PROGRESS REPORT OF THE INTERNATIONAL ASTRONOMICAL UNION DIVISION I WORKING GROUP ON PRECESSION AND THE ECLIPTIC

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ABSTRACT. The IAU Working group on Precession and the Ecliptic was formed at the XXVth General Assembly of the IAU, Sydney 2003, in response to requests for a dynamically consistent precession theory compatible with the IAU 2000A nutation theory. Since that time, the working group has made significant progress towards the adoption of just such a theory. This paper looks at the current state of the process and includes the author's thoughts on the definition of the ecliptic and a recommendation for an adjustment in the nomenclature of precession.

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 misnomers. Fukushima (2003) proposed renaming lunisolar precession as *equator precession* and planetary precession as *ecliptic precession* to more accurately describe these two components of precession. Similarly, Capitaine et al. (2003) proposed the terms *precession of the equator* and *precession of the ecliptic*. Although the terms of Capitaine et al. are more unwieldy than Fukushima's terms, the term *precession of the equator* does make a distinction between it and precession *along* the equator which the term *equator precession* does not. Thus, this paper will adopt the use of precession of the equator and, for symmetry, precession of the ecliptic. Further, 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 24 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 the 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 and 0.01 mas cent^{-2} in latitude. Thus, the precession theory was not dynamically consistent.

Fukushima (2003) showed that ζ_A, one of the traditional angles for parameterizing the precession, becomes unstable near the epoch of precession unless an additional assumption is made about its value at epoch. Thus, the traditional precession parameters may not provide the best representation of it.

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. In addition to the author, the working group consists of: N. Capitaine, Systèmes de Référence Temps-Espace, France; J. Chapront, Systèmes de Référence Temps-Espace, France; J.M. Ferrandiz, U. de Alicante, Spain; A. Fienga, Institut de Mécanique Céleste, France; T. Fukushima, National Astronomical Observatory Japan, Japan; J. Getino, U. de Valladolid, Spain; P. Mathews, U. of Madras, India; J.-L. Simon, Institut de Mécanique Céleste, France; M. Soffel, U. Tübingen, Germany; J. Vondrák, Czech Acad. Sci., Czech Republic; P. Wallace, Her Majesty's Nautical Almanac Office, U.K.; and J. Williams, Jet Propulsion Laboratory, U.S.A. All of these scientists have provided insight and guidance to the working group. This paper constitutes the author's understanding of the current consensus of the working group. Should there be any mistakes or misrepresentations in this paper they are unintended and the sole responsibility of the author.

The precession of the equator will be addressed in Section 2. Section 3 will look at the ecliptic and precession of the ecliptic, and Section 4 will present the draft recommendations of the working group.

2. PRECESSION OF THE EQUATOR

Recently, four high precision precession theories (Bretagnon et al. 2003, Capitaine et al. 2003, Fukushima 2003, and Harada & Fukushima 2004) have been published to address the shortcomings of the precession portion of the IAU 2000A precession-nutation theory. 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. Additionally, all four theories used a different definition for the ecliptic.

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

Regarding the equatorial precession the most important results of Capitaine et al. (2004a) 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 a realistic Earth model and integration constants. More recently, Capitaine et al. (2004b) 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 precession of the equator.

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 the 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 still the origin of the azimuthal celestial coordinate recognized by most of the astronomical community. However, this does not require high accuracy (more accurate than $0\overset{''}{.}1$) for most applications. Similarly, high accuracy celestial mechanics problems have reached the level of accuracy that knowledge of the true rather than the mean plane of the Earth's orbit is required. However, many 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.

3.1. Definitions

Before an expression for the ecliptic can be agreed upon, two problems regarding the definition of the ecliptic have to be addressed. First, there is the question of whether the ecliptic should be defined with respect to inertial space or with respect to an observer on the non-inertial platform of the Earth. Second, there is the question of 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.

