PROGRESS REPORT OF THE IAU WORKING GROUP ON PRECESSION AND THE ECLIPTIC

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ABSTRACT. The IAU Working group on Precession and the Ecliptic looked at several solutions for replacing the precession part of the IAU 2000A precession-nutation model, which is not dynamically consistent. These comparisons show that the Capitaine et al. (2003) precession theory, P03, is both dynamically consistent and the solution most compatible with the IAU 2000A nutation model. The two greatest sources of uncertainty in the precession theory are the rate of change of the Earth's dynamical flattening, ΔJ_2, and the precession rates (i.e. the constants of integration used in deriving the precession). The combined uncertainties limit the accuracy in the precession theory to approximately 2 mas cent^{-2}.

Given that there are difficulties with the traditional angles used to parameterize the precession, $z_{\rm A}$, $\zeta_{\rm A}$, and $\theta_{\rm A}$, the working group has decided that the choice of parameters should be left to the user. We shall provide a consistent set of parameters that may be used with either the traditional rotation matrix, or those rotation matrices described in Capitaine et al. (2003) and Fukushima (2003).

We recommend that the ecliptic pole be explicitly defined by the mean orbital angular momentum vector of the Earth-Moon barycenter in an inertial reference frame, and explicitly state that this definition is being used to avoid confusion with previous definitions of the ecliptic.

Finally, we recommend that the terms *precession of the equator* and *precession of the ecliptic* replace the terms *lunisolar precession* and *planetary precession*, respectively.

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 misleading. Capitaine et al. (2003) proposed the terms *precession of the equator* and *precession of the ecliptic*. 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 Ű24 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 precession observable in 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. Thus, the precession theory was not dynamically consistent.

Furthermore, Fukushima (2003) showed that the values of ζ_A and z_A, two of the traditional angles for parameterizing the precession, are complementary and highly dependent on the precise values that are adopted for the offset between the dynamical frame and the GCRS at J2000.0. Thus, they are unsuited to polynomial representation.

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.

2. PRECESSION OF THE EQUATOR

Three high precision precession theories (Bretagnon et al. 2003, Capitaine et al. 2003, and Fukushima 2003) have been published recently to address the shortcomings of the precession portion, including the ecliptic, of the IAU 2000A precession-nutation theory. In addition, Harada & Fukushima (2004) examined the definition of the ecliptic alone. 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 and/or ecliptic definition.

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 2000A precession-nutation theory. Capitaine et al. (2004) provides just such a comparison.

Regarding the equatorial precession the most important results of Capitaine et al. (2004) 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 an Earth model that is realistic and integration constants that are realistic. More recently, Capitaine et al. (2005) 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 equatorial precession.

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 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 frequently used when describing astronomical phenomena. However, this application does not require high accuracy. Many celestial mechanics 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 work. However, some celestial mechanics problems have reached the level of accuracy ($\sim$1 mas or less) where knowledge of the instantaneous angular momentum of the Earth-Moon barycenter about the solar system barycenter is required instead of the mean angular momentum of the Earth about the solar system barycenter, represented by the plane of the ecliptic.

Before an expression for the ecliptic can be agreed upon, two problems regarding the definition of the ecliptic had to be addressed.

First, whether the ecliptic should be defined with respect to inertial space or the geometric path of the Sun as seen from the Earth (the so called “rotating" ecliptic). This question arises because the ecliptic has been realized as a plane perpendicular to the Earth’s orbital angular momentum vector. Prior to the establishment of the ICRS, it was impossible to establish a truly inertial reference system. Thus, rather than try to separate out the non-inertial component, Newcomb (1894) chose to use geometric path of the Sun. The ICRS, however, established a quasi-inertial coordinate system. Thus, inclusion of the motion of the ecliptic in its realization is no longer an expedient.

Second, 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. The details of these considerations are discussed in Hilton (2006). The main conclusion is that the ecliptic is still useful in low precision applications. In higher precision applications, certain arbitrary decisions have to be made concerning the position of the ecliptic and the equinox. However, the regime in which the equinox and ecliptic become arbitrary is also the regime in which the instantaneous rather than mean angular momentum of the Earth-Moon barycenter is required. Thus, those arbitrary decisions required to realize the ecliptic do not impair the physical models.

The working group recommends the precession of the ecliptic included in the P03 precession theory. More specifically, we recommend that the ecliptic pole should be explicitly defined by the mean orbital angular momentum vector of the Earth-Moon barycenter in an inertial reference frame to simplify the dynamics. We also recommend that both the definition used and the process by which the ecliptic has been determined be made explicit when any future definition is adopted, to avoid confusion.

4. RECOMMENDATIONS

The Working Group on Precession and the Ecliptic has reached a consensus on its recommendations and has submitted its report for publication. The working group will recommend:

The Working Group on Precession and the Ecliptic, recognizing:

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

2. the gravitational attraction of the planets make a significant contribution to the motion of the Earth’s equator (thus making the terms *lunisolar precession* and *planetary precession* misleading),

3. the need for a definition of the ecliptic for both astronomical and civil purposes, and

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

recommends:

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

2. The IAU adopt the P03 precession theory, of Capitaine et al. (2003) for the precession of the equator (Eqs. 37) and the precession of the ecliptic (Eqs. 38); the same paper provides the polynomial developments for the P03 primary angles and a number of derived quantities for use in both the equinox based and CIO based paradigms.

3. The choice of precession parameters be left to the user.

4. The recommended polynomial coefficients for a number of precession angles shall be given in Table 1 of the report, including the P03 expressions set out in Tables 3Ű5 of Capitaine et al. (2005), and those of the alternative Fukushima (2003) parameterization, including the corresponding matrix representations.

5. The ecliptic pole should be explicitly defined by the mean orbital angular momentum vector of the Earth-Moon barycenter in an inertial reference frame, and this definition should be explicitly stated to avoid confusion with older definitions.

The official report of the working group, Hilton et al. (2006), was submitted for publication in October 2005 and should be available shortly.

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