THE NEW EDITION OF THE IERS CONVENTIONS: CONVENTIONAL REFERENCE SYSTEMS AND CONSTANTS

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ABSTRACT. The new reference edition of the IERS Conventions is being completed, the Conventions (2010) replacing the Conventions (2003). The paper presents the main features of this new edition for what concerns the conventional reference systems and the set of adopted constants, including associated relativistic issues. Changes in this domain vs. the Conventions (2003) will be highlighted. It is shown how the Conventions implement the framework set by the Resolutions adopted by the scientific unions (IAU, IUGG and IAG), and also try to keep consistency as much as possible with the conclusions drawn by the Unions' working groups and bodies.

1. INTRODUCTION

The International Earth Rotation and Reference Systems Service (IERS) is finalizing the new reference edition (2010) of the IERS Conventions, that describe the standard reference systems realized by the IERS and the models and procedures used for this purpose. In this paper, we focus on those parts of the Conventions that more directly relate to the reference systems and constants. Section 2 recalls the ensemble of Resolutions, adopted by the scientific Unions over the last 20 years, that make up the present framework in which the Conventions (2010) are presented. In section 3, are briefly presented the present realizations of the celestial and terrestrial reference systems. Section 4 presents a few questions that are being discussed and may become of interest for the next version of the IERS Conventions.

2. THE FRAMEWORK SET BY THE UNIONS RESOLUTIONS

In order to describe observations in astronomy and geodesy, one has to choose the proper relativistic reference systems best suited to the problem at hand. A barycentric celestial reference system (BCRS) should be used for all experiments not confined to the vicinity of the Earth, while a geocentric celestial reference system (GCRS) is physically adequate to describe processes occurring in the vicinity of the Earth. These systems have been defined in a series of Resolutions passed by scientific Unions, mostly the International Astronomical Union (IAU), in the past 20 years.

2.1 Resolutions of the International Astronomical Union

Here we briefly present the resolutions passed by the International Astronomical Union (IAU) that relate to the subject of this paper and that either are technical in nature or define the policy or methods to be used. We start this description with those passed by the 1991 General Assembly (GA), which provide the first consistent representation of coordinate systems for use in the vicinity of a body (Earth, solar system) and introduce general principles for the realization of the Celestial Reference System (CRS). IAU Resolution A4 (1991) contains nine recommendations, some of which are summarized below.

- In the first recommendation, the metric tensor for space-time coordinate systems $(t, \mathbf{x})$ centered at the barycenter of an ensemble of masses is defined. The recommended form of the metric tensor can be used, not only to describe the barycentric reference system of the whole solar system, but also to define the geocentric reference system centered in the center of mass of the Earth, now depending upon geocentric coordinates.
- In the second recommendation, the origin and orientation of the spatial coordinate grids for the barycentric and geocentric reference systems are defined.

- The third recommendation defines TCB (Barycentric Coordinate Time) and TCG (Geocentric Coordinate Time) as the time coordinates of the BCRS and GCRS, respectively.
- In the fourth recommendation, another time coordinate named TT (Terrestrial Time), is defined for the GCRS as a linear function of TCG.
- Recommendations 6 and 7 provide the basis for the realization of the CRS (see section 3.1).

At the 1997 GA, we note mostly Resolution B2 which resolves that the IAU celestial system shall be the International Celestial Reference System (ICRS) as defined by the IERS and the frame shall be the International Celestial Reference Frame (ICRF). This follows from Resolution B5 (1994). Other Resolutions of interest were passed, e.g. B6 stating that no scaling of spatial axes should be applied in any reference system, even if scaled time coordinate like TT is used for convenience of an analysis.

At the 2000 GA, following the work of the IAU WG "Relativity for astrometry and celestial mechanics" together with the BIPM-IAU Joint Committee for relativity, an extended set of Resolutions was adopted extending the IAU 1991 framework; see a more complete description in (Soffel et al., 2003).

