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Precise determination of the motion of planets and some astronomical constants from modern observations

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Abstract. The accomplishments of space flights and introduction of new astrometric methods (radar ranging, lunar laser-ranging, VLBI measurements) in the 1960s required considerably more precise planetary ephemerides than it was possible with classical analytical theories by Leverrier, Hill, Newcomb and Clemence. On the other hand, these modern data made possible the creation of such ephemerides. Two series of numerical ephemerides of planets most complete up to now, and of the same level of accuracy, are considered in this paper. There are the well-known numerical DE ephemerides of JPL as well as the EPM (**E**phemerides of **P**lanets and the **M**oon) ephemerides produced at the Institute of Applied Astronomy. The description of the dynamical models, the brief characteristics of DE118, DE200, DE403, DE405, DE410, EPM87, EPM98, EPM2000, EPM2004 ephemerides, and the comparison between DE410 and EPM2004 are given. The latest DE410 and EPM2004 ephemerides have resulted from a least squares adjustment to observational data totaling about 300 000 position observations (1911–2003) of different types. The accurate radar observations of planets and spacecraft have made it possible not only to improve the orbital elements of planets but to determine a broad set of astronomical constants from the value of the astronomical unit (AU) to parameters of PPN formalism. Recent estimates of different astronomical constant are presented, and progress is shown in the improvement of the AU value, the parameters β, γ, as well as possible variability of the gravitational constant G.

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1. Dynamical models of planetary motion of DE and EPM ephemerides

Until the 1960s, classical analytical theories of planets (Leverrier, Hill, Newcomb, Clemence) were constantly being improved in order to meet practical needs. The accomplishment of space flights and introduction of new astrometric methods (radar ranging, lunar laser-ranging, VLBI measurements) required considerably more precise planetary ephemerides than those possible with classical theories. On the other hand, these modern data made possible the creation of such ephemerides.

Currently, the creation of these ephemerides is an easier process by using numerical integration of the equations of the motion of the planets and the Moon. At the same time, to ensure space flights the construction of numerical planetary ephemerides was undertaken by several groups in the USA and Russia. Two dynamical models of planet motion having the same level of accuracy, and being most complete up to now are considered in this paper. They are the well-known numerical DE ephemerides of JPL and the EPM (**E**phemerides of **P**lanets and the **M**oon) ephemerides produced at the Institute of Applied Astronomy.

As for analytical ephemerides of planets, the most precise analytical theories of planets and the Moon are the series of French ephemerides VSOP (Bretagnon & Francou 1988) and ELP (Chapront & Chapront-Touzé 1987), produced in BDL and IMCCE. Recently, significant progress has been achieved for the new analytical ephemeris VSOP2002b (Fienga & Simon 2004), where perturbations from the Moon, the 300 main belt asteroids, the solar oblateness and relativistic corrections have been accounted for. However, a comparison of this ephemeris with numerical ephemerides which began to be constructed in IMCCE shows differences between them up to 100 m over three decades. Furthermore, the values of the initial conditions of these ephemerides were obtained by fitting to DE200, DE403, DE405 rather than by fitting to the observation data.

Common to all DE and EPM ephemerides is a simultaneous numerical integration of the equations of motion of the nine major planets, the Sun, the Moon and the lunar physical libration performed in the Parameterized Post-Newtonian metric for the harmonic coordinates $\alpha = 0$ and General Relativity values $\beta = \gamma = 1$.

The various ephemerides differ slightly in

- the modeling of the lunar libration,
- the reference frames,
- the accepted value of the solar oblateness,
- the modeling of the perturbations of asteroids upon the planetary orbits,
- the sets of observations to which ephemerides are adjusted.

Some characteristics of DE118, DE200, DE403, DE405, DE410, EPM87, EPM98, EPM2000, EPM2004 ephemerides are given in Table 1.

Earlier ephemerides have been aligned onto the FK4 reference frame, then onto the dynamical equator and equinox and now ephemerides are oriented onto the **I**nternational **C**elestial **R**eference **F**rame (ICRF) by including in the adjustment the ICRF-based VLBI measurements of spacecraft near to planets.

The solar oblateness causes a secular trend in the planetary elements except for the semi-major axis and eccentricity (for example, see Brumberg 1972). Starting with DE405 (Standish 1998) a nonzero value of the solar oblateness $J_2 = 2 \cdot 10^{-7}$ obtained from some astrophysical estimates was accepted for integrating of DE and EPM ephemerides. Now the value of the solar oblateness is determined while processing the observations.

