REPORT OF THE IAU/IAG/COSPAR WORKING GROUP ON CARTOGRAPHIC COORDINATES AND ROTATIONAL ELEMENTS OF THE PLANETS AND SATELLITES: 1991

M.E. DAVIES*
RAND, Santa Monica, California, U.S.A.

V.K. ABALAKIN
Institute for Theoretical Astronomy, St. Petersburg, Russia

A. BRAHIC
Observatoire de Paris, Meudon, France

M. BURSA
Astronomical Institute, Prague, Czechoslovakia

B.H. CHOVITZ
STX, Lanham, Maryland, U.S.A.

J.H. LIESKE
Jet Propulsion Laboratory, Pasadena, California, U.S.A.

P.K. SEIDELMANN
U.S. Naval Observatory, Washington, D.C., U.S.A.

A.T. SINCLAIR
Royal Greenwich Observatory, Cambridge, U.K.

and

Y.S. TJUFLIN**
Central Research Institute of Geodesy, Air Survey, and Mapping (TsNIIGAik), Moscow, Russia

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Abstract. Every three years the IAU/IAG/COSPAR 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 and satellites. Also presented are revised tables giving their sizes and shapes.

Key words: Cartographic coordinates, rotation axes, rotation periods, sizes and 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

* Chair.
** Consultant.

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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 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. 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**, pp. 187–204. 1989.

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. All 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 sec) 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,

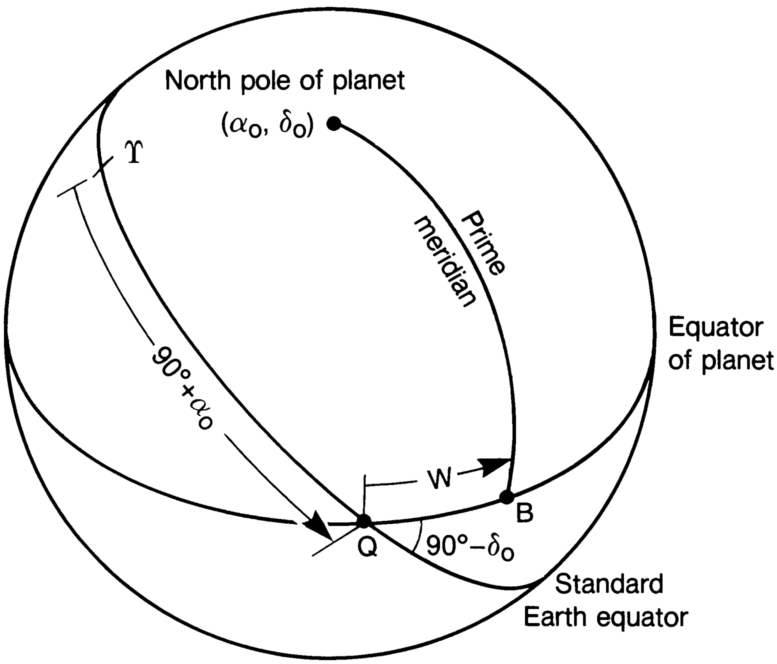

Fig. 1. Reference system used to define orientation of the planet.

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 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 ($\dot{W}$) for computational consistency and are not an indication of significant accuracy. Three decimal places are given in the expressions for the Moon and

TABLE I

Recommended values for the direction of the north pole of rotation and the prime meridian of the Sun and planets (1991)

