Section 4.

TIME AND STANDARDS

Additional Paper

Report on Astronomical Constants

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Abstract. Recent progress in the determinations of astronomical constants is reviewed. First is the latest estimation of the general relativistic scale constants, L_C, L_G, and L_B (Irwin and Fukushima, 1999). By re-estimating the uncertainty, the value of the first constant is given as $L_C = 1.480\ 826\ 867\ 4 \times 10^{-8} \pm 1.4 \times 10^{-17}$. Also noted is the rigorous relation among these three, $L_B = L_C + L_G - L_C L_G$. Based on the latest determination of the geoidal potential W_0 in the IAG 1999 Best Estimate of Geodetic Parmeters (Groten, 1999), L_G and L_B were reevaluated as $L_G = 6.969\ 290\ 09 \times 10^{-10} \pm 6 \times 10^{-18}$ and $L_B = 1.550\ 519\ 767\ 3 \times 10^{-8} \pm 2.0 \times 10^{-17}$. Since L_G is roughly related to W_0, a proposal to fix its numerical value is presented in order to remove the geophysical ambiguity in its evaluation in the future. In that case, L_G becomes a defining constant for the scale difference between the geocentric and terrestrial coordinate systems. While L_C and L_B remain as a primary and derived constant, respectively. Next is the correction to the current precession constant, Δp. The recent estimates of Δp based on Very Long Baseline Interferometry (VLBI) observation seem to converge to a value close to $-0.30\ ''/\mathrm{cy}$ (Mathews *et al.*, 2000; Petrov, 2000; Shirai and Fukushima, 2000; Vondrák and Ron, 2000). Unfortunately this is significantly different from $-0.34\ ''/\mathrm{cy}$, the latest value determined from the Lunar Laser Ranging (LLR) data (Chapront *et al.*, 1999). The difference is roughly ten times larger than the sum of their formal uncertainties. Since the cause of this difference is not clear, we first arranged the best estimates based on VLBI and LLR techniques, respectively, then took a simple mean of these two best estimates, and recommend it as the current best estimate. The value derived is $p = 5\ 028.78 \pm 0.03\ ''/\mathrm{cy}$. Similar estimates were given for some other quantities related to the precession formula; namely the correction to the obliquity rate of the IAU 1976 precession formula (Lieske *et al.*, 1977), $\Delta\varepsilon_1 = (-0.024\ 5 \pm 0.002\ 5)\ ''/\mathrm{cy}$, and the offsets of the Celestial Ephemeris Pole of the International Celestial Reference Ssystem, $\Delta\psi_0 \sin\varepsilon_0 = (-17.5 \pm 0.8)$ mas and $\Delta\varepsilon_0 = (-5.2 \pm 0.4)$ mas. As a result, the obliquity of the ecliptic at the epoch J2000.0 was estimated as $\varepsilon_0 = 23°26'21.''405\ 6 \pm 0.''000\ 5$. The draft IAU 2000 File of Current Best Estimates of astronomical constants, that is to replace the 1994 version (Standish, 1995) or maybe even the formal IAU 1976 System

of Astronomical Constants (Duncombe *et al.*, 1977), after discussion at the 24th General Assembly of the IAU is presented.

1. Introduction

The IAU Working Group on Astronomical Standards (WGAS) has two major tasks. One is the maintainance of a package of standardized software for fundamental astronomy, the Standards Of Fundamental Astronomy (SOFA), and the other is to care for the astronomical constants. The former activity is reviewed by Dr. P. Wallace, the Chair of the SOFA Reviewing Board, in this volume of proceedings. Therefore, we will concentrate ourselves on the latter issue here.

