IOM 343R - 06 - 002

April 21, 2006

TO	: Section 343 (notification by email)
FROM	: E M Standish
SUBJECT	: JPL Planetary Ephemeris DE414

1 Introduction

The JPL Planetary Ephemeris DE414 was created in May 2005 and has been used by a number of people at JPL since then. At this time, DE414 is JPL's latest and most accurate planetary ephemeris. This memo serves to document DE414 and to recommend its use for present-day spacecraft navigation. It is expected that a newer ephemeris will become available sometime later in the year when the observational data sets have been updated.

DE414 is available in navio format via anonymous ftp from ssd.jpl.nasa.gov:

```
cd pub/eph/planets/nio
get de414s.nio
  or
get de414.nio
```

The full version is de414.nio; it extends from 1599 DEC (JED 2305424.5) to 2201 FEB 20 (2525008.5) and occupies 62.5 GBytes. The shorter version, de414s.nio, extends from 1969 DEC 05 (2440560.5) to 2031 JAN 30 (2462896.5) and occupies 4.4 GBytes.

Most of the basic features of the JPL planetary ephemerides have been documented previously (see Standish *et al.*, 1995; Standish, 1998; Standish, 2003a; Standish, 2003b). Also available is a complete description of DE405, which has, since 2003, been the basis of the *Astronomical Almanac*. The description of DE405 will be published (hopefullly soon) in the next version of the *Explanatory Supplement to the Astronomical Almanac*. It is also available via anonymous ftp from ssd.jpl.nasa.gov:

```
cd pub/eph/planets/ioms
get ExplSupplChap8.pdf
```

This memo briefly discusses the reference system of DE414 and the numerical integration of the equations of motion, presents a table listing the full set of observational data to which DE414 was fit and mentions a couple of recent updates which are unique to DE414, presents a table of the more pertinent astronomical constants which were used in the creation of DE414, compares the ephemeris of each planet in DE414 to those in DE405, and briefly mentions the accuracies of DE414.

2 ICRF : the Reference System of DE414

As discussed in previous memos, the JPL planetary ephemerides are now based upon the International Celestial Reference Frame (ICRF). This is accomplished by inclusion of the VLBI measurements into the observational data set. In particular, the Magellan observations of Venus and, especially, the MGS and Odyssey observations of Mars tie the inner planetary system onto the ICRF through the fitting process. The VLBI observations of Galileo do the same thing for Jupiter. The outer planets are referenced to the ICRF by transforming their FK5-based observations using a table provided by Morrison *et al.* (1996) for the La Palma transit observations and angles provided by Kovalevsky (1996) for the other transit observations. In the future, these will be replaced by the formulae of Feissel and Mignard (1998).

The reduction of ranging data requires the orientation of the earth in order to locate the antennas; for this, the earth orientation parameters from the International Earth Rotation Service (IERS) are used. These are also based upon the ICRF, and thus the orientation of the earth is consistent with the ephemerides.

3 The Integration of DE414

DE414 is a fully-integrated ephemeris. The equations of motion are documented in Chapter 8 of the Explanatory Supplement (2007), available via ftp as mentioned above in the Introduction. The basic integrator is "QIVA", a quadruple-precision version of "DIVA", (Krogh, 1997). For the equations of motion, the newtonian part is computed in quadruple precision; all of the rest (relativity, asteroid perturbations, figure effects, tides, etc.) are computed in double precision. Such a mixed-precision integration requires about 16 minutes per century. There is the option of running totally in double precision for approximate accuracy; this requires only 35 seconds per century - 30 times faster than the mixed-precision mode.

4 The Observational Data Fit by DE414

Table I presents a listing of the sets of observations fit by DE414. These data have been discussed previously in the memos mentioned above. Most of the data are available at

<http://iau-comm4.jpl.nasa.gov/plan-eph-data/index.html>.

The following comments are pertinent:

- The set of MGS and Odyssey ranging observations was extended to the end of April, 2005, and the set was condensed into normal points: all of the ranges from a single pass (single orbit around Mars) were combined into one representative point for fitting. As such, 128,392 raw points from MGS and 150,968 points from Odyssey were condensed into 8120 and 4082 points, respectively.
- Up-to-date CCD observations of the five outermost planets and their satellites, taken at many observatories, especially the USNO at Flagstaff and JPL's Table Mountain, were added to the observation set.
- Two data sets were inadvertantly omitted from the fit for DE414: the Magellan doppler points of Venus, 1992-94, and the Galileo VLBI points of Jupiter, 1996-97.
- In addition to the observations listed in Table I, there were

  3488 range measurements to the NEAR spacecraft orbiting Eros. These were pre-fitted residuals with only the signature of the Earth-Moon mass ratio remaining; they were used in DE414 for the determination of only that single parameter.

