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SPECIAL REPORT

Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2009

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Abstract Every three years the IAU Working Group on Cartographic Coordinates and Rotational Elements revises tables giving the directions of the poles of rotation and the prime meridians of the planets, satellites, minor planets, and comets. This report takes into account the IAU Working Group for Planetary System Nomenclature (WGPSN) and the IAU Committee on Small Body Nomenclature (CSBN) definition of dwarf planets, introduces improved values for the pole and rotation rate of Mercury, returns the rotation rate of Jupiter

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to a previous value, introduces improved values for the rotation of five satellites of Saturn, and adds the equatorial radius of the Sun for comparison. It also adds or updates size and shape information for the Earth, Mars' satellites Deimos and Phobos, the four Galilean satellites of Jupiter, and 22 satellites of Saturn. Pole, rotation, and size information has been added for the asteroids (21) Lutetia, (511) Davida, and (2867) Šteins. Pole and rotation information has been added for (2) Pallas and (21) Lutetia. Pole and rotation and mean radius information has been added for (1) Ceres. Pole information has been updated for (4) Vesta. The high precision realization for the pole and rotation rate of the Moon is updated. Alternative orientation models for Mars, Jupiter, and Saturn are noted. The Working Group also reaffirms that once an observable feature at a defined longitude is chosen, a longitude definition origin should not change except under unusual circumstances. It is also noted that alternative coordinate systems may exist for various (e.g. dynamical) purposes, but *specific cartographic* coordinate system information continues to be recommended for each body. The Working Group elaborates on its purpose, and also announces its plans to occasionally provide limited updates to its recommendations via its website, in order to address community needs for some updates more often than every 3 years. Brief recommendations are also made to the general planetary community regarding the need for controlled products, and improved or consensus rotation models for Mars, Jupiter, and Saturn.

Keywords Cartographic coordinates · Longitude · Latitude · Rotation axes · Rotation periods · Sizes · Shapes · Planets · Satellites · Dwarf planets · Minor planets · Comets

1 Introduction

The IAU Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites was established as a consequence of resolutions adopted by Commissions 4 and 16 at the IAU General Assembly at Grenoble in 1976. The Working Group became a joint working group of the IAU and the International Association of Geodesy (IAG) in 1985. Due to a lack of formal communication with the IAG in recent years

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that affiliation has been dropped for this report. It may be re-established in the future. Currently, within the IAU, the Working Group is a joint working group of Divisions I and III, and not part of any commissions. The first report of the Working Group was presented to the General Assembly at Montreal in 1979 and published in the *Trans. IAU* **17B**, 72–79, 1980. The report with appendices was published in *Celestial Mechanics* **22**, 205–230, 1980. The guiding principles and conventions that were adopted by the Group and the rationale for their acceptance were presented in that report and its appendices. The second report of the Working Group was published in the *Trans. IAU* **18B**, 151–162, 1983, and also in *Celestial Mechanics* **29**, 309–321, 1983. In 2003 the name of the Working Group was shortened to the Working Group on Cartographic Coordinates and Rotational Elements. The following table summarizes the references to all the reports.

Report	General Assembly	*Celestial Mechanics and Dynamical Astronomy*
1	Montreal in 1979	**22**, 205–230 (Davies et al. 1980)
2	Patras in 1982	**29**, 309–321 (Davies et al. 1983)
3	New Delhi in 1985	**39**, 103–113 (Davies et al. 1986)
4	Baltimore in 1988	**46**, 187–204 (Davies et al. 1989)
5	Buenos Aires in 1991	**53**, 377–397 (Davies et al. 1992)
6	The Hague in 1994	**63**, 127–148 (Davies et al. 1996)
7	Kyoto in 1997	No report
8	Manchester in 2000	**82**, 83–110 (Seidelmann et al. 2002)
9	Sydney in 2003	**91**, 203–215 (Seidelmann et al. 2005)
10	Prague in 2006	**98**, 155–180 (Seidelmann et al. 2007)
11	Rio de Janeiro in 2009	This paper

Reprints and preprints of the previous reports and this report can be found at the Working Group web site: http://astrogeology.usgs.gov/Projects/WGCCRE. Previous reports are also available at the web site: http://www.springerlink.com/content/100246.

The original impetus for the Working Group was stated in an IAU Resolution: "to avoid a proliferation of inconsistent cartographic and rotational systems, there is a need to define the cartographic and rotational elements of the planets and satellites on a systematic basis and to relate the new cartographic coordinates rigorously to the rotational elements" (International Astronomical Union (IAU) 1977, p. 144). Since its first report (Davies et al. 1980), this Working Group has addressed this need and its purpose has remained essentially unchanged, except for the recognition of the need to address the same issues for small bodies of the Solar System, beginning with the 2003 report.

Therefore in actual execution, the Working Group sees its mission as this: making recommendations that define and relate the coordinate systems of Solar System bodies to their rotational elements to support making cartographic products (i.e. "mapping") of such bodies. The working group incorporates any reasonable and peer reviewed improved determinations that follow previously established conventions, or possibly in some cases may decide between different such determinations. Because of the lack of the necessary resources, however, the Working Group does not verify or validate such determinations. Our recommendations are from the Working Group alone and, if only for reasons of practicality, are not recommendations from the full IAU. The Working Group has no "enforcement" mechanism to assure that its recommendations are followed—the value of these recommendations is only from their development by international consensus and adoption by the planetary community.

The main use of these recommendations should be in cases where standardization is useful. It is, of course, not our intention to limit science or the state of the art. If for cartographic or other purposes these recommendations can be followed without affecting the quality of the product, then they should be followed so that products can be more easily compared and multiple datasets appropriately registered. If a user has sufficient data to update the recommended models or values used so that any cartographic product would be significantly improved, then obviously—following the conventions described here—such updates should be used. (It may also be useful to make alternative products using old and new models for comparison purposes).

Because there will inevitably be some delay before our next triennial report is published (or our website updated—see below), this type of action is almost always necessary when updated parameter estimates are derived. We encourage the publication of such updates in the peer-reviewed literature at the earliest opportunity. This is desirable both so that the Working Group can consider them and as appropriate recommend their use and properly reference them in our next report, but also so others will become aware of such updates, and can use them if necessary in the interim.

At the request of various individuals and missions, in the coming triennium the Working Group will consider providing limited updates to its recommendations via its website. This is in order to address a cited need to update recommendations more often than every 3 years, e.g. for use by operational missions and for updated cartographic products. Details of this procedure are still to be worked out. However, our tentative plan is to determine approximately every 6 months whether such updates are necessary and, if so, announce them on our web site. We also plan to begin listing on the website—without any recommendations and for information purposes only—new recently published and (preferably) peer-reviewed determinations related to Solar System coordinate systems. Note that the posting of recommendations to our web site is not intended to supersede the need for our triennial reports. We plan to reserve the bulk of any new recommendations or changes to our recommendations for these reports, only placing time-critical ones on our website. In our next report, we will consider the usefulness of these procedures and whether they should continue. Input for such updates (whether for Working Group consideration or information only) and comment on these procedures from the community is welcome, particularly from missions and other working groups.

The 2003 report introduced and recommended a consistent system of coordinates for both minor planets (asteroids) and comets, and in this report we extend it to cover dwarf planets. This system is not the same as the system for planets and satellites, which was not changed. It is recognized that the existence of two different systems has the potential for confusion, but the methods required for dwarf planets, minor planets, their satellites, and comets differ sufficiently to justify the use of two different systems. This report includes descriptions of the two systems; one for planets and satellites (Sects. 2, 3, 4, 6) and another for dwarf planets, minor planets, their satellites, and comets (Sects. 5 and 7). Rotational elements (body orientation in inertial space) are covered first (Sects. 2–5), and then cartographic coordinates, e.g. latitude, longitude, and body shape (Sects. 6, 7). Brief recommendations from the Working Group complete this report (Sect. 8). For the purpose of assigning bodies such as Pluto and Ceres to these tables, this report assumes that dwarf planets are the primary bodies on the list maintained by the IAU Working Group for Planetary System Nomenclature (WGPSN) and the IAU Committee on Small Body Nomenclature (CSBN) (2010). The Appendix lists changes made since the previous report.

2 Definition of Rotational Elements for Planets and Satellites

Planetary coordinate systems are defined relative to their mean axis of rotation and various definitions of longitude depending on the body. The longitude systems of most of those bodies with observable rigid surfaces have been defined by references to a surface feature such as a crater. Approximate expressions for these rotational elements with respect to the International Celestial Reference Frame (ICRF) (Ma et al. 1998) have been derived. The ICRF is the reference frame of the International Celestial Reference System and is itself epochless. There is a small (well under 0.1 arcsecond) rotation between the ICRF and the mean dynamical frame of J2000.0. The epoch J2000.0, which is JD 2451545.0 (2000 January 1 12 hours), TDB, is the epoch for variable quantities, which are expressed in units of days (86400 SI seconds) or Julian centuries of 36525 days. Barycentric Dynamical Time (TDB) is the reference time scale for time dependent variables. TDB was clarified in definition at the IAU General Assembly of 2006 in Prague. TDB, sometimes called T_{eph}, is roughly equivalent to Terrestrial Time (TT) in epoch and rate. UTC, TCB, and TCG differ from TT in epoch and rate. For more information on reference systems and time scales see Kovalevsky and Seidelmann (2004), http://www.iers.org, http://rorf.usno.navy.mil/ICRF/, or http://www.usno.navy.mil/USNO/astronomical-applications/astronomical-information-center/icrs-narrative.

The north pole is that pole of rotation that lies on the north side of the invariable plane of the Solar System. The direction of the north pole is specified by the value of its right ascension α_0 and declination δ_0. With the pole so specified, the two intersection points of the body's equator and the ICRF equator are $\alpha_0 \pm 90°$. We choose one of these, $\alpha_0 + 90°$, and define it as the node Q. Suppose the prime meridian has been chosen so that it crosses the body's equator at the point B. We then specify the location of the prime meridian by providing a value for W, the angle measured easterly along the body's equator between the node Q and the point B (see Fig. 1). The right ascension of the point Q is $90° + \alpha_0$ and the inclination of the planet's equator to the celestial equator is $90° - \delta_0$. As long as the planet, and hence its prime meridian, rotates uniformly, W varies nearly linearly with time. In addition, α_0, δ_0, and W may vary with time due to a precession of the axis of rotation of the planet (or satellite).

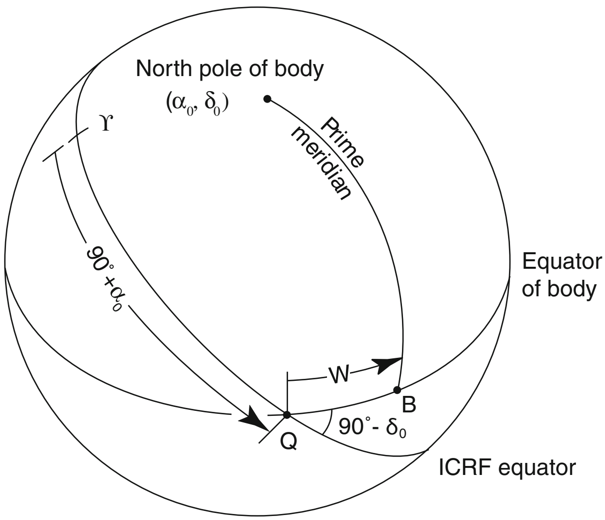


Fig. 1 Reference system used to define orientation of the planets and their satellites

If W increases with time, the planet has a *direct* (or prograde) rotation, and, if W decreases with time, the rotation is said to be *retrograde*.

In the absence of other information, since most satellites fall into this category, the axis of rotation is assumed to be normal to the mean orbital plane of the planet or the satellite. For many of the satellites, it is assumed that the rotation rate is equal to the mean orbital period (i.e. synchronous rotation), but in some cases such an assumption still needs to be validated.

The angle W specifies the ephemeris position of the prime meridian. For planets or satellites without any accurately observable fixed surface features, the adopted expression for W defines the prime meridian and is not subject to correction for this reason. However, the rotation rate may be redefined for other reasons. Where possible, however, the cartographic position of the prime meridian is defined by a suitable observable feature, and so the constants in the expression $W = W_0 + \dot{W}d$, where d is the interval in days from the standard epoch, are chosen so that the ephemeris position follows the motion of the cartographic position as closely as possible; in these cases the expression for W may require emendation in the future. When new higher accuracy mapping is done, the longitude of the fixed feature should be maintained and a new value for W_0 derived, the results published in peer-reviewed literature, and the result reported to this Working Group for possible adoption. For bodies where they are in use, longitude defining features are noted in the footnotes to Tables 1, 2, and 3.

The Working Group would like to emphasize—as it did in the introduction to its first report (Davies et al. 1980, p. 73)—that once an observable feature at a defined longitude is chosen, the longitude definition origin should not change except under unusual circumstances (such as perhaps a change in or loss of the feature). This implies that once such a feature has been adopted, a return to a value of W_0 defined by some other method (e.g. the principal axes of inertia for resonantly or synchronously rotating bodies such as Mercury (Margot 2009), or Jovian or Saturnian satellites) should be avoided. Note, however, that this does not preclude the use of smaller or more precisely determined features, multiple features, or even human artifacts to define longitude—as long as the original definition is maintained to within the accuracy of previous determinations. An example is the redefinition of the origin for longitude for Mars from the large feature then known as Sinus Meridiani to the small crater Airy-0 (de Vaucouleurs et al. 1973).

Recommended values of the constants in the expressions for α_0, δ_0, and W, in celestial equatorial coordinates, are given for the planets and satellites in Tables 1 and 2. In general, these expressions should be accurate to one-tenth of a degree; however, two decimal places are given to assure consistency when changing coordinates systems. Zeros have sometimes been added to rate values ($\dot{W}$) for computational consistency and are not an indication of significant accuracy. Additional decimal places are given in the expressions for Mercury, the Moon, Mars, Saturn, and Uranus, reflecting the greater confidence in their accuracy. Expressions for the Sun and Earth are given to a similar precision as those of the other bodies of the Solar System and are for comparative purposes only.

