EPM – EPHEMERIDES OF PLANETS AND THE MOON OF IAA RAS: THEIR MODEL, ACCURACY, AVAILABILITY

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ABSTRACT. The current state of the last version of the planet part of EPM's ephemerides of IAA RAS (EPM2010) integrated in the PPN metric over the 1800 - 2200 time interval is presented. The updated dynamical model includes perturbations from all Trans-Neptunian Objects at the mean distance of 43 AU in addition to the perturbations from the major planets, the Moon, the Sun, and asteroids of the main belt. EPM2010 ephemerides have resulted from a least square adjustment to observation data totaling about 620000 position observations of different types. EPM2010 have been oriented onto the ICRF by the inclusion of all VLBI spacecraft observations into the fitting. The uncertainty of EPM ephemerides is controlled by comparison with a prior accuracy of observations and the independent DE421 ephemeris. The differences between the times TT and TDB have been constructed for EPM2004 (that is the basis for the Russian Astronomical Yearbook) and EPM2008 ephemerides. The access to these ephemerides with their TT-TDB are available via ftp://quasar.ipa.nw.ru/incoming/EPM/. This package allows a competent user to obtain the rectangular coordinates of the Sun, Moon, and nine major planets by means of a subroutine written in standard languages Fortran, C, Pascal, Java. Moreover this package gives a possibility to obtain access to ephemerides of Ceres, Pallas, Vesta, Eris, Haumea, Makemake, Sedna constructed simultaneously with the main EPM ephemerides.

1. RENEWAL OF EPM EPHEMERIDES: CONSTANTS, MODEL, DATA

The EPM ephemerides (**E**phemerides of **P**lanets and the **M**oon) of IAA RAS originated in the seventies of the last century and have been developed since that time. These ephemerides are based upon relativistic equations of motion for celestial 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 in the barycentric coordinate frame of J2000.0 by Everhart method over the 400 years interval (1800–2200) using the program package ERA-7 (ERA: **E**phemeris **R**esearch in **A**stronomy) developed to support scientific research in dynamical and ephemeris astronomy (Krasinsky & Vasilyev, 1997). This paper concerns a planetary part of the EPM ephemerides, a lunar part of the EPM ephemerides is presented in another paper (Krasinsky et al., 2010) of the same publication.

The updated model of EPM2010 includes the new values of planet masses adopted by the XXVI GA IAU and other constants, the improved dynamical model with Trans–Neptunian Objects (TNO) and the expanded database (1913–2009). The dynamical model includes perturbations from the 21 largest TNO and a massive ring of all other TNO being at the mean distance of 43 AU, in addition to the perturbations from the major planets, the Moon, the Sun, and asteroids of the main belt (the 301 largest asteroids and the massive asteroid ring).

2. OBSERVATIONS, THEIR REDUCTION, TT-TDB

Database, to which EPM2010 have been adjusted (more 620000 measurements) includes, in addition to previous observations since 1913, the recent spacecraft measurements, namely, ranging to Venus Express (VEX, 2006 – 2009), VLBI data of Odyssey, MRO and VEX (2006–2010), three-dimensional normal point observations of Cassini (2004 – 2006), along with CCD Flagstaff and TMO data of the outer planets and their satellites (1995 – 2009), as well as the new VLBI Cassini points (right ascension and declination) 2004 – 2010 (Jones et al., 2010). These measurements have resulted in a significant improvement of planet orbits, especially for Venus and Saturn and the orientation of the EPM2010 ephemerides to ICRF.

All the new data from spacecraft have been obtained due to the kindness of William Folkner and Agnes Fienga.

Three main factors that influence the accuracy of the constructed ephemerides and the estimated parameters are

1) dynamical models of planet motion,
2) observational data proper,
3) reductions of the observational data.

The main reductions of optical observations of planets are the correction to the additional phase effect (the main phase corrections were made by observers themselves) and the corrections of referencing to the ICRF reference frame. The most precise optical data of the outer planets and their satellites, obtained at Flagstaff, Nikolaev, La Palma, Table Mountain Observatory have already been referenced to the ICRF by observers themselves. 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 (Standish), and were finally transformed to the ICRF using the values of the three angles of rotation from the HIPPARCOS to FK5 catalogues, J2000 in mas (Mignard and Froeschle, 2000):

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

The observations of satellites of outer planets are of great importance, as they are more accurate than the observations of their parent planets and are practically free from the phase effect.

