EPM – the high-precision planetary ephemerides of IAA RAS for scientific research, astronavigation on the Earth and space

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- **Dynamical model of EPM2011**
- **Observations, their reduction, TT-TDB**
- **The values of some solution parameters**
- **The orientation of EPM2011**
- **Use of EPM for scientific research and astronavigation**
- **Future improvements in EPM ephemerides**

The **EPM** ephemerides (**E**phemerides of **P**lanets and the **M**oon) of IAA RAS originated in the seventies of the last century to support space flights and have been developed since that time.

All the **modern ephemerides** (DE – JPL, EPM – IAA RAS, INPOP – IMCCE) are based upon **relativistic equations of motion for astronomical 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 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 **by the Everhart method over the 400 years interval (1800 – 2200**) using the program package ERA (**E**phemeris **R**esearch in **A**stronomy) (Krasinsky and Vasilyev, 1997).

The dynamical model of EPM2011 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 asteroid ring with the constant mass distribution;
- perturbations from the 21 largest TNO;
- perturbation from a massive ring of TNO in the ecliptic plane with the radius of 43 au;
- perturbations due to the solar oblateness $J_2=2 \cdot 10^{-7}$;
- perturbations due the figures of the Earth and the Moon;
- relativistic perturbations.

Observations

676 948 observations are used for fitting EPM2011

Planet	Radio		Optical	
	Interval of observ.	Number of obser.	Interval of obser.	Number of obser.
Mercury	1964-2009	948	——	——
Venus	1961-2010	40061	——	——
Mars	1965-2010	578918	——	——
Jupiter +4sat.	1973-1997	51	1914-2011	13023
Saturn+9sat.	1979-2009	126	1913-2011	14744
Uranus+4sat.	1986	3	1914-2011	12045
Neptune+1sat.	1989	3	1913-2011	11474
Pluto	——	——	1914-2011	5552
In total	1961-2010	620110	1913-2011	56838

The reduction of radar data

- relativistic corrections — the time delay of the propagation of radio-signals in the gravitational field of the Sun, Jupiter, Saturn (the Shapiro effect) and the reduction of observations from the coordinate time of the ephemerides to the proper time of the observer;
- the delay from the Earth's troposphere;
- the delay from the solar corona, the parameters of its model are determined from observations for different solar conjunctions (the barest necessity of multiple frequencies !);
- the correction for the surface topography of planets (Mercury, Venus, Mars).

The reduction of optical data

- the different catalogues => FK4 => FK5 => ICRF;
- correction for the additional phase effect (the main phase corrections were made by observers themselves);
- relativistic correction for the light bending.

+ TT-TDB obtained by numerical integrating for EPM

Approximately 270 parameters were determined while improving the of planetary part of EPM2011 ephemerides

- the orbital elements of planets and 18 satellites of the outer planets;
- the value of the astronomical unit or $GM_\odot$;
- three angles of orientation of the ephemerides with respect to the ICRF;
- thirteen parameters of Mars' rotation and the coordinates of three landers on Mars;
- the masses of 21 asteroids; the mean densities of asteroids for three taxonomic types (C, S, and M); the mass and radius of the asteroid belt;
- the mass of the TNO belt;
- the Earth to Moon mass ratio;
- the Sun's quadrupole moment (J_2) and parameters of the solar corona for different conjunctions of planets with the Sun;
- eight coefficients of Mercury's topography and corrections to the level surfaces of Venus and Mars;
- the constant bias for three runs of planetary radar observations and seven spacecraft;
- five coefficients for the supplementary phase effect of the outer planets;
- post - model parameters (β, γ, π advances, $\dot{G}M_\odot/GM_\odot$, change of a_i).

The values of some estimated parameters of EPM2011 (with uncertainties 3σ):

the Astronomical Unit: AU = (149597870695.93 ± 0.12) m, or

the heliocentric gravitation constant: $GM_\odot = (132712440031.1 \pm 0.3)\ km^3/s^2$,

the Earth to Moon mass ratio: $M_{Earth}/M_{Moon} = 81.30056763 \pm 0.00000005$..

