EPM— Ephemerides of Planets and the Moon of IAA RAS: their model, accuracy, availability

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- Renewal of EPM ephemerides: constants, model, data
- Observations, their reduction, TT-TDB
- The orientation of EPM2010
- The values of solution parameters
- Availability of EPM

The **EPM** ephemerides (**E**phemerides of **P**lanets and the **M**oon) of IAA RAS originated in the seventies of the last century to support space flights and have been developed since that time.
All the **modern ephemerides** (DE – JPL, EPM – IAA RAS, INPOP – IMCCE) are based upon **relativistic equations of motion for astronomical bodies and light rays as well as relativistic time scales**.
The numerical integration of the equations of celestial bodies motion has been performed in the Parameterized Post-Newtonian metric for General Relativity in the TDB time scale.

EPM ephemerides are computed by numerical integration of the equations of motion of celestial bodies in the barycentric coordinate frame of J2000.0 **by the Everhart method** over the 400 years interval (**1800 2200**) using the program package ERA (Ephemeris Research in Astronomy) (Krasinsky and Vasilyev, 1997).

The renovation of the planet part of the EPM ephemerides includes the constants, model, observation data.

Recent years of high-precision data of spacecraft have yielded significant improvements of a whole set of constants for planet ephemerides.
Masses of planets were determined from data of spacecraft orbiting and passing near planets or from observation of satellites of these planets.

New values of masses of planets adopted by the 27 GA IAU and used in EPM ephemerides

Planet	Previous value	New value	Year	Authors
M_M/M_E	$1.23000345(5)\cdot10^{-2}$	$1.23000371(4)\cdot10^{-2}$	2009	Pitjeva,Standish
$M_\odot/M_V$	$4.0852371(6)\cdot10^{5}$	$4.08523719(8)\cdot10^{5}$	1999	Konopliv et al.
$M_\odot/M_{Ma}$	$3.098708(9)\cdot10^{6}$	$3.09870359(2)\cdot10^{6}$	2006	Konopliv et al.
$M_\odot/M_J$	$1.0473486(8)\cdot10^{6}$	$1.047348625(17)\cdot10^{3}$	2003	Jacobson
$M_\odot/M_{Sa}$	3.497898(18)	$3.4979018(1)\cdot10^{3}$	2006	Jacobson et al.
$M_\odot/M_P$	1.3521(15)	$1.36564(28)\cdot10^{8}$	2008	Tholen et al.
$M_\odot/M_{Eris}$		$1.191(14)\cdot10^{8}$	2007	Brown et al.
$M_{Ceres}/M_\odot$	4.39(4)	$4.72(3)\cdot10^{-10}$	2009	Pitjeva, Standish
$M_{Pallas}/M_\odot$	1.59(5)	$1.03(3)\cdot10^{-10}$	2009	Pitjeva, Standish
$M_{Vesta}/M_\odot$	1.69(11)	$1.35(3\cdot10^{-10}$	2009	Pitjeva, Standish

The updated model of EPM2008 includes Eris and the other 20 largest trans-Neptunian objects into the process of the simultaneous numerical integration in addition to the major planets, the Moon, the Sun, the 301 biggest asteroids and accounts for the perturbations due to the solar oblateness and the massive ring of small asteroids.

Some tests have been made for estimating the effect of other TNO on the motion of planets, which have been modeled by the perturbation from a circular ring having a radius of 43 AU and different masses.

The minimum mass (EPM_{1-TNO}): 100000 objects, D=100 km, ρ=2 g/cm^3, $Mmin$ = 110 M_{Ceres}, $Mmax$ (EPM_{5-TNO}) = 100 $Mmin$. For EPM_{2-TNO}, EPM_{3-TNO}, EPM_{5-TNO} the mass of the TNO ring are 25%, 50%, and 75% from the maximum mass.

