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Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015

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Abstract This report continues the practice where the IAU Working Group on Cartographic Coordinates and Rotational Elements revises recommendations regarding those topics for the planets, satellites, minor planets, and comets approximately every 3 years. The Working

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Group has now become a "functional working group" of the IAU, and its membership is open to anyone interested in participating. We describe the procedure for submitting questions about the recommendations given here or the application of these recommendations for creating a new or updated coordinate system for a given body. Regarding body orientation, the following bodies have been updated: Mercury, based on MESSENGER results; Mars, along with a refined longitude definition; Phobos; Deimos; (1) Ceres; (52) Europa; (243) Ida; (2867) Šteins; Neptune; (134340) Pluto and its satellite Charon; comets 9P/Tempel 1, 19P/Borrelly, 67P/Churyumov–Gerasimenko, and 103P/Hartley 2, noting that such information is valid only between specific epochs. The special challenges related to mapping 67P/Churyumov–Gerasimenko are also discussed. Approximate expressions for the Earth have been removed in order to avoid confusion, and the low precision series expression for the Moon's orientation has been removed. The previously online only recommended orientation model for (4) Vesta is repeated with an explanation of how it was updated. Regarding body shape, text has been included to explain the expected uses of such information, and the relevance of the cited uncertainty information. The size of the Sun has been updated, and notation added that the size and the ellipsoidal axes for the Earth and Jupiter have been recommended by an IAU Resolution. The distinction of a reference radius for a body (here, the Moon and Titan) is made between cartographic uses, and for orthoprojection and geophysical uses. The recommended radius for Mercury has been updated based on MESSENGER results. The recommended radius for Titan is returned to its previous value. Size information has been updated for 13 other Saturnian satellites and added for Aegaeon. The sizes of Pluto and Charon have been updated. Size information has been updated for (1) Ceres and given for (16) Psyche and (52) Europa. The size of (25143) Itokawa has been corrected. In addition, the discussion of terminology for the poles (hemispheres) of small bodies has been modified and a discussion on cardinal directions added. Although they continue to be used for planets and their satellites, it is assumed that the planetographic and planetocentric coordinate system definitions do not apply to small bodies. However, planetocentric and planetodetic latitudes and longitudes may be used on such bodies, following the right-hand rule. We repeat our previous recommendations that planning and efforts be made to make controlled cartographic products; newly recommend that common formulations should be used for orientation and size; continue to recommend that a community consensus be developed for the orientation models of Jupiter and Saturn; newly recommend that historical summaries of the coordinate systems for given bodies should be developed, and point out that for planets and satellites planetographic systems have generally been historically preferred over planetocentric systems, and that in cases when planetographic coordinates have been widely used in the past, there is no obvious advantage to switching to the use of planetocentric coordinates. The Working Group also requests community input on the question submitting process, posting of updates to the Working Group website, and on whether recommendations should be made regarding exoplanet coordinate systems.

Keywords Cardinal directions · Cartographic coordinates · Coordinate systems · Coordinate frames · Longitude · Latitude · Planetographic · Planetocentric · Rotation axes · Rotation periods · Sizes · Shapes · Planets · Satellites · Dwarf planets · Minor planets · Asteroids · Comets

1 Introduction

The International Astronomical Union (IAU) Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites was established by 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. Following a lack of formal communication with the IAG over several years, that affiliation was dropped. It may be re-established in the future. Currently, within the IAU, the Working Group is a joint working group of Divisions A and F, 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 were presented in that report and its appendices. The complete list of Working Group reports is listed in the table below. In 2003 the name of the Working Group was shortened to the Working Group on Cartographic Coordinates and Rotational Elements.

In 2016 the Working Group became a "Functional Working Group", whose scope and purpose are institutional and naturally extend beyond the IAU 3-year cycle (IAU 2016). Such groups would have the "main responsibility of [providing] state-of-the-art deliverables: standards, references; tools for education, related software (VO), etc., with an official IAU stamp, for universal use" (IAU 2012). The Working Group will continue to serve in the area of standards.

Also in 2016, working with the Presidents of Divisions A and F, the Working Group agreed to open its membership to essentially anyone interested in helping with its work. New members will be welcome at any time. However, the Working Group will at some regular intervals, likely when a new version of the report is finished or at the time of a General Assembly, make appropriate announcements inviting new members to join. We would ask only what expertise applicants feel they are bringing to the Working Group and how they plan to contribute to our main report. In the quite unlikely case of a serious objection to someone joining, the applicant would only be turned down after a vote by the Working Group and the approval of the Division A and F Presidents. Should the Working Group be blessed with a large number of new members, we would develop procedures to split up the Working Group to create our reports, answer questions from individuals, editors, instrument teams, missions, and space agencies, and do other public and community outreach. Anyone interested in joining the Working Group should contact the Chair or Vice-Chair.

The following table provides references to all of the Working Group 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	**109**, 101–135 (Archinal et al. 2011a)
–	(Erratum to 10 and 11)	**110**, 401–403 (Archinal et al. 2011b)
–	(4) Vesta system	(Archinal et al. 2013b)
12	Beijing in 2012	No report
13	Honolulu in 2015	This paper

Reprints and preprints of the previous reports and this report can be found at the Working Group website: https://astrogeology.usgs.gov/groups/iau-wgccre. Previous reports are also available at https://link.springer.com/journal/10569.

The impetus for the Working Group was the 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” (IAU 1977, p. 144). Since its first report (Davies et al. 1980), this Working Group’s purpose has remained unchanged, except for the recognition of the need to include, beginning with the 2003 report, small solar system bodies.

The Working Group’s mission is to make 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 may select among different such determinations. The Working Group does not verify or validate such determinations because of a lack of the resources. Our recommendations are from the Working Group alone, not from the full IAU. The Working Group has no “enforcement” mechanism to assure that its recommendations are followed. The value of these recommendations is from their development by international consensus and adoption by the planetary community.

Other organizations have since referenced these recommendations, e.g., as standards to be followed (PDS 2009, Chapter 2), or by providing services to make it easier to implement the numerical use of recommendations made here (NAIF 2013, 2014).

These recommendations should be followed in cases where standardization is useful. It is not our intention to limit science or the state of the art. They should be followed so that products can be more easily compared and multiple datasets appropriately registered. If a user has sufficient data to significantly improve the recommended models or values, then such updates should be used, following the conventions described here. (It may be useful to make alternative products using old and new models for comparison purposes).

This type of action is almost always necessary when updated parameter estimates are derived, because there will be some delay before our next report is published or our website is updated (see below). We encourage the publication of such updates in the peer-reviewed literature at the earliest opportunity. A document prepared by the Planetary Data System (PDS) Small Bodies Node describes the requirements for proper documentation of any new or updated coordinate system model (PDS 2014). Proper documentation is necessary for the Working Group to consider, recommend, and reference them in our next report. Also others will become aware of such updates, and can use them in the interim.

At the request of various individuals and missions, the Working Group will consider evaluating whether proposed updates or new systems follow the conventions described here and will consider providing interim updates to its recommendations via its website. This service is to address the need to update recommendations and consider proposed updates or new systems between Working Group reports. As described below, in recent years the Working Group has made formal recommendations outside of our reports three times, all relative to the coordinate system for Vesta. This included making recommendations twice directly to the Dawn mission, and making a formal recommendation on our website as to the preferred coordinate system (Archinal et al. 2013b).

Based on this experience and other input, our current procedures are as follows. If any individual researcher or group (e.g., instrument team, mission, PDS, space agency), hereafter the *requestor*, has questions about the recommendations given here or the application of these recommendations for creating a new or updated coordinate system for a given body, we would prefer they first informally address such questions to the Working Group Chair or Vice-Chair. Those individuals will then provide an informal response, consulting the rest of the Working

Group as needed, with their interpretation of the recommendations. Should the requestor feel the response is inadequate or disagrees with it, they can request a formal response from the Working Group. This should be done by preparing a written request, including as appropriate any information on a new or updated coordinate system. Examples of the kind of information required can be seen here in the report and also, for example, in a document prepared by the PDS (2014). The Working Group will discuss the request and seek out additional information from the requestor or others as needed. At the completion of its consideration, the Working Group will provide a formal response to the requestor. The requestor should allow up to 4 weeks for such a response, and possibly longer if additional information is required. Both the request and the response will be published on the Working Group website, and likely referenced in future Working Group reports. If the requestor disagrees with the Working Group response, the requestor is free to discuss any concerns with the Presidents of the IAU Divisions A and F that oversee the Working Group.

If the Working Group agrees that there is a need to formally recommend the use of a newly proposed coordinate system prior to the issuance of one of our regular reports, e.g., due to a need to decide between multiple systems or possible non-IAU compliant systems, for the benefit of multiple groups or space agencies, then we may post on our website such a recommendation, as we did regarding the coordinate system for Vesta (Archinal et al. 2013b) and an appropriate public announcement made via the IAU e-Newsletter (https://www.iau.org/publications/e-newsletters/). Such a recommendation will also again be incorporated, or updated if appropriate, in our next published report. The posting of recommendations to our website is not intended to remove the need for our regular reports. Any recommendations originally posted to our website will also again be incorporated, or updated if appropriate, in our next report. We will continue to include the bulk of any new recommendations or changes to our recommendations in these reports, only placing time-critical ones on our website. Input for updates and comment on these procedures from the community is welcome, particularly from missions and other working groups.

The Working Group does not deal with issues related to mapping product formats. Such issues have largely been left to individual map developers, archiving organizations such as the PDS, the International Planetary Data Alliance, and the NASA Mars Geodesy and Cartography Working Group (MGCWG; Duxbury et al. 2001, 2002) and (now inactive) Lunar Geodesy and Cartography Working Group (Archinal (2009)) and individual missions. Input from such organizations has been welcomed by the Working Group, and the frequency of interaction highlights the strong need for such organizations at mission, space agency, and international levels. The Working Group looks forward to collaborating with the new NASA Mapping and Planetary Spatial Infrastructure Team (MAPSIT; Radebaugh et al. 2017; http://www.lpi.usra.edu/mapsit/) and the new IAU Commission A3 Fundamental Standards (https://www.iau.org/science/scientific_bodies/commissions/A3/).

The 2003 report introduced and recommended a consistent system of coordinates for minor planets (asteroids) and comets. In the 2011 report we extended it to cover dwarf planets. This system is *not* the same as that for planets and satellites. The existence of two different systems has the potential for confusion, but the methods required for other solar system bodies (see Sect. 6) differ sufficiently to justify two different systems. This report includes descriptions of the two systems; planets and satellites (Sects. 2, 3, 5, 7) and other solar system bodies (Sects. 4, 6, 8). Rotational elements (body orientation in inertial space) are covered in Sects. 2 through 6, and cartographic coordinates, e.g., latitude, longitude, and body shape in Sects. 7 and 8). Brief recommendations from the Working Group complete this report (Sect. 9). This report assumes that dwarf planets are the bodies identified as such on the list maintained by the IAU Working Group for Planetary System Nomenclature (WGPSN) and the IAU Committee on Small Body Nomenclature (CSBN) (2015b). Changes made since the previous report are listed in Sect. 10.

2 Definition of rotational elements for planets and satellites

Planetary coordinate systems are defined relative to their mean axis of rotation and body-dependent definitions of longitude. The longitude systems of most of those bodies with observable rigid surfaces have been defined by reference 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 epochless. There is a small (well under 0.1 arcs) rotation between the ICRF and the mean dynamical frame of J2000.0.

Variable quantities are expressed in units of days (86,400 s) or Julian centuries (36,525 days) from the epoch J2000.0.[1] The reference time scale is Barycentric Dynamical Time from the French Temps Dynamique Barycentrique (TDB). 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 from the French Temps Terrestre (TT) in epoch and rate. UTC, Barycentric Coordinate Time from the French Temps Cordonnée Barycentrique (TCB), and Geocentric Coordinate Time from the French Temps Coordonnée Géocentrique (TCG) differ from TT in epoch and rate. For more information on reference systems and time scales, see The Explanatory Supplement to the Astronomical Almanac (Urban and Seidelmann 2012) , Kovalevsky and Seidelmann (2004), https://www.iers.org, http://rorf.usno.navy.mil/ICRF/, or http://aa.usno.navy.mil/faq/docs/ICRS_doc.php.

