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REPORT OF THE IAU/IAG WORKING GROUP ON CARTOGRAPHIC COORDINATES AND ROTATIONAL ELEMENTS OF THE PLANETS AND SATELLITES: 2000

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Abstract. Every three years the IAU/IAG Working Group on cartographic coordinates and rotational elements of the planets and satellites revises tables giving the directions of the north poles of rotation and the prime meridians of the planets, satellites, and asteroids. Also presented are revised tables giving their sizes and shapes. Changes since the previous report are summarized in the Appendix.

Key words: cartographic coordinates, rotation axes, rotation periods, sizes, shapes

1. Introduction

The IAU Working Group on cartographic coordinates and rotational elements of the planets and satellites was established as a consequence of resolutions adopted by Commissions 4 and 16 at the IAU General Assembly at Grenoble in 1976. The 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 and Dynamical Astronomy* **22**, 205-230, 1980. The guiding principles and conventions that were adopted by the Group and the rationale for their acceptance were presented in that report and its appendices will not be reviewed here. The second report of the Working Group was presented to the General Assembly at Patras in 1982 and published in the *Trans. IAU* **18B**,

† Merton Davies, the original chairman of this Working Group, died on April 17, 2001.

151-162, 1983, and also in *Celestial Mechanics and Dynamical Astronomy* **29**, 309-321, 1983. The third report on the Working Group was presented to the General Assembly at New Delhi in 1985 and published in *Celestial Mechanics and Dynamical Astronomy* **39**, 103-113, 1986. The fourth report of the Working Group was presented to the General Assembly at Baltimore in 1988 and was published in *Celestial Mechanics and Dynamical Astronomy* **46**, 187-204, 1989. The fifth report of the Working Group was presented to the General Assembly at Buenos Aires in 1991 and was published in *Celestial Mechanics and Dynamical Astronomy* **53**, 377-397, 1992. The sixth report of the Working Group was presented to the General Assembly at the Hague in 1994 and was published in *Celestial Mechanics and Dynamical Astronomy* **63**, 127-148, 1996. The seventh report of the Working Group was presented to the General Assembly at Kyoto, but the changes were sufficiently minor that the report was not published.

In 1984 the International Association of Geodesy (IAG) and the Committee on Space Research (COSPAR) expressed interest in the activities of the Working Group, and after reviewing alternatives, the Executive Committees of all three organizations decided to jointly sponsor the Working Group. In 1998 COSPAR informed the Working Group that, while the reports and expertise of the Working Group are appreciated, the Working Group does not follow the scientific structure of COSPAR and they wish to terminate the formal affiliation.

This report incorporates revisions to the tables giving the directions of the north poles of rotation and the prime meridians of the planets and satellites since the last report. Also, tables giving the sizes and shapes of the planets, satellites, and asteroids are presented.

2. Definition of Rotational Elements

Planetary coordinate systems are defined relative to their mean axis of rotation and various definitions of longitude depending on the body. The longitude systems of most of those bodies with observable rigid surfaces have been defined by references to a surface feature such as a crater. Approximate expressions for these rotational elements with respect to the J2000 inertial coordinate system have been derived. The International Celestial Reference Frame (ICRF) (Ma et al. 1998) is the reference coordinate frame of epoch 2000 which is January 1.5 (JD 2451545.0), TCB. The variable quantities are expressed in units of days (86400 SI seconds) or Julian centuries of 36525 days.

The north pole is that pole of rotation that lies on the north side of the invariable plane of the solar system. The direction of the north pole is specified by the value of its right ascension α_0 and declination δ_0, whereas

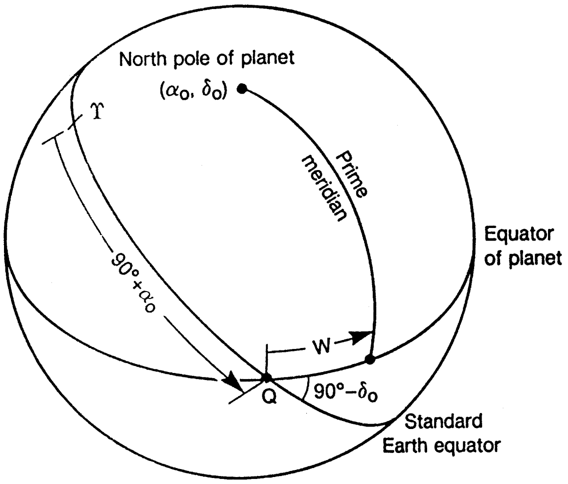

Figure 1. Reference system used to define orientation of the planet.

the location of the prime meridian is specified by the angle that is measured along the planet's equator in an easterly direction with respect to the planet's north pole from the node Q (located at right ascension $90° + \alpha_0$) of the planet's equator on the standard equator to the point B where the prime meridian crosses the planet's equator (see Figure 1). The right ascension of the point Q is $90° + \alpha_0$ and the inclination of the planet's equator to the standard equator is $90°$ - δ_0. Because the prime meridian is assumed to rotate uniformly with the planet, W accordingly varies linearly with time. In addition, α_0, δ_0, and W may vary with time due to a precession of the axis of rotation of the planet (or satellite). 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; Mercury and most of the satellites are in this category. For many of the satellites, it is assumed that the rotation rate is equal to the mean orbital period.