The reduction of the radar measurements maintains all the relevant corrections. Observations have been reduced to relativistic corrections, the effects of propagation of electromagnetic signals in the Earth troposphere and in the solar corona. The largest delay is in the plasma of the solar corona near superior solar conjunctions. 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 correction of observations of Venus and Mars for their topography has been carried out by means of using modern hypsometric maps of surfaces of these planets and 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 radar observations.

For the transition from the time of observations (UTC) to Barycentric Dynamical Time (TDB), time for construction of modern planet ephemerides, it is necessity to have transition between Terrestrial Time (TT) and TDB.

$$TT = TAI + 32.184s, \quad UTC = TAI + \mathbf{c}(i).$$

For relation TT – TDB the differential equation from paper by the Klioner (2008) has been used:

$$\frac{\mathrm{d}(TT - TDB)}{\mathrm{d}TDB} = \left(L_B + \frac{1}{c^2}\alpha'\right)(1 + L_B - L_G) - L_G + \frac{1}{c^4}\beta' \qquad (1)$$

where $L_B = 1.550519768 \cdot 10^{-8}$, $L_G = 6.969290134 \cdot 10^{-10}$, c is the speed of light in vacuum, α' and β':

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

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

$$\left. -\frac{3}{2}v_E^2 - 2v_A^2 + \frac{1}{2}\mathbf{a}_A \cdot \mathbf{r}_{EA} + \frac{1}{2}\left(\frac{\mathbf{v}_A \cdot \mathbf{r}_{EA}}{r_{EA}}\right)^2 + \sum_{B \neq A} \frac{GM_B}{r_{AB}} \right\}.$$

The equation (1) was integrated with positions and velocities of the planets from EPM2004 and EPM2008 over the time intervals on which these ephemerides were constructed. The results of comparison of the obtained differences (TT-TDB) for EPM2004 and EPM2008 over the interval from 1880 to 2020 are shown in Figure 1.

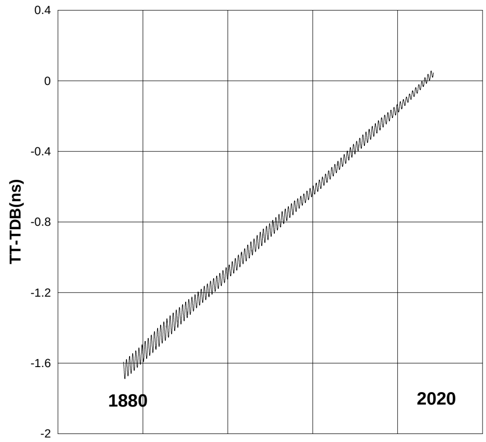

Figure 1: Differences between the difference (TT-TDB) for ephemerides EPM2004 and EPM2008 in ns.

Planet	Type of data	Time interval	N	$< O - C >$	σ
VENUS	VEX τ [m]	2006–2009	1288	0.0	3.6
MARS	spacecraft VLBI [mas]	1989–2010	136	0.0	0.6

Table 1: Mean values and rms residuals for some radiometric observations.

3. THE SOLUTION PARAMETERS

More than 260 parameters have been determined while improving the planetary part of EPM2010 to about 620000 data:

- the orbital elements of all the planets and 18 satellites of the outer planets whose observations were 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 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 mass of the a massive ring of TNO in the ecliptic plane with the radius of 43 AU;
- the mass ratio 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 of the outer planets;
- constant bias for spacecraft and some radar planet observations, that were interpreted as calibration errors of the instruments or as systematic errors of unknown origin;
- the post-model parameters (β, γ, $\dot{G}/G$, $\dot{G}M_\odot/GM_\odot$, secular trends of the planet perihelia and semi-major axes).

Mean values and rms residuals of observations added to the paper (Pitjeva, 2009) are presented in Tables 1, Tables 2 and on Figure 2, where the VEX data are shown. The data residuals do not exceed their a priori accuracies. 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 3.6 m.