Distribution of the radar observations and their rms residuals (σ)

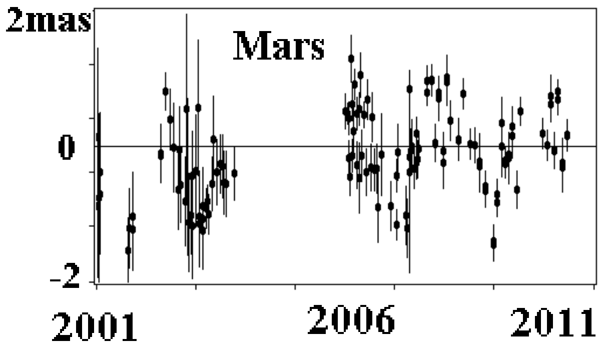
Planet	Data type	Interval	N. of n.p.	σ
Mercury	τ [m]	1964–1997	746	611
	spacecraft τ [m]	1974–2009	5	19.1
	spacecraft α, δ [mas]	2008–2009	6	1.3
Venus	τ [m]	1961–1995	1355	584
	Magellan dr [mm/s]	1992–1994	195	0.007
	MGN,VEX VLBI $\alpha + \delta$ [mas]	1990–2010	47	2.7
	VEX τ [m]	2006–2010	1721	2.9
	Cassini τ [m]	1998–1999	2	5.6
	Cassini α, δ [mas]	1998–1999	4	1.3
Mars	τ [m]	1965–1995	403	747
	spacecraft τ [m]	1971–1989	644	48.6
	Viking τ [m]	1976–1982	1258	9.9
	Viking $d\tau$ [mm/s]	1976–1978	14978	0.89
	Pathfinder τ [m]	1997	90	3.2
	Pathfinder $d\tau$ [mm/s]	1997	7574	0.09
	MGS τ [m]	1998–2006	7341	1.3
	Odyssey τ [m]	2002–2009	8187	1.1
	MRO τ [m]	2006–2009	930	2.5
	MEX τ [m]	2009–2010	970	2.0
	spacecraft VLBI $\alpha + \delta$ [mas]	1989–2010	144	0.6
Jupiter	spacecraft τ [m]	1973–2000	7	11.1
	spacecraft α, δ [mas]	1973–2000	16	5.0
	spacecraft VLBI $\alpha + \delta$ [mas]	1996–1997	24	9.3
Saturn	spacecraft τ [m]	1979–2006	34	2.8
	spacecraft α, δ [mas]	1979–2006	92	0.4
Uranus	VGR2 τ [m]	1986	1	105
	VGR2 α, δ [mas]	1986	2	11.0
Neptune	VGR2 τ [m]	1989	1	14.0
	VGR2 α, δ [mas]	1989	2	3.7

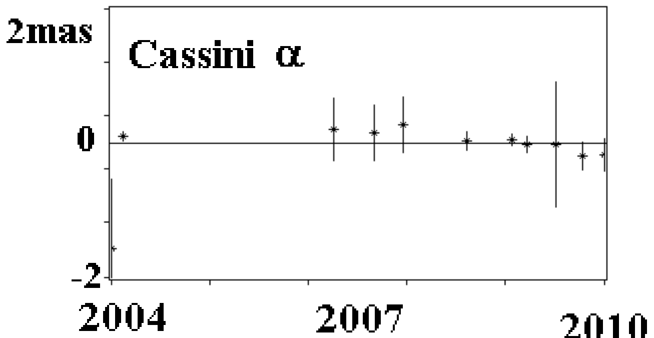
Distribution of the optical observations and their rms residuals, the mean between $\alpha\cos\delta$ and δ (σ), in mas, 1913–2010