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 $\alpha_0 = 273°.85$, $\delta_0 = 66°.99$.	
$T =$	interval in Julian centuries (of 36525 days) from the standard epoch.	
$d =$	interval in days from the standard epoch.	
The standard epoch is 2000 January 1.5, i.e., JD 2451545.0 TDB.		
Sun	$\alpha_0 = 286°.13$	
	$\delta_0 = 63°.87$	
	$W = 84°.10 + 14°.1844000\ d$	
Mercury	$\alpha_0 = 281.01 - 0.003\ T$	
	$\delta_0 = 61.45 - 0.005\ T$	
	$W = 329.71 + 6.1385025\ d$	(a)
Venus	$\alpha_0 = 272.76$	
	$\delta_0 = 67.16$	
	$W = 160.20 - 1.4813688\ d$	(b)
Earth	$\alpha_0 = 0.00 - 0.641\ T$	
	$\delta_0 = 90.00 - 0.557\ T$	
	$W = 190.16 + 360.9856235\ d$	(c)
Mars	$\alpha_0 = 317.681 - 0.108\ T$	
	$\delta_0 = 52.886 - 0.061\ T$	
	$W = 176.868 + 350.8919830\ d$	(d)
Jupiter	$\alpha_0 = 268.05 - 0.009\ T$	
	$\delta_0 = 64.49 + 0.003\ T$	
	$W = 284.95 + 870.5360000\ d$	(e)
Saturn	$\alpha_0 = 40.58 - 0.036\ T$	
	$\delta_0 = 83.54 - 0.004\ T$	
	$W = 38.90 + 810.7939024\ d$	(e)
Uranus	$\alpha_0 = 257.43$	
	$\delta_0 = -15.10$	
	$W = 203.81 - 501.1600928\ d$	(e)
Neptune	$\alpha_0 = 299.36 + 0.70\ \sin\ N$	
	$\delta_0 = 43.46 - 0.51\ \cos\ N$	
	$W = 253.18 + 536.3128492\ d - 0.48\ \sin\ N$	(e)
	$N = 357.85 + 52.316\ T$	
Pluto	$\alpha_0 = 313.02$	
	$\delta_0 = 9.09$	(f)
	$W = 236.77 - 56.3623195\ d$	

Note:
(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 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.
(d) The 0° meridian is defined by the crater Airy-0.
(e) The equations for W for Jupiter, Saturn, Uranus, and Neptune refer to the rotation of their magnetic fields (System III). On Jupiter, System I ($^W\mathrm{I} = 67°.1 + 887°.900\ d$) refers to the mean atmospheric equatorial rotation; System II ($^W\mathrm{II} = 43°.3 + 870°.270\ d$) 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.
(f) 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 (1991)

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	+	$0.003T$	−	3°.878 sin $E1$	−	0°.120 sin $E2$
								+	0.070 sin $E3$	−	0.017 sin $E4$
			δ_0	=	66.541	+	$0.013T$	+	1.543 cos $E1$	+	0.024 cos $E2$
								−	0.028 cos $E3$	+	0.007 cos $E4$
			W	=	38.317	+	13.1763582 d	+	3.558 sin $E1$	+	0.121 sin $E2$
								−	0.064 sin $E3$	+	0.016 sin $E4$
						+	0.025 sin $E5$				

where $E1 = 125°.045 - 0°.052992\,d$, $E2 = 250°.090 - 0°.105984\,d$,
$E3 = 260°.008 - 13°.012001\,d$, $E4 = 176°.625 + 13°.340716\,d$,
$E5 = 357°.529 - 0°.985600\,d$

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	−	0.108 T	+	2.98 sin $M3$
			δ_0	=	53.52	−	0.061 T	−	1.78 cos $M3$
			W	=	79.41	+	285.1618970 d	−	0.520 T^2
						−	2.58 sin $M3$	+	0.19 cos $M3$

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

Table II (continued)

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 sin $J1$			
			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 cos $J3$	+	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 $J7$	

Table II (continued)

	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	$= 43.14 + 50.3176081\,d + 0.033 \sin J4 - 0.389 \sin J5 - 0.082 \sin J6$	(b)
	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	$= 259.67 + 21.5710715\,d + 0.061 \sin J5 - 0.533 \sin J6 - 0.009 \sin J8$	(c)

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

Saturn	XVIII	Pan	α_0	$= 40.6 - 0.036\,T$	
			δ_0	$= 83.5 - 0.004\,T$	
			W	$= 48.8 + 626.0440000\,d$	
	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	$= 296.14 + 587.2890000\,d$	

Table II (continued)