A serious problem in the construction of planetary ephemerides arises due to the necessity to take into account the perturbations caused by minor planets. In DE200 (Standish 1990) and our previous versions, the perturbations from only three or five biggest asteroids were accounted for. The experiment showed that the fitting of these ephemerides to the Viking lander data is poor. The perturbations from 300 asteroids were taken into account in the ephemerides starting with DE403 (Standish et al. 1995), and EPM98 (Pitjeva 2001) ephemerides. EPM2000 and EPM2004 have been produced by simultaneous numerical integrations of equations of motion of all planets and the 300 main belt asteroids, therefore the perturbations of these asteroids are accounted for all planets. However, masses of many of these asteroids are quite poorly known, and as shown by Standish & Fienga (2002), the accuracy of the planetary ephemerides deteriorates due to this factor. Masses of few most massive asteroids which more strongly affect Mars and the Earth can be estimated from observations of martian landers and spacecraft orbiting Mars. The five of 300 asteroids proved to be double and their masses are known now. The masses of Eros (433) and Mathilda (253) have been derived by perturbations of the spacecraft during the NEAR flyby. Unfortunately, the classical method of determining masses of asteroids for which close encounters occur is limited by uncertainty in masses of the large asteroids, perturbations by others, unmodeled asteroids, and the quality of observations. Perhaps masses of many asteroids will be obtained by high accuracy observations during

Table 1. Ephemerides DE and EPM

ephemeris	interval of integration	ref. frame	mathematical model		data	
				type	number	interval
DE118	1599→2169	FK4	Integrating of	optical	44755	1911-1979
(1981)			Sun,Moon,9 planets	radar	1307	1964-1977
⇓		⇓	+perturbations	spacecraft	1408	1971-1980
DE200		dynamic.	from 3 asteroids	LLR	2954	1970-1980
		frame	(Keplerian ellipses)	total	50424	1911-1980
EPM87	1700→2020	FK4	Integrating of	optical	48709	1717-1980
(1987)			Sun,Moon,9 planets	radar	5344	1961-1986
			+perturbations	spacecraft	–	–
			from 5 asteroids	LLR	1855	1972-1980
			(Keplerian ellipses)	total	55908	1717-1986
DE403	−1410→3000	ICRF	Integrating of	optical	26209	1911-1995
(1995)			Sun,Moon,9 planets	radar	1341	1964-1993
⇓	⇓		+perturbations	spacecraft	1935	1971-1994
DE404	−3000→3000		from 300 asteroids	LLR	9555	1970-1995
			(mean elements)	total	39057	1911-1995
EPM98	1886→2006	DE403	Integrating of	optical	–	–
(1998)			Sun,Moon,9 planets	radar	55959	1961-1995
			5 aster.+ perturb.	spacecraft	1927	1971-1982
			from 295 asteroids	LLR	10000	1970-1995
			(mean elements)	total	67886	1961-1995
DE405	1600→2200	ICRF	Integrating of	optical	28261	1911-1996
(1997)			Sun,Moon,9 planets	radar	955	1964-1993
⇓			+perturbations	spacecraft	1956	1971-1995
DE406	−3000→3000		from 300 asteroids	LLR	11218	1969-1996
			(integrated)	total	42410	1911-1996
EPM2000	1886→2011	DE405	Integrating of	optical	–	–
(2000)			Sun,Moon,	radar	58076	1961-1997
			9 planets,	spacecraft	24587	1971-1997
			300 asteroids	LLR	13500	1970-1999
				total	96163	1961-1999
DE410	1901→2019	ICRF	Integrating of	optical	39159	1911-2003
(2003)			Sun,Moon,9 planets	radar	978	1964-1997
			+perturbations	spacecraft	154685	1971-2003
			300 ast.integrated	LLR	9555	1970-1995
				total	204377	1911-2003
EPM2004	1886→2011	ICRF	Integrating of	optical	46064	1913-2003
(2004)			Sun,Moon,	radar	58116	1961-1997
			9 planets,	spacecraft	197271	1971-2003
			301 asteroids,	LLR	15590	1970-2003
			asteroid ring	total	317041	1913-2003

the Gaia mission, but it will not be soon. So at present masses of the rest of the 301 asteroids have been estimated by the astrophysical method. The latest published diameters of asteroids based on infrared data of IRAS (**I**nfra **R**ed **A**stronomical **S**atellite) and MSX (**M**idcourse **S**pace **E**xperiment), as well as observations of occultations of stars by minor planets and radar observations have been used in this paper. The mean densities for C,S,M taxonomy classes have been estimated while processing the observations.

