

RECENT MODELS OF THE PLANET MOTIONS AND FUNDAMENTAL CONSTANTS DETERMINED FROM POSITION OBSERVATIONS OF PLANETS AND SPACECRAFT

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ABSTRACT. More recent planet ephemerides constructed at JPL, IAA RAS and IMCCE, their similarities, differences and solution parameters are considered. Data residuals for EPM2006 (IAA RAS ephemerides) are given. New values of planet and asteroid masses and Astronomical Unit are presented.

1. RECENT PLANET EPHEMERIDES

The most recent planet ephemerides having about the same accuracy and being adequate to modern observations have been constructed at JPL – DE414 (Standish, 2006), IAA RAS – EPM2006 (Pitjeva, 2007) and IMCCE – INPOP06 (Fienga *et al.*, 2007). All the basic versions of these ephemerides have been developed in the TDB coordinate system. Several test versions of these ephemerides for the TCB coordinate system (which are entirely equivalent to TDB ephemerides) were also constructed.

Common to all these ephemerides is the simultaneous numerical integration of the equations of motion of the nine major planets, the Sun, 300 or more biggest asteroids, the Moon, and the lunar physical libration performed in the Parameterized Post-Newtonian metric for General Relativity taking into account perturbations due to the solar oblateness and the massive ring of small asteroids. All the above ephemerides have been oriented to the International Celestial Reference Frame (ICRF) with the accuracy better than 1 mas by including into the total solution the 86 ICRF-base VLBI measurements of spacecraft near the planets (Magellan, Phobos MGS and Odyssey) made in 1989 – 2003.

The dynamical models of these ephemerides differ slightly by:

- the modeling of the lunar libration, but this difference doesn't influence significantly the planet ephemerides (for the EPM ephemerides, the orbital and rotational motions of the Moon were modeled using Krasinsky's (2002) selenodynamical parameters improved from LLR observations);
- the modeling of the perturbations from asteroids (the dynamical model for INPOP06 includes perturbations from 300 asteroids, for EPM2006 from 301, and for DE414 from 342 ones, however, as was shown in the paper (Krasinsky *et al.*, 2002), including into integration the next 51 largest asteroids did not give a better solution due, perhaps, to uncertainty of their masses);
- the numerical integration also includes trans-Neptunian objects for the new EPM2007 ephemerides; for INPOP06 – Earth rotation necessary for the very long time integration in paleoclimate studies, and the additional term $\dot{\mu}_i^*$ of the solar system barycenter, although the impact of this term on displacement of the solar system barycenter is many orders less than the impact of trans-Neptunian objects;
- some procedures of correction (e.g. for the topography of the planet surfaces and the solar corona);
- sets of observations;
- sets of solution parameters.

Observations to which all ephemerides have been fitted are ranging to planets, the Martian landers and spacecraft, including the data of MGS and Odyssey for Mars and a number of spacecraft Jupiter data, differenced range, Doppler measurements, VLBI spacecraft observations and optical data of observations of the outer planets and their satellites. More than 400000 data presented in Tables 1,2 were used for the construction of the EPM2006 ephemerides. EPM2006, as distinct from other ephemerides, cover Russian ranging to Mercury, Venus, Mars (1961–1995) and more observations of satellites for all the outer planets which are more accurate than the observations of their parent planets and are practically free from phase

effect. At present, we are developing numerical theories of motion for main satellites of the outer planets and improving them to the observations.

