EVOLUTION OF EPHEMERIDES EPM OF IAA RAS

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ABSTRACT. The evolution of numerical EPM ephemerides of the IAA RAS from available EPM2004, EPM2008, EPM2011, to the new EPM2014 version is presented briefly. The comparison progress of ephemerides includes: the growing database of different types of observations from classical optical to radio technical of spacecraft from 1913 to 2014, enlarged up to more 800000 measurements; improved dynamical model from mutual perturbations of all planets, the Sun, the Moon, 301 largest asteroids to additional perturbations from of 30 largest trans-neptunian objects (TNO) and perturbations from remaining smaller asteroids and TNO modeled by the two-dimensional asteroid ring and the one-dimensional TNO ring; program software ERA-7 to ERA-8.

1. INTRODUCTION

The EPM ephemerides (**E**phemerides of **P**lanets and the **M**oon) were first created in the 1970s in support of Russian space flight missions and constantly improved at IAA RAS. Several factors influence the progress of planet ephemerides: dynamical models of planet motion; observational data, with the crucial role of spacecraft ranging with their growing accuracy; reduction of observations; updated database of asteroids (masses and orbits); program software; access to ephemerides.

2. DYNAMICAL MODELS

The uncertainty of modern ranging observations is only a few meters, that demands the accuracy of planet positions of at least 12 significant figures, so it is necessary to take into account any significant influencing factors in dynamical models. The dynamical models of planet part of EPM ephemerides have taken into account the following

EPM87 (Krasinsky et al., 1993):

- Mutual perturbations from the major planets, the Sun, the Moon and 5 more 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.

EPM98:

- Perturbations from the other 296 asteroids chosen due to their strong perturbations upon Mars and the Earth. The perturbations from 300 asteroids were taken into account starting with DE230 and were implemented in the well-known DE403 ephemerides (Standish et al. 1995). The perturbations from 300 asteroids were taken into account since EPM98 (Pitjeva, 1998).

EPM2000 (Pitjeva, 2001):

- Perturbations due to the solar oblateness J_2, that is currently determined during the processing of high-precision ranging measurements.

EPM2004:

- Perturbation from the massive one-dimensional asteroid ring with the constant mass distribution. The two parameters characterizing the ring (its mass M_r and radius R_r) were included into the set of parameters that were fitted to observations. That approach was proposed by Krasinsky et al.(2001) and implemented in EPM2004 ephemerides (Pitjeva, 2005).

EPM2008 (Pitjeva, 2010):

- Perturbations from the 21 largest Trans-Neptunian Objects (TNO).;

EPM2011 (Pitjeva, 2013):

- Perturbation from a massive ring of TNO in the ecliptic plane with the radius of 43 au.

EPM2013/EPM2014 (Pitjeva & Pitjev, 2014):

- Perturbation from the massive two-dimensional asteroid annulus (R_1 = 2.06 au, R_2 = 3.27 au). The accuracy of estimation of the the mass of the modeled annulus of small asteroids, as well as the accuracy of the total mass of the main asteroid belt increased by 6.3 times as compared to the previous estimates using the one-dimensional asteroid ring;
- perturbations from the 30 largest Trans-Neptunian Objects (TNO).

3. OBSERVATIONS, THEIR REDUCTIONS, PARAMETERS

The observational data set was increased by an order of magnitude as compared to EPM2000 ephemerides, resulting in more 800000 observations, mostly high-precision data from spacecraft. The planetary part of EPM2013/14 ephemerides has been fitted to observations of different types, spanning 1913-2014. Majority of planet observations was taken from the Jet Propulsion Laboratory (JPL) database (http://iau-comm4.jpl.nasa.gov/ plan-eph-data/index.html). 4086 normal points of new spacecraft data were added to the database of EPM2013 including the observations obtained for Odyssey, Mars Reconnaissance Orbiter (MRO), Mars Express (MEX) and Venus Express (VEX) spacecraft, updated ranging data for Cassini (2004-2014) (Hees et al., 2014), as well as 7861 data for Pluto, They are the CCD observations of Pluto obtained in 1950-2013 at Brazilian Pico dos Dias observatory (Benedetti-Rossi et al., 2014), and a new analysis of photographic plates taken at Lowell Observatory from 1931 to 1951 (Buie & Folkner, 2015). These new data were obtained through the courtesy of Folkner (JPL), Fienga (IMCCE), and Benedetti-Rossi (Observatorio Nacional/MCT). The ephemerides of the inner planets are based fully on radiotechnical observations, mostly measurements of time delays.

