NUMERICAL VALUES OF THE CONSTANTS OF THE JOINT REPORT OF THE WORKING GROUPS OF IAU COMMISSION 4

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Abstract. The Numerical values underlying the Joint Report of the Working Groups of IAU Commission 4 on Precession, Planetary Ephemerides, Units and Time Scales are summarized in this report and additional explanation and references are provided.

The numerical values presented in the Joint Report of the Working Groups of IAU Commission 4 represent the best estimates of the constants currently available. The Working Groups have attempted to give a consistent set of values in agreement where possible with the values of constants being recommended by other scientific groups, particularly the International Association of Geodesy.

The ranges of uncertainty are such that the true values of the constants are believed to lie within the selected limits. It is recognized that scientific knowledge is continually increasing and new determinations of the constants are being made each year. Therefore, any adopted set of constants can not be current with the latest determinations for an extended period of time. It is hoped that all astronomers will use these adopted values, except where the accuracy of the application requires the use of the latest values or of particular values inherent to the application.

The specific values which have been recommended for the various constants are:

Defining Constants

(1) The Gaussian gravitational constant serves to define the astronomical unit of length when the corresponding astronomical units of time and mass are already defined. The value of $\mathbf{k} = 0.017\,202\,098\,95$ is that adopted by the IAU in 1938 and is retained as a fixed and exact value.

Primary Constants

The values and constants presented under the heading of primary constants represent those quantities that can most accurately be determined by observational methods. Therefore, they provide the bases for determining the values of the derived constants, although some derived constants can also be determined observationally, but with reduced accuracy.

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(2) The value of the speed of light (c) is that recommended by the fifteenth General Conference on Weights and Measures in 1975. The value is 299 792 458 ± 1.2 m s^{-1}. It is intended that this value will remain unchanged even if the meter is redefined.

(3) The value of the light-time for unit distance (1 astronomical unit of length) (τ_A) derived from determinations based on radar measurements of planetary distances is as follows:

Value (μs)	Source	Ref.
499 004 780 ± 2	MIT (1970)	[46]
499 004 780 ± 1	MIT (1971)	[8]
499 004 783.6 ± 2	JPL (1974)	[47]
499 004 781 ± 1	MIT (1974)	[33]
499 004 782 ± 2	Recommended value	

The values given for the constants (4), (5) and (6) are those recommended by the International Association of Geodesy at Grenoble in 1975 as currently representative estimates of fundamental geodetic parameters [56].

(4) The term 'equatorial radius for Earth' (a_e) refers to the equatorial radius of an ellipsoid of revolution that approximates to the geoid and the value recommended is 6 378 140 ± 5 m.

(5) The term 'dynamical form-factor for Earth' refers to the coefficient of the second zonal harmonic in the expression for the Earth's gravitational potential (J_2) as defined in *Trans. IAU* **12B** (*1964*), 117, 1966. The value recommended is (108 263 ± 1) × 10^{-8}.

(6) The geocentric gravitational constant (GE) is appropriate for use for geocentric orbits when the units are the meter and the second; E denotes the mass of the Earth including its atmosphere. The value recommended is (3 986 005 ± 3) × 10^{8} m^3 s^{-2}.

(7) The value for the constant of gravitation (G) is (6672 ± 4.1) × 10^{-14} m^3 s^{-2} kg^{-1} and is that given in the CODATA system of physical constants of 1973 [57].

(8) Recent determinations of the Earth/Moon mass ratio ($1/\mu$) corrected for the new Sun/(Earth and Moon) mass ratio and with the mass of the Earth including its atmosphere are as follows:

Value	Source	Ref.
81.300 68 ± 0.000 36	Mariner and Pioneer	[38]
81.300 64 ± 0.000 10	Mariner 9 Cruise phase	[53]
81.300 64	Orbital phase	[24]
81.300 68 ± 0.000 08	Lunar Laser and Lunar Orbiter 4	[49], [51]
81.300 7 ± 0.000 3	Recommended value	

The value recommended is 0.012 300 02 for the ratio of the mass of the Moon to that of the Earth and it is the reciprocal of the value above.

(9) The new value of the general precession in longitude, (p) per Julian century, at standard epoch J2000 is 5029.″0966 with a range of 5028.95 to 5029.25.

