REPORT OF THE IAU/IAG/COSPAR WORKING GROUP ON CARTOGRAPHIC COORDINATES AND ROTATIONAL ELEMENTS OF THE PLANETS AND SATELLITES: 1988

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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**, pp. 72–79, 1980. The report with appendices was published in *Celestial Mechanics*, **22**, pp. 205–230, 1980. The guiding principles and conventions that were adopted by the Group and the rationale for their acceptance are presented in that report and its appendices and will not be reviewed

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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**, pp. 151–162, 1983, and also in *Celestial Mechanics*, **29**, pp. 309–321, 1983. The third report of the Working Group was presented to the General Assembly at New Delhi in 1985 and published in *Celestial Mechanics*, **39**, pp. 103–113, 1986.

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.

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. New tables giving the sizes and shapes of the planets and satellites 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 J2000 coordinate system is defined by the FK5 star catalog and has the standard epoch of 2000 January 1.5 (JD 2451545.0), TDB. 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 the location of the prime meridian is specified by the angle W 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 $90° - \delta_0$. 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.

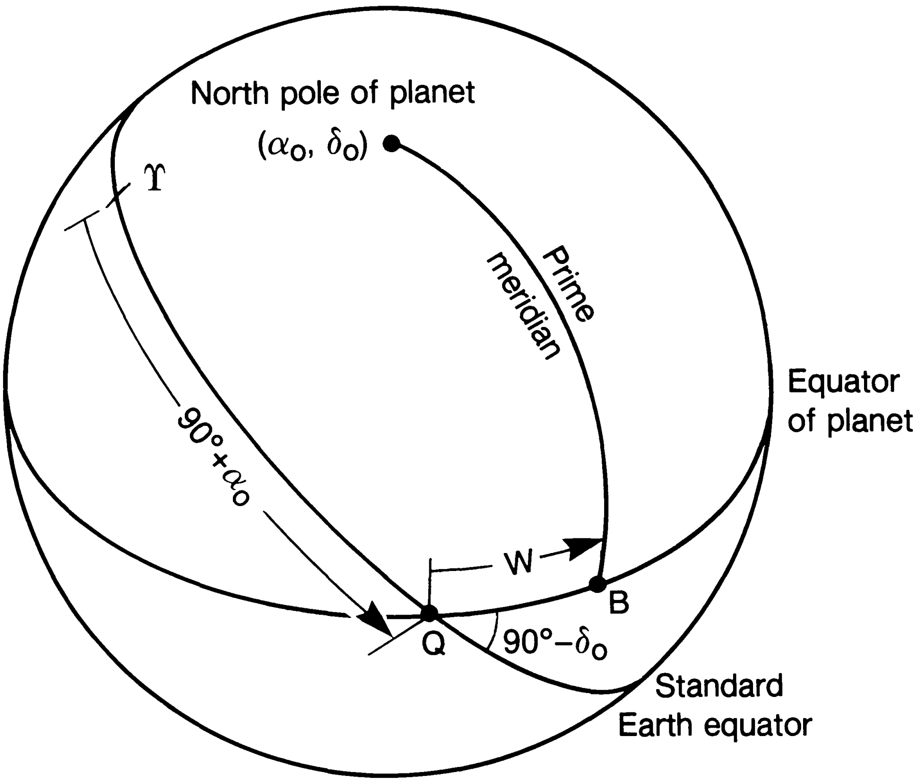

Fig.1. Reference system used to define orientation of the planet.

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 $W = W_0 + Wd$, 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 are given for the planets and satellites in Tables I and II for the standard equatorial coordinates with equinox J2000 at epoch J2000. In general, these expressions should be accurate to one-tenth of a degree; however, two decimal places are given to assure consistency when changing coordinate systems. Zeros are added to rate values (W) for computational consistency and are not an indication of significant accuracy. Three decimal places are given in the expressions for the Moon and Mars, reflecting the greater confidence in their accuracy. Expressions for the Sun 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).