6 points from the frame tie of Folkner *et al.* (1993).
1 pseudo observation to enter the list of initial conditions into the solution program

5 The Various Constants of DE414

Table II shows the masses of the planets in DE414, and, for comparison, the 1994 IAU "Best Estimates" (Standish, 1995). In the future, for consistency with the gravity field models, the values for the earth and moon will be replaced using $GM_M = 4902.8000$ km^3/sec^2 and $GM_E/GM_M = 81.300570$ from Konopliv *et al.* (2002), and the value for GM_4 will be replaced by 42828.37440, the system mass from Konopliv *et al.* (2005).

Table III lists the values of other dynamical parameters from the solution leading to DE414.

6 Comparisons of DE414 to DE405

Figures 1 and 2 show comparisons between DE414 and DE405 for all of the planets, the sun, and the moon. The plots show heliocentric (geocentric for the moon) differences, DE405 - DE414, in right ascension, declination, and distance. Such comparisons are often more informative and provide a better estimate of realistic ephemeris uncertainties than those of formal covariances which are well-known to be optimistic, often by factors of 2^2, or 3^2, or even more. Thus, one may assume for DE405 vs. DE414, that most of the difference is due to errors in DE405, the older ephemeris; DE414 should be more accurate since the observational data set fit by DE414 is greater and more extensive in time.

A more in-depth study for Mars is being prepared by W M Folkner, which will address the martian covariance for both present-day ephemerides, e.g. DE414, and for future ephemerides with assumptions about the acquisition of future Mars observations (VLBI and ranging measurements from MGS and Odyssey).

7 Conclusions

DE414 is the latest planetary ephemeris at JPL; it is recommended for present-day spacecraft navigation. It is expected that an improvement to DE414 will be produced within the next year, taking advantage of additional observational data and recently improved values for a number of the planetary masses.

References

Anderson, J.D., Colombo, G., Esposito, P.B., Lau, E.L. and Trager, G.B.: 1987, "The Mass, Gravity Field, and Ephemeris of Mercury", Icarus, **71**, 337-349.

Border, J.S.: 2003, email deliveries of VLBI points,

Feissel, M. and Mignard, F.: 1998, "The adoption of ICRS on 1 January 1998: meaning and consequences", Astron. Astrophys., **331**, L33-L36.

Explanatory Supplement to the Astronomical Almanac: to be published, 2007(?), P. K. Seidelmann, ed.

Folkner, W.M., Charlot, P., Finger, M.H., Williams, J.G., Sovers, O.J., Newhall, X X, and Standish, E.M.: 1993, "Determination of the extragalactic frame tie from joint analysis of radio interferometric and lunar laser ranging measurements", Astron. Astrophys., **287**, 279-289.

Jacobson, R.A., Campbell, J.K., Taylor, A.H. and Synnott,S.P.: 1992, "The Masses of Uranus and its Major Satellites from Voyager Tracking Data and Earth-based Uranian Satellite Data", Astron J., **103**(6), 2068-2078.

Jacobson, R.A., Riedel, J.E. and Taylor, A.H.: 1991, "The Orbits of Triton and Nereid from Spacecraft and Earth-based Observations", Astron. Astrophys., **247**, 565-575.

Jacobson, R.A.: 2006, private communications.

Konopliv, A.S., Miller, J.K., Owen, W.M., Yeomans, D.K. and Giorgini, J.D.: 2002, "A Global Solution for the Gravity Field, Rotation, Landmarks, and Ephemeris of Eros", *Icarus*, **160**, 289-299.

Konopliv, A.S., Yoder, C.F., Standish, E.M., Yuan, D-N. and Sjogren, W.L.: 2005, "A global solution for the Mars static and seasonal gravity, Mars orientation, Phobos and Deimos masses, and Mars Ephemeris", *Icarus*, in press.

Kovalevsky, J.: 1996, private communication.

Krogh, F.T.: 1997, Calif. Inst. of Technology, 2003 Math a la Carte, Inc.

Morrison, L.V.: 1996: private communication.

Null, G.W.: 1969, "A Solution for the Mass and Dynamical Oblateness of Mars Using Mariner-IV Doppler Data", Bull. Am. Astr. Soc., **1**(4), 356.

Sjogren, W.L., Trager, G.B. and Roldan, G.R.: 1990, "Venus: A Total Mass Estimate", Geophys. Res. Let., **17**(10), 1485-1488.

