Natural Satellite Ephemerides at JPL

A Report to the IAU Commission 20 Working Group On Natural Satellites

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There are currently seventy-seven recognized and thirty-eight provisional natural satellites in the Solar System. NASA's Jet Propulsion Laboratory (JPL) maintains ephemerides for all and makes these ephemerides available electronically through JPL's On-Line Solar System Data Service known as Horizons (Giorgini *et al.* [1996]). Because of the intimate connection between the orbits of the Earth and Moon, the ephemeris of the latter is determined as part of the development of JPL's planetary ephemerides.

We use numerically integrated orbits as the basis for the ephemerides of most of the satellites. The exceptions are the Martian satellites, the five major Uranian satellites, Pluto's satellite, and majority of the minor inner satellites.

The orbits for the Martian satellites, Phobos and Deimos, are represented by the theory of Sinclair (1972,1989) as extended by Morley (1990) and Jacobson (1996a). Orbits from the ESAPHO and ESADE theories developed by Chapornt-Touzé (1988,1990a,1990b) are also available.

The orbits for the five major Uranian satellites are from the theory of Laskar (1986) which was fit to observations by Laskar and Jacobson (1987). The numerically integrated ephemerides used in Voyager operations (Jacobson *et al.* [1986]) are also available.

The orbit of Pluto's satellite, Charon, is modeled as a two body conic orbit with elements from Tholen(1990) and the revised semi-major axis of Null *et al.* (1993).

Precessing ellipses represent the minor satellites' orbits. The sources of the ellipse elements are:

- the four inner Jovian satellites (Jacobson [2001a]).
- four of the minor satellites of Saturn, Prometheus, Pandora, Atlas, and Pan (Jacobson [1995,1996b])
- the ten minor Uranian satellites (Jacobson [1998b])
- the six minor Neptunian satellites (Owen *et al.* [1991]).

To support the Galileo mission we developed numerically integrated orbits for the Galilean satellites (Jacobson [2001a,2002]). These orbits are still being refined using data acquired by the Galileo

spacecraft. We have also extended the integration to include the inner satellites Amalthea and Thebe in order to process the Galileo data from the close flyby of Amalthea.

The Cassini mission is relying on integrated ephemerides for the eight major Saturnian satellites, Phoebe, the inner satellites Janus and Epimetheus, and the Lagrangian satellites Helene, Telesto, and Calypso. The initial integrations were described in (Jacobson [1996b,1998a]). The final pre-encounter ephemeris development is under way; Jacobson (2003) contains a preliminary report on the work.

The ephemerides for Triton and Nereid are from the numerical integration by Jacobson *et al.* (1991). These were used for the Voyager mission to Neptune.

The orbits of the irregular satellites of Jupiter, Saturn, and Uranus are all numerically integrated. Discussions of some of the orbits may be found in Jacobson (1999,2000,2001b). All are being continually updated as additional observations become available.

We also provide, via our website "http:/ssd.jpl.nasa.gov" (Chamberlin *et al.* [1997]), tables of satellite orbital elements. For all of the satellites with integrated orbits the elements represent a precessing ellipse fit to an extended integration. The elements are mean in the sense that they represent an orbit differing from the integrated orbit by only periodic effects over the fit interval.

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References

[1] Chamberlin, A.B., Yeomans, D.K., Chodas, P.W., Giorgini, J.D., Jacobson, R.A., Keesey, M.S., Lieske, J.H., Ostro, S.J., Standish, E.M., Wimberly, R.N. 1997, 'JPL Solar System Dynamics WWW Site', *BAAS*, 29, 1014

[2] Chapornt-Touzé, M.: 1988, 'ESAPHO: a semi-analytical theory for the orbital motion of Phobos',*A&A*, **200**, pp. 255

[3] Chapornt-Touzé, M.: 1990a, 'Phobos' physical libration and complements to the ESAPHO theory for the orbital motion of Phobos', *A&A*, **235**, pp. 447

[4] Chapornt-Touzé, M.: 1990b, 'Orbits of the Martian satellites from the ESAPHO and ESADE theories',*A&A*, **240**, pp. 159