TABLE I

Recommended values for the direction of the north pole of rotation and the prime meridian of the Sun and planets (1988).

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 TDB.

Sun	α_0	$= 286^\circ\!.13$	
	δ_0	$= 63^\circ\!.87$	
	W	$= 84^\circ\!.10 + 14^\circ\!.1844000\ d$	
Mercury	α_0	$= 281.01 - 0.003\ T$	
	δ_0	$= 61.45 - 0.005\ T$	
	W	$= 329.71 + 6.1385025\ d$	(a)
Venus	α_0	$= 272.69$	
	δ_0	$= 67.17$	
	W	$= 160.39 - 1.4813291\ d$	
Earth	α_0	$= 0.00 - 0.641\ T$	
	δ_0	$= 90.00 - 0.557\ T$	
	W	$= 190.16 + 360.9856235\ d$	(b)
Mars	α_0	$= 317.681 - 0.108\ T$	
	δ_0	$= 52.886 - 0.061\ T$	
	W	$= 176.868 + 350.8919830\ d$	(c)
Jupiter	α_0	$= 268.05 - 0.009\ T$	
	δ_0	$= 64.49 + 0.003\ T$	
	W	$= 284.95 + 870.5360000\ d$	(d)
Saturn	α_0	$= 40.58 - 0.036\ T$	
	δ_0	$= 83.54 - 0.004\ T$	
	W	$= 38.90 + 810.7939024\ d$	(d)
Uranus	α_0	$= 257.43$	
	δ_0	$= -15.10$	
	W	$= 203.81 - 501.1600928\ d$	(d)
Neptune	α_0	$= 298.72 + 2.58 \sin N - 0.04 \sin 2N$	
	δ_0	$= 42.63 - 1.90 \cos N + 0.01 \cos 2N$	
	W	$= 313.66 + 483.7625981\ d - 1.75 \sin N + 0.04 \sin 2N$	
	N	$= 359.28 + 54.308\ T$	
Pluto	α_0	$= 311.63$	
	δ_0	$= 4.18$	
	W	$= 252.66 - 56.3640000\ d$	

Note:
(a) The 20° meridian is defined by the crater Hun Kal.
(b) The expression for W might be in error by as much as 0.2 because of uncertainty in the length of the UT day and the TDT-UT on 1 January 2000.
(c) The 0° meridian is defined by the crater Airy-O.
(d) The equations for W for Jupiter, Saturn, and Uranus refer to the rotation of their magnetic fields (System III). On Jupiter, System I ($W_I = 67^\circ\!.1 + 877^\circ\!.900\ d$) refers to the mean atmospheric equatorial rotation; System II ($W_{II} = 43^\circ\!.3 + 870^\circ\!.270\ d$) refers to the mean atmospheric rotation north of the south component of the north equatorial belt, and south of the north component of the south equatorial belt.

TABLE II

Recommended values for the direction of the north pole of rotation and the prime meridian of the satellites (1988).

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 TDB).

Earth:		Moon	α_0	= 270°000	− 3°878 sin $E1$	− 0°120 sin $E2$
					+ 0.070 sin $E3$	− 0.017 sin $E4$
			δ_0	= 66.534	+ 1.543 cos $E1$	+ 0.024 cos $E2$
					− 0.028 cos $E3$	+ 0.007 cos $E4$
			W	= 38.314	+ 13.1763581 d	+ 3.558 sin $E1$
					+ 0.121 sin $E2$	− 0.064 sin $E3$
					+ 0.016 sin $E4$	+ 0.025 sin $E5$

where $E1 = 125°045 - 0°052992\ d$, $E2 = 249°390 - 0°105984\ d$,
$E3 = 196°694 - 13°012000\ d$, $E4 = 176°630 + 13°340716\ d$,
$E5 = 358°219 - 0°985600\ d$

