JET PROPULSION LABORATORY **INTEROFFICE MEMORANDUM**

IOM 312.N – 03 – 009

April 24, 2003

TO : Distribution

FROM : E M Standish

SUBJECT : JPL Planetary Ephemeris DE410

1 Introduction

The latest JPL Planetary Ephemeris, DE410, has been created especially for the MER arrival at Mars in January 2004 and for the Cassini arrival at Saturn in July 2004. DE410 covers the years 1901 through 2019 and is now available on zeus:

"/home/ems/de410.nio" and "/home/ems/de410.ftp"

DE410 represents improvements over its predecessor, DE405, with respect to the positions of all planets, but especially to those of Mars and Saturn. This memo describes the creation of DE410, documents the newer data sets used in the adjustment, discusses some of the solution parameters, shows plots of the more relevant residuals, presents the differences of DE410 vs. DE405, and gives estimates of the realistic accuracies of the Mars and Saturn ephemerides.

DE410 includes recent determinations of the GM values of Venus (Konopliv it et al., 1999), Mars (Yuan *et al.*, 2001), Jupiter (Jacobson, 2003), and Saturn (Jacobson, 2003), along with values of GM for the Earth-Moon Barycenter and the Earth-Moon mass ratio, derived from GM values of the Earth (Tapley*et al.*, 1996) and the Moon (Konopliv *et al.*, 2001). It is noted that these newer values are not (yet) part of the IAU's "List of Best Estimates" (Standish, 1995). These masses are given in Table I.

2 DE405, the Predecessor to DE410

The JPL Planetary and Lunar Ephemerides, DE405/LE405, were created in 1997 and are described by Standish (1998). They form the basis for all planetary and lunar positions in the *Astronomical Almanac*, starting in 2003, and are also the fundamental ephemerides of the latest set of IERS Conventions (2003).

For Mars, in contrast to DE410, the DE405 observational set contained only 1) radar closure points up to 1993 and 2) spacecraft ranging data from Mariner 9 (629 points, 1971-72), Viking (1282 points, 1976-82), and Phobos (2 points, 1989). Further, the orientation of the whole inner planet system, including Mars, was based upon VLBI points of the Magellan spacecraft in orbit around Venus (18 points, 1990-1994) and an indirect frame-tie in 1988.

Thus, the present-day positions of Mars from DE405 represent many years' extrapolation past the accurate range data and are tied only indirectly to the International Celestial Reference Plane (ICRF). There were no *direct* ties of the Mars ephemeris to the ICRF.

For Saturn, the only data fit by DE405 were optical transit timings from Washington and Herstmonceux (1911-1982), photoelectric transit timings from La Palma, Bordeaux, and Tokyo (1984-1996), and observations from Danjon astrolabes (1969-1981).

3 Observational Data since DE405

The ephemeris of Mars over the present years is dramatically improved in all three dimensions: in the radial component by Pathfinder range and doppler measurements (Folkner, 1997), by recent MGS and Odyssey ranging (Konopliv, 2003a), and, in the two plane-of-sky components, by a series MGS and Odyssey VLBI points (Border, 2003). These VLBI points, for the first time, provide an accurate direct tie of the Mars ephemeris onto the ICRF.

CCD data (Stone, 2003) provide a significant adjustment in the present-decade plane-of-sky directions for the five outer planets. Three sets of normal points from ODP fits to spacecraft encounters at Venus, Jupiter, and Saturn (Jacobson, 2003) give strength in the radial directions and also show fairly good consistency with the other optical data.

Table II lists all of the observational data which have been added since the creations of DE403 in 1995 and DE405 in 1997. The earlier data, fit by DE403 and by DE405, are described in Standish *et al.* (1995) and Standish (1998).

4 The Adjustment Leading to DE410

A number of parameters in the solution for DE410 are of interest; Table III presents a short list of these. The given σ's are the formal values from the least squares solution; realistic uncertainties are often many times greater. The full list of solution parameters is available from the author.

As seen in the table, it has been found necessary to introduce biases into the Viking and Odyssey range data. Initially, a plot of the MGS and Odyssey residuals showed a -2.1 m offset, obvious because data from the two spacecraft are often simultaneous in time. It is felt (Konopliv, 2003b) that the MGS data set is the more trustworthy, so that no bias was applied to MGS. Further, consistency between the Viking ranges and those from MGS and Odyssey is achieved only with biases introduced into the Viking ranges: -18.0 m for Viking 1, -12.7 m for Viking 2. As a result, some of the solution parameters, initially determined primarily by the Viking ranging, are now seen to change somewhat from their former values (AU, asteroid densities, etc.). The Viking biases are not particularly surprising; the calibrations performed back in the early 1970's were less reliable than those of the more modern spacecraft.

5 Observational Residuals w.r.t. DE405 and DE410

The fit of DE410 to the more accurate observational data for Mars and Saturn is demonstrated by the post-fit residuals. In some cases, the residuals are shown here with respect to both DE405 and DE410 in order to emphasize the improvement.

5.1 Residuals of Mars

Figures 1 and 2 present the spacecraft ranging and doppler residuals as fit by DE405 and by DE410. The improvement in the range component of the more recent data is striking, though the extrapolation of DE405 over two decades must be considered excellent: the drift of that ephemeris was less than 200 meters in the earth-Mars distance. As discussed above, there have been bias corrections applied to the Viking and Odyssey ranges. Further, the MGS and Odyssey ranges within 6 weeks of Mars' solar conjunction in mid-August, 2002 were not included in the fit. The recent residuals clearly show the establishment of the Mars range to within a few meters (excluding the improbable existence of a very large and unsuspected bias to all of the range measurements).

Figures 3 and 4 show the VLBI residuals of Mars with respect to DE405 and to DE410, both in milliarcseconds and in kilometers. The residuals show the one-dimensional angular determination of Mars along the direction of the baseline between the two participating DSN stations: either Goldstone and Madrid or Goldstone and Canberra. The former pair gives a determination almost entirely in right ascension; the latter gives a determination which is split about 50-50 between right ascension and declination. These residuals are also listed individually in Table IV in order to emphasize their accuracy and consistency.

Formerly, it was the Venus ephemeris that was tied to the ICRF (via the Magellan VLBI). In turn, the ephemerides of Venus and Mars were connected to the earth, and thus to each other, through radar and spacecraft ranging. Now, for DE410, the MGS and Odyssey VLBI measurements provide the first direct link of the Mars ephemeris onto the ICRF. As seen, this tie seems accurate to within a few hundred meters.