XVII	Pandora	α_0	=	40.58	−	0.036 T						
		δ_0	=	83.53	−	0.004 T						
		W	=	162.92	+	572.7891000 d						
XI	Epimetheus	α_0	=	40.58	−	0.036 T	−	3.153 sin $S1$	+	0.086 sin $2S1$		
		δ_0	=	83.52	+	0.004 T	−	0.356 cos $S1$	+	0.005 cos $2S1$		
		W	=	293.87	+	518.4907239 d	+	3.133 sin $S1$	−	0.086 sin $2S1$		(j)
X	Janus	α_0	=	40.58	−	0.036 T	−	1.623 sin $S2$	+	0.023 sin $2S2$		
		δ_0	=	83.52	−	0.004 T	−	0.183 cos $S2$	+	0.001 cos $2S2$		
		W	=	58.83	+	518.2359876 d	+	1.613 sin $S2$	−	0.023 sin $2S2$		(j)
I	Mimas	α_0	=	40.66	−	0.036 T	+	13.56 sin $S3$				
		δ_0	=	83.52	−	0.004 T	−	1.53 cos $S3$				
		W	=	337.46	+	381.9945550 d	−	13.48 sin $S3$	−	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 $S4$				
		δ_0	=	83.52	−	0.004 T	−	1.09 cos $S4$				
		W	=	10.45	+	190.6979085 d	−	9.60 sin $S4$	+	2.23 sin $S5$		(f)
XIII	Telesto	α_0	=	50.51	−	0.036 T						
		δ_0	=	84.06	−	0.004 T						
		W	=	56.88	+	190.6979332 d						(j)

Table II (continued)

XIV	Calypso	α_0	=	36.41	−	0.036 T				
		δ_0	=	85.04	−	0.004 T				
		W	=	153.51	+	190.6742373 d				(j)
IV	Dione	α_0	=	40.66	−	0.036 T				
		δ_0	=	83.52	−	0.004 T				
		W	=	357.00	+	131.5349316 d				(g)
XII	Helene	α_0	=	40.85	−	0.036 T				
		δ_0	=	83.34	−	0.004 T				
		W	=	245.12	+	131.6174056 d				(j)
V	Rhea	α_0	=	40.38	−	0.036 T	+	3.10 sin $S6$		
		δ_0	=	83.55	−	0.004 T	−	0.35 cos $S6$		
		W	=	235.16	+	79.6900478 d	−	3.08 sin $S6$		(h)
VI	Titan	α_0	=	36.41	−	0.036 T	+	2.66 sin $S7$		
		δ_0	=	83.94	−	0.004 T	−	0.30 cos $S7$		
		W	=	189.64	+	22.5769768 d	−	2.64 sin $S7$		
VIII	Iapetus	α_0	=	318.16	−	3.949 T				
		δ_0	=	75.03	−	1.143 T				
		W	=	350.20	+	4.5379572 d				(i)
XI	Phoebe	α_0	=	355.00						
		δ_0	=	68.70						
		W	=	304.70	+	930.8338720 d				

where $S1 = 353°.32 + 75706°.7\,T$, $S2 = 28°.72 + 75706°.7\,T$, $S3 = 177°.40 - 36505°.5\,T$, $S4 = 300°.00 - 7225°.9\,T$, $S5 = 316°.45 + 506°.2\,T$, $S6 = 345°.20 - 1016°.3\,T$, $S7 = 29°.80 - 52°.1\,T$

Table II (continued)

