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THE ORBITS OF THE OUTER JOVIAN SATELLITES

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ABSTRACT

This article describes a fit of numerically integrated orbits for the eight outer Jovian satellites to Earth-based astrometric observations. The principal results are the epoch state vectors for the integration and a set of mean orbital elements, which approximately represent the orbits. An assessment of the quality of the fit and of the accuracy of the orbits is also provided.

Key words: ephemerides — planets and satellites: general — planets and satellites: individual (Jupiter)

1. INTRODUCTION

The eight outer satellites of Jupiter may be divided into two groups of four. Those in the first group, Himalia, Elara, Lysithea, and Leda, are in high inclination direct orbits between 11 and 12 Mkm from Jupiter. Those in the second group, Pasiphae, Sinope, Carme, and Ananke, are in high inclination retrograde orbits between 20 and 24 Mkm from Jupiter.

Representation of the orbits by analytical theory has proven to be quite difficult primarily because of the strong solar perturbation. Although ephemerides have been developed analytically, the production of high-precision ephemerides relies on numerical integration. One of the first integrations was that of Cowell, Crommelin, & Davidson (1909), who fit an integrated orbit of Pasiphae to the observations made in 1908 and 1909. Herget (1968) also determined an integrated orbit for Pasiphae, as well as for Sinope, Lysithea, Carme, and Ananke, using observations from their respective discoveries through the 1967 Ananke observations. Aksnes (1978) produced the first definitive integrated orbit for Leda fit to a 1974–1977 data arc. Revised orbits were determined for all but Ananke and Leda by Bykova (1979) who included observations of Himalia up to 1970. Rocher (1983) repeated Bykova's work for Himalia and Elara extending the data arc to 1976. In a recent analysis, Rocher & Chapront (1996) computed orbits for Himalia, Elara, Pasiphae, and Sinope fitted to observations through 1993. Currently, the positions of the eight satellites given in the Astronomical Almanac are from an unpublished work by James Rohde of the US Naval Observatory based on observations made prior to 1990 (Seidelmann 1992).

To support the *Galileo* project, we fitted numerical integrations of all eight satellites to observations from their discoveries through 1994. In this article, we are reporting on an extension of the fit to include observations through 2000 January. Among the additional observations are highly accurate CCD measures obtained at both the US Naval Observatory's Flagstaff Station (R. C. Stone 2000, private communication; Stone & Harris 2000) and JPL's Table Mountain Observatory (W. M. Owen 1999, private communication).

2. ORBIT MODEL

Our model for the orbits of the satellites is a numerical integration of their equations of motion (Peters 1981), which includes the effects of an oblate Jupiter (J2 only), perturbations from the Galilean satellites, and perturbations from the Sun, Saturn, Uranus, and Neptune. The formulation is in Cartesian coordinates centered at the Jovian system barycenter and referenced to the mean Earth equator and equinox of the J2000.0 system. Because the outer satellites are small and their GMs are unknown, they are assumed to be massless; hence the Jovian barycenter location depends only upon the planet and perturbing satellites. The positions of the Sun, Saturn, Uranus, and Neptune are from JPL planetary ephemeris DE405 (Standish 1998); Lieske's E5 ephemerides (Lieske 1998) provide the Galilean satellite positions. Table 1 lists the GMs of Jupiter and the perturbing bodies and the Jupiter J2 (the values were taken from the analysis of the *Galileo* spacecraft data currently in progress). The GM of the Sun was augmented by the GMs of Mercury, Venus, the Earth-Moon system, and the Martian system to account for part of the perturbing effects of the inner planets.

In evaluating our model, we found that the size of the Saturnian perturbations were of the order of 1000 km for the direct satellites and 20,000 km for the retrograde ones. Perturbations from the other planets were at most of the order of 100 km, which is well below the accuracy of the best observations. The perturbations were retained for completeness, however, because they added little computational overhead.

We also examined a simplified model that replaces the Galilean satellites with uniform circular equatorial rings represented by their quadrupole effect (see Roy et al. 1988). As the differences between this model and the original one were only of the order of 200 km, we could have used it but, instead, chose to remain with the explicit perturbing satellites.

The integration was carried out with a variable order, variable step size, Gauss-Jackson method. An absolute truncation error limit of 10^{-9} km s^{-1} imposed on the velocity controlled the integration step. The maximum order was 15, and the step size was 12,000 s for the direct orbits and 16,000 s for the retrograde ones (each set of orbits was integrated separately).