5.2 Residuals of Saturn

The classical measurements of Saturn are the optical transit timings, stretching back to 1911; earlier observations are not used. Even those since 1911 are plagued with systematic errors. They serve now only to keep the general shape and mean motion of Saturn's orbit.

More modern fixes are provided by ODP processing of the encounter data from Pioneer 11 and from Voyagers 1 & 2 (R A Jacobson, 2003). Unfortunately, all three encounters are within less than two years of each other, 1979-1981. They provide a three-dimensional fix at virtually one point in time. The residuals are given in Table V and show that DE410 tightly fits these points in right ascnsion and in geocentric distance; the residuals in declination show a bias of about 100 *km*. ($0\farcs001 \approx$ 7-8 *km* at these distances.)

CCD measurements over the past five years from the US Naval Observatory in Flagstaff (Stone, 2003) serve to locate Saturn in the plane-of-sky. Residuals from these observations w.r.t. both DE405 and DE410 are shown in Figure 5; their statistics are given in Table VI.

Thus, offsets remain in the CCD and ODP declination observations, indicating an inconsistency between those two data sets. This could be due to an observational bias in the CCD declinations, in the ODP declinations, or in the ODP ranges. Any of the three could cause the offsets seen in Tables V and VI. At worst, though, the declination bias is no greater than about 300 kilometers ($0\farcs040$).

6 Differences: DE410 – DE405

It is assumed that DE410 represents an improvement to DE405. Thus, a comparison of the two gives an estimate of the errors in DE405. Such comparisons are plotted in Figures 6 and 7 for all of the planets; these give heliocentric ecliptic coordinates (longitude, latitude, and distance). The slight changes in mean motion for the four innermost planets (a few *km* per century) are due mainly to differences in the modeling of perturbations from the largest 20 asteroids and the more accurate fitting of Mars' orbit. The lunar longitude shows a difference in the tidal deceleration between DE405 and DE403. Figure 8 gives geocentric equatorial plots of Mars and Saturn in right ascension, declination, and distance, covering short time-spans so that one may easily see the differences to be expected for the MER and Cassini encounters.

7 Uncertainties of Mars and Saturn on DE410

This section presents what are believed to be realistic accuracies for the ephemerides of Mars and of Saturn.

7.1 Mars

The motion of Mars is strongly perturbed by many asteroids whose masses are poorly known; this accounts for most of the uncertainty in extrapolating the martian orbit. Recent accurate data in all three dimensions, however, allow a positional fix from which extrapolation into the future will not deteriorate significantly over only a year or so.

Figure 1 shows that DE405, extrapolated over more than a decade, has a present-day earth-Mars range error of less than 200 meters. Thus, with DE410 now fitting the recent observations to within a few meters, extrapolation in range over the next year should easily be accurate to within a few tens of meters.

For the two plane-of-sky directions, experiments showed that fitting the VLBI observations through only September 2002 and extrapolating through the end of February 2003 showed no appreciable ephemeris drift. The fit was still accurate at the 100-200 meter level, the limit of the observations themselves. Such an accuracy can be maintained with continued VLBI observations from MGS and/or Odyssey, 2 or 3 a month.

- Thus, the ephemeris of Mars on DE410 should be accurate to a few hundred meters at most, in all three dimensions, for the MER encounter.

7.2 Saturn

The older observations of Saturn (transit timings) have large systematic errors, but are the only measures covering the planet's 30-year period. They were effectively the only data for the DE405 adjustment of Saturn. Now they serve to constrain Saturn's mean motion, while the ODP normal points provide positions for 1979-81 and the USNO Flagstaff CCD observations give plane-of-sky positions for the past five oppositions, 1998-2003.

DE410 represents a significant correction to the DE405 down-track ephemeris of Saturn – a sinusoid with an amplitude of nearly 1000 kilometers. For the time of Cassini encounter in mid 2004, the DE410-DE405 correction is about +500 kilometers or so. In the cross-track and radial components, the correction is about –150 km and –180 km, respectively. Again, it is assumed that the majority of these differences are due to errors in the ephemeris of DE405.

- Thus, it is expected that the ephemeris of Saturn on DE410 should have errors no larger than 200-300 kilometers at the time of the Cassini encounter.

8 Accuracy Limit of the Integrator

The ranging observations from the MGS and Odyssey spacecraft over the recent few years have pointed out a problem with the numerical integration program used to create the planetary and lunar ephemerides. Basically, it is impossible to fit the observations at the level of their inherent 1-2 meter accuracy. Previous export ephemerides did not have such a problem: all ephemerides through DE403 were integrated on a Univac (60-bit mantissa); DE405 was integrated in quadruple precision on a DEC Alpha.

For the integrations on the Sun Ultra, it has been determined that the numerical integrator has number noise which accumulates to the level of several meters over the course of a decade. A number of things have been done in order to first, ascertain definitely the source of the problem, and secondly, to provide an alternative to the actual integrator.

- The input tolerance limits of the integrator (DIVA) were lowered as far as possible; the number noise remained.
- The starting epoch of the integration was moved from the old standard of JED 2440400.5 (June 28, 1969) to 2447952.5 (March 2, 1990). This put the accurate sets of data (Viking, 1976-1982; MGS, 1999-2003; Odyssey, 2002-2003) within less than 15 years of the starting epoch, thus reducing the build-up of the number noise.
- The number of asteroids to be handled individually was increased from 3 in DE405 to 20, in the event that there was an unmodeled asteroid signature.
- In order to avoid run-off in the lunar ephemeris, in both the nominal base ephemeris, DE546, and in DE410, the lunar ephemeris was replaced with that of DE403. (The lunar ephemeris of DE403 is judged to be a bit better than that of DE405.)
- The finite-differenced partial derivative files, $\partial \mathbf{r}(t)/\partial \mathbf{r}(0)$, were analysed. As long as the change to the initial conditions is no less than about 100 *meters*, (nor much greater than a few hundred *kilometers*), the resultant partials files are virtually the same. However, for changes on the order of about 10 m, the resulting files do not compare so well with those made from larger changes; for changes of only a couple of meters, the structure of the resulting files is completely lost.

The last item, especially, shows that there is number noise in the integrator itself which prevents accuracies at the 1-2 meter level.

9 Linearized ephemerides

In view of the limited integration accuracy, it was decided to create a linearized ephemeris: a solution vector and the partial derivatives were used to apply linearized corrections to state vectors from the temporary nominal ephemeris, DE546. The new sets of state vectors were then fit with chebychev polynomials in order to create the new ephemeris.

