Parameters of new version EPM Lunar ephemeris on the base of LLR (Lunar Laser Ranging) observations 1970-2016 years

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The new version of the EPM Lunar ephemeris on the base of model of DE430 orbital-rotational motion and internal core of the Moon was developed in IAA RAS. [1]. Astronomical, geophysical and geodynamical models recommended by IERS Conventions 2010 were also included in this new version. This work has been performed using a version of ERA8 software (Ephemeris Research in Astronomy) [2], that underwent a major rewrite, while keeping the basic principles of the older versions. The addition of LLR observations after 2013 till 2016 was made from sites described and used in the processing (about 2800 new observations). The main purpose of this presentation is to show that new values the ephemeris parameters obtained in this solution are compatible with previous result [1] and have good uncertainties.

1. Introduction

The modern Lunar Ephemerides are developing in following Institutes: JPL, DE (USA); IMCCE, INPOP (France); IAA RAS, EPM (Russia). The processing LLR observations on the base of the DE421 ephemeris, which has some changings like relativistic parameters and small other improvements, is made in Leibniz University (Germany). These Lunar ephemerides are being constantly improved and their precisions are obtaining higher with new modern LLR observations. High accuracy of LLR data requires dynamical theories of similar precision. Now the precise model of Lunar ephemeris is considered as DE430 one, and another ones demonstrate close results.
The Russian Lunar Ephemeris EPM-ERA till 2014 was constructed on the base of Krasinsky model of orbital-rotational motion of the Moon [3] and has been created in the frame of ERA7 system from 1989 till 2014 years. This dynamical model was improved during these years. The EPM-ERA2012 Lunar ephemeris [4] was developed by simultaneous numerical integration of the equations of orbital and rotational motion of the Moon, major planets, asteroids, asteroid belts, Trans-Neptunian Objects(TNO) and TNO ring. The potential of the Moon was calculated up to 4-th order harmonics. The potential of the Earth was calculated up to 5-th order harmonics, numerical integration, residuals calculations and LSM fitting were performed using ERA7 system developed in IAA RAS [5]. From 2014 year the new version of ERA system was developing.

In new version of EPM Lunar ephemeris the model of orbital-rotational Moon's motion was substituted for the model orbital-rotational motion of the Moon of the DE430 ephemeris and some up-to-date terrestrial models and solutions of IERS Conventions 2010, all implemented within ERA-8. In the present solution about 2800 new LLR observations after 2013 have been added and new parameters of EPM Lunar ephemeris were obtained.

2. **Observations and determined parameters**.

In the present analysis 21424 LLR observations from 1970 till 2016 were included in the processing. All observations were taken from the different sites: http://cddis.gsfc.nasa.gov/slr/data/npt_crd/), -NASA Archive;

(http://physics.ucsd.edu/~tmurphy/apollo/), Apollo site;

(http://polac.obspm.fr/llrdatae.html), -from the Lunar analysis Center of Paris observatory till 2015;

(http://www.geoazur.fr/astrogeo/?href=observations/donnees/lune/brutes -new site of Grasse station.

There were small problems with uncertainties of some observations at Matera station. After discussion with people responsible for receiving normal points, all observations from the site were included in the processing. LLR observations at every station (1970-2016), time interval, number of deleted observations and one-way wrms in centimeters are shown in Table1.

Table1. Distribution of LLR observations 1970-2016 by stations and RMS corresponding every station and special time interval of observations

Station	Time interval	Number of NP	Used	Deleted	One-way, Wrms, cm
McDonald	1970-1985	3604	3545	43	**20.3**
MLRS1	1983-1988	631	588	43	**11.3**
MLRS2	1988-2015	3653	3221	449	**3.5**
Haleakala	1984-1990	770	743	27	**5.5**
Cerga (Ruby)	1984-1986	1188	1109	3	**16.9**
Cerga (Yag)	1987-2005	8324	8164	152	**2.4**
Cerga(Meo)	2009-2016	1617	1602	15	**1.8**
Matera	2003-2015	117	103	14	**3.3**
Apache	2006-2016	2370	2349	21	**1.4**
Total data	**1970-2016**	**21424**	**20657**	**767**	

The values of the parameters new EPM Lunar ephemeris of this solution and previous one [1] are given in Table2 (this solution) and Table3 (previous one). The comparison shows good agreement as parameters in two version and also good accuracies.

