NUTATION DETERMINATION BY MEANS OF GNSS - COMPARISON WITH VLBI

N. CAPITAINE, K. YAO
SYRTE, Observatoire de Paris, CNRS, UPMC,
61, avenue de l'Observatoire, 75014 – Paris, France
e-mail: n.capitaine@obspm.fr

ABSTRACT. Space geodetic techniques cannot be used for a direct determination of the nutation offsets due to deficiencies in the modeling of the satellite orbits. However, as shown first by Rothacher et al. 1999 and then Weber & Rothacher (2001), GPS can be used to estimate the time derivatives of nutation quantities, similarly to what is done on a regular basis for UT1-UTC rates (or LOD) estimation. We have revisited the potential of GNSS observations for nutation estimation with the high precision currently achieved by this technique. The computations have been carried out by means of a new software, which has been developed in Matlab in the framework of K. Yao's PhD (2013), based on the GPS observations analysis strategy of CNES-GRGS GINS software, but with a few specific characteristics. The reference system for orbit computations is different from that generally used in order to minimize the influence of the a priori values of precession-nutation and UT1-UTC. The method is based on the determination of the time derivatives of the GCRS CIP coordinates (X, Y) with high temporal resolution. The observations used are 3 years of GPS measurements from 1 January 2009, obtained from a dense and globally distributed reference station network. The Xdot and Ydot time series so obtained are then analyzed in order to determine the corrections to the amplitudes of the short periodic terms of the IAU 2000 nutation model. The methodology, time series and results of this analysis are compared with those obtained from Very Long Baseline Interferometry (VLBI) observations of extragalactic radio sources.

1. INTRODUCTION

Space geodetic techniques cannot be used for a direct determination of the nutation offsets due to their correlations with the orbital elements of the satellite the computation of which is affected by the deficiencies in the modeling of the satellite orbits. However, as shown first by Rothacher et al. 1999, GPS can be used to estimate the nutation rates, similarly to what is done on a regular basis for LOD estimation; these authors computed a series of nutation rates covering 3.5 years, which was used for the estimation of the corrections to the IERS 1996 nutation model. Yet, nutation rates are not part of the IGS product and no other series of nutation rates have been provided since that time. The purpose of this study, done in the framework of K. Yao's PhD (2013), is to investigate the potential of GNSS observations for nutation estimation with the high precision that is currently achieved by this technique. We aim at developing the best use of GPS observations, independently of VLBI, for determining the nutation of the Earth's axis with the best possible accuracy.

2. ORBITAL ELEMENTS AND EARTH ORIENTATION PARAMETERS

The observed orbital elements of an artificial satellite referred to the GCRS (Geocentric celestial reference system) depend on the coordinates, X, Y of the CIP (Celestial Intermediate Pole) in the GCRS, and on the Earth Rotation Angle (ERA) at date t. Theoretically, these Earth Orientation Parameters (EOP) can be derived from the corresponding variations in the orbital elements of the satellite. However, due to strong correlations, their estimates are affected by the systematic errors in the orbital elements coming from deficiencies in the gravitational and non gravitational forces. In particular, absolute determination of the "celestial pole offsets" (dX, dY) or ERA are not possible from satellite observations. The systematic effects can be minimized for short term variations and with an appropriate choice of the reference system in which the orbit of the satellite is computed. The rates in X, Y and ERA can be estimated provided that the orbital perturbations are modeled with sufficient accuracy over the short time interval of the estimation.

Simplified relationships between the parameters rates can be expressed (at the 1st order of the offsets and with Keplerian approximation) as follows (Capitaine & Wallace, 2007):

$$
\begin{aligned}
\dot{\text{ERA}} &= -\dot{\Omega} - \cos i \cdot \dot{u}_0 \\
\dot{X} &= -\sin\Omega \cdot \dot{i} + \sin i \cos\Omega \cdot \dot{u}_0 \\
\dot{Y} &= \cos\Omega \cdot \dot{i} + \sin i \sin\Omega \cdot \dot{u}_0.
\end{aligned} \tag{1}
$$

Ω, i, being the right ascension of the ascending node and inclination of the orbital plane of the satellite and u_0 the argument of the latitude of the satellite at the osculating epoch.

3. MAIN CHARACTERISTICS OF THE STUDY

The method

The effect of the Earth Orientation Parameters (EOP) appears through the transformation between coordinates [ITRS] in the International Terrestrial Reference System and [GCRS] in the GCRS by the following equation:

$$[\text{GCRS}] = Q(t) * R(t) * W(t) * [\text{ITRS}], \tag{2}$$

where Q(t) is a matrix determined by the coordinates, X, Y, of the Celestial intermediate pole (CIP) in the GCRS, R(t) is the rotation matrix determined by the Earth rotation angle, ERA, and W(t) is a matrix determined by the the pole coordinates, x_P, y_P, i.e. the coordinates of the CIP in the ITRS.

