NUMERICAL EPHEMERIDES OF PLANETS AND NATURAL SATELLITES OF IAA RAS AND THEIR USES FOR SCIENTIFIC RESEARCH

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ABSTRACT. The dynamical model of the planetary part of the EPM2013 ephemerides of the IAA RAS has been fitted to about 800000 observations of different types (1913-2013). Their reference frame has been established with 321 ICRF-based VLBI measurements of spacecrafts near planets taken into account. EPM ephemerides serve as the basis for the Russian Astronomical and Nautical Astronomical Yearbooks, are planned to be used in the GLONASS and LUNA-RESOURCE programs, and are used for determination of physical parameters (asteroids masses, planet rotation, topography), $GM_\odot$ and its secular variation, the PPN parameters, the upper limit on mass of the dark matter in the Solar System. Moreover, numerical ephemerides of the 22 main planet satellites have been constructed; they also provide the basis for improving positions of the outer planets. Files containing polynomial approximation for EPM ephemerides (EPM2004, EPM2008, EPM2011) along with TT-TDB and ephemerides of Ceres, Pallas, Vesta, Eris, Haumea, Makemake, and Sedna are available from `ftp://quasar.ipa.nw.ru/incoming/EPM/`. The files are provided in IAA's binary and ASCII formats, as well as SPK and PCK formats.

1. THE DEVELOPMENT OF EPM2011 EPHEMERIDES

The EPM ephemerides (**E**phemerides of **P**lanets and the **M**oon) of the IAA RAS originated in the 1970's and are being improved since that time. These ephemerides are based upon relativistic equations of motion for celestial bodies and light rays, as well as relativistic time scales. EPM ephemerides are computed in the barycentric coordinate frame—BCRS, over more than 400-year interval (1787–2214).

Including into the process of simultaneous integration the 21 largest TNO (some of them are quite far, Eris which surpasses Pluto is an example) causes a significant change to the barycenter of the Solar System. The comparison of barycentric coordinates between EPM numerical theories and other ephemerides (DE, INPOOP) knowingly is nonsensical and gives large differences. Only the comparison of relative coordinates (heliocentric or geocentric) shows real differences between ephemerides.

Ephemerides EPM2011 were constructed (2011 – July 2012) before the B2 resolution of 28 GA IAU which fixed the value of the astronomical units of length (au) equal 149597870700 meters and proposed the determination of $GM_\odot$ in SI units. In EPM2011 the au value has been determined: $au_{EPM2011}$ = 149597870695.88 meters. Although following the B2 resolution does not increase the accuracy of constructed ephemerides, the next EPM ephemeris implementation will be made in accordance with the B2 resolution.

The dynamic model of the lunar motion was constructed by G. Krasinsky. Currently M. Vasiliev and E. Yagudina are developing the lunar part of the EPM ephemerides (one can find their publication in this issue). The tidal perturbation in the lunar orbital motion (due to tidal dissipation on the Earth body), as well as in rotational lunar motion (due to tidal dissipation on the Moon body) are computed using model with a delayed argument. The potential of the Moon is calculated up to 4-th order of the zonal index, the potential of the Earth includes the 5-th order harmonics.

During some time the planetary and lunar parts of the EPM2011 ephemerides were being improved separately. For EPM2011/m ephemerides, the parameters of the lunar and planetary parts of ephemerides have been in agreement with each other ("m" stands for "Moon"). The result of this agreement was a moderate change in the lunar motion, whereas the planet positions of EPM2011 and EPM2011/m are practically equivalent. While earlier the lunar libration was being computed along with positions of planets and the Moon for EPM ephemerides, now for the first time it is available to public: `ftp://quasar.ipa.nw.ru/incoming/EPM/`.

EPM2011/m ephemerides contain coordinates and velocities of the Sun, the Moon, nine major planets, three largest asteroids (Ceres, Pallas, Vesta) and 4 TNO (Eris, Haumea, Makemake, Sedna) (in au, au/day) as well as lunar libration (in radians) and TT-TDB (in seconds).