These recommendations are not intended to imply that other coordinate systems with different rotational elements should not be used for planetary bodies for other than cartographic or provisional purposes. For example it is recognized that the use of dynamical coordinate systems such as those tied to a body's principal axis may be needed for computational purposes or for important dynamical work. The use of such coordinate systems is common, for example as described immediately below for the Moon, and also for Mercury (Margot 2009). It is also possible, depending for example on the observational mode and accuracy, that a body fixed coordinate frame can at times be defined relative to inertial space at a higher level of accuracy than to a surface feature fixed frame. Mercury is again an example, where

Table 1 Recommended values for the direction of the north pole of rotation and the prime meridian of the Sun and planets

α_0, δ_0 are ICRF equatorial coordinates at epoch J2000.0.
Approximate coordinates of the north pole of the invariable plane are $\alpha_0 = 273°.85$, $\delta_0 = 66°.99$
T = interval in Julian centuries (of 36525 days) from the standard epoch
d = interval in days from the standard epoch
The standard epoch is JD 2451545.0, i.e. 2000 January 1 12 hours TDB

Sun

$\alpha_0 = 286°.13$

$\delta_0 = 63°.87$

$W = 84°.176 + 14°.1844000d$ (a)

Mercury

$\alpha_0 = 281.0097 - 0.0328T$

$\delta_0 = 61.4143 - 0.0049T$

$$W = 329.5469 + 6.1385025d + 0°.00993822 \sin(\mathrm{M1}) - 0°.00104581 \sin(\mathrm{M2}) - 0°.00010280 \sin(\mathrm{M3}) - 0°.00002364 \sin(\mathrm{M4}) - 0°.00000532 \sin(\mathrm{M5})$$

where

$\mathrm{M1} = 174°.791086 + 4°.092335d$

$\mathrm{M2} = 349°.582171 + 8°.184670d$

$\mathrm{M3} = 164°.373257 + 12°.277005d$

$\mathrm{M4} = 339°.164343 + 16°.369340d$

$\mathrm{M5} = 153°.955429 + 20°.461675d$ (b)

Venus

$\alpha_0 = 272.76$

$\delta_0 = 67.16$

$W = 160.20 - 1.4813688d$ (c)

Earth

$\alpha_0 = 0.00 - 0.641T$

$\delta_0 = 90.00 - 0.557T$

$W = 190.147 + 360.9856235d$

Mars

$\alpha_0 = 317.68143 - 0.1061T$

$\delta_0 = 52.88650 - 0.0609T$

$W = 176.630 + 350.89198226d$ (d)

Jupiter

$$\alpha_0 = 268.056595 - 0.006499T + 0°.000117 \sin \mathrm{Ja} + 0°.000938 \sin \mathrm{Jb} + 0.001432 \sin \mathrm{Jc} + 0.000030 \sin \mathrm{Jd} + 0.002150 \sin \mathrm{Je}$$

$$\delta_0 = 64.495303 + 0.002413T + 0.000050 \cos \mathrm{Ja} + 0.000404 \cos \mathrm{Jb} + 0.000617 \cos \mathrm{Jc} - 0.000013 \cos \mathrm{Jd} + 0.000926 \cos \mathrm{Je}$$

$W = 284.95 + 870.5360000d$ (e)

where $\mathrm{Ja} = 99°.360714 + 4850°.4046T$, $\mathrm{Jb} = 175°.895369 + 1191°.9605T$,
$\mathrm{Jc} = 300°.323162 + 262°.5475T$, $\mathrm{Jd} = 114°.012305 + 6070°.2476T$,
$\mathrm{Je} = 49°.511251 + 64°.3000T$

Table 1 continued

Saturn	
$\alpha_0 = 40.589 - 0.036T$	
$\delta_0 = 83.537 - 0.004T$	
$W = 38.90 + 810.7939024d$	(e)
Uranus	
$\alpha_0 = 257.311$	
$\delta_0 = -15.175$	
$W = 203.81 - 501.1600928d$	(e)
Neptune	
$\alpha_0 = 299.36 + 0.70 \sin N$	
$\delta_0 = 43.46 - 0.51 \cos N$	
$W = 253.18 + 536.3128492d - 0.48 \sin N$	(e)
$\mathrm{N} = 357.85 + 52.316\mathrm{T}$	

(a) The equation W for the Sun is now corrected for light travel time and removing the aberration correction. See the Appendix in Seidelmann et al. (2007)
(b) The 20° meridian is defined by the crater Hun Kal
(c) The 0° meridian is defined by the central peak in the crater Ariadne
(d) The 0° meridian is defined by the crater Airy-0
(e) The equations for W for Jupiter, Saturn, Uranus and Neptune refer to the rotation of their magnetic fields (System III). On Jupiter, System I ($W_I = 67°.1 + 877°.900d$) refers to the mean atmospheric equatorial rotation; System II ($W_{II} = 43°.3 + 870°.270d$) refers to the mean atmospheric rotation north of the south component of the north equatorial belt, and south of the north component of the south equatorial belt

Table 2 Recommended values for the direction of the north pole of rotation and the prime meridian of the satellites

α_0, δ_0, T, and d have the same meanings as in Table 1 (epoch JD 2451545.0, i.e. 2000 January 1 12 hours TDB)

Earth:

Moon (a)

$$\alpha_0 = 269°.9949 + 0°.0031T - 3°.8787 \sin E1 - 0°.1204 \sin E2 + 0.0700 \sin E3 - 0.0172 \sin E4 + 0.0072 \sin E6 - 0.0052 \sin E10 + 0.0043 \sin E13$$

$$\delta_0 = 66.5392 + 0.0130T + 1.5419 \cos E1 + 0.0239 \cos E2 - 0.0278 \cos E3 + 0.0068 \cos E4 - 0.0029 \cos E6 + 0.0009 \cos E7 + 0.0008 \cos E10 - 0.0009 \cos E13$$

$$W = 38.3213 + 13.17635815d - 1.4\times10^{-12}d^2 + 3.5610 \sin E1 + 0.1208 \sin E2 - 0.0642 \sin E3 + 0.0158 \sin E4 + 0.0252 \sin E5 - 0.0066 \sin E6 - 0.0047 \sin E7 - 0.0046 \sin E8 + 0.0028 \sin E9 + 0.0052 \sin E10 + 0.0040 \sin E11 + 0.0019 \sin E12 - 0.0044 \sin E13$$

where

$E1 = 125°.045 - 0°.0529921d$, $E2 = 250°.089 - 0°.1059842d$, $E3 = 260°.008 + 13°.0120009d$,
$E4 = 176.625 + 13.3407154d$, $E5 = 357.529 + 0.9856003d$, $E6 = 311.589 + 26.4057084d$,
$E7 = 134.963 + 13.0649930d$, $E8 = 276.617 + 0.3287146d$, $E9 = 34.226 + 1.7484877d$,
$E10 = 15.134 - 0.1589763d$, $E11 = 119.743 + 0.0036096d$, $E12 = 239.961 + 0.1643573d$,
$E13 = 25.053 + 12.9590088d$

Table 2 continued

Mars:			
I	Phobos	$\alpha_0 = 317.68 - 0.108T + 1.79 \sin M1$ $\delta_0 = 52.90 - 0.061T - 1.08 \cos M1$ $W = 35.06 + 1128.8445850d + 8.864T^2$ $- 1.42 \sin M1 - 0.78 \sin M2$	
II	Deimos	$\alpha_0 = 316.65 - 0.108T + 2.98 \sin M3$ $\delta_0 = 53.52 - 0.061T - 1.78 \cos M3$ $W = 79.41 + 285.1618970d - 0.520T^2$ $- 2.58 \sin M3 + 0.19 \cos M3$	
	where $M1 = 169°.51 - 0°.4357640d$, $M2 = 192°.93 + 1128°.4096700d + 8°.864T^2$, $M3 = 53°.47 - 0°.0181510d$		
Jupiter:			
XVI	Metis	$\alpha_0 = 268.05 - 0.009T$ $\delta_0 = 64.49 + 0.003T$ $W = 346.09 + 1221.2547301d$	
XV	Adrastea	$\alpha_0 = 268.05 - 0.009T$ $\delta_0 = 64.49 + 0.003T$ $W = 33.29 + 1206.9986602d$	
V	Amalthea	$\alpha_0 = 268.05 - 0.009T - 0.84 \sin J1 + 0.01 \sin 2J1$ $\delta_0 = 64.49 + 0.003T - 0.36 \cos J1$ $W = 231.67 + 722.6314560d + 0.76 \sin J1 - 0.01 \sin 2J1$	
XIV	Thebe	$\alpha_0 = 268.05 - 0.009T - 2.11 \sin J2 + 0.04 \sin 2J2$ $\delta_0 = 64.49 + 0.003T - 0.91 \cos J2 + 0.01 \cos 2J2$ $W = 8.56 + 533.7004100d + 1.91 \sin J2 - 0.04 \sin 2J2$	
I	Io	$\alpha_0 = 268.05 - 0.009T + 0.094 \sin J3 + 0.024 \sin J4$ $\delta_0 = 64.50 + 0.003T + 0.040 \cos J3 + 0.011 \cos J4$ $W = 200.39 + 203.4889538d - 0.085 \sin J3 - 0.022 \sin J4$	(b)
II	Europa	$\alpha_0 = 268.08 - 0.009T + 1.086 \sin J4 + 0.060 \sin J5$ $+ 0.015 \sin J6 + 0.009 \sin J7$ $\delta_0 = 64.51 + 0.003T + 0.468 \cos J4 + 0.026 \cos J5$ $+ 0.007 \cos J6 + 0.002 \cos J7$ $W = 36.022 + 101.3747235d - 0.980 \sin J4 - 0.054 \sin J5$ $- 0.014 \sin J6 - 0.008 \sin J7$	(c)
III	Ganymede	$\alpha_0 = 268.20 - 0.009T - 0.037 \sin J4 + 0.431 \sin J5 + 0.091 \sin J6$ $\delta_0 = 64.57 + 0.003T - 0.016 \cos J4 + 0.186 \cos J5 + 0.039 \cos J6$ $W = 44.064 + 50.3176081d + 0.033 \sin J4 - 0.389 \sin J5 - 0.082 \sin J6$	(d)
IV	Callisto	$\alpha_0 = 268.72 - 0.009T - 0.068 \sin J5 + 0.590 \sin J6 + 0.010 \sin J8$ $\delta_0 = 64.83 + 0.003\mathrm{T} - 0.029 \cos J5 + 0.254 \cos J6 - 0.004 \cos J8$ $W = 259.51 + 21.5710715d + 0.061 \sin J5 - 0.533 \sin J6 - 0.009 \sin J8$	(e)
		where $J1 = 73°.32 + 91472°.9T$, $J2 = 24°.62 + 45137°.2T$, $J3 = 283°.90 + 4850°.7T$, $J4 = 355.80 + 1191.3T$, $J5 = 119.90 + 262.1T$, $J6 = 229.80 + 64.3T$, $J7 = 352.25 + 2382.6T$, $J8 = 113.35 + 6070.0T$	
Saturn:			
XVIII	Pan	$\alpha_0 = 40.6 - 0.036T$ $\delta_0 = 83.5 - 0.004T$ $W = 48.8 + 626.0440000d$	
XV	Atlas	$\alpha_0 = 40.58 - 0.036T$ $\delta_0 = 83.53 - 0.004T$ $W = 137.88 + 598.3060000d$	

Table 2 continued

XVI	Prometheus	$\alpha_0 = 40.58 - 0.036T$ $\delta_0 = 83.53 - 0.004T$ $W = 296.14 + 587.289000d$	
XVII	Pandora	$\alpha_0 = 40.58 - 0.036T$ $\delta_0 = 83.53 - 0.004T$ $W = 162.92 + 572.7891000d$	
XI	Epimetheus	$\alpha_0 = 40.58 - 0.036T - 3.153 \sin S1 + 0.086 \sin 2S1$ $\delta_0 = 83.52 - 0.004T - 0.356 \cos S1 + 0.005 \cos 2S1$ $W = 293.87 + 518.4907239d + 3.133 \sin S1 - 0.086 \sin 2S1$	(f)
X	Janus	$\alpha_0 = 40.58 - 0.036T - 1.623 \sin S2 + 0.023 \sin 2S2$ $\delta_0 = 83.52 - 0.004T - 0.183 \cos S2 + 0.001 \cos 2S2$ $W = 58.83 + 518.2359876d + 1.613 \sin S2 - 0.023 \sin 2S2$	(f)
I	Mimas	$\alpha_0 = 40.66 - 0.036T + 13.56 \sin S3$ $\delta_0 = 83.52 - 0.004T - 1.53 \cos S3$ $W = 333.46 + 381.9945550d - 13.48 \sin S3 - 44.85 \sin S5$	(g)
II	Enceladus	$\alpha_0 = 40.66 - 0.036T$ $\delta_0 = 83.52 - 0.004T$ $W = 6.32 + 262.7318996d$	(h)
III	Tethys	$\alpha_0 = 40.66 - 0.036T + 9.66 \sin S4$ $\delta_0 = 83.52 - 0.004T - 1.09 \cos S4$ $W = 8.95 + 190.6979085d - 9.60 \sin S4 + 2.23 \sin S5$	(i)
XIII	Telesto	$\alpha_0 = 50.51 - 0.036T$ $\delta_0 = 84.06 - 0.004T$ $W = 56.88 + 190.6979332d$	(f)
XIV	Calypso	$\alpha_0 = 36.41 - 0.036T$ $\delta_0 = 85.04 - 0.004T$ $W = 153.51 + 190.6742373d$	(f)
IV	Dione	$\alpha_0 = 40.66 - 0.036T$ $\delta_0 = 83.52 - 0.004T$ $W = 357.6 + 131.5349316d$	(j)
XII	Helene	$\alpha_0 = 40.85 - 0.036T$ $\delta_0 = 83.34 - 0.004T$ $W = 245.12 + 131.6174056d$	
V	Rhea	$\alpha_0 = 40.38 - 0.036T + 3.10 \sin S6$ $\delta_0 = 83.55 - 0.004T - 0.35 \cos S6$ $W = 235.16 + 79.6900478d - 3.08 \sin \mathrm{S6}$	(k)
VI	Titan	$\alpha_0 = 39.4827$ $\delta_0 = 83.4279$ $W = 186.5855 + 22.5769768d$	

