Numerical ephemerides of planets (EPM) and natural satellites of IAA RAS and their use for scientific research

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- **The completion of EPM2011**
- **The distinction EPM2013 from EPM2011**
- **Main Satellites of planets at IAA RAS**
- **Use of EPM for scientific research**

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EPM ephemerides are computed by numerical integration of the equations of motion of planets, the Sun, the Moon, asteroids, TNO and the equations of the lunar physical libration in the barycentric coordinate frame of J2000.0 **over the 400 years interval (1800 – 2200**),

The **planet part of EPM2011** was fitted to **680000** observation (1913**–**2011). For **the lunar part of EPM2011**, the potential of the Moon is calculated up to 4-th order of the zonal index, the potential of the Earth up to 5-th order, taking into account the tidal perturbations in the rotational motion of the Moon and the effects of the elasticity of the lunar body. The analysis of **17580 LLR data** 1970-2012 for the 5 lunar reflectors was carried out.

All parameters of the planet and lunar parts of EPM2011 **were agreed.**

The updated program package **Calc_Eph** (**Pavlov D.A.**) containing **IAA Planetary and Moon Ephemerides (EPM2004, EPM2008, EPM2011)** along with associated reading and interpolating routines is available: **ftp://quasar.ipa.nw.ru/incoming/EPM/.**

Following the effort done by IAU Commission 4 Working Group on Standardizing Access to Ephemerides, EPM ephemerides are now provided in the following formats:

- **SPK** (.bsp files) for Earth, Moon, Sun, planets, asteroids, TT-TDB.
- **PCK** (.bpc files) for lunar libration,
- along with its **original text** and **binary formats**.

The distinctions of planet part EPM2013 from EPM2011 are:

- improved dynamical model;
- updated database of asteroids (masses and orbits);
- upgraded database observations.

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

- mutual perturbations from the major planets, the Sun, the Moon and 5 more 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) (in EPM2011 one dimensional asteroid ring was) with the constant mass distribution;
- perturbations from the 30 (was 21) largest 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 massive two-dimensional asteroid ring (R_1, R_2) for EPM2013

The general equations of motion for bodies in a nonrotating barycentric coordinate system are

$$\ddot{\mathbf{r}}_i = A + B + C + D + E,$$

$\mathbf{r}_i$, $\dot{\mathbf{r}}_i$, $\ddot{\mathbf{r}}_i$ – the solar-system-barycentric position, velocity, and acceleration vectors of body i;
$M_r = Gm_r$, R_r – mass and radius of the rings;
F – hypergeometrical function.

Acceleration for the inner point: ($r < R_1$, $\lambda = r/R_1$, $\mu = r/R_2$):

$$\mathbf{D} = \frac{M_r}{{R_2}^2 - {R_1}^2}\left[\frac{1}{R_1}\cdot F(\frac{1}{2},\frac{3}{2},2,\lambda^2) - \frac{1}{R_2}\cdot F(\frac{1}{2},\frac{3}{2},2,\mu^2)\right]\mathbf{r}$$

Acceleration for the outer point: ($r > R_2$, $\lambda = R_1/r$, $\mu = R_2/r$):

$$q = F(-\frac{1}{2},\frac{1}{2},1,\lambda^2) - (1+\lambda^2)F(\frac{1}{2},\frac{1}{2},1,\lambda^2) + \frac{\lambda^2}{2}\cdot[F(\frac{1}{2},\frac{3}{2},2,\lambda^2) + (1-\lambda^2)F(\frac{3}{2},\frac{3}{2},2,\lambda^2)],$$

$$s = F(-\frac{1}{2},\frac{1}{2},1,\mu^2) - (1+\mu^2)F(\frac{1}{2},\frac{1}{2},1,\mu^2) + \frac{\mu^2}{2}\cdot[F(\frac{1}{2},\frac{3}{2},2,\mu^2) + (1-\mu^2)F(\frac{3}{2},\frac{3}{2},2,\mu^2)].$$

$$\mathbf{E} = \frac{2M_r(s-q)}{({R_2}^2 - {R_1}^2)r}\cdot\mathbf{r}$$

Observations

792327 (677670) observations are used for fitting EPM2013

Planet	Radio		Optical	
	Interval of observ.	Number of observ.	Interval of observ.	Number of observ.
Mercury	1964-2009	951	——	——
Venus	1961-2013	53379	——	——
Mars	1965-2012	680030	——	——
Jupiter +4sat.	1973-1997	51	1914-2011	13364
Saturn+9sat.	1979-2009	126	1913-2011	15056
Uranus+4sat.	1986	3	1914-2012	11861
Neptune+1sat.	1989	3	1913-2012	11664
Pluto	——	——	1914-2012	5839
In total (EPM2011)	*1961-2010*	*630110*	*1913-2011*	*57560*
In total	*1961-2012*	*734543*	*1913-2012*	*57784*

