GEODETIC REFERENCE SYSTEM 1980

by H. Moritz

Corrigendum:

Due to some unfortunate error this article appeared wrongly in The Geodesists Handbook 1992 (Bulletin Geodesique, 66, 2, 1992). Among several errors a θ (polar distance) was interchanged with a Φ (geographical latitude) affecting the formulas for normal gravity. It is advised that you use the formulas here or in the Geodesists handbook from Bulletin Geodesique, Vol. 62, no. 3, 1988.

1- Definition

The **Geodetic Reference System 1980** has been adopted at the XVII General Assembly of the IUGG in Canberra, December 1979, by means of the following:

"RESOLUTION N° 7

The International Union of Geodesy and Geophysics

recognizing that the Geodetic Reference System 1967 adopted at the XIV General Assembly of IUGG, Lucerne, 1967, no longer represents the size, shape, and gravity field of the Earth to an accuracy adequate for many geodetic, geophysical, astronomical and hydrographic applications and

considering that more appropriate values are now available,

recommends

a) that the Geodetic Reference System 1967 be replaced by a new **Geodetic Reference System 1980**, also based on the theory of the geocentric equipotential ellipsoid, defined by the following conventional constants:

- equatorial radius of the Earth:

  $a = 6378\ 137$ m,

- geocentric gravitational constant of the Earth (including the atmosphere):

  $GM = 3986\ 005 \times 10^8\ \mathrm{m}^3\ \mathrm{s}^{-2}$,

- dynamical form factor of the Earth, excluding the permanent tidal deformation:

  $J_2 = 108\ 263 \times 10^{-8}$,

- angular velocity of the Earth:

  $\omega = 7292\ 115 \times 10^{-11}\ \mathrm{rad\ s}^{-1}$,

b) that the same computational formulas, adopted at the XV General Assembly of IUGG in Moscow 1971 and published by IAG, be used as for Geodetic Reference System 1967, and

c) that the minor axis of the reference ellipsoid, defined above, be parallel to the direction defined by the Conventional International Origin, and that the primary meridian be parallel to the zero meridian of the BIH adopted longitudes".

For the background of this resolution see the report of IAG Special Study Group 5.39 (**Moritz**, 1979, sec.2).c

Also relevant is the following IAG resolution:

"RESOLUTION N° 1

The International Association of Geodesy

recognizing that the IUGG, at its XVII General Assembly, has introduced a new Geodetic Reference System 1980,

recommends that this system be used as an official reference for geodetic work, and

encourages computations of the gravity field both on the Earth's surface and in outer space based on this system".

2- The Equipotential Ellipsoid

According to the first resolution, the Geodetic Reference System 1980 is based on the theory of the equipotential ellipsoid. This theory has already been the basis of the Geodetic Reference System 1967; we shall summarize (partly quoting literally) some principal facts from the relevant publication (IAG, 1971, Publ. Spéc. n° 3).

An equipotential ellipsoid or level ellipsoid is an ellipsoid that is defined to be an equipotential surface. If an ellipsoid of revolution (semimajor axis **a**, semiminor axis **b**) is given, then it can be made an equipotential surface

$$U = U_0 = \text{const.}$$

of a certain potential function U, called normal potential. This function U is uniquely determined by means of the ellipsoidal surface (semiaxes a, b), the enclosed mass M and the angular velocity ω, according to a theorem of Stokes-Poincaré, quite independently of the internal density distribution. Instead of the four constants a, b, M and ω, any other system of four independent parameters may be used as defining constants.

The theory of the equipotential ellipsoid was first given by **Pizzeti** in 1894; it was further elaborated by **Somigliana** in 1929. This theory had already served as a base for the International Gravity Formula adopted at the General Assembly in Stockholm in 1930.