Table2. The new values of the EPM Lunar ephemeris' parameters (1970-2016)

N	Parameter name	Parameter value	N	Parameter name	Parameter value
1	Moon X	-137136473.64 ±0.05 m	12	ψ	(128918873±2) $\cdot 10^{-8}$
2	Moon Y	-311514603.65±0.03 m	13	$\dot{\varphi}$	-74.539±0.002" /day
3	Moon Z	-141738600.36±0.03 m	14	$\dot{\theta}$	-37.0239±0.0002" /day
4	Moon v_x	962372275.32 ±0.09 µm/sec	15	$\dot{\psi}$	47501.854±0.001" /day
5	Moon v_y	-375608189.65±0.13µm/sec	16	β	(631018.6±0.4) $\cdot 10^{-9}$
6	Moon v_z	-268439309.89±0.05µm/sec	17	γ	(227727.5±0.5) $\cdot 10^{-9}$
7	ω_{cx}	(-866±3)$\cdot 10^{-6}$ rad/day	18	τ	0.104±0.001 day
8	ω_{cy}	(-6482±6) $\cdot 10^{-6}$ rad/day	19	h_2Moon	0.047±0.0005
9	ω_{cz}	(229.79±0.03) $\cdot 10^{-3}$ rad/day	20	µE+µM	403503.2350±0.0001$km^3 s^2$
10	φ	(-5823809±1) $\cdot 10^{-8}$ rad	21	k_v/C_T	(17.4+0.2) $\cdot 10^{-9} day^{-1}$
11	θ	(-395116±1) $\cdot 10^{-8}$ rad	22	f_c	(0.270 ± 0.003)*10e-3

Table3. The previous values of the EPM Lunar ephemeris parameters (1970-2013)

	Parameter name	Parameter value	N	Param. name	Parameters value
1	Moon X	-137136474.05±0.05 m	12	ψ	(113574562±3) $\cdot 10^{-8}$
2	Moon Y	-311514604.01±0.05 m	13	$\dot{\varphi}$	-74.537±0.001" /day
3	Moon Z	141738600.43±0.04 m	14	$\dot{\theta}$	-37.0255±0.0003" /day
4	Moon v_x	962372276.11±0.13μm/sec	15	$\dot{\psi}$	47501.853±0.001" /day
5	Moon v_y	-375608190.19±0.14μm/sec	16	β	(631023.1±0.5) $\cdot 10^{-9}$
6	Moon v_z	-268439311.42±0.06μm/sec	17	γ	(227733.3±0.7) $\cdot 10^{-9}$
7	ω_{cx}	(-890±4)$\cdot 10^{-6}$ rad/day	18	τ	0.096±0.001 day
8	ω_{cy}	(-6453±8) $\cdot 10^{-6}$ rad/day	19	h_2Moon	0.043±0.001
9	ω_{cz}	(229.63±0.05)$\cdot 10^{-3}$ rad/day	20	μE+μM	403503.2365±0.0002km/s^2
10	φ	(-5823800±2) $\cdot 10^{-8}$ rad	21	k_v/C_T	(16.3+0.2) $\cdot 10^{-9}$ day^{-1}
11	θ	(-39511625±1) $\cdot 10^{-8}$ rad	22	f_c	(0.247 ± 0.004) $\cdot 10^{-3}$

The quantity of determined parameters is about 100 ones (including coordinates of the reflectors, coordinates of observational stations and biases). Some of the important determined parameters, their values and accuracy are in the table2 and table3. In the tables: ω_{cx} , ω_{cy} , ω_{cz} -velocity of core, φ, θ, ψ, $\dot{\varphi}$,$\dot{\theta}$, $\dot{\psi}$-Euler angles and their rates at epoch; β, γ-ratios between undistorted main moments of inertia; τ- lunar tidal delay; h_2 Moon- degree-2 lunar radial displacement Love number; k_v/C_T −CMB interaction; f_c- oblatness of the lunar core. The values of parameters, obtained in the new solution, confirmed the correctness of new model and were compared with results in published paper [1]. The comparison of present result with previous one shows not only correctness of new model, but the fact, that all new values of parameters are compatible with presented in the mentioned paper (which was compared with DE430 ephemeris). The uncertainties of parameters determined are good enough. The post-fit residuals of this solution (in centimeters) for best two stations Apache and Grasse (Cerga) are shown on fig.1. and on fig.2.