Standish, E.M.,: 1995, "Report of the IAU WGAS Sub-Group on Numerical Standards", in "Highlights of Astronomy" (Appenzeller, ed.), pp. 180-184, Kluwer Academic Publishers, Dordrecht.

Standish, E.M., Newhall, X X, Williams, J.G. and Folkner, W.F.: 1995, "JPL Planetary and Lunar Ephemerides, DE403/LE403", JPL IOM 314.10-127.

Standish, E.M.: 1998, "JPL Planetary and Lunar Ephemerides, DE405/LE405",JPL IOM 312.F-98-048.

Standish, E.M.: 2003a, "JPL Planetary and Lunar Ephemerides, DE409/LE409",JPL IOM 312.N-03-007.

Standish, E.M.: 2003b, "JPL Planetary and Lunar Ephemerides, DE410/LE410",JPL IOM 312.N-03-009.

Tholen, D.J. and Buie, M.W.: 1988, "Circumstances for Pluto-Charon Mutual Events in 1989", Astron.J., **96**(6), 1977-1982.

Table 1. Observational Data Fit by DE414.

The observational data to which DE414 was fit. The columns contain the planet being measured, the type of measurement, the source of the data, the years over which the data were taken, the number of data points, and the typical accuracy of a single measurement. Observation counts marked with an asterisk (*) are approximate.

Mercury	radar range	misc obs'ys	1966-70,-82,-97	175,240,221	1500, 1000, 700	meters
	radar closure	DSS 14	1989-97	23	700	
	s/c range	Mariner 10	1974-75	2	100	
Venus	radar range	misc obs'ys	1968-70	322	2000	meters
			1971-95	222	1000	
	VLBI	Magellan	1990-94	18	3	mas
	ODP $\alpha, \delta; \rho$	Cassini	1998-99	2,2; 2	8, 3	mas, meters
Mars	radar closure	DSS 14	1971-93	56	100	meters
	s/c range	Mariner 9	1971-72	629	25	
		Viking	1976-80, 80-82	822, 247	8, 12	
		Phobos	1989	1	500	
		Pathfinder	1997	89	5	
		MGS	1999-2005	8120	1.2	
		Odyssey	2002-2005	4082	1.2	
	s/c doppler	Viking	1976-79	13049	5	mm/sec
		Pathfinder	1997	7564	0.2	
	CCD	misc obs'ys	2003	6	200	mas
	VLBI	Phobos	1989	2	3	
		MGS	1999-2003	14	1	
		Odyssey	2002-03	28	1	
Jupiter	transits	misc obs'ys	1911-82	6301	500	mas
	astrolabe	misc obs'ys	1976-81	90	500	
	phot. astr	misc obs'ys	1962-98	2628	200	
	CCD	misc obs'ys	1997-2005	* 5428	200	
	thermal	VLA	1983	2	30, 60	
	ODP $\alpha, \delta; \rho$	Vgrs, Cassini	1973, 74, 2000	6, 6; 6	8, 3	mas, meters
Sat, ... Pl	transits	misc obs'ys	1911-82	19409	500	mas
	astrolabe	misc obs'ys	1969-85	809	500	
	phot. astr.	misc obs'ys	1915-95	* 7374	200	
	CCD	misc obs'ys	1996-2005	* 8918	200	
	thermal	VLA	1984	8	30, 60	
	occultations	misc obs'ys	1977-85	32	200	
	ODP $\alpha, \delta; \rho$	Vgrs	1979, 81	3, 3; 3	8, 3	mas, meters

Table II. GM values in DE414. The 1994 IAU "Best Estimates" are given first for comparison.

	IAU 1994 $[GM_{sun}/GM_{planet}]$	DE414 $[GM_{sun}/GM_{planet}]$	DE414 $[km^3/sec^2]$	Reference for the DE414 value
Mercury	6023600.	6023600.	22032.08...	Anderson *et al.*, 1987
Venus	408523.71	408523.71	324858.60...	Sjogren *et al.*, 1990
Earth	332946.0509...	332946.05051...	398600.43...	(derived)
Mars	3098708.	3098708.	42828.31...	Null, 1969
Jupiter	1047.3486	1047.348625	126712764.86...	Jacobson, 2006
Saturn	3497.898	3497.898	37940626.07...	Jacobson, 2006
Uranus	22902.98	22902.98	5794549.01...	Jacobson *et al.*,1992
Neptune	19412.24	19412.24	6836534.07...	Jacobson *et al.*,1991
Pluto	135×10^6	135.2×10^6	981.60...	Tholen and Buie, 1988
Moon	27068700.387534...	27068702.9...	4902.80...	(derived)
EM-Bary	328900.56	328900.561399...	403503.23...	DE414 solution
Sun	1.0	1.0	132712440044.21...	DE414

The GM's for the earth and moon are derived using the solved-for values of GM_B and, in the IAU case, $GM_M/GM_E = 0.012300034$, or, for DE414, the solved-for value of $GM_E/GM_M = 81.3005677535...$

The conversions into km^3/sec^2 use the solved-for value of the AU scale factor, 149597870.7008525... km/au.