There is a long history of efforts to establish and maintain the systems of astronomical constants. See a concise summary by Wilkins (1989) and its Appendix for information up to the 1980s. As for the physical constants and the international system of units (SI), a comprehensive WWW site is maintained by NIST, `http://physics.nist.gov/cuu/`

The current *formal* list of astronomical constants authorized by the IAU is still the IAU 1976 System of Astronomical Constants (Duncombe *et al.*, 1977). Since its establishment, the International Earth Rotation Service (IERS) has continued the publication of the list of best estimates of fundamental constants as well as the formulation of some basic procedures; IERS Standards 1989 (McCarthy, 1989) and 1992 (McCarthy, 1992), and IERS Conventions 1996 (McCarthy, 1996) and 2000 (McCarthy, 2000). At the Hague General Assembly in 1994, the IAU has changed its approach to this issue by adopting the so-called "two-tier" system, namely to keep the System of Astronomical Constants as a long-time reference while (frequently?) updating the File of Current Best Estimates of astronomical constants as the IERS does. Also the IAU presented the first version of the latter as the IAU 1994 File of Current Best Estimates of astronomical constants (Standish, 1995). The introduction of this policy change was mainly influenced by the adoption of a similar system in geodesy. Actually the IAG has kept the Geodetic Reference System (GRS) 1980 as a formal reference while revising the list of best estimates of geodetic parameters[1] almost every four years at their General Assemblies. See the report by Prof. E. Groten also contained in this volume for details.

2. Scale Constants

The general relativistic scale constants, L_C, L_G, and L_B, are in converting the quantities measured and/or determined in three major coordinate systems currently used; the solar system Barycentric Coordinate System (BCS), the Geocentric Coordinate System (GCS), and the Terrestrial Coordinate System (TCS). Readers are referred to many articles contained in this volume explaining and discussing the relations among these three coordinate systems.

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[1] Exactly, they are entitled *Parameters of Common Relevance to Astronomy, Geodesy, and Geodynamics.*

Now the former estimates of these constants (Fukushima, 1995) were based on the numerical integration of certain quantities using the JPL's planetary/lunar ephemeris DE245. They were recently updated in Irwin and Fukushima (1999) by clarifying the relations among them more rigorously and by replacing the ephemeris by the latest DE405 (Standish, 1998).

As was clearly given in Irwin and Fukushima (1999), the exact relation among these three constants is $1 - L_B \equiv (1 - L_C)(1 - L_G)$, which is translated more compactly as

$$L_B = L_C + L_G - L_C L_G \tag{1}$$

where the third term in the right hand of the above has been ignored so far. Irwin and Fukushima (1999) first evaluated the contribution of the Sun, Moon and major planets except the Earth to L_C by the numerical integration of the Newtonian approximation formula based on DE405. Next they added the effect of minor planets and the post-Newtonian contribution by correctly quoting the results given in Fukushima (1995) and derived the total value as

$$L_C = 1.480\ 826\ 867\ 4 \times 10^{-8} \pm 1.4 \times 10^{-17}, \tag{2}$$

where the uncertainty was reestimated by simply adding the error components discussed in Irwin and Fukushima (1999) as $(9. + 5.) \times 10^{-18}$.

On the other hand, within the Newtonian approximation, the value L_G is directly connected to the geoidal potential W_0 as $L_G \approx W_0/c^2$. The latest estimate of W_0 is found in IAG 1999 Best Estimates of Geodetic Parameterss (Groten, 1999) as

$$W_0 = (62\ 636\ 855.6 \pm 0.5)\,\mathrm{m}^2\mathrm{s}^{-2}, \tag{3}$$

which leads to

$$L_G = 6.969\ 290\ 09 \times 10^{-10} \pm 6 \times 10^{-18}, \tag{4}$$

and therefore

$$L_B = 1.550\ 519\ 767\ 3 \times 10^{-8} \pm 2.0 \times 10^{-17}. \tag{5}$$

This is slightly different from the value given in Irwin and Fukushima (1999) just because the quoted estimate of W_0 was different from the above. In the near future, it is expected that similar changes in the value of L_B will be caused by that of W_0 even if L_C remains the same. This type of frequent changes are not welcome. Further, as we noticed earlier, the relation between L_G and W_0 is only of an approximate nature. Therefore we propose to fix the numerical value of L_G as given above is spite of future changes in the value of W_0. In other words, we propose to classify L_G as not a primary constant determined directly from the observations but a defining constant that defines the numerical relation between the units in the TCS and GCS. See the resolution concerning the redefinition of TT adopted by this Colloquium.

