the implementation of the adjustment. The broadcast of DUT1 would be discontinued. Analysis of historical observations of the Earth's rotation currently indicates that such an adjustment would not be required for at least 500 years.

This proposal was rejected by the Working Party largely because of its early proposed date for implementaion.

8. FUTURE

Discussion continues on this subject. It is important that final resolution is obtained as new navigation and communication systems are being planned that need to be able to plan on a future means to obtain a standard uniform time scale.

If formal recommendation were to be referred to ITU sector members, the IAU would be expected to respond. The draft response would be prepared by IAU Working Group that includes F. Arias, W. Dick, D. Gambis, M. Hosokawa, W. Klepczynski, S. Leschiutta, J. Laverty, Z. Malkin, D. Matsakis, R. Nelson, J. Vondrak, P. Wallace, N. Capitaine (ex officio), D. McCarthy (chair). It would be submitted through Division 1 to General Secretary for IAU approval

9. REFERENCES

Nelson, R. A., McCarthy, D. D., Malys, S., Levine, J., Guinot, B., Fliegel, H. F., Beard, R. L., Bartholomew, T. R., 2001, "The leap second: its history and possible future," Metrologia, 38, pp. 509-529.

Stephenson, F.R., Morrison, L.V., 1995, "Long−Term Fluctuations in the Earths Rotation: 700 BC to AD 1990," *Phil Trans. R. Soc. London*, A 351, 165.

Stephenson, F.R., 1997, *Historical Eclipses and Earths Rotation*, New York, Cambridge University Press.

COORDINATED UNIVERSAL TIME UTC : HISTORICAL BACKGROUND AND PERSPECTIVES

E.F. ARIAS[1,2], B. GUINOT[2]

[1]Bureau International des Poids et Mesures
Pavillon de Breteuil, 92310 Sèvres, France
e-mail: farias@bipm.org
Associated Astronomer to SYRTE

[2]SYRTE, Observatoire de Paris
61, Av. de l'Observatoire, 75014, Paris, France
e-mail: guinot.bernard@wanadoo.fr

ABSTRACT. The system of Coordinated Universal Time, UTC, was initially conceived at the beginning of the 1960's as a means of improving the dissemination of Universal Time, UT1, and to make available the stable frequency of atomic standards in a single time signal emission. It gradually evolved by relaxing the tolerance on UT1 and in 1971 reached the form we know to-day. In spite of its success, borne out by 33 years of existence, the present system suffers increasingly from the inconvenience of leap seconds. The number of users in need of a continuous time scale is increasing, and as a consequence there is a proliferation of scales built for specific purposes due to the fact that UTC is not satisfactory for their applications. Global Navigation Satellite Systems time scales are examples of this situation. These notes bring together some astronomical elements that should be kept in mind in any proposed revision of the UTC system and give our views on a new system of time dissemination.

1. BIRTH AND EVOLUTION OF UTC

1.1 The pre-atomic time era

Regular emissions of intercontinental radio time signals began in 1910 in France, Germany and USA, with important applications in geodesy and especially positioning at sea. A need of coordination appeared immediately, which led to conceive the Bureau International de l'Heure (BIH) in 1912/1913. The Bureau was officially created in 1919, as a service of the International Astronomical Union, but has begun to work towards 1913. Although this early coordination, which involved the solution of many scientific and technical new problems, is interesting, the history considered here begins in 1955, just before the advent of caesium time standards.

In 1955, about 30 time services measured Universal Time UT and about 25 stations emitted radio time signals to disseminate UT. [The distinction UT0/UT1/UT2 was introduced in January 1956. At the BIH, UT was an average of the UT0's of the participating observatories. In January 1955, UT2 began to be used.] There was a great variety of operational modes, however, a typical mode was as follows. Astronomical determinations of UT were referred to a master clock (pendulum or crystal clocks, diapasons) which was then used to extrapolate UT in order to steer signal emission. Also reception times of a huge number of time signals were referred to the master clock. The data of all time services were then centralized at the BIH where they were processed to issue, with a delay of about one year, the *definitive* corrections to the nominal times of emission of the signals.

Let us mention some statistics, for January 1955. Daily corrections for 228 emissions were published. These corrections were ranging from -189 ms to +116 ms, with a majority between +/− 50 ms. Main sources of errors were: wrong values of astronomical longitudes, uncertainties of determinations of UT (10 to 20 ms), periods of bad weather, instability of clocks.

1.2 Atomic time and coordination of time signals

In July 1955, the first operational caesium frequency standard appeared at the National Physical Laboratory (UK) (Essen and Parry, 1955). It was soon followed by others, either laboratory instruments or industrially made ones ("Atomichron"). Some of these standards were used for short periods of time and were used to calibrate the frequency of crystal clocks. Others operated continuously. It was thus possible to construct *integrated* atomic time scales. At the US Naval Observatory (USNO) the frequency of the caesium transition was determined in 1957 by comparison with Ephemeris Time (Markowitz et al., 1958). This value was adopted for the atomic time A1 of USNO and for other integrated atomic times. Then, in 1967, it became the defining value for the definition of the SI second. In 1961, the BIH assigned a common origin to these time scales by coincidence with UT2 on the 1^{st} of January 1958 (Stoyko, 1961). The same origin was used for the BIH mean atomic time.

The divergence of these early atomic times was slow when compared to the divergence of the best clocks. Their largest difference at the end of 1958 was 5 ms and at the end of 1957 it was 7 ms. Then it increased at a much slower rate, following the rapid progress of the frequency standards (1 ms per year corresponds to 3×10^{-11} in relative frequency, level of the frequency inaccuracy of caesium standards in 1960/1961). These time scales brought much improved bases for the extrapolation of UT and the possibility of synchronizing time signal emissions within a few milliseconds.