Thanks to the effort done by the IAU Commission 4 Working Group on Standardizing Access to Ephemerides and File Format Specification, EPM2011/m ephemerides are now provided in the formats developed by the Navigation and Ancillary Information Facility of Jet Propulsion Laboratory at NASA. The formats are: Spacecraft and Planet Kernel (SPK) for the position ephemerides of the Sun, Moon, Earth, other planets, and asteroids; also for the so-called "time ephemerides" containing TT-TDB data. Planetary Constants Kernel (PCK) for lunar orientation (libration angles). It was decided to avoid any kind of recalculations during the conversion from IAA's formats to PCK/SPK formats. To achieve that goal, a new data type (Type 20) has been added to the SPK and PCK specifications to support "velocity-only" Chebyshev polynomials used in EPM. The originally available data types were Type 2 (position only) and Type 3 (position and velocity). With Type 20, the differences between EPM files provided in IAA's binary format and the ones provided in the SPK/PCK formats are only in technical data (file header, section headers, comments etc), while the Chebyshev coefficients are identical in both formats. The SPK and PCK files for the EPM2011/m theory are available on the IAA's FTP site, as well as the original text and binary formats (Pavlov, Skripnichenko, 2014).

2. THE DIFFERENCES BETWEEN EPM2011 AND EPM2013 EPHEMERIDES

Planetary parts of EPM2013 differ from those of EPM2011 in: improved dynamical model; updated database of asteroids (masses and orbits); upgraded database observations.

For constructing planetary ephemerides using the best modern observations, it is necessary to take into account all influencing factors.

The dynamical model of planet part EPM2013 takes into account the following:

- mutual perturbations from the major planets, the Sun, the Moon and 5 most massive asteroids;
- perturbations from the other 296 asteroids chosen due to their strong perturbations upon Mars and the Earth;
- perturbation from the massive two-dimensional asteroid ring ($R_1 = 2.06$ au, $R_2 = 3.27$ au) with the constant mass distribution;
- perturbations from the 30 largest Trans-Neptunean Objects (TNO);
- perturbation from a massive ring of TNO in the ecliptic plane with the radius of 43 au;
- the relativistic perturbations;
- perturbations due to the solar oblateness $J_2 = 2 \cdot 10^{-7}$.

The main improvement of EPM2013 is usage of a massive two-dimensional asteroid ring instead of a one-dimensional asteroid ring in the EPM2011 model, as well as the including of 30 individual TNO into the integration instead 21 TNO for the EPM2011 model.

The EPM2013 ephemerides have been fitted to 792327 observations of different types, spanning 1913-2012, from classical meridian observations to modern planetary and spacecraft ranging (see Table 1). 114657 new observations have been added since EPM2011 (677670) including the observations obtained in 2010–2012 for Odyssey, Mars Reconnaissance Orbiter (MRO), Mars Express (MEX) and Venus Express (VEX) spacecraft, the 108 VLBI data (2011–2013) for VEX, Odyssey, MRO, as well as 224 SSD observations obtained in 2012 at Flagstaff and TMO observatories. These new data were received by us due to the courtesy Dr. W.Folkner and Dr. A.Fienga. The ephemerides of the inner planets are based fully on radio-technical observations (mostly, measurements of time delays).

In addition to optical observations of outer planets, positional observations of their satellites are used for construction of planetary ephemerides, as these observations are more precise and practically free from the phase effect, which is difficult to take into account. Since the position of a satellite relatively to the stars is determined both by the planetary motion and the satellite's own motion around the planet, the measurements of the positions of satellites may be used to define the planetary orbits more accurately. Analytical theories of the motion of the satellites by Lieske, Vienn and Duriez, Lascar and Jacobson are