The processing of observational data was done using proven and reliable techniques with due account for all needed reductions (Standish 1990; Pitjeva 2005, 2013), as well as proper TT-TDB differences (Pitjeva, 2013).

EPM2014 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, Mars Reconnaissance Orbiter, and Cassini) 1989 - 2013 near Venus, Mars, and Saturn.

More than 270 parameters were determined while improving the planetary part of EPM2014 ephemerides. They include, in addition to orbital elements of all planets and 16 satellites of the outer planets, parameters of orientation of ephemerides, parameters of rotation and topography of planets, masses of asteroids. the Earth to Moon ratio, the value $GM_{\odot}$, many postmodel parameters, etc.

The dynamical models of the EPM ephemerides have been improved significantly. Number of observations used for improvement of ephemerides and their accuracy have increased greatly, and the number of adjusted parameters has grown accordingly.

4. PROGRESS OF EPM EPHEMERIDES

The progress of EPM ephemerides may be shown on any new data not used when fitting the ephemeris parameters. Recently the new MEX data obtained from 2013.01.01 to 2014.05.05 have become available for us due to Fienga. Those data were not used for fitting any EPM ephemerides except EPM2014. The decrease of their residuals (without fitting) computed using EPM2004, EPM2008, EPM2011, EPM2013 ephemerides demonstrates the improvement of the Mars orbit from EPM2004 to EPM2013. Their rms standard deviations are equal to 63, 34, 29, and 20 m for EPM2004, EPM2008, EPM2011, EPM2013, respectively (Fig. 1). After improvement of these observations for the new EPM2014 version, their residuals have decreased to 1.5 m. For EPM2014, the WRMS residuals of ranging for Odyssey, MRO, and VEX spacecraft are 1.2 m, 1.2 m, 3.1 m, respectively.

Orbits of all planets have been improved significantly. In particular, formal uncertainties of orbital elements of all planets have decreased by several times. Especially it is notably for the inner planets and Saturn (Table 1).

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
EPM2014		0.065	0.7976	0.5545	0.0857	0.0687	0.1536
EPM2004	Venus	0.329	0.567	0.567	0.041	0.043	0.187
EPM2014		0.004	0.00315	0.00255	0.00013	0.00013	0.00312
EPM2004	Earth	0.146	—	—	0.001	0.001	—
EPM2014		0.005	—	—	0.00005	0.00005	—
EPM2004	Mars	0.657	0.003	0.004	0.001	0.001	0.003
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
EPM2014		347	2.005	1.808	0.128	0.109	0.882
EPM2004	Saturn	4222	3.237	4.085	3.858	2.975	3.474
EPM2014		4.828	0.0807	0.0573	0.00097	0.00035	0.0124
EPM2004	Uranus	38484	4.072	6.143	4.896	3.361	8.818
EPM2014		30033	3.453	4.007	2.849	2.003	3.592
EPM2004	Neptune	478532	4.214	8.600	14.066	18.687	35.163
EPM2014		270479	2.669	5.195	5.546	13.540	12.345
EPM2004	Pluto	3463309	6.899	14.940	82.888	36.700	79.089
EPM2014		563306	0.865	3.312	12.900	8.384	4.870

Table 1: The formal standard deviations of planetary orbital elements adjusted in EPM2004 and EPM2014 ephemerides

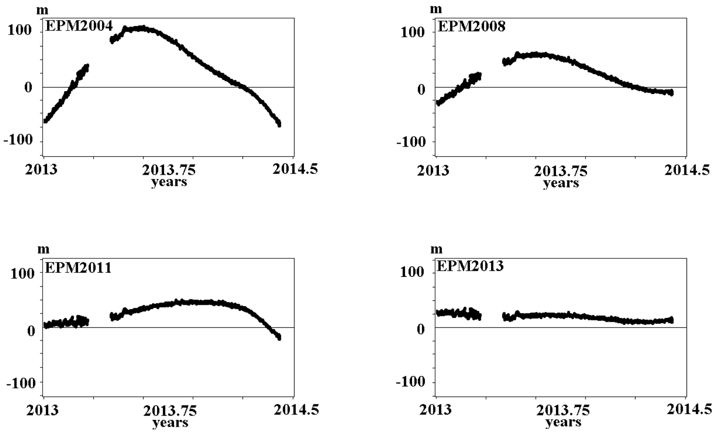

Figure 1: The residuals of one-way ranging for spacecraft MEX from 01.01.2013 to 05.05.2014 (before fitting) computed for EPM2004, EPM2008, EPM2011, EPM2013.