In 1956, the time signals WWV of the National Bureau of Standards (now National Institute of Standards and Technology) of the USA began to be emitted on an uniform time scale, the deviation with respect to UT2 being corrected by time steps of 20 ms. In 1958, this uniform time scale was obtained from atomic time using a constant frequency offset of about -100×10^{-10} in order to follow approximately UT2, with time steps of 20 ms when needed.

This new system was not unanimously approved, probably because it accepted deliberately a departure with respect to UT2. Nevertheless, its advantages incited several observatories and laboratories to adopt it and to synchronize their emissions of time signals. In 1960 the International Union of Radiosciences recommended that the BIH, after consulting the concerned parties, announce the value of the frequency offset to be used during the following year and suggested that the nominal value will not change during the year. Later, the BIH also announced the date of introduction of time steps which were raised to 50 ms in August 1962 then to 100 ms in November 1963.

The name of Coordinated Universal Time UTC appeared in the early sixties at the International Radio Consultative Committee (CCIR) of the International Telecommunications Union (which became IUT-R Working Party 7A).

At the BIH, the acronym UTC was used for the first time in January 1964, with the empirical definition of a time scale deduced from the average time of emission of coordinated time signals. For these signals, the BIH began to publish the monthly averages of the difference E = UTC - Time of emission of the coordinated time signals, which remained fairly constant at the millisecond level (Guinot, 1964). For the best coordinated signals E amounted to a few milliseconds; for the others, E was progressively reduced.

A fundamental change occurred in January 1965: the BIH defined UTC by applying strictly the international frequency offset and time steps to its own atomic time scale, which became in 1972, TAI (Guinot, 1965). Thus, the transformation of UTC from a system of coordination of time signals into a time scale was achieved.

1.3 The present UTC

Most radio time signals had their carrier frequency in constant ratio with the second pulses. Therefore, the change of the frequency offset of UTC required physical adjustments at the emitting stations. With the increasing use of stable frequencies, especially for broadcasting and television stations, many users were also disturbed by the changes of the carrier frequency that they used as standard. This led to abandon a fine tuning of the UTC frequency on that of UT and to keep as long as possible a constant frequency offset, at the cost of an increased number of 100 ms time steps.

At the end of the 1960s, the demand for dissemination of frequencies in conformity with the definition of the second was becoming more pressing. Legal aspects were also evoked. These matters were mainly considered by the CCIR which prepared in 1969 a new definition of UTC without frequency offset and with time steps of one second, to be applied on 1972 January 1^{st}. In the meantime, from the beginning of 1970, two emissions (DCF77, Germany and WWVB, USA) broadcasted signals on a system known as TAS (Stepped Atomic Time). TAS had no frequency offset and a time step of 200 ms was applied at the end of a month when needed to maintain $[UT1\text{-}TAS]$ within $\pm$ 200 ms.

The first version of CCIR Recommendation 460-1 (1970) stipulates that TAI and UTC differ by an integral number of seconds, adjusted when necessary at the end of December or of June by introduction of positive or negative *leap seconds*. [This required on 1972 January 1 a time step of UTC of -0.1077580 s.] The maximum departure $|UT1\text{-}UTC|$ should not exceed 0.7 s. At the end of 1972, it was realized that it was not possible to comply with this rules and the BIH was faced to the choice of exceeding the tolerance of 0.7 s either on 1973 January 1 or 1973 July 1. Consequently, the tolerance was set to 0.9 s and the possibility of introducing a leap second at the end of any month was open. For those who needed the accuracy on UT1 provided by the previous form of UTC, an audible code disseminated $[UT1\text{-}UTC]$ to the nearest 0.1 s.

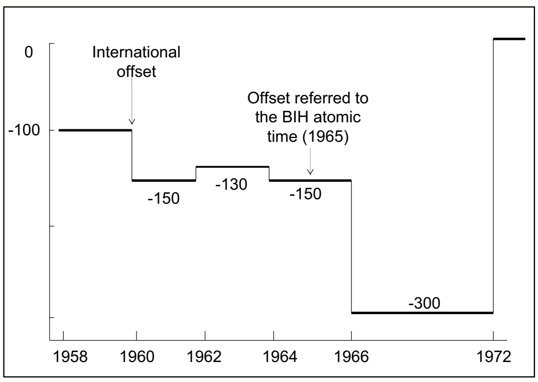

Figure 1: UTC frequency offsets (unit is 10^{-10}).

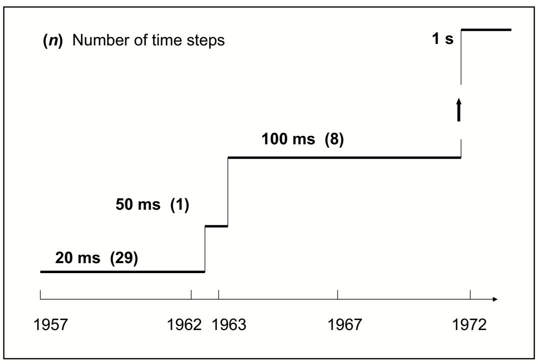

Figure 2: Evolution of UTC time steps.

Then the UTC system functioned without difficulties. Up to now, all leap seconds were positive. At the beginning, their rhythm was one per year. Since 1999, the rate of UT1 is close to that of TAI and no leap second has been introduced (October 2004).

The CCIR gave rules to date events without ambiguity when a leap second occurs. However, in case of positive leap second this is valid only in the system of hour, minute, second. In other systems two events one second apart receive the same date during the positive leap second.

Figures 1 and 2 show the evolution of the frequency offsets and time steps of UTC.