(10) The value of the obliquity of the ecliptic (ε) at the standard epoch J2000 results from applying secular terms computed with the new values of planetary masses to the current value for 1900. The resulting value is 23°26′21.″448 with the range of uncertainty from 21.″35 to 21.″25 [29]. This value may change based on a new theory for the Earth.

(11) The value for the constant of nutation at the standard epoch J2000 is 9.″2109. This results from applying the secular term given by Woolard [55] to the current value for 1900. This value will have to be changed as soon as it is possible to adopt a new theory of nutation based on a non-rigid model of the Earth, or if correction terms for a non-rigid Earth model are included with the present nutation theory.

Derived Constants

The values and ranges of uncertainties of the derived constants have been determined from the defining and primary constants. The values are also consistent with those determined directly from observations.

(12) Since the light-time for the unit distance is the quantity actually observed, the number of meters in one astronomical unit of length is now treated as a derived constant. The value derived is

$$c\tau_A = A = (1\,495\,978\,70 \pm 2) \times 10^3 \text{ m}.$$

(13) The value of the solar parallax to an accuracy consistent with the primary constants is

$$\arcsin(a_e/A) = \pi_\odot = 8.''794\,148 \pm 0.''000\,007.$$

The rounded value 8.″794 may be used except where extra figures are required to ensure numerical consistency.

(14) The constant of aberration is the ratio of the mean speed of the Earth to the speed of light, and is normally expressed in seconds of arc. It is calculated in radians from the expression $Fk\tau_A/86\,400$ where F is the ratio of the mean speed of the Earth to the speed of a hypothetical planet of negligible mass moving around the Sun in a circular orbit of unit radius. The value of F is calculated from

$$Fk = na(1 - e^2)^{-1/2},$$

where n is the sidereal mean motion of the Sun in radians per day, a is the perturbed mean distance of the Sun in astronomical units of length, and e is the mean eccentricity of the Earth's orbit. The value of F is then dependent on the mean elements used and the epoch of the elements. Based on Newcomb's mean elements, F has the following values [59]:

	F
1800	1.000 1427
1900	1.000 1420
2000	1.000 1413

Depending on the mean elements used and the perturbing planets included, the values of F for 2000 range between 1.000 141 325 and 1.000 141 387 [48]. This variation in F along with the uncertainty in τ_A gives a range for κ of 20″.495 518 to 20″.495 520. To the accuracy with which κ is given the uncertainty of the values of F and τ_A are not significant.

(15) The flattening factor for the Earth is derived from the adopted values of the primary geodetic parameters using the condition that the corresponding ellipsoid of revolution shall be an equipotential surface. The value for the flattening recommended by the IAG as a currently representative estimate is $1/f = (298\,257 \pm 1.5) \times 10^{-3}$, which gives the range 0.003 352 79 to 0.003 352 83.

The expression for the flattening factor (f) and the apparent gravity at the equator (γ_e) in terms of the primary constants are, to the third order:

$$f = \frac{3}{2}J_2 + \frac{1}{2}m + \frac{9}{8}J_2^2 + \frac{15}{28}J_2 m - \frac{39}{56}m^2 + \frac{27}{16}J_2^3 + \frac{1143}{784}m J_2^2 - \\ - \frac{537}{784}m^2 J_2 + \frac{709}{784}m^3,$$

$$\gamma_e = (GE/a_e^2)\,(1 - \mu_a + \frac{3}{2}J_2 - m + \frac{27}{8}J_2^2 - \frac{6}{7}m J_2 + \frac{47}{56}m^2 + \\ + \frac{135}{16}J_2^3 + \frac{17}{56}mJ_2^2 - \frac{293}{784}m^2 J_2 - \frac{611}{1176}m^3),$$

where $m = a_e\omega^2/\gamma_e$ is obtained by successive approximations. The angular velocity of the Earth (ω) and the relative mass of the atmosphere are given [56] as

$$\omega = 7\,292\,115 \times 10^{-11}\ \text{rad s}^{-1}$$

and

$$\mu_a = 0.000\,000\,88.$$

These values and expressions result in $\gamma_e = 9.780\,308\,9$ and $m = 0.003\,467\,756$. The value of γ_e recommended by the International Association of Geodesy is deduced from the mass of the Earth without the atmosphere and given as $(978\,032 \pm 1) \times 10^{-5}$ m s^{-2} [56].