[5] Giorgini, J.D., Yeomans, D.K., Chamberlin, A.B., Chodas, P.W., Jacobson, R.A., Keesey, M.S., Lieske, J.H., Ostro, S.J., Standish, E.M., Wimberly, R.N. 1996, 'JPL's On-Line Solar System Data Service', *BAAS*, 28, 1158

[6] Jacobson, R.A., Lewis, G.D., Riedel, J.E., Roth, D.C., Synnott, S.P., and Taylor, A.H.: 1986, 'Ephemerides of the Uranian Satellites Determined from Earth-Based Astrometric and Voyager Imaging Observations', AIAA Paper AIAA-86-2059-CP, AIAA/AAS Astrodynamics Conference, Williamsburg, VA

[7] Jacobson, R.A., Riedel, J.E., and Taylor, A.H.: 1991, 'The orbits of Triton and Nereid from spacecraft and Earthbased observations', *A&A*, **247**, pp. 565

[8] Jacobson, R. A. 1995. The Orbits of the Minor Saturnian Satellites, *BAAS*, **27**, No.3, 1202-1203.

[9] Jacobson, R. A. 1996a. The Orbital Motion of the Martian Satellites: An Application of Artificial Satellite Theory, AAS Paper 96-140 AAS/AIAA Space Flight Mechanics Meeting, Austin, Texas.

[10] Jacobson, R. A. 1996b. The Orbits of the Saturnian Satellites from Earthbased and Voyager Observations, *BAAS*, **28**, No.3, 1185.
[11] Jacobson, R. A. 1998a. The orbit of Phoebe from Earthbased and Voyager observations, *A&AS*, **128**, 7-17.
[12] Jacobson, R. A. 1998b. The orbits of the inner Uranian satellites from Hubble Space Telescope and Voyager 2 observations, *AJ*, **115**, 1195-1199.
[13] Jacobson, R. A. 1999. The Determination and Long-Term Integration of the Orbits of Caliban and Sycorax, *BAAS*, **31**, No.4, 1224.
[14] Jacobson, R. A. 2000. The Orbits of the Outer Jovian Satellites, *AJ.*, **120**, 2679-2686.
[15] Jacobson, R. A. 2001a. Gravity Field of the Jovian System and the Orbits of the Regular Jovian Satellites, *BAAS*, **33**, No.3, 1039.
[16] Jacobson, R. A. 2001b. The Orbits of the Recently Discovered Irregular Jovian and Saturnian Satellites, *BAAS*, **33**, No.3, 1191.
[17] Jacobson, R. A. 2002. Pioneer and Voyager Jupiter Encounter Orbit Reconstruction in the ICRF System, AAS Paper 02-157 AAS/AIAA Space Flight Mechanics Meeting, San Antonio, Texas.
[18] Jacobson, R. A. 2003. Reconstruction of the Voyager Saturn Encounter Orbits in the ICRF System, AAS Paper 03-198, 13th AAS/AIAA Space Flight Mechanics Meeting, Ponce, Puerto Rico.
[19] Laskar, J.: 1986, 'A general theory for the Uranian satellites', *A&A*, **166**, 349
[20] Laskar, J. and Jacobson, R.A.: 1987, 'GUST86. An analytical ephemeris of the Uranian satellites',*A&A*, **188**, pp. 212
[21] Morley, T.A.: 1990, 'An improved analytical model for the orbital motion of the Martian satellites',*A&A*, **228**, pp. 260
[22] Null, G.W., Owen, W.M. and Synnott, S.P.: 1993, 'Masses and Densities of Pluto and Charon', *AJ*, **105**, pp. 2319.
[23] Owen, W.M., Vaughan, R.M, and Synnott, S.P.: 1991, 'Orbits of the Six New Satellites of Neptune', *AJ*, **101**, pp. 1511
[24] Sinclair, A.T.: 1972, 'The Motions of the Satellites of Mars', *MNRAS*, **155**, pp. 249
[25] Sinclair, A.T.: 1989, 'The orbits of the satellites of Mars determined from Earth-based and spacecraft observations', *A&A*, **220**, pp. 321
[26] Tholen, D.J.: 1990, 'Further Analysis of Pluto-Charon Mutual Event Observations', *BAAS*, **22**, pp. 1129