Evolution of EPM ephemerides of IAA RAS

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Ephemerides EPM—Ephemerides of Planets and the Moon

EPM **were** first **created in the 1970s** in support of Russian space flight missions **and constantly improved at IAA RAS**.

Several factors drive the progress of planet ephemerides:

- **dynamical models of planet motion;**
- **observational data, with the crucial role of spacecraft ranging;**
- **reduction of observations;**
- **updated database of asteroids (masses and orbits);**
- **program software;**
- **access to ephemerides.**

The uncertainty of modern ranging observations is only a few meters, that demands the accuracy of planets' positions of at least 12 significant figures, so it is necessary to take into account any significant influencing factors.

The <u>dynamical models</u> of planet part EPM take into account the following

<u>EPM87</u>:

- **mutual perturbations from the major planets, the Sun, the Moon and 5 most massive asteroids;**
- **the relativistic perturbations.**

EPM are based on General Relativity involving the relativistic equations of celestial bodies motion and light propagation as well as the relativistic time-scales.

<u>EPM98</u>: +

- **perturbations from the other 296 asteroids chosen due to their strong perturbations upon Mars and the Earth.**

<u>EPM2000</u>: +

- **perturbations due to the solar oblateness J_2.**

<u>EPM2004</u>: +

- **perturbation from the massive one dimensional asteroid ring with the constant mass distribution.**

<u>EPM2008</u>: +

- **perturbations from the 21 largest TNO;**

<u>EPM2011</u>: +

- **perturbation from a massive ring of TNO in the ecliptic plane with the R=43au.**

<u>EPM2013/EPM2014</u>: +

perturbation from the massive two-dimensional asteroid ring (R_1= 2.06 au, R_2 = 3.27 au);

perturbations from the 30 largest TNO.

Observations

792882 observations are used for fitting EPM2013

Planet	Radio		Optical	
	Interval of observ.	Number of observ.	Interval of observ.	Number of observ.
Mercury	1964-2009	948	——	——
Venus	1961-2013	53370	——	——
Mars	1965-2012	680011	——	——
Jupiter +4sat.	1973-1997	51	1914-2012	13376
Saturn+9sat.	1979-2009	126	1913-2012	15264
Uranus+4sat.	1986	3	1914-2012	11882
Neptune+1sat.	1989	3	1913-2012	11694
Pluto	——	——	1914-2012	6154
In total EPM2013	*1961-2013*	*734512*	*1913-2012*	*58370*
+ EPM2014	2004-2014 (normal points)	+ 4086 Ody,MRO,MEX VEX, Cassini	1931-2013	+ 7861 Pluto (Lowell. Pico dos Dias)

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:

$N_e(r) = A/r^6 + (B+dBt)/r^2$ (the barest necessity of multiple frequencies !);

• the correction for the surface topography of planets (Mercury, Venus, Mars).

The reduction of optical data

• 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.

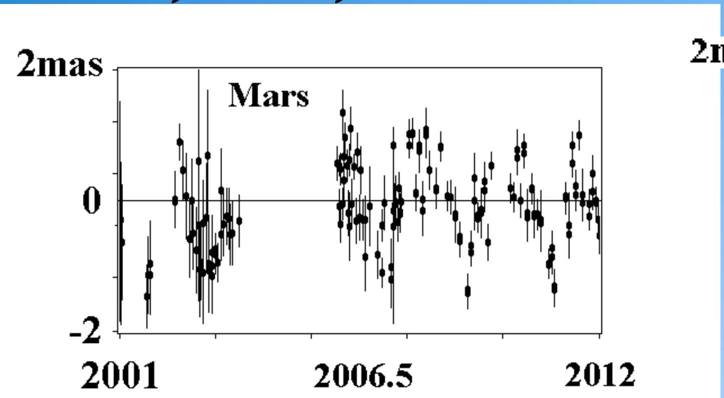
+ TT-TDB obtained by numerical integration for EPM

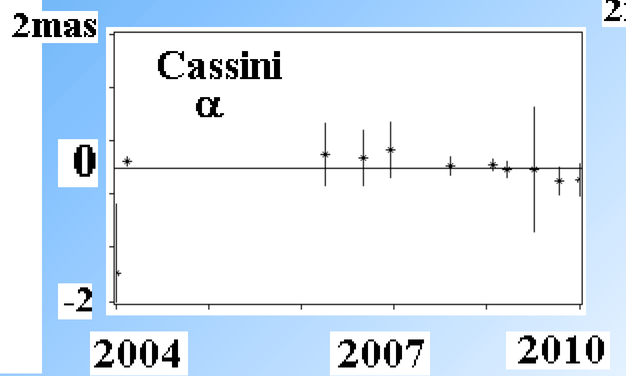
Standish E.M., 1990. – A&A, 233, 252-271.