Mars:	I	Phobos	α_0	= 317°68	− 0°108 T	+ 1°79 sin $M1$
			δ_0	= 52.90	− 0.061 T	− 1.08 cos $M1$
			W	= 35.06	+ 1128.8445850 d	+ 8.864 T^2
					− 1.42 sin $M1$	− 0.78 sin $M2$
	II	Deimos	α_0	= 316.65	− 0.108T	+ 2.98 sin $M3$
			δ_0	= 53.52	− 0.061T	− 1.78 cos $M3$
			W	= 79.41	+ 285.1618970 d	− 0.520 T^2
					− 2.58 sin $M3$	+ 0.19 cos $M3$

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

Jupiter:	XVI	Metis	α_0	= 268.05	− 0.009 T		
			δ_0	= 64.49	+ 0.003 T		
			W	= 302.24	+ 1221.2489660 d		
	XV	Adrastea	α_0	= 268.05	− 0.009 T		
			δ_0	= 64.49	+ 0.003 T		
			W	= 5.75	+ 1206.9950400 d		
	V	Amalthea	α_0	= 268°05	− 0°009 T	− 0°84 sin $J1$	+ 0°01 sin $2J1$
			δ_0	= 64°49	+ 0°003 T	− 0°36 cos $J1$	
			W	= 231°67	+ 722°6314560 d	+ 0°76 sin $J1$	− 0°01 sin $2J1$

XIV	Thebe	α_0	=	268°05	− 0°009 T	− 2°12 sin $J2$	+ 0°04 sin $2J2$	
		δ_0	=	64°49	+ 0°003 T	− 0°91 cos $J2$	+ 0°01 cos $2J2$	
		W	=	9°91	+ 533°7005330 d	+ 1°91 sin $J2$	− 0°04 sin $2J2$	
I	Io	α_0	=	268°05	− 0°009 T	+ 0°094 sin $J3$	+ 0°024 sin $J4$	
		δ_0	=	64.50	+ 0.003 T	+ 0.040 cos $J3$	+ 0.011 cos $J4$	
		W	=	200.39	+ 203.4889538 d	− 0.085 sin $J3$	− 0.022 sin $J4$	
II	Europa	α_0	=	268°08	− 0°009 T	+ 1°086 sin $J4$	+ 0°060 sin $J5$	
						+ 0°015 sin $J6$	+ 0°009 sin $J7$	
		δ_0	=	64.51	+ 0.003 T	+ 0.468 cos $J4$	+ 0.026 cos $J5$	
						+ 0.007 cos $J6$	+ 0.002 cos $J7$	
		W	=	35.72	+ 101.3747235 d	− 0.980 sin $J4$	− 0.054 sin $J5$	(a)
						− 0.014 sin $J6$	− 0.008 sin $J7$	
III	Ganymede	α_0	=	268.20	− 0.009 T	− 0.037 sin $J4$	+ 0.431 sin $J5$	
						+ 0.091 sin $J6$		
		δ_0	=	64.57	+ 0.003 T	− 0.016 cos $J4$	+ 0.186 cos $J5$	
						+ 0.039 cos $J6$		
		W	=	43.14	+ 50.3176081 d	+ 0.033 sin $J4$	− 0.389 sin $J5$	(b)
						− 0.082 sin $J6$		
IV	Callisto	α_0	=	268.72	− 0.009 T	− 0.068 sin $J5$	+ 0.590 sin $J6$	
						+ 0.010 sin $J8$		
		δ_0	=	64.83	+ 0.003 T	− 0.029 cos $J5$	+ 0.254 cos $J6$	
						− 0.004 cos $J8$		
		W	=	259.67	+ 21.5710715 d	+ 0.061 sin $J5$	− 0.533 sin $J6$	(c)
						− 0.009 sin $J8$		

where $J1 = 73°32 + 91472°9\ T$, $J2 = 198°54 + 44243°8\ T$, $J3 = 283°90 + 4850°7\ T$,
$J4 = 355°80 + 1191°3\ T$, $J5 = 119°90 + 262°1\ T$, $J6 = 229°80 + 64°3\ T$,
$J7 = 352°25 + 2382°6\ T$, $J8 = 113°35 + 6070°0\ T$