The method used in this work is largely based on the GNSS observations analysis strategy of the CNES-GRGS GINS multi-technique software for orbit determination and Earth dynamics studies (Marty et al. 2011), but with the following specificities which take advantage of the specificity of the GNSS potential for estimation of the EOPs (cf. previous section):

(i) determination of the time derivatives of the GCRS CIP coordinates X, Y, and ERA, with high temporal resolution, along with x_P, y_P (pole coordinates),

(ii) computation of the satellite orbit in an inertial reference system that minimizes the influence of the a priori values for precession-nutation (i.e. X, Y) and UT1-UTC (i.e. ERA), that GPS cannot determine directly.

The new GPS analysis software

The computations are carried out by means of a new GPS analysis software, developed by K. Yao in Matlab environment and implementing the specificities (i) and (ii) described in the previous section.

The motivations are:

- To obtain long time series of time derivatives of the GCRS CIP coordinates (X, Y) and the ERA.
- To minimize the effect (on the computations) of the a priori values for (X, Y) and ERA.

The advantages of the Matlab environment are that codes are easy to understand, vectorial computation are easily programmed; many scientific algorithms functions are available and science programming library in C/FORTRAN can be re-used (i.e. SOFA library); Moreover, built-in tools are available for the visualization and the data analysis, graphical interface, etc.

The inertial system for orbit computation

The inertial reference system TIRS_0 that is used in this work for the satellite orbit computation is based on the Terrestrial Intermediate Reference System (TIRS) defined at date $t_0 = 00$ h of the beginning epoch of the arc under analysis (cf. Fig. 1). The realization of that reference system, which is not dependent on the X, Y and ERA quantities, minimizes the influence of the a priori values of precession-nutation and UT1-UTC on the computations. For more details on reference systems used for precession-nutation representations, see for example Capitaine & Wallace (2006).

Data set, calculations and estimations

The data set used in this work consists of 3 years of GPS measurements (double-differenced ionosphere-free phase observations) from 1 January 2009, performed every 300 s (315 360 observation epochs) by about 115 stations of IGS tracking network on the Earth on almost 32 satellites. The measurement models and corrections, as well as the models for orbit computations used in the analysis are compliant with the best up-to-date models and corrections.

The GPS observations are analyzed day by day with calculations that are largely based on the GPS analysis method of the GINS software:

- The first part of the calculations consists in the determination of the station clock biases using the GPS ionosphere-free combination, P_c, of the pseudo-range observations.

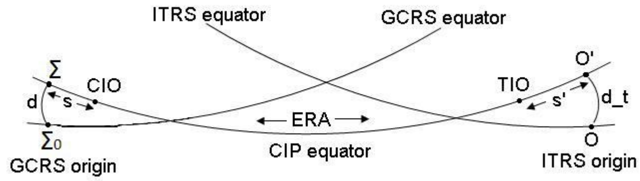


Figure 1: The reference system $TIRS_0$ is defined by the CIP equator and the origin O' on this equator. It is linked to the Terrestrial Intermediate Reference System, TIRS, defined by the CIP and the TIO (Terrestrial intermediate origin). The distance between O' and the TIO is the TIO locator, s'.

- The second part of the calculation consists of 11 successive steps, including the estimation of the parameters based on an iterative least-squares adjustment using the GPS double-differenced ionosphere-free phase observations, DDL_c. This provides time series of the parameters.

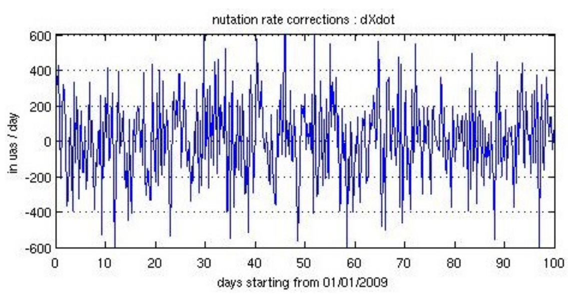
The a priori values for the EOPs are, for polar motion and LOD, the IERS C04 time series and for $\dot{X}, \dot{Y}$, the time derivatives of the IAU2006/2000A precession-nutation series.

The results obtained from the estimation process are composed of time series covering 3 years of (i) corrections to the time derivatives of the celestial pole offsets $d\dot{X}, d\dot{Y}$, every 6 h, i.e. corrections to the nutation rates (see Fig. 2), (ii) corrections to $E\dot{R}A$, i.e. dLOD, and (iii) polar motion corrections (i.e. dx_P, dy_P).

The computation has been successfully validated in several ways: computation of the residuals obtained by a fit to the DDLc observations available on the IGS FTP website (RMS≈ 8 mm), comparison of the zenith tropospheric delay with respect to the IGS product, evaluating the 3D orbit difference in the ITRF w.r.t. the IGS final orbit (typically ≈ 5 cm) and also by comparing the estimated pole coordinates to those obtained by GINS (typically ≈ 50 μas).

The correlations between the EOPs are included between 0.02 and 0.23 ($\dot{X}$ or $\dot{Y}$ and $E\dot{R}A$).