Planet	Type of data	Time interval	N	$\langle O - C \rangle$	σ
MERCURY	planet ranging (τ) [m]	1964–1997	746	0	575
VENUS	planet ranging (τ) [m]	1961–1995	1354	-2	584
	Magellan dr [mm/s]	1992–1994	195	0	0.007
MARS	Magellan VLBI [mas]	1990–1994	18	1	2
	planet ranging (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]	1998–2005	6429	-0.1	2.3
	Odyssey τ [m]	2002–2005	3441	-0.1	2.0
JUPITER	spacecraft VLBI [mas]	1984–2003	44	0	0.8
	spacecraft τ [m]	1973–1995	6	-538	2642
	spacecraft VLBI [mas]	1996–1997	24	-1	11

Table 1: Mean values and rms residuals for radiometric observations (MGS and Odyssey data are normal points representing more than 280000 original observations)

Planet	N	$\langle O - C \rangle_\alpha$	σ_α	$\langle O - C \rangle_\delta$	σ_δ
JUPITER	11562	3	103	-14	128
SATURN	12205	-1	192	-5	190
URANUS	10659	0	205	-5	251
NEPTUNE	9701	0	183	-1	240
PLUTO	4563	0	237	5	236

Table 2: Mean values and rms residuals for optical observations of planets and their satellites ($\alpha \cos \delta$ and δ in mas), 1913–2006

About 230 parameters have been determined while improving the planetary part of the EPM2006 ephemerides. The software for DE414 permits to determine 63 individual asteroid masses, although most masses are constrained using a priori values of the nominal masses. The solution for the planet part of DE414 includes 225 parameters and 34 parameters for the Moon. The number of the adjusted parameters for INPOP06 is 65.

The solution parameters of the planetary part of EPM2006 are:

- the orbital elements of all the planets and 14 satellites of the outer planets the observations of which have been used to improve the orbits of these planets;
- the value of the Astronomical Unit in kilometers;
- three orientation angles of the ephemerides relative to ICRF;
- 13 rotation parameters of Mars and the coordinates of three landers on the Martian surface;
- masses of Jupiter and the seven 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 15 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 unknown origin;
- the relativistic parameters (β , γ , \dot{G}/G , \ddot{G}/G , the secular trend of the planet perihelia).

Some of these parameters, such as the masses of planets and asteroids and the value of the Astronomical Unit, are included into the list of numerical standards for fundamental astronomy. However, the general list of constants and initial values for underlying dynamical theories is too large, moreover the lists are different for different ephemerides and can change for any new solution. Thus, Bulletin WG "Numerical Standards of Fundamental Astronomy" (NSFA) should be supplied with pointers to the websites, where these exact dynamical models and constructed ephemerides are maintained, but not the values of all the ephemeris parameters.

Mean values and rms data residuals of the EPM2006 ephemerides are shown in Tables 1, 2. The detailed description of all the data used, plots of the observations residuals, and values of parameters obtained from the adjustment of the EPM ephemerides are given in the papers (Pitjeva, 2005a; Pitjeva, 2005b; Pitjeva, 2007). As for the accuracy and values of parameters, all the models are based on General Relativity, and certainly depend on many other factors, such as reduction techniques, dynamical models, the amount and quality of the observational data, the method used to fit the data, the amount of parameters included into the solution, and so on. Importantly, these differences are explained from a statistical point of view, and may serve for estimating real uncertainties of the solution parameters.

2. NEW VALUES OF MASSES AND THE ASTRONOMICAL UNIT

Masses of planets are the parameters of dynamical models of planet motions and, in principal, may be determined while fitting these models to the observational data. However, masses are determined more accurately from data of spacecraft orbiting and passing near planets or from observations of satellites of these planets than from position data of the parent planets. Actually, the planet masses of DE200 and DE405 were obtained by different people, different methods and with different errors, and they were chosen by E. M. Standish as the most reasonable at that time.

Some asteroids are double or have satellites and their masses are known now with reasonably good accuracy (five of such main biggest asteroids are included into integration). The masses of (433) Eros and (253) Mathilda have been derived by perturbations of the spacecraft during the NEAR flyby. Masses of the several most massive asteroids which affect Mars and the Earth more strongly have been estimated from the observations of Martian landers and the spacecraft orbiting Mars. In the classical method of determining the masses of asteroids, the perturbed body is another asteroid for which a close encounter with the perturbing body occurs. For some favorable cases if very close encounters are provided with useful data before and after the encounter an accurate determination of an asteroid mass may be obtained. For example, a new determination of (15) Eunomia has been recently obtained by A. Vitagliano and R.M. Stoss (1.64 ± 0.06) $\cdot 10^{-11} M_{\odot}$ and confirmed by two independent groups (O. Kochetova and I. Baer, S. R. Chesley). As for masses of Ceres, Pallas and Vesta, many new significantly more accurate estimations have been obtained recently by different authors from close encounters with other asteroids and from their perturbations onto Mars.

