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The VLBI Contribution to Precession (Present and Future)

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Abstract

In this paper, we emphasize the potential of VLBI for providing the actual position of the pole in the celestial reference system and consequently the precession of the equator and we recall the main characteristics of the IAU 2000 precession and its link to observations. Then, we investigate the possible present and future role of VLBI observations in identifying a replacement for the precession component of IAU 2000, with improved dynamical consistency. We compare the properties and accuracies of the high precision 2003 solutions for precession and describe tests of the solutions against VLBI observations. We conclude by providing what is required from VLBI in the future in order that it can, at the present level of accuracy, discriminate between various precession models.

1. Introduction

The IAU 2000 precession-nutation model [14] was adopted by the IAU and implemented in the IERS Conventions 2003 [12]. The precession component of the IAU 2000 model consists simply of VLBI estimated corrections to the precession rates in longitude and obliquity of the IAU 1976 precession [13]. This represents a significant improvement of the previous precession but further improvements are necessary to improve the dynamical consistency of the model. The possible VLBI contribution to this next stage of improvement has to be investigated.

2. Present Contribution of VLBI to Precession

2.1. The Treatment of Precession

The classical treatment of precession uses the ecliptic as an intermediary in the terrestrial to celestial transformation. This mixes two different phenomena, namely (i) the precession of the ecliptic due to planetary perturbations and (ii) the precession of the equator. Moreover, for historical reasons, precession is considered separately from nutation. The classical representation which is used in the current VLBI procedures thus uses a large number of parameters for precession and nutation and refers to the equinox, the motion of which has to be modeled.

The adoption of the ICRS as the international celestial reference system by the IAU since 1998 made it possible to refer the Earth orientation parameters to a geocentric celestial reference system (GCRS) that verifies the kinematical condition of absence of global rotation with respect to quasars and the realization of which is independent from precession-nutation models. This has been associated with a revision and improvement of concepts regarding the Earth's orientation in space [11], [6], that has been recommended in the IAU 2000 resolutions. This clearly separates the two precession phenomena, considers the combination of precession and nutation of the equator as being the motion of the equator in space and avoids possible systematic errors [18]. More details can be found in [4], and [5] (Figures 3 and 4).

2.2. Positioning the CIP in Space

VLBI currently provides estimated pole offsets that contain both the discrepancies in the precession-nutation model which is used in the VLBI procedure and the pole offset at epoch between the model and the GCRS (see for example Figure 6 in [5]). This means that VLBI provides the actual position of the pole in the GCRS, which shows the potential of VLBI for obtaining the precession of the equator. The current accuracy is of the order of a few hundred microarcseconds.

It should be noted that the GCRS x, y-coordinates of the CIP unit vector used in the new representation provide directly where the pole is in the sky, which corresponds to what VLBI actually determines.

2.3. The IAU 2000 Precession-Nutation

The IAU 2000A Precession-Nutation model was adopted by IAU 2000 Resolution B1.6 to replace the IAU 1976 Precession and the IAU 1980 Theory of Nutation (IAU 2000A for 0.2 mas level and IAU 2000B, its shorter version, for 1 mas level). The nutation series was generated by the convolution of the MHB 2000 transfer function [14] with the rigid-Earth nutation series REN-2000 [17]. It is based upon basic Earth parameters estimated from VLBI observations, including the Earth's dynamical flattening, H. The resulting nutation series includes 678 lunisolar terms and 687 planetary terms and provides the direction of the celestial pole in the GCRS with an observed accuracy of 0.2 mas. Due to the definition of the Celestial Intermediate Pole (CIP), the diurnal and semi-diurnal terms in nutation are considered as variations of polar motion [5]. The Free Core Nutation (FCN), which cannot be predicted rigorously, is not included in the IAU 2000A model, and sets a fundamental "noise level" of a fraction of 1 mas if IAU 2000A is used as it is.

The precession component of the IAU 2000 model is provided by corrections to the IAU 1976 precession of $-0.29965''/c$ in longitude and $-0.02524''/c$ in obliquity and is associated with VLBI estimates for celestial pole offsets at J2000 of $\delta\psi_0 = -41.775$ mas and $\delta\epsilon_0 = -6.8192$ mas.

2.4. The IAU 2000 Expressions for X, Y and GST

IAU 2000A expressions for the x, y-coordinates of the CIP unit vector in the GCRS have been developed [6] which include precession, nutation, coupling between precession and nutation and frame biases, the polynomial part of these expressions being for the precession of the equator [8].

The "Earth Rotation Angle" (ERA) along the equator of the CIP between the Celestial Ephemeris Origin (CEO) and the Terrestrial Ephemeris Origin (TEO) is provided (IAU 2000 Resolution B1.8) by a conventional linear expression of UT1 [11]. Greenwich sidereal time (GST) which refers to the equinox, is the sum of the ERA and the accumulated precession and nutation along the moving equator, from epoch to the date t. It can be written as the sum of a polynomial part, GMST, mainly due to precession and a periodic part, the "complete equation of the equinoxes". The IAU 2000 expression for GST [7] is consistent with the IAU 2000A precession-nutation and with the expressions for ERA(UT1) and the GCRS position of the CEO [6].

3. Further Improvements in Precession

3.1. High Precision Precession Models

The IAU 2000 precession, which consists only of VLBI MHB-estimated corrections to the precession rates in longitude and obliquity of the IAU 1976 precession, suffers from a lack of dynamical consistency. Expressions for the precession of the equator should strictly be (i) solutions of the dynamical equations for the Earth's rotation and (ii) referred to an improved ecliptic precession.