Saturn: XV	Atlas	α_0	=	40°58	− 0°036 T	
		δ_0	=	83°53	− 0°004 T	
		W	=	137°88	+ 598°3060000 d	
XVI	Prometheus	α_0	=	40.58	− 0.036 T	
		δ_0	=	83.53	− 0.004 T	
		W	=	296.14	+ 587.2890000 d	

XVII	Pandora	α_0	$= 40.58$	$- 0.036\ T$			
		δ_0	$= 83.53$	$- 0.004\ T$			
		W	$= 162.92$	$+ 572.7891000\ d$			
I	Mimas	α_0	$= 40^\circ.66$	$- 0^\circ.036\ T$	$+ 13^\circ.56 \sin S1$		
		δ_0	$= 83.52$	$- 0.004\ T$	$- 1.53 \cos S1$		
		W	$= 337.46$	$+ 381.9945550\ d$	$- 13.48 \sin S1$	$- 44.85 \sin S5$	(d)
II	Enceladus	α_0	$= 40.66$	$- 0.036\ T$			
		δ_0	$= 83.52$	$- 0.004\ T$			
		W	$= 2.82$	$+ 262.7318996\ d$			(e)
III	Tethys	α_0	$= 40.66$	$- 0.036\ T$	$+ 9.66 \sin S2$		
		δ_0	$= 83.52$	$- 0.004\ T$	$- 1.09 \cos S2$		
		W	$= 10.45$	$+ 190.6979085\ d$	$- 9.60 \sin S2$	$+ 2.23 \sin S5$	(f)
XIII	Telesto	α_0	$= 50.50$	$- 0.036\ T$			
		δ_0	$= 84.06$	$- 0.004\ T$			
		W	$= 56.88$	$+ 190.6979330\ d$			
IV	Dione	α_0	$= 40.66$	$- 0.036\ T$			
		δ_0	$= 83.52$	$- 0.004\ T$			
		W	$= 357.00$	$+ 131.5349316\ d$			(g)
V	Rhea	α_0	$= 40.38$	$- 0.036\ T$	$+ 3.10 \sin S3$		
		δ_0	$= 83.55$	$- 0.004\ T$	$- 0.35 \cos S3$		
		W	$= 235.16$	$+ 79.6900478\ d$	$- 3.08 \sin S3$		(h)
VI	Titan	α_0	$= 36^\circ.41$	$- 0^\circ.036\ T$	$+ 2^\circ.66 \sin S4$		
		δ_0	$= 83.94$	$- 0.004\ T$	$- 0.30 \cos S4$		
		W	$= 189.64$	$+ 22.5769768\ d$	$- 2.64 \sin S4$		
VIII	Iapetus	α_0	$= 318^\circ.16$	$- 3^\circ.949\ T$			
		δ_0	$= 75.03$	$- 1.143\ T$			
		W	$= 350.20$	$+ 4.5379572\ d$			(i)

where $S1 = 177^\circ.40 - 36505^\circ.5\ T$, $S2 = 300^\circ.00 - 7225^\circ.9\ T$, $S3 = 345^\circ.20 - 1016^\circ.3\ T$,
$S4 = 29^\circ.80 - 52^\circ.1\ T$, $S5 = 316^\circ.45 + 506^\circ.2\ T$