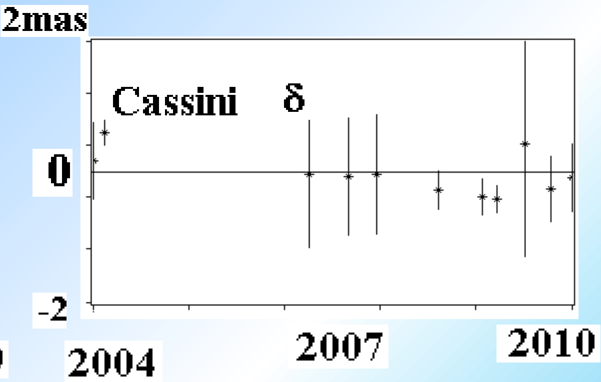
Pitjeva E. V., 2005. – Solar System Research, vol.39, 3, 176-186.

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

Approximately 270 parameters were determined while improving the planetary part of EPM2013/2014 ephemerides

- the orbital elements of planets and 16 satellites of the outer planets;
- the value of the $GM_{\odot}$;
- three angles of orientation of the ephemerides with respect to the ICRF;
- 13 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 of the asteroid 2-dimensional rings; 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 EPM2013 (with uncertainties 3σ):

heliocentric gravitation constant: $GM_{\odot} = (132712440033 \pm 3)$ km^3/s^2 ,

the Earth to Moon mass ratio: $M_{Earth}/M_{Moon} = 81.30056761 \pm 0.00000004$,

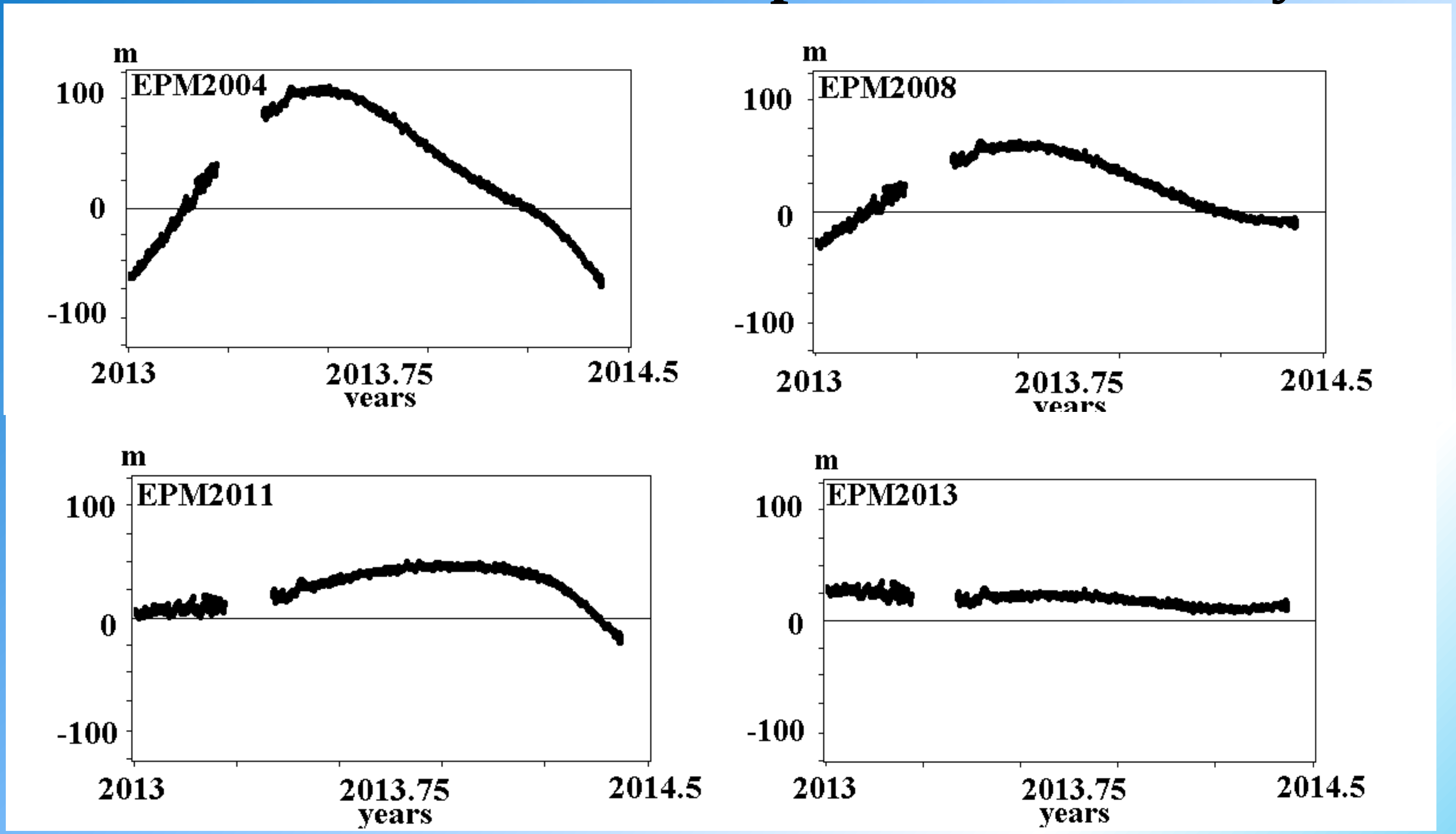
the solar oblateness $J_2 = (2.22 \pm 0.23) \cdot 10^{-7}$.