The north pole is that pole of rotation that lies on the north side of the *invariable plane* of the solar system. Its direction is specified by the values of its right ascension α_0 and declination δ_0. The two nodes of the body's equator on the ICRF equator are at $\alpha_0 \pm 90°$. In Fig. 1, the node Q is defined as the node at $\alpha_0 + 90°$. The prime meridian is defined so that it crosses the body's equator at the point B. The location of B is determined by the value for W, the angle measured *easterly* along the body's equator from the Q to B. The inclination of the planet's equator to the celestial equator is $90° - \delta_0$. As long as the planet rotates uniformly, W varies nearly linearly with time. The parameters $\alpha_{0,}\, \delta_0$, and W may vary with time due to a precession of the axis of rotation of the planet or satellite. 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, the axis of rotation is assumed to be normal to the mean orbital plane of the planet or the satellite. Most satellites fall into this category. For many satellites, it is assumed that the rotation rate is synchronous (i.e., equal to the mean orbital period). In some cases, this is only an assumption that still needs to be validated.

The angle W specifies the ephemeris position of the prime meridian and W_0 is the value of W at J2000.0 (or occasionally, such as for comets, some other specified epoch). For planets or satellites with no accurately observable fixed surface features, the expression for W defines the prime meridian and is not subject to correction for this reason. The rotation rate may be redefined by some other physical property (e.g., observation of the rotation of the body's magnetic field). Where the cartographic position of the prime meridian is defined by an observable feature, the expression for W is chosen so that the ephemeris position follows the

[1] JD 2451545.0 (2000 January 1 12.0 h).

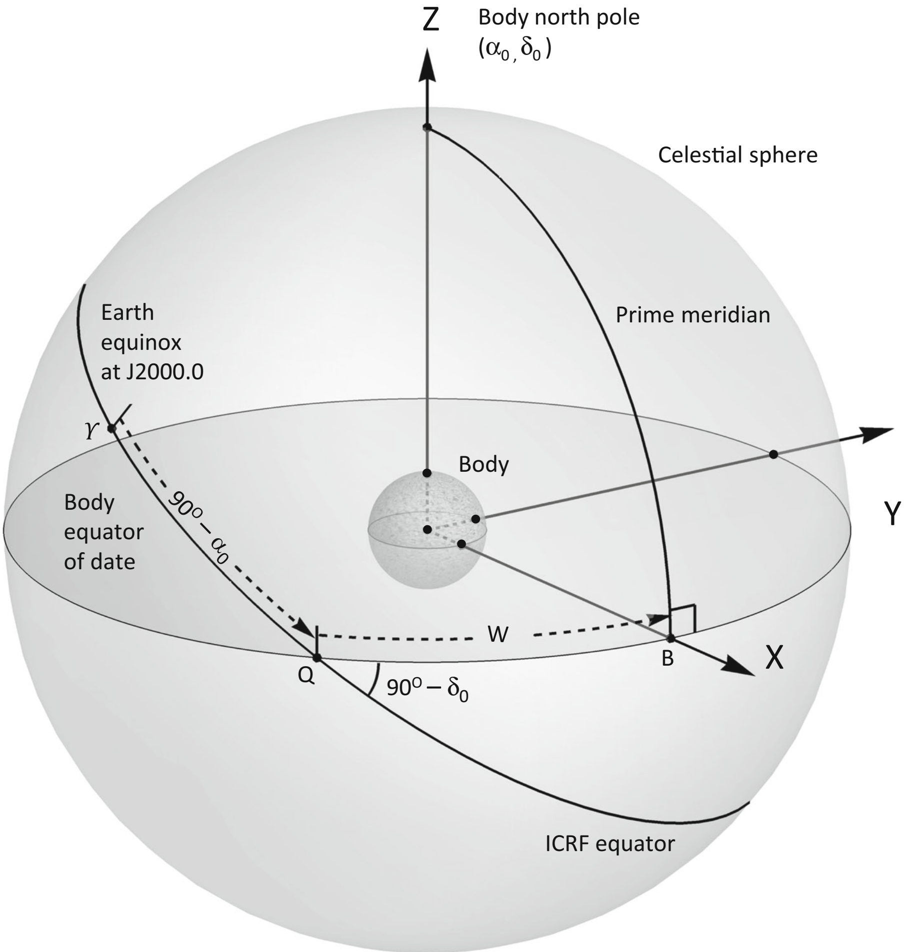

Fig. 1 Reference system used to define orientation of the planets and their satellites. For $\dot{W}(t) > 0$, body rotation is prograde (e.g., Mercury, Jupiter). For $\dot{W}(t) < 0$, body rotation is retrograde (e.g., Venus, Uranus)

motion of the feature as closely as possible. When higher accuracy mapping is done or a new value for W is derived, the longitude of the defining feature *must* be maintained. Bodies with 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)—*once an observable feature is chosen to define the longitude system, that system should not change except under extraordinary circumstances. For example, a few solar system bodies such as Io and various comet nuclei are known to be geologically active at the present time, so it is conceivable that surface processes could render a small reference feature unidentifiable and necessitate the choice of a new (but consistent) reference*. Once such a feature has been adopted, the determination of W_0 relative to some other feature should be avoided. This prescription does not preclude the use of a smaller or more precisely determined feature, multiple features, or even human artifacts to define longitude, *as long as the original definition is maintained to within the accuracy of previous determinations*. For

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 $\alpha_0 = 273^\circ.85$, $\delta_0 = 66^\circ.99$
$T =$	Interval in Julian centuries (36,525 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 h TDB	
Sun	$\alpha_0 = 286^\circ.13$ $\delta_0 = 63^\circ.87$ $W = 84^\circ.176 + 14^\circ.1844000d^{(a)}$
Mercury	$\alpha_0 = 281.0103 - 0.0328\,T$ $\delta_0 = 61.4155 - 0.0049\,T$ $W = 329.5988 \pm 0.0037 + 6.1385108d$ $+ 0^\circ.01067257 \sin M1$ $- 0^\circ.00112309 \sin M2$ $- 0^\circ.00011040 \sin M3$ $- 0^\circ.00002539 \sin M4$ $- 0^\circ.00000571 \sin M5$
where	$M1 = 174^\circ.7910857 + 4^\circ.092335d$ $M2 = 349^\circ.5821714 + 8^\circ.184670d$ $M3 = 164^\circ.3732571 + 12^\circ.277005d$ $M4 = 339^\circ.1643429 + 16^\circ.369340d$ $M5 = 153^\circ.9554286 + 20^\circ.461675d^{(b)}$
Venus	$\alpha_0 = 272.76$ $\delta_0 = 67.16$ $W = 160.20 - 1.4813688d^{(c)}$
Mars	$\alpha_0 = 317.269202 - 0.10927547T$ $+ 0.000068 \sin(198.991226 + 19139.4819985T)$ $+ 0.000238 \sin(226.292679 + 38280.8511281T)$ $+ 0.000052 \sin(249.663391 + 57420.7251593T)$ $+ 0.000009 \sin(266.183510 + 76560.6367950T)$ $+ 0.419057 \sin(79.398797 + 0.5042615T)$ $\delta_0 = 54.432516 - 0.05827105T$ $+ 0.000051 \cos(122.433576 + 19139.9407476T)$ $+ 0.000141 \cos(43.058401 + 38280.8753272T)$ $+ 0.000031 \cos(57.663379 + 57420.7517205T)$ $+ 0.000005 \cos(79.476401 + 76560.6495004T)$ $+ 1.591274 \cos(166.325722 + 0.5042615T)$ $W = 176.049863 + 350.891982443297d$ $+ 0.000145 \sin(129.071773 + 19140.0328244T)$ $+ 0.000157 \sin(36.352167 + 38281.0473591T)$ $+ 0.000040 \sin(56.668646 + 57420.9295360T)$ $+ 0.000001 \sin(67.364003 + 76560.2552215T)$ $+ 0.000001 \sin(104.792680 + 95700.4387578T)$ $+ 0.584542 \sin(95.391654 + 0.5042615T)^{(d)}$
Jupiter	$\alpha_0 = 268.056595 - 0.006499T + 0^\circ.000117 \sin Ja + 0^\circ.000938 \sin Jb$ $+ 0.001432 \sin Jc + 0.000030 \sin Jd + 0.002150 \sin Je$ $\delta_0 = 64.495303 + 0.002413T + 0.000050 \cos Ja + 0.000404 \cos Jb$ $+ 0.000617 \cos Jc - 0.000013 \cos Jd + 0.000926 \cos Je$ $W = 284.95 + 870.5360000d^{(e)}$
where	$Ja = 99^\circ.360714 + 4850^\circ.4046T$, $Jb = 175^\circ.895369 + 1191^\circ.9605T$, $Jc = 300^\circ.323162 + 262^\circ.5475T$, $Jd = 114^\circ.012305 + 6070^\circ.2476T$, $Je = 49^\circ.511251 + 64^\circ.3000T$

Table 1 continued

α_0, δ_0	Are ICRF equatorial coordinates at epoch J2000.0 Approximate coordinates of the north pole of the invariable plane are $\alpha_0 = 273^\circ.85$, $\delta_0 = 66^\circ.99$
$T=$	Interval in Julian centuries (36,525 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 h TDB	
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	$\alpha_0 = 299.36 + 0.70 \sin N$ $\delta_0 = 43.46 - 0.51 \cos N$ $W = 249.978 + 541.1397757d - 0.48 \sin N$ $N = 357.85 + 52.316T^{(f)}$

(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 of Mercury is defined by the crater Hun Kal
(c) The 0° meridian of Venus is defined by the central peak in the crater Ariadne
(d) The longitude of the Viking 1 lander on Mars is defined to be 47°.95137 west (Kuchynka et al. 2014), maintaining the 0° meridian through the crater Airy-0
(e) The equations for W for Jupiter, Saturn, and Uranus refer to the rotation of their magnetic fields (System III). On Jupiter, System I ($W_I = 67^\circ.1 + 877^\circ.900d$) refers to the mean atmospheric equatorial rotation; System II ($W_{II} = 43^\circ.3 + 870^\circ.270d$) 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
(f) The equations for Neptune refer to the rotation of optically observed features in the Neptunian atmosphere (System II), while still using the previous expressions for pole position and precession

example, de Vaucouleurs et al. (1973) redefined the origin for longitude for Mars from the large feature, then known as Sinus Meridiani, to the small crater Airy-0. In this report, we further refine that definition by fixing the longitude of the Viking 1 lander.

Tables 1 and 2 give recommended expressions for α_0, δ_0, and W, in celestial equatorial coordinates, for the planets and satellites. These expressions are generally accurate to one-tenth of a degree. Two decimal digits are given to assure consistency. Zeros have sometimes been appended to values of $\dot{W}$ for computational consistency when compared to the derived spin rate at a given epoch and are not an indication of significant accuracy when far from that epoch. The expressions for Mercury, Mars, Saturn, and Uranus contain additional digits, reflecting a greater confidence in their accuracy. Expressions for the Sun are given to a precision similar to those of the other bodies of the solar system. These solar expressions are for comparative purposes only.[2] These recommendations do not imply that other coordinate systems with different rotational elements cannot be used for planetary bodies for other 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. Such coordinate systems are used for the Moon and Mercury (Margot 2009). It is also possible, depending, for example, on the observational mode and

[2] Previous reports also included approximate expressions for the Earth. Their accuracy was poor, and the expressions failed near the fundamental epoch (J2000.0), yet they were sometimes used as a recommended model. Users should refer to the International Earth Rotation and Reference Systems Service (IERS, https://www.iers.org) for appropriate models of the Earth's rotation.