Uranus:	VI	Cordelia	$\alpha_0 = 257\overset{\circ}{.}31 - 0\overset{\circ}{.}15 \sin U1$	
			$\delta_0 = -15\overset{\circ}{.}18 + 0\overset{\circ}{.}14 \cos U1$	
			$W = 127\overset{\circ}{.}69 - 1074\overset{\circ}{.}5205730\, d$	$- 0\overset{\circ}{.}04 \sin U1$
	VII	Ophelia	$\alpha_0 = 257.31 - 0.09 \sin U2$	
			$\delta_0 = -15.18 + 0.09 \cos U2$	
			$W = 130.35 - 956.4068150\, d$	$- 0.03 \sin U2$
	VIII	Bianca	$\alpha_0 = 257.31 - 0.16 \sin U3$	
			$\delta_0 = -15.18 + 0.16 \cos U3$	
			$W = 105.46 - 828.3914760\, d$	$- 0.04 \sin U3$
	IX	Cressida	$\alpha_0 = 257.31 - 0.04 \sin U4$	
			$\delta_0 = -15.18 + 0.04 \cos U4$	
			$W = 59.16 - 776.5816320\, d$	$- 0.01 \sin U4$
	X	Desdemona	$\alpha_0 = 257.31 - 0.17 \sin U5$	
			$\delta_0 = -15.18 + 0.16 \cos U5$	
			$W = 95.08 - 760.0531690\, d$	$- 0.04 \sin U5$
	XI	Juliet	$\alpha_0 = 257.31 - 0.06 \sin U6$	
			$\delta_0 = -15.18 + 0.06 \cos U6$	
			$W = 302.56 - 730.1253660\, d$	$- 0.02 \sin U6$
	XII	Portia	$\alpha_0 = 257.31 - 0.09 \sin U7$	
			$\delta_0 = -15.18 + 0.09 \cos U7$	
			$W = 25.03 - 701.4865870\, d$	$- 0.02 \sin U7$
	XIII	Rosalind	$\alpha_0 = 257.31 - 0.29 \sin U8$	
			$\delta_0 = -15.18 + 0.28 \cos U8$	
			$W = 314.90 - 644.6311260\, d$	$- 0.08 \sin U8$
	XIV	Belinda	$\alpha_0 = 257.31 - 0.03 \sin U9$	
			$\delta_0 = -15.18 + 0.03 \cos U9$	
			$W = 297.46 - 577.3628170\, d$	$- 0.01 \sin U9$
	XV	Puck	$\alpha_0 = 257.31 - 0.33 \sin U10$	
			$\delta_0 = -15.18 + 0.31 \cos U10$	
			$W = 91.24 - 472.5450690\, d$	$- 0.99 \sin U10$

V	Miranda	α_0	=	257°43	+	4°41 sin $U11$	−	0°04 sin $2U11$			
		δ_0	=	−15.08	+	4.25 cos $U11$	−	0.02 cos $2U11$			
		W	=	30.70	−	254.6906892 d	−	1.27 sin $U12$	+	0.15 sin $2U12$
							+	1.15 sin $U11$	−	0.09 sin $2U11$
I	Ariel	α_0	=	257.43	+	0.29 sin $U13$				
		δ_0	=	−15.10	+	0.28 cos $U13$				
		W	=	156.22	−	142.8356681 d	+	0.05 sin $U12$	+	0.08 sin $U13$
II	Umbriel	α_0	=	257.43	+	0.21 sin $U14$				
		δ_0	=	−15.10	+	0.20 cos $U14$				
		W	=	108.05	−	86.8688923 d	−	0.09 sin $U12$	+	0.06 sin $U14$
III	Titania	α_0	=	257.43	+	0.29 sin $U15$				
		δ_0	=	−15.10	+	0.28 cos $U15$				
		W	=	77.74	−	41.3514316 d	+	0.08 sin $U15$		
IV	Oberon	α_0	=	257.43	+	0.16 sin $U16$				
		δ_0	=	−15.10	+	0.16 cos $U16$				
		W	=	6.77	−	26.7394932 d	+	0.04 sin $U16$		

where $U1 = 115°75 + 54991°87\ T$, $U2 = 141°69 + 41887°66\ T$, $U3 = 135°03 + 29927°35\ T$,
$U4 = 61°77 + 25733°59\ T$, $U5 = 249°32 + 24471°46\ T$, $U6 = 43°86 + 22278°41\ T$,
$U7 = 77°66 + 20289°42\ T$, $U8 = 157°36 + 16652°76\ T$, $U9 = 101°81 + 12872°63\ T$,
$U10 = 138°64 + 8061°81\ T$, $U11 = 102°23 - 2024°22\ T$, $U12 = 316°41 + 2863°96\ T$,
$U13 = 304°01 - 51°94\ T$, $U14 = 308°71 - 93°17\ T$, $U15 = 340°82 - 75°32\ T$,
$U16 = 259°14 - 504°81\ T$