Comparison of EPM2004, EPM2008, EPM2011, and EPM2013 ephemerides

Ephemeris	Integr. interv.	Dynamic model	Type of observations	Number of observ.	Interval of observ.	Param. number
EPM2004 (2004)	1880–2020	Integration: the Sun, the Moon, 9 planets, 301 asteroids, 1-dimension asteroid ring	Optical	46108	1913–2003	204
			Radar/fit n.	58112/2504	1961–1997	
			Spacecraft/fit n.	197163/31177	1971–2003	
			VLBI	86	1984–2003	
			3-D nor.point	21	1973–1995	
			LLR	15590	1970–2003	
			Total	317080	1913–2003	
EPM2008 (2009)	1799–2198	Integration: the Sun, the Moon, 9 planets, 301 asteroids, 21 TNO, 1-dim. ast. ring	Optical	54376	1913–2007	240
			Radar/fit n.	58112/2504	1961–1997	
			Spacecraft/fit n.	437331/38259	1971–2007	
			VLBI	142	1984–2007	
			3-D nor.point	140	1973–1995	
			LLR	15590	1970–2003	
			Total	56569	1913–2007	
EPM2011 (2012)	1787–2214	Integration: Sun, the Moon, 9 planets, 301 asteroids, 21 TNO, 1-dim.ast.ring, TNO ring	Optical	57560	1913–2011	264
			Radar/fit n.	58112/2504	1961–1997	
			Spacecraft/fit n.	619720/43887	1971–2010	
			VLBI	237	1984–2010	
			3-D nor.point	153	1973–2009	
			LLR	17580	1970–2012	
			Total	753362	1913–2012	
EPM2013 (2013)	1787–2214	Integration: Sun, the Moon, 9 planets, 301 asteroids, 30 TNO, aster.annulus, TNO ring	Optical	58370	1913–2012	271
			Radar/fit n.	58112/2504	1961–1997	
			Spacecraft/fit n.	675957/47442	1971–2012	
			VLBI	290	1984–2013	
			3-D nor.point	153	1973–2009	
			LLR	18700	1970–2013	
			Total	811582	1913–2013	