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, Mars Reconnaissance Orbiter, Cassini) 1989 - 2010 near Venus, Mars, Saturn (see Table 3 and Figure 3).

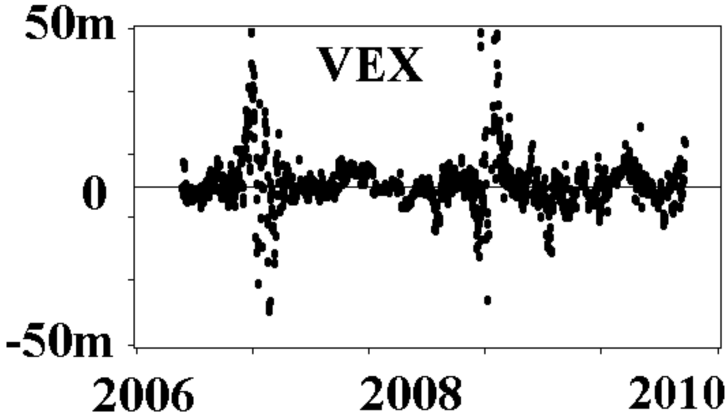

Figure 2: VEX range residuals

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	0.0	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

Table 2: Mean values and rms residuals for optical observations and spacecraft encounters*, α and δ in mas, 1913–2009

The differences between various ephemerides are useful to know since they are indicative of the realistic accuracies of the ephemerides. The comparison of our recent EPM2008 ephemeris with the standard DE405 and the recent DE421 ephemerides has been made (Table 4). The differences of heliocentric distances for the inner planets between EPM2008 and DE405 or DE421 are small. Table 4 shows a significant progress in agreement (and in reduction of the uncertainties) of the orbits of all the planets, especially due to the VEX (Venus) and Cassini (Saturn). The adjusted value of several parameters are further presented. The obtained values of parameters are shown with their real uncertainties estimated by comparing the values obtained in dozens of different test LS solutions, as well as by comparing parameter values produced by independent groups, or the uncertainties equal 5–10 σ of the formal errors of the WRMS method.

Two parameters that characterize the ring modeling the effect from small asteroids (its mass M_{ring} and radius R_{ring}) have been determined:

$$M_{ring} = (0.87\pm0.35)\cdot 10^{-10} M_\odot, \quad R_{ring} = (3.13\pm0.05) \text{ AU}.$$

Time interval	Number of obs.	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±0.060	1.271±0.046
1989–2010	196	-0.099±0.047	-0.052±0.056	0.045±0.030

Table 3: The rotation angles for the orientation of EPM onto ICRF

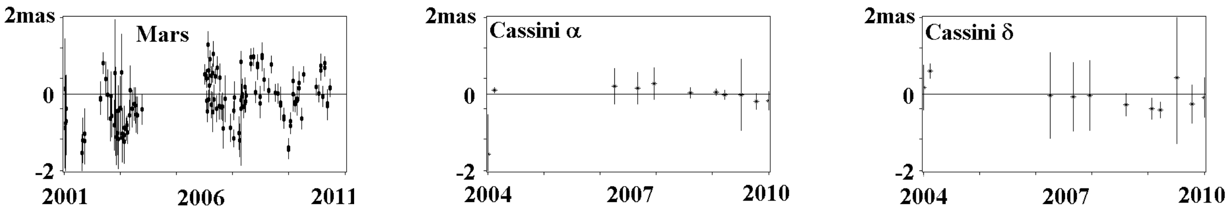

Figure 3: The VLBI residuals of the different Mars spacecraft and Cassini

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

Table 4: Maximum differences in the heliocentric distances of planets for DE and EPM ephemerides, 1950–2050

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

$M_{belt}=(13 \pm 2)\cdot 10^{-10} M_\odot$ (about 3 Ceres mass).

The mass value of the ring of TNO has been obtained:

$M_{TNOring}=(498 \pm 14)\cdot 10^{-10} M_\odot$ (5σ).

Thus, 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:

$M_{TNO}=775\cdot 10^{-10} M_\odot$ (about 164 M_{Ceres} or 2 M_{Moon}).