The angle W specifies the ephemeris position of the prime meridian, and for planets or satellites without any accurately observable fixed surface features, the adopted expression for W defines the prime meridian and is not subject to correction. Where possible, however, the cartographic position of the prime meridian is defined by a suitable observable feature, and so the constants in the expression $W = W_0 + \dot{W}d$, where d is the interval in days from the standard epoch, are chosen so that the ephemeris position follows the motion of the cartographic position as closely as possible; in these cases the expression for W may require emendation in the future.

Recommended values of the constants in the expressions for α_0, δ_0, and W, in standard equatorial coordinates with equinox J2000 at epoch J2000.0, are given for the planets, satellites, and asteroids in Tables I, II, and III. In general, these expressions should be accurate to one-tenth of a degree; however, two decimal places are given to assure consistency when changing coordinates systems. Zeros are added to rate values (W) for computational consistency and are not an indication of significant accuracy. Additional decimal places are given in the expressions for the Moon, Mars, Saturn, and Uranus, reflecting the greater confidence in their accuracy. Expressions for the Sun and Earth are given to a similar precision as those of the other bodies of the solar system and are for comparative purposes only. The recommended coordinate system for the Moon is the mean Earth/polar axis system (in contrast to the principal axis system).

3. Definition of Cartographic Coordinate Systems

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

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

1. The rotational pole of a planet or satellite which lies on the north side of the invariable plane will be called north, and northern latitudes will be designated as positive.

2. The planetographic longitude of the central meridian, as observed from a direction fixed with respect to an inertial system, will increase with time. The range of longitudes shall extend from 0° to 360°.

Thus, west longitudes (i.e., longitudes measured positively to the west) will be used when the rotation is prograde and east longitudes (i.e., longitudes measured positively to the east) when the rotation is retrograde. The origin is the center of mass. Also because of tradition, the Earth, Sun, and

Moon do not conform with this definition. Their rotations are prograde and longitudes run both east and west 180°, or east 360°.

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

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

Calculations of the hydrostatic shapes of some of the satellites (Io, Mimas, Enceladus, and Miranda) indicate that their reference surfaces should be triaxial ellipsoids. Triaxial ellipsoids would render many computations more complicated, especially those related to map projections. Many projections would loose their elegant and popular properties. For this reason spherical reference surfaces are frequently used in mapping programs.

Many small bodies of the solar system (satellites, asteroids, and comet nuclei) have very irregular shapes. Sometimes spherical reference surfaces are used for computational convenience, but this approach does not preserve the area or shape characteristics of common map projections. Orthographic projections often are adopted for cartographic portrayal as these preserve the irregular appearance of the body without artificial distortion.

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

Table IV contains data on the size and shapes of the planets. The first column gives the mean radius of the body (i.e., the radius of a sphere of approximately the same volume as the spheroid). The standard errors of the mean radii are indications of the accuracy of determination of these parameters due to inaccuracies of the observational data. Because the shape of a rotating body in hydrostatic equilibrium is approximately a spheroid, this is frequently a good approximation to the shape of planets, and so the second and third columns give equatorial and polar radii for 'best-fit' spheroids. The origin of these coordinates is the center-of-mass with the polar axis coincident with the spin axis. The fourth column is the root-mean-square (RMS) of the radii residuals from the spheroid and is an indication of the variations of the surface from the spheroid due to topography. The last two columns give the maximum positive and negative residuals to bracket the spread.

Table V contains data on the size and shape of the satellites. The first column gives the mean radius of the body. The standard errors of the mean radii are indications of the accuracy of determination of these parameters due to inaccuracies of the observational data. Because the hydrostatic shape of a body in synchronous rotation about a larger body is approximately an ellipsoid, that shape has been selected to describe the shape of the satellites. The next three columns (2-4) give the axes of the best-fit ellipsoids in the order equatorial subplanetary, equatorial along orbit, and polar. The origin of these coordinates is the center-of-mass with the polar axis coincident with the spin axis. The fifth column is the RMS of the radii residuals from the ellipsoid and is an indication of the variations of the surface from the ellipsoid due to topography. The last two columns give the maximum positive and negative residuals to bracket the spread.

Table VI contains data on the size and shape of selected asteroids. The first column gives the mean radius of the body and an estimate of the accuracy of this measurement. The next three columns give estimates of the radii measured along the three principal axes. The fifth column gives the radii of a best-fit ellipsoid. These are given because an ellipsoid is a common reference shape for photometric analyses. The last column gives an estimate of the maximum deviation of the body from the ellipsoid and is an estimate of the goodness of fit.