As indicated above, the partial derivative files are accurate; the goodness of fit of the post-fit residuals shown here confirm this linearized process. Even though the resulting ephemeris is not actually integrated, it represents the data accurately and is therefore actually preferable to an ephemeris integrated with present software.

10 Future Plans

It is planned to improve the accuracy of the integrator in order to handle observations at and below the 1-*meter* level. A number of factors are relevant:

- Quadruple precision should fix the problem of number noise, but in general, quad precision is very slow - sometimes 100 times slower than double precision. Quad precision for the full set of equations of motion for the planetary and lunar ephemerides would be out of the question, even with modern-day computing speed.

- The equations of motion have been rewritten and split into a quad precision part (newtonian n-body) and a double precision part (the rest of the equations). Since the newtonian accelerations are many orders of magnitude greater than the rest, the split precision should easily suffice.

- A quad precision version of the main integration program, "DIVA", has been made available on a number of platforms.

- An upgrade in hardware (dual 2.4 GHz cpu).

With most of the equations of motion ($\sim 98\%$) in double precision, the execution time will not suffer too much (compared with everything in quad precision). With the faster computer, the integration speed should be acceptable.

An added benefit is the fact that the present software (coded by X X Newhall, now retired) had evolved over the decades, being modified and patched but never fully overhauled and reorganized. The new version is more logically organized and is more understandable. A TeX document of the equations has been written in parallel with the new software.

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Distribution

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Table I. GM values in DE410 which differ from the IAU "List of Best Estimates" (Standish, 1995).

$GM2$	324858.592	$[km^2/sec^2]$	Konopliv it et al., 1999
$GM3$	398600.4415	$[km^2/sec^2]$	Tapley*et al.*, 1996
$GM4$	42828.376212	$[km^2/sec^2]$	Yuan *et al.*, 2001
$GM5$	126712765.454372	$[km^2/sec^2]$	Jacobson, 2003
$GM6$	37940680.299546	$[km^2/sec^2]$	Jacobson, 2003
GMM	4902.800238	$[km^2/sec^2]$	Konopliv *et al.*, 2001
GMB	403503.241738	$[km^2/sec^2]$	(derived from $GM3$ and GMM)

Table II. Recent Observational Data : data fit by DE410 that were *not* fit by DE405. The columns contain the observations source, the time-span, the measured body, the observation type, the standard deviation of a single observation, and the number of data points.

CCD Astrometry					
USNO, Flagstaff	1995-2003	Jup, ..., Plu	r.a., dec.	$0\farcs13$	6130
Spacecraft Ranging					
Pathfinder	1997	Mars	range	5 m	89
MGS	1999-2003	Mars	range	1.3 m	89949
Odyssey	2002-2003	Mars	range	1.3 m	38524
Ma10	1974-1975	Mercury	range	100 m	2
NEAR*	2000-2001	Eros	range	250 m	3488
Spacecraft Doppler					
Viking	1976-1979	Mars	doppler	0.08 mm/sec	13049
Pathfinder	1997	Mars	doppler	0.10 mm/sec	7564
Spacecraft VLBI					
MGS	2001-2003	Mars	r.a./dec.	$0\farcs0005$	13
Odyssey	2002-2003	Mars	r.a./dec.	$0\farcs0005$	18
Spacecraft ODP Normal Points					
Cassini	1998-1999	Venus	r.a.,dec.	$0\farcs002$ –	4
Cassini	1998-1999	Venus	range	2 m	2
Pio, Voy, Uly, Cassini	1979-2000	Jupiter	r.a.,dec.	$0\farcs002$ –	12
Pio, Voy, Uly, Cassini	1979-2000	Jupiter	range	1 m –	6
Pio, Voy	1979-1981	Saturn	r.a.,dec.	$0\farcs02$ –	6
Pio, Voy	1979-1981	Saturn	range	1 km –	3
Mercury Radar Closure Points					
Goldstone	1987-1997	Mercury	range	1 km	23
Optical Meridian Transits					
Nikolaev, Ukraine	1960-1998	Jup, ..., Ura	r.a., dec.	$0\farcs5$ – $0\farcs15$	4768

* The NEAR ranges were used solely for the determination of the Earth-Moon mass ratio.

Table III. Some of the parameters from the solution leading to DE410.

Length of the AU : 149597870.	+ 0.6974 ± 0.0003	[*km*]	DE405 value : + 0.6910
Earth-Moon mass ratio	81.30056746... ± -		determined by GM3 and GMM
J_2 of the sun	2.9 ± 0.5	[$\times 10^{-7}$]	
Mass of an asteroid ring	0.22 ± 0.03	[$\mathcal{M}_{Ceres}$]	ring in ecliptic at 2.8 *au*
Mean Density of Asteroid Class C	1.55 ± 0.04		
Mean Density of Asteroid Class S	2.13 ± 0.08		
Mean Density of Asteroid Class M	4.5		not solved-for
Mass of 0001 Ceres	4.69 ± 0.01	[$10^{-10}\ \mathcal{M}_{\odot}$]	
Mass of 0002 Pallas	1.05 ± 0.01	[$10^{-10}\ \mathcal{M}_{\odot}$]	
Mass of 0004 Vesta	1.36 ± 0.01	[$10^{-10}\ \mathcal{M}_{\odot}$]	
Viking 1 range bias	–18.0 ± 0.6	[*m*]	
Viking 2 range bias	–12.7 ± 7.4	[*m*]	
Odyssey range bias	–2.1 ± 0.2	[*m*]	
Viking 1 corona correction	–0.52 ± 0.20	[× Ma9 value]	
MGS corona correction	+2.00 ± 0.05	[× Ma9 value]	
Odyssey corona correction	+1.90 ± 0.04	[× Ma9 value]	

Table IV. VLBI Residuals from MGS and Odyssey. The angle θ, measured west from north, gives the direction of the baseline of these one-dimensional angular determinations; the observations with $\theta \approx 0$ come from Goldstone–Madrid; those with $\theta \approx 45$ come from Goldstone–Canberra. ρ is the earth-Mars distance.