3. Precession

Precession has been the most controversial constant since the IAU 1994 Current Best Estimates of astronomical constants (Standish, 1995) adopted the latest values of planetary masses. This is mainly because VLBI and other modern techniques have revealed a difference in trend as large as about -0.3 ″/cy between the observations and the precession constant adopted in the IAU 1976 System of Astronomical Constants (Duncombe *et al.*, 1977), $p = 5\,029.096\,6$ ″/cy. This is relatively large when compared with the fact that the recommended value was given to 0.000 1 ″/cy. Since the precession and nutation result from a single phenomenon, the motion of the Earth's figure axis in space, it is not appropriate to discuss them separately.

Table 1. Corrections to Precession Constants

Method & Reference		Δp (″/cy)		$\Delta\varepsilon_1$ (″/cy)	
		Value	σ	Value	σ
V	Fanselow *et al.* (1984)	−0.38	0.09		
V	Herring *et al.* (1986)	−0.239	0.013		
V	Zhu *et al.* (1990)	−0.38	0.05	+0.017	0.017
V	Sovers (1990)	−0.196	0.013		
S	Andrei & Elsmore (1991)	+0.01	0.15		
V	Herring *et al.* (1991)	−0.32	0.10	−0.04	0.05
L+V	Williams *et al.* (1991)	−0.27	0.04		
V	McCarthy & Luzum (1991)	−0.27	0.02	−0.005	0.007
P	Miyamoto & Soma (1993)	−0.27	0.03		
V	Walter & Ma (1994)	−0.36	0.11		
T	Williams (1994)	−0.2368		−0.0244	
L+V	Charlot *et al.* (1995)	−0.30	0.02	−0.020	0.008
V	Herring (1995)	−0.30	0.01	−0.024	0.005
V	Souchay *et al.* (1995)	−0.321	0.003	−0.026	0.001
V	Walter & Sovers (1996)	−0.31	0.01		
O	Vondrák (1999)	−0.154	0.004	−0.013 1	0.001 8
L	Chapront *et al.* (1999)	−0.344	0.004		
P	Vityazev (2000)	−0.28	0.08		
O	Vondrák and Ron (2000)	−0.216	0.005	−0.009 3	0.001 8
V	Petrov (2000)	−0.295	0.002	−0.027	0.000 9
V	Vondrák and Ron (2000)	−0.299 0	0.001 3	−0.022 0	0.000 7
V	Mathews *et al.* (2000)	−0.300 1	0.000 8	−0.024 7	0.000 3
V	Shirai & Fukushima (2000)	−0.293 0	0.000 5	−0.024 3	0.000 2

Note: The symbols of the methods are; V for the VLBI data, S for the short baseline radio interferometry, L for the LLR data, P for the proper motion analysis, T for the theoretical consideration, and O for the optical observation of latitude variations.

As for the nutation, see the report of IAU/IUGG Joint WG on Nutation (Dehant *et al.*, 1999) and related articles included in this volume. In Table 1, we summarize the estimates of the correction to the IAU 1976 value of the precession constant, Δp, since the VLBI observation began. There we also list the estimates of the correction to the precession in obliquity, $\Delta\varepsilon_1$, as well. However, we must remark that the latter quantity is not primarily determined from observations but must be derived from the adopted precession constant, p, and the obliquity