3. ORBIT ANALYSIS

3.1. *Observation Sources*

The literature search of Pierce (1974) reports on the collection of observations of all the Jovian satellites from their respective discoveries to 1972. We have continued to add to that collection, and it now extends through January of 2000. For the most part, the observations of the outer satellites are topocentric photographic or CCD positions referred to

TABLE 1

DYNAMICAL CONSTANTS USED IN THE ORBIT INTEGRATION

Name	Value
Jovian system GM (km^3 s^{-2})	126,712,763.9200
Io GM (km^3 s^{-2})	5959.9100
Europa GM (km^3 s^{-2})	3202.7200
Ganymede GM (km^3 s^{-2})	9887.8200
Callisto GM (km^3 s^{-2}).................	7179.2900
Saturnian system GM (km^3 s^{-2}).......	37,940,629.7640
Uranian system GM (km^3 s^{-2})	5,794,548.6000
Neptunian system GM (km^3 s^{-2})......	6,836,534.9000
Sun GM (km^3 s^{-2})^a	132,713,233,240.2215
Jupiter radius (km)	71,398.0
Jupiter J$_2$	14,735.0 × 10^{-6}
Jupiter pole R.A. (deg)	268.05
Jupiter pole decl. (deg)	64.49
Jupiter pole R.A. rate (cy^{-1})...........	−0.°009
Jupiter pole decl. rate (cy^{-1})	+0.°003

[a] Includes the GMs of the inner planetary systems.

a mean equator and equinox at some epoch (this includes the FK4/B1950.0 and FK5/J2000.0 systems). There are also a small number of apparent positions (actually mean positions converted to apparent for publication). Table 2 lists the sources of the observations used in this analysis; the first