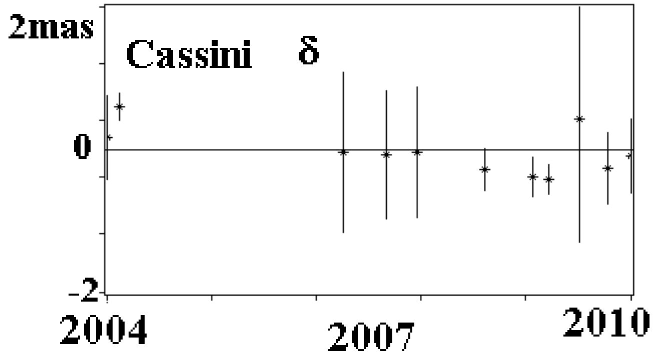
Planet	Observation number	σ
Jupiter+4 sat.	13023	190
Saturn+9 sat.	14744	159
Uranus+4 sat.	11681	188
Neptune+1 sat.	11474	176
Pluto	5552	139
In total	56474	

Orientation

EPM2011 have been oriented to ICRF with the accuracy better than 1 mas by including into the total solution the 213 ICRF-base VLBI measurements of spacecraft (Magellan, Phobos, MGS, Odyssey, Venus Express, and Mars Reconnaissance Orbiter, Cassini) 1989 – 2010 near Venus, Mars, and Saturn.