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

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

The radii and axes of the large gaseous planets, Jupiter, Saturn, Uranus, and Neptune in Table IV 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.

Table I. Recommended values for the direction of the north pole of rotation and the prime meridian of the Sun and planets (2000)

α_0, δ_0 — are standard equatorial coordinates with equinox J2000 at epoch J2000. 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 (of 36525 days) from the standard epoch.

d = — interval in days from the standard epoch.

The standard epoch is 2000 January 1.5, i.e., JD 2451545.0 TCB.

Sun	$\alpha_0 = 286^{\circ}.13$	
	$\delta_0 = 63^{\circ}.87$	
	$W = 84^{\circ}.10 + 14^{\circ}.1844000d$	
Mercury	$\alpha_0 = 281.01 - 0.033T$	
	$\delta_0 = 61.45 - 0.005T$	
	$W = 329.548 + 6.1385025d$	(a)
Venus	$\alpha_0 = 272.76$	
	$\delta_0 = 67.16$	
	$W = 160.20 - 1.4813688d$	(b)
Earth	$\alpha_0 = 0.00 - 0.641T$	
	$\delta_0 = 90.00 - 0.557T$	
	$W = 190.147 + 360.9856235d$	
Mars	$\alpha_0 = 317.68143 - 0.1061T$	
	$\delta_0 = 52.88650 - 0.0609T$	
	$W = 176.630 + 350.89198226d$	(c)
Jupiter	$\alpha_0 = 268.05 - 0.009T$	
	$\delta_0 = 64.49 + 0.003T$	
	$W = 284.95 + 870.5366420d$	(d)
Saturn	$\alpha_0 = 40.589 - 0.036T$	
	$\delta_0 = 83.537 - 0.004T$	
	$W = 38.90 + 810.7939024d$	(d)
Uranus	$\alpha_0 = 257.311$	
	$\delta_0 = -15.175$	
	$W = 203.81 - 501.1600928d$	(d)
Neptune	$\alpha_0 = 299.36 + 0.70 \sin N$	
	$\delta_0 = 43.46 - 0.51 \cos N$	
	$W = 253.18 + 536.3128492d - 0.48 \sin N$	(d)
	$N = 357.85 + 52.316T$	
Pluto	$\alpha_0 = 313.02$	
	$\delta_0 = 9.09$	
	$W = 236.77 - 56.3623195d$	(e)

(a) The 20° meridian is defined by the crater Hun Kal.

(b) The 0° meridian is defined by the central peak in the crater Ariadne.

(c) The 0° meridian is defined by the crater Airy-0.

(d) The equations for W for Jupiter, Saturn, Uranus and Neptune refer to the rotation of their magnetic fields (System III). On Jupiter, System I ($W_I = 67^{\circ}.1 + 877^{\circ}.900d$) 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.

(e) The 0° meridian is defined as the mean sub-Charon meridian.

Table II. Recommended values for the direction of the north pole of rotation and the prime meridian of the satellites (2000)

α_0, δ_0, T, and d have the same meanings as in Table I (epoch 2000 January 1.5, i.e., JD 2451545.0 TCB).

Earth:		Moon	$\alpha_0 = 269.9949$	$+0^{\circ}.0031T$	$-3^{\circ}.8787 \sin E1$	$-0^{\circ}.1204E2$
				$+0.0700 \sin E3$	$-0.0172 \sin E4$	$+0.0072 \sin E6$
				$-0.0052 \sin E10$	$+0.0043 \sin E13$	
			$\delta_0 = 66.5392$	$+0.0130T$	$+1.5419 \cos E1$	$+0.0239 \cos E2$
				$-0.0278 \cos E3$	$+0.0068 \cos E4$	$-0.0029 \cos E6$
				$+0.0009 \cos E7$	$+0.0008 \cos E10$	$-0.0009 \cos E13$
			$W = 38.3213$	$+13.17635815d$	$-1.4 \times 10^{-12} d^2$	$+3.5610 \sin E1$
				$+0.1208 \sin E2$	$-0.0642 \sin E3$	$+0.0158 \sin E4$
				$+0.0252 \sin E5$	$-0.0066 \sin E6$	$-0.0047 \sin E7$
				$-0.0046 \sin E8$	$+0.0028 \sin E9$	$+0.0052 \sin E10$
				$+0.0040 \sin E11$	$+0.0019 \sin E12$	$-0.0044 \sin E13$
		where	$E1 = 125^{\circ}.045 - 0^{\circ}.0529921d$,		$E2 = 250^{\circ}.089 - 0^{\circ}.1059842d$,	$E3 = 260^{\circ}.008 + 13^{\circ}.0120009d$,
			$E4 = 176.625 + 13.3407154d$,		$E5 = 357.529 + 0.9856003d$,	$E6 = 311.589 + 26.4057084d$,
			$E7 = 134.963 + 13.0649930d$,		$E8 = 276.617 + 0.3287146d$,	$E9 = 34.226 + 1.7484877d$,
			$E10 = 15.134 - 0.1589763d$,		$E11 = 119.743 + 0.0036096d$,	$E12 = 239.961 + 0.1643573d$,
			$E13 = 25.053 + 12.9590088d$			
Mars:	I	Phobos	$\alpha_0 = 317.68$	$-0.108T$	$+1.79 \sin M1$	
			$\delta_0 = 52.90$	$-0.061T$	$-1.08 \cos M1$	
			$W = 35.06$	$+1128.8445850d$	$+8.864T^2$	
				$-1.42 \sin M1$	$-0.78 \sin M2$	