		θ	ν [0.″001]	σ [0.″001]	ν/σ	ρ [*au*]	ν [*km*]
Phobos	1989 FEB 17	8.25	-2.18	6.19	0.35	1.43	-2.258
Phobos	1989 MAR 25	42.27	-0.08	3.30	0.02	1.76	-0.103
MGS	2001 JAN 09	43.34	1.30	1.35	0.96	1.70	1.604
MGS	2001 JAN 13	4.02	-0.49	1.09	0.45	1.67	-0.593
MGS	2001 JAN 24	2.37	-0.44	1.30	0.34	1.56	-0.503
MGS	2001 JAN 27	46.90	0.93	0.92	1.01	1.53	1.029
MGS	2001 FEB 03	44.13	0.48	0.93	0.51	1.46	0.502
MGS	2001 AUG 24	46.29	-0.57	0.55	1.03	0.66	-0.272
MGS	2001 SEP 04	48.99	-0.17	0.66	0.26	0.72	-0.091
MGS	2001 SEP 24	45.69	-0.32	0.69	0.46	0.83	-0.192
MGS	2001 SEP 26	51.46	-0.05	0.74	0.07	0.85	-0.032
Odyssey	2002 APR 19	359.26	0.04	0.41	0.10	2.28	0.066
Odyssey	2002 APR 23	357.66	0.07	0.48	0.15	2.30	0.119
Odyssey	2002 MAY 30	48.33	0.09	0.32	0.27	2.49	0.159
Odyssey	2002 JUN 27	49.39	-0.16	0.50	0.33	2.60	-0.307
Odyssey	2002 JUL 22	14.53	0.15	0.70	0.21	2.65	0.283

Odyssey	2002 AUG 25	47.90	-0.34	0.61	0.56	2.67	-0.662
Odyssey	2002 SEP 07	44.03	0.39	0.65	0.60	2.65	0.745
Odyssey	2002 SEP 16	3.17	0.00	0.57	0.01	2.64	-0.008
Odyssey	2002 OCT 16	44.45	0.13	0.66	0.20	2.54	0.242
Odyssey	2002 OCT 30	44.03	1.56	1.40	1.11	2.47	2.790
MGS	2002 NOV 01	3.36	0.13	1.17	0.11	2.46	0.235
Odyssey	2002 NOV 16	2.69	-0.63	0.74	0.85	2.38	-1.087
Odyssey	2002 NOV 26	4.02	-0.51	0.59	0.87	2.32	-0.861
Odyssey	2002 DEC 10	4.40	0.00	0.68	0.00	2.22	-0.001
MGS	2002 DEC 11	42.37	-0.01	0.80	0.01	2.21	-0.010
Odyssey	2003 JAN 04	2.89	0.02	0.87	0.02	2.02	0.028
Odyssey	2003 JAN 19	3.41	1.06	1.07	0.99	1.89	1.451
Odyssey	2003 JAN 27	54.46	0.23	0.73	0.31	1.82	0.303
MGS	2003 JAN 27	53.05	0.11	0.70	0.15	1.82	0.139
MGS	2003 FEB 22	43.80	0.12	0.62	0.19	1.59	0.138
Odyssey	2003 FEB 22	42.98	-0.27	0.63	0.42	1.59	-0.307
Odyssey	2003 FEB 25	47.48	-0.03	0.55	0.05	1.56	-0.034

Table V. Residuals of the ODP Normal Points at Saturn. *A priori* uncertainties are listed.

			α [0.″001]	δ [0.″001]	$\rho[km]$
Pioneer 11	Saturn	1979 SEP 01	0.9 ± 360	11.5 ± 360	9.3 ± 1000.
Voyager 1	Saturn	1980 NOV 12	1.5 ± 011	14.1 ± 180	-0.009 ± 0.020
Voyager 2	Saturn	1981 AUG 26	1.7 ± 022	14.6 ± 216	-0.012 ± 0.060

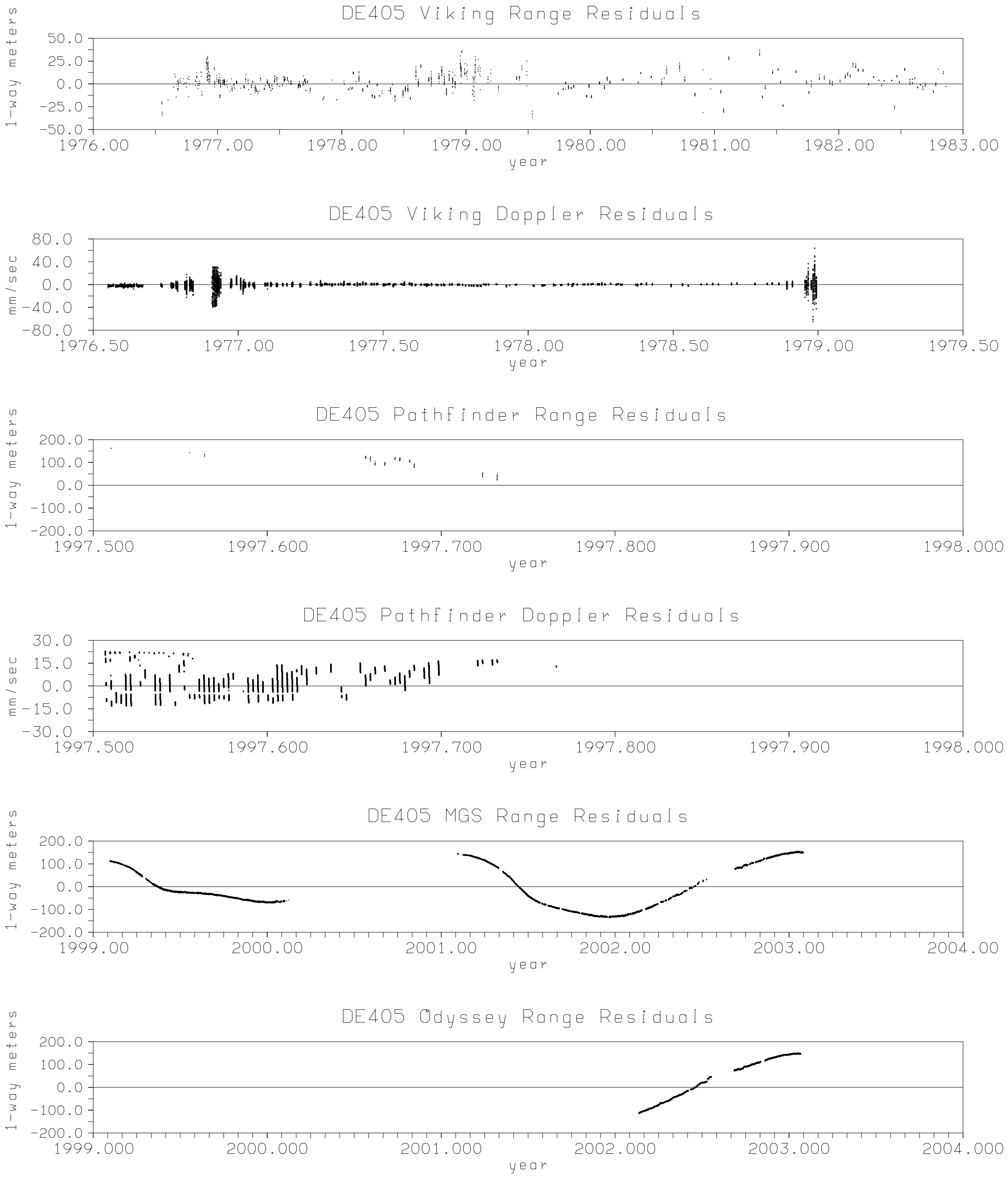
Table VI. CCD Observations of the Saturnian satellites, taken from the US Naval Observatory in Flagstaff.