Pitjeva E.V., Pitjev N.P., 2014. - Celest.Mech. & Dyn. Astr., v. 119

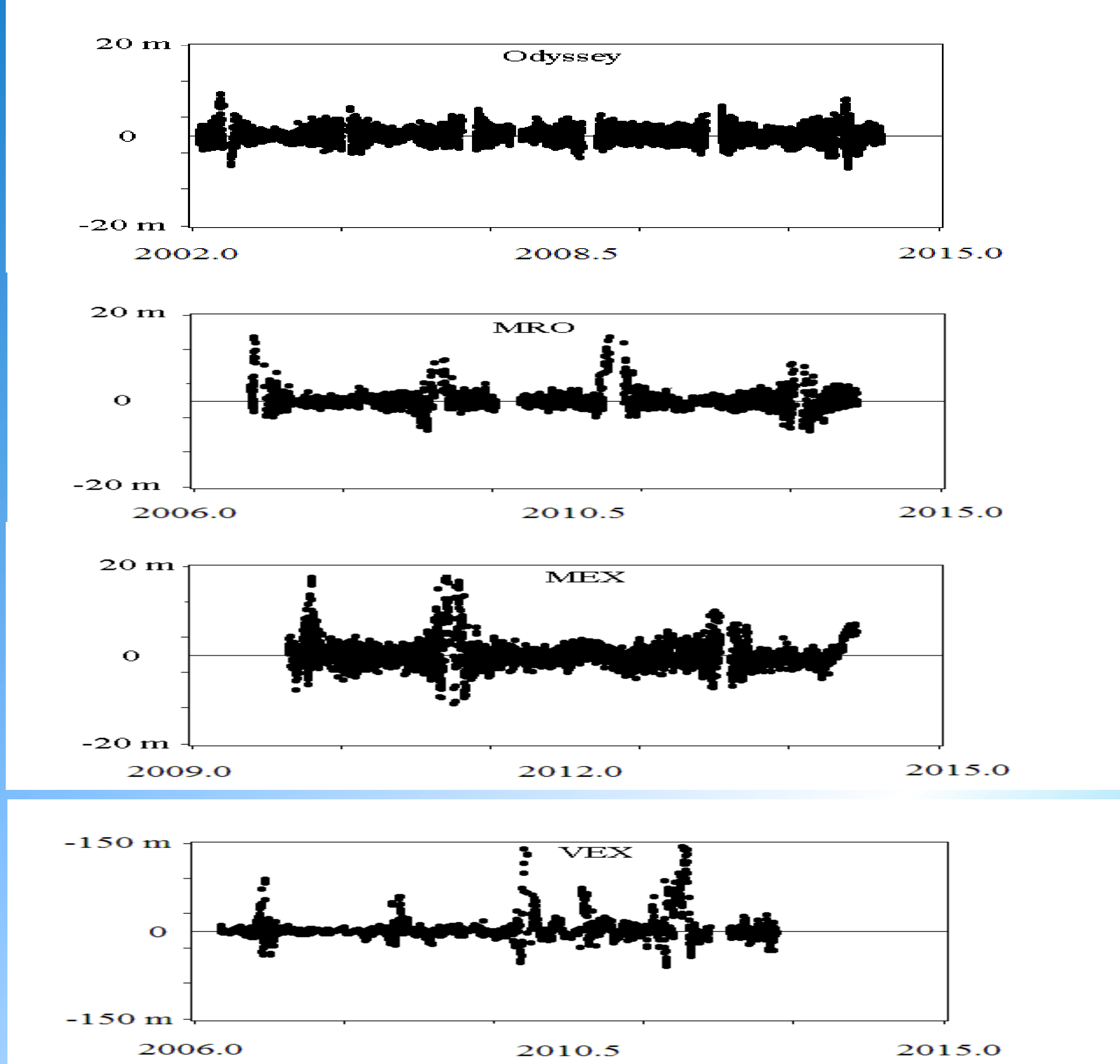
Evolution of ephemeris accuracy



The residuals ranging for spacecraft MEX from 01.01.2013 to 05.05.2014 (before fitting) computed for

EPM2004 – rms = 63 m, EPM2008 – rms =34 m,

EPM2011 – rms = 29 m, EPM2013 – rms = 20 m



The rms residuals of ranging for spacecraft Odyssey − 1.2 m, MRO − 1.2 m, MEX − 1.5 m, VEX − 3.1 m.

The formal standard deviations of planetary orbital elements adjusted in EPM2004, EPM2008, EPM2011, and EPM2013 ephemerides