- Resolution B1.1 describes steps towards the establishment and maintenance of the celestial reference system and frame, following Resolution B2 (1997).
- Resolution B1.6 to B1.8 introduce the IAU 2000 Precession-Nutation model, the Celestial Intermediate Pole, and the Celestial and Terrestrial Ephemeris Origins, respectively.
- Resolution B1.3 concerns the definition of the BCRS and the GCRS. The Resolution extends the form of the metric tensor given in 1991, so that its accuracy is now sufficient for all applications foreseen in the next years, including those involving accurate space clocks. For the GCRS, Resolution B1.3 also adds that the spatial coordinates are kinematically non-rotating with respect to the barycentric ones. Resolution B1.4 then provides the form of the expansion of the post-Newtonian potential of the Earth to be used with the metric of Resolution B1.3.
- Resolution B1.5 applies the formalism of Resolutions B1.3 and B1.4 to the problems of time transformations and realization of coordinate times in the solar system, based upon a mass monopole spin dipole model.
- Resolution B1.9 redefines Terrestrial Time TT, dissociating it from the geoid while maintaining continuity with the previous definition.

At the 2006 GA, we note:

- Resolution B1 that adopts the P03 precession model and a definition of the ecliptic.
- Resolution B2 which supplements the IAU (2000) resolutions on reference systems, e.g. by revising the nomenclature and specifying the default orientation of the BCRS.
- Resolution B3 which redefines Barycentric Dynamical Time (TDB) as a fixed linear transformation of TCB. TDB had been introduced by the IAU in 1976 as a dynamical time scale for barycentric ephemerides. As it had not been unambiguously defined, multiple realizations of TDB were possible.

At the 2009 GA, Resolution B2 defines the IAU 2009 system of astronomical constants as the list published by the NBFA working group (see section 3.3) and Resolution B3 resolves that the second realization of the ICRF, ICRF2, shall be the fundamental realization of the ICRS as of 1 January 2010.

2.2 Resolutions of the International Union of Geodesy and Geophysics (IUGG)

The resolutions of the International Union of Geodesy and Geophysics (IUGG) dealing with reference systems over this period consist mainly of the following two:

- Resolution 2 (1991) on "Definition of a Conventional Terrestrial Reference System" which endorsed the IAU'1991 Recommendations and explicitly based its definition of TRS on the IAU relativistic framework.
- Resolution 2 (2007) on the "Geocentric and International Terrestrial Reference Systems (GTRS and ITRS)", which aims at defining and promoting the ITRS (see section 3.2).

2.3 Recommendations of IAU working groups and commissions

The IERS Conventions also take advantage of the work of several working groups and commissions, notably the Division 1 working group "Numerical Standards in Fundamental Astronomy" (NSFA; Luzum et al., 2010), the Division 1 working group "Nomenclature in Fundamental Astronomy" (NFA; Capitaine, 2009) which acted over the period 2003-2006, and of the Commission 52 "Relativity in fundamental astronomy".

The work of the NSFA group is to update the IAU current Best Estimates, eventually defining a new official system of constants as was done with the IAU Resolution B2 (2009) defining the IAU(2009) system of astronomical constants. In doing so, it has to apply the relativistic framework defined above, and to disseminate the information on the consequences. The NSFA recommendations are passed in the IERS Conventions in many ways, apparent mostly in its chapters 1 and 3. The classes of constants, values and uncertainties are made consistent between the Conventions and the NSFA, as well as the best estimates for solar system bodies. On the other hand, no significant change appeared for the Earth constants with respect to the Conventions (2003).

A task team established by the IAU Commission 52 "Relativity in fundamental astronomy" lead to a series of recommendations on issues linked to the existence of several coordinate times (Klioner et al. 2009). In the IERS Conventions, it was attempted to follow these recommendations, notably to ensure that the notation "TXX-compatible", where TXX represents the coordinate time of interest, is used whenever needed for quantities and values.