Uranus:	VI	Cordelia	α_0	=	257.31	−	$0.15 \sin U1$		
			δ_0	=	−15.18	+	$0.14 \cos U1$		
			W	=	127.69	−	$1074.5205730\,d$	−	$0.04 \sin U1$
	VII	Ophelia	α_0	=	257.31	−	$0.09 \sin U2$		
			δ_0	=	−15.18	+	$0.09 \cos U2$		
			W	=	130.35	−	$956.4068150\,d$	−	$0.03 \sin U2$
	VIII	Bianca	α_0	=	257.31	−	$0.16 \sin U3$		
			δ_0	=	−15.18	+	$0.16 \cos U3$		
			W	=	105.46	−	$828.3914760\,d$	−	$0.04 \sin U3$
	IX	Cressida	α_0	=	257.31	−	$0.04 \sin U4$		
			δ_0	=	−15.18	+	$0.04 \cos U4$		
			W	=	59.16	−	$776.5816320\,d$	−	$0.01 \sin U4$
	X	Desdemona	α_0	=	257.31	−	$0.17 \sin U5$		
			δ_0	=	−15.18	+	$0.16 \cos U5$		
			W	=	95.08	−	$760.0531690\,d$	−	$0.04 \sin U5$
	XI	Juliet	α_0	=	257.31	−	$0.06 \sin U6$		
			δ_0	=	−15.18	+	$0.06 \cos U6$		
			W	=	302.56	−	$730.1253660\,d$	−	$0.02 \sin U6$
	XII	Portia	α_0	=	257.31	−	$0.09 \sin U7$		
			δ_0	=	−15.18	+	$0.09 \cos U7$		
			W	=	25.03	−	$701.4865870\,d$	−	$0.02 \sin U7$

Table II (continued)

XIII	Rosalind	α_0	=	257.31	−	$0.29 \sin U8$				
		δ_0	=	−15.18	+	$0.28 \cos U8$				
		W	=	314.90	−	$644.6311260\, d$	−	$0.08 \sin U8$		
XIV	Belinda	α_0	=	257.31	−	$0.03 \sin U9$				
		δ_0	=	−15.18	+	$0.03 \cos U9$				
		W	=	297.46	−	$577.3628170\, d$	−	$0.01 \sin U9$		
XV	Puck	α_0	=	257.31	−	$0.33 \sin U10$				
		δ_0	=	−15.18	+	$0.31 \cos U10$				
		W	=	91.24	−	$472.5450690\, d$	−	$0.09 \sin U10$		
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	−	$41.3514316\, d$	+	$0.08 \sin U15$		

Table II (continued)

	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	III	Naiad	α_0	=	299°.36	+	0°.70 sin N	−	6°.49 sin $N1$	+	0°.25 sin $2N1$	
			δ_0	=	43.36	−	0.51 cos N	−	4.75 cos $N1$	+	0.09 cos $2N1$	
			W	=	254.06	+	1222.8441209 d	−	0.48 sin N	+	4.40 sin $N1$	− 0.27 sin $2N1$
	IV	Thalassa	α_0	=	299.36	+	0.70 sin N	−	0.28 sin $N2$			
			δ_0	=	43.45	−	0.51 cos N	−	0.21 cos $N2$			
			W	=	102.06	+	1155.7555612 d	−	0.48 sin N	+	0.19 sin $N2$	
	V	Despina	α_0	=	299.36	+	0.70 sin N	−	0.09 sin $N3$			
			δ_0	=	43.45	−	0.51 cos N	−	0.07 cos $N3$			
			W	=	306.51	+	1075.7341562 d	−	0.49 sin N	+	0.06 sin $N3$	
	VI	Galatea	α_0	=	299.36	+	0.70 sin N	−	0.07 sin $N4$			
			δ_0	=	43.43	−	0.51 cos N	−	0.05 cos $N4$			
			W	=	258.09	+	839.6597686 d	−	0.48 sin N	+	0.05 sin $N4$	

Table II (continued)

VII	Larissa	α_0	=	299.36	+	0.70 sin N	−	0.27 sin $N5$		
		δ_0	=	43.41	−	0.51 cos N	−	0.20 cos $N5$		
		W	=	179.41	+	649.0534470 d	−	0.48 sin N	+	0.19 sin $N5$
VIII	Proteus	α_0	=	299.27	+	0.70 sin N	−	0.05 sin $N6$		
		δ_0	=	42.91	−	0.51 cos N	−	0.04 cos $N6$		
		W	=	93.38	+	320.7654228 d	−	0.48 sin N	+	0.04 sin $N6$
I	Triton	α_0	=	299.36	−	32.35 sin $N1$	−	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 $9N7$
		δ_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	−	61.2572637 d	+	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 $9N7$				
		N	=	357.85	+	52.316 T				
		$N1$	=	323.92	+	62606.6 T				
		$N2$	=	220.51	+	55064.2 T				
		$N3$	=	354.27	+	46564.5 T				
		$N4$	=	75.31	+	26109.4 T				
		$N5$	=	35.36	+	14325.4 T				
		$N6$	=	142.61	+	2824.6 T				
		$N7$	=	177.85	+	52.316 T				

Table II (continued)

Pluto	I	Charon	α_0	=	313.02		
			δ_0	=	9.09		
			W	=	56.77	–	56.3623195 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.
(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.