2. LONG TERM VARIATIONS OF UT1

In the long term the variation of [*UT1-TAI*] is dominated by the deceleration of the Earth rotation (fig. 3). [*UT1-TAI*] could reach half an hour in 2700, one hour towards 3000. Figure 4 shows the corresponding rate of introduction of leap seconds in the present UTC. Decade variations are superimposed to the secular terms and introduce variations in rate of order of one to two seconds per year, according to our experience since the 19^{th} century. Such variations referred to TAI are shown in fig. 5.

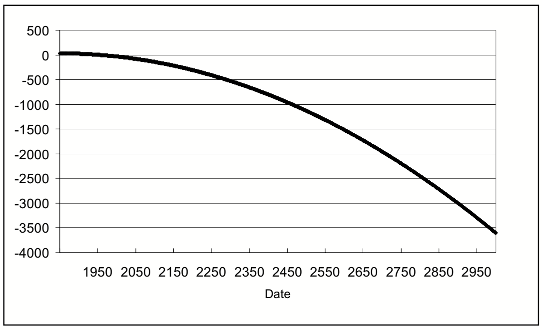

Figure 3: Secular term of [*UT1-uniform time*], in seconds.

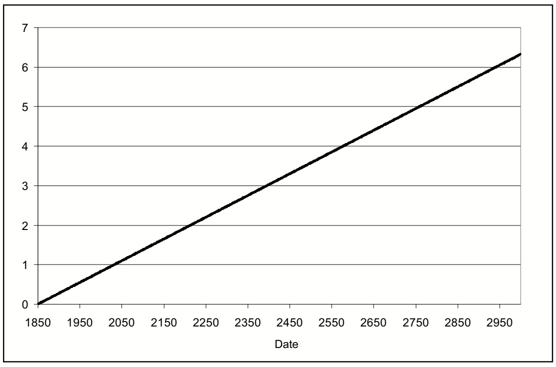

Figure 4: Number of leap seconds per year.

3. PERSPECTIVES

The UTC system has been in use for more than 30 years, and seems to be, a priori, a good compromise. However, the requirements for time keeping have evolved since the definition of UTC. The necessity of a uniform time scale, without the discontinuities introduced by the leap seconds is increasing.

TAI is, according to its first definition (Metrologia, 1971), the reference time coordinate established by the Bureau International de l'Heure (the BIPM at present) on the basis of readings of clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units. This definition evolved to be inserted in the context of general relativity, and TAI became the coordinate scale defined in a geocentric reference frame with SI second as realized on the rotating geoid as the scale unit (Metrologia, 1981). TAI is the uniform conventional time scale, but it is not distributed directly in every-day life. The time in common use (broadcast by different means) is referred to UTC, as recommended by the 15^{th} CGPM in 1975 and defined by the ITU. UTC provides the basis of civil time, it is associated to the legal time of most countries. Local realizations of UTC in time laboratories all over the world guarantee the dissemination of a time scale that represents UTC at the level of some tens of nanoseconds. These local physical realizations, named UTC(k) (k representing the laboratory) are provided by clocks.

In lack of a disseminated uniform time scale, and responding to the request of groups of users or services providers, a diversity of continuous time scales proliferated, constructed in most cases from ensembles of clocks, and differing between them in a number of seconds (see fig. 6). TAI is the uniform time scale, time dissemination responds to the UTC scale, offset by 32 s from TAI at present. GPS time, the scale for internal use in the GPS system is 19 s behind TAI (a constant amount) and 13 s ahead UTC today, this value increasing with the occurrence of positive leap seconds. The Glonass time is traceable to UTC through its Russian realization; it is directly affected by the introduction of a leap second. The future Galileo system plans to avoid the leap second by steering Galileo time to a uniform conventional time scale, namely TAI, but operatively to a sort of "leap second deprived UTC". In any case, the final decision is on hold of a recommendation concerning the definition of UTC. Besides these time scales there are many more designed for different applications, most of them absent in our records (telecommunications, banking, etc.). Should we think that the role of UTC in its present definition is to serve as the link between users of the different scales, each adopting a continuous scale to operate and transforming to UTC in a last step to follow the conventions?

The frequency of occurrence of positive leap seconds will increase, although slowly, in the long term (fig. 4), superimposed to decade fluctuations of the Earth rotation which may well lead in the near future to two leap seconds per year; this could increase the risk of omissions and errors in the files giving the information on [*UTC-TAI*].

An important fact is that dating in UTC is ambiguous when a positive leap second occurs in systems other than those using hours, minutes and seconds; in this latter system the use of the second "60", recommended by the ITU, may be a cause of difficulty. One of the most important role of a time scale is to provide an unambiguous way of dating events. In our opinion, the shortcomings of the present UTC in this respect suffice to condemn the system.

Based on these remarks, it seems that we should move towards the adoption of a world-wide, continuous time scale provided that enough time allowed to the users to prepare for the change. Taking into account that in some national legislations it is established that UTC serves as the basis of the official time, it should be convenient to maintain the same name and acronym. TAI should be preserved as it is; no more leap seconds would be added to UTC, freezing its difference to TAI at its value at the moment of application. Nevertheless, to avoid that the offset between TAI and UTC increase indefinitely, a leap hour could be added when necessary sometime in the far distant future. This proposal does not satisfy the condition of continuity, but the leap hour should not occur before about year 2700.

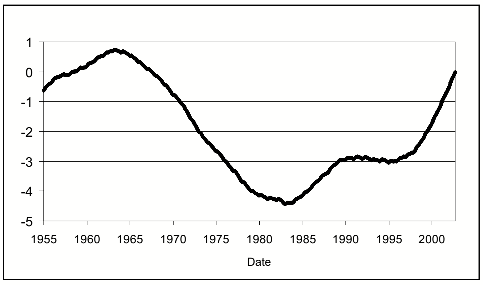

Figure 5: [*UT1-TAI*] corrected for secular variation.