Table II. *(Cont.)*

	II	Deimos	$\alpha_0 = 316.65$	$-0.108T$	$+2.98 \sin M3$	
			$\delta_0 = 53.52$	$-0.061T$	$-1.78 \cos M3$	
			$W = 79.41$	$+285.1618970d$	$-0.520T^2$	
				$-2.58 \sin M3$	$+0.19 \cos M3$	

where $M1 = 169^\circ\!.51 - 0^\circ\!.4357640d$, $M2 = 192^\circ\!.93 + 1128^\circ\!.4096700d + 8^\circ\!.864T^2$,
$M3 = 53^\circ\!.47 - 0^\circ\!.0181510d$

Jupiter:	XVI	Metis	$\alpha_0 = 268.05$	$-0.009T$		
			$\delta_0 = 64.49$	$+0.003T$		
			$W = 346.09$	$+1221.2547301d$		
	XV	Adrastea	$\alpha_0 = 268.05$	$-0.009T$		
			$\delta_0 = 64.49$	$+0.003T$		
			$W = 33.29$	$+1206.9986602d$		
	V	Amalthea	$\alpha_0 = 268.05$	$-0.009T$	$-0.84 \sin J1$	$+0.01 \sin 2J1$
			$\delta_0 = 64.49$	$+0.003T$	$-0.36 \cos J1$	
			$W = 231.67$	$+722.6314560d$	$+0.76 \sin J1$	$-0.01 \sin 2J1$
	XIV	Thebe	$\alpha_0 = 268.05$	$-0.009T$	$-2.11 \sin J2$	$+0.04 \sin 2J2$
			$\delta_0 = 64.49$	$+0.003T$	$-0.91 \cos J2$	$+0.01 \cos 2J2$
			$W = 8.56$	$+533.7004100d$	$+1.91 \sin J2$	$-0.04 \sin 2J2$
	I	Io	$\alpha_0 = 268.05$	$-0.009T$	$+0.094 \sin J3$	$+0.024 \sin J4$
			$\delta_0 = 64.50$	$+0.003T$	$+0.040 \cos J3$	$+0.011 \cos J4$
			$W = 200.39$	$+203.4889538d$	$-0.085 \sin J3$	$-0.022 \sin J4$
	II	Europa	$\alpha_0 = 268.08$	$-0.009T$	$+1.086 \sin J4$	$+0.060 \sin J5$
					$+0.015 \sin J6$	$+0.009 \sin J7$
			$\delta_0 = 64.51$	$+0.003T$	$+0.468 \cos J4$	$+0.026 \cos J5$
					$+0.007 \cos J6$	$+0.002 \cos J7$

Table II. *(Cont.)*

			$W = 36.022$	$+101.3747235d$	$-0.980 \sin J4$	$-0.054 \sin J5$	
					$-0.014 \sin J6$	$-0.008 \sin J7$	(a)
	III	Ganymede	$\alpha_0 = 268.20$	$-0.009T$	$-0.037 \sin J4$	$+0.431 \sin J5$	
						$+0.091 \sin J6$	
			$\delta_0 = 64.57$	$+0.003T$	$-0.016 \cos J4$	$+0.186 \cos J5$	
						$+0.039 \cos J6$	
			$W = 44.064$	$+50.3176081d$	$+0.033 \sin J4$	$-0.389 \sin J5$	(b)
						$-0.082 \sin J6$	
	IV	Callisto	$\alpha_0 = 268.72$	$-0.009T$	$-0.068 \sin J5$	$+0.590 \sin J6$	
						$+0.010 \sin J8$	
			$\delta_0 = 64.83$	$+0.003T$	$-0.029 \cos J5$	$+0.254 \cos J6$	
						$-0.004 \cos J8$	
			$W = 259.51$	$+21.5710715d$	$+0.061 \sin J5$	$-0.533 \sin J6$	(c)
						$-0.009 \sin J8$	
		where	$J1 = 73^\circ.32 + 91472^\circ.9T$,		$J2 = 24^\circ.62 + 45137^\circ.2T$,	$J3 = 283^\circ.90 + 4850^\circ.7T$,	
			$J4 = 355.80 + 1191.3T$,		$J5 = 119.90 + 262.1T$,	$J6 = 229.80 + 64.3T$,	
			$J7 = 352.25 + 2382.6T$,		$J8 = 113.35 + 6070.0T$		
Saturn:	XVIII	Pan	$\alpha_0 = 40.6$	$-0.036T$			
			$\delta_0 = 83.5$	$-0.004T$			
			$W = 48.8$	$+626.0440000d$			
	XV	Atlas	$\alpha_0 = 40.58$	$-0.036T$			
			$\delta_0 = 83.53$	$-0.004T$			
			$W = 137.88$	$+598.3060000d$			