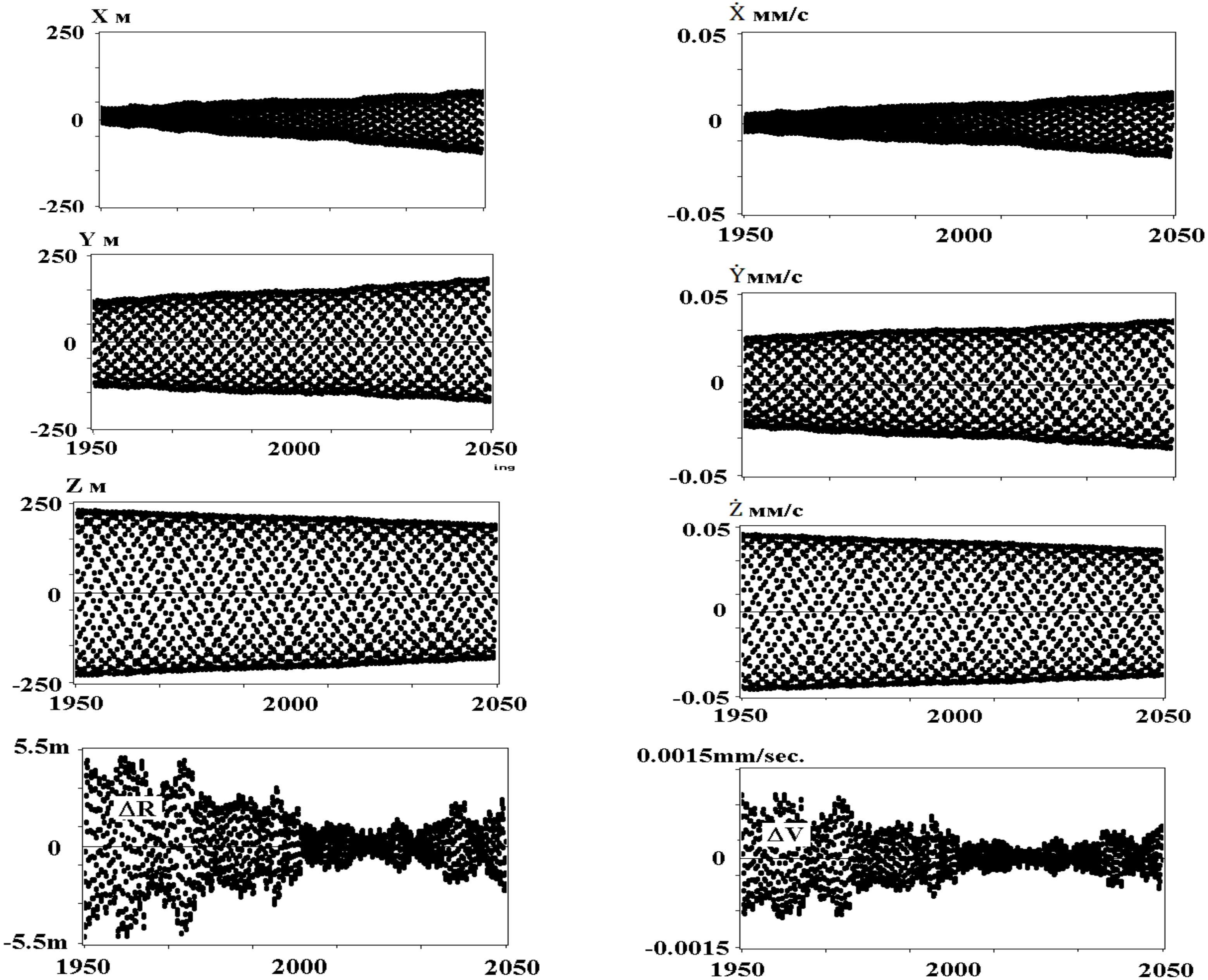


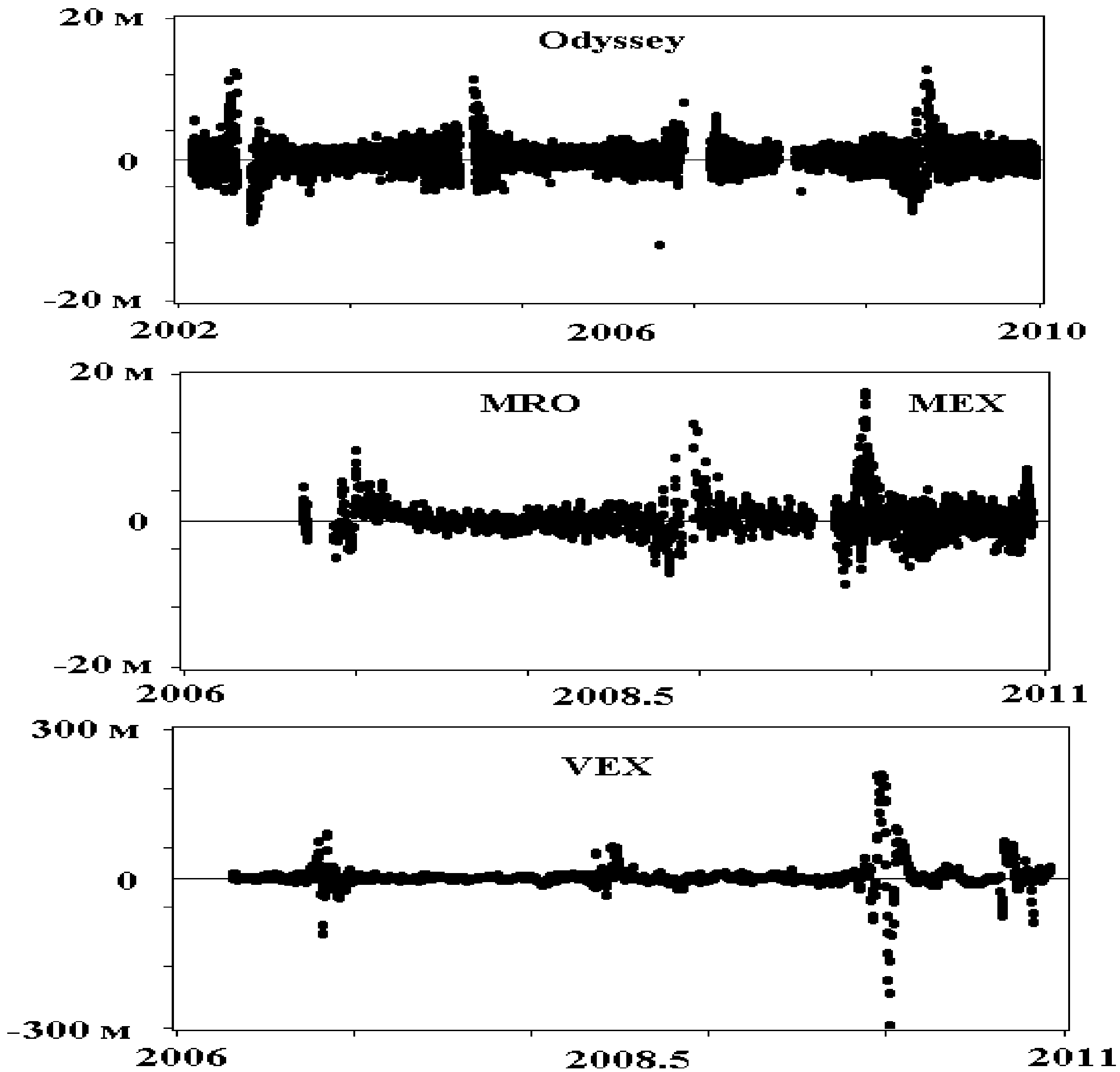
Spacecraft VLBI residuals

The rotation angles for the orientation of EPM2011 onto ICRF

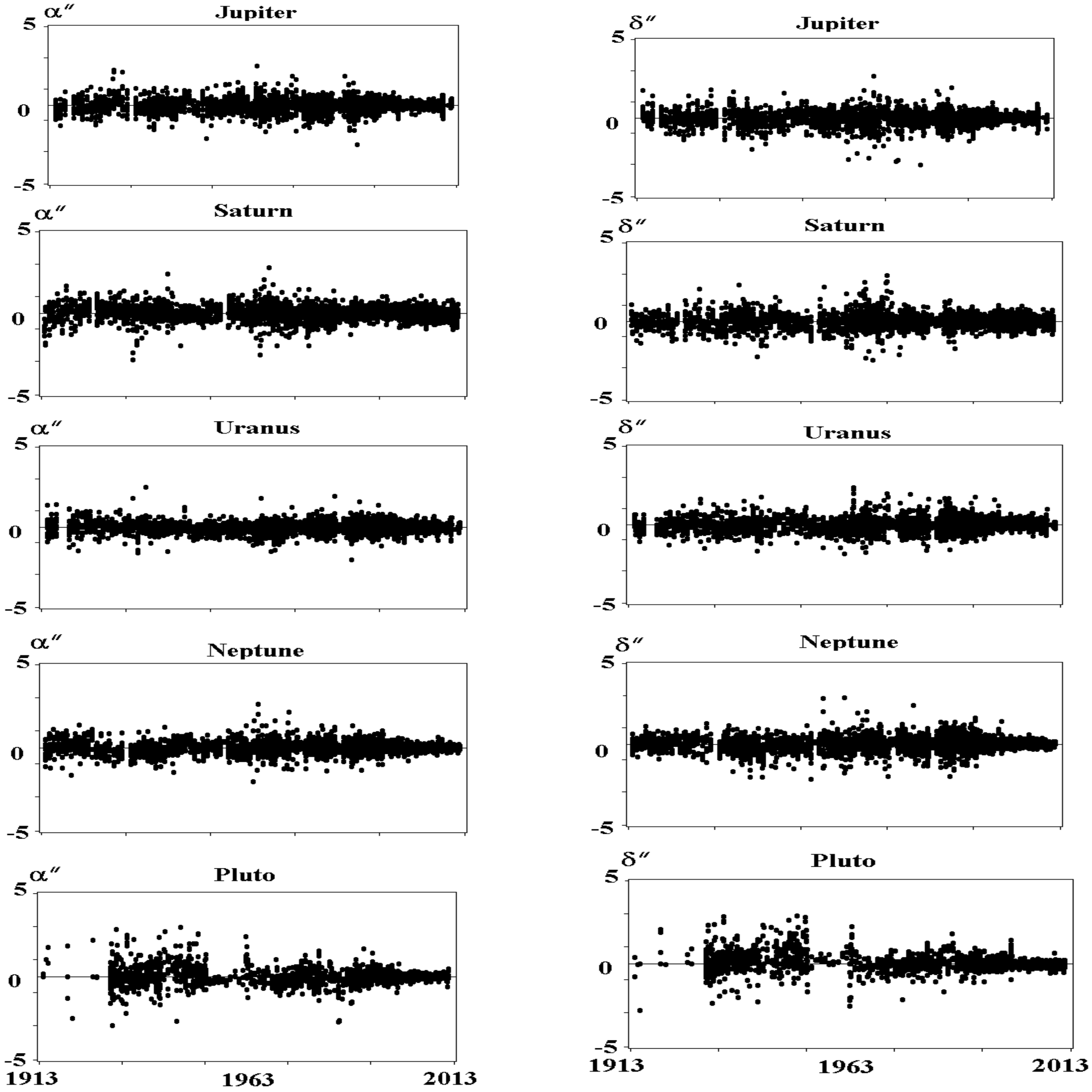
Interval	Number of observ.	ε_x mas	ε_y mas	ε_z mas
1989-1994	20	4.5±0.8	-0.8±0.6	-0.6±0.4
1989-2003	62	1.9±0.1	-0.5±0.2	-1.5±0.1
1989-2007	118	-1.528±0.062	1.025±0.06	1.271±0.046
1989-2010	213	-0.000±0.042	-0.025±0.048	0.004±0.028