New precession models have recently been developed that are compatible with IAU 2000 with improved dynamical consistency:

- the B03 model by Bretagnon *et al.* [3] based on the analytical VSOP87 ecliptic [1], on the SMART 97 nutation theory for a rigid Earth [2] and on the MHB precession rate in longitude,

- the F03 model by Fukushima [10] based on an ecliptic fitted to the JPL numerical ephemerides DE405 [16] on a 600-yr interval, on the SF01 nutation theory [15] and on a quadratic fit to VLBI.

- the P03 model by Capitaine *et al.* [8] that is decribed in the next section.

An IAU Division I WG on "Precession and the Ecliptic" was established at the 2003 GA (Chair: J. Hilton) to recommend a new model.

3.2. The P03 Precession

The P03 ecliptic precession [8] has been derived both from the analytical solution VSOP87 and a fit to the JPL numerical ephemeris DE406 [16] over a 2000-yr interval. It has been evaluated as being the most accurate available model by comparing the various solutions to the best numerical ephemerides and by investigating the deficiencies in the other models [9] .

The P03 integration constants have been derived from (i) theoretical contributions to precession rates for a non-rigid Earth model from [14] and [19], (ii) MHB estimates [14] and (iii) corrections for perturbing effects on the observed quantities [9]. For example the precession in longitude has been shown not to be, as generally considered, the "observed" quantity but its projection parallel to the equator on a conventional ecliptic with the obliquity used in the current VLBI software (*i.e.* the IAU 1976 value). The P03 precession of the equator has been obtained by solving the dynamical precession equations, with an improved ecliptic and updated MHB integration constants.

The polynomial difference 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 [8]:

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

3.3. Checks Against VLBI Data

Checks of the precession models against VLBI data (GSFC series from 1980 to 2003) have been performed using the X and Y expressions. Figures 1 and 2 show plots corresponding to the X coordinate (*i.e.* $\Delta\psi \sin\epsilon$). These checks show that: (i) the IAU 2000A precession-nutation model gives a much better fit to the data than IAU 1976/1980, (ii) the VLBI data before 1990 are excessively noisy, (iii) the FCN should be corrected to avoid systematic errors, but no model exists since 2000, and (iv) VLBI cannot at present allow us to discriminate between the models.

The numerical estimates resulting from quadratic fits (with a RMS of 374 μas for X and 416 μas for Y) are the following where c_0, c_1, c_2 are for the constant, linear and quadratic terms respectively and c_{ij} is for the correlation coefficient between the i and j terms:

(i) $X_{IAU2000A}$: $c_0 = (\ 1 \pm 10)$ μas; $c_1 = (-1368 \pm 304)$ μas; $c_2 = (-11414 \pm 2579)$ μas; $c_{12} = 0.9$;
(ii) X_{P03}: $c_0 = (\ 2 \pm 10)$ μas; $c_1 = (-1119 \pm 304)$ μas; $c_2 = (-13296 \pm 2580)$ μas; $c_{12} = 0.9$;
(iii) $Y_{IAU2000A}$: $c_0 = (33 \pm 11)$ μas; $c_1 = (+2134 \pm 338)$ μas; $c_2 = (+24024 \pm 2870)$ μas; $c_{12} = 0.9$;
(iv) Y_{P03}: $c_0 = (33 \pm 11)$ μas; $c_1 = (+1620 \pm 338)$ μas; $c_2 = (+23991 \pm 2870)$ μas; $c_{12} = 0.9$.

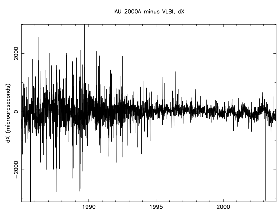

Figure 1. Fit of X(IAU 2000) to VLBI data

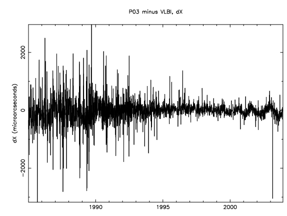

Figure 2. Fit of X(P03) to VLBI data

4. Conclusion

This paper has tried to make clear the following points:

- VLBI is potentially the most powerful technique to estimate the GCRS motion of the celestial equator (and consequently the precession of the equator) but not the ecliptic precession,

- the IAU 2000A precession-nutation is not "dynamically consistent" but gives a very good fit to VLBI,

- improvement in the precession model for the ecliptic is necessary, the resulting effect on the precession of the equator being at a level of 100 μas for one century (in the t^2 term in ψ),

- improvement in the precession model for the equator is necessary. However, the possible improvement in the model is dependent on the model for some parameters of the non-rigid Earth as the J_2 rate,

- observations covering a longer period of time are necessary in order to separate

(i) the precession rates and amplitudes of long-period nutations, (ii) the precession rates and the t^2 terms in the developments (which would give an indirect access to the motion of the ecliptic).

What is required from VLBI in the future in order for it to be a powerful tool, at the present level of accuracy, for discriminating between various precession models is the following:

- the availability of a refined International Celestial Reference Frame (ICRF) both without any global rotation and with a larger number of sources,

- the availability of a long interval of celestial pole offsets with low noise level and no systematic error (*i.e.* with the FCN corrected by a model),

- the adoption of IAU 2000 precession-nutation model in order than the celestial pole offsets can be considered as being first order quantities, concentrating on the X, Y representation that is close to the parameters to which VLBI is sensitive, and

- adoption of the CEO instead of the equinox to avoid possible risks of inconsistencies in the terrestrial to celestial transformation (enabling microarcsecond accuracy).

It should be noted that it would be necessary that, in parallel, models for the contributions to the precession of a non-rigid Earth (t term and t^2 term) be improved (resulting in an "improved" MHB model).

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