Fundamental Parameters and Current (2004) Best Estimates of the Parameters of Common Relevance to Astronomy, Geodesy, and Geodynamics

by

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At present, systems of fundamental constants are in a state of transition. Even though the uncertainties of many constants have substantially decreased, the numerical values themselves did not substantially change. On the other hand, relativistic reductions and corrections underwent a variety of revisions that, however, did not yet find final agreement within the scientific working groups of international committees in charge of evaluating relevant quantities and theories. Consequently, substantial changes and revisions still have to be expected in IAU, IERS, IUGG etc. within the next few years.

Therefore SC 3 (i.e. the old structure), after lengthy discussions and considerations, decided not to propose, at this time, any change of existing geodetic reference systems such as WGS 84 (in its recent form updated by NIMA, 1997) and GRS 80. This would only make sense in view of relatively small numerical changes which would not justify, at this moment, complete changes of systems and would rather produce more confusion within user communities – as soon as working groups within IAU, IERS etc. have made up their minds concerning the background of new systems and will be prepared to discuss new numerical values. This should be around the year 2004.

The present situation is also reflected by the fact that in view of substantial progress in evaluating temporal changes of fundamental „constants“ and related accuracies, we should better speak about „fundamental parameters“ instead of „fundamental constants“.

Interrelations between IERS, IAU, IAG etc. make it, however, more difficult to implement necessary changes in fundamental systems. This was particularly realized in discussing adoption of new fundamental constants. This fact may be explained by the discussion of small changes inherent in the adoption of particular tidal corrections which became relevant in view of higher accuracies of $\pm 10^{-8}$ or $\pm 10^{-9}$. It turns out to be almost impossible to explain to other scientific bodies the modern relevance of the dependence of the numerical value of the semi-major axis „a“ of the *Earth* on specific tidal corrections. Other temporal variations imply similar difficulties.

From the view point of users, i.e. in deriving fundamental parameters, it is, to some extent, confusing that a variety of global or/and regional systems exist; it would be best to use only one global terrestrial and one celestial system such as ITRF, referred to a specific epoch, and an associated celestial system, unless precise transition and transformation formulae are available such as those between ETRF, ITRF, EUREF, and perhaps WGS 84 (in updated form), IGS, GRS 80 etc. where IERS-systems, in general, could serve to maintain transformation accuracy and precision.

However, the consequent replacement of „a“ by a quantity such as the geopotential at the geoid W_0 (which is independent of tides) in a geodetic reference system (or a similar system) was not well understood and not supported by other working groups so that we finally gave up the idea of a reformation of systems of fundamental constants in this way even though quantities such as W_0 are now precisely determined by satellite altimetry etc. Whether seasonal variations (Bursa et al. 1998a) of W_0 are significant or not is still an open question, when expressed in $R_0 = GM/W_0$ they amount to a few centimeters in global radius.

SI units are used throughout (except for the TDB-value (value below (4))
(SI-value can be associated with TCB or TCG)

- velocity of light in vacuum

$$c = 299\,792\,458 \text{ m s}^{-1}. \qquad (1)$$

- Newtonian gravitational constant

$$G = (6\,672.59 \pm 0.30) \times 10^{-14} \text{ m}^3 \text{ s}^{-2} \text{ kg}^{-1}. \qquad (2)$$

- Geocentric gravitational constant (including the mass of the Earth's atmosphere); reconfirmed by J. Ries (1998, priv. comm.)

$$GM = (398\,600\,441.8 \pm 0.8) \times 10^6 \text{ m}^3 \text{ s}^{-2}. \qquad (3)$$

For the EGM 96 global gravity model $GM = 398\,600\,441.5 \times 10^6 \text{ m}^3 \text{ s}^{-2}$

was adopted. E. Pavlis (2002) found GM = 398 600 441.6 and 1.7, respectively. For details see (Groten, 2004).