Normal gravity $\gamma = |\text{grad U}|$ at the surface of the ellipsoid is given by the closed formula of **Somilgiana**,

$$\gamma = \frac{a\gamma_e \cos^2\Phi + b\gamma_p \sin^2\Phi}{\sqrt{a^2\cos^2\Phi + b^2\sin^2\Phi}},$$

where the constants γ_e and γ_p denote normal gravity at the equator and at the poles, and Φ denotes geographical latitude.

The equipotential ellipsoid furnishes a simple, consistent and uniform reference system for all purposes of geodesy: the ellipsoid as a reference surface for geometric use, and a normal gravity field at the earth's surface and in space, defined in terms of closed formulas, as a reference for gravimetry and satellite geodesy.

The standard theory of the equipotential ellipsoid regards the normal gravitational potential as a harmonic function outside the ellipsoid, which implies the absence of an atmosphere. (The consideration of the atmosphere in the reference system would require an ad-hoc modification of the theory, whereby it would lose its clarity and simplicity.)

Thus, in the same way as in the Geodetic Reference System 1967, the computation are based on the theory of the equipotential ellipsoid without an atmosphere. The reference ellipsoid is defined to enclose the whole mass of the earth, including the atmosphere; as a visualization, one might, for instance, imagine the atmosphere to be condensed as a surface layer on the ellipsoid. The normal gravity field at the earth's surface and in space can thus be computed without any need for considering the variation of atmospheric density.

If atmospheric effects must be considered, this can be done by applying corrections to the measured values of gravity; for this purpose, a table of corrections will be given later (sec.5).

3- Computational Formulas

An equipotential ellipsoid of revolution is determined by four constants. The IUGG has chosen the following ones:

a	equatorial radius,
GM	geocentric gravitational constant,
$\mathbf{J_2}$	dynamical form factor,
ω	angular velocity.

The equatorial radius **a** is the semimajor axis of the meridian ellipse; the semiminor axis will be denoted by **b**. The geocentric gravitational constant **GM** is the product of the Newtonian gravitational constant, **G**, and the total mass of the earth, **M**. The constant J_2 is given by:

$$J_2 = \frac{C - A}{Ma^2},$$

where **C** and **A** are the principal moments of inertia of the level ellipsoid (**C**... polar, **A**... equatorial moment of inertia).

We shall also use the first excentricity **e**, defined by:

$$e^2 = \frac{a^2 - b^2}{a^2},$$

and the second excentricity **e′**, defined by:

$$e'^2 = \frac{a^2 - b^2}{b^2}$$

Closed computational formulas are given in sec.3 of (IAG, 1971, Pub.Spéc. n° 3); we shall here reproduce this section practically unchanged.

The derivation of these formulas is found in the book (**Heiskanen** and **Moritz**, 1967) sections 2–7 to 2–10. Reference to this book is by page number and number of equation.

Computation of e^2

The fundamental derived constant is the square of the first excentricity, $\mathbf{e^2}$, as defined above.

From p. 73, equations (2-90) and (2-92′), we find:

$$J_2 = \frac{e^2}{3}\left(1 - \frac{2}{15}\frac{me'}{q_o}\right)$$

This equation can be written as:

$$e^2 = 3J_2 + \frac{2me'e^2}{15q_0}$$

with:

$$m = \frac{\omega^2 a^2 b}{GM}$$

(p. 69, eq. (2-70)) and with $be' = ae$ it becomes:

$$e^2 = 3J_2 + \frac{4}{15}\frac{\omega^2 a^3}{GM}\frac{a^3}{2q_0}$$

This is the basic equation which relates e^2 to the data a, GM, J_2 and ω. It is to be solved iteratively for e^2, taking into account:

$$\begin{aligned} 2q_0 &= \left(1 + \frac{3}{e'^2}\right)\arctan e' - \frac{3}{e'} \\ &= \sum_{n=1}^{\infty} \frac{4(-1)^{n+1} n}{(2n+1)(2n+3)} e'^{2n+1} \end{aligned}$$

with

$$e' = \frac{e}{\sqrt{1 - e^2}} \quad \text{(second excentricity)}$$

(p. 66, eq. (2-58), p. 72, second equation from top).