Ephemerides of the main satellites of planets

The numeral ephemerides of the main satellites of planets have been constructed: Jupiter (Io, Europa, Ganymede, Callisto), Saturn (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, Phoebe), Uranus (Ariel, Umbriel, Titania, Oberon, Miranda), Neptune (Triton, Nereid) on the interval 1960–2020; and ephemerides of Mars satellites (Phobos, Deimos) on the interval 1890–2020 within the framework of the program package ERA.

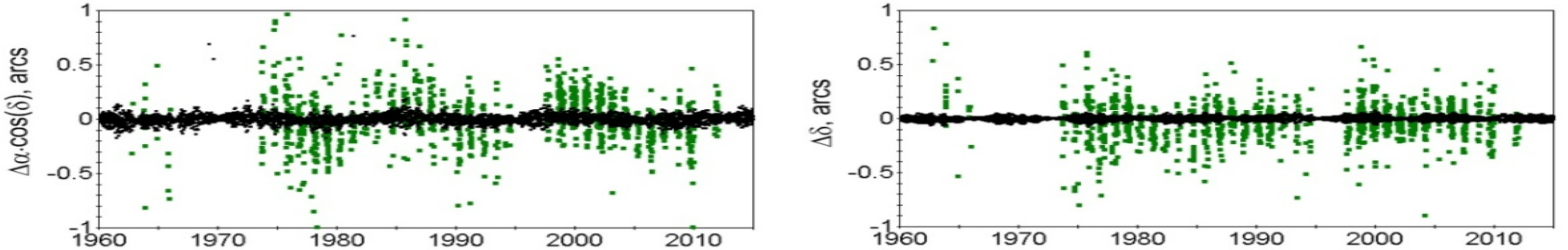
The dynamical models include the mutual perturbations of the satellites, disturbances of the Sun, major planets and oblateness of the central planet (J_2, J_4 for Saturn and Uranus, up to J_6 for Jupiter, the expansion of the Mars gravity field up to degree and order 12). For the Phobos and Deimos motion, the tidal perturbations from Mars are taken into account.

The ephemerides were improved to about 70000 astrometrical observations of different types (position, differential, mutual events observations of Saturnian satellites, spacecraft observations for Martian satellites) 1877 – 2011. The created ephemerides were compared with observations and ephemerides of other authors.

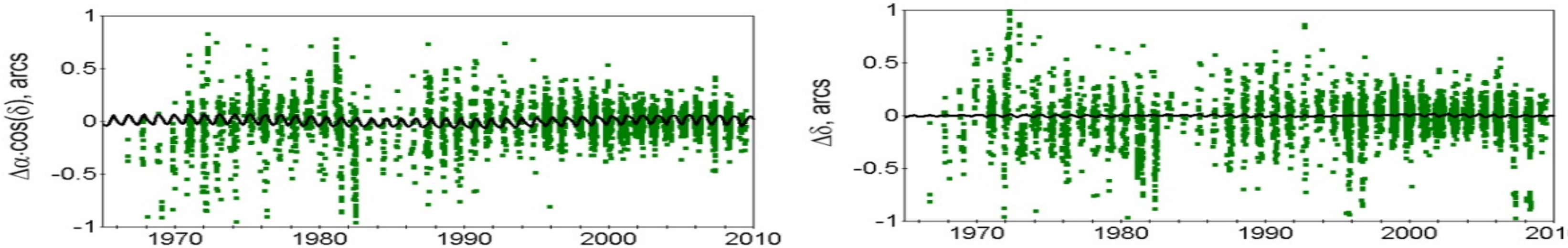
WRMS are 0.15″ – 0.25″, and do not exceed the a priory errors. Comparison shows that results agree.

The constructed ephemerides of satellites are used also for improvement of orbital motion of their central planets, as well as for calculation of the different ephemeris positions in their systems, which are available at the IAA RAS website http://www.ipa.nw.ru/PAGE/rusipa.htm.