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).

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.

Planetocentric longitudes of a solar system body are measured from the prime meridian from 0° to 360°, positively to the east. Planetographic longitudes are also measured from the prime meridian from 0° to 360°, but they are measured positively in the direction opposite to the rotation, i.e., positively to the west on the body if the rotation is prograde and positively to the east on the body if the rotation is retrograde. Thus, for a distant observer, the planetographic longitude of the center of the apparent disk increases with time. The rotations of the Earth, Moon and Sun are prograde, however, because of tradition, planetographic longitudes are designated east longitude and west longitude from 0° to 180° measured from the prime meridian. East longitude is generally considered the positive direction and west longitude the negative direction.

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.

TABLE III
Size and shape parameters of the planets (in kilometers)

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	3390 ± 4	3397 ± 4	3375 ± 4	3.1	27	6
Jupiter[a]	69911 ± 6	71492 ± 4	66854 ± 10	62.1	31	102
Saturn[a]	58232 ± 6	60268 ± 4	54364 ± 10	102.9	8	205
Uranus[a]	25362 ± 7	25559 ± 4	24973 ± 20	16.8	28	0
Neptune[a]	24622 ± 19	24764 ± 15	24341 ± 30	8	14	0
Pluto	1151 ± 6	same	same			

[a] The radii correspond to a one bar surface.

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 rotation 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 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						

Table IV (continued)

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)
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		
	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		
Saturn	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	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	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		

Table IV (continued)

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)
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	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 IV (see pp. 17–19) 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

This Appendix summarizes the changes that have been made to the tables since the 1988 report (*Celestial Mechanics and Dynamical Astronomy* **46**, pp. 187–204, 1989). Publication of this report was delayed to incorporate early results from the Magellan mission to Venus.

In Table I, the new equations for Venus are from Davies *et al.*, 1992. The decision to define the 0° meridian of Venus by the central peak in the crater Ariadne had been incorporated in the 1988 report; however, the note failed to be included. The Neptune equations were derived by J. Lieske from polar data in Jacobson, 1990, and the Warwick *et al.*, 1989 rotation period. New Pluto and Charon equations were computed by J. Lieske from Tholen and Buie, 1990. It was decided to define the 0° meridian on Pluto as the sub-Charon meridian.

In Table II, equations for the newly discovered Saturnian satellite Pan (Showalter, 1991) have been added. Equations for Epimetheus, Janus, Calypso, and Helene have been added. These equations and those of other small satellites of Saturn are based on orbital parameters derived by S. Synott at the time of the Voyager encounters and are valid for that period only. Equations for Phoebe have been added, based on Colvin *et al.*, 1989.

Equations for the newly discovered satellites of Neptune – Naiad, Thalassa, Despina, Galatea, Larissa, and Proteus – were derived by J. Lieske based on the orbits determined by Owen *et al.*, 1991. The equations for Triton were derived by J. Lieske based on an orbit solution of Jacobson, 1990. Equations for Nereid have been deleted because it was not in synchronous rotation (Williams *et al.*, 1991). As already mentioned, updated equations for Charon are incorporated.

In Table III a new radius for Venus has been derived from Magellan data (Ford and Pettengill, 1992). New radii for Neptune were measured by Lindal *et al.*, 1990. A new radius of Pluto was derived by Tholen and Buie, 1990.

In Table IV, the radius of Pan has been added to Saturn's satellites (Showalter, 1991). New radii for Tethys are given in Thomas and Dermott, 1991. Radii of the small satellites of Neptune are from Thomas and Veverka, 1991 and the radius of Triton is from Davies *et al.*, 1991. The new radius of Charon is from Tholen and Buie, 1990.

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