4. NUTATION ESTIMATION



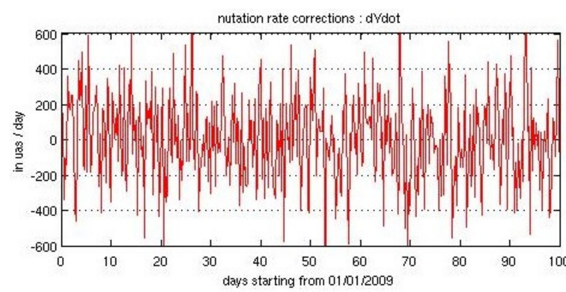


Figure 2: Time series (over a 100-day interval) of the estimated corrections (d$\dot{X}$, d$\dot{Y}$) to the time derivatives of the X (left) and Y (right) GCRS CIP coordinates; unit: μas/day.

We have used the 3-yr d$\dot{X}$, d$\dot{Y}$ time series as pseudo-observations to estimate corrections to the most important short-period terms of the nutation rates, using the following expressions, expressed as functions of the prograde and retrograde circular nutations:

$$d\dot{X}(t) = \sum_i [-a_{real,i}\sin(\alpha_i) - a_{imag,i}\cos(\alpha_i)]\dot{\alpha_i} \quad (3)$$

$$d\dot{Y}(t) = \sum_i [a_{real,i}\cos(\alpha_i) - a_{imag,i}\sin(\alpha_i)]\dot{\alpha_i}, \quad (4)$$

where where j is the unit of imaginary number, α_i is the argument of the IAU 2000 nutation term, i, and the coefficients $a_{real,i}, a_{imag,i}$ are the corrections to the coefficients of the nutation term with argument α_i.

The corrections estimates for the most important periodic terms are listed in Table 1. These discrepancies are expected to be due to geophysical causes, such as tidal or atmospheric perturbations. The

period (days)	$a_{real,i}$ μas	sigma μas	$a_{imag,i}$ μas	sigma μas
-15.39	6	9	-15	9
15.39	-5	9	-7	9
13.66	-14	8	-8	8
-12.66	2	7	19	7
-9.56	-10	5	-2	5

Table 1: GPS nutation estimation results (largest corrections)

accuracy obtained for the estimation of the corrections to the nutation terms is included between 2 to 14 microarcseconds according to the period of the term. It should be noted that such an accuracy is better than the accuracy which can be obtained by VLBI for the short periodic terms of nutation.

These nutation corrections derived from the 3-year (2009-2012) time series of corrections to the IAU 2006/2000 X and Y rates estimated by GPS have been compared to nutation corrections derived from the 22-year (1990-2012) time series of corrections to IAU 2006/2000 X, Y estimated by VLBI. The two set of corrections have been found to be of the same order of magnitude, but not perfectly consistent.

5. SUMMARY

GPS observations covering a 3-yr interval have been analyzed for estimating corrections to the short periodic terms of nutation. The computations have been carried out by means of a new GPS analysis software in Matlab environment, developed by K. Yao in the framework of his PhD (2013). In this analysis, the satellite orbit has been integrated in an appropriate inertial system which reduces the influence of the error in the a priori values for precession-nutation and the Earth rotation angle ERA.

This analysis has provided a 3-year time series of nutation rates corrections to the IAU2006/2000A a priori values along with corrections to the ERA rate and pole coordinates. These time series have been used to estimate corrections to the 28 largest nutation terms with period less than 20 days with an accuracy of about 10 μas.

This study proves that the GNSS technique alone (i.e. without any use of VLBI estimates) has the potential to determine the short-period terms of nutation. The corrections obtained by GPS for the short periodic terms of nutation has been compared with those obtained by VLBI. The two set of corrections are of the same order of magnitude, but they are not perfectly consistent. A better understanding of such discrepancies require further studies (Yao & Capitaine 2014).

6. REFERENCES

Capitaine N. & Wallace P.T., 2006, "High precision methods for locating the celestial intermediate pole and origin", A&A 450, 855

Capitaine N. & Wallace P.T., 2007, "The transformation between the Terrestrial and Celestial Reference Systems: Needs and potential of GPS and Galileo", Proceedings of the ESA 1st Colloquium Scientific and Fundamental Aspects of the Galileo Programme, ESA (ed.), on CD

Marty J.C., Loyer S., Perosanz F., Mercier F., Bracher G., Legresy, B. Portier L., Capdeville H., Fund F., Lemoine J.M. , Biancale R., 2011, "GINS: The CNES/GRGS GNSS scientific software", in Proceedings of the ESA 2011 Galileo scientific meeting

Rothacher M., Beutler G., Herring T. A., Weber R., 1999, "Estimation of nutation using the Global Positioning System", JGR 104, n^{0}B3, pp. 4835–4859

Weber, R., Rothacher M., 2001, "A Revised Set of Nutation Amplitudes Calculated From six Years of GPS Data", AGU Meeting 2001, abstract G51C-0252

Yao, K. 2013, "Nutation determination by VLBI and GPS techniques", Thèse de doctorat (PhD), Université Pierre et Marie Curie, 29 avril 2013

Yao K. & Capitaine N., 2014, in preparation