(16) The value of the heliocentric gravitational constant is determined directly as

$$GS = A^3\mathbf{k}^2/D^2 = (132\,712\,438 \pm 5) \times 10^{12} \text{ m}^3 \text{ s}^{-2}$$

(17) The ratio of the mass of the Sun to that of the Earth is then

$$S/E = GS/GE = 332\,946.0 \pm 0.3.$$

(18) The ratio of the mass of the Sun to that of the Earth + Moon is

$$(S/E)/(1 + \mu) = 328\,900.5 \pm 0.5.$$

This value is consistent with the results from spacecraft data [12] and more recent results based on lunar laser ranging data. The lunar laser ranging results are the more accurate and the values obtained are

Value	Ref.
328 900.5 ± 0.03	[47]
328 900.53	[51]

Thus, there is internal consistency among the values involved in deriving the ratio of the mass of the Sun to that of the Earth + Moon.

(19) The mass of the Sun is derived then as

$$GS/G = S = (19\,891 \pm 12) \times 10^{26} \text{ kg}.$$

(20) A summary of planetary mass determinations was given in [12] and [27]. The recent determinations, their basis, references and the resulting recommended values and ranges based on all available data are as follows:

Mercury	Value	Basis	Ref.
	5 983 000 ± 370 0	Venus radar	[35]
	5 934 000 ± 520 000	Icarus	[30]
	6 025 000 ± 150 00	Radar and optical data	[6]
	6 023 600 ± 600	Mariner 10	[21]
Recommended 6 023 600			
Range 6 020 000 – 6 027 000			

Venus	Value	Basis	Ref.
	408 520 ± 100	Radar and optical data	[6]
	408 523.9 ± 1.2	Mariner 10	[20]
	408 523.5 ± 1.0	Mariner 5	[2]
Recommended 408 523.5			
Range 408 521 – 408 526			

Mars	Value	Basis	Ref.
	3 098 716 ± 132	Mariner 6	[4]
	3 098 709 ± 9	Mariner 4	[4]
	3 098 000 ± 4000	Radar and optical data	[6]
Recommended 3 098 710			
Range 3 098 600 – 3 098 760			

Jupiter	Value	Basis	Ref.
	1047.364 ± 0.005	Minor planets	[12]
	1047.352 ± 0.004	Satellites	[12]
	1047.184 ± 0.089	Comets	[12]
	1047.4 ± 0.1	Radar and optical data	[6]
	1047.342 ± 0.02	Pioneer 10	[5]
Recommended 1047.355			
Range 1047.330 – 1047.380			

Saturn	Value	Basis	Ref.
	3498.5 ± 0.3	Hidalgo	[32]
	3497.6 ± 0.2	Comet	[18]
	3498.7 ± 0.2	Jupiter	[26]
	3498.5 ± 0.5	Radar and optical data	[6]
	3499.9 ± 1.4	Minor planets	[42]
Recommended 3498.5			
Range 3497 – 3500			

Uranus	Value	Basis	Ref.
	22 692 ± 33	Saturn	[26]
	22 945 ± 15	Satellites	[13]
	22 900 ± 200	Radar and optical data	[6]
Recommended 22 869			
Range 22 650 – 23 100			

Neptune	Value	Basis	Ref.
	19 296 ± 31	Triton	[16]
	19 349 ± 23	Uranus	[44]
	19 400 ± 100	Radar and optical data	[6]
	19 438 ± 116	Nereid	[41]
Recommended 19 314			
Range 19 300 – 19 450			

Pluto	Value	Basis	Ref.
	3 000 000 ± 500 000	Neptune	[45]
	4 000 000 ± 2 000 000	Radar and optical data	[6]
Recommended 3 000 000			
Range 2 000 000 – 15 000 000			

Pluto presents a particular problem; the density resulting from the recommended mass and equatorial radius is 10 g cm^{-3}, which is greater than the density of any other planet. Since Pluto is a peculiar planet, the expected density is uncertain, so any, all or none of the values for the mass, equatorial radius or density may be incorrect.

Other Quantities for Use in Preparation of Ephemerides

(1) Determinations of the masses of minor planets:

Minor Planet	Mass in solar mass	Basis	Ref.
(1) Ceres	$(5.9 \pm 0.3) \times 10^{-10}$	Pallas	[43]
(2) Pallas	$(1.1 \pm 0.2) \times 10^{-10}$	Ceres	[43]
(4) Vesta	$(1.2 \pm 0.1) \times 10^{-10}$	Arete	[19]

(2) The recommended values for the masses of the Galilean satellites are from determinations based on the motion of Pioneer 10. These determinations are much more precise than the previous determinations by Sampson and de Sitter, so only the recommended values are listed.