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 h TDB)

Earth:		Moon	See Sect. 3
Mars:	I	Phobos	$\alpha_0 = 317.67071657 - 0.10844326\mathrm{T}$ $- 1.78428399 \sin(\mathrm{M1}) + 0.02212824 \sin(\mathrm{M2})$ $- 0.01028251 \sin(\mathrm{M3}) - 0.00475595 \sin(\mathrm{M4})$ $\delta_0 = 52.88627266 - 0.06134706\mathrm{T}$ $- 1.07516537 \cos(\mathrm{M1}) + 0.00668626 \cos(\mathrm{M2})$ $- 0.00648740 \cos(\mathrm{M3}) + 0.00281576 \cos(\mathrm{M4})$ $\mathrm{W} = 34.9964842535 + 1128.84475928d + 12.72192797\mathrm{T}^2$ $+ 1.42421769 \sin(\mathrm{M1}) - 0.02273783 \sin(\mathrm{M2})$ $+ 0.00410711 \sin(\mathrm{M3}) + 0.00631964 \sin(\mathrm{M4})$ $+ 1.143 \sin(\mathrm{M5})$
	II	Deimos	$\alpha_0 = 316.65705808 - 0.10518014\mathrm{T}$ $+ 3.09217726 \sin(\mathrm{M6}) + 0.22980637 \sin(\mathrm{M7})$ $+ 0.06418655 \sin(\mathrm{M8}) + 0.02533537 \sin(\mathrm{M9})$ $+ 0.00778695 \sin(\mathrm{M10})$ $\delta = 53.50992033 - 0.05979094\mathrm{T}$ $+ 1.83936004 \cos(\mathrm{M6}) + 0.14325320 \cos(\mathrm{M7})$ $+ 0.01911409 \cos(\mathrm{M8}) - 0.01482590 \cos(\mathrm{M9})$ $+ 0.00192430 \cos(\mathrm{M10})$ $\mathrm{W} = 79.39932954 + 285.16188899d$ $- 2.73954829 \sin(\mathrm{M6}) - 0.39968606 \sin(\mathrm{M7})$ $- 0.06563259 \sin(\mathrm{M8}) - 0.02912940 \sin(\mathrm{M9})$ $+ 0.01699160 \sin(\mathrm{M10})$
	where	$\mathrm{M1} = 190.72646643 + 15917.10818695\mathrm{T}$ $\mathrm{M2} = 21.46892470 + 31834.27934054\mathrm{T}$ $\mathrm{M3} = 332.86082793 + 19139.89694742\mathrm{T}$ $\mathrm{M4} = 394.93256437 + 38280.79631835\mathrm{T}$ $\mathrm{M5} = 189.63271560 + 41215158.18420050\mathrm{T}$ $+ 12.71192322\mathrm{T}^2$ $\mathrm{M6} = 121.46893664 + 660.22803474\mathrm{T}$ $\mathrm{M7} = 231.05028581 + 660.99123540\mathrm{T}$ $\mathrm{M8} = 251.37314025 + 1320.50145245\mathrm{T}$ $\mathrm{M9} = 217.98635955 + 38279.96125550\mathrm{T}$ $\mathrm{M10} = 196.19729402 + 19139.83628608\mathrm{T}$	
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	$\alpha_0 = 268.05 - 0.009T + 0.094 \sin J3 + 0.024 \sin J4$ $\delta_0 = 64.50 + 0.003T + 0.040 \cos J3 + 0.011 \cos J4$ $W = 200.39 + 203.4889538d - 0.085 \sin J3 - 0.022 \sin J4$ [(a)]

Table 2 continued

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 h TDB)			
	II	Europa	$\alpha_0 = 268.08 - 0.009T + 1.086 \sin J4 + 0.060 \sin J5 + 0.015 \sin J6 + 0.009 \sin J7$ $\delta_0 = 64.51 + 0.003T + 0.468 \cos J4 + 0.026 \cos J5 + 0.007 \cos J6 + 0.002 \cos J7$ $W = 36.022 + 101.3747235d - 0.980 \sin J4 - 0.054 \sin J5 - 0.014 \sin J6 - 0.008 \sin J7$[b]
	III	Ganymede	$\alpha_0 = 268.20 - 0.009T - 0.037 \sin J4 + 0.431 \sin J5 + 0.091 \sin J6$ $\delta_0 = 64.57 + 0.003T - 0.016 \cos J4 + 0.186 \cos J5 + 0.039 \cos J6$ $W = 44.064 + 50.3176081d + 0.033 \sin J4 - 0.389 \sin J5 - 0.082 \sin J6$[c]
	IV	Callisto	$\alpha_0 = 268.72 - 0.009T - 0.068 \sin J5 + 0.590 \sin J6 + 0.010 \sin J8$ $\delta_0 = 64.83 + 0.003T - 0.029 \cos J5 + 0.254 \cos J6 - 0.004 \cos J8$ $W = 259.51 + 21.5710715d + 0.061 \sin J5 - 0.533 \sin J6 - 0.009 \sin J8$[d]
		where	$Jl = 73°.32 + 91472°.9T$, $J2 = 24°.62 + 45137°.2T$, $J3 = 283°.90 + 4850°.7T$, $J4 = 355.80 + 1191.3T$, $J5 = 119.90 + 262.1T$, $J6 = 229.80 + 64.3T$, $J7 = 352.25 + 2382.6T$, $J8 = 113.35 + 6070.0T$
Saturn:	XVIII	Pan	$\alpha_0 = 40.6 - 0.036T$ $\delta_0 = 83.5 - 0.004T$ $W = 48.8 + 626.0440000d$
	XV	Atlas	$\alpha_0 = 40.58 - 0.036T$ $\delta_0 = 83.53 - 0.004T$ $W = 137.88 + 598.3060000d$
	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	$\alpha_0 = 40.58 - 0.036T - 3.153 \sin S1 + 0.086 \sin 2S1$ $\delta_0 = 83.52 - 0.004T - 0.356 \cos S1 + 0.005 \cos 2S1$ $W = 293.87 + 518.4907239d + 3.133 \sin S1 - 0.086 \sin 2S1$[e]
	X	Janus	$\alpha_0 = 40.58 - 0.036T - 1.623 \sin S2 + 0.023 \sin 2S2$ $\delta_0 = 83.52 - 0.004T - 0.183 \cos S2 + 0.001 \cos 2S2$ $W = 58.83 + 518.2359876d + 1.613 \sin S2 - 0.023 \sin 2S2$[e]
	I	Mimas	$\alpha_0 = 40.66 - 0.036T + 13.56 \sin S3$ $\delta_0 = 83.52 - 0.004T - 1.53 \cos S3$ $W = 333.46 + 381.9945550d - 13.48 \sin S3 - 44.85 \sin S5$[f]
	II	Enceladus	$\alpha_0 = 40.66 - 0.036T$ $\delta_0 = 83.52 - 0.004T$ $W = 6.32 + 262.7318996d$[g]
	III	Tethys	$\alpha_0 = 40.66 - 0.036T + 9.66 \sin S4$ $\delta_0 = 83.52 - 0.004T - 1.09 \cos S4$ $W = 8.95 + 190.6979085d - 9.60 \sin S4 + 2.23 \sin S5$[h]
	XIII	Telesto	$\alpha_0 = 50.51 - 0.036T$ $\delta_0 = 84.06 - 0.004T$ $W = 56.88 + 190.6979332d$[e]

Table 2 continued

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 h TDB)			
	XIV	Calypso	$\alpha_0 = 36.41 - 0.036T$ $\delta_0 = 85.04 - 0.004T$ $W = 153.51 + 190.6742373d$ [e]
	IV	Dione	$\alpha_0 = 40.66 - 0.036T$ $\delta_0 = 83.52 - 0.004T$ $W = 357.6 + 131.5349316d$ [i]
	XII	Helene	$\alpha_0 = 40.85 - 0.036T$ $\delta_0 = 83.34 - 0.004T$ $W = 245.12 + 131.6174056d$
	V	Rhea	$\alpha_0 = 40.38 - 0.036T + 3.10 \sin S6$ $\delta_0 = 83.55 - 0.004T - 0.35 \cos S6$ $W = 235.16 + 79.6900478d - 3.08 \sin S6$ [j]
	VI	Titan	$\alpha_0 = 39.4827$ $\delta_0 = 83.4279$ $W = 186.5855 + 22.5769768d$
	VIII	Iapetus	$\alpha_0 = 318.16 - 3.949T$ $\delta_0 = 75.03 - 1.143T$ $W = 355.2 + 4.5379572d$ [k]
	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	$\alpha_0 = 257.31 - 0.03 \sin U9$ $\delta_0 = -15.18 + 0.03 \cos U9$ $W = 297.46 - 577.3628170d - 0.01 \sin U9$

Table 2 continued

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 h TDB)			
	XV	Puck	$\alpha_0 = 257.31 - 0.33 \sin U10$ $\delta_0 = -15.18 + 0.31 \cos U10$ $W = 91.24 - 472.5450690d - 0.09 \sin Ul0$
	V	Miranda	$\alpha_0 = 257.43 + 4.41 \sin U11 - 0.04 \sin 2U11$ $\delta_0 = -15.08 + 4.25 \cos U11 - 0.02 \cos 2U11$ $W = 30.70 - 254.6906892d - 1.27 \sin U12 + 0.15 \sin 2Ul2$ $+1.15 \sin U11 - 0.09 \sin 2U11$
	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	$\alpha_0 = 257.43 + 0.21 \sin U14$ $\delta_0 = -15.10 + 0.2 \cos U14$ $W = 108.05 - 86.8688923d - 0.09 \sin U12 + 0.06 \sin U14$
	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	$\alpha_0 = 299.36 - 32.35 \sin N7 - 6.28 \sin 2N7 - 2.08 \sin 3N7$ $- 0.74 \sin 4N7 - 0.28 \sin 5N7 - 0.11 \sin 6N7$ $- 0.07 \sin 7N7 - 0.02 \sin 8N7 - 0.01 \sin 9N7$ $\delta_0 = 41.17 + 22.55 \cos N7 + 2.10 \cos 2N7 + 0.55 \cos 3N7$ $+ 0.16 \cos 4N7 + 0.05 \cos 5N7 + 0.02 \cos 6N7$ $+ 0.01 \cos 7N7$ $W = 296.53 - 61.2572637d + 22.25 \sin N7 + 6.73 \sin 2N7$ $+ 2.05 \sin 3N7 + 0.74 \sin 4N7 + 0.28 \sin 5N7$ $+ 0.11 \sin 6N7 + 0.05 \sin 7N7 + 0.02 \sin 8N7$ $+ 0.01 \sin 9N7$

Table 2 continued

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

(a) The 0° meridian of Io is defined by the mean sub-Jovian direction since it is assumed surface features will not last long enough to serve as a long-term reference
(b) The 182° meridian of Europa is defined by the crater Cilix
(c) The 128° meridian of Ganymede is defined by the crater Anat
(d) The 326° meridian of Callisto is defined by the crater Saga
(e) These equations are correct for Janus, Epimetheus, Telesto, and Calypso 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
(f) The 162° meridian of Mimas is defined by the crater Palomides
(g) The 5° meridian of Enceladus is defined by the crater Salih
(h) The 299° meridian of Tethys is defined by the crater Arete
(i) The 63° meridian of Dione is defined by the crater Palinurus
(j) The 340° meridian of Rhea is defined by the crater Tore
(k) The 276° meridian of Iapetus is defined by the crater Almeric

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 the currently known orientation of the dynamically oriented body-fixed frame is possibly more accurately known than that of the established feature fixed frame. When such systems and frames in such systems are used, the relationships between them and the recommended cartographic coordinate system should be derived so that conversions between the systems can be accomplished at some known level of accuracy. This will 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 remapped at improved resolution and accuracy.

3 The lunar coordinate system

The recommended coordinate system for the Moon is the mean Earth/polar axis (ME) system. There is an offset between this system and the principal axis (PA) system, sometimes called the axis of figure system (Davies and Colvin 2000).

The ME system is recommended because nearly all cartographic products have been aligned to it (ibid.). The offset between these coordinate systems of a point on the lunar surface is approximately 860 meters. Previous reports included the rotation and pole position for the ME system using closed formulae in Table 2. We are not continuing to provide those formulae as they are *only* accurate to approximately 150 m (e.g., Konopliv et al. 2001, Fig. 3). For high accuracy work (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.