In TT units (Terrestrial Time) the value is

$$GM = (398\,600\,441.5 \pm 0.8) \times 10^6 \text{ m}^3 \text{ s}^{-2}. \qquad (4)$$

Note that if expressed in old TDB units (solar system Barycentric Dynamical Time), the value is

$GM = 398\ 600\ 435.6 \times 10^6\ m^3\ s^{-2}$.

Based on well known transformation formulas we may relate GM in SI-units to TT/TCG/TCB; see IERS-Convention 1996 p. 85. The well known secular term was not originally included in the GM(E)-analysis, therefore it was related to TT, neither to SI nor (TCG, TCB); as still satellite analysis occurs without the secular term, GM(E) in TT is still of geodetic interest; GM(E) = GM of the Earth.

- Mean angular velocity of the Earth's rotation

$$\omega = 7\ 292\ 115 \times 10^{-11}\ rad\ s^{-1}. \qquad (5)$$

Table 1. Mean angular velocity of the Earth's rotation 1978-1999

Year	ω [10^{-11} rad s^{-1}]	Year	ω [10^{-11} rad s^{-1}]	Mean LOD [ms/day]
min: 1978	7 292 114.903	1995	7 292 114.952	-
max: 1999	292 115.063	1996	.992	-
		1997	.991	-
		1998	115.031	1.37
		1999	.063	0.99

- Long-term variation in ω

$$\frac{d\omega}{dt} = (-4.5 \pm 0.1) \times 10^{-22}\ rad\ s^{-2}. \qquad (6)$$

This observed average value is based on two actual components:

a) due to tidal dissipation

$$\left(\frac{d\omega}{dt}\right)_{tidal} = (-6.1 \pm 0.4) \times 10^{-22}\ rad\ s^{-2}. \qquad (7)$$

This value is commensurate with a tidal deceleration in the mean motion of the Moon n

$$\frac{dn}{dt} = (-25.88 \pm 0.5)\ arc\sec\ cy^{-2}. \qquad (8)$$

b) non-tidal in origin

$$\left(\frac{d\omega}{dt}\right)_{non-tidal} = (+1.6 \pm 0.4)\ \times\ 10^{-22}\ rad\ s^{-2}. \qquad (9)$$

- Second-degree zonal geopotential (Stokes) parameter (tide-free, fully normalized, Love number k_2 = 0.3 adopted), in agreement with EGM 96,

$$\bar{J}_2 = 4.84165371736 \times 10^{-4} \pm 3.56 \times 10^{-11} \qquad (10)$$

To be consistent with the I.A.G. General Assembly Resolution 16, 1983 (Hamburg), the indirect tidal effect on J_2 should be included: then in the zero-frequency tide system (JGM-3)

$$J_2 = (1082\ 635.9 \pm 0.1) \times 10^{-9}. \qquad (11)$$

Table 2. The Stokes second-degree zonal parameter; marked with a bar: fully normalized; k_2 = 0.3 adopted for the tide-free system

Geopotential model	Zero-frequency tide system $\bar{J}_2$ [10^{-6}]	J_2 [10^{-6}]	Tide-free $\bar{J}_2$ [10^{-6}]	J_2 [10^{-6}]
JGM-3	484.16951	1082.6359	484.16537	1082.6267
EGM 96			484.16537	

- Long-term variation in J_2

$$\frac{dJ_2}{dt} = -(2.6 \pm 0.3) \times 10^{-9}\ cy^{-1} \qquad (12)$$

- second-degree sectorial geopotential (Stokes) parameters (conventional, not normalized, geopotential model JGM-3)

$$J_2^2 = (1574.5 \pm 0.7) \times 10^{-9}, \qquad (13)$$

$$S_2^2 = -(903.9 \pm 0.7) \times 10^{-9}, \qquad (14)$$

$$J_{2,2} = \left[\ (J_2^2)^2 + (S_2^2)^2\ \right]^{1/2} = (1815.5 \pm 0.9) \times 10^{-9}. \qquad (15)$$

Table 3. The Stokes second-degree sectorial parameters; marked with a bar: fully normalized

Geopotential model	$\bar{C}_2^2$ [10^{-6}]	$\bar{S}_2^2$ [10^{-6}]
JGM-3	2.43926	-1.40027
EGM 96	2.43914	-1.40017

Only the last decimal is affected by the standard deviation.