At the several meters level of accuracy the orbit of Mars is very sensitive to perturbations from many minor planets. These objects are mostly too small to be observed from the Earth, but their total mass is large enough to affect the orbits of the major planets. The main part of these celestial bodies moves in the asteroid belt and their instantaneous positions may be considered homogeneously distributed along the belt. Thus, it seems reasonable to model the perturbations from the remaining small asteroids (for which individual perturbations are not accounted for) by computing additional perturbations from a massive ring with the constant mass distribution in the ecliptic plane (Krasinsky et al. 2002). Two parameters that characterize the ring (its mass and radius) are included in the set of solution parameters for EPM2004.

The quality of ephemerides, i.e. their accuracy, mostly depends upon improvement of quality and increase of amount of observational data. The section below maintains the description of the database of modern ephemerides. However, we should stress here the uniqueness of the EPM87 ephemeris (Krasinsky et al. 1993), whose parameters were fit to a large variety of observational data for the time span of XVIII–XX centuries, including observations of 32 transits of Mercury (1723–1973) and 4 transits of Venus (1761–1881) across the solar disc, used in order to correct the adopted Brouver system of differences between ET and UT back into the past till 1715, to estimate variations of the solar radius, the Mercury perihelion and node advance.

Along with the planetary ephemerides the ephemerides of the orbital and rotational motions of the Moon were being produced and improved on by processing LLR observations at JPL and IAA RAS. The last versions of the lunar theory of the JPL are given in Williams & Dickey (2002) and of the IAA — in Krasinsky 2002 where a number of subtle selenodynamical effects is described.

The lunar-planetary integrator for EPM is embedded into the program package (Krasinsky & Vasilyev 1997) ERA-7 (**ERA**: **E**phemeris **R**esearch in **A**stronomy) developed to support scientific research in dynamical and ephemeris astronomy. Integrating and other computations have been done by using this package.

2. Processing radar and optical data

Since the creation of DE405 in 1997, the quality and quantity of observational data have vastly improved. New high accuracy observations have evolved: ranging and Doppler measurements from the martian lander Pathfinder, range and VLBI points from MGS and Odyssey, CCD astrometric data of the outer planets and their satellites. So, the latest DE410 and EPM2004 ephemerides have resulted from a least squares adjustment to the observational data totaling about 300 000 position observations (1911–2003) of different types. Data used for the production of the EPM2004 ephemeris were taken from databases of the JPL website (http:/ssd.jpl.nasa.gov/iau-comm4/) created and kept by Dr. Standish, the database of optical observations of Dr. Sveshnikov and extended to include Russian radar observations of planets (on the website of IAA http: //www.ipa.nw.ru/PAGE/DEPFUND/LEA/ENG/englea.htm). All the observations used are described in Tables 2 and 3.

The reduction of the radar measurements maintains all the relevant corrections, including the modeling of Mercury, Venus and Mars topography. However, uncertainties due to planetary topography do remain in radar ranging despite the modeling of topography. So, observations of the martian Viking, Pathfinder landers, MGS and Odyssey data which are free from these uncertainties are of great importance.

Unfortunately, observations of MGS and Odyssey as distinct from two frequencies measurements of Viking were carried out at one frequency and the effect of the solar corona delay was considerable, particularly near superior solar conjunctions in 1998 and

Table 2. Radiometric observations used in the ephemeris solutions.