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 comet

d is the interval in days from the standard epoch, i.e., J2000.0 = JD 2451545.0, i.e., 2000 January 1 12 h TDB or from the given epoch for the listed comets. α_0, δ_0, W, and $\dot{W}$ are as defined in the text

(1) Ceres	$\alpha_0 = 291^\circ.418 \pm 0^\circ.03$ $\delta_0 = 66^\circ.764 \pm 0^\circ.03$ $W = 170^\circ.650 + (952^\circ.1532 \pm 0^\circ.00003)d^{(a)}$
(2) Pallas	$\alpha_0 = 33^\circ$ $\delta_0 = -3^\circ$ $W = 38^\circ + 1105^\circ.8036d^{(b)}$
(4) Vesta	$\alpha_0 = 309^\circ.031 \pm 0^\circ.01$ $\delta_0 = 42^\circ.235 \pm 0^\circ.01$ $W = 285.39^\circ + 1617^\circ.3329428d^{(c)}$
(21) Lutetia	$\alpha_0 = 52^\circ \pm 5^\circ$ $\delta_0 = 12^\circ \pm 5^\circ$ $W = 94^\circ + 1057^\circ.7515d^{(d)}$
(52) Europa	$\alpha_0 = 257^\circ$ $\delta_0 = 12^\circ$ $W = 55^\circ + 1534^\circ.6472187d^{(e)}$
(243) Ida	$\alpha_0 = 168^\circ.76$ $\delta_0 = -87^\circ.12$ $W = 274^\circ.05 + 1864^\circ.6280070d^{(f)}$
(433) Eros	$\alpha_0 = 11^\circ.35 \pm 0^\circ.02$ $\delta_0 = 17^\circ.22 \pm 0^\circ.02$ $W = 326^\circ.07 + 1639^\circ.38864745d^{(g)}$
(511) Davida	$\alpha_0 = 297^\circ$ $\delta_0 = 5^\circ$ $W = 268^\circ.1 + 1684^\circ.4193549d^{(h)\,(i)}$
(951) Gaspra	$\alpha_0 = 9^\circ.47$ $\delta_0 = 26^\circ.70$ $W = 83^\circ.67 + 1226^\circ.9114850d^{(j)}$
(2867) Šteins	$\alpha_0 = 91^\circ \pm 5^\circ$ $\delta_0 = -62^\circ \pm 5^\circ$ $W = 321^\circ.76 + 1428^\circ.09917d^{(k)}$
(25143) Itokawa	$\alpha_0 = 90^\circ.53$ $\delta_0 = -66^\circ.30$ $W = 0^\circ + 712^\circ.143d^{(l)}$
(134340) Pluto	$\alpha_0 = 132^\circ.993$ $\delta_0 = -6^\circ.163$ $W = 302^\circ.695 + 56^\circ.3625225d^{(m)}$
(134340) Pluto : I Charon	$\alpha_0 = 132^\circ.993$ $\delta_0 = -6^\circ.163$ $W = 122^\circ.695 + 56^\circ.3625225d^{(n)}$
9P/Tempel 1	$\alpha_0 = 255^\circ$ $\delta_0 = 64.5^\circ$ (Thomas et al. 2013a) Epoch: DI Impact 2005−07−04 05:45:38.4±2 TDB = JD 2453555.740027 $W = 109^\circ.7 \pm ?^\circ$; $\dot{W} = 211^\circ.849/d$ (o) (Belton et al. 2011) $d^2W/dt^2 = 0^\circ.024/d^2$ (Belton et al. 2011) Epoch: Stardust NExT closest approach 2011−02−15 04:40:18.6 TDB = JD 2455607.694660 $W = 69^\circ.2 \pm ?^\circ$; $\dot{W} = 212^\circ.807/d$ (o) (Veverka et al.(2013))

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 h TDB or from the given epoch for the listed comets. α_0, δ_0, W, and $\dot{W}$ are as defined in the text	
19P/Borrelly	Epoch:1994 – 2001 $\alpha_0 = 218°.5 \pm 3°$ $\delta_0 = -12°.5 \pm 3°$ $\dot{W} = 324°.3/d \pm 7°/\mathrm{d}$
67P/Churyumov–Gerasimenko	Epoch: 2014 Mar 23–2014 Sep 3 $\alpha_0 = 69°.54 \pm 0°.05$ $\delta_0 = 64°.11 \pm 0°.03$ $W = 114°.69 + 696°.543884683/\mathrm{d};\ \pm 0°.1(p)$
103P/Hartley 2 Epoch:	EPOXI Closest Approach 2010−11−04 14:00:53.9 TDB = JD 2455505.083957(q) $\alpha_X = 285°.1$ $\delta_X = -31°.8$ $\alpha_Y = 350°.4$ $\delta_Y = 34°.4$ $\alpha_Z = 226°.1$ $\delta_Z = 39°.4$

(a) The 0° meridian of Ceres is defined by the crater Kait. "The location of this small crater is within the envelope of the broad feature identified in HST data to which the previous system was anchored" (Raymond and Roatsch 2015), with the broad feature being the unnamed bright spot shown in Figure 1 in Thomas et al. (2005) and Figures 5 and 6 at the 0° meridian in Li et al. (2006)
(b) The 0° meridian of Pallas is defined by the direction (positive x) of the long axis of the Carry et al. (2010) shape model
(c) The 146° meridian of Vesta is defined by the crater Claudia. This definition maintains the location of a feature not formally named, but referred to as Olbers Regio by Thomas et al. (1997), at the 0° meridian
(d) The 0° meridian of Lutetia has (so far) been arbitrarily defined based on light curve information
(e) Although it is not called out there specifically, the value of 55° for W_0 for Europa can be derived from Merline et al. (2013) as follows. The 0° meridian is defined by the direction of the long axis that pointed toward the Earth on 2007 May 28 8.3125 UT (light-time corrected). This would have been the left edge of Figure 7 in Merline et al
(f) The 0° meridian of Ida is defined by the crater Afon
(g) The 0° meridian of Eros is defined by an unnamed crater
(h) The 0° meridian of Davida 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)
(i) Values for Davida 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)
(j) The 0° meridian for Gaspra is defined by the crater Charax
(k) The 0° meridian for Šteins is defined by a feature referred to as the crater informally named Spinel by Jorda et al. (2012) and later formally named Topaz (Besse et al. 2012)
(l) Since only rotation rate information is available, the 0° meridian for Itokawa is currently arbitrarily defined with $W_0 = 0°$
(m) The 0° meridian for Pluto is defined as the mean sub-Charon meridian
(n) The 0° meridian for Charon is defined as the mean sub-Pluto meridian
(o) The 0° meridian for Tempel 1 is defined by a 350 m diameter unnamed circular feature near the Deep Impactor impact site (Thomas et al. 2007). See additional discussion in text
(p) The 0° meridian for Churyumov–Gerasimenko is defined relative to a large 'boulder' called Cheops by the Rosetta team (Scholten et al. 2015; Preusker et al. 2015)
(q) The 0° meridian for Hartley 2 is defined by an isolated large mount on the waist, near the large lobe as shown in Figures 2 and 3 of Thomas et al. (2013a)

At this time, the Working Group is not recommending the use of a new orientation model for the Moon. Although the new JPL planetary and lunar ephemeris DE430 is available (Folkner et al. 2014), various lunar missions, such as the Lunar Reconnaissance Orbiter (LRO) (LRO 2008), continue to use the previously recommended DE421 ephemeris as rotated into the ME system (Williams et al. 2008; Folkner et al. 2008, 2009). Users needing the highest possible accuracy might wish to consider the use of the DE430, although the differences between these two ephemerides for lunar orientation in the ME system are on the order of a few meters. The INPOP lunar and planetary ephemeris (http://www.imcce.fr/inpop) is also available although in order to use it for cartographic purposes the lunar orientation ephemeris would have to be rotated into the ME system. The Working Group anticipates working with various missions and groups to work toward recommending the general use (for lunar orientation) of DE430 or a possible newer version of the JPL lunar and planetary ephemeris at some point, e.g., with a separate publication with such a recommendation or via our next general report.

An ASCII version of the DE421 ephemeris may be downloaded from ftp://ssd.jpl.nasa.gov/pub/eph/planets/ascii/de421/. This ephemeris consists of coefficients for the Chebyshev polynomial representations of the Euler lunar libration angles in the PA system. The 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 ascending node to the lunar prime meridian.

A rectangular unit vector, P, in the DE421 PA system can be rotated into the equivalent unit vector, M, in ME system with (Williams et al. 2008, p. 10):

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

where R_x, R_y, and R_z are the standard rotation matrices for right-handed rotations around the X, Y, and Z axes, respectively. Conversely, a rectangular unit vector, M, in the ME system can be rotated to, P, in the PA system using the following expression:

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

The user should obtain ϕ, θ, and ψ, at the desired epoch from the ephemeris file and convert them to P, and then apply the transformation (1), and extract the equivalent angles in the ME system from M. These angles can then be converted with:

$$\alpha_0 = \phi - 90^\circ$$
$$\delta_0 = 90^\circ - \theta$$
$$W = \psi$$

to the lunar rotation angles in the ME system with the α_0, δ_0, and W formulation of Table 2.

Alternatively, if the point is defined by a unit vector in ICRF coordinates, I, then the ME unit vector at a given epoch is:

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

where ϕ, θ, and ψ are again obtained from the ephemeris file at the desired epoch. *The values for the rotation matrices are specific to DE421.*

If there is a desire to use the DE430 ephemeris, a unit vector in the PA system can be rotated into the equivalent unit vector in the DE421 ME system, using equation 20 of Folkner et al. (2014).

The NASA/JPL Navigation and Ancillary Information Facility (NAIF) provides software and data files to facilitate the above transformations. This includes a Planetary Constants Kernel (PCK) containing the DE421 lunar libration ephemeris, and a special lunar frames kernel (FK) providing the specifications and data required for the PA to ME system transformation. See https://naif.jpl.nasa.gov or (for DE421) https://naif.jpl.nasa.gov/naif/lunar_kernels.txt for further information. A new version of the PCK for DE430 is also available at ftp://ssd.jpl.nasa.gov/pub/eph/planets/bsp. Although written before DE421 became available, Roncoli (2005) also provides useful information on lunar constants and coordinates.

4 Coordinate system for (4) Vesta

We detail the coordinate system for the asteroid (4) Vesta, as a guide to readers who need to understand the different coordinate systems used in various publications and products. This also is an example of how the recommendations of this Working Group are intended to be put into effect.

The NASA/DLR/ASI Dawn mission (Rayman et al. 2006) orbited Vesta during the period July 16, 2011–September 5, 2012 (Aron 2012). Prior to the mission's arrival, the Working Group had described and recommended a coordinate system for Vesta (Archinal et al. 2011a, following earlier versions of our report) based largely on HST observations, in particular those of Thomas et al. (1997) with an update to the pole position based on Li (2012). The prime meridian of Vesta, as defined by Thomas et al. and recommended for use by the Working Group, was centered on a dark albedo feature informally known as Olbers Regio. That feature is easily identified in Dawn mission images as an area of lower albedo consisting mostly of a degraded topographic depression on Vesta.

Following the IAU and the Working Group's long standing recommendations (given in Sect. 2), it was expected that once the Dawn mission reached Vesta and started obtaining data, the coordinate system would be updated, i.e., with a better determination of the pole position, and a refinement of the position of the prime meridian.

Instead, Dawn mission personnel defined successive new longitude systems for Vesta that were not aligned to the existing one. The Dawn mission principal investigator and other mission personnel were informed by the Working Group chair in 2011 August that this was likely going to cause serious problems in the use of Dawn data by others outside the Dawn mission. A formal request was received from the mission for the full Working Group to consider the issue, and in 2011 September the Working Group found that the particular system being proposed (which included an arbitrary offset of 138° from the recommended system) did not follow past IAU and Working Group recommendations. The Working Group recommended that a system be used in which the Olbers feature would still be on the prime meridian. The Dawn mission did not adopt the Working Group's recommendations.