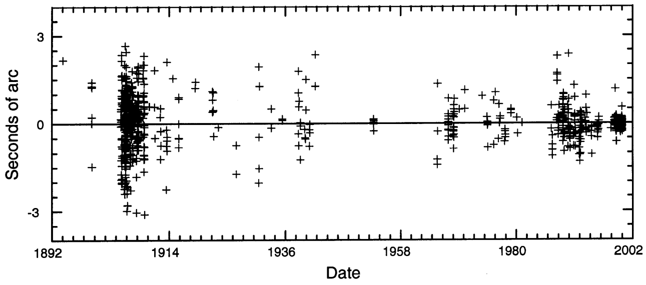

FIG. 1.—Himalia right ascension residuals

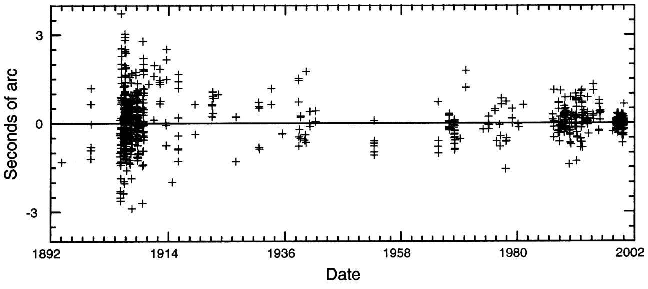

FIG. 2.—Himalia declination residuals

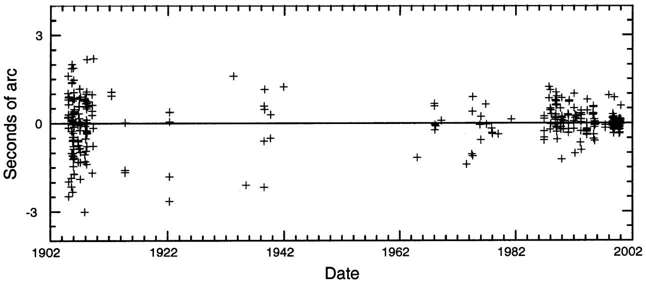

FIG. 3.—Elara right ascension residuals

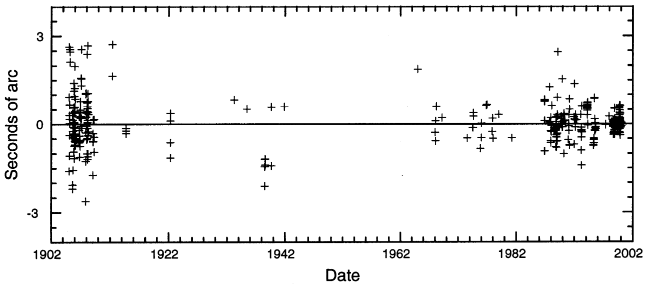

FIG. 4.—Elara declination residuals

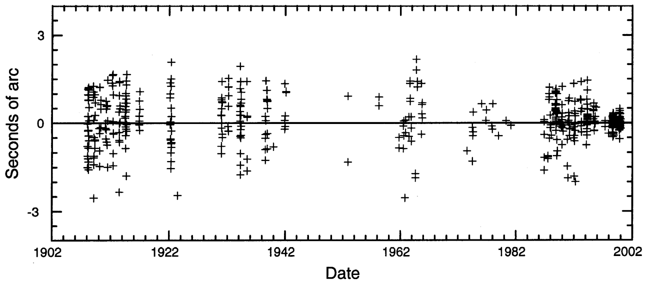

FIG. 5.—Pasiphae right ascension residuals

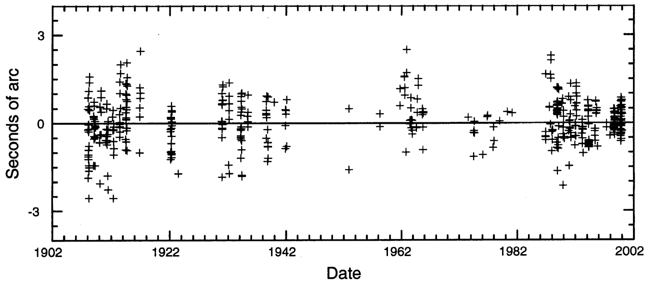

FIG. 6.—Pasiphae declination residuals

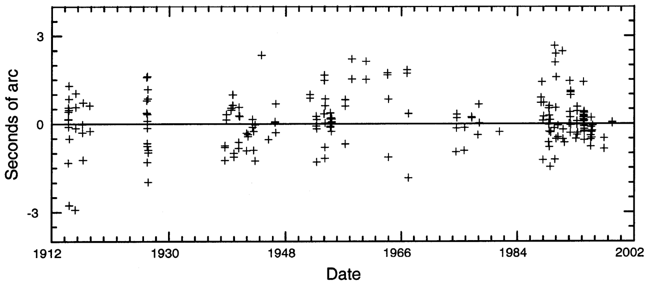

FIG. 7.—Sinope right ascension residuals

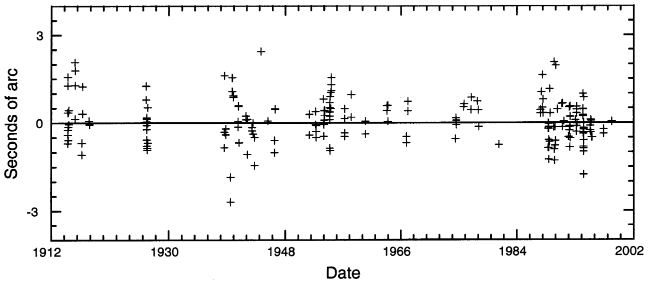

FIG. 8.—Sinope declination residuals

TABLE 2

OBSERVATION SETS

Years	Observatory	Instrument	Reference
1894, 1899	Arequipa	24 inch (0.6 m) Bruce	Pickering (1906)
1904–1905	Lick	36 inch (0.9 m) Crossley reflector	Perrine (1905)
1905	USNO	26 inch (0.7 m) refractor	Rice (1906)
1905–1906	Greenwich	30 inch (0.8 m) reflector	Christie (1906)
1905–1908	Lick	36 inch Crossley reflector	Perrine (1909)
1906	Yerkes	40 inch (1.0 m) refractor	Barnard (1906)
1906	Heidelberg	71 cm Waltz reflector	Wolf (1907a); Wolf (1907b)
1906–1907	Greenwich	30 inch reflector	Christie (1907)
1907–1908	Greenwich	30 inch reflector	Christie (1908)
1908	Yerkes	40 inch refractor	Barnard (1908)
1908	Heidelberg	71 cm Waltz reflector	Wolf (1908)
1909	Heidelberg	71 cm Waltz reflector	Kopff (1909)
1909	USNO	26 inch refractor	Frederickson (1909)
1909	Greenwich	30 inch reflector	Christie (1909)
1910	Greenwich	30 inch reflector	Christie (1910)
1910–1911	USNO	26 inch refractor	Eppes (1915)
1911	Helwan	30 inch Reynolds reflector	Astronomer Royal (1911)
1912	Lick	36 inch Crossley reflector	Morehouse & Meyer (1912)
1912–1915	USNO	26 inch refractor	Burton (1917)
1912	Helwan	30 inch Reynolds reflector	Knox-Shaw (1912)
1913	Lick	36 inch Crossley reflector	Haynes (1915)
1913–1914	Helwan	30 inch Reynolds reflector	Knox-Shaw (1916)
1914	Lick	36 inch Crossley reflector	Nicholson (1915); Nicholson (1918b)
1915	Yerkes	40 inch refractor	Barnard (1916)
1915	Lick	36 inch Crossley reflector	Sanford (1917)
1916	Helwan	30 inch Reynolds reflector	Knox-Shaw (1920)
1916	Mt. Wilson	60 inch (1.5 m) reflector	Nicholson & Shapley (1917)
1917	Mt. Wilson	60 inch reflector	Nicholson (1918a)
1918	USNO	26 inch refractor	USNO (1929)
1922–1923	USNO	26 inch refractor	Bower (1923)
1922	Yerkes	24 inch reflector	Van Biesbroeck (1922)
1922	Helwan	30 inch Reynolds reflector	Knox-Shaw (1922)
1923	Yerkes	24 inch reflector	Van Biesbroeck (1923)
1926	USNO	26 inch refractor	Burton (1927)
1926	Mt. Wilson	60 inch reflector	Nicholson & Losh (1927)
1930–1931	Heidelberg	71 cm Waltz reflector	Wolf (1931)
1930–1931	Yerkes	24 inch reflector	Van Biesbroeck (1931)
1930, 1934	Mt. Wilson	60 inch reflector	Nicholson & Richmond (1934)
1932–1933	Hamburg	1 m Zeiss reflector	Schorr (1934)
1932	Yerkes	24 inch reflector	Van Biesbroeck (1932); Grosch (1948)
1933–1934	Yerkes	24 inch reflector	Van Biesbroeck (1934)
1934	Lowell, Flagstaff	42 inch (1.1 m) reflector	Lampland (1935)
1934	Lick	36 inch Crossley reflector	Swanson & Jeffers (1934)
1934	Mt. Wilson	100 inch (2.5 m) reflector	Nicholson & Richmond (1934)
1935	Mt. Wilson	100 inch reflector	Nicholson & Richmond (1936)
1935	Lick	36 inch Crossley reflector	Jeffers & Swanson (1935)
1938	Cordoba	Normal astrograph	Bobone (1939)
1938	Mt. Wilson	100 inch reflector	Nicholson (1939)
1939	Cordoba	Normal astrograph	Bobone (1940)
1939	Mt. Wilson	60/100 inch reflector	Nicholson & Richmond (1940)
1940–1943	Mt. Wilson	100 inch reflector	Nicholson & Richmond (1943)
1941	Lick	36 inch Crossley reflector	Herbig (1944)
1941	USNO	40 inch reflector	Willis & Grosch (1941)
1944	McDonald	82 inch (2.1 m) reflector	Van Biesbroeck (1945)
1945	Mt. Wilson	60 inch reflector	Nicholson (1945)
1946	Mt. Wilson	60/100 inch reflector	Newnam (1969)
1951	Mt. Wilson	100 inch reflector	Nicholson (1951)
1951	Mt. Wilson	60 inch reflector	Cunningham (1951a)
1951	Mt. Wilson	100 inch reflector	Cunningham (1951b)
1951, 1954	McDonald	82 inch reflector	Newnam (1969)
1952	Cordoba	Normal astrograph	Bobone (1953)
1952	Alma-Ata	50 cm astrograph	Rozkovskii (1953)
1953	Lick	36 inch Crossley reflector	Jeffers, Vasilevskis, & Roemer (1954)
1953–1954	McDonald	82 inch reflector	Van Biesbroeck (1955)
1954	Lick	36 inch Crossley reflector	Jeffers & Roemer (1955)