Planet	Radio		Optical	
	Interval of observations	Number of observations	Interval of observations	Number of observations
Mercury	1964–2009	951	—	—
Venus	1961–2013	53379	—	—
Mars	1965–2012	680030	—	—
Jupiter+4 sat.	1973–1997	51	1914–2012	13364
Saturn+9 sat.	1979–2009	126	1913–2012	15056
Uranus+4 sat.	1986	3	1914–2012	11861
Neptune+1 sat.	1989	3	1913–2012	11664
Pluto	—	—	1914–2012	5839
In total	1961–2013	734543	1913–2012	57784

Table 1: 792327 observations used for fitting of EPM2013

incorporated in the ERA software system. However there is no opportunity to correctly introduce to these analytical theories the parameters of the satellites' motion improved from observations. Therefore, the researchers at the IAA RAS construct their own numerical theories of the motion of the satellites of Mars and the outer planets (Poroshina et al., 2012). The dynamical models of satellites' motion include mutual perturbations of the satellites, perturbations from the Sun, major planets, and figure of the central planet. For the Phobos and Deimos motion, the tidal perturbations from Mars are also taken into account. The satellite ephemerides were improved to about 70 000 astrometric observations of different types: position, differential, observations of mutual events of Jupiterian and Saturnian satellites, spacecraft observations for Martian satellites. The obtained ephemerides have been compared to observations and ephemerides of other authors and are successfully used for improvement of orbital motion of satellites themselves as well as of their central planets.

EPM2013 have been oriented to ICRF with the accuracy better than 1 mas by including into the total solution 321 ICRF-based VLBI measurements of spacecraft 1989–2013 near Venus, Mars, and Saturn. in EPM2011, there were only 213 VLBI observations.

3. USAGE OF EPM FOR SCIENTIFIC RESEARCH

At present EPM ephemerides are used for astronavigation on the Earth and space: they are the basis for the Russian Astronomical and Nautical Astronomical Yearbooks since 2006, and are planned to be used in the GLONASS and LUNA-RESOURCE programs and for various other programs.

Masses of 21 of 301 largest asteroids have been estimated directly from spacecraft ranging; masses of the rest asteroids were obtained from their known diameters and the estimated densities for the three taxonomic types (C, S, M). The total mass of the asteroid main belt including the masses of all asteroids and the asteroid ring has been obtained: $M_{\text{belt}} = (12.3 \pm 1.2) \cdot 10^{-10} M_{\odot}$ ($\approx 3\, M_{\text{Ceres}}$). From the estimate of the mass of the TNO ring and the known masses of the 21 largest TNO and Pluto we obtained the mass of the whole set of TNO: $M_{\text{TNO}} = 790 \cdot 10^{-10} M_{\odot}$ ($\approx 164\, M_{\text{Ceres}}$ or $2\, M_{\text{Moon}}$) (Pitjeva, 2013). Those estimates shed light on the dynamics of the Solar System now and at the time of its formation.

New estimations of PPN parameters have been obtained: $\beta - 1 = -0.00002 \pm 0.00003$, $\gamma - 1 = 0.00004 \pm 0.00006$. The good correspondence of the planetary motions and the propagation of light to the predictions of General Relativity narrows significantly the range of possibilities for alternative theories of gravitation (Pitjeva & Pitjev, 2013).

It has been found from planet observations that heliocentric gravitational constant $GM_{\odot}$ is decreasing with the rate $G\dot{M}_{\odot}/GM_{\odot} = (-6.3 \pm 4.3) \cdot 10^{-14}$ per year (2σ). The variation of $GM_{\odot}$ reflects the balance between the mass lost through radiation and solar wind and the material falling onto the Sun. Using the maximum limits for a possible change of $M_{\odot}$, it has been obtained that the annual change of the gravitation constant G must fall within the interval $-7.0 \cdot 10^{-14} < \dot{G}/G < +7.8 \cdot 10^{-14}$ with a 95% probability (Pitjeva & Pitjev, 2012; Pitjeva & Pitjev, 2013).