In 2011 October, it was made clear to the Dawn mission that the PDS required that data submitted to the PDS by the Dawn mission was required to follow IAU recommendations in order to be archived (PDS 2009). There was another formal request from the mission in mid-February of 2012 to the Working Group to consider a new request for approval of the offset coordinate system, or alternatively coordinate systems with other large offsets. The Working Group considered the issues involved at length and again made the same recommendations as in 2011 September. The Working Group also stated "[…] we believe it is important to indicate when it is used that it is different from one that follows IAU recommendations." The mission began publishing papers using their system from 2011 September, with no mention that it did not follow IAU recommendations.

Starting in late June 2012 and continuing through July and early August, a large number of requests were received from the PDS Small Bodies Node and the PDS Asteroids Subnode regarding a review that was taking place of the data the Dawn mission submitted to the PDS to be archived. The PDS determined during the review, with assistance from the Working Group, that the mission had submitted data in one of the systems it proposed to use in February, which the Working Group had already decided was not in compliance with IAU recommendations. The Dawn mission was informed how their system could be modified in order to comply with IAU recommendations. The mission stated it would soon submit its data to the PDS in a system where the Olbers feature was maintained at 0° longitude.

In 2012 October the mission proposed to the Working Group a longitude system that did have the Olbers feature at zero degrees. The Working Group recommended that the mission use that system for all further publications so as not to cause continued confusion regarding the multiple systems in use. We received the reply that "The team is trying to find an acceptable solution to the map publication process." (private communication, Raymond 2012). The mission then began delivering data to the PDS for publication in the system with the Olbers feature at 0° longitude. The dataset was described in the PDS archive document (Li 2012; Li and Mafi 2013), where it is listed (see Table 1 only, as different values appear in the text of the document) as the "Claudia Double-Prime" system, with $W_0 = 285.39°$. As noted there this system leaves the Olbers feature at 0° longitude, by defining the longitude of the small crater Claudia (shown in Fig. 1) as positive 146°.

In 2013, Giovanni Valsecchi (then President of IAU Division F on Planetary Systems and Bioastronomy) requested that the Working Group explicitly recommend a coordinate system for Vesta. Such a recommendation would support further use of this system by the IAU Working Group for Planetary System Nomenclature (WGPSN), the IAU generally, and the international science community.

In response, the Working Group chose to recommend the same system as the one proposed by the Dawn mission in 2012 October with the Olbers feature at 0° longitude. The Working Group made this recommendation in Archinal et al. (2013b), and recommended this system be known as the "IAU Coordinate System for (4) Vesta," with the publication year of that announcement (2013) specified if necessary to differentiate it from the earlier or later systems recommended for Vesta. We note, however, that in following the IAU recommendations, these systems are essentially indistinguishable from each other as higher accuracy and resolution data became available for Vesta.

Compared to the values recommended by the WGCRRE in our previous full report (Archinal et al. 2011a), the recommended system has an offset of 2.5° in pole position and an increase in rotation rate of 0.0001668°/day and a constant W term (or W_0) decrease of 6.61°. The change in this latter value is mostly due to the change in pole position and the total change in rotation since J2000.0 due to the improved rotation rate.

Further improved values for the pole position and spin rate have become available from Konopliv et al. (2014), both with and without a model for precession and nutation. The model without precession and nutation corresponds to that given here, but with updated parameter values that move the pole by 0°.009, and increase the rotation rate by $0.0001807°/day$. However, since Konopliv et al. did not give the value of W_0 for that model, it is incomplete for cartographic use. Rather than trying to derive an appropriate W_0 value, we recommended the continued use of the parameter values from Li (2012) given in Table 3, which should be sufficiently accurate for making products from the Dawn mission or other observations of Vesta.

5 Rotation elements for planets and satellites

Table 1 provides recommended rotation elements for the major planets, while Table 2 provides them for planetary satellites.

The MESSENGER spacecraft has performed three flybys and more than four years of orbital observations of Mercury. A new orientation model has been derived and adopted for data release by the MESSENGER mission team (see Stark et al. (2017b) for details), which is recommended for use here. The values for the rotation axis orientation at J2000.0 and the libration amplitude cited in this report are based on 10 years of Earth-based radar observations of Mercury (Margot et al. 2012). The rotation rate is based on MESSENGER radio science observations and modeling of Mercury's gravity field (Mazarico et al. 2014). The rotation rate of Mercury was found to differ significantly from the previously adopted value, which dates back to Davies et al. (1980). Hence, this required an update for the prime meridian constant W_0. In order to comply with the definition of the prime meridian through the small crater Hun Kal, W_0 was changed by 0.0519° ($\sim$ 2.2 km) based on a preliminary analysis of images showing this crater (Stark 2016). While the analysis of MESSENGER data is still ongoing, more recent rotational parameters for Mercury, relevant for geophysical analysis, are available now (Stark et al. 2015; Verma and Margot 2016).

New models for the orientation of Mars have been derived by Kuchynka et al. (2014) and Konopliv et al. (2016). Both have successively been recommended for use by the NASA Mars Geodesy and Cartography Working Group (MGCWG) (Duxbury et al. 2013, 2017). The Konopliv et al. (2016) model is based on additional data compared to that used by Kuchynka et al. (2014). However, only Kuchynka et al. (2014) provide a series expansion of the Mars orientation model in the conventional form (α_0, δ_0, and W), so its use is recommended here.[3] Either of these models provides substantial improvement over the model previously recommended by the MGCWG (Duxbury et al. 2001, 2002) and the Working Group (Seidelmann et al. 2002). As shown by earlier work by Konopliv et al. (2006, Fig. 19), the difference between the previous recommended model and revised models can be on the order of as much 40 m in longitude and pole position over 10 years. With a million time steps from January 1, 2000 to January 1, 2030 , the maximum rotation difference between the previous model and the Kuchynka et al. model is about 180 m. The difference between the Kuchynka et al and Konopliv et al. (2016) models compared over the same period is just over 13 m (Bachman, personal communication). Should a series expansion of the Konopliv et al. (2016) model in the conventional form become available, the Working Group will consider updating its recommendation.

The origin of the longitude system for Mars is now defined by assigning a longitude of 47°.95137 west to the Viking 1 lander. This is based on work by Parker et al. (2012) and Kuchynka et al. (2014), and related work by Duxbury et al. (2014), and as adopted by Konopliv et al. (2016) and the MGCWG (Duxbury et al. 2017). Previously the longitude system was defined by assigning a zero longitude to the center of the crater Airy-0. The longitude uncertainty within which landed resources can be determined by radiometric tracking is now 0°.0001 (about 6 m) (Kuchynka et al. 2014). Since that is significantly smaller than the uncertainty of determining the center of the $\sim$ 500 m diameter Airy-0, the time has come to transition the orientation of the longitude system from being based on Airy-0 to the much smaller Viking 1 lander, for which there are extensive radiometric tracking data. Note though

[3] Jacobson (personal communication) et al. have submitted a paper to Planetary and Space Sciences, which includes a series expansion for the Konopliv et al. (2016) model in the convention form, as well as improved orientation models for Phobos and Deimos (see below). The Working Group is not recommending the use of these models at this time, pending review and publication.

that within current cartographic uncertainties, this definition still maintains the position of the center of Airy-0 at 0° longitude.

The rotation rate of Saturn given in Table 1 is based on Voyager observations of kilometer-wavelength radio signals. Giampieri et al. (2006) give a period of about 10 h and 47 min from Cassini observations of a signal in Saturn's magnetic field. This period is about 8 min longer than the previously determined one. It is 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 (2010, private communication) reports that results indicating a specific period in Russell and Dougherty (2010) are in doubt, and it appears 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 trying to find a consensus solution. So, the rotation rate of Saturn remains unchanged. It is possible that there will be new results from the Cassini mission.

The rotation rate of Uranus was determined from the Voyager mission in 1986. The uncertainty of the rotation rate is large enough that the present uncertainty of the prime meridian is more than a complete rotation.

The orientation model for Neptune is derived from that previously reported, but updated by a new rotation rate of 15.96630 ± 0.00003 h from Karkoschka (2011), derived from long-term optical observations of two features of the Neptunian atmosphere, and thus improving dramatically on the rotation rate derived from Voyager observations. It is called there "System II" which is a terminology we continue here. Karkoschka's recommendation to have the rotation, W, match the previously recommended System III and System II at August 3, 1989 12:00:00.0 UT = JD 2447742 UT has been followed, resulting in the new value for the first term of W of 249°.978 at J2000.0. We note that Jacobson (2011) has derived new expressions for the pole position of Neptune (as well as improved orbits for Triton, Nereid, and Proteus) that may be of interest. However, it is not clear if there is a significant improvement over the current pole position and precession model, so we are not recommending a change in that model at this time.

It has recently been pointed out (Duxbury, private communication) that the orientation models recommended by the Working Group previously for Phobos and Deimos are out of date at current epochs, since they are based on orbital elements derived in the 1980s and earlier that have since changed. New models have been developed (e.g., Stark et al. 2017a; Jacobson, private communication via T. Duxbury). The MGCWG notes and recommends (Duxbury et al. 2017): "The MGCWG validated that these new expressions couple the orbits and orientations to accuracies at the meter level for Stark and sub-meter level for Jacobson, both sufficiently accurate for today's and near-term applications. The MGCWG recommends that the IAU WGCCRE adopt the expressions by Jacobson, however there is no external reference for this work. Therefore, the expressions by Stark, also sufficiently accurate for today's and near future work, [have been] documented in an abstract that can be referenced and therefore the IAU WGCCRE may choose to adopt these expressions." Due to an urgent need for updated models, the Working Group accepts the MGCWG recommendation and chooses to use the Stark et al. model since it exists in published form (2017a). For the physical libration in longitude and the accordingly adapted W_0 of Phobos we adopt the values obtained by Burmeister et al. (2018). Stark et al. (2017a) note that "The current accuracy is considered sufficient for cartographic purposes but might need improvement for tasks like high precision landing on Phobos."

Satellites for which no suitable data are yet available have been omitted from this table. Hyperion is not included in this table because it is in chaotic rotation. Nereid is not included in this table because no simple model for its rotation exists and it may be in chaotic rotation (Dobrovolskis 1995).

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

For dwarf planets, minor planets (or asteroids), their satellites, and comets substantial indirect evidence exists for large precession of the rotational poles. So the definition of a *north pole* has been rethought. Situations exist in which the pole that is clearly on the north side of the invariant plane is thought to precess over several decades to become clearly on the south side of the invariant plane. Comet 2P/Encke is an example of a comet for which very large precession has been inferred.

There is also clear evidence for excited state rotation for comets 1P/Halley and 103P/Hartley 2 and minor planet (4179) Toutatis. In this case, the body-fixed reference system moves with respect to the angular momentum vector. The rotation vector makes substantial excursions from the angular momentum vector. The motion of the rotation vector is detected in the object's light curve. It is likely there are other cases where the rotation pole moves between north and south of the invariant plane on a time scale of days. Thus, the definition of the pole for small bodies is, since the 2006 report, different from the definition for the planets and their satellites.

The rotation pole for a body is chosen to be the one following the right-hand rule. This rotation pole is called the *positive* pole to avoid confusion with the north–south terminology. For common usage, this positive pole is often referred to as the *north pole*, but in papers that rely on coordinates one should make it clear that the *north pole* refers to the positive spin pole rather than the traditional definition for planets and satellites, which is relative to the invariant plane. The other cardinal directions are then named in relation to north in the same way as on planets and satellites. For example, "east" is 90° to the right from north and thus is always the direction of rotation and of increasing longitude on minor bodies. This informal terminology greatly simplifies the description of geographic and geological relations on such objects. Ideally the pole chosen for excited state rotation reduces to this definition as the rotational energy relaxes to the ground state. For SAM (short-axis mode) rotation states (e.g., Samarasinha et al. 2004), it is possible to define a body-fixed axis that circulates in a complex pattern about the angular momentum vector and approaches the simple right-hand rule definition as the rotational energy relaxes to the simple rotation ground state. The appropriate body-fixed pole is the axis of maximum moment of inertia. The definition for a body in a LAM (long-axis mode) rotational state is not as obvious, because there is 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 according to the right-hand rule. This choice also allows simple cylindrical projection mapping with far less distortion than if the axis of maximum moment of inertia were chosen.