w.r.t. DE405

#obs	interval	$\Delta\alpha$ ["]	σ ["]	$\Delta\delta$ ["]	σ ["]
450	1998.631-1999.043	-0.019	0.17	-0.018	0.23
446	1999.674-2000.051	+0.020	0.19	-0.083	0.20
391	2000.679-2001.102	+0.038	0.15	-0.030	0.15
494	2001.711-2002.124	+0.058	0.15	-0.059	0.16
316	2002.746-2003.150	+0.082	0.14	-0.060	0.13

w.r.t. DE410

#obs	interval	$\Delta\alpha$ ["]	σ ["]	$\Delta\delta$ ["]	σ ["]
450	1998.631-1999.043	-0.020	0.17	-0.009	0.23
446	1999.674-2000.051	+0.012	0.19	-0.074	0.20
391	2000.679-2001.102	+0.021	0.15	-0.021	0.15
494	2001.711-2002.124	+0.033	0.15	-0.050	0.16
316	2002.746-2003.150	+0.047	0.14	-0.050	0.13



DE405 Viking Range Residuals

DE405 Viking Doppler Residuals

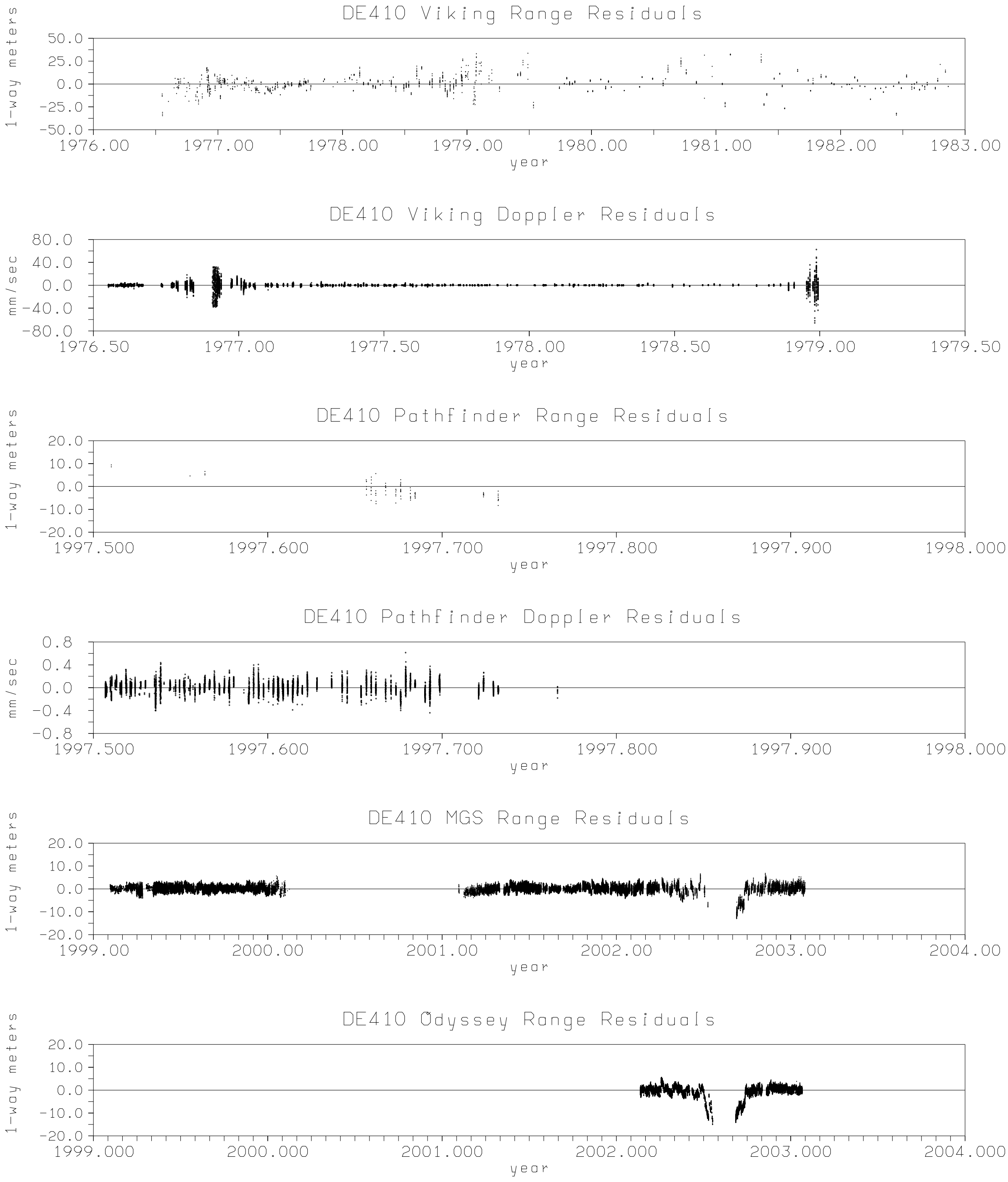
DE405 Pathfinder Range Residuals

DE405 Pathfinder Doppler Residuals

DE405 MGS Range Residuals

DE405 Odyssey Range Residuals

Figure 1: Mars spacecraft ranging and doppler residuals w.r.t. DE405. The recent data show the error in the earth-Mars range, extrapolated over the years, with only the 1993 Mars radar since the end of the Viking data in 1982.