Table 2 continued

VIII	Iapetus	$\alpha_0 = 318.16 - 3.949T$	
		$\delta_0 = 75.03 - 1.143T$	
		$W = 355.2 + 4.5379572d$	(1)
IX	Phoebe	$\alpha_0 = 356.90$	
		$\delta_0 = 77.80$	
		$W = 178.58 + 931.639d$	
	where $S1 = 353°.32 + 75706°.7T$, $S2 = 28°.72 + 75706°.7T$, $S3 = 177°.40 - 36505°.5T$		
	$S4 = 300.00 - 7225.9T$, $S5 = 316.45 + 506.2T$, $S6 = 345.20 - 1016.3T$		
Uranus:			
VI	Cordelia	$\alpha_0 = 257.31 - 0.15 \sin U1$	
		$\delta_0 = -15.18 + 0.14 \cos U1$	
		$W = 127.69 - 1074.5205730d - 0.04 \sin U1$	
VII	Ophelia	$\alpha_0 = 257.31 - 0.09 \sin U2$	
		$\delta_0 = -15.18 + 0.09 \cos U2$	
		$W = 130.35 - 956.4068150d - 0.03 \sin U2$	
VIII	Bianca	$\alpha_0 = 257.31 - 0.16 \sin U3$	
		$\delta_0 = -15.18 + 0.16 \cos U3$	
		$W = 105.46 - 828.3914760d - 0.04 \sin U3$	
IX	Cressida	$\alpha_0 = 257.31 - 0.04 \sin U4$	
		$\delta_0 = -15.18 + 0.04 \cos U4$	
		$W = 59.16 - 776.5816320d - 0.01 \sin U4$	
X	Desdemona	$\alpha_0 = 257.31 - 0.17 \sin U5$	
		$\delta_0 = -15.18 + 0.16 \cos U5$	
		$W = 95.08 - 760.0531690d - 0.04 \sin U5$	
XI	Juliet	$\alpha_0 = 257.31 - 0.06 \sin U6$	
		$\delta_0 = -15.18 + 0.06 \cos U6$	
		$W = 302.56 - 730.1253660d - 0.02 \sin U6$	
XII	Portia	$\alpha_0 = 257.31 - 0.09 \sin U7$	
		$\delta_0 = -15.18 + 0.09 \cos U7$	
		$W = 25.03 - 701.4865870d - 0.02 \sin U7$	
XIII	Rosalind	$\alpha_0 = 257.31 - 0.29 \sin U8$	
		$\delta_0 = -15.18 + 0.28 \cos U8$	
		$W = 314.90 - 644.6311260d - 0.08 \sin U8$	
XIV	Belinda	$\alpha_0 = 257.31 - 0.03 \sin U9$	
		$\delta_0 = -15.18 + 0.03 \cos U9$	
		$W = 297.46 - 577.3628170d - 0.01 \sin U9$	
XV	Puck	$\alpha_0 = 257.31 - 0.33 \sin U10$	
		$\delta_0 = -15.18 + 0.31 \cos U10$	
		$W = 91.24 - 472.5450690d - 0.09 \sin U10$	
V	Miranda	$\alpha_0 = 257.43 + 4.41 \sin U11 - 0.04 \sin 2U11$	
		$\delta_0 = -15.08 + 4.25 \cos U11 - 0.02 \cos 2U11$	
		$W = 30.70 - 254.6906892d - 1.27 \sin U12 + 0.15 \sin 2U12$	
		$+1.15 \sin U11 - 0.09 \sin 2U11$	

Table 2 continued

I	Ariel	$\alpha_0 = 257.43 + 0.29 \sin U13$
		$\delta_0 = -15.10 + 0.28 \cos U13$
		$W = 156.22 - 142.8356681d + 0.05 \sin U12 + 0.08 \sin U13$
II	Umbriel	$\alpha_0 = 257.43 + 0.21 \sin U14$
		$\delta_0 = -15.10 + 0.20 \cos U14$
		$W = 108.05 - 86.8688923d - 0.09 \sin U12 + 0.06 \sin U14$
III	Titania	$\alpha_0 = 257.43 + 0.29 \sin U15$
		$\delta_0 = -15.10 + 0.28 \cos U15$
		$W = 77.74 - 41.3514316d + 0.08 \sin U15$
IV	Oberon	$\alpha_0 = 257.43 + 0.16 \sin U16$
		$\delta_0 = -15.10 + 0.16 \cos U16$
		$W = 6.77 - 26.7394932d + 0.04 \sin U16$
	where $U1 = 115°.75 + 54991°.87T$, $U2 = 141°.69 + 41887°.66T$, $U3 = 135°.03+29927°.35T$, $U4 = 61.77 + 25733.59T$, $U5 = 249.32 + 24471.46T$, $U6 = 43.86 + 22278.41T$, $U7 = 77.66 + 20289.42T$ $U8 = 157.36 + 16652.76T$, $U9 = 101.81 + 12872.63T$, $U10 = 138.64 + 8061.81T$, $U11 = 102.23 - 2024.22T$, $U12 = 316.41 + 2863.96T$, $U13 = 304.01 - 51.94T$, $U14 = 308.71 - 93.17T$, $U15 = 340.82 - 75.32T$, $U16 = 259.14 - 504.81T$	
Neptune		
III	Naiad	$\alpha_0 = 299.36 + 0.70 \sin N - 6.49 \sin N1 + 0.25 \sin 2N1$
		$\delta_0 = 43.36 - 0.51 \cos N - 4.75 \cos N1 + 0.09 \cos 2N1$
		$W = 254.06 + 1222.8441209d - 0.48 \sin N + 4.40 \sin N1 - 0.27 \sin 2N1$
IV	Thalassa	$\alpha_0 = 299.36 + 0.70 \sin N - 0.28 \sin N2$
		$\delta_0 = 43.45 - 0.51 \cos N - 0.21 \cos N2$
		$W = 102.06 + 1155.7555612d - 0.48 \sin N + 0.19 \sin N2$
V	Despina	$\alpha_0 = 299.36 + 0.70 \sin N - 0.09 \sin N3$
		$\delta_0 = 43.45 - 0.51 \cos N - 0.07 \cos N3$
		$W = 306.51 + 1075.7341562d - 0.49 \sin N + 0.06 \sin N3$
VI	Galatea	$\alpha_0 = 299.36 + 0.70 \sin N - 0.07 \sin N4$
		$\delta_0 = 43.43 - 0.51 \cos N - 0.05 \cos N4$
		$W = 258.09 + 839.6597686d - 0.48 \sin N + 0.05 \sin N4$
VII	Larissa	$\alpha_0 = 299.36 + 0.70 \sin N - 0.27 \sin N5$
		$\delta_0 = 43.41 - 0.51 \cos N - 0.20 \cos N5$
		$W = 179.41 + 649.0534470d - 0.48 \sin N + 0.19 \sin N5$
VIII	Proteus	$\alpha_0 = 299.27 + 0.70 \sin N - 0.05 \sin N6$
		$\delta_0 = 42.91 - 0.51 \cos N - 0.04 \cos N6$
		$W = 93.38 + 320.7654228d - 0.48 \sin N + 0.04 \sin N6$
I	Triton	$\alpha_0 = 299.36 - 32.35 \sin N7 - 6.28 \sin 2N7 - 2.08 \sin 3N7$
		$- 0.74 \sin 4N7 - 0.28 \sin 5N7 - 0.11 \sin 6N7$
		$- 0.07 \sin 7N7 - 0.02 \sin 8N7 - 0.01 \sin 9N7$
		$\delta_0 = 41.17 + 22.55 \cos N7 + 2.10 \cos 2N7 + 0.55 \cos 3N7$
		$+ 0.16 \cos 4N7 + 0.05 \cos 5N7 + 0.02 \cos 6N7$
		$+ 0.01 \cos 7N7$

Table 2 continued

$$W = 296.53 - 61.2572637d + 22.25 \sin N7 + 6.73 \sin 2N7$$
$$+2.05 \sin 3N7 + 0.74 \sin 4N7 + 0.28 \sin 5N7$$
$$+0.11 \sin 6N7 + 0.05 \sin 7N7 + 0.02 \sin 8N7$$
$$+0.01 \sin 9N7$$

where $N = 357°.85 + 52°.316T$, $N1 = 323°.92 + 62606°.6T$, $N2 = 220°.51 + 55064°.2T$,
$N3 = 354.27 + 46564.5T$, $N4 = 75.31 + 26109.4T$, $N5 = 35.36 + 14325.4T$,
$N6 = 142.61 + 2824.6T$, $N7 = 177.85 + 52.316T$

(a) *Caution: These formulae are only precise to approximately* 150 *m*. For higher precision an ephemeris should be used as described in Sect. 3 of the text
(b) The 0° meridian is defined by the sub-Jovian direction since it is assumed surface features will not last long enough to serve as a long term reference
(c) The 182° meridian is defined by the crater Cilix
(d) The 128° meridian is defined by the crater Anat
(e) The 326° meridian is defined by the crater Saga
(f)These equations are correct for the period of the Voyager encounters. Because of precession these may change. Additionally, orbital swaps between Janus and Epimetheus induce changes in their mean spin rates, and they are subject to forced librations
(g) The 162° meridian is defined by the crater Palomides
(h) The 5° meridian is defined by the crater Salih
(i) The 299° meridian is defined by the crater Arete
(j) The 63° meridian is defined by the crater Palinurus
(k) The 340° meridian is defined by the crater Tore
(l) The 276° meridian is defined by the crater Almeric
Satellites for which no suitable data are yet available have been omitted from this table. Nereid is not included in this table because it is not in synchronous rotation

the currently known orientation of the dynamically oriented body fixed frame is probably more accurately known than that of the established feature fixed frame. When such systems and frames in such systems are used, work to derive the relationships between them and the recommended cartographic coordinate system should be undertaken so that conversions between the systems can be accomplished at some known level of accuracy when necessary. This will also eventually allow the creation of final cartographic products in the recommended system. Users should also be aware that at high levels of precision (e.g. for the Moon and probably, but not yet measured, for Mercury) a principal axis system is not necessarily coincident with systems defined via principles of synchronous or resonant rotation. Principal axis frames usually rely on a specific gravity field model for their definition, and may often change with improved gravity field determinations—just as frames that rely on fixed features may often change when a body is first being mapped or mapped at improved resolution and accuracy.

3 Coordinate system for the Moon

The recommended coordinate system for the Moon is the mean Earth/polar axis (ME) system. This is in contrast to the principal axis (PA) system, sometimes called the axis of figure system. The ME system, sometimes called the mean Earth/rotation axes system, is recommended because nearly all cartographic products of the past and present have been aligned to it (Davies and Colvin 2000). The difference in the coordinates of a point on the surface of the Moon between these systems is approximately 860 m. In past reports the rotation and pole position for the Moon have been given for the ME system using closed formulae. For convenience for many users, those formulae are repeated here in Table 2. However, users should note that these are valid only to the approximately 150 m level of accuracy, as shown e.g., by Konopliv et al. (2001, Figure 3). For high precision work involving e.g., spacecraft operations, high-resolution mapping, and gravity field determination, it is recommended that a lunar ephemeris be used to obtain the libration angles for the Moon from which the pole position and rotation can be derived.

Specifically, the NASA/JPL planetary and lunar ephemeris DE 421 (Williams et al. 2008; Folkner et al. 2008, 2009) is considered the best currently available lunar ephemeris. We follow the recommendations of the Lunar Reconnaissance Orbiter mission and the (NASA) Lunar Geodesy and Cartography Working Group (LRO Project and LGCWG 2008) regarding its use. The DE 421 ephemeris may be downloaded in an ASCII version from ftp://ssd.jpl.nasa.gov/pub/eph/planets/ascii/de421/. The development of a new JPL lunar ephemeris is under consideration (Williams 2009, private communication) and, if it does become available, it might be used for the highest possible accuracy. Polynomial representations of the (Euler) lunar libration angles and their rates in the PA system are stored in the ephemeris file. These three libration angles are:

a) φ, the angle along the ICRF equator, from the ICRF X-axis to the ascending node of the lunar equator;
b) θ, the inclination of the lunar equator to the ICRF equator; and
c) ψ, the angle along the lunar equator from the node to the lunar prime meridian.

Coordinates or Euler angles in the ME system (vector M) can be rotated to the PA system (vector P) using the following expression (Williams et al. 2008, p. 10):

$$\mathrm{P} = \mathrm{R_z}\left(67''.92\right)\mathrm{R_y}\left(78''.56\right)\mathrm{R_x}\left(0''.30\right)\mathrm{M} \tag{1}$$

Conversely, coordinates or Euler angles in the PA system can be rotated into the ME system with:

$$\mathrm{M} = \mathrm{R_x}\left(-0''.30\right)\mathrm{R_y}\left(-78''.56\right)\mathrm{R_z}\left(-67''.92\right)\mathrm{P} \tag{2}$$

where $\mathrm{R_x}$, $\mathrm{R_y}$, and $\mathrm{R_z}$ are the standard rotation matrices for right-handed rotations around the X, Y, and Z axes respectively.

Therefore, for a given epoch, the user should obtain φ, θ, and ψ from the ephemeris file and store them as the vector P, apply the transformation in Eq. 2, and extract the angles, now in the ME system, from the vector M. These angles can then be converted with:

$$\begin{aligned}\alpha_0 &= \varphi - 90^\circ\\ \delta_0 &= 90^\circ - \theta\\ W &= \psi\end{aligned}$$

giving the lunar rotation angles in the standard $\alpha_{0,}\,\delta_0$, and W formulation (of Table 2) and in the ME system.