Finally, the work of the NFA working group, see http://syrte.obspm.fr/iauWGnfa/NFA_Glossary.html, has been passed into the Conventions. The text of Chapter 5 (transformation between celestial and terrestrial systems) follows the NFA and all terms of the NFA that are relevant in the Conventions are reproduced *verbatim* in the Conventions glossary.

3. THE CELESTIAL AND TERRESTRIAL REFERENCE SYSTEMS

The IERS Conventions (2010) describe the most recent realizations of the celestial and terrestrial reference systems, i.e. the ICRF2 (IERS, 2009) for the celestial frame and ITRF2008 (Altamimi et al., 2010) for the terrestrial frame.

3.1 The celestial reference system and frame

The set of resolutions specifying the definition and realization of the celestial system stem from the IAU'1991 resolution A4, recommendations 6 and 7, which specified that lists of primary sources to define the new conventional reference frame should be established and how the coordinate axes of the new frame should be set. IAU'1997 resolution B2 then determined that, from 1/1/1998, the IAU system shall be the ICRS as defined by the IERS, and that the frame shall be the ICRF. IAU'2000 resolution B1.1 later specified the working group and procedure to maintain the ICRS. Finally, IAU'2009 resolution B3 states that, from 1/1/2010, the fundamental realization shall be the ICRF2 as defined by the IERS/IVS working group.

The following short presentation is extracted from Chapter 2 of the IERS Conventions (2010) and shows the significant improvements in the new realization ICRF2. *The generation of a second realization of the International Celestial Reference Frame (ICRF2) was constructed in 2009 by using positions of 295 new "defining" compact extragalactic radio sources selected on the basis of positional stability and the lack of extensive intrinsic source structure (IERS, 2009). Future maintenance of the ICRS will be made using this new set of 295 sources. ICRF2 contains accurate positions of an additional 3119 compact extragalactic radio sources; in total the ICRF2 contains more than five times the number of sources as in the first realization ICRF1. The position formal uncertainties of the set of positions obtained by this analysis were calibrated to render their values more realistic. The noise floor of ICRF2 is found to be only* ≈ 40 *μas, some* $5-6$ *times better than ICRF1. [....] The scatter of the rotation parameters obtained in the different comparisons indicate that the axes are stable to within 10 μas, nearly twice as stable as for ICRF1. The position stability of the 295 ICRF2 defining sources, and their more uniform sky distribution, eliminates the two largest weaknesses of ICRF1.*

3.2 The terrestrial reference system and frame

IUGG'1991 Resolution 2 introduced the Conventional TRS (CTRS) derived from a geocentric non-rotating system, as defined by the IAU Resolution A4 (1991), with the following prescriptions: use TCG as a coordinate time; have origin as the geocenter including oceans and atmosphere; show no global residual rotation with respect to horizontal motions at the Earth's surface. In 2007, IUGG Resolution 2 introduced as a new notation the GTRS, system of geocentric space-time coordinates, derived from GCRS following Resolution IAU B1.3 (2000). It then defined the ITRS as a specific GTRS.

We note that ITRF itself is not explicitly defined, which implies that it is defined by the practical realizations ITRFXXXX. However ITRS and ITRF have differences in this respect:

- ITRS is 4-dimensional (in principle) while the ITRFXXXX are 3-dimensional.
- For the scale, ITRS is TCG-compatible, ITRF is TT-compatible.
- For the origin, ITRS is geocentric (instantaneous), ITRF is "geocenter averaged over time span" (see section 4.1).
- The tide convention for ITRS is not explicitly written while ITRF realizations are *de facto* conventional tide-free (see IERS Conventions chapter 1).

Recently, the IAG created the Inter-commission WG ICGG 1-3 "Concepts and terminology related to GRS", to come up to a unified and accepted terminology. This could imply a redefinition of the ITRS.