Geometric Constants

Now the other geometric constants of the reference ellipsoid can be computed by the well-known formulas:

$$\begin{aligned} b &= a\sqrt{1 - e^2} && \text{(semiminor axis)}, \\ f &= \frac{a - b}{a} && \text{(flattening)}, \\ E &= \sqrt{a^2 - b^2} && \text{(linear excentricity)}, \\ c &= \frac{a^2}{b} && \text{(polar radius of curvature)}. \end{aligned}$$

The arc of meridian from equator to pole (meridian quadrant) is given by:

$$Q = c \int_0^{\pi/2} \frac{d\Phi}{(1 + e'^2 \cos^2 \Phi)^{3/2}}$$

where Φ is the geographical latitude. This integral can be evaluated by a series expansion:

$$Q = c\frac{\pi}{2}\left(1 - \frac{3}{4}e'^2 + \frac{45}{64}e'^4 - \frac{175}{256}e'^6 + \frac{11025}{16384}e'^8\right)$$

Various mean radii of ellipsoid are defined by the following formulas:

arithmetic mean:

$$R_1 = \frac{a + a + b}{3} = a\left(1 - \frac{f}{3}\right)$$

radius of sphere of the same surface:

$$\begin{aligned} R_2 &= c\left(\int_0^{\pi/2} \frac{\cos\Phi}{(1 + e'^2 \cos^2 \Phi)^2} d\Phi\right)^{1/2} \\ &= c\left(1 - \frac{2}{3}e'^2 + \frac{26}{45}e'^4 - \frac{100}{189}e'^6 + \frac{7034}{14175}e'^8\right) \end{aligned}$$

radius of sphere of the same volume:

$$R_3 = \sqrt[3]{a^2 b}.$$

Physical Constants

The reference ellipsoid is a surface of constant normal potential, $\mathbf{U} = \mathbf{U_0}$. This constant U_0, the normal potential of the reference ellipsoid, is given by:

$$\begin{aligned} U_0 &= \frac{GM}{E} \arctan e' + \frac{1}{3}\omega^2 a^2 \\ &= \frac{GM}{b}\left(1 + \sum_{n=1}^{\infty} (-1)^n \frac{e'^{2n}}{2n+1} + \frac{1}{3}m\right) \end{aligned}$$

(p. 67, eq. (2-61)).

The normal gravitational potential **V** (gravity potential **U** minus potential of centrifugal force) can be developed into a series of zonal spherical harmonics:

$$V = \frac{GM}{r}\left(1 - \sum_{n=1}^{\infty} J_{2n}\left(\frac{a}{r}\right)^{2n} P_{2n}(\cos\theta)\right);$$

where **r** (radius vector) and θ (polar distance) are spherical coordinates. The coefficient $\mathbf{J_2}$ is a defining constant; the other coefficients are expressed in terms of $\mathbf{J_2}$ by:

$$J_{2n} = (-1)^{n+1} \frac{3e^{2n}}{(2n+1)(2n+3)}\left(1 - n + 5n\frac{J_2}{e^2}\right)$$

(p.73, eqs. (2-92) and (2-92′)).

Normal gravity at the equator, γ_e, and normal gravity at the poles, γ_p, are given by the expressions:

$$\begin{aligned} \gamma_e &= \frac{GM}{ab}\left(1 - m - \frac{m}{6}\frac{e' q_0'}{q_0}\right) \\ \gamma_p &= \frac{GM}{a^2}\left(1 + \frac{m}{3}\frac{e' q_0'}{q_0}\right) \end{aligned}$$

with

$$q_0' = 3\left(1 + \frac{1}{e'^2}\right)\left(1 - \frac{1}{e'} \arctan e'\right) - 1$$

and

$$m = \frac{\omega^2 a^2 b}{GM}$$

(p. 69, eqs. (2-73) and (2-74); p.68, eq. (2-67)).