station, object	type	time interval	number of obs.	normal points	a priori accuracy
MERCURY					
Millstone	τ	1964	5	—	7.5–75 km
Haystack	τ	1966–1971	217	—	3 km
Arecibo	τ	1964–1982	341	323	3–30 km
Goldstone	τ	1971–1997	259	138	1.5–3 km
Goldstone cl.p.	τ	1990–1997	40	—	0.15–2.5 km
Crimea	τ	1980–1995	75	23	1.2–4.8 km
Mariner-10	τ	1974–1975	—	2	0.1 km
VENUS					
Millstone	τ	1961–1967	135	—	1.5–120 km
Haystack	τ	1966–1971	219	—	1.5 km
Arecibo	τ	1964–1970	319	—	3–15 km
Goldstone	τ	1964–1990	512	—	1.5–6 km
Crimea	τ	1962–1995	1139	170	0.15–22.5 km
Magellan	$\alpha\delta$	1990–1994	—	18	$0.''001$–$0.''004$
MARS					
Haystack	τ	1967–1973	3801	133	0.075–12 km
Arecibo	τ	1965–1973	1680	43	0.075–45 km
Goldstone	τ	1969–1994	48989	149	0.075–0.6 km
Crimea	τ	1971–1995	381	78	0.15–4.8 km
Mariner-9	τ	1971–1972	643	—	15–270 m
Viking-1	τ	1976–1982	1161	—	7–12 m
Viking-1	$d\tau$	1976–1978	14980	—	0.16–3.2 m
Viking-2	τ	1976–1977	80	—	7–10 m
Pathfinder	τ	1997	90	—	10–22 m
Pathfinder	$d\tau$	1997	7576	—	0.012 m
Phobos	τ	1989	—	1	0.2 km
MGS	τ	1998–2003	110538	4930	2–7.5 m
Odyssey	τ	2002–2003	62093	1715	2-3 m
spacecraft	$\alpha\delta$	1984–2003	—	44	$0.''0003$–$0.''006$
JUPITER					
spacecraft, VLA	α	1979–1995	—	4	$0.''003$–$0.''046$
spacecraft, VLA	δ	1979–1995	—	4	$0.''005$–$0.''2$
spacecraft	τ	1973–1995	—	6	1–6 km
spacecraft	$\alpha\delta$	1996–1997	—	24	$0.''007$–$0.''012$
Arecibo s 3,4	τ	1992	—	4	3–14 km

2002. The following model was used for the solar corona reduction:

$$N_e(r) = \frac{A}{r^6} + \frac{B + \dot{B}t}{r^2}$$

where $N_e(r)$ is the electron density.

The parameters B and $\dot{B}$ determined from observations were different for different solar conjunctions. Although residuals decreased considerably, remaining influence of the corona has been seen in them (see rms of MGS and Odyssey in Fig. 3). Moreover, the parameters of the corona are correlated with other estimated parameters of the Mars orbit and deteriorate their determination. This fact should be taking into account for highly precise astrometrical measurements of future space missions.

The residuals of all radiometric data are shown in Figs 1–3. The rms residuals of ranging for the Mercury are 1.4 km, for Venus and Mars are 0.7 km, for Viking are 8 m, for Pathfinder 4.4 m, for MGS and Odyssey 1.4 m. The estimations of biases due to uncertainties of the calibration for Viking ranges (about 20 m) and for Odyssey ranges (about 2 m) have been obtained from the observations the way it has been done for the DE410 ephemeris.

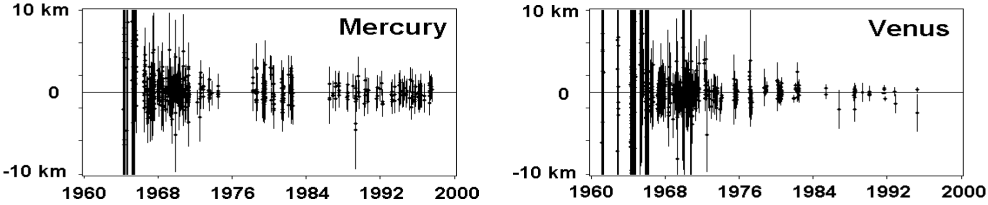

Figure 1. Ranging residuals for Mercury and Venus.

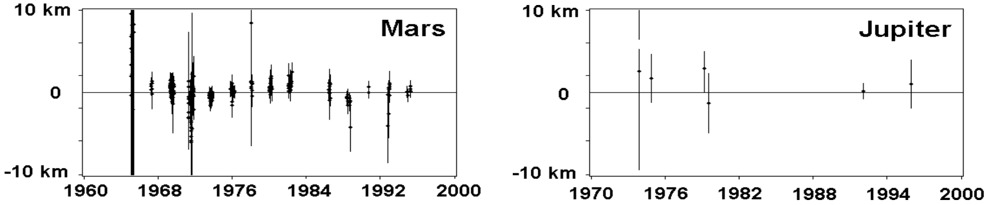

Figure 2. Ranging residuals for Mars and Jupiter.