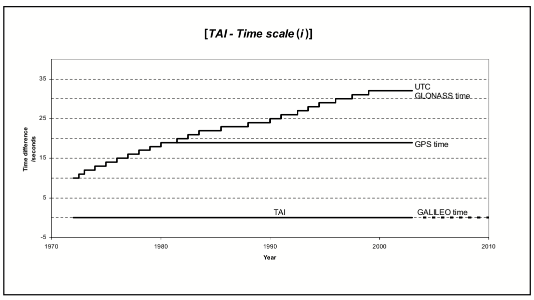

Figure 6: Differences between the various time scales and TAI.

4. ACCESS TO UT1

The dissemination of data depending on UT1 is and will remain essential. The critical case is that of annual ephemeredes for astronomical navigation (sea, air), for public use (sunrise, sunset, visibility of stars, planets, etc.) which require a precision of order of 1 second. It has been shown that a prediction of [*UT1-TAI*] within ± 1 second is possible over two or three years. These ephemeredes should be based on this prediction, and expressed directly with UTC as time argument. The authorities responsible for the monitoring of the Earth rotation (at present the IERS) should be in charge of the prediction of [*UT1-TAI*] needed for preparation of the ephemeredes.

The other needs of UT1 would be satisfied as they are presently, by dissemination of [*UT1-TAI*], either predicted for real time, or observed for deferred time. One can conceive improvements of the dissemination of these quantities, when needed, for example by satellite navigation systems.

5. REFERENCES

Essen L, Parry J.V.I, 1957, Phil. Trans. R. Soc. London, Series A, **250**, 45-69.

Guinot B., 1964, Buletin Horaire du BIH, Série J, n ° 1.

Guinot B., 1965, Buletin Horaire du BIH, Série J, n ° 7. Markowitz W, Hall R.G., Essen L., Parry J.V.I., 1958, Phys. Rev. Lett.,**1**, 105-107.

Metrologia, 1971, **7**, 43.

Metrologia, 1981, **17**, 70.

Stoyko A., 1961, Bulletin Horaire du BIH, Série G, 241-245.

DETERMINATION AND PREDICTION OF UT1 AT THE IERS RAPID SERVICE/PREDICTION CENTER

W.H. WOODEN, T.J. JOHNSON, P.C. KAMMEYER, M.S. CARTER, A.E. MYERS
U.S. Naval Observatory
Washington, DC 20392 USA
e-mail: whw@usno.navy.mil

ABSTRACT. According to the terms of reference of the International Earth Rotation and Reference Systems Service (IERS), the Rapid Service/Prediction Center (RS/PC) is responsible for producing Earth orientation parameters (EOP) on a rapid turnaround basis, primarily for real-time users and others needing the highest quality EOP information sooner than that available in the final series published by the IERS Earth Orientation Center. The IERS Bulletin A and its associated data files contain preliminary and predicted EOP information including Universal Time (UT1). This paper focuses on the RS/PC′s current combination and prediction process for UT1, recent improvements to the process, accuracy of the current solutions, and planned improvements.

1. INTRODUCTION

Accurate knowledge of Earth orientation parameters (EOP) is needed for a variety of high-precision applications including modern navigation, astronomy, geodesy, communications, and time-keeping. The EOP provide the time-varying alignment of the Earth′s terrestrial reference frame with respect to the celestial reference frame. The U.S. Naval Observatory (USNO) operates the Rapid Service/Prediction Center (RS/PC) for the International Earth Rotation and Reference Systems Service (IERS). The RS/PC produces the IERS Bulletin A on a rapid turnaround basis, primarily for real-time users and others needing the highest quality EOP information before the IERS final (Bulletin B) values are available. Bulletin A and its associated standard and the daily rapid EOP data files constitute the near real-time IERS products. Bulletin A includes polar motion (x, y), universal time (UT1-UTC), and the celestial pole offsets ($\delta\psi, \delta\varepsilon$ and dX, dY) and predictions of these parameters. Two versions of Bulletin A are prepared, a daily and a weekly. Long-term stability and consistency with the other IERS products is achieved by aligning Bulletin A with the IERS final (Bulletin B) series, which is produced by the IERS Earth Orientation Center at the Paris Observatory in France. The emphasis of the RS/PC is on near-term prediction (weeks) rather than long-term prediction (years) of EOP.

The observational estimates of EOP from the IERS Technique Centers, especially their rapid and preliminary series, are key contributions to the Bulletin A. USNO′s ability to function as the RS/PC is enhanced by its active involvement in the Technique Centers. As an Associate Analysis Center of the International GPS Service (IGS), USNO has the opportunity to examine ways to improve the contribution of GPS observations to EOP. As an Operations Center, Correlator, and supporter of observing stations within the International VLBI Service, USNO is intimately involved in all aspects of the collection of VLBI observations and understanding their impact on EOP. Both GPS and VLBI are key data sets contributing to the determination and prediction of universal time (UT1-UTC), the focus of this paper.

2. COMBINATION AND PREDICTION PROCESS

The combination and prediction process contains five major steps: data preparation, combination, prediction, product generation, and dissemination. To a great extent this process has been automated. The contributed observations used in the preparation of the Bulletin A are available at ftp://maia.usno.navy.mil/bulla-data.html. The contributed analysis results are based on data from Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), the Global Positioning System (GPS) satellites, and meteorological predictions of variations in Atmospheric Angular Momentum (AAM).

