NEW VERSION OF EPM-ERA LUNAR THEORY

G.A. KRASINSKY, S.O. PROKHORENKO, E.I. YAGUDINA
Institute of Applied Astronomy, Acad. Sci., Russia
10, Kutuzov quay, 191187-St-Petersburg, Russia
e-mail: kra@ipa.nw.ru; prs@ipa.nw.ru; eiya@ipa.nw.ru

ABSTRACT. The numerical Lunar theory EPM-ERA has been developed in IAA RAS (Krasinsky 2002, Aleshkina et al.1996). In the paper (Yagudina 2008) 16320 LLR data (1970-2008) have been included for the process of improving the Moon ephemeris and obtaining some selenodynamical parameters. A new version of ERA-EPM Lunar theory was corrected by the improved model of dissipative effect of the lunar rotation by integrating the orbital and rotational motions with the retarded argument. The comparison of the improved dynamical model with 17131 LLR data from 1970 till 2010 has been made. This version has been compared with three versions of DE ephemerides.

1. INTRODUCTION

The lunar part of EPM ephemerides of IAA RAS is called EPM-ERA. In the paper, a new version of EPM-ERA2010 is presented. This version differs from the previous ones by the following:

1. Tidal perturbations in the orbital Lunar motion (due to the tidal dissipation on the Earth's body), as well as in the rotational motion of the Moon (due to tidal dissipation on the Moon's body) are computed by a more complicated model with the retarded argument (compare with the previous EPM-ERA2008);

2. In the processing of LLR observations 17131 were used instead of 16320 LLR observations in the previous version;

3. The new version was transformed in the new ERA-Windows. The previous versions were calculated in DOS version (Krasinsky and Vasiliev, 1996).

2. MODEL AND ESTIMATED PARAMETERS

A dynamical model has been developed by the simultaneous numerical integration of the orbital and rotational motion of the Moon, major planets and biggest asteroids. The potential of the Moon is calculated up to 4-th order of the zonal index. The potential of the Earth includes the 2-th order harmonics C_{20}, C_{22}. Tidal perturbation in the lunar orbital motion (due to tidal dissipation on the Earth's body) and also in rotational Lunar motion (due to tidal dissipation on the Moon's body) was computed by a model with a retarded argument. Method of integration is Everhart's method with the constant step of integration. Partials of lunar ranging with respect to the dynamical parameters of the

N	Parameters estimated
1-6	Lunar orbital state vector for the epoch JD 2446000.5
7-12	Euler's angles and their time derivatives for the same epoch
13-18, 22-24	Coordinates of reflectors A11, A14, L2
20	X coordinate for reflector Apollo 15 (A15)
25-42	Coordinates of 6 observational stations
44	Lag of Earth's body tides
48-51	Secular trends in sidereal angles of the Earth and Moon
55	Lag of Moon's body tides
52-54, 59-63	Harmonics of lunar potential from C_{20} to S_{33}
56-58	Lunar Love numbers k_2, h_2, l_2
64-65	Secular trends of the corrections to the parameters of Earth's equator

Table 1: Parameters determined

orbital and rotational model of the Moon are computed by the integration of variational equations; in few cases, they were obtained by integration of a rigorous system of equations with slightly varying values of the parameter (k_2). The set of parameters includes the lunar initial coordinates and velocities, libration angles and their velocities, harmonics of lunar potential from C20 to S33, Lunar Love numbers k_2, h_2, l_2, the coordinates of reflectors, observational stations and others (Table 1). In LLR analysis, a number of parameters appeared to be strongly correlated and may only be estimated because four reflectors could be observed. Unfortunately, such disparity of the observation distribution deteriorates the estimate reliability of a number of selenodynamical parameters. As lunar rangings are invariant relatively to the rotation of the Earth-Moon system as a whole, the whole set of the orientation parameters of this system cannot be determined simultaneously. Due to this reason, two coordinates of the most frequently observable reflector Apollo 15 were fixed (longitude and latitude). The values of these two parameters were obtained from a simplified solution made as the first step, in which lunar libration was not improved. The LLR observations are sensitive to the Earth's gravitational constant Gm_E. The investigation shows that the observable effect cannot be reliably separated from corrections to X coordinate of the reflectors. Thus, the Gm_E value has not been included in the list of parameters.