Alternatively, if the user has coordinates for a point in ICRF coordinates (vector I) that they wish to convert to ME coordinates, for a given epoch the user should obtain φ, θ, and ψ from the ephemeris file, and then do the conversion:

$$\mathrm{M} = \mathrm{R_x}\left(-0''.30\right)\mathrm{R_y}\left(-78''.56\right)\mathrm{R_z}\left(-67''.92\right)\ \mathrm{R_z}(\psi)\ \mathrm{R_x}(\theta)\ \mathrm{R_z}(\varphi)\ \mathrm{I} \tag{3}$$

with M now being the coordinates of the point in the ME system. The user should note that the numerical values for the rotations in Eqs. 1, 2, and 3 *are specific to DE 421 and are different for past and future ephemerides*.

Note that the NASA/JPL Navigation and Ancillary Information Facility (NAIF) provides software and files to facilitate the above transformations. This includes a Planetary Constants Kernel (PCK) made using the lunar libration information extracted from the DE 421 ephemeris, and a special lunar frames kernel (FK) providing the specifications and data needed to construct the PA to ME system transformation. A new version of the PCK will also be provided when a new JPL ephemeris is released. See http://naif.jpl.nasa.gov or (for DE 421) http://naif.jpl.nasa.gov/naif/lunar_kernels.txt for further information. Although written before DE 421 became available, Roncoli (2005) also provides useful information on lunar constants and coordinates.

4 Rotation elements for planets and satellites

The orientation model for Mercury has been updated using improved pole position and short period longitude libration information from Margot (2009). Margot also recommends (in essence) returning the longitude origin of Mercury to a dynamically defined one, oriented along the long principal axis of Mercury, as it was in the past. However, following the practice of this Working Group since its original report (Davies et al. 1980) and the established principle that "where possible, however, the cartographic position of the prime meridian is defined by a suitable observable feature," we continue to use the crater Hun Kal (which means "twenty" in the Mayan language) to define the 20° meridian. Therefore, we base the value of W_0 on that used previously ($W_0 = 329^\circ.548$, Robinson et al. 1999; Seidelmann et al. 2002, 2005, 2007), although corrected for the total of the libration terms at J2000.0 ($\gamma_{J2000.0}$). This results in a new recommended value of:

$$W_0 = 329^\circ.548 - \gamma_{\mathrm{J2000.0}} = 329^\circ.5469$$

We encourage and look forward to a new determination of this value from new MESSENGER or a combination of MESSENGER and Mariner 10 mapping.

The rotation rate of Saturn, that is given in Table 1 is based on Voyager observations of kilometer wavelength radio signals. Recent Cassini observations (Giampieri et al. 2006) of a signal in Saturn's magnetic field gives a period of about 10 h and 47 min, about 8 min longer than the previously determined period. At this time, it is still uncertain whether this is the true rotation rate or what physical mechanism is causing the different signals (Stevenson 2006). See Kurth et al. (2007), Gurnett et al. (2007), Anderson and Schubert (2007), and Russell and Dougherty (2010) for additional discussion. Russell reports (2010, private communication) though that the Russell and Dougherty (2010) results indicating a specific period are in doubt, and it appears as if the rotation period cannot be obtained reliably from Cassini magnetic field observations alone. He and others involved with the Cassini Project (Spilker 2010, private communication) are looking into whether some general or consensus solution can be achieved. Hence, the rotation rate of Saturn has not been changed, while more results from the Cassini mission are anticipated.

The rotation rates of Uranus and Neptune were determined from the Voyager mission in 1986 and 1989. The uncertainty of those rotation rates are such that the uncertainty of the actual rotation position in the present day is more than a complete rotation in each case.

A new model for the pole position and rotation of Mars has been proposed by Konopliv et al. (2006) based on the most recent spacecraft data. At this time, following the advice of the NASA Mars Geodesy and Cartography Working Group and its chair (Duxbury 2006; Duxbury 2009, private communication), the use of this new model is not recommended for cartographic purposes. This is for a number of reasons including that for the immediate future the new model would have little if any effect on cartographic products, and also that it is expected to be significantly changed in the next few years as new data become available. However, users with high accuracy requirements, such as Mars gravity field determination, may wish to consider using it.

5 Rotational elements for dwarf planets, minor planets, their satellites, and comets

For planets and satellites, the IAU definition of north pole is the pole that lies above the invariant plane of the Solar System, and the rotation can be either direct or retrograde. For dwarf planets, minor planets, their satellites, and comets, given substantial indirect evidence for large precession of the rotational poles of some comets, this first definition needs to be rethought. In particular, situations exist in which the pole that is clearly "north" in the IAU sense precesses over several decades to become clearly "south" in the IAU sense. Comet 2P/Encke is a prime example of a comet for which very large precession has been inferred.

There is also clear evidence for excited state rotation for comet 1P/Halley and minor planet (4179) Toutatis. In this case, the angular momentum vector moves around on the surface of the body. The rotational spin vector describes substantial excursions from the angular momentum vector during the course of the 7-day periodicity that is seen in the light curve. We can, therefore, anticipate cases in which the rotational spin pole moves back and forth between north and south on a time scale of days. Thus, there is the issue of needing to change our definition of the rotational pole.

The choice of a rotational pole for a body in simple rotation with slow precession is straightforward. One can choose the pole that follows either the right-hand rule or the left-hand rule, and the right-hand rule is chosen here. This would be the "positive" pole to avoid confusion with the north-south terminology. Ideally one would like to choose a pole for excited state rotation that reduces to this definition as the rotational energy relaxes to the ground state. For SAM (short-axis mode) rotational states, it is possible to define a body-fixed axis that circulates in a generally complex pattern about the angular momentum vector and this approaches the simple right-hand rule definition as the rotational energy relaxes to the ground state of simple rotation. Presumably the appropriate body-fixed pole is the axis of maximum moment of inertia. However, the definition for a body in a LAM (long-axis mode) rotational state is not so obvious, because there is then complete rotation about the long axis of the body as well as rotation about a short axis. In this case, the pole should be taken as the minimum moment of inertia (the long axis of an ellipsoid) according to the right-hand rule.

In practice, the initial encounter with a small irregular body may not provide enough information to determine the shape, moments of inertia, and rotational dynamics with sufficient accuracy that rotational parameters based on them will stand the test of time. In such cases, the recommended approach to defining rotational parameters and coordinate axes should be based on the same general principles that apply to planets and satellites. If possible, the initial definition of a body-fixed coordinate system should be based on a shape model and estimate of the moments of inertia, with the polar axis chosen as described above. If there is insufficient information to determine the moments of inertia, it may be necessary to define a coordinate system based on the instantaneous axis of rotation at the time of encounter. The choice of prime meridian is potentially arbitrary, but there is precedent (e.g. with (433)

Eros) for choosing it so it aligns with the longest axis (or minimum moment of inertia, if this can be estimated).

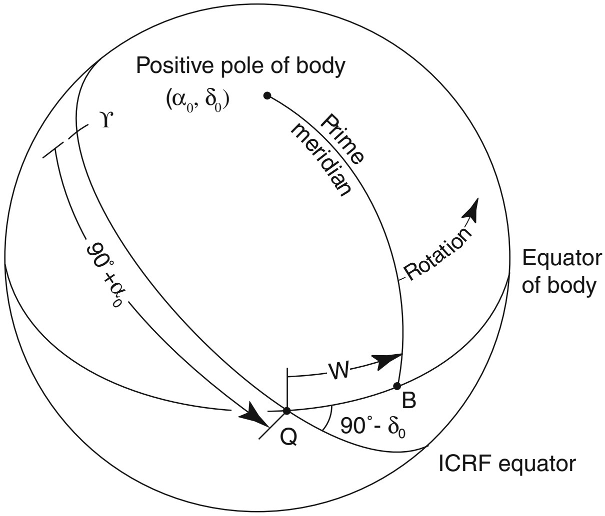
The orientation of the body at subsequent encounters is likely to differ from the predictions of a model based on initial encounter data. Such departures may be gross, as a result of rapid precession in which the spin axis varies relative to the body, or more subtle, simply because of the limits of accuracy of the initial observation. In either case, it should be borne in mind that (as for planets and satellites) the main purpose of defining a body-fixed coordinate system is to facilitate mapping of surface features. It is, therefore, desirable to relate the axes of the initial system to identifiable surface features. When new observations become available, the axes should in most cases be left unchanged with respect to the surface features and the rotational model amended to model the inertial-space orientation of the axes more accurately. In contrast to the case of planets and satellites, for which the rotation axis is often determined more accurately than the rotation rate, for irregular bodies both axis and rate may vary over time or be poorly determined. It follows that two or three landmark features will be required to determine the body-fixed orientation of the coordinate axes, rather than the single landmark that suffices to define the prime meridian of a regularly rotating body.

As specified in Sect. 6, for planets and satellites, longitude should increase monotonically for an observer fixed in inertial space. For dwarf planets, minor planets, their satellites, and comets however, with the above rule for poles, this definition corresponds always to a left-hand rule for increasing longitude, since the concept of retrograde rotation is no longer relevant. Therefore, for dwarf planets, minor planets, their satellites, and comets, to be consistent with the above pole definition, increasing longitude should always follow the right-hand rule. This definition is consistent with the sense of increasing longitude used for Eros by Miller et al. (2002), but is inconsistent with the sense of increasing longitude used for Eros by Thomas et al. (2002).

For each such body, the positive pole of rotation is selected as the maximum or minimum moment of inertia according to whether there is short or long axis rotational state and according to the right-hand rule. So the positive pole is specified by the value of its right ascension α_0 and declination δ_0. With the pole so specified, the two intersection points of the body's equator and the ICRF equator are $\alpha_0 \pm 90°$. We choose one of these, $\alpha_0 + 90°$, and define it as the node Q. Suppose the prime meridian has been chosen so that it crosses the body's equator at the point B. We then specify the location of the prime meridian by providing a value for W, the angle measured along the body's equator between the node Q and the point B in a right-hand system with respect to the body's positive pole (see Fig. 2). The right ascension of the point Q is $90° + \alpha_0$ and the inclination of the body's equator to the celestial equator is $90° - \delta_0$. As long as the planet, and hence its prime meridian, rotates uniformly, W varies linearly with time according to the right-hand rule. In addition, $\alpha_{0,}$, δ_0, and W may vary with time due to a precession of the axis of rotation of the body. It should be noted that for bodies whose spin precesses rapidly with large amplitude, this simple formulation of the body orientation in terms of pole orientation and spin angle may be insufficient. In such cases it may be necessary to develop expressions for the body orientation in terms of a full set of time-varying Euler angles. At the present time, however, the formulation given here suffices to represent the rotation of those bodies for which data are available.

The angle W specifies the ephemeris position of the prime meridian, and for dwarf planets, minor planets, their satellites, and comets without any accurately observable fixed surface features, the adopted expression for W defines the prime meridian. Where possible, however, the cartographic position of the prime meridian is defined by a suitable observable feature, and so the constants in the expression $W = W_0 + \dot{W}\ d$, where d is the interval in days from the standard epoch, are chosen so that the ephemeris position follows the motion of the

Fig. 2 Reference system used to define orientation of dwarf planets, minor planets, their satellites, and comets



cartographic position as closely as possible; in these cases the expression for W may require emendation in the future. Table 3 gives the recommended rotation values for the direction of the positive pole of rotation and the prime meridian of selected dwarf planets, minor planets, their satellites, and comets. Values are given for objects that have been imaged by spacecraft, radar, or high resolution Earth-based imaging systems with sufficient resolution to establish accurate pole orientation and rotation rates. Values are not given for objects where the observations are limited to photometric light curves.

When new higher accuracy mapping is done, the longitudes and possibly latitudes of the fixed feature or features should be maintained and a new value for W_0 (and, as necessary, the other rotational parameters) derived, published in peer-reviewed literature, and reported to this Working Group for possible adoption. For bodies where they are in use, longitude defining features are noted in the footnotes to Table 3. As already described in Sect. 2 above, once one or more features has or have been chosen with defined cartographic coordinates, they should not be changed except in unusual circumstances or in cases where the change amounts to refining the landmark position within the precision to which it was originally measured.

A dwarf planet, minor planet, one of their satellites, or a comet will typically be included in Table 3 only if it meets fundamental publication, data quality, and applicability criteria. Estimated values for α_0, δ_0, and W_0 should appear in a publication that appears in a refereed journal (or a revision that is in preparation). The analysis to determine these values will have been derived from data of sufficient fidelity and quality to assure an accurate estimate, and some portion of that data will have been acquired via direct methods (e.g., direct imaging from a spacecraft, a space telescope, or an adaptive optics system) although possibly used in combination with data from other methods, including indirect ones (e.g. photometry, multichord stellar occultation). Lastly, a cartographic need must exist that justifies the definition of a prime meridian and pole for this body.

As described above for planets and satellites, these recommendations are not intended to imply that other coordinate systems with different rotational elements should not be used for minor planets and comets for other than cartographic purposes. See Sect. 2 for a discussion of possible options, such as using a principal axis system for other than cartographic purposes.