The constant:

$$f^{*} = \frac{\gamma_p - \gamma_e}{\gamma_e} \quad \text{(gravity flattening)}$$

is also needed.

A check is provided by the closed form of **Clairaut's** theorem for the equipotential ellipsoid:

$$f + f^{*} = \frac{\omega^2 b}{\gamma_e}\left(1 + \frac{e' q_0'}{2 q_0}\right)$$

(p. 69, eq. (2-75)).

The Gravity Formula

Somiglinana's closed formula for normal gravity is

$$\gamma = \frac{a\gamma_e \cos^2\Phi + b\gamma_p \sin^2\Phi}{\sqrt{a^2\cos^2\Phi + b^2\sin^2\Phi}}$$

For numerical computations, the form

$$\gamma = \gamma_e \frac{1 + k\sin^2\Phi}{\sqrt{1 - e^2\sin^2\Phi}}$$

with

$$k = \frac{b\gamma_p}{a\gamma_e} - 1$$

is more convenient.

The conventional abbreviated series expansion is:

$$\gamma = \gamma_e\left(1 + f^{*}\sin^2\Phi - \frac{1}{4}f_4\sin^2 2\Phi\right)$$

with

$$f_4 = \frac{1}{2}f^2 + \frac{5}{2}fm$$

(p.77, eqs. (2-115) and (2-116)).

More generally, the above closed formula for normal gravity may be expanded into the series

$$\gamma = \gamma_e\left(1 + \sum_{n=1}^{\infty} a_{2n}\sin^{2n}\Phi\right)$$

where

$$a_2 = \frac{1}{2}e^2 + k, \qquad a_6 = \frac{5}{16}e^6 + \frac{3}{8}e^4 k,$$

$$a_4 = \frac{3}{8}e^4 + \frac{1}{2}e^2 k, \qquad a_8 = \frac{35}{128}e^8 + \frac{5}{16}e^6 k,$$

The average value of gravity over the ellipsoid is

$$\bar{\gamma} = \int_0^{\pi/2} \frac{\gamma\cos\Phi d\Phi}{(1 - e^2\sin^2\Phi)^2} : \int_0^{\pi/2} \frac{\cos\Phi d\Phi}{(1 - e^2\sin^2\Phi)^2}$$

$$= 1 + \frac{1}{6}e^2 + \frac{1}{3}k + \frac{59}{360}e^4 + \frac{5}{18}e^2 k$$

$$+ \frac{2371}{15120}e^6 + \frac{259}{1080}e^4 k + \frac{270229}{1814400}e^8 + \frac{9623}{45360}e^6 k.$$

4- Numerical Values

The following derived constants are accurate to the number of decimal places given. In case of doubt or in those cases where a higher accuracy is required, these quantities are to be computed from the defining constants by means of the closed formulas given in the preceding section.

Defining Constants (exact)

a	= 6378 137 m	semimajor axis
GM	= $3\ 986\ 005 \times 10^8\ m^3\ s^{-2}$	geocentric gravitational constant
J_2	= $108\ 263 \times 10^{-8}$	dynamic form factor
ω	= $7\ 292\ 115 \times 10^{-11}$ rad s^{-1}	angular velocity

Derived Geometric Constants

b	= 6 356 752.3141 m	semiminor axis
E	= 521 854.0097 m	linear excentricity
c	= 6 399 593.6259 m	polar radius of curvature
e^2	= 0.006 694 380 022 90	first excentricity (e)
e'^2	= 0.006 739 496 775 48	secondexcentricity (e′)
f	= 0.003 352 810 681 18	flattening
f^{-1}	= 298.257 222 101	reciprocal flattening
Q	= 10 001 965.7293 m	meridian quadrant
R_1	= 6 371 008.7714 m	mean radius
R_1	= $(2a + b)/3$	
R_2	= 6 371 007.1810 m	radius of sphere of same surface
R_3	= 6 371 000.7900 m	radius of sphere of same volume