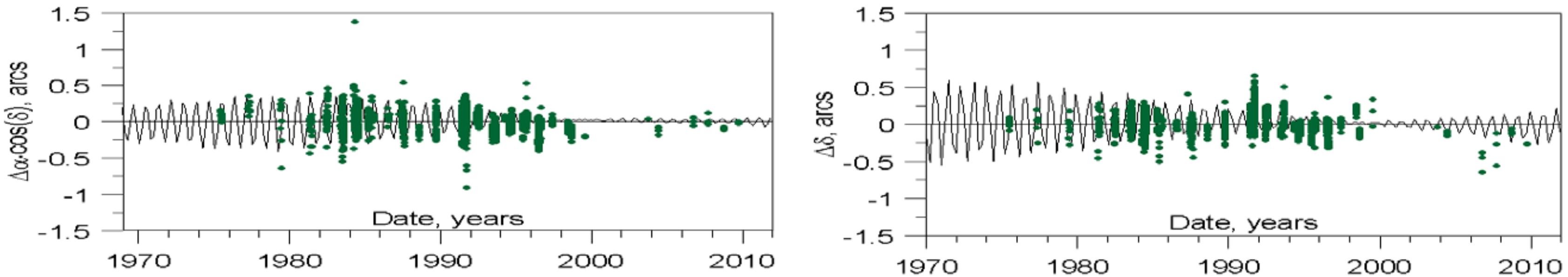
PoroshinaA., Zamarashkina M., Kosmodamianskiy G., IAA Transaction, 2012, 26, 75-87.



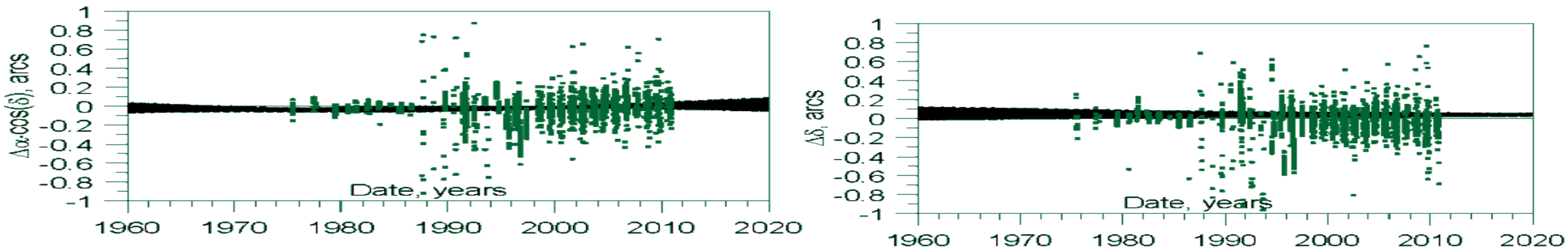
The residuals (green) and comparison with V. Lainey theory (black) for Io (Jupiter–1).



The residuals (green) and comparison with TASS1.7 of A.Vienne, L.Duriez (black) for Titan (Saturn–6).



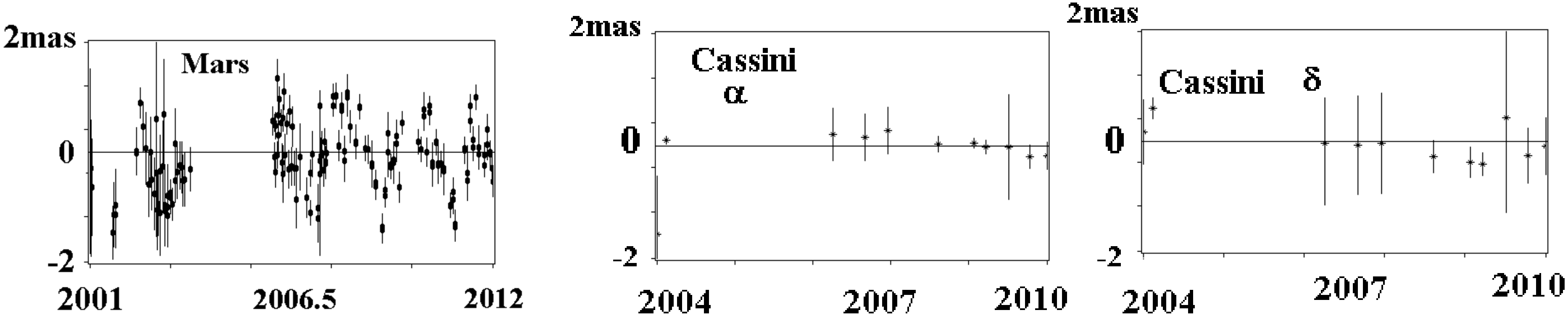
The residuals (green) and comparison with JPL ephemerides (black) for Ariel (Uranus –1).