Table 3 Recommended rotation values for the direction of the positive pole of rotation and the prime meridian of selected dwarf planets, minor planets, their satellites, and comets

d is the interval in days from the standard epoch, i.e. J2000.0 = JD 2451545.0, i.e. 2000 January 1 12 hours TDB. α_0, δ_0, and W are as defined in the text

(1) Ceres	$\alpha_0 = 291^\circ \pm 5^\circ$	
	$\delta_0 = 59^\circ \pm 5^\circ$	
	$W = 170^\circ.90 + 952^\circ.1532d$	(a)
(2) Pallas	$\alpha_0 = 33^\circ$	
	$\delta_0 = -3^\circ$	
	$W = 38^\circ + 1105^\circ.8036d$	(b)
(4) Vesta	$\alpha_0 = 305^\circ.8 \pm 3^\circ.1$	
	$\delta_0 = 41^\circ.4 \pm 1^\circ.5$	
	$W = 292^\circ + 1617^\circ.332776d$	(c)
(21) Lutetia	$\alpha_0 = 52^\circ \pm 5^\circ$	
	$\delta_0 = 12^\circ \pm 5^\circ$	
	$W = 94^\circ + 1057^\circ.7515d$	(d)
(243)Ida	$\alpha_0 = 168^\circ.76$	
	$\delta_0 = -2^\circ.88$	
	$W = 265^\circ.95 + 1864^\circ.6280070d$	(e)
(433) Eros	$\alpha_0 = 11^\circ.35 \pm 0^\circ.02$	
	$\delta_0 = 17^\circ.22 \pm 0^\circ.02$	
	$W = 326^\circ.07 + 1639^\circ.38864745d$	(f)
(511) Davida	$\alpha_0 = 297^\circ$	
	$\delta_0 = 5^\circ$	
	$W = 268^\circ.1 + 1684^\circ.4193549d$	(g) (h)
(951) Gaspra	$\alpha_0 = 9^\circ.47$	
	$\delta_0 = 26^\circ.70$	
	$W = 83^\circ.67 + 1226^\circ.9114850d$	(i)
(2867) Šteins	$\alpha_0 = 90^\circ$	
	$\delta_0 = -62^\circ$	
	$W = 93^\circ.94 + 1428^\circ.852332d$	(j)
(25143) Itokawa	$\alpha_0 = 90^\circ.53$	
	$\delta_0 = -66^\circ.30$	
	$W = 000^\circ + 712^\circ.143d$	(k)
(134340) Pluto	$\alpha_0 = 132^\circ.993$	
	$\delta_0 = -6^\circ.163$	
	$W = 237^\circ.305 + 56^\circ.3625225d$	(l)
(134340) Pluto : I Charon	$\alpha_0 = 132^\circ.993$	
	$\delta_0 = -6^\circ.163$	
	$W = 57^\circ.305 + 56^\circ.3625225d$	(m)
9P/Tempel 1	$\alpha_0 = 294^\circ$	
	$\delta_0 = 73^\circ$	
	$W = 252^\circ.63 + 212^\circ.064d$	(n)

Table 3 continued

d is the interval in days from the standard epoch, i.e. J2000.0 = JD 2451545.0, i.e. 2000 January 1 12 hours TDB. α_0, δ_0, and W are as defined in the text		
19P/Borrelly	$\alpha_0 = 218°.5 \pm 3°$	
	$\delta_0 = -12°.5 \pm 3°$	
	$W = 000° + 390°.0d$	(k)

(a) The 0° meridian is defined by the unnamed bright spot shown in Fig. 1 in Thomas et al. (2005) and Figures 5 and 6 at the 0° meridian in Li et al. (2006a)
(b) The 0° meridian is defined by the direction (positive x) of the long axis of the Carry et al. (2010a) shape model
(c) The 0° meridian is defined by a feature not yet formally named, but referred to as Olbers Regio by Thomas et al. (1997)
(d) The 0° meridian has (so far) been arbitrarily defined based on light curve information
(e) The 0° meridian is defined by the crater Afon
(f) The 0° meridian is defined by an unnamed crater
(g) The 0° meridian is defined by the direction of the long axis that points toward the Earth on 2002 December 27 7.83 UT (Conrad et al. 2007)
(h) Values have been revised from those which appear in Conrad et al. (2007) to the values given above, which appear in a publication by the same authors (in preparation)
(i) The 0° meridian is defined by the crater Charax
(j) The 0° meridian is defined by a feature not yet formally named, but referred to as the crater Spinel by Jorda et al. (2010)
(k) Since only rotation rate information is available, the 0° meridian is currently arbitrarily defined with $W_0 = 0°$
(l) The 0° meridian is defined as the mean sub-Charon meridian
(m) The 0° meridian is defined as the mean sub-Pluto meridian
(n) The 0° meridian is defined by a 350 m diameter unnamed circular feature near the Deep Impactor impact site (Thomas et al. 2007). We expect that the rotational elements will be changed in our next report to show a time-variable rotation rate

6 Definition of cartographic coordinate systems for planets and satellites

In mathematical and geodetic terminology, the terms 'latitude' and 'longitude' refer to a right-hand spherical coordinate system in which latitude is defined as the angle between a vector passing through the origin of the spherical coordinate system and the equator, and longitude is the angle between the vector and the plane of the prime meridian measured in an eastern direction. This coordinate system, together with Cartesian coordinates, is used in most planetary computations, and is sometimes called the planetocentric coordinate system. In this system, longitudes are always positive toward the east. The origin is the center of mass.

Because of astronomical tradition, planetographic coordinates (those commonly used on maps) may or may not be identical with traditional spherical coordinates. Planetographic coordinates are defined by guiding principles contained in a resolution passed at the fourteenth General Assembly of the IAU in 1970. These guiding principles state that:

(1) The rotational pole of a planet or satellite which lies on the north side of the invariable plane will be called north, and northern latitudes will be designated as positive.
(2) The planetographic longitude of the central meridian, as observed from a direction fixed with respect to an inertial system, will increase with time. The range of longitudes shall extend from 0° to 360°.

Thus, west longitudes (i.e., longitudes measured positively to the west) will be used when the rotation is direct, i.e. the sign of the second term in the expression for W is positive. East longitudes (i.e., longitudes measured positively to the east) will be used when the rotation is retrograde, i.e. the sign of the second term in the expression for W is negative. The origin is the center of mass. Also because of tradition, the Earth, Sun, and Moon do not conform with this definition. Their rotations are direct and longitudes run both east and west 180°, or east 360°.

For planets and satellites, latitude is measured north and south of the equator; north latitudes are designated as positive. The planetographic latitude of a point on the reference surface is the angle between the equatorial plane and the normal to the reference surface at the point. In the planetographic system, the position of a point (P) not on the reference surface is specified by the planetographic latitude of the point (P') on the reference surface at which the normal passes through P and by the height (h) of P above P'.

The topographic reference surface of Mars is that specified in the final MOLA Mission Experiment Gridded Data Record (MEGDR) Products (Smith et al. 2003). In particular, the 128 pixels/° resolution, radius and topographic surfaces are recommended, although the lower resolution versions may be used where appropriate and documented, and for the areas poleward of ±88° latitude.

For Mercury, the use of a planetocentric, east-positive (right-handed) system was adopted by the MESSENGER project more than 9 years ago to facilitate geodetic analysis, particularly topography and gravity, as well as all cartography. The Mariner 10 mission used the IAU standard system. There are standard transformations between the two coordinate sets. For the Mars Global Surveyor mission, an areocentric, east-positive system was used despite years of Mariner 4, 6, 7, and 9 and Viking data mapped with the IAU standard system.

The reference surfaces for some planets (such as Earth and Mars) are ellipsoids of revolution for which the radius at the equator (A) is larger than the polar semi-axis (C).

Calculations of the hydrostatic shapes of some of the satellites (Io, Mimas, Enceladus, and Miranda) indicate that their reference surfaces should be triaxial ellipsoids. Triaxial ellipsoids would render many computations more complicated, especially those related to map projections. It would be difficult to generalize many projections so as to retain their elegant and popular properties and there is a lack of agreement on basic matters such as the appropriate definitions of latitude and longitude. For these reasons spherical reference surfaces are frequently used in mapping programs.

Many small bodies of the Solar System (satellites, minor planets, and comet nuclei) have very irregular shapes. Sometimes spherical reference surfaces are used for computational convenience, but this approach does not preserve the area or shape characteristics of common map projections. Orthographic projections often are adopted for cartographic portrayal as these preserve the irregular appearance of the body without artificial distortion. A more detailed discussion of cartographic coordinate systems for small bodies is given in Sect. 7 of this report.

Table 4 gives the size and shape parameters for the planets. The Sun is included for comparison purposes. Average (AVG), north (N), and south (S) polar radii are given for Mars. For the purpose of adopting a best-fitting ellipsoid for Mars, the average polar radius should be used—the other values are for comparison only, e.g. to illustrate the large dichotomy in shape between the northern and southern hemispheres of Mars. In applications where these differences may cause problems, the earlier recommended topographic shape model for Mars should probably be used as a reference surface. The mean radii shown in Tables 4, 5, and 6 in general (the Earth is an exception) are from the original authors and have not been computed from the other radii by the Working Group on the assumption that at least some of them are independently computed.

Table 5 gives the size and shape of satellites where known. Only brightnesses are known for many of the newly discovered satellites. Poles and rotation rates are also not yet known for the new discoveries, so those satellites are not listed. A mean radius and best fitting triaxial radii are given for Titan. The triaxial radii are for comparison only, as the differences are small enough that the mean radius should be used for most cartographic purposes.

The values of the radii and axes in Tables 4 and 5 are derived by various methods and do not always refer to common definitions. Some use star or spacecraft occultation measurements, some use limb fitting, others use altimetry measurements from orbiting spacecraft, and some use control network computations. For the Earth, the spheroid refers to mean sea level, clearly a very different definition from other bodies in the Solar System.

The uncertainties in the values for the radii and axes in Tables 4 and 5 are generally those of the authors, and, as such, frequently have different meanings. Sometimes they are standard errors of a particular data set, sometimes simply an estimate or expression of confidence. The radii and axes of the large gaseous planets, Jupiter, Saturn, Uranus, and Neptune in Table 4 refer to a one-bar-pressure surface. The radii given in the tables are not necessarily the appropriate values to be used in dynamical studies; the radius actually used to derive a value of J_2 (for example) should always be used in conjunction with it. In Table 5, ellipsoidal fit axes of objects less than 200 km in radius are for convenient comparison and their use for any modeling can only be approximate.

7 Cartographic coordinates for dwarf planets, minor planets, their satellites, and comets

For large bodies, a spherical or ellipsoidal model shape has traditionally been defined for mapping, as in our past reports. For irregularly shaped bodies the ellipsoid is obviously useless, except perhaps for dynamical studies. For very irregular bodies, the concept of a reference ellipsoid ceases to be useful for most purposes. For these bodies, topographic shapes are usually represented by a grid of radii to the surface as a function of planetocentric latitude and longitude (when possible, or also by a set of vertices and polygons).

Another problem with smaller bodies is that two coordinates (i.e. spherical angular measures) may not uniquely identify a point on the surface of the body. In other words it is possible to have a line from the center of the object intersect the surface more than once. This can happen on large and even mostly ellipsoidal objects such as the Earth, because of such features as overhanging cliffs and natural bridges and arches. However, on large bodies these features are relatively very small and often ignored at the scale of most topographic maps. For small bodies they may be fairly large relative to the size of the body. Example cases are on Eros (at a small patch west of Psyche), and certainly on Kleopatra (Ostro et al. 2000), possibly on Toutatis near its 'neck,' and perhaps near the south pole of Ida, some radii may intersect the surface more than once. Even on small bodies this problem is usually restricted to small areas, but it still may make a planetocentric coordinate system difficult to use. Cartographers always have ad hoc tricks for a specific map, such as interpolating across the problem area from areas which are uniquely defined, or by showing overlapping contours. A Cartesian or other coordinate geometry may be preferable for arbitrarily complex shapes, such as a toroidal comet nucleus, where an active region has eaten its way through the nucleus. Such coordinate geometries may also be useful for irregular bodies imaged only on one side, such as for 19P/Borrelly and 81P/Wild 2.

Table 4 Size and shape parameters of the planets

Planet	Mean radius (km)	Equatorial radius (km)	Polar radius (km)	RMS deviation from spheroid (km)	Maximum elevation (km)	Maximum depression (km)
(Sun)		696000				
Mercury	2439.7 ± 1.0	Same	Same	1	4.6	2.5
Venus	6051.8 ± 1.0	Same	Same	1	11	2
Earth	6371.0084 ± 0.0001	6378.1366 ± 0.0001	6356.7519 ± 0.0001	3.57	8.85	11.52
Mars	3389.50 ± 0.2	3396.19 ± 0.1	AVG 3376.20 ± 0.1	3.0	22.64 ± 0.1	7.55 ± 0.1
			N 3373.19 ± 0.1			
			S 3379.21 ± 0.1			
Jupiter*	69911 ± 6	71492 ± 4	66854 ± 10	62.1	31	102
Saturn*	58232 ± 6	60268 ± 4	54364 ± 10	102.9	8	205
Uranus*	25362 ± 7	25559 ± 4	24973 ± 20	16.8	28	0
Neptune*	24622 ± 19	24764 ± 15	24341 ± 30	8	14	0

* The radii correspond to a one-bar surface

Table 5 Size and shape parameters of the satellites

Planet	Satellite	Mean radius (km)	Subplanetary equatorial radius (km)	Along orbit equatorial radius (km)	Polar radius (km)	RMS deviation from ellipsoid (km)	Maximum elevation (km)	Maximum depression (km)
Earth	Moon	1737.4 ± 1	Same	Same	Same	2.5	7.5	5.6
Mars	I Phobos	11.08 ± 0.04	13.0	11.4	9.1	0.5		
	II Deimos	6.2 ± 0.25	7.8	6.0	5.1	0.2		
Jupiter	XVI Metis	21.5 ± 4	30	20	17			
	XV Adrastea	8.2 ± 4	10	8	7			
	V Amalthea	83.5 ± 3	125	73	64	3.2		
	XIV Thebe	49.3 ± 4	58	49	42			
	I Io	1821.49	1829.4	1819.4	1815.7		13	3
	II Europa	1560.8 ± 0.3	1562.6	1560.3	1559.5	0.32		
	III Ganymede	2631.2 ± 1.7	Same	Same	Same			
	IV Callisto	2410.3 ± 1.5	Same	Same	Same	0.6		
	XIII Leda	5						
	VI Himalia	85 ± 10						
	X Lysithea	12						
	VII Elara	40 ± 10						
	XII Ananke	10						
	XI Carme	15						
	VIII Pasiphae	18						
	IX Sinope	14						