The rms residuals in m and the weight unit errors σ_0 for EPM ephemerides with differen masses of the TNO ring

Observations Interval Numbers n.p.	Martian landers 1976-1997 1348	Martian spacecraft 1998-2008 13903	Venus Express 2006-2007 547	Spacecraft at Jupiter 1973-2001 7	Spacecraft at Saturn 1979-2006 34	σ_0 1913-2008 97101
EPM2008	11.82	2.04	2.59	13.09	3.04	0.876
EPM_{1-TNO}	12.00	1.87	2.59	13.08	3.02	0.876
EPM_{2-TNO}	13.16	1.90	2.63	13.20	64.35	1.000
EPM_{3-TNO}	13.35	2.00	2.68	13.29	129.7	1.305
EPM_{4-TNO}	13.83	2.05	2.74	17.64	195.0	1.696
EPM_{5-TNO}	14.26	2.06	2.80	27.43	200.3	2.126

The dynamical model of EPM2010 ephemerides takes into account the following:

- mutual perturbations from major planets, the Sun, the Moon and 5 more massive asteroids;
- perturbations from the other 296 asteroids chosen due to their strong perturbations on Mars and the Earth;
- perturbation from the massive asteroid ring with constant mass distribution ;
- perturbations from the 21 largest TNO;
- perturbation from a massive ring of TNO in the ecliptic plane with the radius of 43 AU;
- perturbations due to the solar oblateness $J_2 = 2 \cdot 10^{-7}$.

More 550000 data were used for construction of EPM2008.

Observations used for constructing EPM2008

Optical data of outer planets and satellites 1913–2008, 49890

USNO
Pulkovo
Nikolaev
Tokyo
Bordeaux
LaPalma
Flagstaff
TMO

Types	Years	*A priori* accuracy
optical transit	1913–1994	$1'' \to 0''.5$
photoelectric transit	1963–1998	$0''.8 \to 0''.25$
photographic	1913–1998	$1'' \to 0''.2$
CCD	1995–2008	$0''.2 \to 0''.06$

Radar observations of Mercury, Venus, Mars, 58112

Millstone
Haystack
Arecibo
Goldstone
Crimea

Types	Years	*A priori* accuracy
ranging	1961–1997	100 km → 150 m

Spacecraft data obtained by DSN 1971–2008, 437612

Mariner – 9	*Venus*
Pioneer – 10, 11	*Jupiter*
Voyager	*Jupiter*
Phobos	*Mars*
Ulysses	*Jupiter*
Magelan	*Venus*
Galileo	*Jupiter*
Viking – 1, 2	*Mars*
Pathfinder	*Mars*
MGS	*Mars*
Odyssey	*Mars*
Cassini	*Saturn*
VEX	*Venus*
MRO	*Mars*

Types	Years	*A priori* accuracy
ranging	1971–2008	6 km → 1 m
differenced range	1976–1997	1.3 → 0.1 mm/sec
radial velocity	1992–1994	0.1 → 0.002 mm/sec
Δ VLBI	1990–2007	12 mas → 0.3 mas

The main reductions of optical observations

- correction for the additional phase effect (the main phase corrections were made by observers themselves);
- corrections for referencing to the ICRF refrence frame:

different catalogues $\rightarrow$ FK4 (Sveshnikov, 1974; 2000)

FK4 $\rightarrow$ FK5 (Standish, 1995)

FK5 $\rightarrow$ ICRF (Mignard and Froeschle, 2000)

The required reductions of radar observations:

- **the relativistic correction — the tine delay of the propagation of radio-signals in the gravitational field of the Sun (the Shapiro effect) and the reduction of observations from the coordinate time of the ephemerides to the proper time of the observer;**
- **the delay from the Earth's troposphere (the model of Niell, 1996 has been used for the global mapping function);**
- **the delay from the solar corona**

