EPM-ERA 2013 - THE NEW VERSION OF LUNAR EPHEMERIS DEVELOPED IN IAA RAS

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ABSTRACT. EPM-ERA 2013 is the newest version of the lunar ephemeris developed in IAA RAS after 2011. New Lunar ephemeris EPM-ERA 2013 was compared with USA DE405, DE421, DE423, DE430 and French INPOP10e lunar ephemerides. Comparison showed that EPM-ERA 2013 is still slightly worse than all of these ephemerides, suggesting the necessity of further improving the dynamical model of EPM-ERA. The fact that all modern lunar ephemerides evidently cannot adequately describe most accurate LLR observations makes this task especially pressing for authors. Several practical applications were also considered to estimate the impact of the using different lunar ephemerides on the orbit determination accuracy of such objects as GNSS satellites and Near-Earth asteroids.

1. INTRODUCTION

Modern Lunar ephemerides have been developed in JPL, USA: DE405, DE421, DE423, DE430; IMCCE: INPOP10e-Intégrateur Numérique Planétaire de Observatoire de Paris; IAA RAS, Russia: EPM-ERA2013. These ephemerides are being constantly improved, and their precision become higher with new measurable information such as modern LLR observations. High accuracy of LLR data requires dynamical theories of adequate precision. The analysis of 18700 LLR observations (1970-2013), which includes 105 measurements of newly discovered Lunokhod1, has been presented in the paper. The comparison with all listed ephemerides of the Moon is given.

2. MATHEMATICAL MODEL

The dynamical model EPM-ERA 2013 is constructed by simultaneous numerical integration of the equations of orbital motion of the Moon, major planets, asteroids, TNO (Trans-Neptunian Objects), rotational motion of the Moon (Krasinsky 1999; Krasinsky 2002) and taking into account perturbations from asteroid belt and TNO ring. Numerical integration, residuals calculations and LSM fitting are performed using ERA system developed in IAA RAS (Krasinsky & Vasilev 1996). The most important model updates are the following ones: numerical integration with retarded argument was realized; the potential of the Earth is calculated according to recommendations of IERS for artificial Earth's satellites; 80-bites instead of 64-bites floating point calculation was realized in the numerical integration; the interaction between Moon figure and the potential of point mass of Jupiter and Venus was added; the difference between receiving and transmitting stations at Haleakala were taken into account; weighting procedure was revised for most accurate Apache LLR observation; 4-sigma criterion was used for the observation rejection.

3. OBSERVATIONS AND PARAMETERS DETERMINED

In the present analysis 18700 LLR observations have been included in the processing. The station Apache was presented by new 1576 highest precision LLR measurements. The number of observations at each site is shown in Table 1.

The number of ranging to Apollo 11, Apollo 14, Apollo 15, Lunahod 2 are 1585, 1557, 12724 and 452 respectively. 105 LLR observations of Lunakhod 1 were also added into the fitting process. Before 1998 the observations were obtained by request from observatories, later on they have been retrieved from FTP server *ccdisa.gsfc.nasa.gov/pub/slr*, partly from *oca.eu/gemini/donnees/las$_l$une*, some of them were obtained by private correspondence. During the fitting process 65 parameters have been determined.

Station	Time interval	Number of LLR observations
McDonald	1970 Mar - 1985 Jun	3440
MLRS1	1985 Jan - 1988 Jan	275
MLRS2	1988 Aug - 2012 Jan	3114
HALEAKALA	1984 Nov - 1990 Aug	694
CERGA	1985 Jan - 2013 Feb	9599
Apache	2006 July - 2012 Aug	1576
TOTAL	1970 Mar- 2013 Feb	18700

Table 1: Distribution of LLR observations

The set of parameters includes the lunar initial coordinates and velocities, libration angles and their velocities, Stokes coefficients of the selenopotential, Lunar love numbers k_2,h_2, l_2, the angles of time delay, the coordinates of 5 reflectors, the coordinates of 6 observational stations etc. Since lunar rangings are invariant relatively to the rotation of the Earth-Moon system as a whole, all the set of orientation parameters of this system cannot be determined simultaneously. Due to this reason, longitude and latitude of the most often observable reflector Apollo 15 have been fixed. Values of these two parameters were obtained from a simplified solution made as the first step, in which lunar libration has not been improved. LLR observations are sensitive to the Earth's gravitational constant Gm_E. The investigation shows that the correction to Gm_E cannot be reliably separated from corrections to X coordinate of the reflectors. Thus the value Gm_E has not been included into the list of parameters.