DE410 Viking Range Residuals

DE410 Viking Doppler Residuals

DE410 Pathfinder Range Residuals

DE410 Pathfinder Doppler Residuals

DE410 MGS Range Residuals

DE410 Odyssey Range Residuals

Figure 2: Mars spacecraft ranging and doppler residuals w.r.t. DE410. The MGS and Odyssey ranges within 6 weeks of Mars' solar conjunction in mid-August, 2002 were not included in the fit.

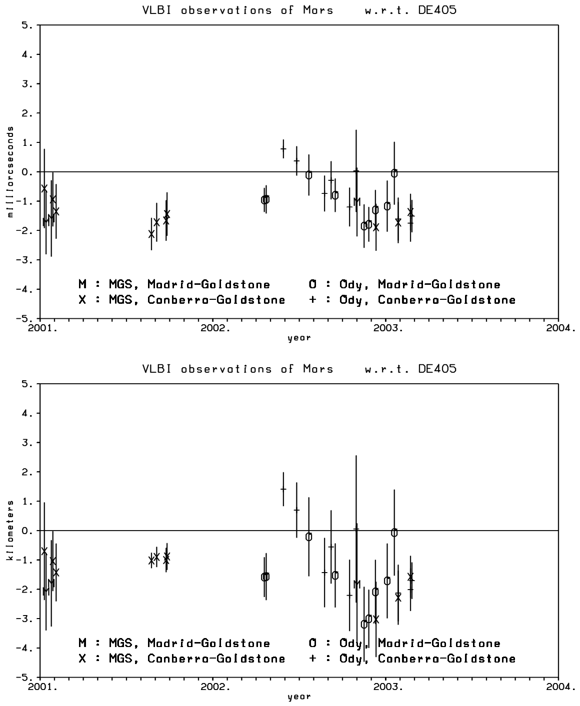


Figure 3: VLBI residuals for MGS and Odyssey w.r.t. DE405, shown in both milliarcseconds and in kilometers. The obvious signature reaches 2 milliarcseconds ($\sim 2\ km$ or so) in amplitude.

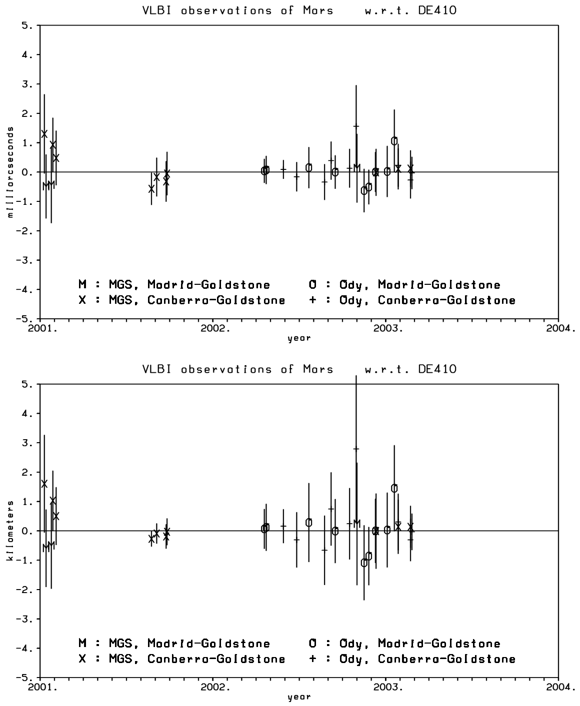


Figure 4: VLBI residuals for MGS and Odyssey w.r.t. DE410. These show that the orientation of Mars' orbit is now determined in DE410 to a level of only a few hundred meters over the present era.