Neptune: I	Triton	α_0	=	298°72	−	30°72 sin $N1$	−	5°58 sin $2N1$	−	1°75 sin $3N1$
					−	0°58 sin $4N1$	−	0°21 sin $5N1$	−	0°08 sin $6N1$
					−	0°03 sin $7N1$	−	0°01 sin $8N1$		
		δ_0	=	40°59	+	21°79 cos $N1$	+	1°91 cos $2N1$	+	0°48 cos $3N1$
					+	0°13 cos $4N1$	+	0°04 cos $5N1$	+	0°01 cos $6N1$
		W	=	297°14	−	61°2572675 d	+	20°81 sin $N1$	+	6°01 sin $2N1$
					+	1°73 sin $N1$	+	0°59 sin $4N1$	+	0°21 sin $5N1$
					+	0°08 sin $6N1$	+	0°03 sin $7N1$	+	0°01 sin $8N1$

II	Nereid	α_0	=	$273.^{\circ}48$	$-$	$17.^{\circ}81 \sin N2$	$+$	$2.^{\circ}56 \sin 2N2$	$-$	$0.^{\circ}51 \sin 3N3$
							$+$	$0.^{\circ}11 \sin 4N2$	$-$	$0.^{\circ}03 \sin 5N2$
		δ_0	=	$67.^{\circ}22$	$-$	$6.^{\circ}67 \cos N2$	$+$	$0.^{\circ}47 \cos 2N2$	$-$	$0.^{\circ}07 \cos 3N2$
							$+$	$0.^{\circ}01 \cos 4N2$		
		W	=	$237.^{\circ}22$	$+$	$0.^{\circ}9996465\ d$	$+$	$16.^{\circ}48 \sin N2$	$-$	$2.^{\circ}57 \sin 2N2$
					$+$	$0.^{\circ}51 \sin 3N2$	$-$	$0.^{\circ}11 \sin 4N2$	$+$	$0.^{\circ}02 \sin 5N2$

where $N1 = 179.^{\circ}28 + 54.^{\circ}308\ T$

$N2 = 45.^{\circ}06 + 3.^{\circ}650\ T$

Pluto:	Charon	α_0	=	$312.^{\circ}98$		
		δ_0	=	$8.^{\circ}49$		
		W	=	$56.^{\circ}11$	$-$	$56.^{\circ}3624607\ d$

Note: (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.

Satellites for which no suitable data are yet available have been omitted from this table.

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 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.

Because of astronomical tradition, planetographic coordinates (those used in the preparation of maps) may or may not be identical with traditional spherical coordinates. Planetographic longitudes of a solar system body will increase with time when the body is viewed from a distance such as with a telescope. Thus, with prograde rotation, where W is positive, west longitude is used, and with retrograde rotation, where W is negative, east longitude is used. 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° instead of the usual 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 of the equator (A) is larger than the polar semiaxis (C). The reference surface for Mars was defined for the Mariner 9 mapping program (de Vaucouleurs *et al.*, 1973) and has an equatorial radius of 3393.4 km and a polar radius of 3375.8 km. For some planets (such as Mercury and Venus) and most satellites, the reference surface is a sphere ($A = C$). Planetographic latitudes are then numerically identical to the mathematical latitude.

Calculations of the hydrostatic shapes of some of the satellites (Io, Mimas, Enceladus, 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 lose 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 to preserve convenient projection properties. 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 data bases are particularly important to the irregularly shaped 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 III 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 III
Size and shape parameters of the planets (in kilometers).