TABLE 2—*Continued*

Years	Observatory	Instrument	Reference
1957	Palomar	122 cm Schmidt	Newnam (1969)
1958–1965......	USNO, Flagstaff	40 inch reflector	Roemer & Lloyd (1966)
1958–1965......	USNO, Flagstaff	40 inch reflector	Roemer, Thomas, & Lloyd (1966)
1965	El Leoncito	20 inch (0.5 m) double astrograph	Cesco & Klemola (1967)
1966–1967......	Bordeaux	13 inch (0.3 m)refractor	Soulie (1968)
1966–1968......	Catalina	154 cm reflector	Newnam (1969)
1967	Steward	21 inch (0.5 m) reflector	Charnow, Musen, & Maury (1968)
1967–1969......	Lick	51 inch (1.3 m) double astrograph	Klemola (1973)
1968	Table Mt.	60 inch reflector	Mulholland (1990)
1968	Bordeaux	13 inch refractor	Soulie (1972)
1970	Goethe	16 inch (0.4 m) reflector	Andersson & Burkhead (1970)
1973	McDonald	2.1 m reflector	Mulholland, Shelus, & Abbot (1976)
1974	Palomar	122 cm Schmidt	Kowal et al. (1975)
1974	Kitt Peak	229 cm reflector	Kowal et al. (1975)
1974–1977......	McDonald	2.1 m reflector	Benedict et al. (1978)
1975	Kitt Peak	229 cm reflector	Roemer (1975a); Roemer (1976)
1975	Catalina	154 cm reflector	Roemer (1975b)
1975–1976......	McDonald	2.1 m reflector	Mulholland & Shelus (1977)
1975–1976......	McDonald	2.1 m reflector	Mulholland, Shelus, & Benedict (1979)
1976–1977......	McDonald	2.1 m reflector	Shelus, Mulholland, & Benedict (1979)
	Palomar	122 cm Schmidt	Kowal (1977)
1977–1981......	McDonald	2.1 m reflector	Shelus et al. (1992)
1986–1988......	Lowell, Mesa	33 cm reflector	E. L. C. Bowell (1988, private communication)
1986–1990......	Tokyo-Kiso	105 cm Schmidt	Nakamura, Kinoshita, & Kosai (1991)
1987	Mauna Kea	ITRF	D. J. Tholen (1988, private communication)
1988–1989......	McDonald	2.1 m reflector	Shelus, Whipple, & Benedict (1991)
1988	Mauna Kea	ITRF/2.24 m reflector	D. J. Tholen (1989, private communication)
1989–1990......	McDonald	2.1 m reflector	Whipple, Shelus, & Benedict (1992)
1990–1992......	Tokyo-Kiso	105 cm Schmidt	Nakamura & Sasaki (1998)
1990–1992......	McDonald	2.1 m reflector	Whipple, Shelus, & Benedict (1993)
1992–1993......	ESO	1 m Schmidt	Hernius et al. (1996)
1993	Siding Spring	48 inch (1.2 m) Schmidt	Hernius et al. (1996)
1993	McDonald	2.1 m reflector	Shelus, Whipple, & Benedict (1993)
1994–1995......	McDonald	2.1 m reflector	A. L. Whipple (1995, private communication)
1997	McDonald	2.1 m reflector	P. J. Shelus (1997, private communication)
1997–1998......	Table Mt.	60 cm reflector	W. M. Owen (1999, private communication)
1998	USNO, Flagstaff	FASTT	Stone and Harris (20000
1998	USNO, Flagstaff	FASTT	A. Monet (1998, private communication)
1999	Table Mt.	60 cm reflector	W.M. Owen (1999, private communication)
1999–2000......	USNO, Flagstaff	FASTT	R. C. Stone (2000, private communication)