For EGM 96 Marchenko and Abrikosov (1999) found more detailed values:

Table 3a. Parameters of the linear model of the potential of 2nd degree

Harmonic coefficient	Value of coefficient $\times 10^6$	Temporal variation $\times 10^{11}$[yr^{-1}]
$\bar{C}_{20} = -\bar{J}_2$	-484.165371736	1.16275534
$\bar{C}_{21}$	-0.00018698764	-0.32
$\bar{S}_{21}$	0.00119528012	1.62
$\bar{C}_{22} = -\bar{J}_2^2$	2.43914352398	-0.494731439
$\bar{S}_{22}$	1.40016683654	-0.203385232

- Coefficient H associated with the precession constant as derived in (Mathews et al., 2000)

$$H = \frac{C - \frac{1}{2}(A+B)}{C} = 3.2737875 \times 10^{-3}. \qquad (16)$$

(with an uncertainty better than 0.2 ppm); with Fricke's corrected precession constant we had

$$H = (3\ 273763 \pm 20) \times 10^{-9}. \qquad (16a)$$

For a more detailed discussion of non-linear changes in $\bar{J}_2$ see (Groten 2004). Associated changes of the semi-major axis of the earth ellipsoid and its current best estimate are given in the same paper.

The value of H as derived by Mathews et al. (ibid.) contains the full permanent tide (direct and indirect effects) (Mathews, priv. Comm., 2000) in principle, this fact depends on the VLBI-data, on which the semi-empirical solution is based; if the permanent tide is not fully included there, a different tidal reference is being used. Fukushima (2003) just reported his best estimate as H = (3.2737804±0.0000003)×10^{-3}.

- The geoidal potential W_0 and the geopotential scale factor $R_0 = GM/W_0$ derived by Bursa et al. (1998) read

$$W_0 = (62\ 636\ 855.611 \pm 0.5)\ m^2s^{-2}, \qquad (17)$$

$$R_0 = (6\ 363\ 672.58 \pm 0.05)\ m.$$

$W_0 = (62636856.4 \pm 0.5)\ m^2s^{-2}$ J. Ries (priv. comm, 1998) found globally.

If W_0 is preserved as a primary constant the discussion of the ellipsoidal parameters could become obsolete; as the Earth ellipsoid is basically an artifact. Modelling of the altimeter bias and various other error influences affect the validity of W_0-determination. The variability of W_0 and R_0 was studied by Bursa (Bursa et al. 1998) recently; they detected interannual variations of W_0 and R_0 amounting to 2 cm.

The relativistic corrections to W_0 were discussed by Kopejkin (1991); see his formulas (67) and (77) where tidal corrections were included. Whereas he proposes average time values, Grafarend insists in corrections related to specific epochs in order to illustrate the time-dependence of such parameters as W_0, GM, J_n, which are usually, in view of present accuracies, still treated as constants in contemporary literature.

Based on recent GPS data, E. Grafarend and A. Ardalan (1997) found locally (in the Finnish Datum for Fennoscandia): $W_0 = (6\ 263\ 685.58 \pm 0.36)$ kgal m.

The temporal variations were discussed by Wang and Kakkuri (1998), in general terms.

- Mean equatorial gravity in the zero-frequency tide system

$$g_e = (978\ 032.78 \pm 0.2) \times 10^{-5} m\ s^{-2}. \qquad (18)$$

- Equatorial radius of the Reference Ellipsoid (mean equatorial radius of the Earth) in the zero-frequency tide system (Bursa et al. 1998)

$$a = (6\ 378\ 136.62 \pm 0.10)\ m. \qquad (19)$$

- The corresponding value in the mean tide system (the zero-frequency direct and indirect tidal distortion included) comes out as

$$a = (6\ 378\ 136.72 \pm 0.10)\ m \qquad (20)$$

and the tide-free value

$$a = (6\ 378\ 136.59 \pm 0.10)\ m. \qquad (21)$$

The tide free-value adopted for the new EGM-96 gravity model reads a = 6 378 136.3 m.