Derived Physical Constants

U_0	= $6\ 263\ 686.0850 \times 10\ m^2\ s^{-2}$	normal potential at ellipsoid
J_4	= −0.000 002 370 912 22	
J_6	= 0.000 000 006 083 47	spherical-harmonic
J_8	= −0.000 000 000 014 27	coefficients
m	= 0.003 449 786 003 08	$m = \gamma^2 a^2 b/GM$
γ_e	= 9.780 326 7715 ms^{-2}	normal gravity at equator
γ_p	= 9.832 186 3685 ms^{-2}	normal gravity at pole
f^{*}	= 0.005 302 440 112	$f^{*} = \frac{(g_p - g_e)}{g_e}$
k	= 0.001 931 851 353	$f k^{*} = \frac{(b g_p - a g_e)}{a g_e}$

Gravity Formula 1980

Normal gravity may be computed by means of the closed formula:

$$\gamma = \gamma_e \frac{1 + k \sin^2 \Phi}{\sqrt{1 - e^2 \sin^2 \Phi}},$$

with the values of γ_e, **k**, and $\mathbf{e^2}$ shown above.

The series expansion, given at the end of sec. 3, becomes:

$$\begin{aligned}\gamma = \gamma_e(1 &+ 0.005\ 279\ 0414 \sin^2 \Phi \\ &+ 0.000\ 023\ 2718 \sin^4 \Phi \\ &+ 0.000\ 000\ 1262 \sin^6 \Phi \\ &+ 0.000\ 000\ 0007 \sin^8 \Phi);\end{aligned}$$

it has a relative error of 10^{-10}, corresponding to 10^{-3} μm s^{-2} = 10^{-4} mgal.

The conventional series

$$\begin{aligned}\gamma &= \gamma_e(1 + f^* \sin^2 \Phi - \frac{1}{4} f_4 \sin^2 2\Phi) \\ &= 9.780\ 327(1 + 0.005\ 3024\ \sin^2 \Phi \\ &\qquad - 0.000\ 0058\ \sin^2 2\Phi) \mathrm{m\, s}^{-2}\end{aligned}$$

has only an accuracy of **1 μm $\mathbf{s^{-2}}$ = 0.1 mgal**. It can, however, be used for converting gravity anomalies from the International Gravity Formula (1930) to the Gravity Formula 1980:

$$\gamma_{1980} - \gamma_{1930} = (-16.3 + 13.7\ \sin^2 \Phi)\mathrm{mgal},$$

where the main part comes from a change of the Postdam reference value by – 14 mgal; see also (IAG, 1971, Publ. Spéc. n° 3, p.74).

For the conversion from the Gravity Formula 1967 to the Gravity Formula 1980, a more accurate formula, corresponding to the precise expansion given above, is:

$$\begin{aligned}\gamma_{1980} - \gamma_{1967} = (0.8316 &+ 0.0782\ \sin^2 \Phi \\ &- 0.0007\ \sin^4 \Phi)\mathrm{mgal},\end{aligned}$$

Since former gravity values are expressed in the units "**gal**" and "**mgal**", we have, in the conversion formulas, used the unit **1 mgal = $\mathbf{10^{-5}}$ m $\mathbf{s^{-2}}$**.

Mean values of normal gravity are:

$\bar{\gamma} = 9.797\ 644\ 656$ m s^{-2} average over ellipsoid,

$\gamma_{45} = 9.806\ 199\ 203$ m s^{-2} γ

at latitude $\Phi = 45°$.

The numerical values given in this section have been computed independently by **Mr. Chung-Yung Chen**, using series developments up to f^5, and by **Dr. Hans-Sünkel**, using the formulas presented in sec. 3.