The terminology of planetographic and planetocentric coordinate systems does not apply to such bodies since it is not necessary when the coordinate system will always follow the right-hand rule, but will continue to be used for planets and their satellites. However, if referenced to the body center, latitude and longitude on such bodies may be called planetocentric, and planetodetic if referenced to an ellipsoidal reference surface.

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 such that rotational parameters based on them will stand the test of time. 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 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).

It is now clear that predicting future rotational states of cometary nuclei is very difficult, based only on flybys and Earth-based data, even for a relatively well-behaved comet like 9P/Tempel 1 (Belton et al. 2011). At subsequent encounters, the orientation of a comet nucleus will likely differ from the model prediction derived from initial encounter data. The differences may be large, due to strong torques from outgassing, rapid precession of the spin axis relative to the body, and the accuracy of the initial observation. 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 highly 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 parameters amended to model the orientation of the axes more accurately. For irregular bodies both axis orientation and rate may be poorly determined or vary over time. So, two or three landmark features will be required to determine the body-fixed orientation of the coordinate axes, rather than the single landmark required to define the prime meridian of a regularly rotating body. For comets it may be necessary to give a simple formula (in terms of α_0, δ_0, W at an epoch, and $\dot{W}$) that is adequate over a short interval but does not try to describe how those parameters evolve. Or in the worst case, it may be necessary to specify only the orientation at one or more specific epochs rather than providing a formula for the rotational orientation.

For planets and satellites, longitude should increase approximately monotonically in an inertial reference frame as specified in Sect. 5.

For dwarf planets, minor planets, their satellites, and comets increasing longitude should always follow the right-hand rule.[4] For each such body, the positive pole of rotation is selected as the maximum or minimum moment of inertia according to whether it is in a short or long-axis rotational state. So the positive pole is specified by the value of its right ascension α_0 and declination δ_0. The two nodes of the body's equator and the ICRF equator are at $\alpha_0 \pm 90°$. The node $\alpha_0 + 90°$ is defined as the node Q, and the inclination of the body's equator to the celestial equator is $90° - \delta_0$. The prime meridian is chosen so it crosses the body's equator at B. The angle W is measured along the body's equator from Q to B in a right-hand system with respect to the body's positive pole (Fig. 2). The right ascension of the node Q is $90° + \alpha_0$. The value of W changes approximately linearly with time according to the right-hand rule. The values of α_0, δ_0, and W may also vary with time due to a precession of the rotation axis of the body. This formulation of the body orientation in terms of pole orientation and spin angle may be insufficient for bodies whose spin precesses rapidly with large amplitude. Several such examples, new in this report, are discussed below.

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

[4] This definition is consistent with the sense of increasing longitude used for Eros by Miller et al. (2002), and inconsistent with the sense of increasing longitude used for Eros by Thomas et al. (2002).

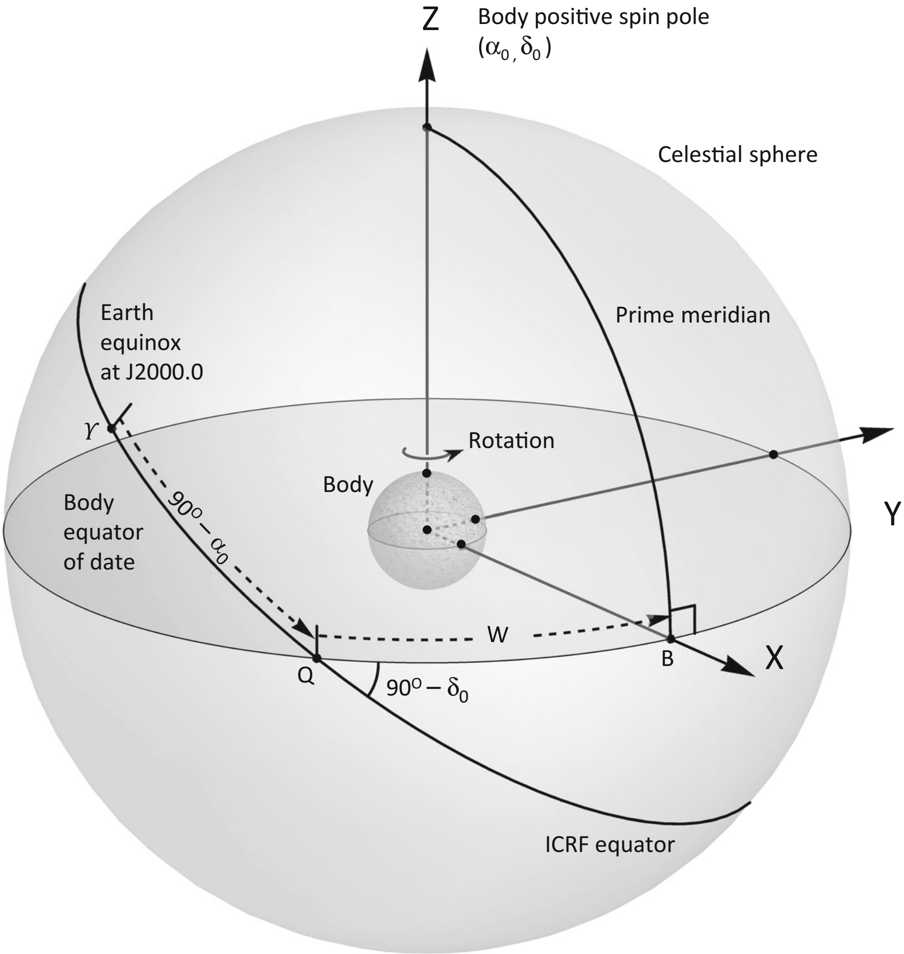

Fig. 2 Reference system used to define the orientation of dwarf planets, minor planets, their satellites, and comets

features, the adopted expression for W defines the prime meridian. Where possible, the cartographic position of the prime meridian is defined by a suitable observable feature, and 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 observations allow; in these cases the expression for W may require emendation in the future. Table 3 gives the recommended positions of the positive pole of rotation and the prime meridian of selected dwarf planets, minor planets, their satellites, and comets. Included objects 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 listed for objects where the observations are limited to photometric light curves.

If new higher accuracy mapping is done, the longitudes of the defining feature or features are to be maintained and, as necessary, improved rotational parameters derived, published in peer-reviewed literature, and submitted to this Working Group for possible adoption. Defining features are noted in the footnotes to Table 3 for those bodies where they are in use. As noted in Sect. 2, 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, features and their associated longitudes chosen to define cartographic coordinates should not be changed.

For bodies whose instantaneous rotation axis varies significantly, it is still useful to have a single, body-fixed coordinate system. In order to make such a definition, it will be necessary to define not only the longitude of a single feature but the latitudes and longitudes of three or more features. In such cases the choice of coordinate axes cannot reflect the exact rotational state (except perhaps at a given epoch). However, it should be defined to do so as closely as possible, by putting the coordinate pole somewhere near the average location over some interval or the location at some epoch.

A dwarf planet, minor planet, one of their satellites, or a comet is included in Table 3 only if it meets publication and data quality criteria, and a cartographic need exists that justifies the definition of a prime meridian and pole for the body. Estimated values for α_0, δ_0, and W_0 (i.e., W at J2000.0, or W at a given observational epoch if appropriate—see below) should appear in a refereed publication. The analysis to determine these values must be derived from data of sufficient fidelity and quality to assure an accurate estimate, and a significant portion of those data must have been acquired via direct methods (e.g., direct imaging from a spacecraft, a space telescope, or an adaptive optics system), but may be combined with data from indirect methods (e.g., photometry, multi-chord stellar occultation).

As for planets and satellites, these recommendations are not intended to imply that other coordinate systems with different rotational elements cannot be used for minor planets and comets for other than cartographic purposes. Section 2 contains a discussion of possible options.

Each of those comets, whose rotation cannot be described with a simple rotational axis position coupled with a longitude zero point and a rotation rate with or without a small number of derivatives, constitutes a unique case, so they are discussed individually. The IAU WGPSN does not officially accept names for cometary features due to their potentially transient nature, but the defining features are shown in the cited literature, sometimes with informal names. Unless there is evidence for validity of the rotational formula over an extended period, rotational states should not be specified at J2000.0. Rather the rotational states will be specified at the relevant epochs of observation.

Comet 9P/Tempel 1 was visited by the Deep Impact mission in 2005 and the NExT mission in 2011. There is no evidence for either slow precession or excited state rotation. Thus, a simple, ground-state rotation with a fixed pole has been assumed at the position given in Table 3. The zero point of longitude was defined by an unnamed 350 m diameter circular feature after the Deep Impact encounter (Thomas et al. 2007), and this defines the reference frame of the latest shape model (Farnham and Thomas 2013a). It is clear that the rotation period of 9P/Tempel 1, roughly 40 h, varies significantly from one apparition to the next, currently decreasing by about 15 min per perihelion passage. There is indirect evidence that the derivative changes sign twice each orbit.

Comet 19P/Borrelly was visited by the Deep Space 1 (DS1) mission on 2001 September 22, but the limited range of observations by this technology demonstration mission did not allow direct determination of the rotation or of a full shape model. Thus, only digital terrain models (DTMs) in an arbitrary Cartesian system exist (Kirk et al. 2004) and no cartographic coordinate system has been defined. The rotational pole has been studied both from Earth and from DS1 assuming that an observed, stationary jet is pointing toward the pole (Soderblom et al. 2004 and references therein). There is evidence for precession on the time scale of a century, but no indication of precession across the two apparitions from 1994 to 2001 (Schleicher et al. 2003). We adopt the pole from Soderblom et al. (2004) and the rotational rate from Mueller et al. (2010).

Comet 67P/Churyumov–Gerasimenko, the target of the Rosetta mission, was mapped in detail during the early phases of the mission. Diverse shape models have been produced, but all are tied to the same reference frame (Scholten et al. 2015; Preusker et al. 2015) and only the ones produced by Jorda et al. (2016) have been refereed and archived at the time of this report. It is clear that the rotation changes from one apparition to the next. However, Preusker et al. show that the rotation was stable over the period from wake-up of Rosetta until the end of the first mapping period. We adopt the classical description of the rotation for that period. There is a precession of the pole with half-cone angle $0^\circ.14 \pm 0^\circ.02$, with a period of 10.7 days. This is at the limit of the precision of the pole. At this time, we do not make a recommendation on this term. These recommendations are valid only for the limited period specified, since large changes in the rotational period are being observed at the time of this report. Updated parameters will be included in the next report.

Comet 103P/Hartley 2 is in an excited state rotation, but the details are not well-determined using EPOXI flyby data. There is disagreement on whether the rotational state is a LAM or a SAM. The axes of the shape model reference frame (Farnham and Thomas 2013b), and, thus, the coordinate system, assume that it is a LAM. The precession period under this assumption varied dramatically (16–18 h) over the apparition (see Belton et al. 2013). The period of rotation around the long axis, which is the rotation related to the coordinate system, is also ambiguous. Thus, we present only the orientation of the body axes at the epoch of closest approach, where Z is the long axis, which is the rotational axis and the basis of published maps assuming the rotational state is a LAM. One standard deviation uncertainties are somewhat less than one degree.

7 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 (the XY plane, where Z is taken as the polar axis), and longitude is the angle between the vector projected onto the XY plane and the positive X axis (the projection of the prime meridian on the XY plan) 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.

In astronomical tradition, *planetographic* coordinates (commonly used on maps) may not be identical with traditional spherical coordinates. Planetographic coordinates are defined by guiding principles contained in a resolution passed at the 14th General Assembly of the IAU in 1970. These guiding principles state:

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[5] are used when the rotation is direct,[6] and east longitudes are used when the rotation is retrograde.[7] The origin is the center of mass. The Earth, Sun, and Moon do not traditionally conform to this definition. Their rotations are direct and longitudes run both east and west 180°, or positive to the east 360°. NASA missions have adopted the use of 0°–360° east longitude for the Moon (LRO 2008).

For planets and satellites, latitude is measured north and south of the equator, with north latitudes 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'.

