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THE ROTATION OF THE EARTH: NEW MODELS AND CONCEPTS

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RESUMEN

A finales del siglo XX, las observaciones VLBI pusieron en evidencia inconsistencias del orden de varios milésimos de segundo de arco en los modelos convencionales que representaban la posición del polo celeste. La Unión Astronómica Internacional (IAU), conjuntamente con la Unión Internacional de Geofísica y Geodesia (IUGG), establecieron el grupo de trabajo IAU/IUGG sobre la nutación para una Tierra no-rígida y le encargaron la elaboración de un nuevo modelo para un mejor ajuste de las observaciones. Esta tarea concluyó con el modelo de precesión-nutación IAU 2000, basado en la función de transferencia de Mathews et al. (2002). En este trabajo se presentan las principales características del modelo, se introducen los nuevos conceptos y se discute la transformación entre los sistemas de coordenadas terrestre y celeste.

ABSTRACT

At the end of the 20th century, the VLBI observations put in evidence inconsistencies at the level of a few milliarcseconds in the conventional models that represented the position of the celestial pole. The International Astronomical Union (IAU), jointly with the International Union of Geophysics and Geodesy (IUGG), established the IAU/IUGG Working Group on Nutation for a non-rigid Earth to elaborate a new model that fits the observations better. The WG activities concluded with the elaboration of the precession-nutation model IAU 2000, based on the transfer function of Mathews et al. (2002). In this paper, we present the characteristics of the model, introduce the new concepts and discuss the transformation between the terrestrial and the celestial frames.

Key Words: **EARTH — REFERENCE SYSTEMS — EPHEMERIDES**

1. GENERAL

The observations of extragalactic radio sources with the technique of VLBI revealed the existence of inconsistencies in the nutation series IAU 1980 (Seidelmann 1982) and in the IAU 1976 precession model (Lieske et al. 1977). Corrections to the models, at the milliarsecond order, were obtained in the adjustment of the VLBI observations, simultaneously to the astrometric and geodetic parameters.

The international celestial reference system (ICRS)(Arias et al. 1995), adopted by the IAU in 1994, is based on barycentric directions of extragalactic objects with a precision better than 0.5 mas. The ICRS is a kinematically defined and realized reference system: it presents no global rotation with respect to the extragalactic radio sources. The barycentric celestial reference system (BCRS) and the geocentric celestial reference system (GCRS) are coordinate systems defined in the framework of general relativity. The ICRS was born to answer the need of more precise definitions. To provide support to it, there is the necessity of an improved nutation model coming from the geophysics.

The IAU and the IUGG created the Working Group on Nutation for a non-rigid Earth and assigned the Group the responsibility to reach the recommendation of a new model for the celestial pole position. A model representing the observations at the sub-mas level has been elaborated by taking into account periodic planetary effects on the ecliptic and a more complete geophysical representation of the inner of the Earth.

2. THE IAU 2000 PRECESSION-NUTATION MODEL

The old theories (IAU 1976 and IAU 1980) decomposed the motion of the celestial pole in three components: the *luni-solar precession*, representing the secular motion of the mean celestial pole around the pole of the ecliptic provoked by the actions of the Sun and the Moon; the *planetary precession*, representing the perturbations of the planets on the orbit of the Earth; and the *nutation* produced by the Sun and the Moon on the Earth, provoking a periodic motion. The model IAU 2000 completes this representation by adding the *planetary nutation*. A more complete model of the interior of the Earth has been

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developed, introducing non-rigidity by considering a solid inner core within a liquid outer core, a deformable convective mantle, the atmosphere and the oceans, and their coupling affects.

The new theory is based on the rigid nutation theory by Souchay et al. (1999) plus a transfer function developed by Mathews et al. (2002). The complete model is precise at 0.2 mas level, adequate to the most demanding applications. It has been denominated IAU 2000A. For those applications not requesting submilliarcsecond precision, it has been recommended the IAU 2000B model, at 1 mas level.

3. THE TRANSFORMATION BETWEEN THE TERRESTRIAL AND THE CELESTIAL REFERENCE SYSTEMS

3.1. *The new elements*

At the XXIVth IAU General Assembly (Manchester, August 200), resolutions concerning the transformation between the celestial and the terrestrial reference systems have been adopted. It is to be noted that these resolutions conclude the process of redefinition of the conventional reference system for astronomy started at the end of the 80's. The ensemble of IAU resolutions adopted since the IAU General Assembly in Baltimore (1988) led to the adoption of a kinematically defined celestial reference system to replace the dynamical system realized by the FK5. The ICRS is a barycentric system of directions realized by the coordinates of radio sources observed with the VLBI technique. Resolution B1.3 specifies that the systems of space-time coordinates for the Solar System and the Earth within the framework of General Relativity are the Barycentric Celestial Reference System (BCRS) and the Geocentric Celestial Reference System (GCRS) respectively. GCRS is independent from the mean pole and equinox of a reference epoch and from the models adopted to represent precession-nutation, in opposition to the FK5 system.

Resolution B1.6 (January 1st, 2003) recommends the adoption of the precession-nutation model IAU 2000A (Mathews et al. 2002) for those applications needing 0.2 mas precision, and a shorter version IAU 2000B for less stringent applications (1 mas), together with the associated celestial pole offsets.