5- Atmospheric Effects

The table given here is reproduced from (IAG, 1971, Publ. Spéc. n° 3, p.72). It shows atmospheric gravity correction δ**g** as a function of elevation **h** above sea level. The values δ**g** are to be added to measured gravity. The effect of this reduction is to remove, by computation, the atmosphere outside the Earth by shifting it vertically into the interior of the geoid.

Atmospheric Gravity Corrections δg
(to be added to measured gravity)

h [km]	δg [mgal]	h [km]	δg [mgal]
0	0.87	10	0.23
0.5	0.82	11	0.20
1.0	0.77	12	0.17
1.5	0.73	13	0.14
2.0	0.68	14	0.12
2.5	0.64	15	0.10
3.0	0.60	16	0.09
3.5	0.57	17	0.08
4.0	0.53	18	0.06
4.5	0.50	19	0.05
5.0	0.47	20	0.05
5.5	0.44	22	0.03
6.0	0.41	24	0.02
6.5	0.38	26	0.02
7.0	0.36	28	0.01
7.5	0.33	30	0.01
8.0	0.31	32	0.01
8.5	0.29	34	0.00
9.0	0.27	37	0.00
9.5	0.25	40	0.00

6- Origin and Orientation of the Reference System

IUGG Resolution n° 7, quoted at the begining of this paper, specifies that the Geodetic Reference System 1980 be geocentric, that is, that its origin be the center of mass of the earth. Thus, the center of the ellipsoid coincides with the geocenter.

The orientation of the system is specified in the following way. The rotation axis of the reference ellipsoid is to have the direction of the Conventional International Origin for the Polar Motion (**CIO**), and the zero meridian as defined by the Bureau International de l'Heure (**BIH**) is used.

To this definition there corresponds a rectangular coordinate system **XYZ** whose origin is the geocenter, whose **Z**-axis is the rotation axis of the reference ellipsoid, defined by the direction of **CIO**, and whose **X**-axis passes through the zero meridian according to the **BIH**.

References

W.A. HEISKANEN, and H. MORITZ (1967): Physical Geodesy. W.H. Freeman, San Francisco.

International Association of Geodesy (1971): Geodetic Reference System 1967. Publi. Spéc. n° 3 du Bulletin Géodésique, Paris.

H. MORITZ (1979): Report of Special Study Group N° 539 of I.A.G., Fundamental Geodetic Constants, presented at XVII General Assembly og I.U.G.G., Canberra.

Editor's Note:

Additional useful constants can be obtained from:
"*United States Naval Observatory, Circular N°* 167, December 27, 1983, Project MERIT Standards", *with updates of December 1985.*

Parameters of Common Relevance of Astronomy, Geodesy, and Geodynamics

By E. Groten (President of IAG Sub-commission 3)

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 substantial 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, 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 2001.

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"; however, the majority of members of SC 3 preferred to preserve the traditional name of SC 3.

In view of this situation and of the fact that IERS in its "conventions" which are edited at regular intervals SC 3 cannot and should not act independently in proposing changes of fundamental parameters, – there will consequently be relatively small changes in the following part on "current best estimates" and only minimal changes in the part on "official numerical values" within this report. It is, moreover, proposed to strengthen the interrelations between IERS and SC 3.

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 SC 3, 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 very 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.

I Current (1999) best estimates of the parameters of common relevance to astronomy, geodesy, and geodynamics

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
  $$c = 299\ 792\ 458\,\mathrm{m\,s^{-1}} \qquad (1)$$
- Newtonian gravitational constant
  $$G = (6\ 672.59 \pm 0.30) \times 10^{-14}\,\mathrm{m^3\,s^{-2}\,kg^{-1}} \qquad (2)$$
- Geocentric gravitational constant (including the mass of the Earth's atmosphere); reconfirmed by J. Ries (1998, priv. comm.)
  $$GM = (398\ 600\ 441.8 \pm 0.8) \times 10^6\,\mathrm{m^3\,s^{-2}} \qquad (3)$$