The data preparation consists of retrieving each of the data types, preprocessing the data, and applying the biases and rates for each data type. Each of the following data types are processed: VLBI data (24-hr and Intensive sessions), GPS data (EOP and UTGPS), SLR data, and AAM data. The combination program calculates polar motion (x, y), UT1-UTC, length of day (LOD), and nutation offsets ($\delta\psi, \delta\varepsilon$). For polar motion, UT1-UTC, and LOD, known signals are removed (e.g., zonal solid Earth tides), the data are sorted by time and a cubic-spline fit to the data is determined, the fit is used to determine the daily solution, data for the fit and residual plots are written to files, the known signals are added back into the daily solution, and the final data file is updated. For the nutation offsets, VLBI 24-hour session data are read in, weights applied, the appropriate nutation theory is subtracted from the observations, the data are sorted by date and a cubic fit is determined, the fit is used to determine the daily solution data for fit and residual plots are written to files, and $\delta\psi$ and $\delta\varepsilon$ offsets are written to the final data file.

For the prediction of UTI-UTC approximately 365 days$'$ worth of data are used in an autoregressive integrated moving average (ARIMA) model. Additional details on the processing and prediction techniques are given by Luzum et al. (2001), Wooden and Johnson (2003), Johnson et al. (2004a), and Wooden et al. (2004). The variability of UT1-UTC as shown in the examples of Figure 1 highlights the difficulty of near-term prediction. The difficulty is predicting the occurrence of an inflection point and the resulting change of direction.

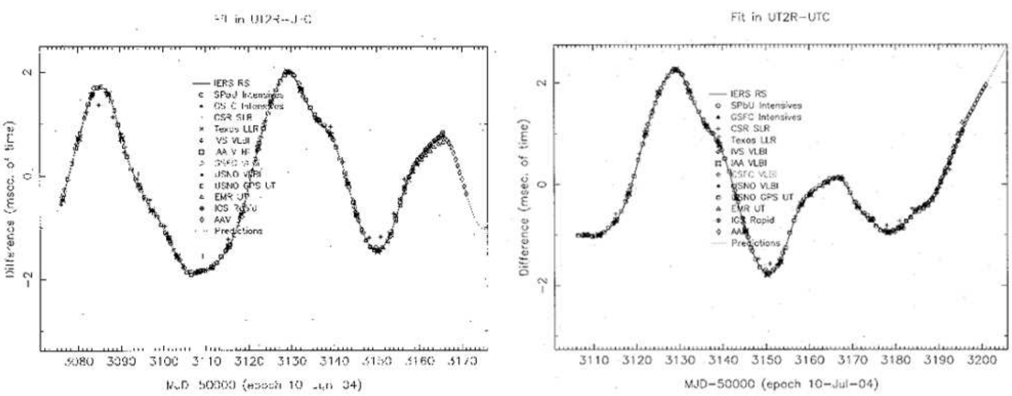

Figure 1: Residuals of the fit of UT1R-UTC for June and July 2004

3. IMPROVEMENT TO THE PROCESS

The recent improvements to the process include the enhanced GPS UT1-like quantity that improves UT1-UTC combination results at the solution epoch, the introduction of AAM UT1-like quantity that improves near-term UT1-UTC prediction, changing the processing criteria for some of the data sets to eliminate systematic effects, and the modernization of six programs within the combination and prediction process. The GPS UT1-like quantity, UTGPS, and the AAM UT1-like quantity, UTAAM, are discussed in the following sections. A careful evaluation of the VLBI data sets was done to better understand potential sources of error affecting the results and to determine improved editing criteria. Some VLBI data, which are from experiments not designed to measure EOP, were degrading the results. New editing criteria were established to mitigate this problem. The introduction of a new VLBI data set caused a problem with one of the processing routines. As a consequence of this incident, an effort to modernize the current operational code was initiated. Currently, six programs have been updated.

4. GPS UT1-LIKE QUANTITY

Kammeyer developed a UT1-like quantity, UTGPS, which improves the UT1-UTC combination results at solution epoch and strongly influences the very-near-term UT1-UTC prediction. UTGPS is determined from the Rapid GPS orbit files produced by the IGS. These Earth-referenced positions are, for each day and for each GPS satellite considered, compared to a propagated orbit plane, and this comparison gives an estimate of UT1 from that satellite alone. In propagating each orbit plane, that part of the motion of the normal caused by radiation pressure cannot be expressed by standard models and is therefore expressed empirically by a component along the projection of the Sun direction on this plane and one in the perpendicular direction in this plane. These two components are functions of the angular distance of the Sun direction from this plane. These functions have, until now, been updated occasionally, most recently in 2000. The median of the single-satellite estimates of UT1 is UTGPS. For additional details see Kammeyer (2000).

5. AAM UT1-LIKE QUANTITY

The AAM UT1-like quantity is generated from AAM analysis and forecast files of the U.S. National Center for Environmental Prediction (NCEP). Each day the operational NCEP AAM daily analysis and forecast files are retrieved from the U.S. National Oceanic and Atmospheric Administration. The daily analysis and forecast files are combined with the previous 19 day′s worth of AAM analysis data. All five days of forecast data are used in the combination. The bias between the forecast and analysis data is determined and applied to the forecast data. The analysis time series is smoothed and sub-sampled. AAM forecast data are then appended to the analysis time series. Finally, results are integrated to produce the UT1-like quantity, UTAAM. Additional details are given by Johnson et al. (2004b).

Recently, the actual reduction in UT1-UTC prediction errors resulting from the introduction of UTAAM into the EOP combination was more rigorously determined. This estimate was computed by comparing the C04 UT1-UTC time series to both the operational UT1-UTC that uses both geodetic and UTAAM and the formerly used operational geodetic-only daily UT1-UTC for the same 12-month period starting March 2003. Table 1 gives the results. The results indicate that the introduction of UTAAM reduces prediction error by approximately 60 percent at 10 days. This comparison clearly shows that for predictions of 5 to 60 days, the addition of

UTAAM into the combination process significantly reduces the UT1-UTC prediction error.