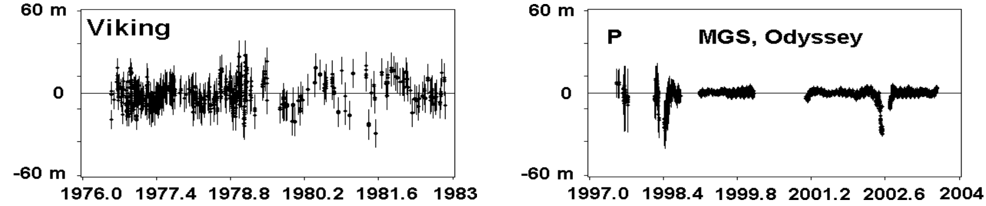

Figure 3. Ranging residuals of Viking, Pathfinder-P (1997), MGS (1998–2003), Odyssey (2002–2003).

The observations of satellites of Jupiter and Saturn are of great importance for optics, as they are more accurate than the observations of their parent planets and practically free from the phase effect. CCD data, obtained at Flagstaff observatory, whose observational program started in 1995 and is still being continued are the most accurate. Another group of high accuracy data is photographic observations of satellites of Jupiter, Saturn, as well as Uranus and Neptune planets obtained at Nikolaev observatory during 1962–1998. Combination of the data from Flagstaff and Nikolaev has been successfully used to improve the planet ephemerides. Residuals of all the observations of the outer planets are shown in Fig. 4. Unfortunately, observations of Pluto are mainly photographic and of quite poor accuracy, so their rms residuals are worse.

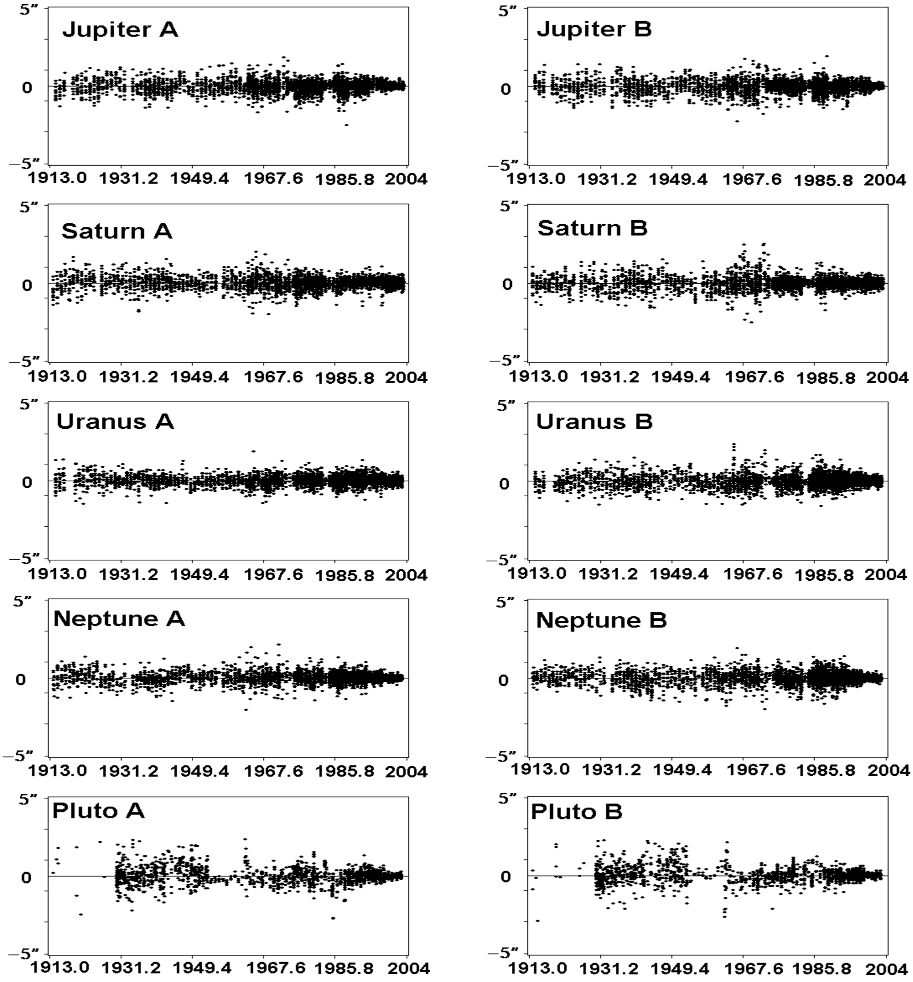

Figure 4. Residuals of the outer planets 1913–2003 in $\alpha \cos \delta$ (A) and in δ (B), the scale ±5″.