The classical elements representing the motions of the principal planes are not suitable for new theory. Instead, the following elements have been defined as represented in Fig.1:

Celestial Intermediate Pole (CIP) is the axis whose motion is specified in the GCRS by the motion of the Tisserand mean axis of the Earth with

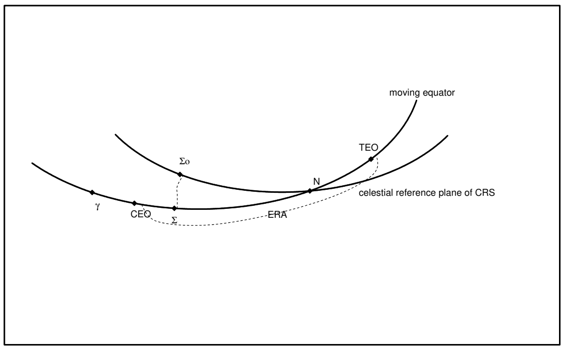

Fig. 1. New elements for the coordinate transformation betwen the terrestrial and the celestial reference systems

periods larger than 2 days. Periods smaller than 2 days are included in the model for the motions in the terrestrial reference system. The motion of the CIP in the GCRS is realized by the IAU 2000A model for precession and forced nutation for periods longer than 2 days, plus additional time-dependent corrections provided by the IERS through appropriate astro-geodetic observations. The motion on the CIP in the ITRS is provided by the IERS through appropriate astro-geodetic observations and models, including high frequency variations. With this definition, the Celestial Ephemeris Pole is no longer necessary.

The concept of "non rotating origin" has been developed by Guinot (1979) and analyzed by Capitaine et al. (1986) well before the adoption of the IAU resolutions for the new system and associate models for the pole position. This concept allows the definition of the origin in both, the celestial and the terrestrial systems. Instead of the theoretically defined equinox of date, the origin is a point denominated Celestial Ephemeris Origin (CEO) in the GCRS defined on the equator of the CIP. The "non rotating" condition of the CEO refers to the absence of a component of motion along the equator; the instantaneous motion of the CEO is about an axis in the equatorial plane, so that there is no rotation about the z-axis.

When referring to the Earth orientation, the Terrestrial Ephemeris Origin (TEO) is introduced: it is the "non rotating origin" in the ITRS defined on the equator of the CIP.

Connecting the CEO and the TEO, the Earth Rotation Angle (ERA) is defined along the equator of the CIP between the unit vectors directed towards the CEO and the TEO. UT1 is linearly proportional to the ERA.

3.2. *The transformation*

The coordinate transformation from the terrestrial system [TRS] to the celestial system [CRS] can be expressed as:

$$[\text{CRS}] = Q(t)R(t)W(t)\ [\text{TRS}],$$

where $Q(t)$ is the transformation matrix representing the motion of the celestial pole in the celestial system, $R(t)$ is the matrix representing the rotation of the Earth with respect to the polar axis and W(t) is the matrix of polar motion. The precession-nutation quantities to be used in matrix $Q(t)$ are based on the models IAU 2000A or IAU 2000B, depending on the required precision. The realized celestial pole is the Celestial Intermediate Pole (CIP).

With respect to the "classical" transformation, there are two fundamental differences: one is how the separation is done between polar motion and nutation. The CIP is defined in such a way that all nutation terms with period smaller than 2 days are included in the polar motion. The other difference is the choice of the CEO instead of the mean equinox on the equator. The motion of the CIP in the GCRS is realized by the IAU 2000 precession-nutation model for periods longer than 2 days, plus time-dependent corrections provided by the IERS. The motion of the CIP in the ITRS is provided by the IERS.

The transformation between the ITRS and the GCRS is specified by the position of the CIP in the GCRS, the position of the CIP in the ITRS and the Earth rotation angle.

Two procedures can be used to transform coordinates between the TRS and the CRS. The traditional procedure uses the equinox to realize the intermediate reference frame at the date t. In this case, the matrix R(t) uses the apparent Greenwich Sidereal Time (GST); the matrix Q(t) includes the classical precession-nutation parameters.

The new procedure makes use of the "non rotating origin" to realize the intermediate frame at the date t. The matrix R(t) contains, in this case, the ERA; the matrix Q(t) has the coordinates of the celestial pole in the CRS.

A detailed description of the transformation can be found in the IERS Conventions (2003). The IERS Conventions web page (`ftp://maia.usno.navy.mil/conv2000/chapter5`) provides fortran routines for the implementation of the IAU 2000 transformations.

4. CONCLUSION

The IAU recommended the adoption of the International Celestial Reference System (ICRS), the Celestial Intermediate Pole (CIP) and the Celestial Ephemeris Origin (CEO) to match with the improved accuracies achieved and those expected in the near future. In doing so, we have shifted from a dynamical celestial reference system moving with time to a kinematically defined set of directions independent of the date. New models for precession and nutation have been developed for accuracies, reaching the sub-milliarsecond level. The concepts of *true* and *mean* equinox are no longer valid since there is a unique model involving precession-nutation. Furthermore, the separation between terms representing polar motion and nutation has been made differently, including in polar motion the terms with periods shorter than 2 days.

The IAU/IUGG Working Group on Nutation for a non-rigid Earth, chaired by Véronique Dehant (Royal Observatory of Belgium) developed the IAU 2000 precession-nutation model. The model has been adopted by the IAU and the IUGG and is in force since January 2003. Scientists from many institutions have participated to the elaboration of the model, including the author of this paper. In recognition to the efforts of the Working Group, it has been distinguished with the Descartes Prize 2003, awarded annually by the European Union for outstanding scientific and technological achievements resulting from collaborative research.

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