The obtained value of the Moon-Earth mass ratio is

$$M_{Earth}/M_{Moon} = 81.3005676 \pm 0.0000030$$

The quadrupole moment of the Sun J_2 and the values of PPN parameters are:

$$J_2 = (2.0 \pm 0.5)\cdot 10^{-7},\ |\beta - 1| < 0.0002,\ |\gamma - 1| < 0.0002.$$

The value $GM_\odot$ in the physical system of units $[m^3 s^{-2}]$ may be estimated from fitting ephemerides to observations. However, according to the present definition of the Astronomical Unit, this value may be calculated from an entirely equivalent process – that of adjusting the AU value, obtained in meters while fitting planet ephemerides, by the relation,

$$GM_\odot[m^3 s^{-2}] = k^2 \cdot AU[m]^3/86400[s]^2,$$

where k=0.01720209895 is Gaussian gravitational constant.

The two estimations of $GM_\odot$ have been obtained A) from the estimated value of AU, B) the direct estimation of $GM_\odot$ if the value of AU is fixed:

A) AU=(149597870696.2±0.4)m (10 σ), then $GM_\odot$=(132712440031.9±0.1) km^3/s^2 (10 σ);

B) fixed AU=149597870696.4 m, obtained $GM_\odot$=(132712440032.7±0.7) km^3/s^2 (10 σ).

In the second case (B) the formal error of WRMS is significantly larger than in case A due to strong correlation of $GM_\odot$ with the orbital elements of the inner planets, especially with their major semi-axes; whereas the AU correlation with all the estimated parameters is considerably less. Thus, the present AU definition does not prevent the estimation of $GM_\odot$, $G\dot{M}_\odot$, AU and gives the possibility to estimate $GM_\odot$ more accurately.

4. SOFTWARE SUPPORT FOR EPHEMERIDES EPM

A new program package Calc_Eph containing IAA Planetary and Moon Ephemerides (EPM2004, EPM2008) along with associated reading and interpolating routines has been recently created. Routines of this package allow a competent user to obtain the rectangular coordinates of the Sun, the Moon, and nine major planets, three asteroids (Ceres, Pallas, Vesta) and four TNO (Eris, Haumea, Makemake, Sedna), the so called "dwarf planets", as well as TT-TDB differences. The program package affords an opportunity to get the rectangular coordinates of the Sun, the Moon, and nine major planets with respect to different centers (barycentric, geocentric, heliocentric and planetocentric) and barycentric (Solar System) coordinates of the dwarf planets. Routines included in the package support ephemeris EPM2004, as well as EPM2008. They support polynomial approximation for both binary and ASCII ephemeris files. Source code of the package Calc_Eph is free and available for outside users by FTP:
ftp://quasar.ipa.nw.ru/incoming/EPM/. The package is implemented in four standard languages: Fortran (Intel Fortran), ANSI C, Pascal, Java. The software package consists of a main test program ("Demo") and a module which contains reading and interpolating routines ("Calc_Eph") The interface of the calculating routines is unified with the other well known software products: DE, INPOP. The list of the subroutines contained in Calc_Eph are of primary interest to the user:

- InitBin, InitBinD, InitBinT: Read binary ephemeris or TT-TDB files;
- InitTxt, InitTxtD, InitTxtT: Read ASCII ephemeris or TT-TDB files;
- Calc_EPM, Calc_EPD: Calculate position and velocity (in AU, AU/day) of specified object with respect to specified center at the specified date;
- Calc_TDB: Calculate differences (in s) between TT and TDB times.

The initializing routines download the whole ephemeris in RAM without bufferization. The program package Calc_Eph is made for multiple call of interpolating routine in one program. User can obtain ephemerides of big planets, the "dwarf planets" or TT-TDB differences either in one program in any sequence, or one group at a time.

Clac_Eph is actually being supported and renovated. The package is accompanied by a manual. The routines of the package are easy to use, can be embedded in the user's software and can be called together with the existing products (DE, INPOP). At the present time, within the framework of the Working Group on Standardizing Access to Ephemerides activity, the unified ephemerides representation format and software are being developed.

5. REFERENCES

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