Ephemeris	Planet	a [m]	$\sin i \cos \Omega$ [mas]	$\sin i \sin \Omega$ [mas]	$e \cos \pi$ [mas]	$e \sin \pi$ [mas]	λ [mas]
EPM2004	Mercury	0.105	1.654	1.525	0.123	0.099	0.375
EPM2008		0.427	1.655	1.597	0.1245	0.09940	0.4059
EPM2011		0.170	0.8275	0.5639	0.0907	0.06885	0.1617
EPM2013		0.065	0.7976	0.5545	0.0857	0.06874	0.1536
EPM2004	Venus	0.329	0.567	0.567	0.041	0.043	0.187
EPM2008		0.181	0.00796	0.00578	0.00065	0.00056	0.00740
EPM2011		0.089	0.00364	0.00288	0.00033	0.00020	0.00325
EPM2013		0.038	0.00338	0.00264	0.00015	0.00016	0.00275
EPM2014		0.004	0.00315	0.00255	0.00013	0.00013	0.00312
EPM2004	Earth	0.146	—	—	0.001	0.001	—
EPM2008		0.101	—	—	0.00039	0.00014	—
EPM2011		0.131	—	—	0.00043	0.00017	—
EPM2013		0.100	—	—	0.00029	0.00013	—
EPM2014		0.005	—	—	0.00005	0.00005	—
EPM2004	Mars	0.657	0.003	0.004	0.001	0.001	0.003
EPM2008		0.446	0.00161	0.00133	0.00080	0.00041	0.00132
EPM2011		0.616	0.00143	0.00115	0.00142	0.00071	0.00278
EPM2013		0.468	0.00122	0.00097	0.00114	0.00048	0.00211
EPM2014		0.015	0.00077	0.00082	0.00007	0.00013	0.00039
EPM2004	Jupiter	639	2.410	2.207	1.280	1.170	1.109
EPM2008		396	2.274	2.057	0.142	0.121	0.978
EPM2011		351	2.008	1.811	0.129	0.110	0.884
EPM2013		347	2.005	1.808	0.128	0.109	0.882
EPM2004	Saturn	4222	3.237	4.085	3.858	2.975	3.474
EPM2008		12.026	0.09448	0.09246	0.00161	0.00135	0.02477
EPM2011		70.519	0.10792	0.12023	0.01093	0.00327	0.03434
EPM2013		67.973	0.09517	0.10313	0.01021	0.00276	0.02885
EPM2014		4.828	0.08065	0.05726	0.00097	0.00035	0.01239
EPM2004	Uranus	38484	4.072	6.143	4.896	3.361	8.818
EPM2008		34662	3.838	4.758	3.469	2.244	4.465
EPM2011		30075	3.458	4.013	2.853	2.006	3.598
EPM2013		30033	3.453	4.007	2.849	2.003	3.592
EPM2004	Neptune	478532	4.214	8.600	14.066	18.687	35.163
EPM2008		301550	3.043	6.767	6.436	15.136	14.410
EPM2011		270853	2.673	5.202	5.554	13.558	12.363
EPM2013		270479	2.669	5.195	5.546	13.540	12.345
EPM2004	Pluto	3463309	6.899	14.940	82.888	36.700	79.089
EPM2008		2956231	4.762	13.985	67.880	38.028	31.169
EPM2011		2022765	2.759	10.021	43.896	31.381	18.215
EPM2013		2011658	2.753	9.931	43.676	31.170	18.088

Software

- Individual astronomical programs ─ 1970's
- Constrained astronomical programs (system "MAMONT 1981") ─ Krasinsky G.A.. 1982
- Program package ERA (Ephemerides for Research in Astronomy) ─ Krasinsky G.A, Agamirzian I. R., Novikov F.A., 1986; problem oriented language "SLON" for ERA ─ Krasinsky G.A, Novikov F.A., Skripnichenko, Cel.Mech., v. 45, 1989
- Program complex ERA-7 ─ Krasinsky G.A., Vasilyev M.V., 1997. - IAU Coll. N 165, 1997
- Program complex ERA-8 (Portable across Windows/Linux, 32- and 64-bit) with improved stability, diagnostics, and debugging programs ─ Pavlov D.A., Skripnichenko V. I., IAA Transaction, issue 28, 2014 (talk of D. Pavlov will be tomorrow)

The internals of programs are being improved permanently!

Access to ephemerides

- **Sending files with coordinates and velocities of objects ─ 1970's-1980's**
- **Chebyshev polynomial approximation of object positions and access program ─ Vasi1yev M.V., 1998; website since 2004 (Pascal)**
- **Access package (Calc_Eph) to ephemerides of the Sun, the Moon, 3 asteroids, 4 TNO and TT-TDB differences (Fortran, C, Pascal, Java) ─ Bratseva O.A. et al., IAA Transaction, issue 21, 2010**
- **Standardizing Access to Ephemerides and File Format Speci-fication:**

SPK (Spacecraft and Planet Kernel) **(.bsp files) for Earth, Moon, Sun, planets, asteroids, TT-TDB,**
PCK (.bpc files) for lunar libration;
PCK and SPK formats are being supported by the IAA in parallel to its original text and binary formats ─ Pavlov D.A., Skripnichenko V. I., IAA Transaction, issue 28, 2014

Conclusion

The progress in the accuracy of planet ephemerides is due to the improvement of reduction techniques and dynamical models and also to he improvement of quality and growth of quantity of observational data with the crucial role of spacecraft ranging.

Expansion of such data on other bodies of the Solar System and on a larger time interval allows to construct more accurate ephemerides and estimate small effects and parameters more precisely.

Thank you for your attention !