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

  In TT units (Terrestrial Time) the value is

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

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

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

  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

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

Table 1. Mean angular velocity of the Earth's rotation 1978–1994

Year	ω [10^{-11} rad s^{-1}]	Year	ω [10^{-11} rad s^{-1}]	DLOD [ms]
Min: 1978	7 292 114.903	1994	7.292 114.964	2.17
Max: 1986	292 115.043	1995	.952	2.31
		1996	.992	1.83
		1997	.991	1.84
		1998	–	–

- Long-term variation in ω

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

This observed average value is based on two actual components:

a) due to tidal dissipation

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

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

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

b) non-tidal in origin

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

- Second-degree zonal geopotential (Stokes) parameter (tide-free, conventional, not normalized, Love number $k_2 = 0.3$ adopted)

$$J_2 = (1082\ 626.7 \pm 0.1) \times 10^{-9} \qquad (10)$$

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

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

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		Tide-free	
	$\bar{J}_2$ [10^{-6}]	J_2 [10^{-6}]	$\bar{J}_2$ [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

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

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

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

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

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

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 4. Parameters of the linear model of the potential of 2nd degree

Harmonic coefficient	Value of coefficient × 10^6	Temporal variation × 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

$$\mathrm{H} = \frac{C - \frac{1}{2}(A+B)}{C} = (3\ 273\ 763 \pm 20) \times 10^{-9}. \qquad (16)$$

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

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

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

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

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

The relativistic corrections to $\mathrm{W_0}$ 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 $\mathrm{W_0}$, GM, $\mathrm{J_n}$, 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): $\mathrm{W_0} = (6\ 263\ 685.58 \pm 0.36)$ kgal m. The temporal variations were discussed by Wang and Kakkuri (1998), in general terms.

- Mean equatorial gravity in the zero-frequency tide system

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

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

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

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

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

and the tide-free value

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

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 $\mathrm{J_2}$ in the zero-frequency tide system)

$$1/\mathrm{f} = 298.25642 \pm 0.00001 \qquad (22)$$

The corresponding value in the mean tide system comes out as

$$1/\mathrm{f} = 298.25231 \pm 0.00001 \qquad (23)$$

and the tide-free

$$1/\mathrm{f} = 298.25765 \pm 0.00001 \qquad (24)$$

- Equatorial flattening (geopotential model JGM-3).

$$1/\alpha_1 = 91026 \pm 10. \qquad (25)$$

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

$$\Lambda_\mathrm{a} = (14.9291^\circ \pm 0.0010^\circ)\mathrm{W}. \qquad (26)$$

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 $\mathrm{W_0}$ 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 5. 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

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

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)

$$\frac{C-A}{Ma_0^2} = J_2 + 2J_{2,2} = (1086\cdot 267 \pm 0.001)\times 10^{-6}, \quad (28)$$

$$\frac{C-B}{Ma_0^2} = J_2 - 2J_{2,2} = (1079.005 \pm 0.001)\times 10^{-6},$$

$$\frac{B-A}{Ma_0^2} = 4J_{2,2} = (7.262 \pm 0.004)\times 10^{-6};$$

$$Ma_0^2 = \frac{GM}{G}a_0^2 = (2.43014 \pm 0.00005)\times 10^{38}\ \mathrm{kg\,m^2}, \quad (29)$$

$(a_0 = 6\cdot 378\ 137\,\mathrm{m})$;