Days into future	Bulletin A without AAM (ms)	Bulletin A with AAM (ms)
1	0.091	0.130
5	0.992	0.421
10	2.11	0.840
20	3.68	2.53
30	5.22	4.28
60	9.62	8.88

Table 1: Standard deviation of the differences between the UT1-UTC time series predictions produced by the daily Bulletin A solutions (with and without AAM) and C04 from March 2003 to February 2004

6. ACCURACY

As a measure of the UT1-UTC prediction error of the weekly Bulletin A solutions, each solution (from August 2002 to August 2003) was propagated forward for 365 days and then compared to the C04 solution at each day. The resulting prediction errors were calculated and then averaged for each of the weekly solutions. The standard deviation of the differences between the Bulletin A and C04 at each prediction interval is shown in Figure 2.

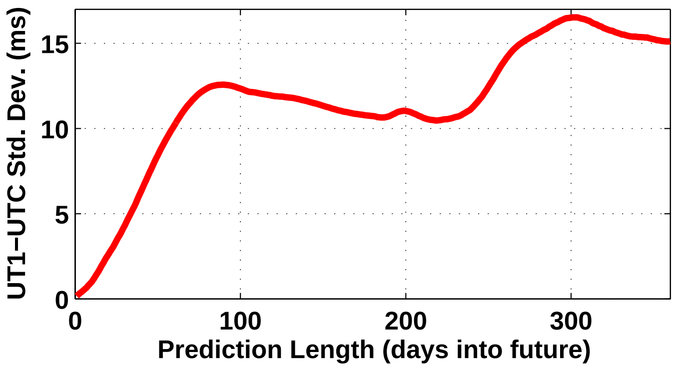

Figure 2: Prediction error of the weekly Bulletin A solutions with respect to the C04 series from August 2002 to August 2003

The accuracy of the UT1-UTC solutions is assessed by comparing the daily Bulletin A solutions to the IERS C04 and the Bulletin B series. Figure 3 shows these comparisons from the beginning of 2004. The agreement is relatively good. The occasional large difference in UT1-UTC is a result of the lack of VLBI data due to problems with the observing network.

7. FUTURE IMPROVEMENTS

Because of the critical role played by UTGPS in the very near-term prediction of UT1-UTC, the modeling of the rates of motion of GPS angular momentum vectors is continuing. The uncertainty in the rates caused by lack of knowledge of radiation pressure effects dominates that due to time variations in the Earth′s gravitational field. Past values of gravitational field

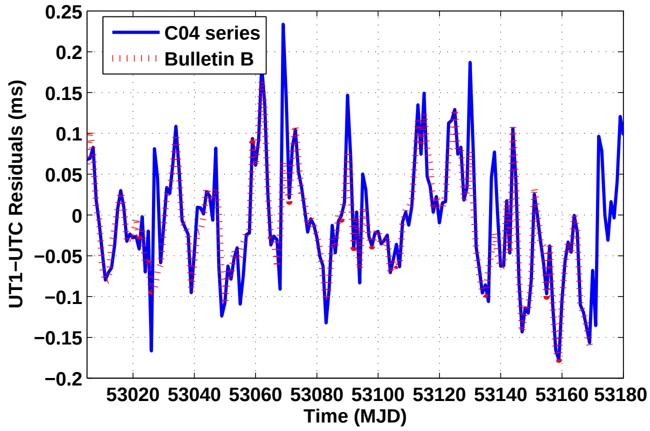

Figure 3: Difference between the daily Bulletin A UT1-UTC solutions and the Bulletin B and C04 series

variations can be determined from other satellite systems such as LAGEOS and GRACE. Thus, the emphasis for improvement is on radiation pressure effects.

The geophysical processes related to AAM are not well modeled. Although significant progress on near-term prediction of UT1-UTC using AAM has been made, the interaction between the oceans and the atmosphere needs further study if progress is to be made in understanding variations in Earth rotation.

Additional areas of research being pursued to improve the accuracy of Bulletin A products are the following: improvement and standardization of the techniques used in estimating the rates and biases that are applied to the different analysis center data products, an examination of the weighting applied to data from different analysis centers to improve the high frequency signal content of the combination, and an investigation of different prediction methods to quantify the potential improvement in current prediction accuracies.

Acknowledgments. It is a pleasure to acknowledge the contribution of agencies and individuals that provide Earth orientation data to the IERS. In addition the ongoing efforts of the staff of the Earth Orientation Department who make this work possible and the helpful discussions with Dr. Dennis McCarthy are gratefully acknowledged.

8. REFERENCES

Johnson, T.J., Carter, M.S., Myers, A.E., Wooden, W.H. (2004a) "Rapid Service/Prediction Centre," IERS Annual Report 2003, pp 48-57

Johnson, T.J., Luzum, B.J., and Ray, J.R. (2004b) "Improved Near-term UT1R Predictions Using Forecasts of Atmospheric Anugular Momentum," *Journal of Geodynamics*, In press

Kammeyer, P. (2000) "A UT1-like Quantity from Analysis of GPS Orbit Planes," *Celestial Mechanics and Dynamical Astronomy, 77*, pp 241-272

Luzum, B.J., Ray, J.R., Carter, M.S., and Josties, F.J. (2001) "Recent Improvements to IERS Bulletin A Combination and Prediction," *GPS Solutions, Vol 4*, No. 3, pp 34-40

Wooden, W.H. and Johnson, T.J. (2003) "Rapid Service/Prediction Centre," IERS Annual Report 2002, pp 46-53

Wooden, W.H., Johnson, T.J., Carter, M.S., and Myers, A.E. (2004) "Near Real-time IERS Products," *Journées Systèmes de Référence Spatio-Temporels 2003*, pp 160-163