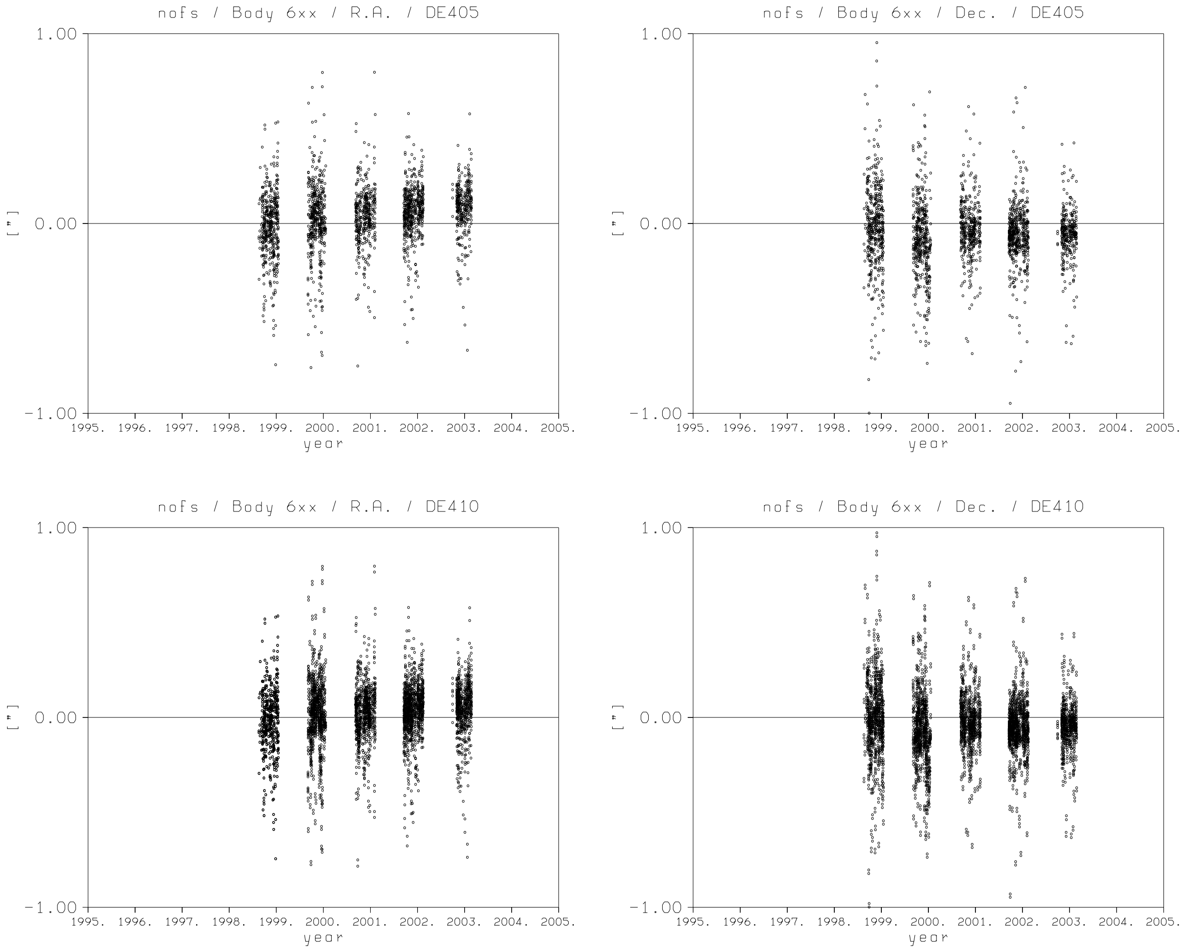


Figure 5: CCD residuals of seven of Saturn's satellites. Those w.r.t. DE405 have signatures in both right ascension (α) and declination (δ). In DE410 the α signatures w.r.t. DE410 are gone; the δ signatures are greatly diminished. The statistics are given in Table V.

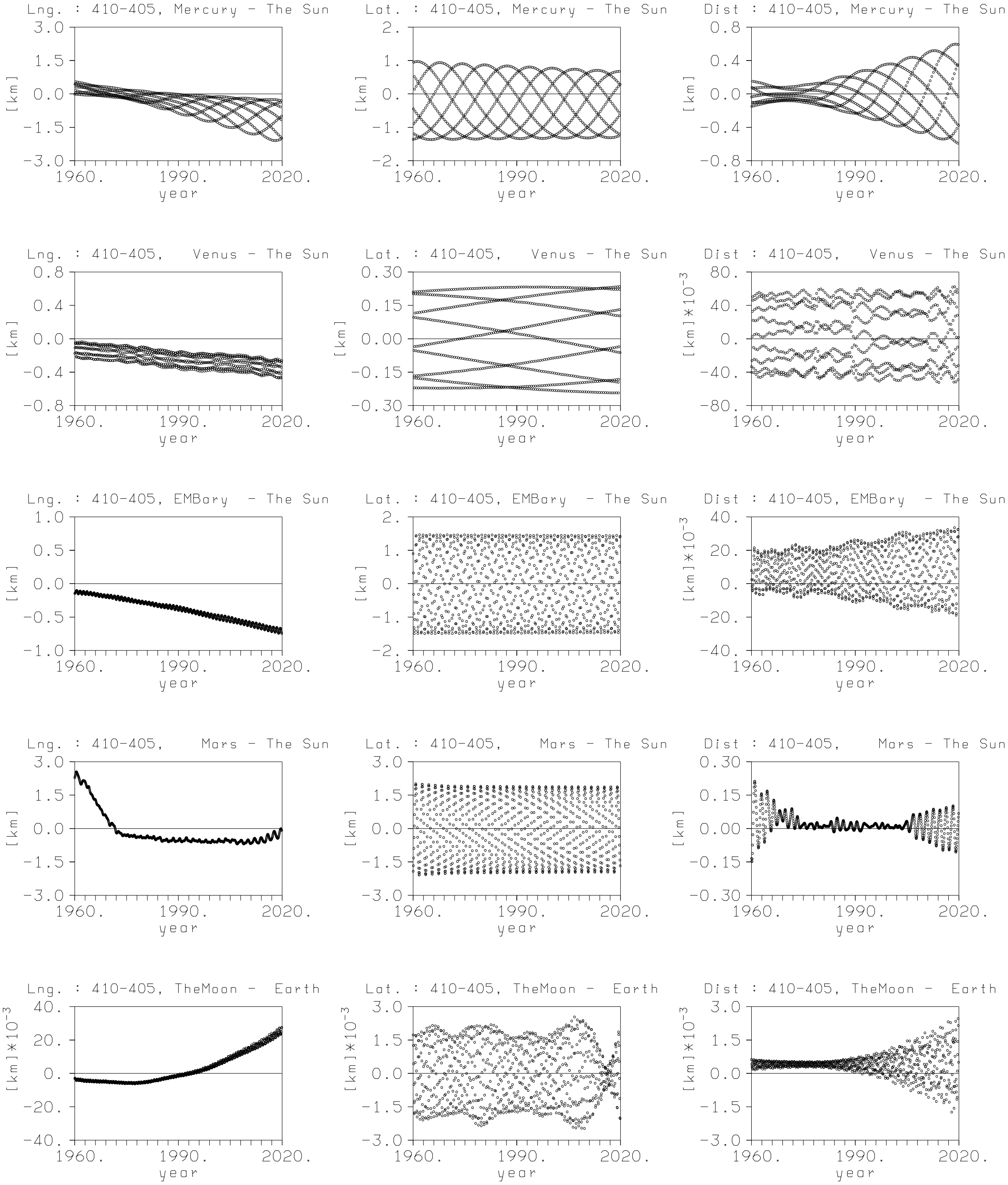


Figure 6: DE410-DE405: heliocentric, ecliptic differences for the inner solar system.