5. SOFTWARE AND ACCESS TO EPM EPHEMERIDES

The software for ephemeris construction has changed radically since 1970's from individual astronomical programs, and the first constrained astronomical programs and program package to complicated program complex ERA (Ephemeris Research in Astronomy) -7 (Krasinsky & Vasilyev, 1997) and ERA-8 (portable across Windows/Linux, 32- and 64-bit) with improved stability, diagnostics, and debugging programs (Pavlov & Skripnichenko, 2014).

The access to EPM ephemerides improved greatly from distribution of files with coordinates and velocities of objects (1970's-1980's), then access to Chebyshev polynomial approximation of object positions (about 2000), to the access package (Calc_Eph), and Standardizing Access to Ephemerides and File

Format Specification developed by the IAU Commission 4 Working Group on Standardizing Access. 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). PCK and SPK formats are being supported by the IAA in parallel to its original text and binary formats. The files containing polynomial approximation for EPM ephemerides are available from ftp://quasar.ipa.nw.ru/incoming/EPM/.

6. 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.

7. REFERENCES

Benedetti-Rossi, G., Vieira Martins, R., Camargo, J., Assafin, M., Braga-Ribas, F., 2014, "Pluto: improved astrometry from 19 years of observations", A&A, 570, A86.

Buie, M., Folkner, W., 2015, "Astrometry of Pluto from 1930–1951 Observations", AJ, 149, 22.

Hees, A., Folkner, W.M., Jacobson, R.A., Park, R.S., 2014, "Constraints on modified Newtonian dynamics theories from radio tracking data of the Cassini spacecraft", Physical Review D, 89(10), 102002.

Krasinsky, G.A., Pitjeva, E.V., Sveshnikov, M.L., Chunajeva, L.I., 1993, "The motion of major planets from observations 1769–1988 and some astronomical constants", Celest. Mech., 55, pp. 1–23.

Krasinsky, G., Vasyliev, M., 1997, "ERA: knowledge base for ephemeris and dynamic astronomy", Proc. IAU Colloquium 165, pp. 239–244.

Krasinsky, G.A., Pitjeva, E.V., Vasilyev, M.V., Yagudina, E.I., 2002, "Hidden mass in the asteroid belt", Icarus, 158, pp. 98–105.

Pavlov, D.A., Skripnichenko, V.I., 2014, "Preliminary results in implementation of a cross-platform version of the ERA software system", IAA Transactions, No. 30, pp. 32–40. (in Russian)

Pitjeva, E.V., 1998, "The new numerical planet ephemeris EPM98, its comparison with DE403 ephemeris of Jet Propulsion Laboratory of USA", IAA Transaction, 3, pp. 5–23.

Pitjeva, E.V., 2001, "Modern numerical ephemerides of planets and the importance of ranging observations for their creation", Celest. Mech. Dyn. Astr., 80, pp. 249–271.

Pitjeva, E.V., 2005, "High-precision ephemerides of planets – EPM and determinations of some astronomical constants", Solar System Research, 39, pp. 176–186.

Pitjeva, E.V., 2010. "Influence of trans-neptunian objects on motion of major planets and limitation on the total TNO mass from planet and spacecraft", Proc. IAU Symp. 263, D. Lazzaro, D. Prialnik, R. Schulz, J.A. Fernandez (eds.), pp. 93–97.

Pitjeva, E.V., 2013, "Updated IAA RAS Planetary Ephemerides EPM2011 and their use in scientific research", Solar System Research, 47, pp. 386–402.

Pitjeva, E.V., Pitjev, N.P., 2014, "Development of planetary ephemerides EPM and their applications", Celest. Mech. Dyn. Astr., 119, pp. 237–256.

Standish, E.M., Jr., 1990, "The observational basis for JPL's DE200, the planetary ephemerides of the Astronomical Almanac", A&A, 233, pp. 252–271.

Standish, E.M., Newhall, XX, Williams, J.G., Folkner, W.M., 1995, "JPL Planetary and Lunar Ephemerides, DE403/LE403", Interoffice Memorandum 314.10-127.