Using the estimates of the additional perihelion advances obtained from observation for different planets, it has been found that the density of dark matter ρ_{dm} must be less than $1.1 \cdot 10^{-20}$ gcm^{-3} at the distance of Saturn's orbit, and the mass of dark matter inside Saturn's orbit must be less than

$7.9 \cdot 10^{-11} M_{\odot}$, even if it is concentrated toward the center (Pitjev & Pitjeva.,2013; Pitjeva & Pitjev,2013).

4. RESULTS AND CONCLUSION

Improvement of the dynamical model of planet motion and increase of the number of high-precision spacecraft data have resulted in the following progress:

- the accuracy of estimation of the mass of the two-dimensional asteroid ring and the total mass of the asteroid belt increased by the order of magnitude: $M_{belt} = (12.242 \pm 0.106) \cdot 10^{-10}\ M_{\odot}$;
- orbits of all planets have changed and were improved distinctly. In particular, the formal uncertainties of the semi-major axes of the inner planets have halved
- the residuals also have been improved; the rms residuals of ranging for Odyssey, MRO, MEX spacecraft have decreased up to 1.1 m (see Figure 1).

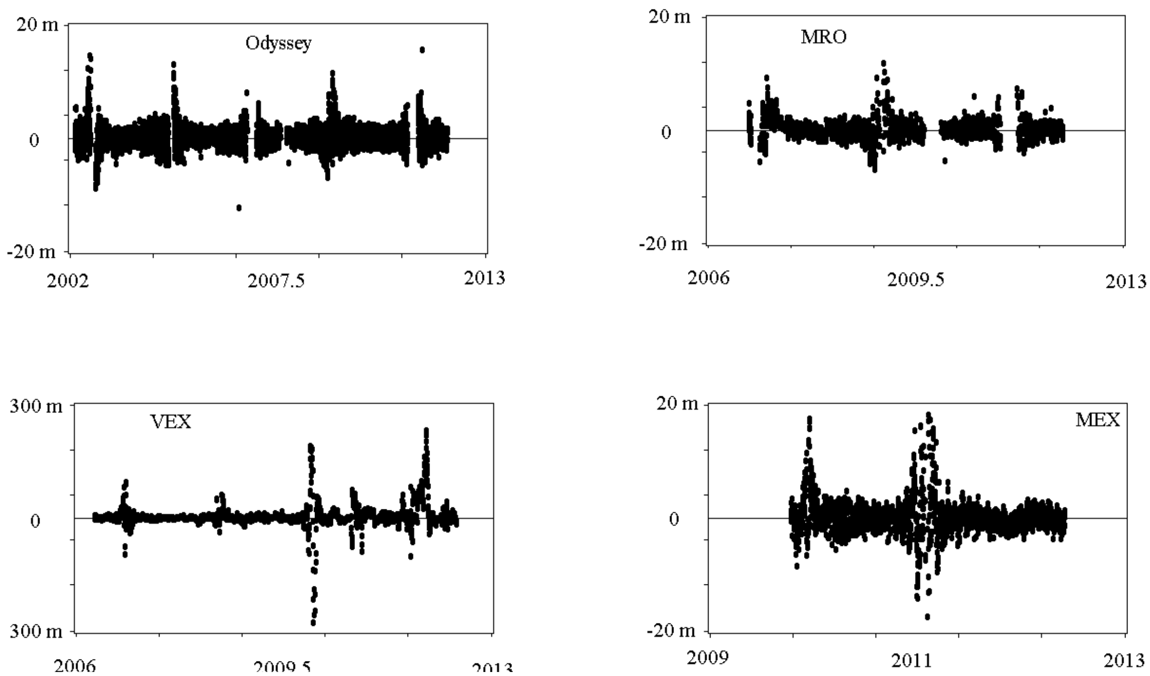

Figure 1: The rms ranging residuals for spacecraft Odyssey 1.1 m, MRO 1.1 m, MEX 1.4 m, VEX 3.1 m.

5. REFERENCES

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