Standish (1981) pointed out there are two definitions of the ecliptic that have been used in the past: the inertial definition and the rotating definition. The difference between these two definitions arise from whether the reference frame defining the ecliptic is situated in inertial space (inertial definition) or comoving with the Earth (rotating definition). The difference between these two definitions results in a difference in the position of the equinox of 93.66 mas and a difference in the obliquity of the ecliptic of 3.34 mas at J2000.0. In the working group's opinion, the inertial definition of the ecliptic should be used for two reasons. First, it is the definition in which the dynamics are most easily represented. Second, it is the definition that is used in IAU 2000A. However, the rotating definition of the ecliptic has also been used in several places such as Lieske. Thus, for the foreseeable future, the inertial nature of ecliptic definition being used should be explicitly stated to avoid confusion.

The second question, how to define a barycentric plane in a geocentric reference frame, arises from the distortion caused trying to transform a plane from one reference frame to another using a paradigm where space is no longer separate from time. However, although the ecliptic is thought of and formally defined as a plane, it has been practically defined (e.g. Newcomb 1906, Lieske, Simon et al. 1994) in terms of the mean direction of the Earth's orbital angular momentum vector. While there is not complete agreement on what constitutes angular momentum in a general relativistic sense, the size of the effect of transforming a vector from a barycentric reference frame to a geocentric one is extremely small. On the other hand the uncertainty in the Earth's orbit, on the order of 1 mas (Standish 2004), is orders of magnitude larger than the possible loss of precision that would be introduced by ignoring relativity. Thus, the problem of transforming a plane from a barycentric to a geocentric frame of reference is sidestepped by using the Newtonian angular momentum vector as the practical realization of the ecliptic and acknowledging that those digits more precise than 1 mas in the orientation of the ecliptic are arbitrary.

3.2. Determining the Mean Plane

How to determine the mean direction of the angular momentum vector is the third problem in determining the ecliptic.

Newcomb (1906) determined the ecliptic using a modified approach to determining the proper elements of the Earth's orbit. In this method, Newcomb estimated the motion of the Earth's orbital plane at three different epochs (1600.0, 1850.0, and 2100.0), in terms of the parameters $\mathrm{d}p/\mathrm{d}t = \mathrm{d}/\mathrm{d}t(\sin\pi\sin\Pi)$ and $\mathrm{d}q/\mathrm{d}t = \mathrm{d}/\mathrm{d}t(\sin\pi\cos\Pi)$ where π is the inclination of the ecliptic of date to the ecliptic of 1850.0 and Π is the node of the ecliptic of date on the ecliptic of 1850.0 measured from the equinox of 1850.0. The motions at these epochs were determined using a method similar to that described in chapters 6 and 7 of Murray & Dermott (2000). In this technique, the disturbing function is expanded in an infinite series and those perturbations depending on the mean motions of the perturbing bodies are dropped. The remaining perturbations are considered secular (although, in fact, they may have periodicities as short as 45,000 years). The elements, called *proper elements*, were then derived from the integration of the resulting equation. What was left are the mean elements in the sense that the short-period perturbations caused by the mean motions of the planets have been removed. In his work Newcomb used only the first order of the expansion to determine the motion of the pole of the ecliptic. The ecliptic was then determined by fitting a polynomial to the rate of motion at these three dates and integrating using the position of the equinox and the obliquity at 1850.0 as the initial conditions. This method had the advantage of using the very-long-term change in the Earth's orbital elements, but avoiding the use of numerical integration that would have been difficult in the pre-computer era using a polynomial approximation for the slowly changing mean elements.

The ecliptic of Lieske followed the same method used by Newcomb but with updated values for the masses and elements of the planets, and the equinox and obliquity of J2000.0 as the initial conditions.