The following short presentation is extracted from Chapter 4 of the IERS Conventions (2010) and describes the main characteristics of ITRF2008. *ITRF2008 is based on reprocessed solutions of four space geodesy techniques: VLBI, SLR, GPS and DORIS, spanning 29, 26, 12.5 and 16 years of observations, respectively. The ITRF2008 is composed of 934 stations located at 580 sites, with an imbalanced distribution between the northern (463 sites) and the southern hemisphere (117 sites). There are in total 105 co-location sites; 91 of these have local ties available for the ITRF2008 combination.*

The accuracy of ITRF2008 makes it possible to identify systematic effects present in the realization ITRF2000 of the Conventions (2003), of order 1 cm and 1 mm/yr.

4. SOME PRESENT AND FUTURE WORK IN THE IERS CONVENTIONS

In establishing the IERS Conventions (2010), some questions arose that were not fully resolved and are still being discussed. This section presents three discussion topics that are linked to the realization of reference systems. The first one is the relation between the geocenter and the origin of the frames and the associated treatment of geocenter motion. The second topic concerns models for space-time coordinates and equations of motion (chapter 10 of the Conventions) and the third one concerns the models for signal propagation (chapter 11 of the Conventions).

4.1. Geocenter motion

As exposed in section 3.2, there are practical differences between ITRS and ITRF. We here assume that the differences in the scale and the possible difference in the tide convention can be taken into account explicitly with adequate accuracy, thus they have no practical impact. On the other hand, questions linked to the difference between the origin of the frame (ITRF) and the geocenter (origin of ITRS) cannot be treated in the same way. When a phenomenon (e.g. ocean tides) causes displacements of fluid masses, the center of mass of the fluid masses moves and must be compensated by an opposite motion of the center of mass of the solid Earth. The stations, being fixed to the solid Earth, are subject to this counter motion which has components in a wide spectrum. As ITRF is presently realized with linear station motions, ITRF is geocentric only in the sense of a long-term average. Space geodesy results show that the origin translation due to geocenter motion is significant but models or series representing it have not yet been fully assessed.

This may have implications on the transformation used to relate the ITRS to the GCRS at the date t of the observation which (see chapter 5 of the IERS Conventions) can be written as:

$$[\mathrm{GCRS}] = Q(t)R(t)W(t)\ [\mathrm{ITRS}], \tag{1}$$

where $Q(t)$, $R(t)$ and $W(t)$ are the transformation matrices arising from the motion of the celestial pole in the celestial reference system, from the rotation of the Earth around the axis associated with the pole, and from polar motion, respectively. Eq. (1), as well as the formulas to represent its terms, are theoretical formulations that refer to reference "systems". However, it should be clear that the numerical implementation of those formulas involves the IAU/IUGG adopted realization of those reference systems, *i.e.* the ITRF and the ICRF, respectively. It remains to be established if the Earth orientation parameters implicit in (1) are affected by this assimilation.

4.2. Models for space-time coordinates and the equations of motion

In Chapter 10 of the Conventions, the presentation of coordinate time scales now accounts for all IAU Resolutions (see section 2.1). TT and TDB having conventional definitions, the only transformations of interest are TCB−TCG and $\tau - \mathrm{TT}$, where τ is proper time.

The TCB−TCG formula may be expressed, at the geocenter, as

$$\mathrm{TCB} - \mathrm{TCG} = \frac{L_C \times (TT - T_0) + P(TT) - P(T_0)}{1 - L_B} + \mathcal{O}(c^{-4}) \tag{2}$$

where TT_0 corresponds to JD 2443144.5 TAI and where the values of L_C and L_B may be found the Conventions chapter 1. Non-linear terms denoted by $P(TT)$ have a maximum amplitude of around 1.6 ms.