Ephemerides EPM were oriented onto the **I**nternational **C**elestial **R**eference **F**rame (ICRF). The most precise optical data of the outer planets and their satellites, obtained at Flagstaff, Nikolaev, La Palma have already been referenced to the ICRF. The remaining optical observations, referenced to different catalogues, at first were transformed to the FK4 systems by Sveshnikov. Then they were referenced to the FK5 using known formulae (see as the example Standish et al. 1995), and were finally transformed to the ICRF using the values of the three angles of the rotation between the HIPPARCOS and FK5 catalogues, J2000 in mas (Mignard 2000):

$$\varepsilon_x = -19.9, \ \varepsilon_y = -9.1, \ \varepsilon_z = 22.9.$$

Orbits of the four inner planets (with the exception of angles of the orientation) are determined entirely by the ranging observations of planets and spacecraft. The orientation of this system is provided by the using the ICRF-base VLBI measurements of spacecraft. The orientation has been improved considerably due to an addition to previous Magellan and Phobos data of new VLBI points of MGS and Odyssey. The angles of the rotation

Table 3. Optical and radio observations used in the ephemeris solutions of the outer planets.

station, object	planet satellite	type	time interval	number of obs.	a priori accuracy
		JUPITER			
USNO	p	transit	1913–1994	4388	0.″5
Tokyo	p	ph-e transit	1963–1988	568	0.″5–0.″8
La Palma	s 3,4	ph-e transit	1986–1997	1316	0.″25
Nikolaev	s 1,2,3,4	photo	1962–1998	2628	0.″2
Flagstaff	s 1,2,3,4	CCD	1998–2003	2408	0.″2
Mountain	s 1,2,3,4	CCD	2002–2002	16	0.″5
		SATURN			
USNO	p	transit	1913–1982	3054	0.″5
Tokyo	p	ph-e transit	1963–1988	506	0.″5–0.″8
Bordeaux	s 6,8	ph-e transit	1987–1993	238	0.″25
La Palma	s 5,6,7,8	ph-e transit	1987–1997	1460	0.″25
Nikolaev	s 3,4,5,6,8	photo	1973–1997	1264	0.″2
Flagstaff	s 3,4,5,6,7,8	CCD	1998–2003	4014	0.″2
Mountain	s 3,4,5,6,7,8	CCD	2002–2003	628	0.″15
VLA	p	radio	1984	8	0.″03–0.″06
		URANUS			
USNO	p	transit	1913–1993	4244	0.″5
Tokyo	p	ph-e transit	1963–1988	366	0.″5–0.″8
Bordeaux	p	ph-e transit	1985–1992	330	0.″25
Bordeaux	p	CCD	1997	34	0.″2
La Palma	p, s 4	ph-e transit	1984–1997	2072	0.″25
Nikolaev	p	photo	1961–1998	440	0.″2
Flagstaff	p, s 3,4	CCD	1995–2003	2324	0.″2
Mountain	p, s 3,4	CCD	1998–2003	174	0.″15
VLA,ring occ.	p	radio	1977–1985	16	0.″03–0.″2
		NEPTUNE			
USNO	p	transit	1913–1993	3804	0.″5
Tokyo	p	ph-e transit	1963–1988	320	0.″5–0.″8
Bordeaux	p	ph-e transit	1985–1993	366	0.″25
Bordeaux	p	CCD	1997	28	0.″2
La Palma	p	ph-e transit	1984–1998	2212	0.″25
Nikolaev	p	photo	1961–1998	436	0.″2
Flagstaff	p, s 1	CCD	1995–2003	1888	0.″2
Mountain	p, s 1	CCD	1998–2003	120	0.″15
VLA,ring occ.	p	radio	1981–1997	22	0.″03–0.″2

between EPM2004 and the ICRF have been obtained (in mas):

$$\varepsilon_x = 1.9 \pm 0.1, \varepsilon_y = -0.5 \pm 0.2, \varepsilon_z = -1.5 \pm 0.1,$$

which are close to the rotation angles between DE405 and DE410.