Planet	Mean Radiu (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	6051.9 ± 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	3390 ± 4	3397 ± 4	3375 ± 4	3.1	27	6
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*	25112 ± 15	25269 ± 10	24800 ± 30			
Pluto	1162 ± 20	same	same			

*The radii correspond to a one bar surface.

Table IV (see pp. 200–201) 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 as a reference figure for 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.

The values of the radii and axes in Tables III and IV 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 III and IV 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 III 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.

Appendix

There have been many changes to the tables since the 1985 report (*Celestial Mechanics* **39**, pp. 103–113, 1986). In the past Tables III and IV contained recommended reference shapes for mapping the planets and satellites. In this report Tables III and IV give the current estimates of size and shape parameters of the planets and satellites.

Expressions for the Earth have been added to Table I; these were derived by A. Sinclair. The constant term in the W equation for Mars was changed based on recent control network computations by M. Davies and F. Katayama. New equations for the direction of the pole of Neptune were derived by R. Jacobson, 1988a and modified by J. Lieske. The W equation of Neptune incorporates the rotation period of 17.86 ± 0.02 hr reported by Hammel and Buie, 1987.

In Table II, the equations for Phobos and Deimos have been modified based on work by T. Duxbury and J. Callahan, 1988. The constant terms in the equations for Europa, Ganymede, Callisto, Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus have been changed based on recent control network computations by M. Davies and F. Katayama. The expressions for Triton have been modified by J. Lieske from Jacobson, 1987b, Jacobson, 1988b, and also for Nereid (Jacobson, 1987a). The equations for Charon were updated by D. Tholen from the report of Tholen and Buie, 1988.

Many small satellites were discovered on images taken by the Voyager spacecraft and their orbital elements determined. Expressions in defining their coordinate systems were computed by J. Lieske, assuming that they are synchronous rotation with their spin axis normal to their orbital plane. The orbital elements for the satellites of Jupiter

TABLE IV
Size and shape parameters of the satellites (in kilometers).

Planet		Satellite	Mean Radius (km)	Subplanetary Equatorial Radius (km)	Along Orbit Equatorial Radius (km)	Polar Radius (km)	RMS Deviation from Elipsoid (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	20 ± 10	20		20			
	XV	Adrastea	10 ± 10	13	10	8			
	V	Amalthea	86.2 ± 3	131.0	73.0	67.0	3.2		
	XIV	Thebe	50 ± 10	55		45			
	I	Io	1821.3 ± 0.2	1830.0 ± 0.2	1818.7 ± 0.2	1815.3 ± 0.2	1.4	5–10	3
	II	Europa	1565 ± 8	same	same	same	0.5		
	III	Ganymede	2634 ± 10	same	same	same	0.6		
	IV	Callisto	2403 ± 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						
Saturn	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		
	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	198.8 ± 0.6	210.3 ± 0.5	197.4 ± 0.5	192.6 ± 0.5	0.6		2
	II	Enceladus	249.1 ± 0.3	256.2 ± 0.4	247.3 ± 0.8	244.0 ± 0.7	0.4		1
	III	Tethys	523 ± 5	same	same	same	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	141.5 ± 20	180 ± 20	140 ± 20	112.5 ± 20	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
	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	I	Triton	1750 ± 250						
	II	Nereid	345 ± 180						
Pluto		Charon	606 ± 20						

are given in Synnott, 1984; those of Saturn in Synnott *et al.*, 1983, and those of Uranus in Owen and Synnott, 1987.

Tables III and IV are new. Frequently the RMS deviation from a spheroid or ellipsoid, and the maximum elevation and depression are not available or are based on partial coverage. Often the values presented have been derived from data presented in the references. Authors of new work in this field are encouraged to produce new results in the form of these tables.