In the Conventions (2003), several options were given to realize equation (2), none of which however provided a complete realization of all terms. In the Conventions (2010) one conventional transformation, XHF2002_IERS, is proposed. It is composed of the analytical formula XHF2002 based on the time ephemeris TE405 (Harada and Fukushima, 2003) complemented by an additional linear term to represent terms neglected or missing in TE405. It is expected that XHF2002_IERS is only limited by the accuracy of TE405. In this respect, Fienga et al. (2009) show that TT-TDB from TE405 and from INPOP08 display a 2×10^{-18} rate difference. The full accuracy of XHF2002_IERS is yet to be ascertained.

The transformation between proper time τ and coordinate time in the vicinity of the Earth (typically up to geosynchronous orbit or slightly above) is covered in the Conventions (2010). It is based on the IAU'1991 metric which is found to be sufficient for time and frequency applications in the GCRS in the light of present clock accuracies. When considering TT as coordinate time, the proper time of a clock located at the GCRS coordinate position $\mathbf{x}_A(t)$, and moving with the coordinate velocity $\mathbf{v}_A$, is

$$\frac{d\tau_A}{dTT} = 1 + L_G - 1/c^2 \left[\mathbf{v}_A^2/2 + U_\mathrm{E}(\mathbf{x}_A)\right], \tag{3}$$

where the values of L_G is given in the Conventions chapter 1 and where U_E denotes the Newtonian potential of the Earth at the position $\mathbf{x}_A$ of the clock in the geocentric frame. In this expression, tidal terms have been neglected as their contribution will be limited to below 1×10^{-16} in frequency and 1 ps in time amplitude up the GPS orbit. Nevertheless, some care needs to be taken when evaluating the Earth's potential U_E at the location of the clock as the uncertainty in U_E should be consistent with the uncertainty expected on (3). For example, the conventional formula used in GNSS applications uses only the first term of the Newtonian potential.

By retaining also the oblateness term (J2) of the potential, one can derive (see details and references in chapter 10 of the Conventions) a simple analytical approximation that contains an apparent relativistic clock rate and a 6-h term due to J2. The frequency instability of the passive Hydrogen maser in the Galileo satellites is expected at a few parts in 10^{15} for an averaging time of several hours. Because the 6-h J2 term is of similar magnitude, this term should be accounted for when determining and using the broadcast satellite clock model. It is known that analytical expressions may be obtained, but a conventional one has yet to be chosen.

For low Earth orbit satellites, the term in J2 is more important than at the GPS altitude and it is necessary to perform a numerical integration of Equation (3) using the term in J2 for the potential.

4.3. Models for signal propagation

The chapter 11 of the Conventions (2010) "Models for signal propagation" describes the relativistic model for the VLBI time delay and to obtain the coordinate time of propagation in ranging techniques. For these space-geodesy techniques, models have been designed to ensure an accuracy of about 1 mm.

The present VLBI model, the so-called "Consensus model" adopted at a USNO workshop in 1990, has been designed for 1 ps accuracy. It is now envisioned that future VLBI observations have a measurement noise of order a few ps i.e. call for a model uncertainty below 1 ps. Therefore the developments done 20 years ago, e.g. as explicited in (Soffel et al. 1991), may need to be re-examined in view of the new accuracy goal.

The section on ranging techniques should cover all techniques using electromagnetic signals in the vicinity of the Earth (up to the Moon), i.e. GNSS, SLR, LLR, plus some other techniques outside the direct IERS scope e.g. radar altimetry or two-way time transfer. As it has been shown (Klioner, 2007) that post-post Newtonian terms are not required in view of the present uncertainty, no significant model change is expected.

5. CONCLUSION

The IERS Conventions (2010) are now reaching completion and are available electronically at the URL http://tai.bipm.org/iers/conv2010/conv2010.html (also at http://maia.usno.navy.mil/conv2010). The Conventions (2010) implement the framework set by the Resolutions adopted by the scientific unions and describe the standard reference systems realized by the IERS and the models and procedures used for this purpose. A reference edition represents the situation at a given moment but cannot escape the fact that several issues are not fully resolved. In this respect, the IERS Conventions are a work in progress.

6. REFERENCES

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