Table 3. Optical and radio observations used in the ephemeris solutions of the outer planets. (continued)

PLUTO

station, object	planet satellite	type	time interval	number of obs.	a priori accuracy
Different stat.	p	photo	1914–1967	1164	$0\farcs5$–$1''$
Different stat.	p	photo	1969–1988	674	$0\farcs5$–$1''$
Different stat.	p	photo	1989–1995	82	$0\farcs5$–$1''$
Pulkovo	p	photo	1930–1993	416	$0\farcs5$
Tokyo	p	photo	1994	24	$0\farcs3$
Bordeaux	p	ph-e transit	1996	12	$0\farcs3$
Bordeaux	p	CCD	1995–1997	64	$0\farcs2$
La Palma	p	ph-e transit	1986-1998	760	$0\farcs25$
Flagstaff	p	CCD	1995–2003	1152	$0\farcs2$
Mountain	p	CCD	2000–2003	68	$0\farcs15$

Table 4. The formal standard deviations of elements of the planets

planet	a [m]	$\sin i \cos\Omega$ [mas]	$\sin i \sin\Omega$ [mas]	$e\cos\pi$ [mas]	$e\sin\pi$ [mas]	λ [mas]
Mercury	0.105	1.654	1.525	0.123	0.099	0.375
Venus	0.329	0.567	0.567	0.041	0.043	0.187
Earth	0.146	—	—	0.001	0.001	—
Mars	0.657	0.003	0.004	0.001	0.001	0.003
Jupiter	639	2.410	2.207	1.280	1.170	1.109
Saturn	4222	3.237	4.085	3.858	2.975	3.474
Uranus	38484	4.072	6.143	4.896	3.361	8.818
Neptune	478532	4.214	8.600	14.066	18.687	35.163
Pluto	3463309	6.899	14.940	82.888	36.700	79.089

Table 5. The parameters of the Mars rotation.

$\dot{V}$ [^{o}/day]	I_q [^{o}]	$\dot{I}_q$ [$''$/year]	Ω_q [^{o}]	$\dot{\Omega}_q$ [$''$/year]
350.891985294 ± 0.000000012	25.1893930 ±0.0000053	-0.0002 ±0.0007	35.437685 ± 0.000021	-7.5844 ± 0.0015

3. Results obtained

The formal standard deviations of the orbital elements of planets are shown in the Table 4, where a – the semi-major axis, i – the inclination of the orbit, Ω – the ascending node, e – the eccentricity, π – the longitude of perihelion, λ – the mean longitude. Note that the uncertainties, given in this paper, are formal standard deviations; realistic error bounds may be an order of magnitude larger.

Accurate radar observations of planets and spacecraft have made it possible not only to improve the orbital elements of planets but to determine a broad set of astronomical constants as well: AU, parameters of Mars' rotation including its precessional rate, the masses of Ceres, Pallas, Vesta, Iris, Bamberga, Juno; the estimation of the total mass of the main asteroid belt, parameters of the PPN formalism (β, γ), the variability of the gravitational constant G, the solar quadrupole moment. Values for them are in Tables 5, 6 and 7.

Table 6. Masses of Ceres, Pallas, Juno, Vesta, Iris, Bamberga in $(\mathrm{GM}_i/\mathrm{GM}_\odot)\cdot 10^{-10}$.

(1)Ceres	(2)Pallas	(3)Juno	(4)Vesta	(7)Iris	(324)Bamberga
4.753 ±0.007	1.027 ±0.003	0.151 ±0.003	1.344 ±0.001	0.063 ±0.001	0.055 ±0.001

Table 7. The solar quadrupole moment, the radius and the mass of the asteroid ring, the total mass of the main asteroid belt.

J_2 10^{-7}	R_{ring} AU	M_{ring} $10^{-10}M_\odot$	M_{belt} $10^{-10}M_\odot$
1.9±0.3	3.13±0.05	3.35±0.35	15.0±2.0

Table 8. Progress in the determination of the parameters of PPN formalism and $\dot{G}/G$.

year	β	γ	$\dot{G}/G(10^{-11}\mathrm{yr}^{-1})$
1985	0.76±0.12	0.87±0.06	4.1 ±0.8
1994	1.014±0.070	1.006±0.037	0.28 ±0.32
2004	1.0000±0.0001	0.9999±0.0001	0.001 ±0.005

The value of the precession constant for Mars is close to the recent value obtained from Viking, Pathfinder landers and MGS radio tracking data (Yoder et al. 2003):

$$\dot{\Omega}_q = [-7.''597 \pm 0.''025(10\sigma)]/\mathrm{year}.$$

Lately some papers have appeared where impossibility of a separate determination of PPN parameters and the solar oblateness from ranging observations is stated. However, the PPN parameters (β, γ) and the solar oblateness cause secular and periodic effects among different planets and other orbital elements, therefore the estimations of the this parameters and possible variability of the gravitational constant have been simultaneously obtained.