Table 5 continued

Planet	Satellite	Mean radius (km)	Subplanetary equatorial radius (km)	Along orbit equatorial radius (km)	Polar radius (km)	RMS deviation from ellipsoid (km)	Maximum elevation (km)	Maximum depression (km)
Saturn	XVIII Pan	14.1 ± 1.3	17.2 ± 1.9	15.7 ± 1.3	10.4 ± 0.84			
	XXXV Daphnis	3.8 ± 0.8	4.3 ± 0.7	4.1 ± 0.9	3.2 ± 0.8			
	XV Atlas	15.1 ± 0.9	20.4 ± 1.2	17.7 ± 0.7	9.4 ± 0.8			
	XVI Prometheus	43.1 ± 2.7	67.8 ± 3.1	39.7 ± 3.1	29.7 ± 1.9			
	XVII Pandora	40.7 ± 1.5	52.0 ± 1.8	40.5 ± 2.0	32.0 ± 0.9			
	XI Epimetheus	58.1 ± 1.8	64.9 ± 2.0	57.0 ± 3.7	53.1 ± 0.7			
	X Janus	89.5 ± 1.4	101.5 ± 1.9	92.5 ± 1.2	76.3 ± 1.2			
	I Mimas	198.2 ± 0.4	207.8 ± 0.5	196.7 ± 0.5	190.6 ± 0.3			
	XXXII Methone	1.6 ± 0.6	Same	Same	Same			
	XLIX Anthe	∼1						
	XXXIII Pallene	2.5 ± 0.6	2.9 ± 0.6	2.8 ± 0.8	2.0 ± 0.4			
	II Enceladus	252.1 ± 0.2	256.6 ± 0.6	251.4 ± 0.2	248.3 ± 0.2	0.4		
	III Tethys	531.0 ± 0.6	538.4 ± 0.3	528.3 ± 1.1	526.3 ± 0.6			
	XIII Telesto	12.4 ± 0.4	16.3 ± 0.5	11.8 ± 0.3	10.0 ± 0.3			
	XIV Calypso	10.7 ± 0.7	15.1 ± 0.3	11.5 ± 2.2	7.0 ± 0.6			
	IV Dione	561.4 ± 0.4	563.4 ± 0.6	561.3 ± 0.5	559.6 ± 0.4	0.5		
	XII Helene	17.6 ± 0.4	21.7 ± 0.5	19.1 ± 0.3	13.0 ± 0.3			
	XXXIV Polydeuces	1.3 ± 0.4	1.5 ± 0.6	1.2 ± 0.4	1.0 ± 0.2			
	V Rhea	763.5 ± 0.6	765.0 ± 0.7	763.1 ± 0.6	762.4 ± 0.6			
	VI Titan	2574.73 ± 0.09	2575.15 ± 0.02	2574.78 ± 0.06	2574.47 ± 0.06	0.26		

Table 5 continued

Planet	Satellite	Mean radius (km)	Subplanetary equatorial radius (km)	Along orbit equatorial radius (km)	Polar radius (km)	RMS deviation from ellipsoid (km)	Maximum elevation (km)	Maximum depression (km)
	VII Hyperion	135 ± 4	180.1 ± 2.0	133.0 ± 4.5	102.7 ± 4.5			
	VIII Iapetus	734.3 ± 2.8	745.7 ± 2.9	745.7 ± 2.9	712.1 ± 1.6			
	IX Phoebe	106.5 ± 0.7	109.4 ± 1.4	108.5 ± 0.6	101.8 ± 0.3			
Uranus	VI Cordelia	13 ± 2						
	VII Ophelia	15 ± 2						
	VIII Bianca	21 ± 3						
	IX Cressida	31 ± 4						
	X Desdemona	27 ± 3						
	XI Juliet	42 ± 5						
	XII Portia	54 ± 6						
	XIII Rosalind	27 ± 4						
	XIV Belinda	33 ± 4						
	XV Puck	77 ± 5				1.9		
	V Miranda	235.8 ± 0.7	240.4 ± 0.6	234.2 ± 0.9	232.9 ± 1.2	1.6	5	8
	I Ariel	578.9 ± 0.6	581.1 ± 0.9	577.9 ± 0.6	577.7 ± 1.0	0.9	4	4
	II Umbriel	584.7 ± 2.8	Same	Same	Same	2.6		6
	III Titania	788.9 ± 1.8	Same	Same	Same	1.3	4	
	IV Oberon	761.4 ± 2.6	Same	Same	Same	1.5	12	2

Table 5 continued

Planet	Satellite	Mean radius (km)	Subplanetary equatorial radius (km)	Along orbit equatorial radius (km)	Polar radius (km)	RMS deviation from ellipsoid (km)	Maximum elevation (km)	Maximum depression (km)
Neptune	III Naiad	29 ± 6						
	IV Thalassa	40 ± 8						
	V Despina	74 ± 10						
	VI Galatea	79 ± 12						
	VII Larissa	96 ± 7	104		89	2.9	6	5
	VIII Proteus	208 ± 8	218	208	201	7.9	18	13
	I Triton	1352.6 ± 2.4						
	II Nereid	170 ± 25						

With the introduction of large mass storage to computer systems, digital cartography has become increasingly popular. Cartographic databases are important when considering irregularly shaped bodies and other bodies, where the surface can be described by a file containing the coordinates for each pixel. In this case the reference sphere has shrunk to a unit sphere. Other parameters such as brightness, gravity, etc., if known, can be associated with each pixel. With proper programming, pictorial and projected views of the body can then be displayed.

Taking all of this into account, our recommendation is that longitudes on dwarf planets, minor planets, their satellites, and comets should be measured positively from 0 to 360 degrees using a right-hand system from a designated prime meridian. The origin is the center of mass, to the extent known.

Latitude is measured positive and negative from the equator; latitudes toward the positive pole are designated as positive. For regular shaped bodies the cartographic latitude of a point on the reference surface is the angle between the equatorial plane and the normal to the reference surface at the point. In the cartographic system, the position of a point (P) not on the reference surface is specified by the cartographic latitude of the point (P') on the reference surface at which the normal passes through P and by the height (h) of P above P'.

For irregular bodies orthographic digital projections often are adopted for cartographic portrayal as these preserve the irregular appearance of the body without artificial distortion. These projections should also follow the right-hand rule.

Table 6 contains data on the size and shape of selected dwarf planets, minor planets, their satellites, and comets. The first column gives the effective radius of the body and an estimate of the accuracy of this measurement. This effective radius is for a sphere of equivalent volume. The next three columns give estimates of the radii measured along the three principal axes.

The uncertainties in the values for the radii in Table 6 are generally those given by the authors, and, as such, frequently have different meanings. Sometimes they are standard errors of a particular data set, sometimes simply an estimate or expression of confidence.

A dwarf planet, minor planet, one of their satellites, or a comet will typically be included in Table 6 only if it meets fundamental publication, data quality, and applicability criteria. Estimated values for the body's size and shape (modeled as a spheroid) should have been published in a refereed journal (or a revision that is in preparation). The analysis to determine these values will have been derived from data of sufficient fidelity and quality to assure an accurate estimate, and some portion of that data will have been acquired via direct methods (e.g. direct imaging from a spacecraft, a space telescope, or an adaptive optics system). Lastly, a cartographic need must exist that justifies the definition of a size and shape for this body.

The radii given in the tables are not necessarily the appropriate values to be used in dynamical studies; the radius actually used to derive a value for the dynamical form factor (J_2) (for example) should always be used in conjunction with it.

8 Recommendations

Although we have not done so in the past, the Working Group briefly summarizes here what we have come to see as current urgent needs relative to the development of planetary cartographic products.

Table 6 Size and shape parameters of selected dwarf planets, minor planets, their satellites, and comets

Body	Effective radius (km)	Radii measured along principal axes (km)	(km)	(km)	
(1) Ceres	476.2 ± 1.7	487.3 ± 1.8	Same	454.7 ± 1.6	(a)
(4) Vesta		289 ± 5	280 ± 5	229 ± 5	
(21) Lutetia	52.5 ± 2.5	62.0 ± 2.5	50.5 ± 2.0	46.5 ± 6.5	
(243) Ida	15.65 ± 0.6	26.8	12.0	7.6	
(253) Mathilde	26.5 ± 1.3	33	24	23	
(433) Eros	8.45 ± 0.02	17.0	5.5	5.5	
(511) Davida	150	180	147	127	(b)
(951) Gaspra	6.1 ± 0.4	9.1	5.2	4.4	
(2867) Šteins	2.70	3.24	2.73	2.04	
(4179) Toutatis		2.13	1.015	0.85	
(25143) Itokawa		0.535	0.294	0.209	
(134340) Pluto	1195 + 5	Same	Same	Same	
(134340) Pluto: I Charon	605 ± 8				
1P/Halley		8.0 ± 0.5	4.0 ± 0.25	4.0 ± 0.25	
9P/Tempel 1	3.0 ± 0.1	3.7	2.5		(c)
19P/Borrelly	4.22 ± 0.05	3.5 ± 0.2	–	–	
81P/Wild 2	1.975	2.7	1.9	1.5	

(a) An oblate spheroid. Carry et al. (2008) cite values of $r = 467.6 \pm 2.2$, $a = b = 479.7 \pm 2.3$, $c = 444.4 \pm 2.1$. However the amount of improvement over the Thomas et al. (2005) values is not clear, so no change is recommended
(b) Values have been updated from the diameter values which appear in Conrad et al. (2007) to the radii values given above, which result from additional observations and appear in a publication by the same authors (in preparation)
(c) The maximum and minimum radii are not properly the values of the principal semi-axes, they are half the maximum and minimum values of the diameter. Due to the large deviations from a simple ellipsoid, they may not correspond with measurements along the principal axes, or be orthogonal to each other

1. The importance of geodetically controlled cartographic products—i.e., derived from least squares photogrammetric, radargrammetric, or altimetric (cross-over) solutions—is well known. These products are valuable since they are precise and cosmetically ideal products at the sub-pixel level of the data, with known or derivable levels of precision and accuracy. In addition global control solutions also provide for improved body pole position, spin, and shape information, with reduced effects of random error and often systematic error. Such solutions would allow for improvements in the recommended models, and more importantly provide for higher (and known) precision and accuracy cartographic products. Although a flood of new planetary datasets is currently arriving, it appears that the production of such products is often not planned for or funded. We strongly recommend that this trend be reversed and that such products be planned for and made as part of the normal mission operations and data analysis process.
2. As indicated above, Konopliv et al. (2006) have developed an improved model for the orientation of Mars. We note that by the time of our next report, the orientation of Mars from that model will start to diverge significantly from that currently recommended by this Working Group and dating to our 2000 report. We recommend their model be updated or a similar model be developed that takes advantage of the substantial additional Mars

data available since the time of their work, so that it can be adopted by this Working Group and operational Mars missions in the 2012 time frame.

3. As described above, there appear to be a number of slightly conflicting determinations for the rotation rates of Jupiter and Saturn. We urge the planetary community to jointly address resolving the various determinations and to develop consensus determinations, such as was done in the past for Jupiter by Riddle and Warwick (1976).

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Appendix: changes since the last report

This appendix summarizes the changes that have been made since the 2006 report *(Celestial Mechanics and Dynamical Astronomy* **98**, 155–180, 2007).

1. Following the list of dwarf planets defined by the IAU WGPSN and the CSBN (2010), the entries for Pluto and Charon have been moved to Tables 3 and 6 and adapted to the positive pole definition, and the entry for Ceres moved to Table 6.
2. A new pole and rotation model has been implemented for Mercury, based on the determination of Margot 2009, but using the previous value of W_0. See Sect. 4 for further details.
3. An algorithm is described in the text for expressing the orientation of the Moon using the JPL DE 421 lunar ephemeris, rotated to the mean Earth/polar axis system, in order to obtain the pole and rotation with high precision.
4. The new pole and rotation model of Konopliv et al. (2006) for Mars continues to be noted in the text, but is *not* recommended for general use at this time.
5. The rotation rate of Jupiter was updated in the 2000 report (Seidelmann et al. 2002) based on a new determination by Higgins et al. (1997). That rate is different from the previously accepted value ("System III (1965)") of Riddle and Warwick (1976) and is not in agreement with new determinations by Russell et al. (2001) and Yu and Russell (2009). After discussion with some of these authors (Higgins 2010, private communication; Russell 2010, private communication), here it is changed back to the previous Riddle and Warwick (1976) value. Higgins, Russell, and the Working Group recommend that a community consensus on a new value be achieved—much as was facilitated by Riddle and Warwick—before a new value is adopted.
6. Several proposed new rotation models for Saturn are noted in the text, but *not* recommended for general use at this time. As with Jupiter, the Working Group recommends that a community consensus on a new model be achieved before a new value is adopted.
7. The rotation models of Mimas, Enceladus, Tethys, Dione, and Iapetus have been updated in Table 2 based on the Table 24.4 values in Roatsch et al. (2009a). (The Dione model is originally from Roatsch et al. (2008b); the Mimas, Tethys, and Iapetus models are originally from Roatsch et al. (2009b); the revised Enceladus model was not yet derived when Roatsch et al. (2008a) was published.). These changes are to the values of W_0 for these bodies, based on semi-controlled (including limb fitting) new mapping of these bodies. Note that in some further interim revisions of the relevant mapping products, W_0 has not been further updated, resulting in some variation in longitude of the defining features in the interim products. Final products will be made later with associated further updates to the W_0 values (Roatsch 2009, private communication).