4. ANALYSIS OF THE RESULTS

EPM-ERA2013 ephemeris has been obtained using 18700 LLR observation and adjusting the set of 65 parameters listed above. Residuals statistics depending on the observational station and the time interval of observations can be seen in table 2.

Residuals wrms (cm)	Number of observations	Observational stations	Interval of observations
26.8	3162	McDonald	19700415.0-19850630.0
11.6	191	MLRS1	19850301.0-19880127.1
18.8	1136	CERGA	19840407.2-19860612.2
7.4	3247	CERGA	19871012.2-19941213.2
4.2	5060	CERGA	19950107.2-20130219.2
10.9	538	Haleakala	19841113.1-19900830.1
5.8	989	MLRS2	19880229.0-19951228.0
6.1	1775	MLRS2	19960125.0-20120401.0
3.5	1564	Apache	20060407.1-20120828.1
4.9	17662	Total	19700415.0-20130202.2

Table 2: EPM-ERA ephemeris, statistics of residuals

It is known that the analysis of LLR data depends not only on the dynamical model but on partial derivatives relative to a number of parameters, many of which also require numerical integration. To compare our result with the results obtained using DE and INPOP10e ephemerides, residuals calculations have been made with the ephemerides mentioned using derivatives from EPM-ERA 2013. Statistics of post-fit residuals and the number of LLR observations used to calculate these residuals for DE405, DE421, DE423, DE430, INPOP10e and EPM-ERA 2013 ephemerides are presented in Table 3. The direct comparison of the post-fit residuals statistics obtained by using EPM-ERA2013 ephemeris and INPOP10e one are given in Table 4. For INPOP10e ephemeris, the statistics of residuals were taken from the following website: arXiv1301.1510[astro-ph.EP].

Ephemerides	Wrms(cm) residuals	Number of observations	Number of deleted observations
DE 405	4.5	18121	579
DE 421	3.8	18154	546
DE 423	3.8	18141	559
DE 430	3.6	18144	556
INPOP10	4.4	18214	586
EPM-ERA 2013	4.9	17662	1038

Table 3: Statistics of residuals for EPM-ERA ephemeris, compared with DE and INPOP10 ephemerides

Station		INPOP10e			EPM-ERA 2013	
	Period	Std. dev.	N	Period	Std. dev.	N
Cerga	1984-1986	15.9	1158	1984-1986	18.8	1136
Cerga	1987-1995	6.4	3415	1987-1995	7.3	3247
Cerga	1995-2012	4.0	5058	1995-2013	4.2	5060
McDonald	1969-1986	31.3	3487	1970-1986	26.8	3162
MLRS1	1982-1985	73.4	405	1982-1985	-	-
MLRS1	1985-1988	7.4	163	1985-1988	11.6	191
MLRS2	1988-1996	4.7	1148	1988-1996	5.8	981
MLRS2	1996-2012	5.6	1972	1996-2012	6.1	1775
Haleakala	1984-1990	8.1	733	1984-1990	10.9	538
Apache	2006-2010	5.2	935	2006-2012	3.5	1564
Matera	2003-2012	29.5	33	2003-2012	-	-

Table 4: Comparison of results EPM-ERA2013 and INPOP10e ephemerides, statistics of residuals

All post-fit residuals of LLR observations processed in EPM-ERA2013 are presented in Fig.1. Fig.2 and Fig.3 demonstrate post-fit residuals for McDonald and Apache stations respectively.