column contains the year of the observations, the second and third columns identify the observatory and instrument, and the last column gives the reference or publication.

3.2. *Observation Modeling*

The orbit determination procedure employs an algorithm that minimizes the weighted sum of squares of the residuals of the actual minus-computed observations. Hence, the procedure requires the formation of computed observables. In our approach, we attempt, where possible, to compute the values of the observables as actually recorded rather than transform those values to a standard system (e.g., B1950.0 or J2000.0 system) as other authors have often done. Philosophically, we feel that it is more correct to attempt to match the original observations rather than to alter them for computational convenience. Moreover, we believe that to properly account for observational error, the data weights should apply directly to the original observations. Residuals against those original observations also provide a better measure of the quality of the observations

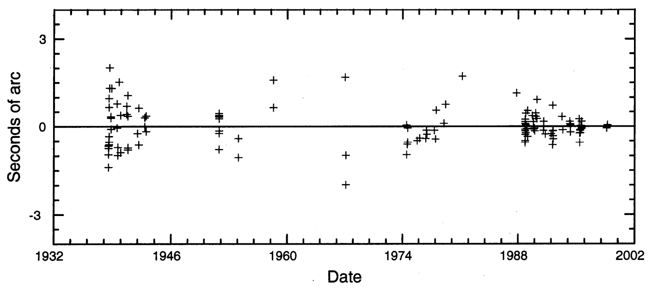

FIG. 9.—Lysithae right ascension residuals

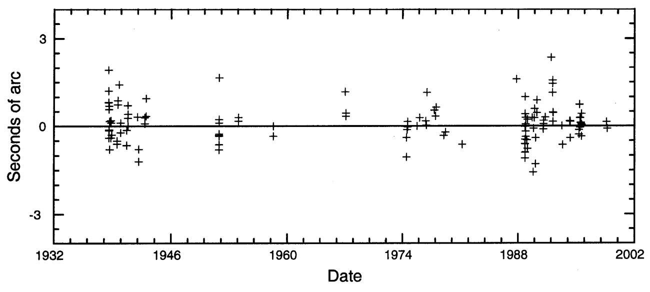

FIG. 10.—Lysithae declination residuals

TABLE 3

Barycentric State Vectors

Satellite	Position (km)	Velocity (km s^{-1})
Himalia.......	−11,648,291.006280670	0.1564090991029501
	−4,838,652.372259759	−2.2131292268395140
	3,741,902.337230613	−1.8162992946620010
Elara..........	8,940,233.143776048	1.8955518845672010
	−3,818,178.575759732	2.8716990228133590
	−5,330,150.951442327	−0.3881690968135960
Pasiphae......	−7,304,738.343221538	−1.7015271762307630
	−18,806,014.917535730	1.8797123903140890
	6,054,704.459355949	0.5666178550274720
Sinope	−19,539,663.959108290	1.1778391155956410
	20,745,758.290860710	1.1496652414771450
	9,704,212.584426932	−0.3682458874781593
Lysithea	−4,361,882.517106299	−3.3762160880581720
	5,948,204.625319973	−0.8839742210963922
	7,835,578.065015925	−0.6950481785867580
Carme	−19,893,713.508058590	−0.7690179986643800
	−8,804,042.388985746	1.9284125144547430
	−10,651,803.542569790	0.9400568462103589
Ananke	16,472,422.017624930	0.6426896208765603
	11,738,103.486130800	−2.4863494688899510
	1,041,144.057369726	0.2727376774846144
Leda	4,165,225.444423386	−3.3994990484065460
	9,044,848.217131410	1.1819200854965170
	1,324,909.959221727	−0.9672437855996924

Note.—At Julian date 2,451,600.5 (2000 February 26.0) T_{eph} referred to the mean Earth equator and equinox of J2000.0 (see Standish 1998 for T_{eph} timescale definition).