  (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,**

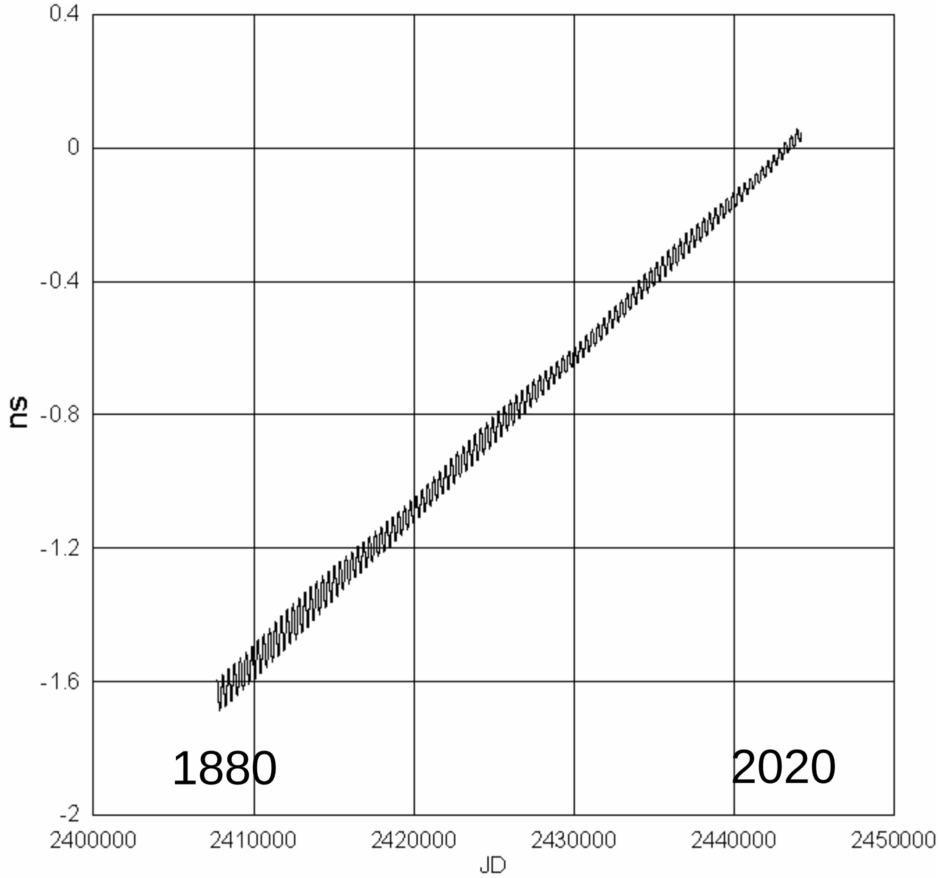
  The parameters B **and** $\dot{B}$ **determined from observations were different for different solar conjunctions);**
- **the corrections for the topography of the planet surfaces**

  (for Venus and Mars for their topography has been carried out with the help of modern hypsometric maps of surfaces, and using the representation of the global topography by an expansion of spherical functions of 16 – 18 degrees; the topography of Mercury has been represented by Legendre functions to the second order with estimating the expansion coefficients from observations).

$$TT(TAI) = TAI + 32.184s;$$

$$UTC = TAI + \mathbf{c}(i);$$

$$\frac{d(TT - TDB)}{dTDB} = \left(L_{\mathbf{B}} + \frac{1}{c^2}\alpha' \right)(1 + L_{\mathbf{B}} - L_{\mathbf{G}}) - L_{\mathbf{G}} + \frac{1}{c^4}\beta'$$



$$\alpha' = -\frac{1}{2}v_E^2 - \sum_{A \neq E} \frac{GM_A}{r_{EA}}$$

$$\beta' = -\frac{1}{8}v_E^4 + \frac{1}{2}\left[\sum_{A \neq E} \frac{GM_A}{r_{EA}} \right]^2 +$$

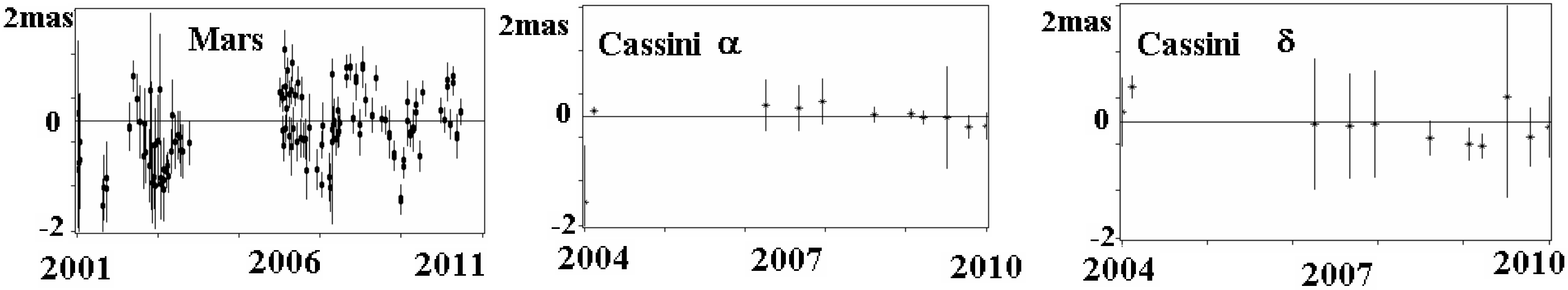
$$+ \sum_{A \neq E} \frac{GM_A}{r_{EA}} \left\{ 4v_A \cdot v_E - \frac{3}{2}v_E^2 - 2v_A^2 + \right.$$

$$\left. + \frac{1}{2}\mathbf{a}_A \cdot \mathbf{r}_{EA} + \frac{1}{2}\left(\frac{\mathbf{v}_A \cdot \mathbf{r}_{EA}}{r_{EA}} \right)^2 + \sum_{B \neq A} \frac{GM_B}{r_{AB}} \right\}.$$