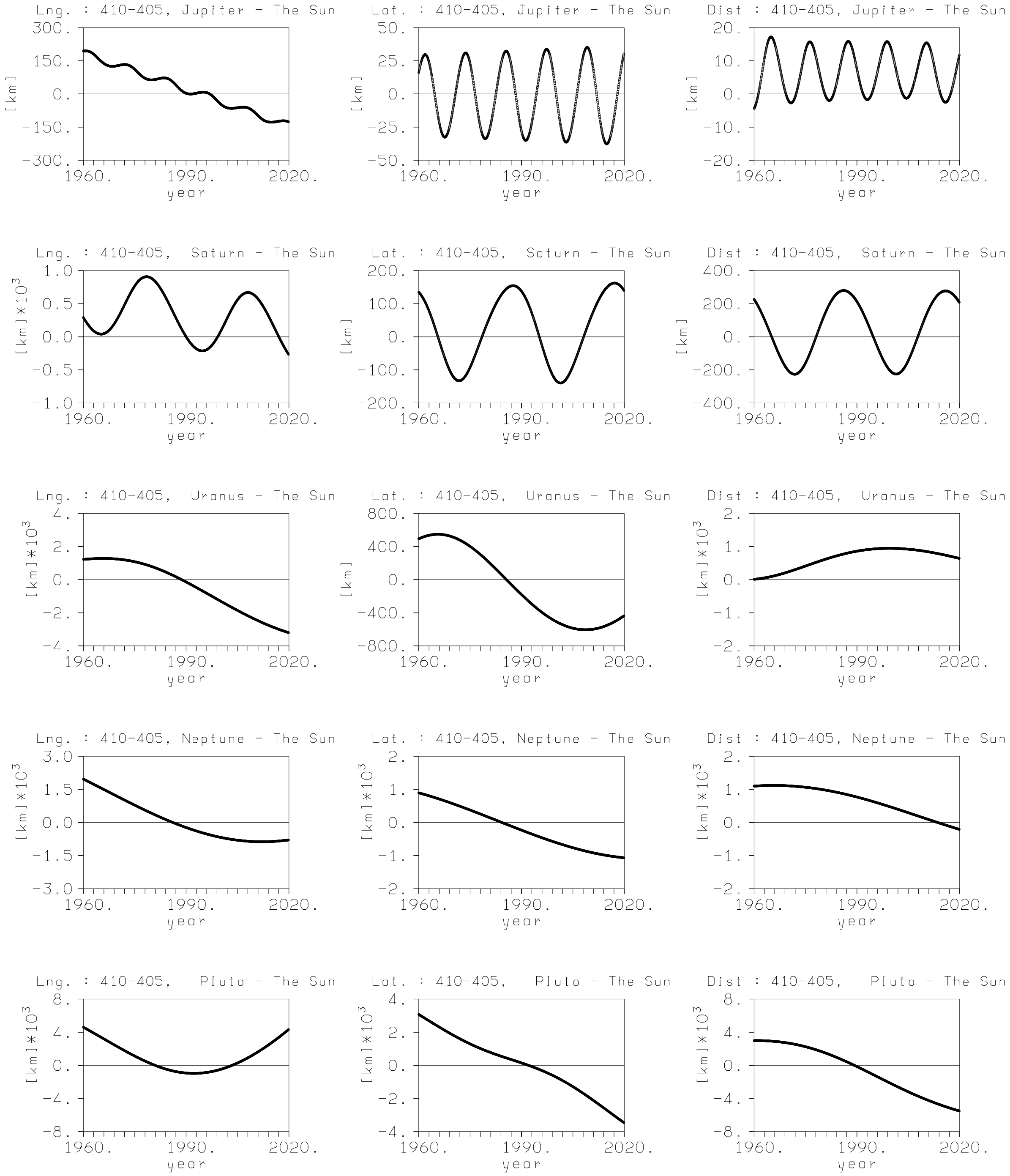


Figure 7: DE410-DE405: heliocentric, ecliptic differences for the outer solar system.

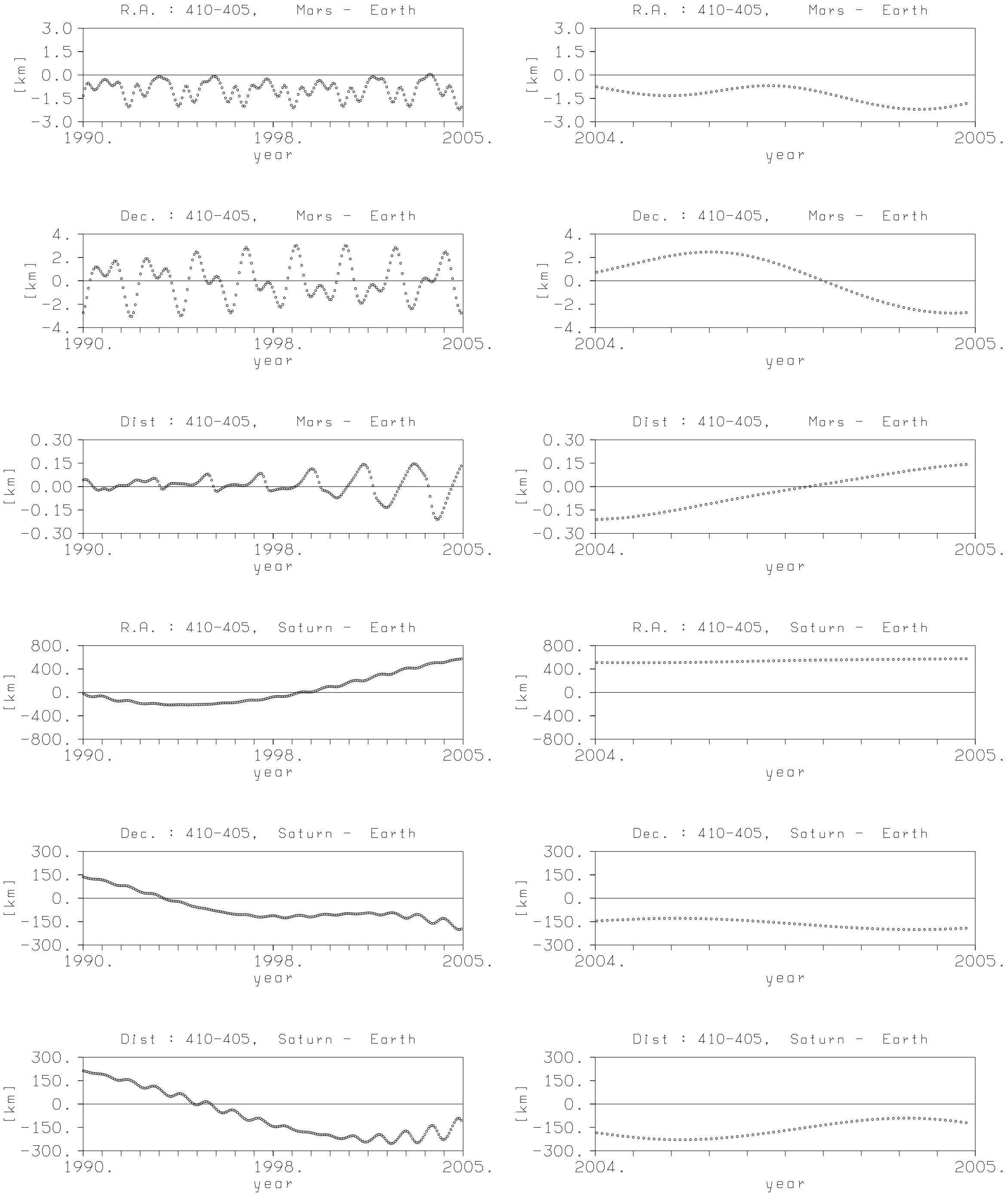


Figure 8: DE410-DE405 for geocentric, equatorial differences for Mars and Saturn.