Table II. *(Cont.)*

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	$\alpha_0 = 40.58$	$-0.036T$	$-3.153 \sin S1$	$+0.086 \sin 2S1$	
		$\delta_0 = 83.52$	$-0.004T$	$-0.356 \cos S1$	$+0.005 \cos 2S1$	
		$W = 293.87$	$+518.4907239d$	$+3.133 sin S1$	$-0.086 \sin 2S1$	(j)
X	Janus	$\alpha_0 = 40.58$	$-0.036T$	$-1.623 \sin S2$	$+0.023 \sin 2S2$	
		$\delta_0 = 83.52$	$-0.004T$	$-0.183 \cos S2$	$+0.001 \cos 2S2$	
		$W = 58.83$	$+518.2359876d$	$+1.613 \sin S2$	$-0.023 \sin 2S2$	(j)
I	Mimas	$\alpha_0 = 40.66$	$-0.036T$	$+13.56 \sin S3$		
		$\delta_0 = 83.52$	$-0.004T$	$-1.53 \cos S3$		
		$W = 337.46$	$+381.9945550d$	$-13.48 \sin S3$	$-44.85 \sin S5$	(d)
II	Enceladus	$\alpha_0 = 40.66$	$-0.036T$			
		$\delta_0 = 83.52$	$-0.004T$			
		$W = 2.82$	$+262.7318996d$			(e)
III	Tethys	$\alpha_0 = 40.66$	$-0.036T$	$+9.66 \sin S4$		
		$\delta_0 = 83.52$	$-0.004T$	$-1.09 \cos S4$		
		$W = 10.45$	$+190.6979085d$	$-9.60 \sin S4$	$2.23 \sin S5$	(f)
XIII	Telesto	$\alpha_0 = 50.51$	$-0.036T$			
		$\delta_0 = 84.06$	$-0.004T$			
		$W = 56.88$	$+190.6979332d$			(j)
XIV	Calypso	$\alpha_0 = 36.41$	$-0.036T$			
		$\delta_0 = 85.04$	$-0.004T$			
		$W = 153.51$	$+190.6742373d$			(j)

Table II. *(Cont.)*

	IV	Dione	$\alpha_0 = 40.66$	$-0.036T$		
			$\delta_0 = 83.52$	$-0.004T$		
			$W = 357.00$	$+131.5349316d$		(g)
	XII	Helene	$\alpha_0 = 40.85$	$-0.036T$		
			$\delta_0 = 83.34$	$-0.004T$		
			$W = 245.12$	$+131.6174056d$		
	V	Rhea	$\alpha_0 = 40.38$	$-0.036T$	$+3.10 \sin S6$	
			$\delta_0 = 83.55$	$-0.004T$	$-0.35 \cos S6$	
			$W = 235.16$	$+79.6900478d$	$-3.08 \sin S6$	(h)
	VI	Titan	$\alpha_0 = 36.41$	$-0.036T$	$+2.66 \sin S7$	
			$\delta_0 = 83.94$	$-0.004T$	$-0.30 \cos S7$	
			$W = 189.64$	$+22.5769768d$	$-2.64 \sin S7$	
	VIII	Iapetus	$\alpha_0 = 318.16$	$-3.949T$		
			$\delta_0 = 75.03$	$-1.143T$		
			$W = 350.20$	$+4.5379572d$		(i)
	IX	Phoebe	$\alpha_0 = 355.00$			
			$\delta_0 = 68.70$			
			$W = 304.70$	$+930.8338720d$		
	where	$S1 = 353^{\circ}.32 + 75706^{\circ}.7T$,	$S2 = 28^{\circ}.72 + 75706^{\circ}.7T$,	$S3 = 177^{\circ}.40 - 36505^{\circ}.5T$		
		$S4 = 300.00 - 7225.9T$,	$S5 = 316.45 + 506.2T$,	$S6 = 345.20 - 1016.3T$,		
		$S7 = 29.80 - 52.1T$				
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	$\alpha_0 = 257.31$	$-0.09 \sin U2$		
			$\delta_0 = -15.18$	$+0.09 \cos U2$		
			$W = 130.35$	$-956.4068150d$	$-0.03 \sin U2$	