More than <u>260 parameters</u> are estimated for EPM2008:

- **the orbital elements of all the planets and 18 satellites of the outer planets observations whose been used to improve the orbits of these planets;**
- **the value of the Astronomical Unit in m;**
- **three orientation angles of the ephemerides relative to the International Celestial Reference Frame (ICRF) and their velocities;**
- **13 rotation parameters of Mars and the coordinates of the three landers on the martian surface;**
- **masses of Jupiter and the ten asteroids that perturb Mars most strongly, mean densities for three taxonomic classes of asteroids (C, S, M), the mass and the radius of the asteroid ring, the ratio masses of the Earth and the Moon;**
- **the solar quadrupole moment (J_2) and 21 parameters of the solar corona for different conjunctions with the Sun;**
- **eight coefficients of Mercury's topography and the corrections to the surface levels of Venus and Mars;**
- **five coefficients of the phase effect correction for the outer planets;**
- **constant bias for Viking-1, Viking-2, Pathfinder, MGS and Odyssey data and some other series of observations, that were interpreted as calibration errors of the instruments or as systematic errors of unkhown origin;**
- **the post-model parameters ($\beta,\ \gamma,\ \dot{G}/G,\ \ddot{G}/G, \dot{\pi}_i, \dot{a}_i/a_i$).**

EPM2010 have been oriented to ICRF with the accuracy better than 1 mas by including into the total solution the 196 ICRF-base VLBI measurements of spacecraft (Magellan, Phobos, MGS, Odyssey, Venus Express, and Mars Reconnaissance Orbiter, Cassini) 1989 – 2010 near Venus and Mars, Saturn.



Spasecraft VLBI residuals

The rotation angles for the orientation of EPM2008 onto ICRF

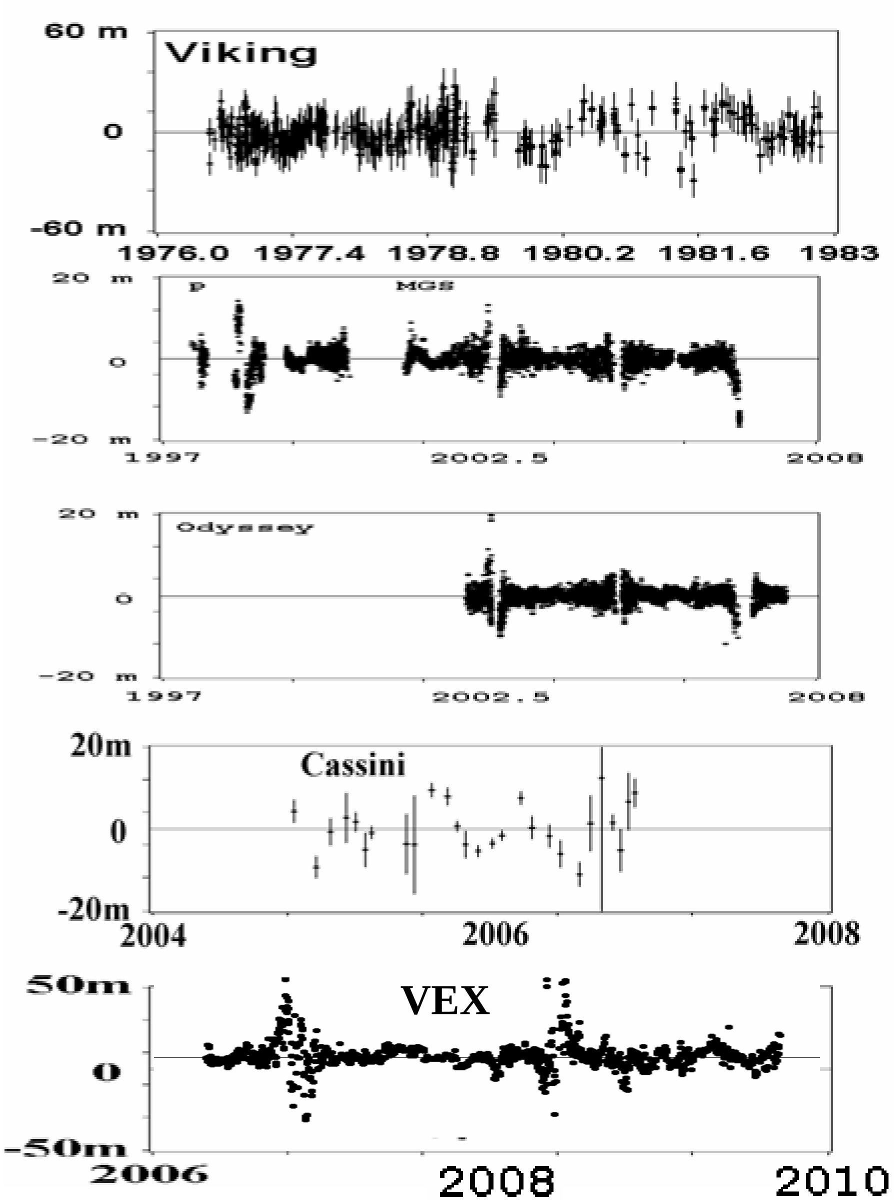
Interval	Number of observations	ε_x mas	ε_y mas	ε_z mas
1989-1994	20	4.5±0.8	-0.8±0.6	-0.6±0.4
1989-2003	62	1.9±0.1	-0.5±0.2	-1.5±0.1
1989-2007	118	-1.528±0.062	1.025±0.06	1.271±0.046
1989-2010	196	0.099±0.047	-0.052±0056	0.045±0.030