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

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

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

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

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

$$\boldsymbol{\alpha} = \frac{C-B}{A} = (327\ 353 \pm 6)\times 10^{-8},$$

$$\boldsymbol{\gamma} = \frac{B-A}{C} = (2\ 196 \pm 6)\times 10^{8}$$

$$\boldsymbol{\beta} = \frac{C-A}{B} = (329\ 549 \pm 6)\times 10^{-8}$$

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

$$a = 6\ 378\ 136.7\,\mathrm{m}$$

is adopted as primary, the derived values are

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

$$(R_0 = 6\ 363\ 672.46\,\mathrm{m}), \quad (37)$$

$$g_e = 978\ 032.714\times 10^{-5}\,\mathrm{m\,s^{-2}}. \quad (38)$$

(ii) If

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

$$R_0 = (6\ 363\ 672.6 \pm 0.05)\,\mathrm{m},$$

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

$$a = 6\ 378\ 136.62\,\mathrm{m}, \quad (39)$$

$$g_e = 978\ 032.705\times 10^{-5}\,\mathrm{m\,s^{-2}}. \quad (40)$$

(iii) If (18)

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

is adopted as primary, the derived values are

$$a = 6\ 378136.38\,\mathrm{m}, \quad (41)$$

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

$$(R_0 = 6\ 363\ 672.26\,\mathrm{m}). \quad (43)$$

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

$$W_0 = (62\ 636\ 856.0 \pm 0.5)\mathrm{m^2\,s^{-2}} \quad (44)$$

$$R_0 = (6\ 363\ 672.6 \pm 0.1)[\mathrm{m}] \quad (45)$$

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

$$a = (6\ 378\ 136.7 \pm 0.1)\mathrm{m}, (\text{for zero-tide}: 6\ 378\ 136.6) \quad (46)$$

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

$$g_e = (978\ 032.7 \pm 0.1)\times 10^{-5}\,\mathrm{m\,s^2}. \quad (47)$$

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

III Consistent set of fundamental constants (1997)

- Geocentric gravitational constant (including the mass of the Earth's atmosphere)
  $GM = (398\ 600\ 441.8 \pm 0.8) \times 10^6\ m^3\ s^{-2}$, [value (3)]

- Mean angular velocity of the Earth's rotation
  $\omega = 7\ 292\ 115 \times 10^{-11}\ rad\ s^{-1}$ [value (5)]

- Second-degree zonal geopotential (Stokes) parameter (in the zero-frequency tide system, Epoch 1994)
  $J_2 = (1\ 082\ 635.9 \pm 0.1) \times 10^{-9}$ [value (11)]

- Geoidal potential
  $W_0 = (62\ 636\ 856.0 \pm 0.5)\ m^2\ s^{-2}$, [value (44)]

- Geopotential scale factor
  $R_0 = GM/W_0 = (6\ 363\ 672.6 \pm 0.05)\ m$
  [value (45)]

- Mean equatorial radius (mean tide system)
  $a = (6\ 378\ 136.7 \pm 0.1)\ m$ [value (46)]

- Mean polar flattening (mean tide system)
  $1/f = 298.25231 \pm 0.00001$ [value (23)]

- Mean equatorial gravity
  $g_e = (978\ 032.78 \pm 0.1) \times 10^{-5}\ m\ s^{-2}$, [value (18)].

Grafarend and Ardalan (1999) 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

$(J_2 = -C_{20})$

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

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

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

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

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

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

$GM_L = 4\ 902.799 \times 10^9\ m^3s^{-2}$
(selenocentric grav. Const.),
$GM_S = 13\ 271\ 244.0 \times 10^{13}\ m^3s^{-2}$,
$\Delta_{\oplus L} = 384\ 400$ km
(mean geocentric distance to the Moon),
$\Delta_{\oplus S} = 1\ AU = 1.4959787 \times 10^{11}$ m,
$a_0 = 6\ 378\ 137$ m
(scaling parameter associated with J_2),
$\varepsilon_0 = 23°26'21.4''$ (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),
$v = a_0/R_0 = 1.0022729$;
$k_s = 0.9383$
(secular-fluid Love number associated with the zero-frequency second zonal tidal term);
$\delta J_2 = -\delta C_{20} = (3.07531 \times 10^{-8})\ k_s$ (conventional);
$\delta\overline{J}_2 = -\delta\overline{C}_{20}(1.37532 \times 10^{-8)}k_s$(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 included both direct and indirect permanent tidal distortions.

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