Table III. Other constants of DE414

Scale factor [km/au]	149597870.7008525	
Earth-Moon mass ratio	81.3005677535...	
	GM_A/GM_{sun} $\times 10^{10}$	km^3/sec^2
GM_{Ceres}	4.70...	62.36...
GM_{Pallas}	1.03...	13.61...
GM_{Vesta}	1.36...	18.03...
	gm/cm^3	
Mean density, C-asteroids, ρ_C	1.62...	
Mean density, S-asteroids, ρ_S	2.08...	
Mean density, M-asteroids, ρ_M	4.32...	

In addition, there were 64 other asteroids for which the initial mass was estimated from their taxonomic class and measured diameters. These masses were then adjusted in the DE414 solution, though they were heavily constrained to their initial values.

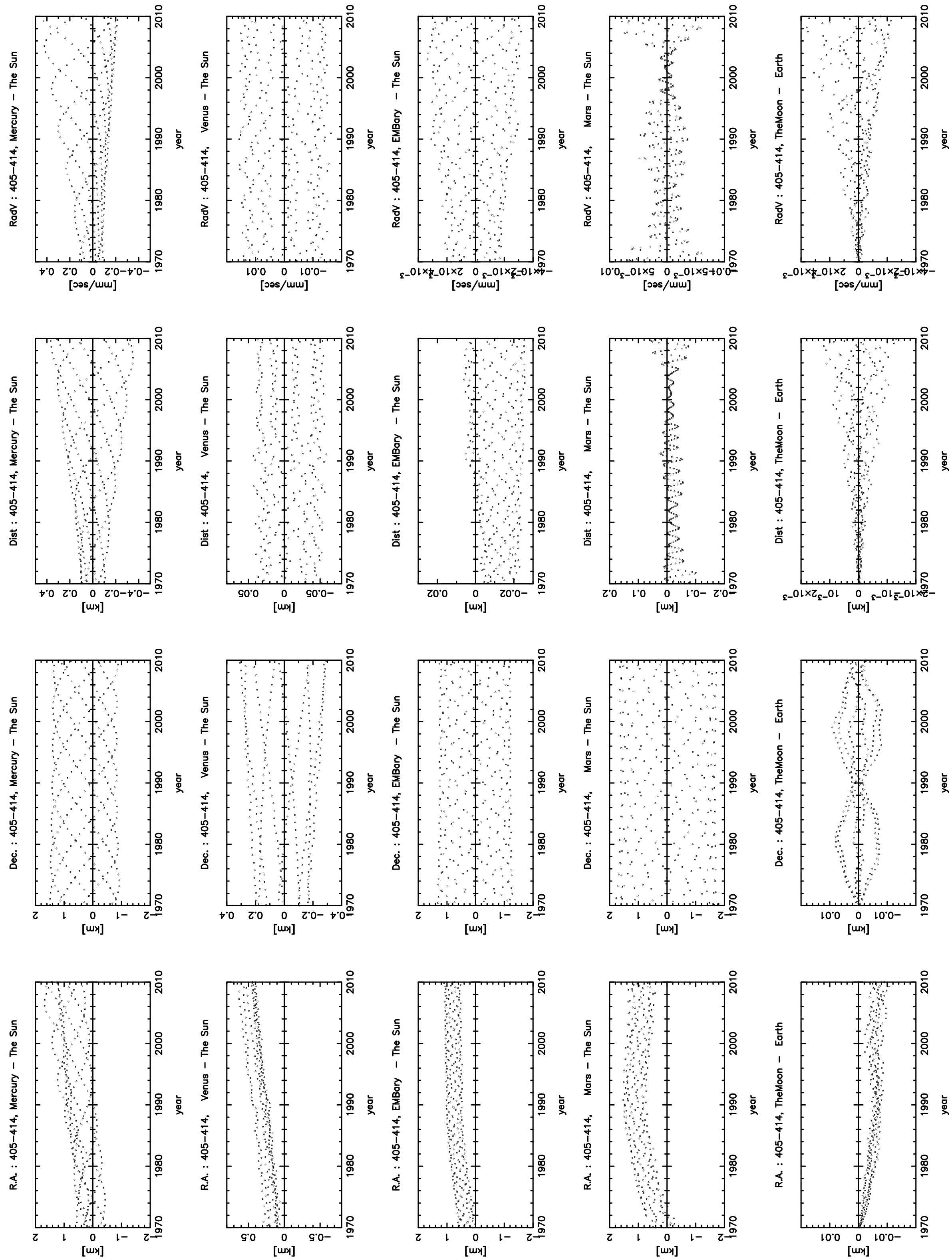

Figure 1: DE410-DE405 for heliocentric, equatorial differences for Mercury - Mars, (geocentric) Moon.