Three main factors influence the progress in the improvement of parameters — reductions of the observational data, dynamical models of planet motion, and the observational data themselves. As an example, the progress in the determination of the AU (in km) in Russia from ranging (Table 9), as well as in the estimation of parameters of PPN formalism and the time variation of the gravitation constant (Table 8) is given.

The last AU value of Table 9 differs from the value of the DE410 (Standish 2003) 149 597 870.6974 ± 0.0003 by 1.4 m, which is the real error of the determination of the AU.

4. Comparison DE410 and EPM2004

The differences between various ephemerides are useful to know since they are indicative of the realistic accuracies of the ephemerides. Comparison between the latest versions of DE410 and EPM2004 over the time interval 1970–2010 has been made. These ephemerides are based on the similar data and the mathematical models, but distinguish by different way of taking into account asteroids, by their masses as well as corrections for the topography of planet surfaces and the solar corona.

Coordinates of Mercury and Venus have been obtained from fitting radar observations of these planets, having the uncertainties mainly about km, so the maximum differences of geliocentric distances up to 258 m for Mercury and up to 139 m for Venus (Fig. 5) can be considered acceptable.

Table 9. Progress in the determination of the AU (in km) in Russia from ranging.

149599300	±600	Kotelnikov et al. 1962
149597867.3	±0.3	Akim et al. 1986
149597870.62	±0.18	Krasinsky et al. 1993
149597870.6960	±0.0001	Pitjeva, 2004

The maximum differences of geliocentric distances for the Earth and the Mars are considerably less: up to 12.8 m for the Earth and up to 35.7 m for Mars, which is not surprising as data of MGS and Odyssey used have the uncertainties at the two-meter level. The differences may be explained by different account of asteroids and solar corona.

The availability of a number of spacecraft Jupiter data (besides optical observations) allow its ephemerides to be known better than those of other outer planets. The distance differences for Jupiter are less than 10 km. For the other four outer planets the only observations are optical. Moreover, for Neptune and Pluto a single orbital period has not yet elapsed since the time when more or less accurate observations of these planets appeared. The distance differences amount for Saturn to 180 km, for Uranus to 410 km, for Neptune to 1200 km, for Pluto to 14000 km. Those are the current accuracies of the modern ephemerides.

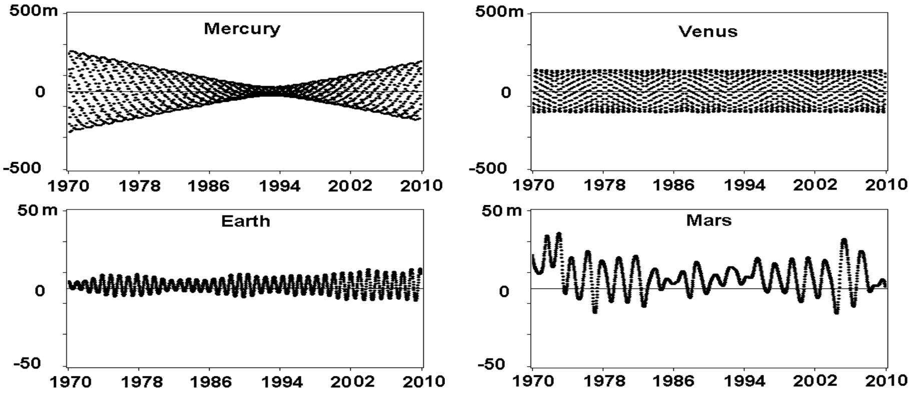

Figure 5. DE410-EPM2004: heliocentric distance differences for the inner planets, 1970–2010.

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Discussion

NICOLE CAPITAINE: Can you say for which kind of parameters the observations of transits of planets are useful?

ELENA PITJEVA: This observation may be used for the estimation of the variation of the solar radius. There are some examples where the variation of the solar radius has been estimated from transits.

JESUS DE ALBA: Do you use your model to calculate the ephemeredes of potentially dangerous near-Earth objects?

MYLES STANDISH: I will comment on that question: It would not be practical to use her model for that computation because the equations of motion are extremely complicated; it would terribly long to integrate. What you do is use her ephemeris after it is computed as perturbations on a different integration.