VARIATION OF ΔT BETWEEN AD 800 AND AD 1200 DERIVED FROM ANCIENT SOLAR ECLIPSE RECORDS

M. SÔMA, K. TANIKAWA
National Astronomical Observatory
Osawa 2-chome, Mitaka, Tokyo 181-8588, Japan
e-mail: somamt@cc.nao.ac.jp, tanikawa.ky@nao.ac.jp

ABSTRACT. In our recent series of work (Tanikawa and Sôma 2002, 2004a,b, Sôma et al. 2003, 2004, Kawabata et al. 2004) we have applied our own method using nearly contemporary observations of eclipses and occultations to derive simultaneously the values of $\Delta T = \mathrm{TT} - \mathrm{UT}$ and the tidal acceleration $\dot{n}$ of the lunar motion. Here we apply our method to the total and annular solar eclipses recorded between the years 800 and 1200, and show that the ΔT values were decreased abruptly between the years 873 and 912 by more than 600 sec.

1. ΔT VALUES BETWEEN AD 968 AND AD 1140

The following records are found for the deep solar eclipses between AD 968 and 1004:
Total eclipse at Constantinople (Istanbul) in Turkey and Farfa in Italy on 968 Dec. 22,
Total eclipse at Kyoto in Japan on 975 Aug. 10, and
Very large partial eclipse at Cairo in Egypt on 1004 Jan. 24.
By applying our own method of obtaining simultaneously the ΔT values and the correction to the coefficient of the lunar tidal term (Fig. 1 of Sôma et al. 2004), we can obtain that the correction to the coefficient of the tidal term was larger than or equal to -1.4 arcsec/cy^2. If we accept the present tidal acceleration of the Moon, the derived ΔT values are:

1513 sec – 2654 sec	for 968,	(1)
1167 sec – 4452 sec	for 975,	(2) and
<1520 sec or >1917 sec	for 1004.	(3)

The solar eclipse of 1133 Aug. 2 was recorded at several places as total (Ausburg and Heilsbronn in Germany, Reichersburg and Saltzburg in Austria, and Kerkrade in the Netherlands; see Stephenson 1997), and they give the consistent parameter area, and therefore they can be regarded as very reliable. The solar eclipse of 1153 Jan. 26 was recorded at Erfurt in Germany, and several recorded sketches showed that the Sun was seen as a crescent, but there were no words indicating that the eclipse was annular, and therefore Stephenson (1997) regarded it as partial at Erfurt. However, this contradicts the 1133 Aug. 2 total solar eclipse mentioned above, i.e. the solar eclipse of 1153 Jan. 26 at Erfurt should have been annular based on the 1133 Aug. 2 total solar eclipse at several places. The 1140 Mar. 20 solar eclipse was recorded at Malmesbury in England as “they saw stars around the Sun”, and therefore we can see that the eclipse was total there. By combining this eclipse with the 1133 Aug. 2 eclipse, we see that the correction to the coefficient of the lunar tidal term was less than or equal to 0.0 arcsec/cy^2.

If we accept the present tidal acceleration of the Moon, we can obtain the ΔT values as:

433 sec – 1117 sec for 1133, (4)

and

1111 sec – 3330 sec for 1140. (5)

2. ΔT VALUES OF AROUND AD 900

The solar eclipse on 873 July 28 was recorded as annular both at Nishapur in Iran and at Kyoto in Japan (see Tanikawa and Sôma 2004). The solar eclipse on 912 June 17 was recorded as total at Cordoba in Spain. If we apply our method to these eclipses, we cannot obtain the ΔT value and the tidal acceleration of the Moon common to these eclipses. This means that either record was spurious or the ΔT value changed largely between the two eclipses. We show that the latter is correct, i.e. the ΔT value was decreased between the years 873 and 912 by more than 600 sec.

If we accept the present tidal acceleration of the Moon, the ΔT value derived from the 873 July 28 annular eclipse at Nishapur and Kyoto is:

3237 sec – 3760 sec for 873, (6)

and the value derived from the 912 June 17 total eclipse at Cordoba is:

1296 sec – 2593 sec for 912. (7)

On 891 Aug. 8 there was an annular eclipse in Europe, and at Constantinople in Turkey it is written that stars were seen (Stephenson 1997, p. 382). It is not written that the eclipse was annular, but it can be considered that the eclipse was at least very close to annular. Accepting the present tidal acceleration of the Moon, the condition that the eclipse was annular at Constantinople is:

2863 sec – 3908 sec for 891. (8)

This fact supports the value given in (6).

The 939 July 19 eclipse was recorded as total in Olmos or Cueva del la Mora in Spain. But as Stephenson points out, there were two inconsistent expressions, "the Sun was eclipsed totally", and "its disk became dark except for a slight portion as seen by eye". In any case the eclipse was at least very close to total. Accepting the present tidal acceleration of the Moon, the conditions that the eclipse was total at Olmos and at Cueva del la Mora are, respectively:

328 sec – 2283 sec, (9)

186 sec – 2164 sec for 939. (10)

This fact supports the value given in (7).

These considerations show that it is most likely that the values of ΔT given by (6) and (7) are correct.

Details about the present researches will be published elsewhere.

3. REFERENCES

Kawabata, K., Tanikawa, K., and Sôma, M.: 2004, *Astronomical Instruments and Archives from the Asia-Pacific Region*, 113–118, Yonsei University Press, Seoul.

Sôma, M., Tanikawa, K., and Kawabata, K.: 2003, Proc. Journées 2002, *Astronomy from Ground and from Space*, 248–250, (25–28 September, 2002, Bucharest, Romania).

Sôma, M., Tanikawa, K., and Kawabata, K.: 2004, Proc. Journées 2003, *Astrometry, Geodynamics and Solar System Dynamics: from Milliarcseconds to Microarcseconds*, 122–127, (22–25 September, 2003, St. Petersburg, Russia).