Differences of heliocentric coordinates, velocities, distances of the Earth for DE424 and EPM2011, 1950 – 2050





The rms residuals of ranging for spacecraft Odyssey − 1.1 m, MRO − 2.5 m, MEX − 2.0 m, VEX − 2.9 m.



Residuals of the outer planets in α cosδ and δ, 1913—2011, the scale ±5″.

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:

$M_{belt} = (12.3 \pm 2.1) \cdot 10^{-10} M_{\odot}$ **(≈ 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 alternative theories of gravitation</u>

Pitjeva, Proc. IAU Symp. No. 261, 2010, 170-178

- **The <u>heliocentric gravitational constant GM$_\odot$ decreases with rate</u>**

$$(G\dot{M}_\odot)/GM_\odot = (-5.04 \pm 4.14) \cdot 10^{-14} \text{ per year } (3\sigma).$$

Using the limits for the solar mass M$_\odot$, the G/G change falls within the interval

$-4.2 \cdot 10^{-14} < \dot{G}/G < +7.5 \cdot 10^{-14}$ per year **with a 95% probability.**

Pitjeva, Pitjev. Solar System Research, 2012, 46, 78-87.

- **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•10^{-20} g/cm^3 on the distance of the Saturn orbit,

the mass of dark matter in the area inside the orbit of Saturn must be less than 1.7•10^{-10} M$_\odot$, even taking into account its possible concentration to the center.

Pitjev, Pitjeva. Astronomy Letters, 2013, in print.

Future improvements in EPM ephemerides

Updating our main software — the programming package ERA for a better accuracy and speed of computation, a better availability and understanding:

- **choice of the new integrator,**
- **rewriting all ERA subroutines with the extended precision,**
- **giving a more precise formulas for some reductions, where this is necessary,**
- **doing Chebyshev polynomials for positions of ephemeris objects (currently for velocities) and the SPK format versions.**

Improvements of the dynamical model of planet motions:

- **including the oblatenees of Jupiter,**
- **taking into account satellites together with planets (currently integrating planet barycenters),**
- **enhancing asteroid perturbation and including the uncertainties of undetermined asteroid masses in the uncertainties of estimated parameters,**
- **taking into account decrease of the solar mass,**
- **possible including terms of the second order of the post–Newtonian approximation of General Relativity.**

Thank you for your attention !