The residuals (green) and comparison with JPL ephemerides (black) for Triton (Neptune –1).

Orientation

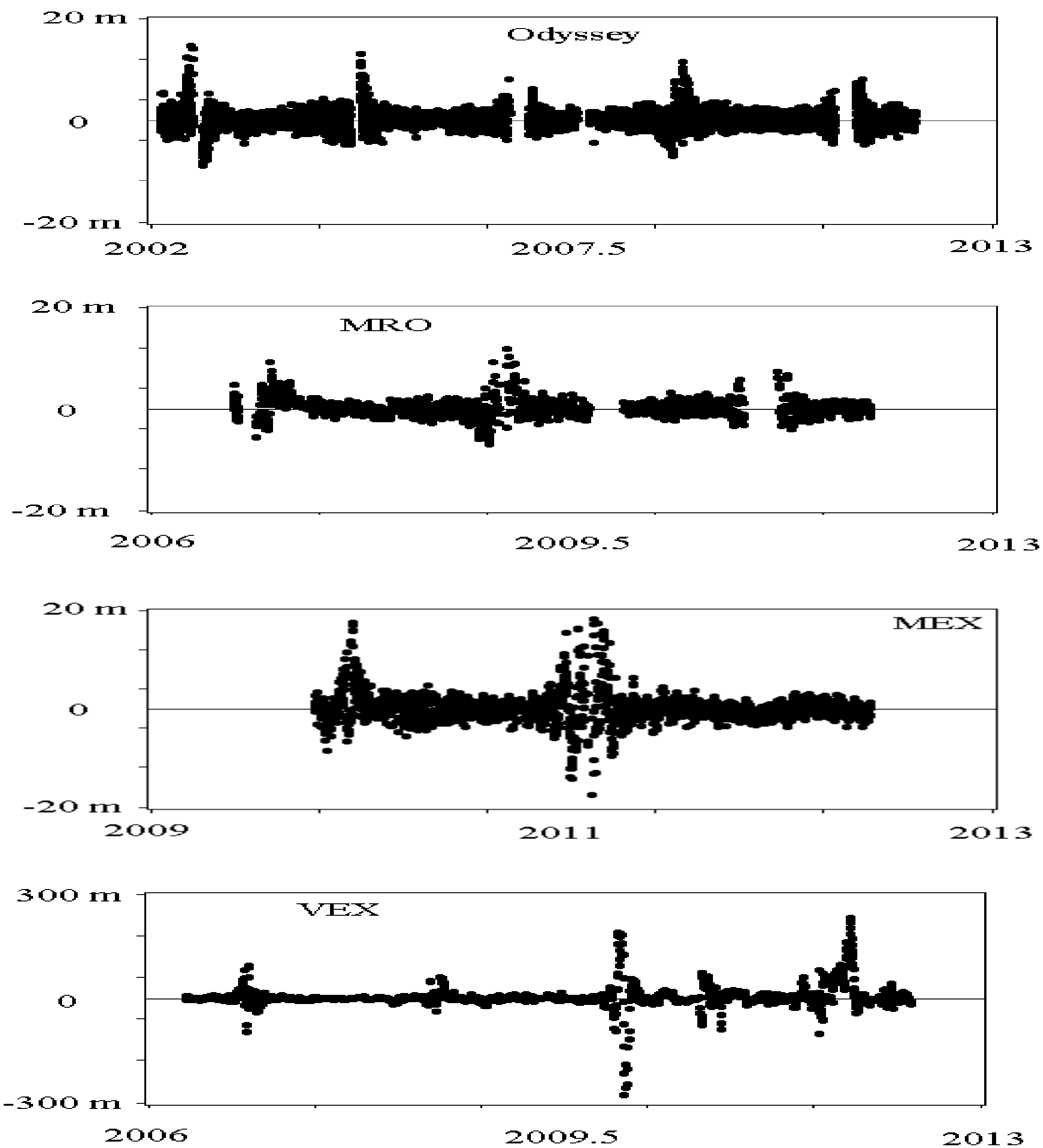
EPM2013 have been oriented to ICRF with the accuracy better than 1 mas by including into the total solution the 321 ICRF-base VLBI measurements of spacecraft (Magellan, Phobos, MGS, Odyssey, Venus Express, and Mars Reconnaissance Orbiter, Cassini) 1989 – 2013 near Venus, Mars, and Saturn.