Satellite	Satellite/Planet mass	Basis	Ref.
I Io	$(4.70 \pm 0.06) \times 10^{-5}$	Pioneer 10	[24]
II Europa	$(2.56 \pm 0.06) \times 10^{-5}$	Pioneer 10	[24]
III Ganymede	$(7.84 \pm 0.08) \times 10^{-5}$	Pioneer 10	[24]
IV Callisto	$(5.60 \pm 0.17) \times 10^{-5}$	Pioneer 10	[24]

Two determinations of the mass of Titan are available. It is felt that the determination based on the motion of the orbital plane of Iapetus provides the more reliable indication of the mass of Titan and is therefore the recommended value.

Satellite/Primary mass	Basis	Ref.
$(2.412 \pm 0.018) \times 10^{-4}$	Motion of orbital plane of Iapetus	[23]
$(2.4622 \pm 0.0013) \times 10^{-4}$	Hyperion	[36]
Recommended 2.41×10^{-4}		

The determinations of the mass of Triton based on the motion of Neptune are as follows. The recommended value is within the range of the determinations and is given to an accuracy consistent with the uncertainties of the determinations.

Satellite/Primary mass	Basis	Ref.
5.26×10^{-3}	Neptune	[37]
1.34×10^{-3}	Neptune	[1]
Recommended 2×10^{-3}		

(3) The values of the equatorial radii of the planets are based on the most accurate determination available. A summary of the determinations of the radii of the planets is given by Dollfus [11]. Where available, spacecraft determinations have been adopted. The table gives the values, the basis for the value and the reference.

Object	Equatorial radii (km)	Basis	Ref.
Mercury	$2\,439 \pm 1$	Mariner 10	[21]
Venus	$6\,052 \pm 6$	Radar Measurements	[7], [34]
Earth	$6\,378.140 \pm 0.005$	IAG	[56]
Mars	$3\,397.2 \pm 1$	Mariner 9	[3]
Jupiter	71 398	Pioneer 10 and 11	[39]
Saturn	60 000	Optical	[2]
Uranus	25 400	Optical	[2]
Neptune	24 300	Optical	[2]
Pluto	2 500	Estimate	[28], [17]
Moon	1 738	Apollo Altimeter	[25]
Sun	696 000	Optical	[58]
Venus cloud layer	6110 ± 15	Optical	[11]
Moon-Watt's profile	1738.065	Optical	[50]

(4) The gravity fields of the planets are specified to the extent that the terms can have some effect on the motion of some body. The notation is specified by Eckhardt [14]. For the Earth the terms are taken from the IAG recommendation [56], but only the three terms J_2, J_3, J_4 are recommended.

Earth zonal harmonic coefficients

Recommended	
$J_2 = (108\,263 \pm 1) \times 10^{-8}$	$J_5 = (-23 \pm 1) \times 10^{-8}$
$J_3 = (-254 \pm 1) \times 10^{-8}$	$J_6 = (54 \pm 1) \times 10^{-8}$
$J_4 = (-161 \pm 1) \times 10^{-8}$	

For the Mars gravity field, based on the motion of Mariner 9 [2], only the terms J_2, J_3, C_{22}, S_{22} and S_{31} are recommended since they are the only ones having a significant effect on the orbital motion of the satellites.

Gravity field of Mars

Harmonic coefficient	Value $\times 10^5$
J_2	196.4 ± 0.6
C_{22}	-5.5 ± 0.1
S_{22}	3.1 ± 0.2
J_3	3.6 ± 2.0
C_{31}	0.5 ± 0.4
S_{31}	2.6 ± 0.5
C_{32}	-0.6 ± 0.2
S_{32}	0.3 ± 0.2
C_{33}	0.48 ± 0.03
S_{33}	0.35 ± 0.03

The summary of the current knowledge of the gravity fields is adopted from Anderson [2]. The theoretical models of Jupiter and Saturn are taken from De Marcus [10], Peebles [40], and Hubbard [22]. Theoretical values of J_2, J_4 and J_6 have been computed for all the major planets by Zharkov and Trubitsyn [54] for assumed linear and quadratic density distributions in the interiors. The 'observed' values (see [39] and [9]) are based on the following: Jupiter–Pioneer 10 and 11; Saturn – motion of nearby satellites; Uranus – optical measures of flattening which are in reasonable agreement with dynamical determinations; Neptune – motion of nearby satellites. The values actually recommended are underlined in the table.