- Polar flattening computed in the zero-frequency tide system, (adopted GM, ω, and J_2 in the zero-frequency tide system)

$$1/f = 298.25642 \pm 0.00001 \tag{22}$$

The corresponding value in the mean tide system comes out as

$$1/f = 298.25231 \pm 0.00001 \tag{23}$$

and the tide-free

$$1/f = 298.25765 \pm 0.00001 \tag{24}$$

- Equatorial flattening (geopotential model JGM-3).

$$1/\alpha_1 = 91\ 026 \pm 10. \tag{25}$$

- Longitude of major axis of equatorial ellipse, geopotential model JGM-3

$$\Lambda_a = (14.9291° \pm 0.0010°)\ \mathrm{W}. \tag{26}$$

In view of the small changes (see Table 3) of the second degree tesserals it is close to the value of EGM 96. We may raise the question whether we should keep the reference ellipsoid in terms of GRS 80 (or an alternative) fixed and focus on W_0 as a parameter to be essentially better determined by satellite altimetry, where however the underlying concept (inverted barometer, altimeter bias etc.) has to be clarified.

Table 4. Equatorial flattening α_1 and Λ_a of major axis of equatorial ellipse

Geopotential model	$\frac{1}{\alpha_1}$	Λ_a [deg]
JGM-3	91026	14.9291 W

- Coefficient in potential of centrifugal force

$$q = \frac{\omega^2 a^3}{GM} = (3\ 461\ 391 \pm 2) \times 10^{-9}. \tag{27}$$

Computed by using values (3), (5) and a = 6 378 136.6

- Principal moments of inertia (zero-frequency tide system), computed using values (11), (15), (3), (2) and (16)

$$\frac{C-A}{Ma_0^2} = J_2 + 2J_{2,2} = (1086.267 \pm 0.001) \times 10^{-6}, \tag{28}$$

$$\frac{C-B}{Ma_0^2} = J_2 - 2J_{2,2} = (1079.005 \pm 0.001) \times 10^{-6},$$
$$\frac{B-A}{Ma_0^2} = 4J_{2,2} = (7.262 \pm 0.004) \times 10^{-6};$$
$$Ma_0^2 = \frac{GM}{G} a_0^2 = (2.43014 \pm 0.00005) \times 10^{38}\ kg\ m^2, \tag{29}$$

(a_0 = 6 378 137 m);

$$C-A = (2.6398 \pm 0.0001) \times 10^{35}\ \mathrm{kg\ m^2},$$
$$C-B = (2.6221 \pm 0.0001) \times 10^{35}\ \mathrm{kg\ m^2}, \tag{30}$$
$$B-A = (1.765 \pm 0.001) \times 10^{33}\ \mathrm{kg\ m^2};$$

$$\frac{C}{Ma_0^2} = \frac{J_2}{H} = (330\ 701 \pm 2) \times 10^{-6}, \tag{31}$$

$$\frac{A}{Ma_0^2} = (329\ 615 \pm 2) \times 10^{-6},$$
$$\frac{B}{Ma_0^2} = (329\ 622 \pm 2) \times 10^{-6}; \tag{32}$$

$$A = (8.0101 \pm 0.0002) \times 10^{37}\ \mathrm{kg\ m^2},$$
$$B = (8.0103 \pm 0.0002) \times 10^{37}\ \mathrm{kg\ m^2}, \tag{33}$$
$$C = (8.0365 \pm 0.0002) \times 10^{37}\ \mathrm{kg\ m^2},$$

$$\alpha = \frac{C-B}{A} = (327\ 353 \pm 6) \times 10^{-8},$$
$$\gamma = \frac{B-A}{C} = (2\ 196 \pm 6) \times 10^{-8},$$
$$\beta = \frac{C-A}{B} = (329\ 549 \pm 6) \times 10^{-8}.$$