Table II. *(Cont.)*

VIII	Bianca	$\alpha_0 = 257.31$	$-0.16 \sin U3$	
		$\delta_0 = -15.18$	$+0.16 \cos U3$	
		$W = 105.46$	$-828.3914760d$	$-0.04 \sin U3$
IX	Cressida	$\alpha_0 = 257.31$	$-0.04 \sin U4$	
		$\delta_0 = -15.18$	$+0.04 \cos U4$	
		$W = 59.16$	$-776.5816320d$	$-0.01 \sin U4$
X	Desdemona	$\alpha_0 = 257.31$	$-0.17 \sin U5$	
		$\delta_0 = -15.18$	$+0.16 \cos U5$	
		$W = 95.08$	$-760.0531690d$	$-0.04 \sin U5$
XI	Juliet	$\alpha_0 = 257.31$	$-0.06 \sin U6$	
		$\delta_0 = -15.18$	$+0.06 \cos U6$	
		$W = 302.56$	$-730.1253660d$	$-0.02 \sin U6$
XII	Portia	$\alpha_0 = 257.31$	$-0.09 \sin U7$	
		$\delta_0 = -15.18$	$+0.09 \cos U7$	
		$W = 25.03$	$-701.4865870d$	$-0.02 \sin U7$
XIII	Rosalind	$\alpha_0 = 257.31$	$-0.29 \sin U8$	
		$\delta_0 = -15.18$	$+0.28 \cos U8$	
		$W = 314.90$	$-644.6311260d$	$-0.08 \sin U8$
XIV	Belinda	$\alpha_0 = 257.31$	$-0.03 \sin U9$	
		$\delta_0 = -15.18$	$+0.03 \cos U9$	
		$W = 297.46$	$-577.3628170d$	$-0.01 \sin U9$
XV	Puck	$\alpha_0 = 257.31$	$-0.33 \sin U10$	
		$\delta_0 = -15.18$	$+0.31 \cos U10$	
		$W = 91.24$	$-472.5450690d$	$-0.09 \sin U10$

Table II. *(Cont.)*

	V	Miranda	$\alpha_0 = 257.43$	$+4.41 \sin U11$	$-0.04 \sin 2U11$		
			$\delta_0 = -15.08$	$+4.25 \cos U11$	$-0.02 \cos 2U11$		
			$W = 30.70$	$-254.6906892d$	$-1.27 \sin U12$	$+0.15 \sin 2U12$	
					$+1.15 \sin U11$	$-0.09 \sin 2U11$	
	I	Ariel	$\alpha_0 = 257.43$	$+0.29 \sin U13$			
			$\delta_0 = -15.10$	$+0.28 \cos U13$			
			$W = 156.22$	$-142.8356681d$	$+0.05 \sin U12$	$0.08 \sin U13$	
	II	Umbriel	$\alpha_0 = 257.43$	$+0.21 \sin U14$			
			$\delta_0 = -15.10$	$+0.20 \cos U14$			
			$W = 108.05$	$-86.8688923d$	$-0.09 \sin U12$	$+0.06 \sin U14$	
	III	Titania	$\alpha_0 = 257.43$	$+0.29 \sin U15$			
			$\delta_0 = -15.10$	$+0.28 \cos U15$			
			$W = 77.74$	$-41.3514316d$	$+0.08 \sin U15$		
	IV	Oberon	$\alpha_0 = 257.43$	$+0.16 \sin U16$			
			$\delta_0 = -15.10$	$+0.16 \cos U16$			
			$W = 6.77$	$-26.7394932d$	$+0.04 \sin U16$		
	where		$U1 = 115^\circ.75 + 54991^\circ.87T$,	$U2 = 141^\circ.69 + 41887^\circ.66T$,	$U3 = 135^\circ.03 + 29927^\circ.35T$,		
			$U4 = 61.77 + 25733.59T$,	$U5 = 249.32 + 24471.46T$,	$U6 = 43.86 + 22278.41T$,		
			$U7 = 77.66 + 20289.42T$,	$U8 = 157.36 + 16652.76T$,	$U9 = 101.81 + 12872.63T$,		
			$U10 = 138.64 + 8061.81T$,	$U11 = 102.23 - 2024.22T$,	$U12 = 316.41 + 2863.96T$,		
			$U13 = 304.01 - 51.94T$,	$U14 = 308.71 - 93.17T$,	$U15 = 340.82 - 75.32T$,		
			$U16 = 259.14 - 504.81T$				
Neptune	III	Naiad	$\alpha_0 = 299.36$	$+0.70 \sin N$	$-6.49 \sin N1$	$+0.25 \sin 2N1$	
			$\delta_0 = 43.36$	$-0.51 \cos N$	$-4.75 \cos N1$	$+0.09 \cos 2N1$	
			$W = 254.06$	$+1222.8441209d$	$-0.48 \sin N$	$+4.40 \sin N1$	$-0.27 \sin 2N1$