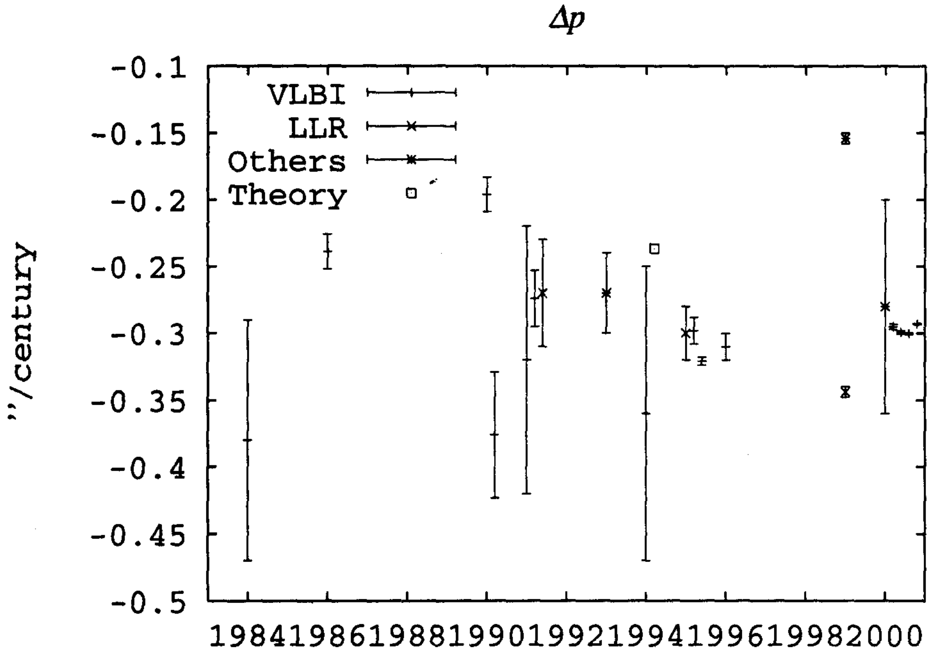

Figure 1. Corrections to Precession in Longitude

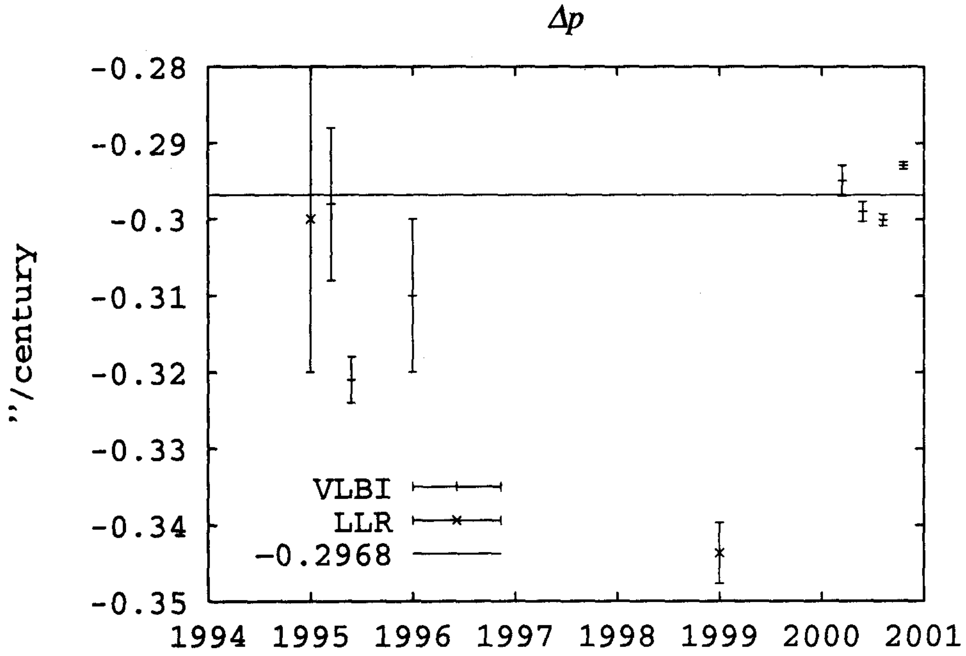

Figure 2. Close-up of corrections to precession in longitude.

constant, ε_0, and the masses of the Sun, the Moon, and the planets as well as the planetary motions given in certain ephemerides. Figures 1 through 4 illustrate the change of these estimates graphically.

The table and figures show clearly the recent determinations of Δp, especially those published since 1999, seem to converge to some value close to $-0.3''/\mathrm{cy}$ except for that deduced from the analysis of optical observation of latitude variation in the entire 20th century (Vondrák, 1999; Vondrák and Ron, 2000). This big difference is thought to be due to some unknown systematic correction (Vondrák and Ron, 2000). Anyhow, the four values derived from the VLBI observations (Mathews *et al.*, 2000; Petrov, 2000; Shirai and Fukushima, 2000; Vondrák and Ron, 2000) are quite similar[2]. Thus, by taking the simple mean of these four estimates, we obtained the VLBI-based best estimate as