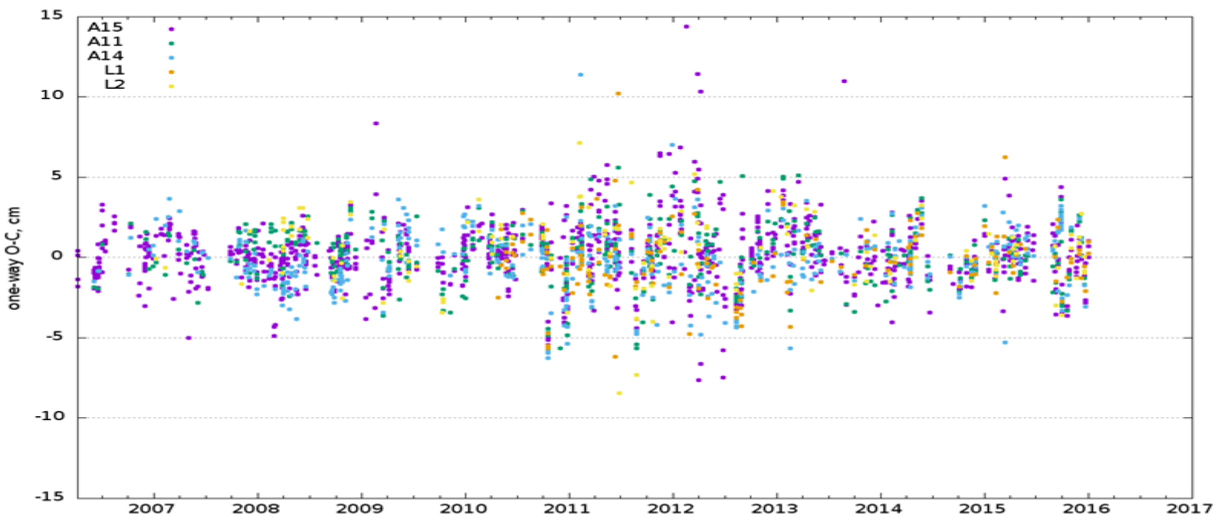

Fig.1. Post-fit residuals for Apache station (1970-2016 years)

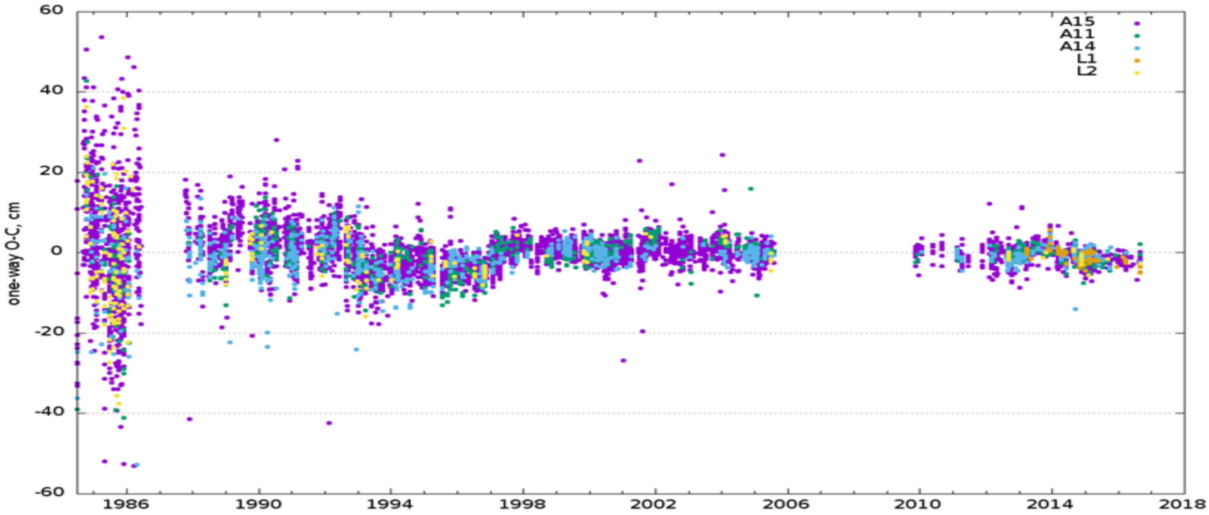

Fig.2 Post-fit residuals for Gerga(Grasse) station (1970-2016 years)

The post-fit residuals (wrms in centimeters), number of rejected observations, total number of observations for all stations and intervals of observations previous (2013) and present (2016) solutions are presented in Table4.

Table4. The comparison two solutions of new version of the EPM Lunar ephemeris.

Station	SOLUTION 2013				SOLUTION 2016			
	Data span	used	Rejected	Wrms (cm)	Data span	used	Reject.	Wrms (cm)
McDonald	1970-1985	3545	59	**19.9**	1970-1985	3545	43	**20.3**
MLRS1	1983-1988	587	44	**11.0**	1983-1988	588	43	**11.3**
MLRS2	1988-2015	3210	443	**3.5**	1988-2015	3221	449	**3.5**
Haleakala	1984-1990	748	22	**5.4**	1984-1990	743	27	**5.5**
Cerga(Ruby)	1984-1986	1109	79	**17.2**	1984-1986	1109	3	**16.9**
Cerga(Yag)	1987-2005	8272	52	**2.3**	1987-2005	8164	152	**2.4**
Cerga(MeO)	2009-2013	645	9	**2.2**	2009-2016	1602	15	**1.8**
Apache	2006-2012	1546	27	**1.4**	2006-2016	2349	21	**1.4**
Matera	2003-2013	64	19	**3.8**	2003-2015	103	14	**3.3**

Conclusion

1. Using new version of EPM Lunar ephemeris, the processing LLR observations on interval 1970-2016 was carried out.

2. The results are in good accordance with previous solution.

3. Parameters from last solution are in a good agreement with ones recommended by IERS Conventions and are compatible with previous ones.

4. The new version of EPM Lunar ephemeris is in the progress.

References

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