EPHEMERIDES EPM2008: THE UPDATED MODEL, CONSTANTS, DATA

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The EPM ephemerides of IAA RAS originated in seventies of the last century and have been developed since that time. 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 have been determined by different authors from data of spacecraft orbiting and passing near planets or from observations of satellites of these planets. Other constants like the value of the Astronomical Unit (AU) in meters, masses of the largest asteroids, the ratio of the masses of the Earth and the Moon, etc. have been obtained inside the EPM2008 ephemeris fitting process.

The updated model of EPM2008 includes Eris which surpasses Pluto in the mass and the other 20 largest trans-Neptunian objects into a process of the simultaneous numerical integration in addition to other bodies. The simultaneous numerical integration of the equations of motion of the nine major planets, the Sun, 301 biggest asteroids and 21 TNO, the Moon, and the lunar physical libration has performed in the Parameterized Post-Newtonian metric for General Relativity taking into account perturbations due to the solar oblateness and perturbation from the massive ring of small asteroids.

Moreover, some tests have been made for estimating influence other TNO on the motion of planets. Their perturbations have been modeled by the perturbation from a circular ring having a radius 43 AU and different masses. The minimum mass of this ring is equal to the mass of 100000 bodies with 100 km in diameter and density is equal 2 g/cm^3, it is 110 masses of Ceres or 1.5 mass of the Moon. The maximum mass of the ring is expected the minimum mass by 100 times. Influence of the ring is noticeable for more accurate observations — data from spacecraft. The rms residuals and the weight unit errors for these date after fitting standard and test EPM ephemerides are given in Table 2.

Ephemeris	Viking-1	Viking-2	MGS	Odyssey	σ_0
EPM	9.15	3.0	1.45	1.34	0.764
EPM$_{MmaxTNO}$	10.85	5.54	1.98	1.70	0.786

Table 1: The rms residuals in m and the weight unit errors σ_0 for EPM and EPM$_{MmaxTNO}$

It is seen that the maximal mass of the TNO ring is too large, but perhaps, its value may be estimated in future.

Database, to which EPM2008 have been adjusted (more 550000 measurements), includes in addition to previous observations since 1913, recently spacecraft measurements (Odyssey, Cassini, VEX, MRO) (see below). As for optical data, we use observations of satellites for all the outer planets which are more accurate than the observations of their parent planets and are practically free from the phase effect. We are developing numerical theories of main satellites of the outer planets and are improving them to the observations.

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, 437613

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

More 260 parameters have been determined while improving the planetary part of EPM2008. As compared with our previous version EPM2006 described in the paper of Pitjeva (2008), the orbital] elements of the addition 4 satellites of the outer planets, velocities for three orientation angles of the EPM2008 ephemerides relative to the International Celestial Reference Frame (ICRF), masses of the addition three asteroids, constant bias for the new VEX and MRO spacecrafts were estimated also.

EPM2008 have been oriented to ICRF with the accuracy better than 1 mas by including into the total solution the 118 ICRF-base VLBI measurements of spacecraft (Magellan, Phobos, MGS, Odyssey, Venus Express, and Mars Reconnaissance Orbiter) 1989 – 2007 near Venus and Mars.

Mean values and rms data residuals obtained from the adjustment of the EPM2008 ephemerides are shown in Tables 2–3, plots of some observations are given on Fig. 1–3. For example, it is seen from Table 2, the rms residuals of ranging for Viking are 8.8 m, for Pathfinder 2.8 m, for MGS 1.4 m, and for Odyssey 1.2 m.

The values of some parameters are given below. The Astronomical Unit = 149597870697(3) m, the Earth-Moon mass ratio $M_{Earth}/M_{Moon} = 81.300568(3)$, the masses of Ceres, Pallas, Vesta: $M_{Ceres}/M_{\odot} = 4.71(3) \cdot 10^{-10}, M_{Pallas}/M_{\odot} = 1.03(2) \cdot 10^{-10}, M_{Vesta}/M_{\odot} = 1.34(2) \cdot 10^{-10}$, where the real errors are shown, obtained from comparison with different fitting versions of DE and EPM ephemerides.

REFERENCES

Pitjeva, E.V., 2008, "Recent models of planet motion and fundamental constants determined from position observations of planets and spacecraft" Journées 2007: "The Celestial Reference Frame for the Future", N. Capitaine (ed), Paris, pp. 65–69.

Planet	Type of data	Time interval	N	$\lvert < O-C > \rvert$	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]	2006–2007	547	0.0	2.45
MARS	τ [m]	1965–1995	402	0	738
	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]	2002–2008	5682	0	1.2
	MRO τ [m]	2006–2007	378	0	1.6
	spacecraft VLBI [mas]	1984–2007	96	0.0	0.7
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

Table 2: Mean values and rms residuals for radiometric observations

Planet	N	$\lvert < O-C >_\alpha \rvert$	σ_α	$\lvert < O-C >_\delta \rvert$	σ_δ
VENUS*	4	1.5	2.0	1	6.5
JUPITER	12518	15	187	-30	199
JUPITER*	16	0.1	1.9	-4.1	6.1
SATURN	14296	-1	167	-3	160
SATURN*	68	2.2	2.9	4.2	5.9
URANUS	11446	6	178	2	208
URANU*	2	-45	9	-25	12
NEPTUNE	10982	7	160	9	205
NEPTUNE*	2	-11	3.5	-14	4.0
PLUTO	5134	1	191	6	197