3. OBSERVATIONS

In the present analysis, 17131 LLR observations have been included in the processing. They were carried out mainly at McDonald (Texas), where at different epochs three different sites were activated as McDonald observatory, MLRS1 and MLRS2; Cerga station (France) and a set of observations of the two years duration made at Haleakala Observatory (Hawai) and 643 observations were made in Apache station (mm accuracy). The number of observations at each site is shown in Table 2. Four reflectors could be observed: 1-Apollo 11, 2-Apollo 14, 3-Apollo 15, 4-Lunahod2. The number of ranging to Apollo 11, Apollo 14, Apollo 15, Lunahod2 are 1723, 1670, 13231 and 486, respectively.

Station	Time interval	Number of LLR observations
McDonald	1970 Mar - 1985 Jun	3440
MLRS1	1985 Jan - 1988 Jan	275
MLRS2	1988 Aug - 1900 August	3066
HALEAKALA	1989 Nov - 2010 March	694
CERGA	1985 Jan - 2010 March	9013
APACHE	2006 August - 2009 June	643
TOTAL	1970 Mar- 2010 April	17131

Table 2: Distribution of LLR observations caption

4. ANALYSIS OF RESULTS

Using the derivatives from EPM-ERA, all the calculations have been made with the three versions of DE ephemerides: DE403, DE405, DE421. The O-C, post-fit residuals (wrms), the number of included and rejected LLR observations by the processing of DE ephemerides along with EPM are given in Table 3. Because the EPM-ERA model was been implemented by the obtained corrections, the post-fit residuals practically coincide with the O-C difference computed with the improved model equal (6.8 cm).

Ephemeris	O-C Wrms (cm)	Residuals Wrms (cm)	Number of observations	Number of deleted observations
DE403	22.2	5.2	16827	304
DE405	258.2	5.6	16837	294
DE421	561.8	5.7	16833	298
EPM-ERA2010	6.8	6.8	16821	310

Table 3: O-C and residuals for DE ephemerides compared with EPM-ERA2010

For the current version of EPM-ERA, the post-fit residuals and O-C coincide. For DE ephemerides, a similar work could not be carried out on the full scale and only corrections to reflector coordinates and observational stations were incorporated.

wrms (cm) O-C	wrms(cm) residuals	number of observations	Observational stations	Interval of observations
39.5	30.3	3411	McDonald	19700415.0 - 19850630.0
10.7	7.2	275	MLRS1	19850301.0 - 19880127.1
16.4	4.1	8996	CERGA	19840407.2 - 20100121.2
14.3	7.2	694	Haleakala	19841113.1 - 19900830.1
17.6	5.6	2808	MLRS2	19880229.0 - 20100405.1
39.5	3.4	643	Apache	20060407.1 -20090615.1
22.2	5.2	16827	All stations	19700415.0 -20100405.1

Table 4: DE403 ephemeris, statistics of residuals

wrms (cm) O-C	wrms(cm) residuals	number of observations	Observational stations	Interval of observations
267.9	28.9	3416	McDonald	19700415.0 - 19850630.0
227.6	7.5	275	MLRS1	19850301.0 - 19880127.1
246.9	4.5	8996	CERGA	19840407.2 - 20100121.2
133.8	7.6	694	Haleakala	19841113.1 - 19900830.1
215.0	5.8	2811	MLRS2	19880229.0 - 20100405.1
348.6	4.7	643	Apache	20060407.1 -20090615.1
258.2	5.6	16837	All stations	19700415.0 -20100405.1

Table 5: DE405 ephemeris, statistics of residuals

wrms (cm) O-C	wrms(cm) residuals	number of observations	Observational stations	Interval of observations
577.7	29.5	3411	McDonald	19700415.0 - 19850630.0
533.9	6.5	275	MLRS1	19850301.0 - 19880127.1
535.7	4.6	8999	CERGA	19840407.2 - 20100121.2
288.8	8.3	694	Haleakala	19841113.1 - 19900830.1
483.2	6.1	2811	MLRS2	19880229.0 - 20100405.1
750.4	3.9	643	Apache	20060407.1 -20090615.1
561.8	5.7	16833	All stations	19700415.0 -20100405.1

Table 6: DE421 ephemeris, statistics of residuals

Tables 4, 5, 6, 7 demonstrate the post-fit residuals and O-C (cm wrms, the number of observations for 6 stations, the observational interval at each station and the same parameters for all the stations together for all DE ephemerides (DE403, De405, DE421) and for EPM-ERA2010. The plots of Fig. 1, Fig. 2, Fig. 3, Fig. 4 show us the statistics of residuals for all ephemerides.