Stephenson, F.R.: 1997, *Historical Eclipses and Earth's Rotation*, Cambridge University Press.

Tanikawa, K. and Sôma, M.: 2002, *Astronomical Herald*, **95**, 27 (in Japanese).

Tanikawa, K. and Sôma, M.: 2004a, *Publ. Astron. Soc. Japan*, **56**, 215–224.

Tanikawa, K. and Sôma, M.: 2004b, *Publ. Astron. Soc. Japan*, **56**, 879–885.

REPORT ON THE GROUP DISCUSSION ON THE FUTURE OF UTC

D. D. MCCARTHY
U. S. Naval Observatory
Washington, DC 20392 USA
e-mail: dmc@maia.usno.navy.mil

In a brief discussion following the presentations, some participants felt that the official report of the Torino Colloquium on the definition of UTC had not represented accurately the discussion that they recalled. Other discussion brought out the point that the principal advantage of retaining the current definition of UTC is the potential cost of revising existing software that uses UTC as a substitute for UT1. In these applications the requirements for precision are satisfied by the current 0.9-second tolerance, and the software has been designed accordingly. Should the definition of UTC be modified in any way that would permit this tolerance to be exceeded, substantial costs might be required to make non-trivial changes in existing software.

However, it was pointed out that, although UT1 is expressed as a time, it is not used practically as a time scale. Rather, it is used as an angle that is related to the rotation angle of the Earth in the celestial reference frame. Knowledge of UT1 is essential in relating celestial and terrestrial reference systems, and the IERS provides daily values and predictions for up to a year in the future. It is conceivable that the systems served by legacy software based on the current UTC definition could benefit from using more realistic values for UT1 as opposed to the UTC approximation.

Another reason mentioned for retaining the current definition was that referring UTC to UT1 does provide a means to keep UTC in synchronization with the position of the Sun in the sky, which is desirable to meet society traditions.

Some participants discussed the need to modify the definition of UTC to meet growing requirements to accommodate advances in telecommunications, navigation and related fields with a single, internationally recognized uniform time scale. The issue is that the operational model to accommodate the discontinuities in the current definition is to generate internal system time scales. This situation could lead to multiple *de facto* time scales, and these "pseudo time scales" could lead to confusion and potentially serious consequences. There are also concerns regarding the current timing sequence followed during the implementation of a leap second. The convention is to number the leap second with the label "60" in the minute in which it has been inserted. Unfortunately many timing system do not permit a second to be labeled "60." In the past, this may have resulted in 2 seconds labeled 59 or even a second without a label. A conventional means to resolve this problem has not been adopted.

The discussion closed without consensus regarding recommendations for the future definition of UTC.

POSTFACE

JOURNÉES 2005 SYSTÈMES DE RÉFÉRENCE SPATIO-TEMPORELS

"Earth dynamics and reference systems:
five years after the adoption of the IAU 2000 Resolutions"
Warsaw (Poland), 19-21 September 2005

Scientific Organizing Committee
N. Capitaine, France (Chair); A. Brzeziński (co-Chair), Poland; P. Defraigne, Belgium; T. Fukushima, Japan; D.D. McCarthy, USA; M. Soffel, Germany; J. Vondrák, Czech R.; Ya. Yatskiv, Ukraine

Local Organizing Committee
B. Kolaczek (Chair), W. Baran, A. Brzeziński (Vice Chair), J. Kryński, J. Nawrocki, J. Nastula (Secretary), S. Oszczak, J. Rogowski, M.Rutkowska, S. Schillak, J. Zieliński

Scientific objectives
The Journées 2005 "Systèmes de référence spatio-temporels", with the sub-title "Earth dynamics and reference systems: five years after the adoption of the IAU 2000 Resolutions", will be organized at the Space Research Centre of the Polish Academy of Sciences in Warsaw, Poland, from 19 to 21 September 2005. These Journées will be the seventeenth conference in this series whose main purpose is to provide a forum for researchers in the fields of Earth rotation, reference frames, astrometry and time. Ten years after the Journées 1995, these Journées will be held again in Warsaw. The conference will be organized in cooperation between the SRC of the Polish Academy of Sciences in Warsaw and the Department "Systèmes de Référence Temps Espace" (SYRTE) of Paris Observatory. The Journées 2005 will be devoted to recent contributions and developments in the fields of reference systems and modeling Earth's rotation. There will be a special discussion on the status of the implementation of the IAU 2000 resolutions and the latest proposals of the IAU Working Groups of Division I on "Nomenclature in Fundamental Astronomy" and also a special session on progress in the "Descartes-nutation" projects.

Scientific programme

Session 1 : Celestial and terrestrial reference systems, with sub-sessions on "Astrometry/The International Celestial Reference Frame" and on "Realization of the systems and scientific applications"

Session 2 : Precession, nutation and polar motion, with sub-sessions on "Recent developments of observation and modeling", "Implementation of the IAU 2000 resolutions and new nomenclature" and "Presentations of progress in the Descartes-Nutation projects"

Session 3 : Excitation of Earth rotation by geophysical fluids

Session 4 : Time and time transfer: recent developments and projects

Session 5 : Global reference frames and Earth rotation: impact of the gravitational satellite missions (CHAMP, GRACE, GOCE), new techniques (ring laser etc.), new international projects (IAG-GGOS, GALILEO)

Contact : Space Research Centre of PAS Journées 2005
Bartycka 18a, 00-716 Warsaw, Poland
tel: +48 22 840 37 66; tel/fax: +48 22 8403131;
e-mail: jsr2005@cbk.waw.pl
or see : http://jsr2005.cbk.waw.pl:8080/proz451/