Spacecraft VLBI residuals

The rotation angles for the orientation of EPM2013 onto ICRF

Interval	Number of observ.	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	213	-0.000±0.042	-0.025±0.048	0.004±0.028
1989-2013	321	-0.000±0.038	0.013±0.041	-0.002±0.025



The rms residuals of ranging for spacecraft Odyssey − 1.1 m, MRO − 1.1 m, MEX − 1.4 m, VEX − 3.1 m.

Conclusion concerning EPM2013

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:**

$$\mathbf{M_{belt} = (12.242 \pm 0.106) \cdot 10^{-10}\, M_{Sun.}}$$

- Orbits of all planets, changed and were improved distinctly.

  In particular, the formal uncertainties of the semi-major axes of the inner planets **decreased by two times**.

- The residuals improved also; The rms residuals of ranging for Odyssey, MRO, MEX spacecraft **decreased up to 1.1 m**.

Use of EPM for scientific research and astronavigation

• Navigation on the Earth — EPM ephemerides are the basis for the Russian Astronomical Yearbooks and Nautical Astronomical Yearbooks.

• Navigation in space — using EPM ephemerides in programs GLONASS and LUNA-RESOURCE.

• Orientation of EPM to ICRF with the accuracy better then tenth part of 1 mas reduces to decrease uncertainties of the heliocentric coordinates of the Eath to less 250 m

=> investigation of pulsars and exoplanets.

• The parameters of Mars rotations (precession, nutation, seasonal teams, the polar moment of inertia => Mars geophysics

Pitjeva, IAA Transaction, 1999, 4, 22-35.

• Masses of 21 asteroids;

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

$M_{belt} = (12.3 \pm 1.1) \cdot 10^{-10} M_{\odot}$ (≈ 3 Ceres mass);

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:

$M_{TNO} = 790 \cdot 10^{-10} M_{\odot}$, (≈ 164 Ceres mass or 2 lunar mass).

=> dynamics of the Solar System and its forming.

Pitjeva, Proc. Inter. Conf. "Asteroid-comet hazard-2009", 2010, 237-241.

Use of EPM for scientific research and astronavigation

- **PPN parameters:**

β-1 = –0.00002±0.00003, γ-1 = +0.00004±0.00006

=> a correspondence of the planetary motions and the propagation of light to General Relativity and <u>narrow</u> significantly the range of <u>possible values for aternative theories of gravitation</u>

Pitjeva E.V., Pitjev N. P., MNRAS, 432, 2013, 3431-3437

- **The <u>heliocentric gravitational constant $GM_{\odot}$ decreases with rate</u>**

$$(G\dot{M}_{\odot})/GM_{\odot} = (-6.3 \pm 4.3) \cdot 10^{-14} \text{ per year } (2\sigma)$$

Using the limits for the solar mass $M_{\odot}$, the $\dot{G}/G$ change falls within the interval

$$-7.0 \cdot 10^{-14} < \dot{G}/G < +7.8 \cdot 10^{-14} \text{ per year with a 95\% probability.}$$

Pitjeva, Pitjev: Solar System Research, 2012, 46, 78-87; MNRAS, 432, 2013, 3431-3437

- **Using estimates of the perihelion advans and $GM_{\odot}$ obtained from observation for different planets, <u>limitations on dark matter in the Solar System were found</u>:**

distributed density of dark matter ρ_{dm} must be less than $1.1 \cdot 10^{-20}$ g/cm^3 at the distance of the Saturn orbit,

the mass of dark matter in the area inside the orbit of Saturn must be less than $7.9 \cdot 10^{-11}$ $M_{\odot}$, even taking into account its possible concentration to the center.

Pitjev, Pitjeva: Astronomy Letters, 2013, 39,141-149; MNRAS, 432, 2013, 3431-3437

Thank you for your attention !