Mean values and rms residuals for radiometric observations

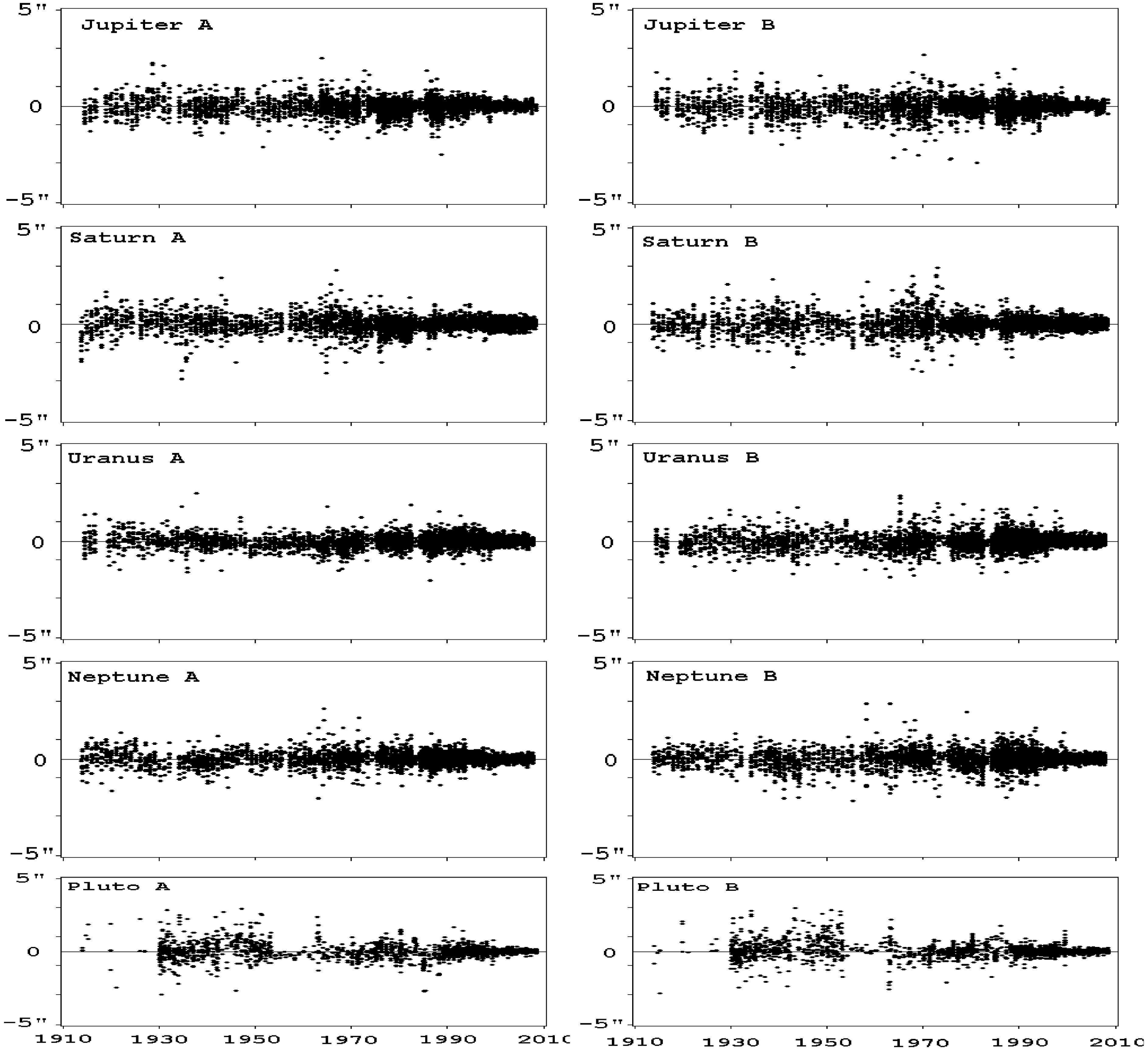
Planet	Type of data	Time interval	N	$<O-C>$	σ
MERCURY	τ [m]	1964–1997	746	0	575
VENUS	τ [m]	1961–1995	1354	-2	584
	Magellan dr [mm/s]	1992–1994	195	0	0.007
	MGN,VEX VLBI [mas]	1990–2007	22	1.6	3.0
	Cassini τ [m]	1998–1999	2	4.0	2.4
	VEX τ [m]	2006–2009	1288	0.0	3.6
MARS	τ [m]	1965–1995	403	0	719
	Viking τ [m]	1976–1982	1258	0	8.8
	Viking $d\tau$ [mm/s]	1976–1978	14978	-0.02	0.89
	Pathfinder τ [m]	1997	90	0	2.8
	Pathfinder $d\tau$ [mm/s]	1997	7569	0	0.09
	MGS τ [m]	1998–2006	7342	0	1.4
	Odyssey τ [m]	2002–2007	5257	0	1.2
	MRO τ [m]	2006–2007	380	0	2.5
	spacecraft VLBI [mas]	1989–2010	136	0.0	0.6
JUPITER	spacecraft τ [m]	1973–2000	7	0.0	11.8
	spacecraft VLBI [mas]	1996–1997	24	-1.8	9.5
SATURN	spacecraft τ [m]	1979–2006	33	1.0	20.2
URANUS	VGR2 τ [m]	1986	1	1.9	105
NEPTUNE	VGR2 τ [m]	1989	1	0.0	14

Mean values and rms residuals for optical optical observations and spacecraft encounters*, α and δ in mas, 1913–2009

Planet	N	$<O-C>_\alpha$	σ_α	$<O-C>_\delta$	σ_δ
VENUS*	4	1.5	2.0	1	6.5
JUPITER	13038	10	184	-29	197
JUPITER*	16	0	1.9	-4.9	8.0
SATURN	16246	-2	153	-1	146
SATURN*	92	0.1	0.4	0.0	0.4
URANUS	11692	3.7	172	0.8	204
URANUS*	2	-43	9	-26	12
NEPTUNE	11342	4.9	155	6.4	198
NEPTUNE*	2	-9	3.5	-14	4.0
PLUTO	5470	0.4	141	3	142