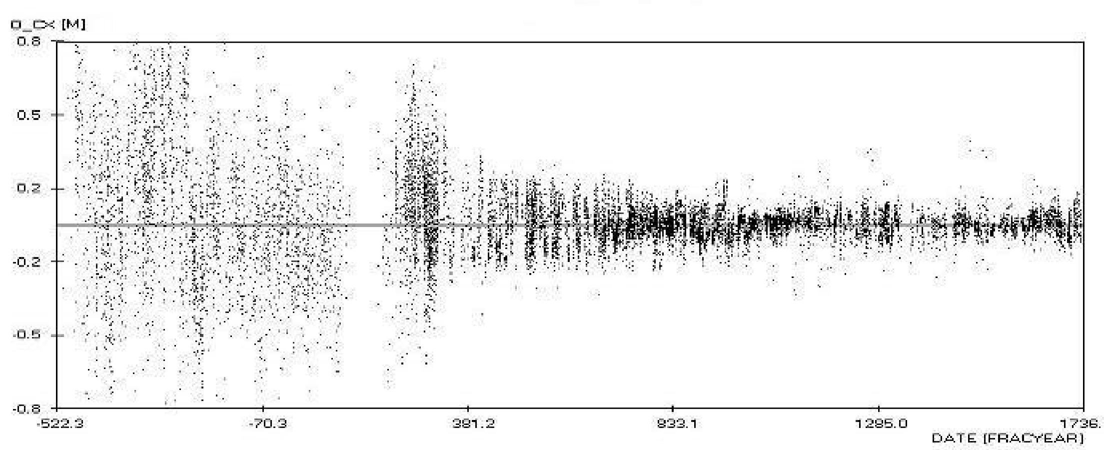

Figure 1: EPM-ERA2013, residuals (laser ranging)

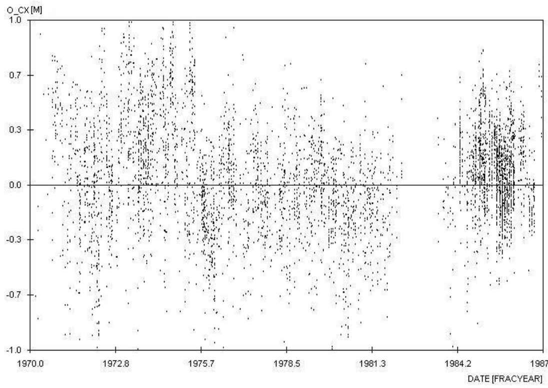

Figure 2: MacDonald station, 1970-1987

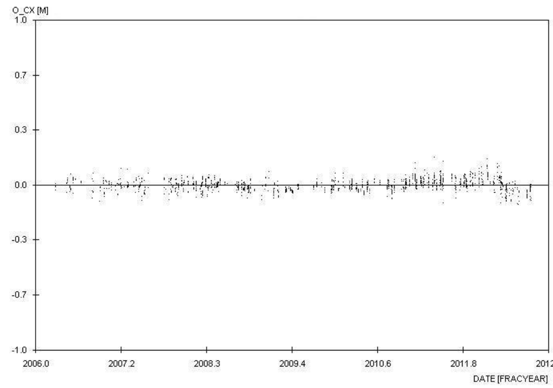

Figure 3: Apache station, 2006-2012

One can see the drastic improvement in the accuracy of LLR observations during the last decade which requires adequate improvement of the rotational motion model of the Moon.

5. CONCLUSION

The investigation shows that the inner accuracy of EPM-ERA 2013 was improved to 4.9 cm from 6.0 cm in the previous version. Most likely EPM-ERA 2013 provides the upper limit of accuracy in case when the model of lunar rotation described by Krasinsky is used. Nevertheless, Lunar rotation model requires further improvements and a more sophisticated model than the Krasinsky one. The work is in progress.

6. REFERENCES

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