Table II. *(Cont.)*

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 II. *(Cont.)*

		where	$N = 357^\circ.85 + 52^\circ.316T$,	$N1 = 323^\circ.92 + 62606^\circ.6T$,	$N2 = 220^\circ.51 + 55064^\circ.2T$,
			$N3 = 354.27 + 46564.5T$,	$N4 = 75.31 + 26109.4T$,	$N5 = 35.36 + 14325.4T$,
			$N6 = 142.61 + 2824.6T$,	$N7 = 177.85 + 52.316T$	
Pluto	I	Charon	$\alpha_0 = 313.02$		
			$\delta_0 = 9.09$		
			$W = 56.77 \quad -56.3623195d$		

(a) The 182° meridian is defined by the crater Cilix.
(b) The 128° meridian is defined by the crater Anat.
(c) The 326° meridian is defined by the crater Saga.
(d) The 162° meridian is defined by the crater Palomides.
(e) The 5° meridian is defined by the crater Salih.
(f) The 299° meridian is defined by the crater Arete.
(g) The 63° meridian is defined by the crater Palinurus.
(h) The 340° meridian is defined by the crater Tore.
(i) The 276° meridian is defined by the crater Almeric.
(j) These equations are correct for the period of the Voyager encounters. Because of precession they may not be accurate at other time periods.

Satellites for which no suitable data are yet available have been omitted from this table. Nereid is not included in this table because it is not in synchronous rotation.

Table III. Recommended rotation values for the direction of the north pole of rotation and the prime meridian of selected asteroids (2000)

α_0, δ_0, W, and d have the same meanings as in Table I (epoch 2000 January 1.5, i.e., JD 2451545.0 TCB).

243	Ida	$\alpha_0 = 348^\circ\!.76$	
		$\delta_0 = 87^\circ\!.12$	
		$W = 265^\circ\!.95 - 1864^\circ\!.6280070d$	(a)
951	Gaspra	$\alpha_0 = 9^\circ\!.47$	
		$\delta_0 = 26^\circ\!.70$	
		$W = 83^\circ\!.67 + 1226^\circ\!.9114850d$	(b)
4	Vesta	$\alpha_0 = 301^\circ$	
		$\delta_0 = 41^\circ$	
		$W = 292^\circ + 1617^\circ\!.332776d$	
433	Eros	$\alpha_0 = 11^\circ\!.35 \pm 0.02$	
		$\delta_0 = 17^\circ\!.22 \pm 0.02$	
		$W = 326^\circ\!.07 + 1639^\circ\!.38864745d$	

(a) The 0 meridian is defined by the crater Afon.

(b) The 0 meridian is defined by the crater Charax.

4. Appendix

This appendix summarizes the changes that have been made to the tables since the 1994 report (*Celestial Mechanics and Dynamical Astronomy* **63**, 127-148, 1996).

The reference frame now used is the International Celestial Reference Frame (ICRF) as adopted by the IAU and defined by Ma et al. (1998).

In Table I, the new value for the W_0 of Mercury was the result of a new control network computation by Robinson et al. (1999). The new values of α_0 and δ_0 for Mars are due to Folkner et al. (1997). The new value for W of Mars was the result of a control network computation by Davies et al. (1999). The value for the d term in W for Jupiter is from Higgins et al. (1996).

The new value for the d term in W for Jupiter is a new radio rotation period by Higgins et al. (1996).

In Table II the value of W for Metis is from Lieske (1997). In Table III the values for Vesta are from Thomas et al. (1997) and the values of Eros are from Thomas et al. (2001). In Table IV the Mars model is that determined by the Mars Geodesy and Cartography Working Group from Archinal (2001).

Table IV. 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)
Mercury	2439.7 ± 1.0	same	same	1	4.6	2.5
Venus	6051.8 ± 1.0	same	same	1	11	2
Earth	6371.00 ± 0.01	6378.14 ± 0.01	6356.75 ± 0.01	3.57	8.85	11.52
Mars	3389.50 ± 0.2	3396.19 ± 0.1	AVG 3376.20 ± 0.1	3.0	22.64 ± 0.1	7.55 ± 0.1
			N 3373.19 ± 0.1			
			S 3379.21 ± 0.1			
Jupiter*	69911 ± 6	71492 ± 4	66854 ± 10	62.1	31	102
Saturn*	58232 ± 6	60268 ± 4	54364 ± 10	102.9	8	205
Uranus*	25362 ± 7	25559 ± 4	24973 ± 20	16.8	28	0
Neptune*	24622 ± 19	24764 ± 15	24341 ± 30	8	14	0
Pluto	1195 ± 5	same	same			

*The radii correspond to a one-bar surface.