II Primary geodetic Parameters, discussion

It should be noted that parameters a, f, J_2, g_e, depend on the tidal system adopted. They have different values in tide-free, mean or zero-frequency tidal systems. However, W_0

and/or R_0 are independent of tidal system (Bursa 1995). The following relations can be used:

$$a\ (\text{mean}) = a\ (\text{tide-free}) + \frac{1}{2}(1+k_s)R_0\frac{\delta J_2}{k_s}, \quad (34)$$

$$\alpha\ (\text{mean}) = \alpha\ (\text{tide-free}) + \frac{3}{2}(1+k_s)\frac{\delta J_2}{k_s};$$

$$a\ (\text{zero-frequency}) = a\ (\text{tide-free}) + \frac{1}{2}R_0\delta J_2; \quad (35)$$

$$\alpha\ (\text{zero-frequency}) = \alpha\ (\text{tide-free}) + \frac{3}{2}\delta J_2;$$

k_s = 0.9383 is the secular Love number, δJ_2 is the zero-frequency tidal distortion in J_2. First, the *internal consistency* of parameters a, W_0, (R_0) and g_e should be examined:

(i) If

a = 6 378 136.7 m

is adopted as primary, the derived values are

W_0 = 62 636 856.88 $m^2\ s^{-2}$, (36)

(R_0 = 6 363 672.46 m), (37)

g_e = 978 032.714 × 10^{-5} m s^{-2}. (38)

(ii) If

W_0 = (62 636 855.8 ± 0.5) $m^2\ s^{-2}$,

R_0 = (6 363 672.6 ± 0.05) m,

is adopted as primary, the derived values are (mean system)

a = 6 378 136.62 m, (39)

g_e = 978 032.705 ×10^{-5} m s^{-2}. (40)

(iii) If (18)

g_e = (978 032.78 ± 0.2) ×10^{-5} m s^{-2},

is adopted as primary, the derived values are

a = 6 378 136.38 m, (41)

W_0 = 62 636 858.8 $m^2\ s^{-2}$ (42)

(R_0 = 6 363 672.26 m). (43)

There are no significant discrepancies, the differences are about the standard errors.

However, the inaccuracy in (iii) is much higher than in (i) and/or (ii). That is why solution (iii) is irrelevant at present.

If the rounded value

W_0 = (62 636 856.0 ± 0.5) $m^2\ s^{-2}$ (44)
R_0 = (6 363 672.6 ± 0.1) [m] (45)

is adopted as primary, then the derived length of the semimajor axis in the mean tide system comes out as

a = (6 378 136.7 ± 0.1) m, (46)
(for zero-tide: 6 378 136.6)

which is just the rounded value (20), and (in the zero frequency tide system)

g_e = (978 032.7 ± 0.1) ×10^{-5} m s^{-2}. (47)

However, SC 3 recommends that, at present, GRS 1980 should be retained as the standard.

III Consistent set of fundamental constants (1997)

It is important to realize the consistency problem: In "current best estimates" the best available numerical values are given. In sets of fundamental constants such as the Geodetic Reference System 1980 (GRS 80) consistent sets are demanded. When fundamental parameters are derived (incl. time variations) from one data set, as is often the case with satellite derived data, then this principle is often violated ; see, e.g., the dependence of GM and a. Similarly, when data derived from systems with different "defining constants", as is often the case for time systems, similar inconsistency problems arise. The typical case of an inconsistent system is the WGS 84 global systems which, contrary to GRS 80, is inconsistent but being widely used.

- Geocentric gravitational constant (including the mass of the Earth's atmosphere)

GM = (398 600 441.8 ± 0.8) ×10^6 $m^3\ s^{-2}$,
[value (3)]

- Mean angular velocity of the Earth's rotation

ω = 7 292 115 × 10^{-11} rad s^{-1}
[value (5)]

- Second-degree zonal geopotential (Stokes) parameter (in the zero-frequency tide system, Epoch 1994)

J_2 = (1 082 635.9 ±0.1) × 10^{-9}
[value (11)]

- Geoidal potential

W_0 = (62 636 856.0 ± 0.5) m^2 s^{-2},
[value (44)]

- Geopotential scale factor

R_0 = GM/W_0 = (6 363 672.6 ± 0.05) m
[value (45)]

- Mean equatorial radius (mean tide system)

a = (6 378 136.7 ± 0.1) m
[value (46)]

- Mean polar flattening (mean tide system)

1/f = 298.25231 ± 0.00001
[value (23)]

- Mean equatorial gravity

g_e = (978 032.78 ± 0.1) ×10^{-5} m s^{-2},
[value (18)].