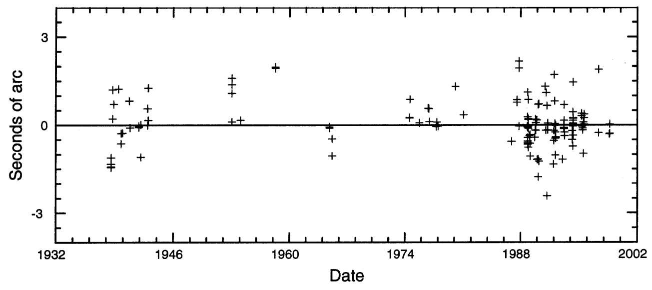

Fig. 11.—Carme right ascension residuals

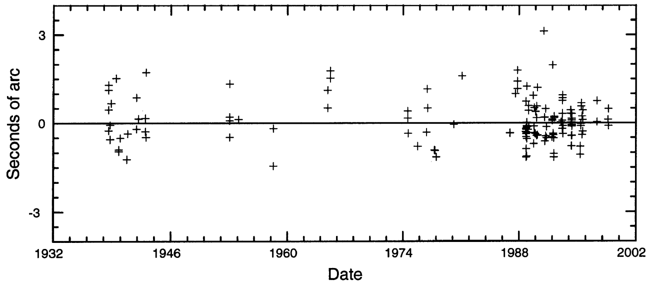

Fig. 12.—Carme declination residuals

and our ability to model them. In addition, our observation database need only contain original observations, which can be directly traced to their source and can remain unaltered should we change the standard computational system.

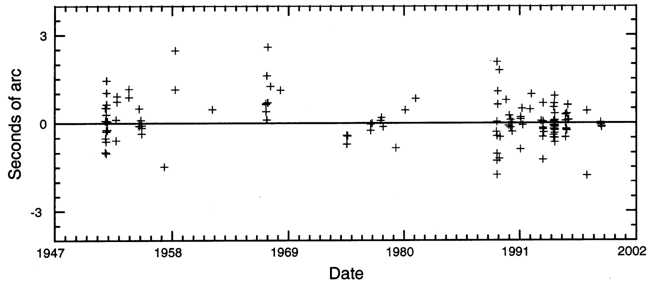

Fig. 13.—Ananke right ascension residuals

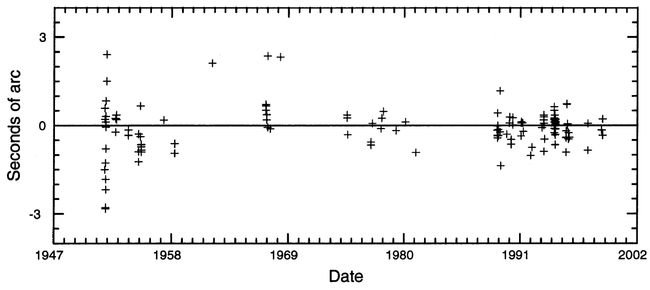

Fig. 14.—Ananke declination residuals

TABLE 4

Observation Biases in Right Ascension (α) and Declination (δ)

Year	α (arcsec)	δ (arcsec)	Year	α (arcsec)	δ (arcsec)	Year	α (arcsec)	δ (arcsec)
	Lick			Mt. Wilson			Palomar	
1905......	0.94	−0.36	1916/1917	−0.32	−0.05	1957	1.82	−0.62
1906......	0.62	−0.62	1926	0.02	1.36		McDonald	
1907......	0.67	0.39	1930/1934	0.87	0.53	1973–1981	0.15	0.21
1908......	1.46	0.44	1935	0.33	−0.71	1988–1989	0.22	0.56
1914......	0.18	0.53	1938	−0.67	0.41	1989–1990	0.21	0.23
	Greenwich		1939	−0.38	0.25	1990–1991	0.39	0.14
1906......	0.40	0.33	1940	1.07	1.01	1991–1992	0.36	0.25
1907......	1.27	0.45	1941–1942	0.95	0.53	1993	0.80	−0.04
1908......	1.98	0.40	1942–1943	1.32	0.02	1994	0.84	−0.96
1909......	2.97	0.37	1945/1946	1.98	0.22	1995	0.52	−0.25
1910......	1.15	−0.22	1951	0.10	0.26	1997	−0.24	0.13
			1952	0.87	0.82			
			1953–1954	1.37	−0.20			
			1955	1.33	0.40			