5. CONCLUSION

The investigation shows that the inner accuracy of DE ephemerides (5.4-5.7cm) is slightly better than that of EPM-ERA2010 (6.8 cm). But the accuracy of DE ephemerides cannot be used by an independent researcher because it is not possible to feed back the corrected values of the parameters. In the current version of EPM-ERA2010 ephemeris, an attempt to improve the model of the tidal perturbations in the rotational motion of the Moon (due to dissipation in Moon's body) has been carried out. The expansion of the retarded function in a power series of delay is used. This part of the model needs small further improvements.

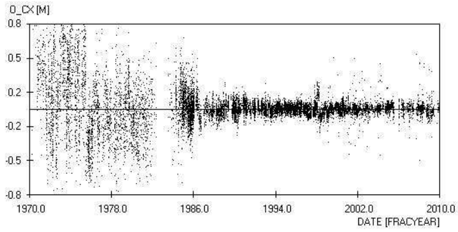

Figure 1: DE403

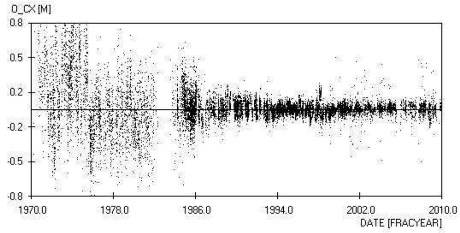

Figure 2: DE405

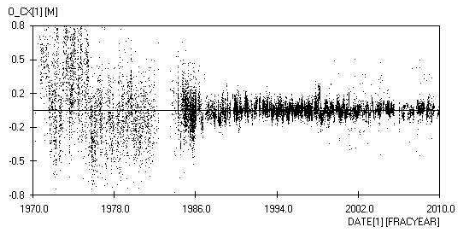

Figure 3: DE421

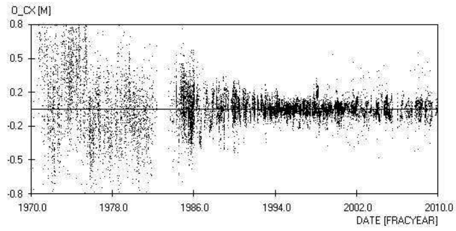

Figure 4: EPM-ERA2010

wrms (cm) O-C	wrms(cm) residuals	number of observations	Observational stations	Interval of observations
31.5	31.5	3399	McDonald	19700415.0 - 19850630.0
12.2	12.2	275	MLRS1	19850301.0 - 19880127.1
5.1	5.1	8996	CERGA	19840407.2 - 20100121.2
13.6	13.7	694	Haleakala	19841113.1 - 19900830.1
6.7	6.7	2808	MLRS2	19880229.0 - 20100405.1
5.7	5.7	643	Apache	20060407.1 -20090615.1
6.8	6.8	16821	All stations	19700415.0 -20100405.1

Table 7: EPM-ERA2010 ephemeris, statistics of residuals

6. REFERENCES

Krasinsky G.A.,2002, “Selenodynamical parameters from analysis of LLR observations of 1970-2001”, Communications of the IAA RAS, N 148, pp.1–27.

Aleshkina E.Yu., KrasinskyG.A., Vasiliev M.V .1996, “Analysis of LLR data by the program ERA”, Proceedings of IAU Colloquium 165, Poznan, Poland, pp. 228–232.

Yagudina E.I., 2008. “Numerical Lunar Theory EPM2008 from Analysis of LLR data”, Book of abstracts Journées, Dresden, 22-24 September, pp11.

Krasinsky G.A., Vasiliev M.V.1996, “ERA: knowledge base for Ephemeris and dynamical astronomy”, Proceedings of IAU Colloquium 165, Poznan, Poland, pp.239–244.