Grafarend and Ardalan (1999, 2001) have evaluated a (consistent) normal field based on a unique set of current best values of four parameters (W°, ω, J_2 and GM) as a preliminary "follow-up" to the Geodetic Reference System GRS 80. It can lead to a level-ellipsoidal normal gravity field with a spheroidal external field in the Somigliana-Pizetti sense. By comparing the consequent values for the semimajor and semi-minor axes of the related equipotential ellipsoid with the corresponding GRS-80 axes (based on the same theory) the authors end up with axes which deviate by –40 and –45 cm, respectively from GRS 80 axes and within standard deviations from the current values such as in (21); but no g-values are given until now.

IV Appendix

A1. Zero-frequency tidal distortion in J_2

(J_2 = -C_{20})

$$\delta J_2 = k_s \frac{GM_L}{GM}\left(\frac{\overline{R}}{\Delta_{\oplus L}}\right)^3\left(\frac{\overline{R}}{a_0}\right)^2 (E_2+\delta_{2L}) + $$
$$+ k_s \frac{GM_S}{GM}\left(\frac{\overline{R}}{\Delta_{\oplus S}}\right)^3\left(\frac{\overline{R}}{a_0}\right)^2 (E_2+\delta_{2S}),$$

$$E_2 = -\frac{1}{2}+\frac{3}{4}\sin^2\varepsilon_0,$$

$$\delta_{2L} = \frac{3}{4}\left(\sin^2 i_L - e_L^2\right)+\frac{9}{8}e_L^2\left(\sin^2\varepsilon_0-\sin^2 i_L\right),$$

$$\delta_{2S} = -\frac{3}{4}\ e_S^2\ \left(1-\frac{3}{2}\sin^2\varepsilon_0\right),$$

$$\overline{R} = R_0\left(1+\frac{25}{21}\ \nu^3 q-\frac{10}{7}\ \nu^2 J_2\right)^{1/5}$$

GM_L = 4 902.799 × 10^9 m^3s^{-2} (selenocentric grav. Const.),
GM_S = 13 271 244.0 × 10^{13} m^3s^{-2},
$\Delta_{\oplus L}$ = 384 400 km (mean geocentric distance to the Moon),
$\Delta_{\oplus S}$ = 1 AU = 1.4959787 × 10^{11} m,
a_0 = 6 378 137 m (scaling parameter associated with J_2),
ε_0 = 23°26'21.4" (obliquity of the ecliptic),
e_L = 0.05490 (eccentricity of the orbit of the Moon),
i_L = 5°0.9' (inclination of Moon's orbit to the ecliptic),
e_S = 0.01671 (eccentricity of the heliocentric orbit of the Earth-Moon barycenter),
ν = a_0/R_0 = 1.0022729;
k_s = 0.9383 (secular-fluid Love number associated with the zero-frequency second zonal tidal term);
δJ_2 = $-\delta C_{20}$ = (3.07531 × 10^{-8}) k_s (conventional);
$\delta\overline{J}_2 = -\delta\overline{C}_{20}(1.37532\times10^{-8})\,k_s$ (fully normalized).
L = Lunar
S = Solar

A2. Definition

Because of tidal effects on various quantities, the tide-free, zero-frequency and mean values should be distinguished as follows:

- A tide-free value is the quantity from which all tidal effects have been removed.
- A zero-frequency value includes the indirect tidal distortion, but not the direct distortion.
- A mean tide value includes both direct and indirect permanent tidal distortions.

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