The radius and topography measurements of Mercury came from Harmon *et al.*, 1986. The radius of Venus came from P. Ford and is an update of the data presented in Pettengill *et al.*, 1980. Bills and Kobrick, 1985 report a mean radius of 6051.45 ± 0.04 km based on altimetric measurements presented in Pettengill *et al.*, 1980 (where a mean radius of 6051.5 ± 0.1 km is reported). The radii for the Earth were supplied by R. Rapp. The radii of Mars were computed by M. Davies and T. Colvin from the Mariner 9 occultation measurements (Kliore *et al.*, 1972), the Viking occultation measurements (Lindal *et al.*, 1979), and the Viking lander radii (Michael, 1979). Bills and Ferrari, 1978 computed a sixteenth-degree harmonic series model of the Martian global topography based on occultation, radar, spectral, and photogrammetric measurements. They reported ellipsoidal radii of 3399.2 ± 0.3 km, 3394.5 ± 0.3 km, and 3376.1 ± 0.4 km. The origin of the ellipsoid was translated from the center of mass, and a mean radius of 3389.92 ± 0.04 km was reported.

The radii of the one bar surfaces of Jupiter, Saturn, and Uranus were reported in Lindal *et al.*, 1981, Lindal *et al.*, 1985, and Lindal *et al.*, 1987, respectively. Also presented were graphs of the radii as a function of latitude; from these data M. Davies and P. Rogers computed the RMS deviation from the spheroid and the maximum elevation and depression. The radii of Neptune at the 1-μbar pressure level were presented in Hubbard *et al.*, 1987. W. Hubbard was kind enough to convert the radii to the one bar pressure level for this report.

The radius of the Moon was computed by M. Davies and T. Colvin from the Apollo altimeter measurements. Kaula *et al.*, 1974 analyzed this same data and reported a mean radius of 1737.7 km with a center-of-mass to center-of-figure offset of 2.55 km. Bills and Ferrari, 1977 expanded the data set to include photogrammetry and limb profiles and computed coefficients for a 12 degree spherical harmonic model. The radii for the ellipsoid were 1738.43 km, 1737.50 km, and 1736.66 km with a mean radius of 1737.53 ± 0.03 km with a center-of-figure offset from the center-of-mass of 1.98 ± 0.06 km.

Thomas, 1988b measured the radii of Phobos and Deimos by limb fitting and Duxbury and Callahan, 1988 computed the radii from their control network. The results were essentially the same.

The radii of Metis, Adrastea, and Thebe are from S. P. Synnott, personal communication, 1988. The radii of Amalthea are contained in Thomas, 1988b. The radii and topography of Io come from Gaskell *et al.*, 1988. The radii of Europa, Ganymede, and Callisto are based on recent control network computations by M.

Davies and F. Katayama. The radii of the distant satellites of Jupiter came from Morrison, 1977.

The radii of Prometheus, Pandora, Epimetheus, Janus, and Calypso are taken from Thomas, 1988b. The radii of Atlas, Telesto, and Helene come from Thomas *et al.*, 1983b. The radii of Mimas are given in Dermott and Thomas, 1988. The radii of Enceladus are from P. C. Thomas, personal communication, 1988. The radii of Tethys, Dione, Rhea, and Iapetus were measured in recent control network solutions by M. Davies and F. Katayama. The radius of Titan was measured by the Voyager 1 radio occultation (Lindal *et al.*, 1983). The radii of Hyperion are from Thomas and Veverka, 1985 and the radii of Phoebe are from Thomas *et al.*, 1983a.

The radii of Cordelia, Ophelia, Bianca, Cressida, Desdemona, Juliet, Portia, Rosalind, and Belinda are from P. C. Thomas, personal communication, 1988. The radius of Puck is from Thomas *et al.*, 1987. Data on Miranda, Ariel, Umbriel, Titanic, and Oberon are contained in Thomas, 1988a.

The radii of Triton and Nereid are given in Cruikshank, 1984 and the radius of Charon is from Tholen and Buie, 1988.

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