Table V. Size and shape parameters of the satellites

Planet		Satellite	Mean Radius (km)	Subplanetary equatorial radius (km)	Along Orbit equatorial radius (km)	Polar radius (km)	RMS deviation from ellipsoid (km)	Maximum elevation (km)	Maximum depression (km)
Earth		Moon	1737.4 ± 1	same	same	same	2.5	7.5	5.6
Mars	I	Phobos	11.1 ± 0.15	13.4	11.2	9.2	0.5		
	II	Deimos	6.2 ± 0.18	7.5	6.1	5.2	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	1821.46	1829.4	1819.3	1815.7	1.4	5-10	3
	II	Europa	1562.09	1564.13	1561.23	1560.93	0.5		
	III	Ganymede	2632.345	2632.4	2632.29	2632.35	0.6		
	IV	Callisto	2409.3	2409.4	2409.2	2409.3	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						
Saturn	XVIII	Pan	10 ± 3						
	XV	Atlas	16 ± 4	18.5	17.2	13.5			
	XVI	Prometheus	50.1 ± 3	74.0	50.0	34.0	4.1		
	XVII	Pandora	41.9 ± 2	55.0	44.0	31.0	1.3		

Table V. *(Cont.)*

	XI	Epimetheus	59.5 ± 3	69.0	55.0	55.0	3.1		
	X	Janus	88.8 ± 4	97.0	95.0	77.0	4.2		
	I	Mimas	198.6 ± 0.6	209.1 ± 0.5	196.2 ± 0.5	191.4 ± 0.5	0.6		
	II	Enceladus	249.4 ± 0.3	256.3 ± 0.3	247.3 ± 0.3	244.6 ± 0.5	0.4		
	III	Tethys	529.8 ± 1.5	535.6 ± 1.2	528.2 ± 1.2	525.8 ± 1.2	1.7		
	XIII	Telesto	11 ± 4	15 ± 2.5	12.5 ± 5	7.5 ± 2.5			
	XIV	Calypso	9.5 ± 4	15.0	8.0	8.0	0.6		
	IV	Dione	560 ± 5	same	same	same	0.5		
	XII	Helene	16	17.5 ± 2.5		0.7			
	V	Rhea	764 ± 4	same	same	same			
	VI	Titan	2575 ± 2	same	same	same			
	VII	Hyperion	133 ± 8	164 ± 8	130 ± 8	107 ± 8	7.4		
	VIII	Iapetus	718 ± 8	same	same	same	6.1	12	
	IX	Phoebe	110 ± 10	115 ± 10	110 ± 10	105 ± 10	2.7		
Uranus	VI	Cordelia	13 ± 2						
	VII	Ophelia	15 ± 2						
	VIII	Bianca	21 ± 3						
	IX	Cressida	31 ± 4						
	X	Desdemona	27 ± 3						
	XI	Juliet	42 ± 5						
	XII	Portia	54 ± 6						
	XIII	Rosalind	27 ± 4						
	XIV	Belinda	33 ± 4						
	XV	Puck	77 ± 5				1.9		
	V	Miranda	235.8 ± 0.7	240.4 ± 0.6	234.2 ± 0.9	232.9 ± 1.2	1.6	5	8
	I	Ariel	578.9 ± 0.6	581.1 ± 0.9	577.9 ± 0.6	577.7 ± 1.0	0.9	4	4
	II	Umbriel	584.7 ± 2.8	same	same	same	2.6		6

Table V. *(Cont.)*

	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
Neptune	III	Naiad	29 ± 6						
	IV	Thalassa	40 ± 8						
	V	Despina	74 ± 10						
	VI	Galatea	79 ± 12						
	VII	Larissa	96 ± 7	104		89	2.9	6	5
	VIII	Proteus	208 ± 8	218	208	201	7.9	18	13
	I	Triton	1352.6 ± 2.4						
	II	Nereid	170 ± 25						
Pluto	I	Charon	593 ± 13						

Table VI. Size and shape parameters of selected asteroids

Asteroid	Mean radius (km)	Radii measured along principal axes (km)	(km)	(km)	Radii of best-fit Ellipsoid (km)	Maximum deviation from ellipsoid (km)
243 Ida	15.65 ± 0.6	26.8	12.0	7.6	30.0, 12.6, 9.3	8.4
951 Gaspra	6.1 ± 0.4	9.1	5.2	4.4	9.1, 5.2, 4.7	2.1
216 Kleopatra		108.5	47	40.5		
433 Eros	7.311 ± 0.01				9.236 ± 0.1	

In Table V the sizes of the inner satellites of Jupiter are from Thomas et al. (1998). The sizes of the Galilean satellites are from Davies et al. (1998). The size of Hyperion is from Thomas et al. (1995). In Table VI the parameters for 216 Kleopatra are from Ostro et al. (2000). The parameters for 433 Eros are from Zuber et al. (2000).

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