The determination of proper elements does have a drawback. Laskar (1988) showed that numerous overlapping weak resonances in the inner solar system result in a large number of low amplitude periodic terms when using a higher-order expansion of the disturbing function. However, all of these terms have amplitudes smaller than the current accuracy of the Earth's ephemeris (Standish 2004). Hence, including these higher-order terms would *not* increase the ecliptic's accuracy. Thus, as with the relativistic transformation of the angular momentum vector, the higher-order portion of the expansion can be ignored as long as we acknowledge that the equation for the ecliptic is arbitrary at accuracies less than about a milliarcsecond.

The IAU (1992), however, presented a different definition for the ecliptic. Here it is the uniformly rotating plane of the orbit of the Earth-Moon barycenter averaged over the entire period for which the ephemerides are valid. This definition has been used by the most of the recent determinations of the ecliptic such as Simon et al. (1994), Harada (2003), and Capitaine et al. (2003). While this definition of the ecliptic is simpler, it is in conflict with the previous definition of the ecliptic, that is the mean plane of the *Earth's* orbit. Since the Earth and Moon form a closed system, the mean orbital plane of the Earth-Moon barycenter and the mean orbital plane of the Earth's orbit are the same thing, so it would seem that using the Earth-Moon barycenter would result in the same ecliptic. However, perturbations to the lunar orbit directly affect the Earth-Moon barycenter. Thus, the mean must be taken over an integral number of the periodic perturbations arising from the lunar motion. Otherwise, the mean orbital plane of the Earth-Moon barycenter as determined from the ephemeris will not be the same as the ecliptic. Meeting this condition is difficult to do with an integrated ephemeris.

Also, as Capitaine et al. (2004a) demonstrated, long-period planetary perturbations may cause a significant difference in the ecliptic determined. These are the perturbations that the proper element method is designed to remove. Thus, an ecliptic determined from an ephemeris is tied to that ephemeris and has no validity outside the time range of the ephemeris. On the other hand, an ecliptic derived from the Earth's proper elements could be extended indefinitely.

For both methods the accuracy of the ecliptic as a physical entity is limited by the accuracy of the initial conditions. The ecliptic's applications are now purely fiducial, that is it provides an equinox for use for both astronomical and civil purposes and a fiducial plane for use in solar system dynamics. Observations have become accurate enough that the true orbital plane, rather than the ecliptic, is required for celestial mechanics computations of the Earth-Moon system to match the accuracy of the observations. Thus, there is no compelling reason to choose either definition for the ecliptic. To avoid confusion, however, both the source for the ecliptic and the set of equations defining it should be explicitly stated.

Since there is no compelling reason to do otherwise and the parameters for the Capitaine et al. (2003), P03, precession of the ecliptic are already being used along with the P03 precession of the equator, the working group recommends the adoption of the Capitaine et al. (2003) precession of the ecliptic.

4. RECOMMENDATIONS

The Working Group on Precession and the Ecliptic has not yet proposed a set of recommendations. However, discussions on what should be in the recommendations has begun. The following represents the author's understanding of the current consensus of the working group.

The Working Group on Precession and the Ecliptic recognizing:

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

2. Recent improvements in the accuracy to which the precession can be determined blurs the distinction between the terms *lunisolar precession* and *planetary precession*,

3. The need for an ecliptic that acts as a fiducial plane for both astronomical and civil purposes,

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

definition), and

5. The loss of precision in the definition of the ecliptic caused by ignoring the relativistic transformations is insignificant compared to the accuracy of the ephemerides from which the ecliptic is determined

makes the following recommendations:

1. The IAU should adopt the Capitaine et al. (2003) precession theory, designated P03,
2. The terms *lunisolar precession* and *planetary precession* be replaced by *precession of the equator* and *precession of the ecliptic*, respectively,
3. The inertial definition of the ecliptic should be used, and should be explicitly stated to avoid confusion.
4. The ecliptic should be defined as the plane perpendicular to the Earth's mean orbital angular momentum vector.
5. There is no compelling reason to choose whether future realizations of the ecliptic are determined using either the proper element or the averaged ephemeris method. However, the method used and defining relations for the ecliptic should be clearly stated.

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