$$\Delta^{(\mathrm{V})}p = (-0.296\,8 \pm 0.004\,3)''/\mathrm{cy}, \quad \Delta^{(\mathrm{V})}\varepsilon_1 = (-0.024\,5 \pm 0.002\,5)''/\mathrm{cy}, \tag{6}$$

where the uncertainty was calculated by taking the largest difference between the averaged and raw values. The observationally determined value $\Delta^{(\mathrm{V})}\varepsilon_1$ is strikingly close to the theoretically predicted value (Williams 1994)

$$\Delta^{(\mathrm{T})}\varepsilon_1 = -0.024\,4''/\mathrm{cy}. \tag{7}$$

On the other hand, the latest LLR-based determination (Chapront *et al.*, 1999) of Δp, $\Delta^{(\mathrm{L})}p = (-0.343\,7 \pm 0.004\,0)''/\mathrm{cy}$. was clearly different from the VLBI-based ones. Unfortunately, there is no clear explanation on this large difference. Therefore, we simply apply the same procedure we used in deriving the best VLBI-based estimate again to evaluate the best estimate of Δp,

$$\Delta p = (-0.320 \pm 0.024)''/\mathrm{cy}. \tag{8}$$

By adding this to the IAU 1976 value of the precession constant, we now have the best estimate of the general precession in longitude as

$$p = (5\,028.78 \pm 0.03)''/\mathrm{cy}. \tag{9}$$

On the other hand, the recent estimates of the offset of the Celestial Ephemeris Pole at the epoch J2000.0, $\Delta\psi_0 \sin\varepsilon_0$ and $\Delta\varepsilon_0$, seem to converge to a single pair of values independent of the observation type. See Table 2.

By adopting a similar[3] procedure as we did in deriving p, we obtained as

$$\Delta^{(\mathrm{V})}\psi_0 \sin\varepsilon_0 = (-16.7 \pm 0.5)\mathrm{mas}, \quad \Delta^{(\mathrm{V})}\varepsilon_0 = (-4.9 \pm 0.3)\mathrm{mas}, \tag{10}$$

$$\Delta^{(\mathrm{L})}\psi_0 \sin\varepsilon_0 = (-18.3 \pm 0.4)\mathrm{mas}, \quad \Delta^{(\mathrm{L})}\varepsilon_0 = (-5.6 \pm 0.2)\mathrm{mas}, \tag{11}$$

$$\Delta\psi_0 \sin\varepsilon_0 = (-17.5 \pm 0.8)\mathrm{mas}, \quad \Delta\varepsilon_0 = (-5.2 \pm 0.4)\mathrm{mas}, \tag{12}$$

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[2] However, some differences are clearly larger than the formal uncertainties given. This is an open problem to be investigated in the near future.

[3] This time, we took the simple mean of Vondrák (2000), Mathews *et al.* (2000), and Shirai and Fukushima (2000) in deriving the VLBI-based best estimates.