Reference surfaces used for various bodies can be spherical, ellipsoids of revolution for which the equatorial semi-axis (A) is larger than the polar semi-axis (C), triaxial ellipsoids where the equator is best defined by an ellipse with two semi-axes (A and B), or a topographic surface defined by a detailed model. These surfaces may have many different purposes, such as: (1) for defining map scale; (2) for use in map projections; (3) for orthoprojection of data and analysis of occultation data; (4) as a reference surface for measuring geometric height (elevation); (5) for geophysical analysis (e.g., for determining the volume of a body; and using an estimate for mass, the bulk density of a body); and (6) for comparative planetology. Our recommendations here are primarily for cartographic purposes, therefore, addressing primarily applications 1–4. However, recognizing that shape parameters are often used for other purposes, we often provide additional information such as uncertainties, and triaxial parameters, even where the latter are not necessarily useful for, e.g., application 1 (map scale) but may be useful for application 3 (orthoprojection of data) or 5 (geophysical analysis), particularly if a detailed topographic model is not available.

Large bodies such as planets or dwarf planets in near hydrostatic equilibrium can be considered ellipsoids of revolution with corresponding A and C semi-axes.

Hydrostatic shapes for large satellites close to their primary, such as Io, Mimas, Enceladus, and Miranda, can be considered triaxial ellipsoids, with significant differences between their A, B, and C semi-axes lengths. However, spherical reference surfaces are frequently used for mapping in order to specify scale and for map projection (applications 1 and 2). Use of triaxial ellipsoids would render computations more complicated, especially those related to map projections. It would be difficult to generalize many projections and retain their elegant and popular properties, and there is a lack of agreement on matters such as the appropriate definitions of latitude and longitude. Therefore, the triaxial shape information tends to be used only for the other types of applications (3–6).

For some bodies an accepted spherical radius or rotational ellipsoid parameters (A and C) have been used to establish a reference surface for mapping, e.g., for map scale, map projection use, and elevation determination (applications 1, 2, and 4 above). These values may not represent the current best determined shapes for the body in question (which might be desired for orthoprojection of data (application 3) or geophysical use (application 5)), but seem to have been generally accepted in the community or by relevant mission personnel for

[5] Longitudes measured positively to the west.

[6] The sign of the linear term in the expression for W is positive.

[7] The sign of the linear term in the expression for W is negative.

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)		695,700				
Mercury[a]	2439.4 ± 0.1	2440.53 ± 0.04	2438.26 ± 0.04	1	4.6	2.5
Venus	6051.8 ± 1.0	Same	Same	1	11	2
Earth[b]	$6371.0084^{b} \pm 0.0001$	$6378.1366^{b} \pm 0.0001$	$6356.7519^{b} \pm 0.0001$	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[c,d]	69911 ± 6	$71492^{c} \pm 4$	$66854^{c} \pm 10$	62.1	31	102
Saturn[c]	58232 ± 6	60268 ± 4	54364 ± 10	102.9	8	205
Uranus[c]	25362 ± 7	25559 ± 4	24973 ± 20	16.8	28	0
Neptune[c]	24622 ± 19	24764 ± 15	24341 ± 30	8	14	0

(a) Since the shape of Mercury is close to spherical, the given radius is recommended for cartographic use, such as map scale and map projection, and for elevation reference. Perry et al. (2015), however, have derived best fit triaxial ellipsoid semi-axes values, and those are given here for comparison or other uses. The value cited for equatorial radius is the semimajor (long equatorial) axis length, while the intermediate (short equatorial) axis length was measured as 2439.28 ± 0.04 km

(b) These values for the Earth are for comparison only. An IAU resolution (IAU 2015a) has adopted values for the equatorial and polar radii with less precision, giving values of 6378.1 and 6356.8 km, respectively

(c) The radii correspond to a one-bar surface

(d) The equatorial and polar radius values for Jupiter have been adopted by an IAU Resolution (IAU 2015a)

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[a]	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	14.0 ± 1.2	17.2 ± 1.7	15.4 ± 1.2	10.4 ± 0.9			
	XXXV	Daphnis	3.8 ± 0.8	4.6 ± 0.7	4.5 ± 0.9	2.8 ± 0.8			
	XV	Atlas	15.1 ± 0.8	20.5 ± 0.9	17.8 ± 0.7	9.4 ± 0.8			
	XVI	Prometheus	43.1 ± 1.2	68.2 ± 0.8	41.6 ± 1.8	28.2 ± 0.8			
	XVII	Pandora	40.6 ± 1.5	52.2 ± 1.8	40.8 ± 2.0	31.5 ± 0.9			
	XI	Epimetheus	58.2 ± 1.2	64.9 ± 1.3	57.3 ± 2.5	53.0 ± 0.5			
	X	Janus	89.2 ± 0.8	101.7 ± 1.6	93.0 ± 0.7	76.3 ± 0.4			
	I	Mimas	198.2 ± 0.4	207.8 ± 0.5	196.7 ± 0.5	190.6 ± 0.3			
	LIII	Aegaeon	0.33 ± 0.06	0.7 ± 0.05	0.25 ± 0.06	0.2 ± 0.08			
	XXXII	Methone	1.45 ± 0.03	1.94 ± 0.02	1.29 ± 0.04	1.21 ± 0.02			
	XLIX	Anthe	0.5						
	XXXIII	Pallene	2.23 ± 0.07	2.88 ± 0.07	2.08 ± 0.07	1.8 ± 0.07			
	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	9.8 ± 0.3			
	XIV	Calypso	9.6 ± 0.6	15.3 ± 0.3	9.3 ± 2.2	6.3 ± 0.6			
	IV	Dione	561.4 ± 0.4	563.4 ± 0.6	561.3 ± 0.5	559.6 ± 0.4	0.5		
	XII	Helene	18.0 ± 0.4	22.5 ± 0.5	19.6 ± 0.3	13.3 ± 0.2			
	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	2575.0^{b}	2575.15 ± 0.02	2574.78 ± 0.06	2574.47 ± 0.06	0.26		
	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			

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)
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 ± 51.9				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[c]	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						

(a) The mean radius for the Moon is for cartographic use (related to map scale and map projection) and for elevation reference

(b) The mean radius for Titan is for cartographic use (related to map scale and map projection) and for elevation reference. The current best fitting mean radius for Titan (e.g., for orthoprojection, geophysical, or other purposes) is 2574.73 ± 0.09 km, from Zebker et al. (2009)

(c) The size of Larissa was determined from only one image, showing a long semi-axis size of 104 km and a short semi-axis size of 89 km, with the mean radius assumed as halfway between those values (Thomas and Veverka 1991)

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

Body	Mean Radius (km)	Radii measured along principal axes (km)	(km)	(km)	
(1) Ceres	470	487.3	487.3	446	(a)
(4) Vesta		289 ± 5	280 ± 5	229 ± 5	
(16) Psyche	113 ± 23	139.5 ± 10%	116 ± 10%	94.5 ± 10%	(b)
(21) Lutetia	52.5 ± 2.5	62.0 ± 2.5	50.5 ± 2.0	46.5 ± 6.5	
(52) Europa	157.5 ± 7	189.5 ± 16	165 ± 8	124.5 ± 10	
(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	(c)
(951) Gaspr	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		0.268	0.147	0.104	
(134340) Pluto	1188.3 ± 1.6	Same	Same	Same	
(134340) Pluto: I Charon	606.0 ± 1.0	Same	Same	Same	
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		(d)
19P/Borrelly	4.22 ± 0.05	3.5 ± 0.2	–	–	(e)

Table 6 continued

Body	Mean Radius (km)	Radii measured along principal axes (km)	(km)	(km)	
67P/Churyumov–Gerasimenko	1.65	2.40	1.55	1.20	(f)
81P/Wild 2	1.975	2.7	1.9	1.5	
103P/Hartley 2	0.58	0.34	1.16	$\sim$ 1.16	(g)

(a) An oblate spheroid. Values here for Ceres were determined from Dawn mission results (Raymond and Roatsch 2015). The authors note these values have been determined at "a level of precision commensurate with the preliminary nature of this determination and the needs of the users of the associated kernel"

(b) The principal axes of Psyche have been used to define the longitude system (Shepard et al. 2017, p. 393). 10% uncertainties in axis diameters are repeated here as the assumed uncertainties in semi-axis lengths. The 23 km uncertainty in the volume-equivalent spherical-diameter is repeated here as an assumed uncertainty in the radius. Users should be aware that an orientation model and alternate size information for Psyche are also given by Drummond et al. (2018), but use of that information is not yet recommended here as that has not yet been published

(c) Values for Davida 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)

(d) The maximum and minimum radii for Tempel 1 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

(e) Since essentially only one side of Comet Borrelly was imaged in stereo, only a likely maximum length was determined, so no values are given for the second and third semi-axes

(f) Due to limited mapping of the negative (southern) hemisphere of Churyumov–Gerasimenko, the third axis (parallel to the rotational axis) was constrained to match the volume (Preusker et al. 2015)

(g) The intermediate and small semi-axes of Hartley 2 are very similar to each other (Thomas et al. 2013a) mapping use. For example, their use to define map scale and/or an elevation reference for the body in question avoids small annoying scale differences in maps, mapped datasets, and heights as the body radius estimate continued to be refined with minor changes. Currently such bodies include Earth (rotational ellipsoid), the Moon (sphere), and Titan (sphere). The Tables below indicate the relevant parameters.

Many satellites, minor planets, and comet nuclei have very irregular shapes. Spherical reference surfaces are sometimes used for computational convenience (for all the application cases above), 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. 8 of this report.

Table 4 gives size and shape parameters for the planets. The Sun is included for comparison purposes with the specified value as derived by Haberreiter et al. (2008) and adopted via IAU Resolution B3 (IAU 2015a). Aside from the Earth, the mean radii shown in Tables 4, 5, and 6 are from the original authors and have not been computed from the other radii by the Working Group assuming that some of them are independently computed.

A planetocentric, east-positive (right-handed) system was adopted for Mercury by the MESSENGER project prior to 2002. The Mariner 10 mission used the IAU standard (planetographic) coordinate system with longitude increasing to the east for Mercury (Hall et al. 1971). The MESSENGER PDS products use a mean radius for Mercury of 2439.4 ± 0.1 km, which we recommend for use in mapping projects. The value for the radius is motivated by analysis of laser altimetry and radio link occultation data by Perry et al. (2015), who derived an area-averaged radius of 2439.36 ± 0.02 km, as well as separate values for equatorial and polar radius. While the observed ellipsoidal shape of Mercury may be relevant for geophysical studies, the spherical approximation is sufficient for production and interpretation of maps (scale, map projection, and elevation reference) based on MESSENGER data.

For the Mars Global Surveyor mission, an areocentric, east-positive system was used despite years of mapping using the IAU standard system by Mariner 4, 6, 7, and 9 and Viking. The MGCWG (Duxbury et al. 2002) recommended the use of such an areocentric, east-positive system for all NASA Mars mapping. 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.[8] In applications where these differences may cause problems, a topographic shape model for Mars should probably be used as a reference surface. The current recommended 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 per degree resolution, radius and topographic surfaces are recommended; the lower resolution versions may be used, if documented, where appropriate, and for the areas poleward of $\pm 87°$ latitude.

Table 5 gives the size and shape of satellites where known. Only brightness is known for many of the more recently discovered satellites. Poles and rotation rates are also not yet known for the more recent discoveries, so those satellites are not listed. The mean radius given for the Moon and Titan are reference surface radii meant for cartographic purposes and for elevation measurement. The current best fitting mean radius for Titan is given in a footnote.

[8] The other values are used to illustrate the large dichotomy in shape between the northern and southern hemispheres of Mars.

The values for the radii and axes in Tables 4, 5 and 6 are derived by various methods. Some use star or spacecraft occultation measurements, some use limb fitting, others use altimetry measurements from orbiting spacecraft, and some use control network computations. The mean radius cannot be consistently derived from triaxial semi-axes values alone, since different authors have used different formulae for such a calculation. 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 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 must recognize their uncertainty.

Note that the presentation of uncertainties in these tables is *not* meant to imply that users can or should adopt a value within the range of uncertainty rather than the specific cited value(s) themselves. One of the primary reasons for our recommendations is to allow users to compare and co-register their results, and the use of values even slightly different than those cited makes such efforts difficult or impossible. This recommendation is obviously not to dissuade users from determining their own values, if they can do so at higher levels of accuracy (e.g., with new data or improved processing methods), but to allow for easier comparison and registration of results when the use of new values is not warranted.