Table 3: Mean values and rms residuals for optical observations and spacecraft encounters* (α and δ in mas, 1913–2008)

Time interval	Number of obs.	ε_x mas	ε_y mas	ε_y mas	ω_x mas/cy	ω_y mas/cy	ω_z mas/cy
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	1.2±0.2	1.1±0.2	0.5±0.1	−49.6±3.0	−4.5±3.5	16.0±2.0

Table 4: The rotation angles for the orientation of EPM2008 onto ICRF

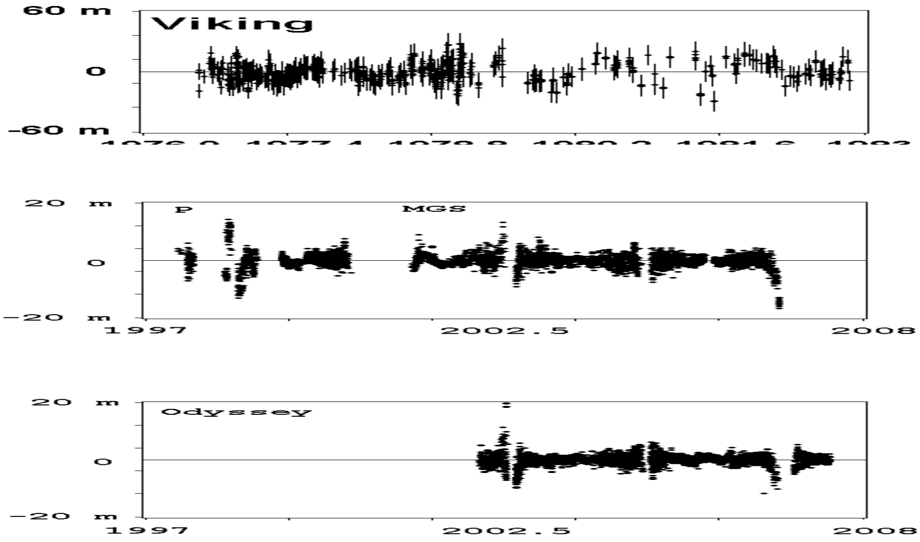

Figure 1: Viking, Pathfinder (P), MGS, Odyssey range residuals

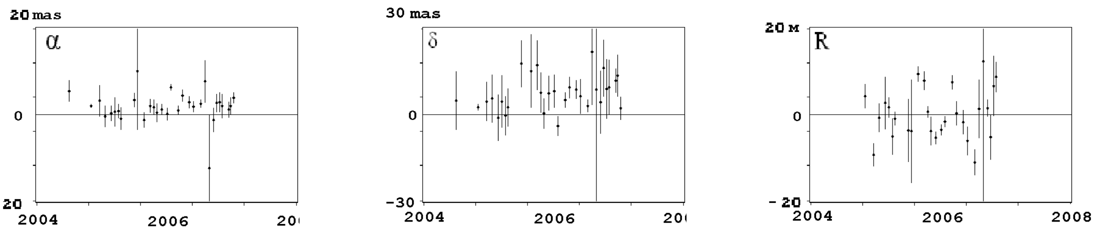

Figure 2: Saturn residuals from Cassini encounters

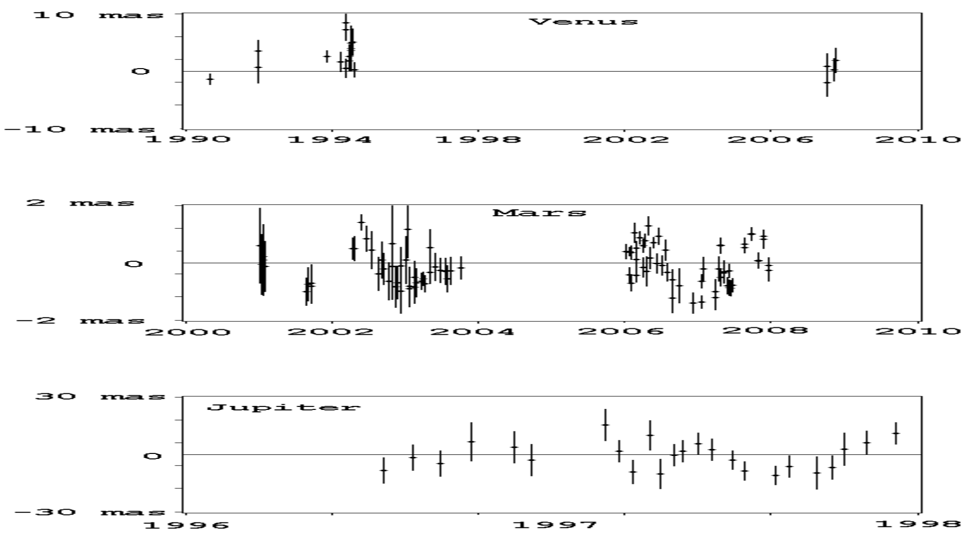

Figure 3: Venus, Mars, Jupiter spacecraft VLBI residuals