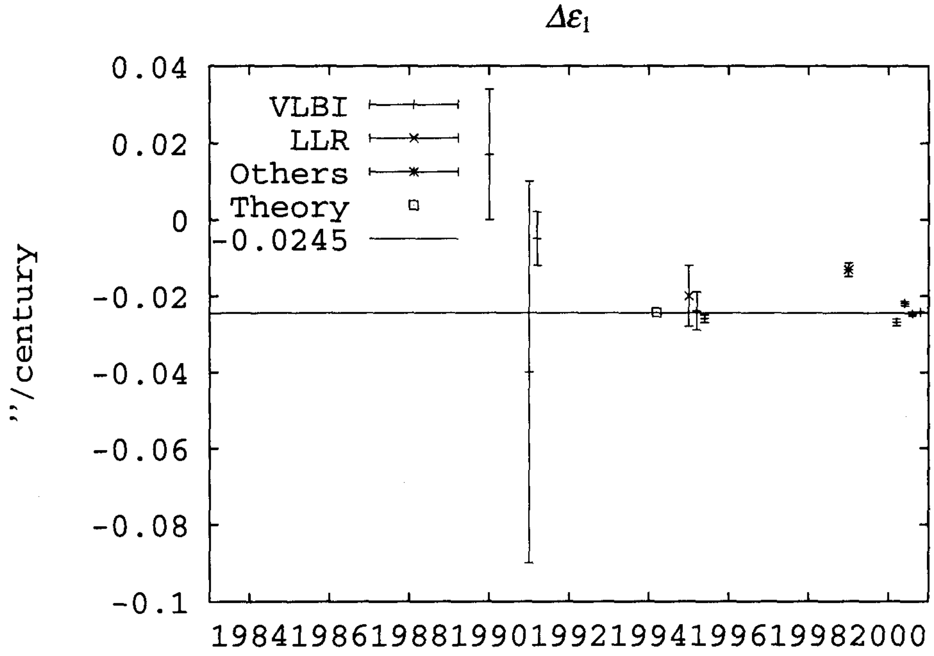

Figure 3. Corrections to Precession in Obliquity.

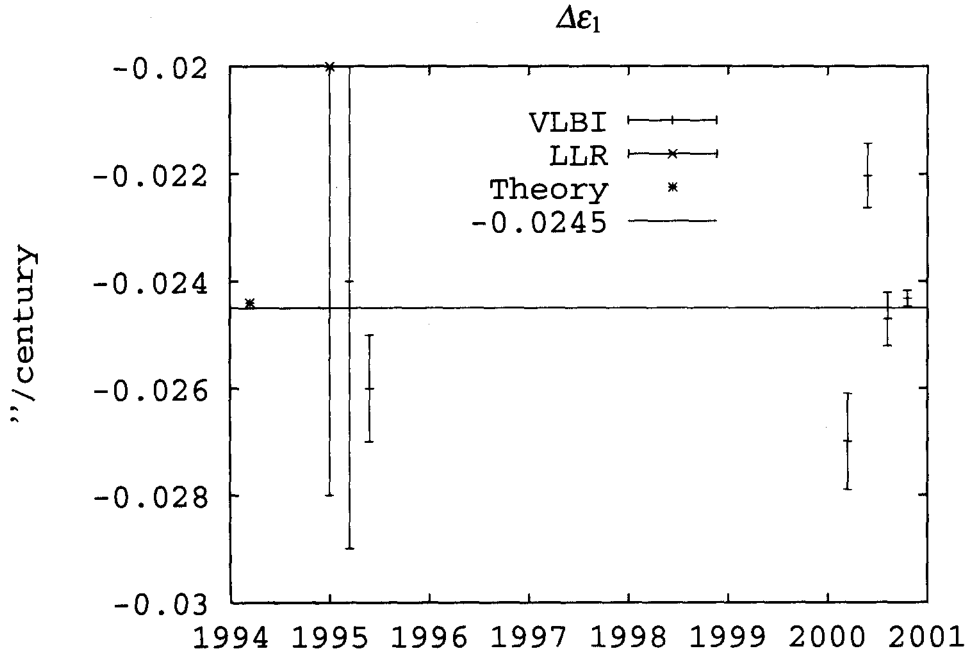

Figure 4. Close-up of corrections to precession in obliquity.

Table 2. Offsets of Celestial Ephemeris Pole at J2000.0

Method & Reference		$\Delta\psi_0 \sin\varepsilon_0$ (mas)		$\Delta\varepsilon_0$ (mas)	
		Value	σ	Value	σ
V	Herring (1995)	−17.3	0.2	−5.1	0.2
L	Chapront *et al.* (1999)	−18.3	0.4	−5.6	0.2
O	Vondrák & Ron (2000)	−12.3	0.7	−9.2	0.6
V	Vondrák & Ron (2000)	−17.10	0.05	−4.95	0.05
V	Mathews *et al.* (2000)	−16.18		−4.53	
V	Shirai & Fukushima (2000)	−16.889	0.013	−5.186	0.013

The derived $\Delta\varepsilon_0$ is the correction *not* to the IAU 1976 value, $23°26'21.''448$, but to the angle between the ecliptic and the reference plane of the International Celestial Reference System (ICRS). See Fig.1 and Table 11 of Chapront *et al.* (1999), where the obliquity of the inertial mean ecliptic to the ICRS equator was estimated as

$$\varepsilon_0(\mathrm{ICRS}) = 23°26'21.''410\,81 \pm 0.''000\,07. \tag{13}$$

Thus we have the best estimate of the obliquity of the ecliptic at J2000.0 as

$$\varepsilon_0 = 23°26'21.''405\,6 \pm 0.''000\,5. \tag{14}$$

This is significantly different from the value used in JPL's DE series, $23°26'21.''412$.