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

A spherical or ellipsoidal model shape has traditionally been defined for mapping large bodies. Except for dynamical studies, there is no choice of ellipsoid that well represents either the shape or equipotential surface for smaller, irregularly shaped bodies. However, a sphere may still be useful in concept as a reference surface, with spherical (planetocentric) coordinates still being used. For these bodies, topographic shapes are usually represented by a grid of heights above the spherical reference surface, or a grid of radii distances to the body center, as a function of planetocentric latitude and longitude (when possible, or also by a set of vertices and polygons defined in a Cartesian coordinate system).

It is possible for irregularly shaped smaller bodies to have a line from the center of the body intersect the surface more than once. So, a coordinate pair may not uniquely identify a point on the surface of the body. Larger bodies, such as the Earth, may also have non-unique coordinate pairs because of such features as overhanging cliffs and natural bridges and arches. However, these features on large bodies are relatively very small and often ignored at the scale of most topographic maps. On small bodies, they may be large relative to the size of the body. Even on small bodies, this problem is usually restricted to small areas, but it still may make a planetocentric coordinate system difficult to use. Following are some example cases: Eros for a small patch west of Psyche, Kleopatra (Ostro et al. 2000), possibly on Toutatis near its 'neck', and near the south pole of Ida some radii may intersect the surface more than once. Cartographers have ad hoc tricks for a specific map, such as interpolating across the problem area from areas that are uniquely defined, or showing overlapping contours. A Cartesian or other coordinate geometry may be preferable for arbitrary, complex shapes, such as a toroidal comet nucleus, where an active region has eaten its way through the center. Such coordinate geometries are also useful for irregular bodies imaged only on one side, such as for 19P/Borrelly and 81P/Wild 2. In the extreme case of 67P/Churyumov–Gerasimenko, where there are large regions in which planetocentric radii are multi-valued, the Rosetta team has suggested, at least for internal use, that the two lobes be mapped separately (Scholten et al. 2015; Preusker et al. 2015).

Digital cartography has become increasingly popular with the introduction of large mass storage to computer systems. Cartographic databases are important particularly when considering irregularly shaped bodies. The surface is mapped by a table of the coordinates for each surface element. Other parameters such as brightness and gravity can be also associated with each surface element. Pictorial and projected views of the body can then be generated.

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 (again, the XY plane, where Z is taken as the polar axis); latitudes toward the positive pole are designated as positive. For regularly 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 are often adopted for cartographic portrayal as they preserve the irregular appearance of the body without distortion.

Table 6 contains data on the size and shape of selected dwarf planets, minor planets, their satellites, and comets. As in Tables 4 and 5, the mean radius values may or may not be derived from the semi-axes values. Some of these values may instead be the effective radius of the body, which is the radius of a sphere of equivalent volume. The uncertainties in the values for the radii in Table 6 are generally those given by the authors, and, frequently have different meanings. Sometimes they are standard errors of a particular data set, sometimes simply an estimate or expression of confidence.

A body is 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) must have been published in a refereed journal or the equivalent. The analysis to determine these values must have been based on data of sufficient accuracy, and some portion of those data must 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. For example, the radius used to derive the dynamical form factor, J_2, should be used consistently with the J_2 value itself.

9 Recommendations and requests for community input

The Working Group makes the following recommendations regarding the development of planetary coordinate systems and cartographic products. Also included are issues on which the Working Group is requesting feedback.

1. The importance of geodetically controlled cartographic products (derived from least squares photogrammetric, radargrammetric, or altimetric (cross-over) solutions) is well known (e.g., Archinal et al. 2016). These products are precise and can be cosmetically ideal products at the sub-pixel level of the data, *with known or derivable levels of precision and accuracy*. Global control solutions also provide improved body pole position, spin, and shape information, with reduced random and, often, systematic error. Such solutions allow improvements in the recommended models and provide demonstrably higher precision and accuracy cartographic products. It appears that the production of such products using the current flood of new planetary datasets is often neither planned nor adequately funded. We strongly recommend that generation of such products be planned as part of the normal mission operations and data analysis process. Since making this recommendation in our previous report, there have been several publications giving either interim or final results for Mercury (Becker et al. 2016b), Ganymede (Zubarev et al. 2015), Enceladus (Thomas et al. 2016; Becker et al. 2016a), and Titan (Archinal et al. 2013a), but similar work still needs to be completed or reported on for other bodies.
2. To facilitate use by the community, publications describing new or updated models for orientation or shape should use common notation to express orientation and size. While other formulations are welcome, expressions should at least be given for α_0, $\delta_{0,}$ and W at J2000.0 (or for comets at some epoch near that of the observations), and values for radius and/or ellipsoid semi-axes lengths in km, along with uncertainties where available.
3. There are a number of slightly conflicting determinations of the rotation rates of Jupiter and Saturn. We urge the planetary community to jointly develop consensus determinations, such as was done in the past for Jupiter by Riddle and Warwick (1976).
4. We note the excellent and detailed historical summary regarding the evolution and usage of the various coordinate systems for Pluto by Zangari (2015). The creation of such summaries would be useful for other bodies that have seen significant changes or updates in coordinate system usage, such as the Moon, Mars, Mercury, and Vesta.
5. In discussions at the IAU General Assembly in August 2012, there was agreement (Meech et al. 2012) to remind authors, journal editors, instrument teams, missions, and space agencies that a substantial number of IAU recommendations exist that have been developed over many decades of input by IAU members, national space agencies, and other institutions. We believe that it is important to carefully follow these recommendations or to present well-reasoned arguments why they should be changed. The IAU and its various components stand ready to help such groups understand and follow IAU recommendations.
6. Having received occasional inquiries regarding the preference for using planetographic or planetocentric coordinate systems for planets and satellites, we note that historically the preference has apparently been to use planetographic coordinates. See, for example, the IAU resolution (Hall et al. 1971) that predates this Working Group, and which only mentions planetographic coordinates. The Working Group acknowledges that both systems have long been in use for some bodies, with Mars as an example, so it makes little sense at this point when starting with a body ab inito, to prefer one over the other. However, the Working Group does note that where planetographic coordinates have been widely used for maps and publications in the past, there is no obvious advantage to switching to the use of planetocentric coordinates. So the Working Group believes that continuing to use such planetographic coordinates would greatly minimize future confusion. However, we would welcome further input on this issue.

7. The Working Group requests input on its plans (noted in Sect. 1) to evaluate whether proposed updates or new coordinate systems follow the conventions described here, and whether providing limited updates to its recommendations via its website is reasonable.
8. Given the publication of thermal maps of exoplanets (e.g., Knutson et al. 2007), we request community input on whether the domain of the Working Group should extend beyond the Solar System. In other words, should our procedures for establishing coordinate systems for Solar System bodies apply to exoplanets? For example, in order to avoid reference to the invariable plane of the Solar System, such coordinate systems could follow a right-hand rule, similar to that recommended here for dwarf planets, minor planets, their satellites, and comets.

10 Summary of changes since the last report

The following list includes items related to orientation first and then size and shape.

1. The recommended model for the orientation of Mercury has been updated based on MESSENGER results.
2. Approximate expressions for the rotation of the Earth have been removed to avoid confusion over their accuracy.
3. The low precision series expression for the orientation of the Moon has been removed.
4. An improved model is recommended for the orientation of Mars, as well as a refined longitude definition based on fixing the longitude of the Viking 1 lander, based on Kuchynka et al. (2014).
5. New models from Stark et al. (2017a) are recommended for the orientation of Phobos and Deimos A revised value for the physical libration of Phobos was adopted based on measurements by Burmeister et al. (2018).
6. A new Sect. 4 has been added to provide information on the background and evolution of the coordinate system for (4) Vesta, including a summary of requests from the Dawn mission and responses from the Working Group.
7. The expression for the rotation of Neptune has been updated to refer to the rotation of optically observed features in the Neptunian atmosphere (to be called System II) as derived by Karkoschka (2011). The previous expressions for pole position and precession continue in use.
8. The *W* equations for (243) Ida, (134340) Pluto, and (134340) Pluto: I Charon in Table 3 have been corrected (Archinal et al. 2011b; Eq. 2). The declination of the pole for (243) Ida was off by 90° since our 2003 report (Seidelmann et al. 2005) and has been corrected.
9. The orientation model for (1) Ceres has been updated based on Dawn mission results (Raymond and Roatsch 2015), although further refinement of those results is expected in the future. An alternate model for the orientation of Ceres has also been presented by Preusker et al. (2016). An orientation model has been given for (52) Europa by Merline et al. (2013). The orientation model for (2867) Šteins in our previous report originated from private communication with L. Jorda, not from Jorda et al. (2012, previously listed as 2010). The declination of the pole was incorrectly rounded and should have previously been 91°. The values in this report *are* from Jorda et al. (2012, Table 3).
10. Data have been added for comet 9P/Tempel 1 based on the Stardust NExT flyby, 19P/Borrelly based on the DS1 flyby and subsequent ground-based measurements, 103P/Hartley 2 based on the EPOXI flyby, and 67P/Churyumov–Gerasimenko based on the pre-perihelion approach mapping from the Rosetta orbiter. These additions required

additional discussion of the uncertainty of individual rotational states and the need to present rotational states that are only valid for specific epochs. For Tempel 1 the uncertainty of the rotational state limits us to specifying the orientation of the shape model at the time of the NExT closest approach.

11. In Sect. 7, clarification is made that the reference radius for a body may have many uses, such as map scale, map projection, and reference elevation, and for orthoprojection of data and geophysical uses. The current reference radius for the Moon is noted to be for cartographic use. The recommended reference radius for Titan is returned to its previous value, partially at the recommendation of and following the usage of the Cassini Project (2016) and the Cassini RADAR team in particular (private communication, Kirk). The relevance of the cited uncertainty information is also discussed.
12. The size of the Sun has been updated in Table 4, as derived by Haberreiter et al. (2008) and adopted via IAU Resolution B3 (IAU 2015a). Notation has also been added to indicate that the same IAU Resolution recommended similar (rounded) values for the Earth's ellipsoidal radii, and the previously recommended values from the Working Group for Jupiter's ellipsoidal radii.
13. The recommended radius for Mercury has been updated based on MESSENGER results, as described in the text above.
14. Based on the results of Thomas et al. (2013b), size information has been updated for 13 inner small Saturnian satellites, XVIII Pan, XXXV Daphnis, XV Atlas, XVI Prometheus, XVII Pandora, XI Epimetheus, X Janus, XXXII Methone, XLIX Anthe, XXXIII Pallene, XIII Telesto, XIV Calypso, and XII Helene. Size and shape information for LIII Aegaeon has also been added.
15. In our 2006 and 2009 reports, axes lengths were given rather than semi-axes lengths for (25143) Itokawa. The values have been corrected in Table 6, based on the values given by Fujiwara et al. (2006).
16. The discussion of terminology for the poles (hemispheres) of small bodies has been modified and a discussion of cardinal directions on small bodies added. It is noted that the planetographic and planetocentric coordinate system definitions do not apply to such bodies.
17. The difficulty of mapping 67P/Churyumov–Gerasimenko is discussed.
18. The size information for (1) Ceres has been updated in Table 6, based on Dawn mission results (Raymond and Roatsch 2015), although further refinement of those results is expected. Shape information has been given for (16) Psyche in Table 6, from Shepard et al. (2017). Shape information has been given for (52) Europa in Table 6, from Merline et al. (2013). Uncertainties in axes diameters and the volume-equivalent spherical-diameter are repeated here as uncertainties in semi-axes and the radius.
19. The radii of (134340) Pluto and Charon have been updated based on the image processing results of Nimmo et al. (2017) from the New Horizons mission. The values given in Table 6 for their radii include 2 σ uncertainty estimates. Since upper bounds on oblateness uncertainty are small (<0.6 and $<0.5\%$, respectively), a spherical shape is assumed.
20. Updates have been made to Sect. 9 on recommendations, and requests for community input also added to that section.

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