The rotation model of Titan has been updated in Table 2 based on the improved pole position and synchronous spin model of Stiles et al. (2008) and as formulated in Cassini Project (2009). This model was derived from Cassini RADAR observations of Titan. A model for nonsynchronous spin, resulting from surface-atmosphere interactions and possibly indicating, by its magnitude, the presence of a sub-surface ocean (Lorenz et al. 2008), is as yet not sufficiently definitive to be adopted. Note that the adopted model does not include any terms for precession and nutation, but for pole position fits the data better than the previous WG model that assumed a pole perpendicular to the orbital plane. Stiles et al. (2010) note a correction to their earlier work, substantially reducing the inferred nonsynchronous rotation rate and giving a slightly different pole position, but they do not provide a compatible spin model, so the newer determination is not adopted here.

8. Clarification has been added to Sect. VI to explain when positive longitudes are east or west in the planetocentric and planetographic coordinate systems.
9. (1) Ceres has been added to Table 3 based on work described by Thomas et al. (2005), Li et al. (2006a), and Li et al. (2006b). W_0 has been derived from $W = 333.14°$ at the UTC epoch 2003-12-28T10:51:59 (Thomas 2010, private communication). The period of 9.074170 hours from Chamberlain et al. (2007) has been used to derive the rotation rate. (2) Pallas, (21) Lutetia, (511) Davida, and (2867) Šteins have been added to Table 3 from Carry et al. (2010a) (Pallas); Carry et al. (2010b) (Lutetia), Conrad et al. (2007) (Davida); and Jorda et al. (2010) and Keller et al. (2010) (Šteins). Schmidt et al. (2009) have determined a pole position for (2) Pallas of $\alpha_0 = 42° \pm 10$ and $\delta_0 = -12° \pm 10$. However, since they provide no corresponding information on spin, values for the pole position and spin from Carry et al. (2010a) have been recommended here. The pole position for (4) Vesta has been updated from Li et al. (2010).
10. The equatorial radius of the Sun has been added to Table 4 for comparison, as specified in the IAU (1976) System of Astronomical Constants (International Astronomical Union (IAU) 1977, pp. 31, 52–66).
11. The size and shape of the Earth has been updated based on International Association of Geodesy recommendations (Groten 2000). The (zero frequency tide) mean equatorial radius, a, is used as is (ibid., equation 46), while the (zero frequency tide) mean polar flattening, $1/f$ (ibid., equation 22), is used to calculate the mean polar radius, $b = a - af$. The mean radius is calculated via the arithmetic mean $(2a + b)/3$ (Moritz 1980, 392). The RMS deviation from the spheroid, the maximum elevation, and maximum depression has been left at their previous values since they are only intended to be approximate. The a and $1/f$ values used are also those recommended in the IERS Conventions (McCarthy and Petit 2004).
12. Sizes and shapes have been updated in Table 5 for Phobos and Deimos based on Willner et al. (2010) and Thomas (1993) respectively.
13. Sizes and shapes have been updated in Table 5 for the Galilean satellites of Jupiter based on Thomas et al. (1998) (Io); Anderson et al. (2001a) (Ganymede), Anderson et al. (2001b) (Callisto), and Nimmo et al. (2007) (Europa). While making these updates, we have noted that the previous recommended sizes and shapes for the Galilean satellites do not originate from Davies et al. (1998) as indicated in the 2000 report (Seidelmann et al. 2002) but rather from the Galileo SSI instrument team (K. P. Klassen, e-mail of 2000 November 13). The mean radii for Europa, Ganymede, and Callisto there came from M. Davies and T. Colvin via photogrammetric solutions and the mean radius for Io and the triaxial radii for all four satellites came from P. Thomas via limb fit solutions.

14. Sizes and shapes have been updated in or added to Table 5 for the Saturnian satellites (in order outward from Saturn) Pan, Daphnis, Atlas, Prometheus, Pandora, Epimetheus, Janus, Mimas, Methone, Pallene, Tethys, Telesto, Calypso, Dione, Helene, Polydeuces, Rhea, Hyperion, Iapetus, and Phoebe, based on new determinations listed by Thomas (2010); and for Anthe based on a new determination listed by Porco et al. (2007). Size and shape information for Titan is updated from Zebker et al. (2009). Also note that in the 2006 report (Seidelmann et al. 2007, pp. 174–175) the along orbit equatorial radius of Metis should have been listed as 20 km, the polar radius as 17 km, and the RMS deviation from the ellipsoid as blank; and the mean radius of Helene should have been listed as 16 km and the RMS deviation from the ellipsoid as 0.7 km.
15. In Table 6 a mean radius value from Thomas et al. (2005) has been added for (1) Ceres and a footnote added to note an alternate determination of Ceres' shape by Carry et al. (2008). Clarifying what was shown in the 2006 report (Seidelmann et al. 2007, p. 177) since it is an oblate spheroid, the first and second axes are listed as being the same, different from the third axis. (21) Lutetia, (511) Davida and (2867) Šteins have been added to Table 6 from Drummond et al. (2010) (Lutetia), Conrad et al. (2007) (Davida), and Jorda et al. (2010) and Keller et al. (2010) (Šteins). Schmidt et al. (2009) and Carry et al. (2010a) have both determined shape parameters for (2) Pallas. These are respectively: r = 272, a = 291 ± 9, b = 278 ± 9, and c = 250 ± 9; r = 256 ± 3, a = 275 ± 4, b = 258 ± 3, and c = 238 ± 3 km. We have been unable to clearly differentiate which is superior so make no recommendation as to which to use at this time.

References

Anderson, J.D., Schubert, G.: Saturn's gravitational field, internal rotation, and interior structure. Science **317**, 1384–1387 (2007). doi:10.1126/science.1144835

Anderson, J.D., Jacobson, R.A., Lau, E.L., Moore, W.B., Olsen, O., Schubert, G., Thomas, P.C.: Galileo Gravity Science Team: Shape, Mean Radius, Gravity Field and Interior Structure of Ganymede. DPS Meeting #33. Bull. Am. Astron. Soc. **33**, 1101 (2001)

Anderson, J.D., Jacobson, R.A., McElrath, T.P., Moore, W.B., Schubert, G., Thomas, P.C.: Shape, mean radius, gravity field, and interior structure of callisto. Icarus **153**, 157–161 (2001)

Carry, B., Dumas, C., Fulchignoni, M., Merline, W.J., Berthier, J., Hestroffer, D., Fusco, T., Tamblyn, P.: Near-infrared mapping and physical properties of the dwarf-planet Ceres. Astron. Astroph. **478**, 235–244 (2008). doi:10.1051/0004-6361:20078166

Carry, B., Dumas, C., Kaasalainen, M., Berthier, J., Merline, W.J., Erard, S., Conrad, A., Drummond, J.D., Hestroffer, D., Fulchignoni, M., Fusco, T.: Physical properties of (2) Pallas. Icarus **205**, 460–472 (2010). doi:10.1016/j.icarus.2009.08.007

Carry, B., Kaasalainen, M., Leyrat, C., Merline, W.J., Drummond, J.D., Conrad, A., Weaver, H.A., Tamblyn, P.M., Chapman, C.R., Dumas, C., Colas, F., Christou, J.C., Dotto, E., Perna, D., Fornasier, S., Bernasconi, L., Behrend, R., Vachier, F., Kryszczynska, A., Polinska, M., Fulchignoni, M., Roy, R., Naves, R., Poncy, R., Wiggins, P.: Physical properties of ESA Rosetta target asteroid (21) Lutetia: shape and flyby geometry. Astron. & Astroph. (2010, in press). doi:10.1051/0004-6361/201015074

Cassini Project: Planetary Constants (PcK) SPICE kernel. May 7 (2009), ftp://naif.jpl.nasa.gov/pub/naif/CASSINI/kernels/pck/cpck07May2009.tpc. Accessed 2010 October 18

Chamberlain, M.A., Sykes, M.V., Esquerdo, G.A.: Ceres lightcurve analysis—period determination. Icarus **188**, 451–456 (2007)

Conrad, A.R., Dumas, C., Merline, W.J., Drummond, J.D., Campbell, R.D., Goodrich, R.W., Le Mignant, D., Chaffee, F.H., Fusco, T., Kwok, S.H., Knight, R.I.: Direct measurement of 511 the size, shape, and pole of Davida with Keck AO in a single night. Icarus **191**, 616–627 (2007). doi:10.1016/j.icarus.2007.05.004

Davies, M.E., Abalakin, V.K., Cross, C.A., Duncombe, R.L., Masursky, H., Morando, B., Owen, T.C., Seidelmann, P.K., Sinclair, A.T., Wilkins, G.A., Tjuflin, Y.S.: Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites. Celest. Mech. **22**, 205–230 (1980)

Davies, M.E., Abalakin, V.K., Lieske, J.H., Seidelmann, P.K., Sinclair, A.T., Sinzi, A.M., Smith, B.A., Tjuflin, Y.S.: Report of the IAU working group on cartographic coordinates and rotational elements of the planets and satellites: 1982. Celest. Mech. **29**, 309–321 (1983)

Davies, M.E., Abalakin, V.K., Bursa, M., Lederle, T., Lieske, J.H., Rapp, R.H., Seidelmann, P.K., Sinclair, A.T., Teifel, V.G., Tjuflin, Y.S.: Report of the IAU/IAG COSPAR working group on cartographic coordinates and rotational elements of the planets and satellites: 1985. Celest. Mech. **39**, 103–113 (1986)

Davies, M.E., Abalakin, V.K., Bursa, M., Hunt, G.E., Lieske, J.H., Morando, B., Rapp, R.H., Seidelmann, P.K., Sinclair, A.T., Tjuflin, Y.S.: Report of the IAU/IAG/COSPAR working group on cartographic coordinates and rotational elements of the planets and satellites: 1988. Celest. Mech. Dyn. Astron. **46**, 187–204 (1989)

Davies, M.E., Abalakin, V.K., Brahic, A., Bursa, M., Chovitz, B.H., Lieske, J.H., Seidelmann, P.K., Sinclair, A.T., Tjuflin, Y.S.: Report of the IAU/IAG/COSPAR working group on cartographic coordinates and rotational elements of the planets and satellites: 1991. Celest. Mech. Dyn. Astron. **53**, 377–397 (1992)

Davies, M.E., Abalakin, V.K., Bursa, M., Lieske, J.H., Morando, B., Seidelmann, P.K., Sinclair, A.T., Yallop, B., Tjuflin, Y.S.: Report of the IAU/IAG/COSPAR working group on cartographic coordinates and rotational elements of the planets and satellites: 1994. Celest. Mech. Dyn. Astron. **63**, 127–148 (1996)

Davies, M.E., Colvin, T.R., Oberst, J., Zeitler, W., Schuster, P., Neukum, G., McEwen, A.S., Phillips, C.B., Thomas, P.C., Veverka, J., Belton, M.J.S., Schubert, G.: The control networks of the Galilean satellites and implications for global shape. Icarus **135**, 372–376 (1998). doi:10.1006/icar.1998.5982

Davies, M.E., Colvin, T.R.: Lunar coordinates in the regions of the Apollo landers. JGR **105**(E8), 20,277–20,280 (2000)

de Vaucouleurs, G., Davies, M.E., Sturms, F.M Jr..: Mariner 9 areographic coordinate system. JGR **78**, 4395–4404 (1973)

Drummond, J.D., Conrad, A., Merline, W.J., Carry, B., Chapman, C.R., Weaver, H.A., Tamblyn, P.M., Christou, J.C., Dumas, C.: The triaxial ellipsoid dimensions, rotational pole, and bulk density of ESA Rosetta target asteroid (21) Lutetia. Astron. & Astroph. (2010, in press). doi:10.1051/0004-6361/201015075

Duxbury, T.: Minutes of 2006 October 3 Meeting of the MGCWG, as of 2006 October 31 (2006)

Folkner, W.M., Williams, J.G., Boggs, D.H.: The Planetary and Lunar Ephemeris DE 421. JPL Memorandum IOM 343R-08-003, 31 March (2008). Available as ftp://ssd.jpl.nasa.gov/pub/eph/planets/ioms/de421.iom.v1.pdf. Accessed 2010 October 18

Folkner, W.M., Williams, J.G., Boggs, D.H.: The Planetary and Lunar Ephemeris DE 421. IPN Progress Report 42-178, August 15 (2009). Available as http://ipnpr.jpl.nasa.gov/progress_report/42-178/178C.pdf. Accessed 2010 October 18

Giampieri, G., Dougherty, M.K., Smith, E.J., Russell, C.T.: A regular period for Saturn's magnetic field that may track its internal rotation. Nature **441**, 62–64 (2006)

Groten, E.: Report of Special Commission 3 of IAG. In: Johnston, K. J, et al. (eds.) Toward Models and Constants for Sub-Microarcsecond Astrometry, U.S. Naval Observatory, Washington, D.C., pp. 337–352 (2000). Available as http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA435898. Accessed 2010 October 18

Gurnett, D.A., Persoon, A.M., Kurth, W.S., Groene, J.B., Averkamp, T.F., Dougherty, M.K., Southwood, D.J.: The variable rotation period of the inner region of Saturn's plasma disk. Science **316**, 442–445 1–16, April 20 (2007)

Higgins, C.A., Carr, T.D., Reyes, F., Greenman, W.B., Lebo, G.R.: A redefinition of Jupiter's rotation period. JGR **102**(A10), 22,033–22,041 (1997)

International Astronomical Union (IAU): Proceedings of the Sixteenth General Assembly. Transactions of the IAU, **XVI B**, D. Reidel Publishing Company, Dordrecht (1977). A copy of the 1976 IAU Resolutions including the "IAU (1976) System of Astronomical Constants" is available on-line as http://www.iau.org/static/resolutions/IAU1976_French.pdf. Accessed 2010 October 18

International Astronomical Union (IAU) Working Group for Planetary System Nomenclature (WGPSN) and International Astronomical Union Committee on Small Body Nomenclature: Dwarf Planets and their Systems (2010), http://planetarynames.wr.usgs.gov/append7.html#DwarfPlanets. Accessed 2010 October 18

Jorda, L., Lamy, P., Groussin, O., Besse, S., Faury, G., Gaskell, R., Gesquière, G., Kaasalainen, M.: Asteroid (2867) Steins: shape, topography and geology from OSIRIS observations, to be submitted to Icarus (2010)