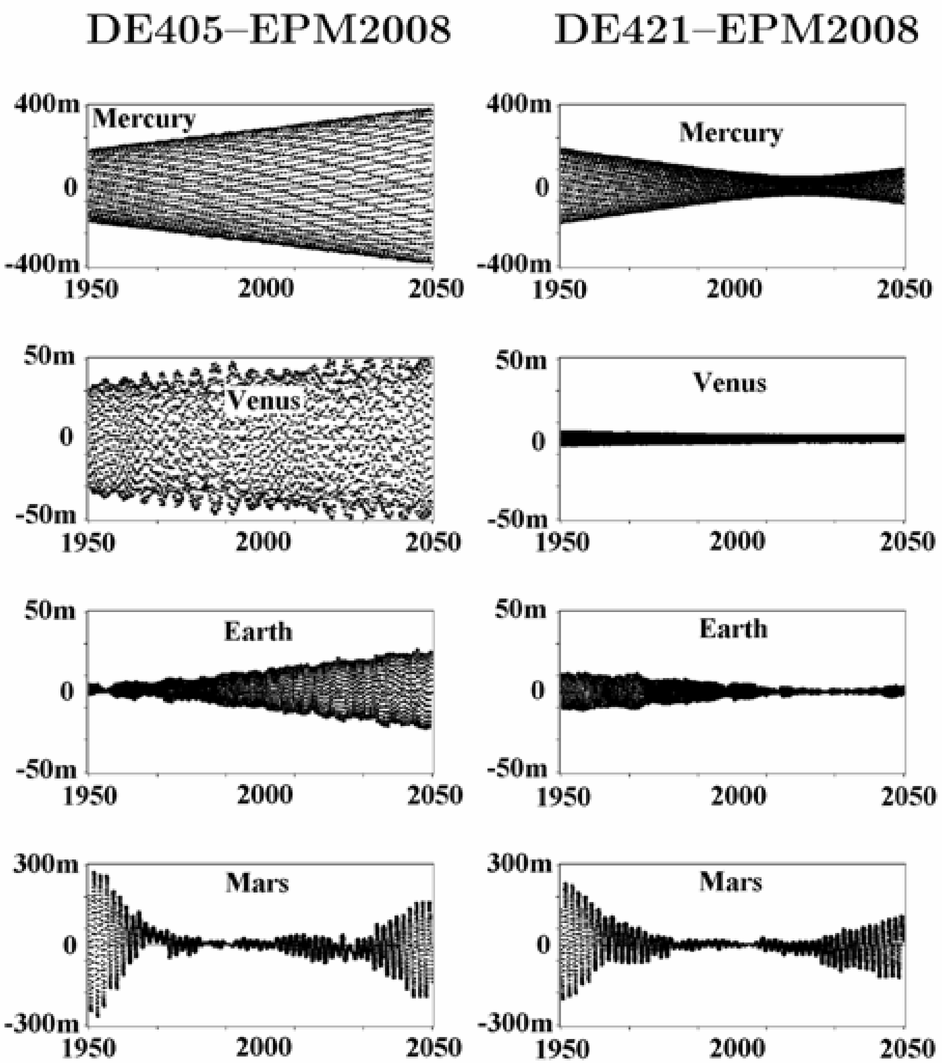


The rms residuals of ranging for Viking are 8.8~m, for Pathfinder 2.8~m, for MGS and Odyssey 1.2--1.4 m, for Cassini (Saturn) 3.0 m, for VEX 2.6 m. VEX – 3.6 м.



Residuals of the outer planets 1913–2008
in $\alpha \cos\delta$ (A) and in δ (B), the scale $\pm 5''$.

Comparison of DE and EPM ephemerides



Differences in the heliocentric distances of inner planets for DE and EPM ephemerides, 1950-2050

Maximum Deferences in the heliocentric distances of planets for DE and EPM ephemerides, 1950–2050

Planet	DE405–EPM2008	DE421–EPM2008
Mercury	384 m	185 m
Venus	53.7 m	4.6 m
Earth	26.8 m	11.9 m
Mars	272 m	233 m
Jupiter	19.7 km	4.8 km
Saturn	29.3 km	0.4 km
Uranus	864 km	310 km
Neptune	6100 km	848 km
Pluto	29000 km	1800 km

Parameters obtained from the DE, EPM ephemeris improvement processes at JPL and at IAA RAS, proposed to WG NSFA and adopted at 27 IAU GA as current best estimates of astronomical constants

Masses of the largest asteroids:

$M_{Ceres}/M_{\odot} = 4.72(3) \cdot 10^{-10}$,

$M_{Pallas}/M_{\odot} = 1.03(3) \cdot 10^{-10}$,

$M_{Vesta}/M_{\odot} = 1.35(3) \cdot 10^{-10}$.

The Earth-Moon mass ratio:

$M_{Earth}/M_{Moon} = 81.300568 \pm 0.000003$

or as the Moon_Earth mass ratio, at it is customary in the NSFA:

$M_{Moon}/M_{Earth} = 0.0123000371 \pm 0.0000000004$.

The value of the Astronomical Unit: AU = (149597870700 ± 3) м

Is consistent with the value $GM_{\odot} = 1.32712442099(10) \cdot 10^{20} [m^3 s^{-2}]$ proposed to the NSFA WG by W. Folkner.