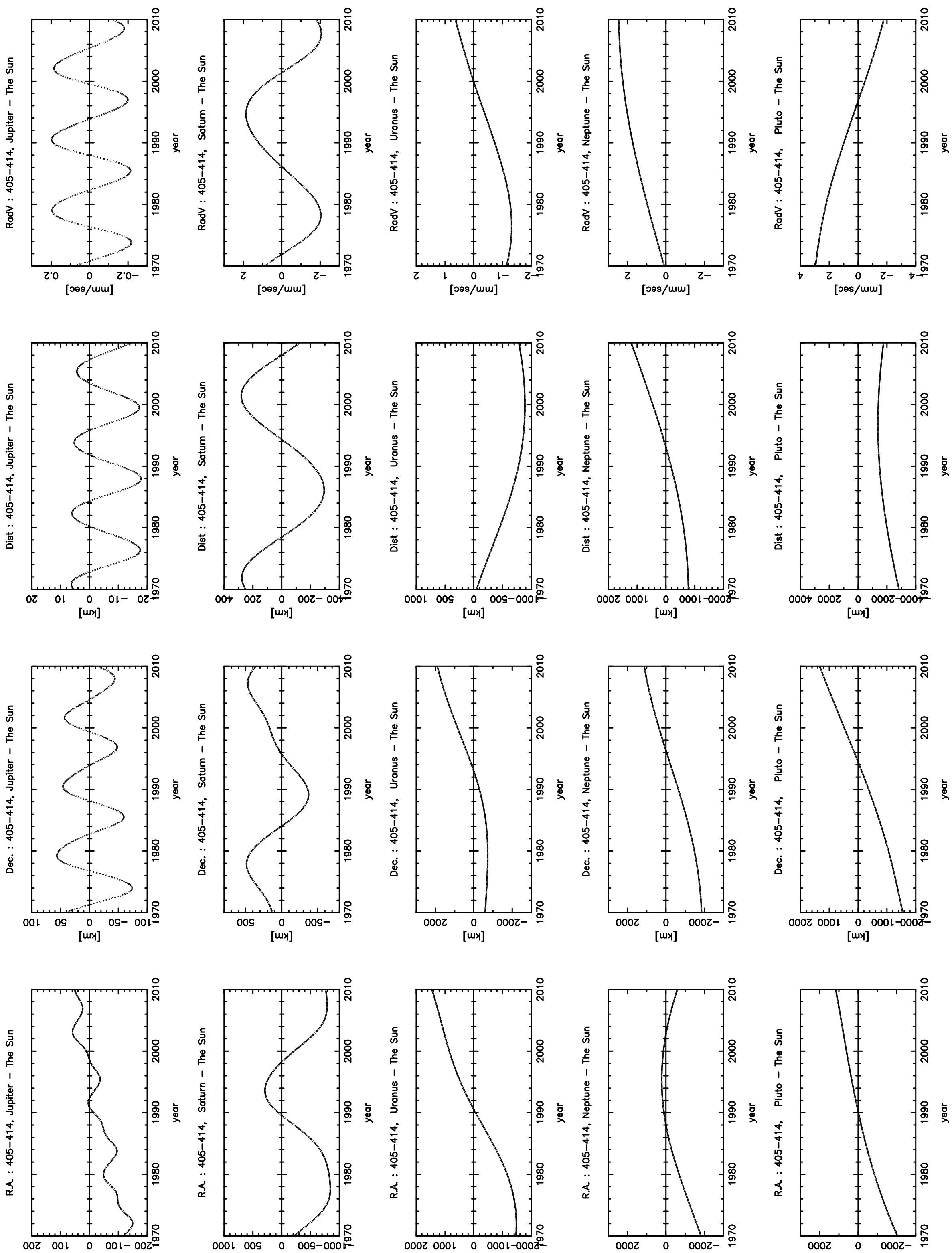

Figure 2: DE410-DE405 for heliocentric, equatorial differences for Jupiter - Pluto.