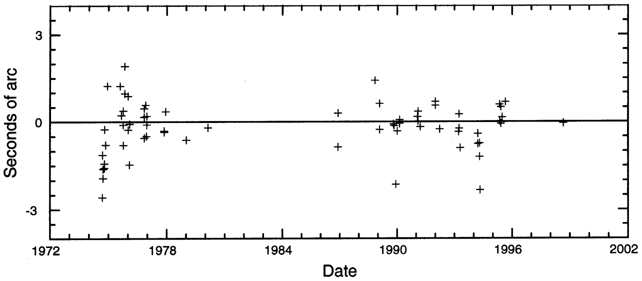

FIG. 15.—Leda right ascension residuals

For observations referred to a mean equator and equinox of epoch system (other than the FK5/J2000.0), we first precess the J2000.0 satellite position to the mean equator at the time of the observation with the IAU76 precession. We then precess it from that time to the mean equator of epoch using the Kinoshita (1975) formulae based on the Newcomb precession constant. Where necessary, we apply corrections for the FK4-FK5 equinox offset and the elliptic aberration. For observations made prior to 1940 we apply an additional correction of $-0''.75$ to all right ascensions to account for the offset between Newcomb's equinox and that of the FK4 (Fricke 1985). In applying this latter correction, we are assuming that the star catalogs used in the reduction of the early data measured right ascensions from Newcomb's equinox. This assumption appears to be justified because the correction significantly improves the fit to nearly all of the early observations. Although not strictly correct, we treated the apparent positions as if they were apparent positions in the J2000.0 system; a previous investigation (Jacobson 1998) found that errors introduced by this procedure are below the other systematic errors present in the observations.

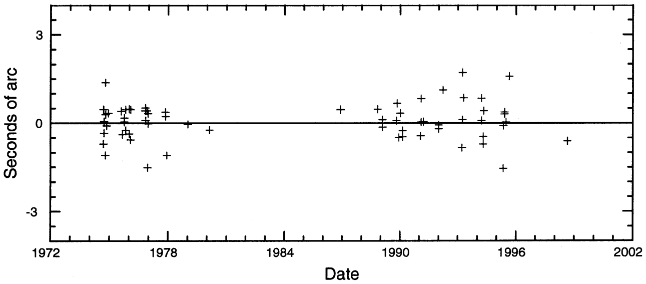

FIG. 16.—Leda declination residuals

3.3. *Observation Processing and Results*

We divided the observations into sets according to opposition and observer and assigned to each set a weight numerically equal to the reciprocal of the assumed accuracy of the observations in the set. For most sets, we took the accuracy to be the root mean square (rms) of the residuals as determined through an iterative process. Some sets, however, we deweighted to varying degrees; these sets included those with few observations or with an unusually small residual rms. We used a least-squares procedure based on Householder transformations (Lawson & Hanson 1974) to fit the orbits to the observation sets by adjusting the epoch state vectors of the integrated orbits.

The publications of the Greenwich observations give positions of Jupiter that were reduced in the same manner as those of the satellites. In the publications, these positions are compared with the tabular place of Jupiter in the Nautical Almanac to develop a set of corrections for the elimination of star catalog and Jupiter ephemeris errors. Rather than apply the published corrections, we chose, instead, to determine our own corrections through direct processing of the Jupiter positions. We formed residuals against positions computed from the DE405 and E5 ephemerides (the former gives the Jovian system barycenter position, and the latter relates the planet position to the barycenter). We extended our processing to include the determination of right ascension and declination biases, which minimize these residuals. The biases affect the computed positions of all of the satellites and Jupiter.

We also included biases for the extensive observation sets of C. D. Perrine at the Lick Observatory, S. B. Nicholson at the Mount Wilson and Palomar observatories, and G. F. Benedict, J. D. Mulholland, P. J. Shelus, and A. L. Whipple at the McDonald Observatory. Although no planet observations were available in these cases, each observation set normally included many observations of more than one satellite over several nights each year. The biases, again, attempt to account for star catalog and Jupiter ephemeris errors, which are common to all of the observations in each set.

The epoch state vectors obtained from the fit appear in Table 3, and the observation biases are listed in Table 4. Some of the biases are rather large. Similar large biases were

TABLE 5

OBSERVATION RESIDUAL STATISTICS

			$\Delta\alpha \cos \delta$			$\Delta\delta$	
TIME SPAN	SATELLITE	No.	Mean (arcsec)	rms (arcsec)	No.	Mean (arcsec)	rms (arcsec)
1894–2000......	Himalia	730	0.03	0.84	728	0.06	0.80
1905–2000......	Elara	339	0.00	0.74	339	0.04	0.75
1908–2000......	Pasiphae	455	0.08	0.77	455	0.03	0.78
1914–1998......	Sinope	205	0.11	0.88	205	0.08	0.74
1938–1998......	Lysithea	124	0.02	0.63	124	0.13	0.67
1938–1998......	Carme	142	0.03	0.78	142	0.09	0.75
1951–1998......	Ananke	134	0.08	0.70	134	−0.10	0.77
1974–1998......	Leda	67	−0.19	0.88	67	0.06	0.62
Total.........		2196	0.04	0.80	2194	0.05	0.76