Keller, H.U., Barbieri, C., Koschny, D., Lamy, P., Rickman, H., Rodrigo, R., Sierks, H., A'Hearn, M.F., Angrilli, F., Barucci, M.A., Bertaux, J.-L., Cremonese, G., Da Deppo, V., Davidsson, B., De Cecco, M., Debei, S., Fornasier, S., Fulle, M., Groussin, O., Gutierrez, P.J., Hviid, S.F., Ip, W.-H., Jorda, L., Knollenberg, J., Kramm, J.R., Kührt, E., Küppers, M., Lara, L.-M., Lazzarin, M., Moreno, J.L., Marzari, F., Michalik, H., Naletto, G. Sabau, G. Thomas, G. Wenzel, G. Bertini, G. Besse, G. Ferri, G. Kaasalainen, G. Lowry, G. Marchi, G. Mottola, G. Sabolo, G. Schröder, G. Spjuth, G. Vernazza, G.: E-Type Asteroid (2867)

Steins as Imaged by OSIRIS on Board Rosetta. Science **327**, 190–193 (2010). doi:10.1126/science.1179559

Konopliv, A.S., Asmar, S.W., Carranza, E., Sjogren, W.L., Yuan, D.-N.: Recent gravity models as a result of the Lunar Prospector mission. Icarus **150**, 1–18 (2001)

Konopliv, A.S., Yoder, C.F., Standish, E.M., Yuan, D.-N., Sjogren, W.L.: A global solution for the Mars static and seasonal gravity, Mars orientation, Phobos and Deimos masses, and Mars ephemeris. Icarus **182**, 23–50 (2006)

Kovalevsky, J., Seidelmann, P.K.: Fundamentals of Astrometry. Cambridge University Press, Cambridge (2004)

Kurth, W.S., Lecacheux, A., Averkamp, T.F., Groene, J.B., Gurnett, D.A.: A Saturnian longitude system based on a variable kilometric radiation period. GRL **24**, L02201 (2007). doi:10.1029/2006GL028336

Li, J.-Y., McFadden, L.A., Parker, J.W., Young, E.F., Stern, S.A., Thomas, P.C., Russell, C.T., Sykes, M.V.: Photometric analysis of 1 Ceres and surface mapping from HST observations. Icarus **182**, 143–160 (2006a). doi:10.1016/j.icarus.2005.12.012

Li, J.-Y., Young, E.F., Thomas, P.C., Parker, J.Wm., McFadden, L.A., Russell, C.T., Stern, S.A., Sykes, M.V.: HST Images, Albedo Maps, and Shape of 1 Ceres V1.0. EAR-A-HSTACS-5-CERESHST-V1.0. NASA Planetary Data System (2006b). Available at http://sbn.psi.edu/pds/resource/cereshst.html. Accessed 2010 October 18

Li, J.-Y., Thomas, P.C., Carcich, B., Mutchler, M.J., McFadden, L.A., Russell, C.T., Weinstein-Weiss, S.S., Rayman, M.D., Raymond, C.A.: Improved Measurement of Asteroid (4) Vesta's Rotational Axis Orientation. Icarus. (2010, in press). doi:10.1016/j.icarus.2010.09.019

Lorenz, R.D., Stiles, B.W., Kirk, R.L., Allison, M.D., Persidel Marmo, P., Iess, L., Lunine, J.I., Ostro, S.J., Hensley, S.: Titan's rotation reveals an internal Ocean and changing zonal winds. Science **319**, 1649–1651 (2008). doi:10.1126/science.1151639

LRO Project and LGCWG (2008). A Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter and Lunar Datasets, Version 5, October 1. Available at http://lunar.gsfc.nasa.gov/library/LunCoordWhitePaper-10-08.pdf. Accessed 2010 October 18

Ma, C., Arias, E.F., Eubanks, T.M., Fey, A.L., Gontier, A.-M., Jacobs, C.S., Sovers, O.J., Archinal, B.A., Charlot, P.: The international celestial reference frame as realized by very long baseline interferometry. Astron. J. **116**, 516–546 (1998)

Margot, J.-L.: A Mercury orientation model including non-zero obliquity and librations. Celest. Mech. Dyn. Astron. **105**, 329–336 (2009). doi:10.1007/s10569-009-9234-1

McCarthy, D.D., Petit, G.: IERS Conventions (2003), IERS Technical Note no. 32, IERS Conventions Centre, U.S. Naval Observatory and Bureau International des Poids et Mesures (2004). Available on-line from http://www.iers.org/IERS/EN/DataProducts/Conventions/conventions.html?__nnn=true. Accessed 2010 October 18

Miller, J.K., Konopliv, A.S., Antreasian, P.G., Bordi, J.J., Chesley, S., Helfrich, C.E., Owen, W.M., Wang, T.C., Williams, B.G., Yeomans, D.K., Scheeres, D.J.: Determination of shape, gravity, and rotational state of asteroid 433 Eros. Icarus **155**, 3–17 (2002)

Moritz, H.: Geodetic Reference System 1980. In: Tscherning, C.C. (ed.) The Geodesist's Handbook 1984, Bulletin Géodésique, **58**(3), pp. 388–398 (1980)

Nimmo, F., Thomas, P.C., Pappalardo, R.T., Moore, W.B.: The global shape of Europa: constraints on lateral shell thickness variations. Icarus **191**, 183–192 (2007)

Ostro, S.J., Hudson, R.S., Nolan, M.C., Margot, J.-L., Scheeres, D.J., Campbell, D.B., Magri, C., Giosini, J.D., Yeomans, D.K.: Radar observations of asteroid 216 kleopatra. Science **288**, 836–839 (2000)

Porco, C.C., Thomas, P.C., Weiss, J.W., Richardson, D.C.: Saturn's small inner satellites: clues to their origins. Science **318**, 1602–1607 (2007). doi:10.1126/science.1143977

Riddle, A.C., Warwick, J.W.: Redefinition of system III longitude. Icarus **27**, 457–459 (1976)

Roatsch, T., Wählisch, M., Giese, B., Hoffmeister, A., Matz, K.-D., Scholten, F., Kuhn, A., Wagner, R., Neukum, G., Helfenstein, P., Porco, C.C.: High-resolution Enceladus atlas derived from Cassini-ISS images. Planet. Space Sci. **56**, 109–116 (2008)

Roatsch, T., Wählisch, M., Hoffmeister, A., Matz, K.-D., Scholten, F., Kersten, E., Wagner, R., Denk, T., Neukum, G., Porco, C.C.: High-resolution Dione atlas derived from Cassini-ISS images. Planet. Space Sci. **56**, 1499–1505 (2008)

Roatsch, Th., Jaumann, R., Stephan, K., Thomas, P.C.: Cartographic mapping of the Icy satellites using ISS and VIMS data. In: Dougherty, et al. (eds.) Saturn from Cassini-Huygens. Springer, Berlin (2009a). doi:10.1007/978-1-4020-9215-2

Roatsch, Th., Wählisch, M., Hoffmeister, A., Kersten, E., Matz, K.-D., Scholten, F., Wagner, R., Denk, T., Neukum, G., Helfenstein, P., Porco, C.: High-resolution Atlases of Mimas, Tethys, and Iapetus derived from Cassini-ISS images. Planet. Space Sci. **57**, 83–92 (2009b). doi:10.1016/j.pss.2008.10.014

Robinson, M.S., Davies, M.E., Colvin, T.R., Edwards, K.: A revised control network for Mercury. JGR **104**(E12), 847–852 (1999)

Roncoli, R.: Lunar Constants and Models Document. JPL D-32296 (2005), available at http://ssd.jpl.nasa.gov/?lunar_doc. Accessed 2010 October 18

Russell, C.T., Yu, Z.J., Kivelson, M.G.: The Rotation Period of Jupiter. GRL **28**(10), 1911–1912 (2001)

Russell, C.T., Dougherty, M.K.: Magnetic Fields of the Outer Planets, SSR. January (2010). doi:10.1007/s11214-009-9621-7

Schmidt, B.E., Thomas, P.C., Bauer, J.M., Li, J.-Y., McFadden, L.A., Mutchler, M.J., Radcliffe, S.C., Rivkin, A.S., Russell, C.T., Parker, J.Wm., Stern, S.A.: The shape and surface variation of 2 Pallas from the Hubble Space Telescope. Science **326**, 275–278 (2009). doi:10.1126/science.1177734

Seidelmann, P.K., Abalakin, V.K., Bursa, M., Davies, M.E., de Bergh, C., Lieske, J.H., Oberst, J., Simon, J.L., Standish, E.M., Stooke, P., Thomas, P.C.: Report of the IAU/IAG working group on cartographic coordinates and rotational elements of the planets and satellites: 2000. Celest. Mech. Dyn. Astron. **82**, 83–110 (2002)

Seidelmann, P.K., Archinal, B.A., A'Hearn, M.F., Cruikshank, D.P., Hilton, J.L., Keller, H.U., Oberst, J., Simon, J.L., Stooke, P., Tholen, D.J., Thomas, P.C.: Report on the IAU/IAG working group on cartographic coordinates and rotational elements: 2003. Celest. Mech. Dyn. Astron. **91**, 203–215 (2005)

Seidelmann, P.K., Archinal, B.A., A'Hearn, M.F., Conrad, A., Consolmagno, G.J., Hestroffer, D., Hilton, J.L., Krasinsky, G.A., Neumann, G., Oberst, J., Stooke, P., Tedesco, E., Tholen, D.J., Thomas, P.C., Williams, I.P.: Report of the IAU/IAG working group on cartographic coordinates and rotational elements: 2006. Celest. Mech. Dyn. Astron. **98**, 155–180 (2007)

Smith, D., Neumann, B., Arvidson, R.E. Guinness, E.A., Slavney, S.: Mars global surveyor laser altimeter mission experiment gridded data record. NASA Planetary Data System, MGS-M-MOLA-5-MEG-DR-L3-V1.0, 2003. Available on-line from http://pds-geosciences.wustl.edu/missions/mgs/megdr.html. Accessed 2010 October 18

Stevenson, D.J.: A new spin on Saturn. Nature **441**, 35–344 (2006)

Stiles, B.W., Kirk, R.L., Lorenz, R.D., Hensley, S., Lee, E., Ostro, S.J., Allison, M.D., Callahan, P.S., Gim, Y., Iess, L., Percidel Marmo, P., Hamilton, G., Johnson, W.T.K., West, R.D.: The Cassini RADAR Team: Determining Titan's spin state from Cassini RADAR images. Astron. J. **135**, 1669–1680 (2008). doi:10.1088/0004-6256/135/5/1669

Stiles, B.W., Kirk, R.L., Lorenz, R.D., Hensley, S., Lee, E., Ostro, S.J., Allison, M.D., Callahan, P.S., Gim, Y., Iess, L., Percidel Marmo, P., Hamilton, G., Johnson, W.T.K., West, R.D.: The Cassini RADAR Team: ERRATUM: Determining Titan's Spin State from Cassini RADAR Images. Astronomical Journal **139**, 311 (2010). doi:10.1088/0004-6256/139/1/311

Thomas, P.C.: Gravity, tides, and topography on small satellites and asteroids: Application to surface features of the martian satellites. Icarus **105**, 326–344 (1993)

Thomas, P.C.: Sizes, shapes, and derived properties of the saturnian satellites after the Cassini nominal mission. Icarus **208**, 395–401 (2010). doi:10.1016/j.icarus.2010.01.025

Thomas, P.C., Davies, M.E., Colvin, T.R., Oberst, J., Schuster, P., Neukum, G., Carr, M.H., McEwen, A., Schubert, G., Belton, M.J.S.: The shape of Io from Galileo limb measurements. Icarus **135**, 175–180 (1998)

Thomas, P.C., Parker, J.Wm., McFadden, L.A., Russell, C.T., Stern, S.A., Sykes, M.V., Young, E.F.: Differentiation of the asteroid Ceres as revealed by its shape. Nature **437**, 224–226 (2005)

Thomas, P.C., Veverka, J., Belton, M.J.S., Hidy, A., A'Hearn, M.F., Farnham, T.L., Groussin, O., Li, J.-Y., McFadden, L.A., Sunshine, J., Wellnitz, D., Lisse, C., Schultz, P., Meech, K.J., Delamere, W.A.: The shape, topography, and geology of Tempel 1 from Deep Impact observations. Icarus **187**, 4–15 (2007)

Thomas, P.C., Joseph, J., Carcich, B., Veverka, J., Clark, B.E., Bell, J.F., Byrd, A.W., Chomko, R., Robinson, M., Murchie, S., Prockter, L., Cheng, A., Izenberg, N., Malin, M., Chapman, C., McFadden, L.A., Kirk, R., Gaffey, M., Lucey, P.G.: Eros: shape, topography, and slope processes. Icarus **155**, 18–37 (2002)

Williams, J.G., Boggs, D.H., Folkner, W.M.: DE421 Lunar Orbit, Physical Librations, and Surface Coordinates. JPL Interoffice Memorandum IOM 335-JW,DB,WF-20080314-001, 14 March (2008). Available as ftp://ssd.jpl.nasa.gov/pub/eph/planets/ioms/de421_moon_coord_iom.pdf. Accessed 2010 October 18

Willner, K., Oberst, J., Hussmann, H., Giese, B., Hoffmann, H., Matz, K.-D., Roatsch, T., Duxbury, T.: Phobos control point network, rotation, and shape. Earth Planet. Sci. Lett. **294**, 541–546 (2010)

Yu, Z.J., Russell, C.T.: Rotation Period of Jupiter from the observation of its magnetic field. GRL **36**, L20202 (2009). doi:10.1029/2009GL040094

Zebker, H.A., Stiles, B., Hensley, S., Lorenz, R., Kirk, R.L., Lunine, J.: Size and shape of Saturn's moon Titan. Science **324**, 921–923 (2009)