Gravity fields of the major planets

Planet	Model	$J_2 \times 10^3$	$J_4 \times 10^4$	$J_6 \times 10^5$	$J_8 \times 10^6$	$J_{10} \times 10^7$
Jupiter	De Marcus	14.2	−5.9	3.9	−2.8	2.2
	Peebles	15.3	−6.5	4.3	−3.2	2.5
	Hubbard	15.3	−6.3	4.1	−3.0	2.3
	Observed	14.71 ± 0.14	−6.7 ± 3.8			
	Pioneer	14.75 ± 0.50	−5.8 ± 0.4			
	Adopted	14.75	−5.8	4.2	−3.1	2.4
Saturn	De Marcus	16.8	−12.9	15.8	−19	24
	Peebles	17.0	−11.2	12.4	−14	17
	Hubbard	24.9	−16.7	18.3	−21	26
	Observed	16.67 ± 0.02	−10.3 ± 0.8			
	Adopted	16.45	−10	13	−16	20
Uranus	Quadratic law	12.4	−4.0	1.9		
	Linear law	10.8	−3.2			
	Observed	~5				
	Adopted	12	−4	2		
Neptune	Quadratic law	5.8	−0.86	0.18		
	Linear law	4.9	−0.66			
	Observed	4.9 ± 0.5				
	Adopted	4	−0.9	0.2		

Gravity field of the Moon
(Harmonics and $\beta, \gamma \times 10^6$)

Quantity	Lunar orbiter Liu and Laing [31]	Sjogren [49]	Gapcynski [15]	Lure 2 [51]	Recommended
C_{20}	-199.6 ± 2.0	-204.8 ± 3	-202.7 ± 1.5	-203.8 ± 2.5*	-202.7
C_{22}	23.6 ± 5.3	22.1 ± 0.5		22.4 ± 0.3*	22.3
C_{30}	-5.9 ± 2.9	-10.7 ± 9		-10.4 ± 6	-6
C_{31}	30.0 ± 2.7	31.6 ± 5		28.6**	29
S_{31}	1.4 ± 3.2	4.3 ± 12		8.8**	4
C_{32}	4.7 ± 2.8	5.5 ± 1		4.8 ± 0.2	4.8
S_{32}	0.6 ± 1.7	2.7 ± 1		1.7 ± 0.2	1.7
C_{33}	4.8 ± 2.2	1.8 ± 0.3		2.7**	1.8
S_{33}	-2.9 ± 1.3	-1.0 ± 0.2		-1.1 ± 1	-1
$\beta = (C\text{-}A)/B$				631.3 ± 0.3	631.3
$\gamma = (B\text{-}A)/C$				227.4 ± 0.6	227.8
C/MR^2			0.392 ± 0.003	0.394 ± 0.005	0.392
I				5552.7 ± 0.1	$5552''.7 = 1°32'32''.7$

* Not measured, but Sjogren's values with constraint of β and γ.
** Unweighted average from three sets of lunar orbiter results.

(5) The table on p. 175 gives the values for the gravity field of the Moon from two lunar orbital fields, a value of C_{20} from orbiters, the field derived from lunar laser measurements of librations and the recommended values [51]. All the values in the table are not independent, because there are constraints among the different parameters [52].

Conclusion

It is recognized that some necessary constants have not been specified. Particular mention should be made of some of these constants.

(a) The value of the correction to the equator and equinox of the FK4 has not been specified because there is conflicting data at the present time.

(b) The secular acceleration of the Moon, i.e. the contribution to the mean longitude of the Moon due to tidal friction, is currently the subject of a number of investigations and it is anticipated that there will be a consensus of opinion concerning a value in the near future.

(c) The rotational elements of the planets, i.e. the periods of rotation and location of the poles of rotation, have not been specified at the present time. Commissions 4 and 16 of the IAU intend to establish a working group to investigate the notation and values for these quantities. Therefore, it was considered inappropriate for this report to include values for these quantities.

It is also recognized that in the process of preparing new ephemerides based on this set of constants and fitting these ephemerides to the observations, it may be necessary to introduce corrections to some of the constants or to adopt values for other unspecified quantities. Such values and corrections will have to be presented for adoption at a future IAU meeting.

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