TABLE 6

Planetocentric Mean Orbital Elements

Element	Himalia (J VI)	Elara (J VII)	Pasiphae (J VIII)	Sinope (J IX)	Lysithea (J X)	Carme (J XI)	Ananke (J XII)	Leda (J XIII)
a (km)	11,460,000	11,740,000	23,620,000	23,940,000	11,720,000	23,400,000	21,280,000	11,160,000
e	0.16	0.22	0.41	0.25	0.11	0.25	0.24	0.16
I (deg)	27.50	26.63	151.43	158.11	28.30	164.91	148.89	27.46
λ (deg)	97.96	225.93	43.63	97.87	24.14	15.96	357.03	357.56
ϖ (deg)	29.24	252.96	123.44	289.48	55.01	141.94	108.23	129.49
Ω (deg)	57.24	109.37	312.99	303.08	5.53	113.74	7.62	217.14
n (deg day^{-1})	1.4368	1.3865	0.5084	0.4969	1.3889	0.5126	0.5897	1.4942
$d\varpi/dt$ (deg day^{-1})	0.0037	0.0039	0.0244	0.0223	0.0042	0.0233	0.0160	0.0036
$d\Omega/dt$ (deg day^{-1})	−0.0034	−0.0039	0.0122	0.0112	−0.0033	0.0111	0.0090	−0.0033
P (days)	250.56	259.64	708.04	724.51	259.20	702.28	610.45	240.92
$\alpha^{\rm a}$(deg)	275.67	273.20	273.44	273.26	271.36	272.62	279.09	271.67
$\delta^{\rm a}$(deg)	67.43	68.24	67.64	66.88	67.11	66.69	66.15	66.85

Note.—At Julian date 2,451,544.5 (2000 January 1.0) referred to the local Laplacian planes.

[a] Right ascension and declination of the local Laplacian plane with respect to the mean Earth equator and equinox of J2000.0.

also found in the Greenwich observations of the Saturnian satellite Phoebe during the same era (Jacobson 1998). Figures 1–16 display the residuals giving an indication of their scatter, as well as the time distribution of the observations. Table 5 gives the number of observations of each satellite and the mean and rms of the postfit residuals (after the removal of the observation biases).

4. MEAN ORBITAL ELEMENTS

To obtain a set of descriptive elements, we fitted a precessing-ellipse model to each of the integrations over the period 1900 to 2000. Table 6 contains the elements. The reference plane for each element set is the respective satellite's Laplacian plane, the plane on which the orbit precesses almost uniformly. The orientation angles for the Laplacian plane poles, determined as part of the fit to the integration, are also given in the table. For each satellite the epoch mean longitude (λ), longitude of periapsis (ϖ), and longitude of the ascending node (Ω) are measured from the ascending node of the Laplacian plane on the Earth's mean equator of J2000.0. We should emphasize that these elements provide only an approximate representation of the orbits: periodic differences between the mean orbits and integrated ones can be as large as 8 Mkm.

5. ACCURACY ASSESSMENT

The accuracy to which the orbits can be determined is limited primarily by the observation errors (e.g., star catalog errors, measurement errors, reduction limitations). The error in the DE405 ephemeris of Jupiter is less that 0″.1 and has little effect on the modeling of the observations. Relative to the observation errors, dynamical modeling errors are small. The most important dynamical parameters, the GMs, are well known from spacecraft data, and inaccuracies in the ephemerides of the perturbing bodies degrade the orbit integrations by less than 100 km.

To estimate the accuracy of the orbits, we first examined the formal covariance from the fit. The accuracy predicted by the covariance is a lower bound because it only accounts for observation errors as represented by the data weights. We then performed a number of sensitivity studies with various data subsets and weights. Table 7 gives our assessment of the orbit accuracies at the integration epoch based on this analysis (these accuracies are in the range of 3 to 5 times the formal errors). Error growth will occur primarily in the in-orbit direction as a consequence of the period error.

TABLE 7

Ephemeris Accuracy: $-1\ \sigma$

Satellite	Radial (km)	In-orbit (km)	Normal (km)	Period (s)
Himalia	200	500	300	6
Elara	250	625	350	10
Pasiphae	325	900	500	30
Sinope	800	2000	600	40
Lysithea	400	1100	600	15
Carme	500	1600	800	50
Ananke	600	1500	800	60
Leda	600	2000	800	50

6. CONCLUDING REMARKS

This article has reported on the determination of the orbits of the eight outer satellites of Jupiter using numerical integration fit to Earth-based astrometric observations. The dynamical model includes all major perturbations with the most recent values of the dynamical parameters. The observation set contains all available observations from the time of each satellite's discovery through 2000 January. This determination of the orbits is the first to incorporate modern high precision CCD observations reduced using modern highly accurate reference star positions. We expect to continue improving our knowledge of the orbits as more of these CCD observations become available.

Ephemerides based on the orbits described in this article are available electronically from the JPL Horizons on-line solar system data and ephemeris computation service (Giorgini et al. 1996).

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