In collaboration with Dr. Standish, we have chosen the best estimations of masses of planets and asteroids (Table 3) and offered them to the IAU WG NSFA (see <http://maia.usno.navy.mil/NSFA/CBE.html>). The ratio of the masses of the Earth and the Moon has been obtained by E. M. Standish while fitting the DE414 to all the data; the masses of Venus and Mars have been determined by Konopliv and colleagues from the data of spacecraft Magellan for Venus and MGS and Odyssey for Mars; the masses of Jupiter and Saturn have been obtained by Jacobson and the colleagues from the data of spacecraft near these planets and the Earth-based observations of the satellites of these planets; the mass of Pluto has been improved recently by Tholen and colleagues from astrometrical observations of Charon and the two small Pluto's satellites; the mass of Eris has been estimated by Brown and Schaller from observations the Eris's satellite Dysnomia. Values and their errors of the asteroid masses are road ones taken from looking at a number of recent sources.

The value of the Astronomical Unit in SI meters or after dividing by the the speed of light in SI seconds is one of basic parameters of DE and EPM ephemerides. The value $\tau_A=499.00478368061$ [SI s] was obtained for ephemerides DE405 constructed by Standish (1998). However, at present this value is slightly obsolete. For WG NSFA we have proposed the mean value: $\tau_A = 499.004783826(10)$ [SI s],

Planet	Previous values	New values	Year	Authors
M_M/M_E	$1.23000345(5)\cdot 10^{-2}$	$1.23000371(4)\cdot 10^{-2}$	2006	Standish
M_\odot/M_V	$4.0852371(6)\cdot 10^5$	$4.08523719(8)\cdot 10^5$	1999	Konopliv et al.
M_\odot/M_{Ma}	$3.098708(9)\cdot 10^6$	$3.09870359(2)\cdot 10^6$	2006	Konopliv et al.
M_\odot/M_J	$1.0473486(8)\cdot 10^3$	$1.047348625(17)\cdot 10^3$	2003	Jacobson
M_\odot/M_{Sa}	$3.497898(18)\cdot 10^3$	$3.4979018(1)\cdot 10^3$	2006	Jacobson et al.
M_\odot/M_P	$1.3521(15)\cdot 10^8$	$1.36578(32)\cdot 10^8$	2007	Tholen et al.
M_\odot/M_{Eris}		$1.191(14)\cdot 10^8$	2007	Brown et al.
M_{Ceres}/M_\odot	$4.39(4)\cdot 10^{-10}$	$4.72(3)\cdot 10^{-10}$	2007	Pitjeva,Standish
M_{Pallas}/M_\odot	$1.59(5)\cdot 10^{-10}$	$1.03(2)\cdot 10^{-10}$	2007	Pitjeva,Standish
M_{Vesta}/M_\odot	$1.69(11)\cdot 10^{-10}$	$1.35(2)\cdot 10^{-10}$	2007	Pitjeva,Standish

Table 3: New values of masses of planets and asteroids proposed to WG NSFA

taken from papers (Standish, 2005 and Pitjeva, 2005). However, all the values of τ_A were obtained while fitting DE and EPM ephemerides constructed for the TDB coordinate system. The conversion τ_A from TDB ephemerides to TCB ephemerides is ambiguous. There are two different versions of conversion to TCB ephemerides proposed by Brumberg and Simon, Fukushima, and Standish. Thus, I think that the constant $\tau_A = 499.004783826(10)$ [SI s] should be followed by the words "the TDB coordinate system".

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