4. Conclusion

By collecting the results on the two topics described in the previous sections, we updated the former IAU File of Current Best Estimates (of astronomical constants) (Standish, 1995). The revised list is illustrated in Table 3. Here the references for the items differ from the previous version are; (1) Tholen and Buie (1997) for the mass ratio of Pluto+Charon to that of the Sun, M_S/M_P, (2) DE405 (Standish, 1998) for τ_A and M_M/M_E, (3) IAG 1999 (Groten, 1999) for the geodetic constants, a_E, J_2, GM_E, $1/f$, and W_0, (4) CODATA 1998 (Mohr and Taylor, 1999) for G, and (5) this article for L_G, L_C, p, and ε_0.

Table 3. IAU 2000 File of Current Best Estimates.

Class & Item	Value (Uncertainty) [Unit]	Reference
DEFINING		
k	$1.720\,209\,895 \times 10^{-2}$	IAU 1976
c	$2.997\,924\,58 \times 10^{8}$ [ms^{-1}]	CODATA 1998
L_G	$6.969\,290\,09 \times 10^{-10}$	This article
PRIMARY		
L_C	$1.480\,826\,867\,4(14) \times 10^{-8}$	Irwin and Fukushima (1999)
p	$5.028\,78(3) \times 10^{3}$ [$''$/cy]	This article
ε_0	$8.438\,140\,56(5) \times 10^{4}$ [$''$]	This article
τ_A	$4.990\,047\,863\,9(2) \times 10^{2}$ [s]	DE405
M_M/M_E	$1.230\,003\,45(5) \times 10^{-2}$	DE405
M_S/M_{Me}	$6.023\,6(3) \times 10^{6}$	Andersen *et al.* (1987)
M_S/M_V	$4.085\,237\,1(6) \times 10^{5}$	Sjogren *et al.* (1990)
M_S/M_{Ma}	$3.098\,708(9) \times 10^{6}$	Null (1969)
M_S/M_J	$1.047\,348\,6(8) \times 10^{3}$	Campbell and Synott (1985)
M_S/M_{Sa}	$3.497\,898(18) \times 10^{3}$	Campbell and Anderson (1989)
M_S/M_U	$2.290\,298(3) \times 10^{4}$	Jacobson *et al.* (1992)
M_S/M_N	$1.941\,224(4) \times 10^{4}$	Jacobson *et al.* (1991)
M_S/M_P	$1.352\,1(15) \times 10^{8}$	Tholen and Buie (1997)
a_E	$6.378\,136\,6(1) \times 10^{6}$ [m]	IAG 1999
J_2	$1.082\,626\,7(1) \times 10^{-3}$	IAG 1999
GM_E	$3.986\,004\,418(8) \times 10^{14}$ [m^{3}s^{-2}]	IAG 1999
W_0	$6.263\,685\,561(5) \times 10^{7}$ [m^{2}s^{-2}]	IAG 1999
$1/f$	$2.982\,564\,2(1) \times 10^{2}$	IAG 1999
ω	$7.292\,115\,0(1) \times 10^{-11}$ [rad s^{-1}]	IAG 1999
G	$6.673(10) \times 10^{-11}$ [m^{3}kg^{-1}s^{-2}]	CODATA 1998

Note: The units of uncertainties are the last digit of the values shown. The value of τ_A shown here is that after the scale transformation was applied. The value before transformation, namely that in TDB, is 499.004 783 806 1... (Standish, 1998). The geophysical values are those for the zero-frequency tide system (Groten, 1999). Suffices of radii and masses indicate the celestial objects; E for the Earth, M for the Moon, S for the Sun, Me for Mercury, V for Venus, Ma for Mars, J for Jupiter, Sa for Saturn, U for Uranus, N for Neptune, and P for Pluto. The planetary masses *except* for the Earth include the contribution of their satellites. Derived constants that are easily computed were omitted because of the shortage of space.

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