Two parameters characterizing the ring modeling the effect from the rest of small asteroids are:

$$M_{ring} = (0.87 \pm 0.35) \bullet 10^{-10} M_{\odot}, \quad R_{ring} = (3.13 \pm 0.05)\ \text{AU}.$$

The total mass of the main belt asteroids represented by the sum masses of 301 asteroids and the asteroid ring is:

$$M_{belt} = (13 \pm 2) \bullet 10^{-10} M_{\odot} \quad (\approx 3\ \text{Ceres mass}).$$

The mass value of the ring of TNO is:

$$M_{TNOring} = (498 \pm 14) \bullet 10^{-10} M_{\odot},\ (5\sigma).$$

The total mass of all TNO including Pluto, the 21 largest TNO and the TNO ring of other TNO objects with the 43 AU radius is:

$$M_{TNO} = 775 \bullet 10^{-10} M_{\odot}, \quad (\approx 164\ \text{Ceres mass or 2 lunar mass}).$$

The quadrupole moment of the Sun:

$$J_2 = (2.0 \pm 0.5) \bullet 10^{-7}.$$

PPN parameters:

$$|\beta - 1| < 0.0002, \qquad |\gamma - 1| < 0.0002.$$

A possible variability of the gravitational constant

$$\dot{G}/G = (-5.87 \pm 4.44) \bullet 10^{-14}\ \text{в год} \quad (3\sigma)$$

New program package **Calc_Eph** containing **IAA Planetary and Moon Ephemerides (EPM2004, EPM2008)** along with associated reading and interpolating routines was recently created.

ftp://quasar.ipa.nw.ru/incoming/EPM/

Routines included in the package:

- support polynomial approximation for both binary and ASCII ephemeris files,
- allow user to obtain the rectangular coordinates of the sun, moon, and nine major planets with respect to different centers (barycentric, geocentric, geliocentric and planetocentric),
- written in standard languages: Fortran, C, Pascal, Java,
- source code available to outside users via FTP,
- easy to use, accompanied by user manual.

Moreover, Fortran realization of this package gives a possibility to obtain access to differences between the times **TT and TDB** (for **EPM2004** and **EPM2008**) and ephemerides of the other seven bodies code named "planets – dwarves": **Ceres, Pallas, Vesta, Eris, Haumea, Makemake, Sedna**, obtained simultaneously with the main **EPM2008** ephemerides.

The updated model of EPM2008 includes the 21 largest TNO into the process of the simultaneous numerical integration.

Name	a [AU]	e	i [°]	D [km]	$GM_i/GM_\odot$ $[10^{-10}]$
Pluto+Charon	39.48	0.25	17.14	2390	73.23
Eris	67.67	0.44	44.19	2397	83.99
2003 EL_{61}	43.34	0.19	28.19	1490	21.12
Sedna (90377)	523.45	0.85	11.93	1490	17.42
2005 FY_9	45.74	0.15	29.00	1800	30.71
Quaoar (50000)	43.09	0.04	8.00	1260	10.53
2002 TC_{302} (84522)	55.49	0.30	35.05	1064	6.34
Orcus (90482)	39.39	0.22	20.52	946	3.77
Varuna (20000)	43.16	0.06	17.15	890	1.84
2002 UX_{25} (55637)	42.85	0.14	19.41	838	3.10
Ixion (28978)	39.31	0.25	19.70	820	2.90
2002 MS_4	41.65	0.15	17.69	804	2.74
2003 MW_{12}	42.95	0.14	21.49	765	2.36
2006 QH_{181}	42.15	0.11	26.96	764	2.35
2004 XR_{190}	57.05	0.08	46.75	750	1.67
2002 AW_{197} (55565)	47.51	0.13	24.31	790	2.22
2005 RN_{43}	41.58	0.02	19.29	730	2.05
1995 SM_{55} (24835)	42.15	0.11	26.96	704	1.84
2004 GV_9 (90568)	41.90	0.08	22.03	697	1.78
2005 RR_{43}	43.07	0.14	28.55	697	1.78
2003 AZ_{84}	39.69	0.17	13.54	686	2.06
2002 TX_{300} (55636)	43.51	0.12	25.86	620	1.26

The total mass of the 21 largest TNO is $204 \cdot 10^{-10} M_\odot$.