EPM-ERA 2013 – New Version of Lunar Ephemeris Developed in IAA RAS

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INTRODUCTION

I. Modern Ephemerides:
   1. JPL, USA: DE405, DE421, DE423, DE430;
   2. IMCCE: INPOP10e-Integrateur Numerique Planetaire de l”Observatoire de Paris”);
   3. IAA RAS, Russia: EPM-ERA2013 .

II. Analysis of 18700 LLR observations (1970-2013)

EPM-ERA 2013: model description

- **The dynamical model EPM-ERA2013 is constructed by simultaneous numerical integration of the equations of orbital and rotational motion of the Moon, major planets, asteroids, asteroid belts and TNO (Trans-Neptunian Objects) and TNO ring**

- **Lunar rotational motion was computed by model described by Krasinsky [1999, Cel. Mech.]**

- **The potential of the Moon is calculated up to 4-th order harmonics**

- **The potential of the Earth is calculated up to 5-th order harmonics**

- **Numerical integration, residuals calculations and LSM fitting are performed using ERA system developed in IAA RAS**

EPM-ERA 2013: what's new?

1. **80-bites instead of 64-bites floating point calculation was realized in the numerical integration**
2. **Potential of the Earth is calculated up to 5-th order harmonics according recommendations of IERS for artificial Earth's satellites**
3. **Numerical integration with retarded argument is realized by Krasinsky model**
4. **The interaction between Moon figure and the potential of point mass of Jupiter and Venus had been included in the mathematical model**
5. **The model of reduction LLR observation at Haleakala station was changed: the difference between receiving and transmitting stations were taking into account**
6. **Weighting procedure was revised for most accurate Apache LLR observation. 4-sigma criterion is used for the observation rejection**
7. **105 observations of Lunakhod1 have been included in the processing**
8. **New 1120 LLR observation have been added**

Station	Time interval	NumberLLR observations
McDonald	1970 March-1985 June	3440
MLRS1	1985 Jan-1988 January	275
MLRS2	1988 August-2012 April	3114
HALEAKALA	1988 August-1990 August	694
CERGA	1985 Jan-2013 February	9599
APACHE	2006 July-2012 August	1576
Total	1970 March-2013February	18700

Table 1: Distribution of LLR observations

Reflectors:	number of ranging:
1. Apollo-11	1990;
2. Apollo-14	1961;
3. Apollo-15	14091;
4. Lunochod2	503;
5. Lunokhod1	105.

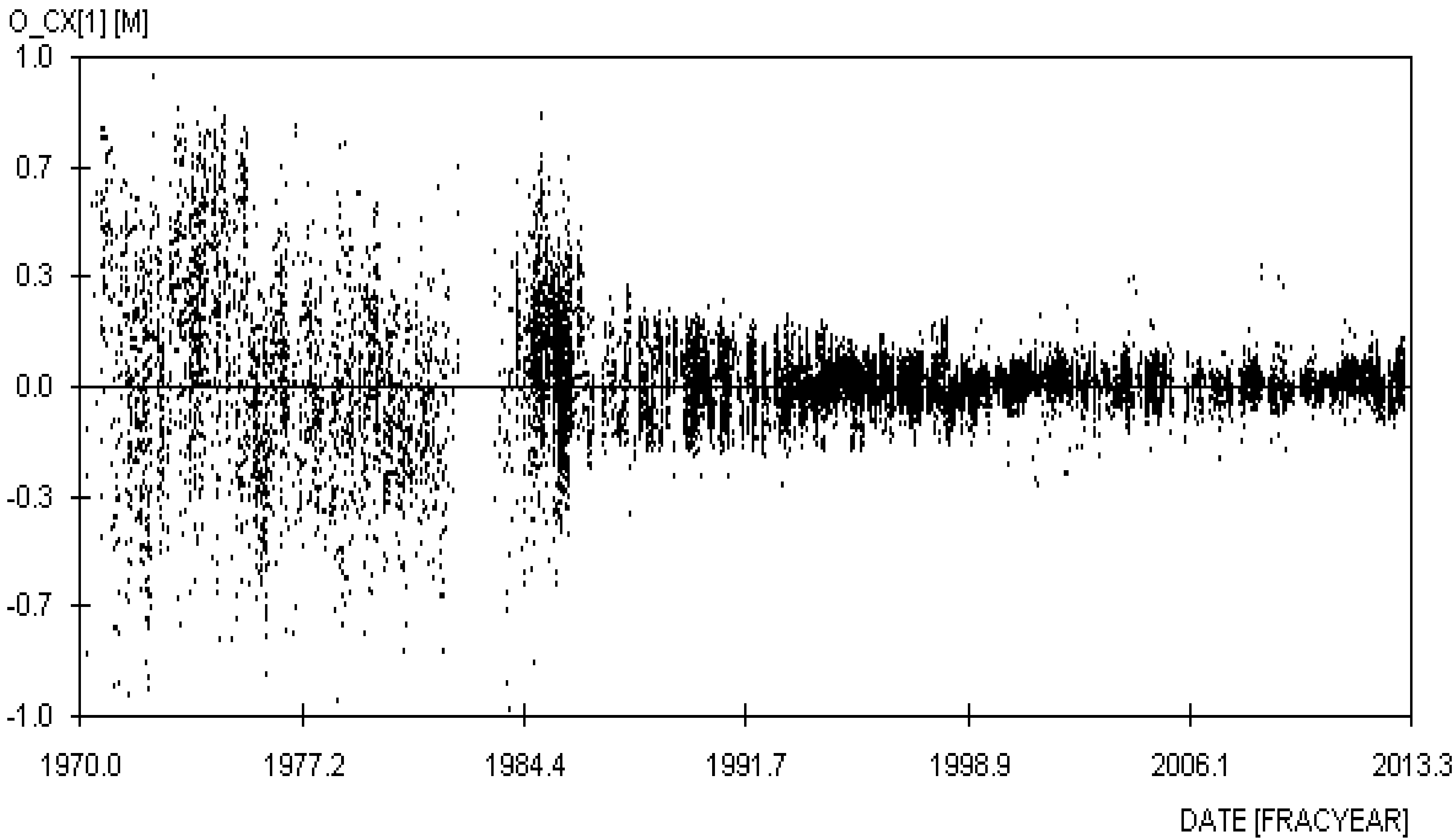
Observations obtained using FTP servers:
ccdisa.gcfc.nasa.gov/pub /slr,
Oca.eu/gemini/donnes/las_lune,
(Partly from private correspondence , thank to Dominique Feraudy)

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
45-47	Coordinates of reflector L1
44	Lag of the Earth's body tides
55	Lag of the Moon's body tides
48-51	Secular trends of the siderial angles for the Earth and the Moon
56-58	Lunar Love numbers k_2, h_2, l_2
52-54, 59-63	Harmonics of lunar potential from C_{20} to S_{33}
64-65	Secular trends of the corrections to the orientation parameters of Earth's equator ε,Φ

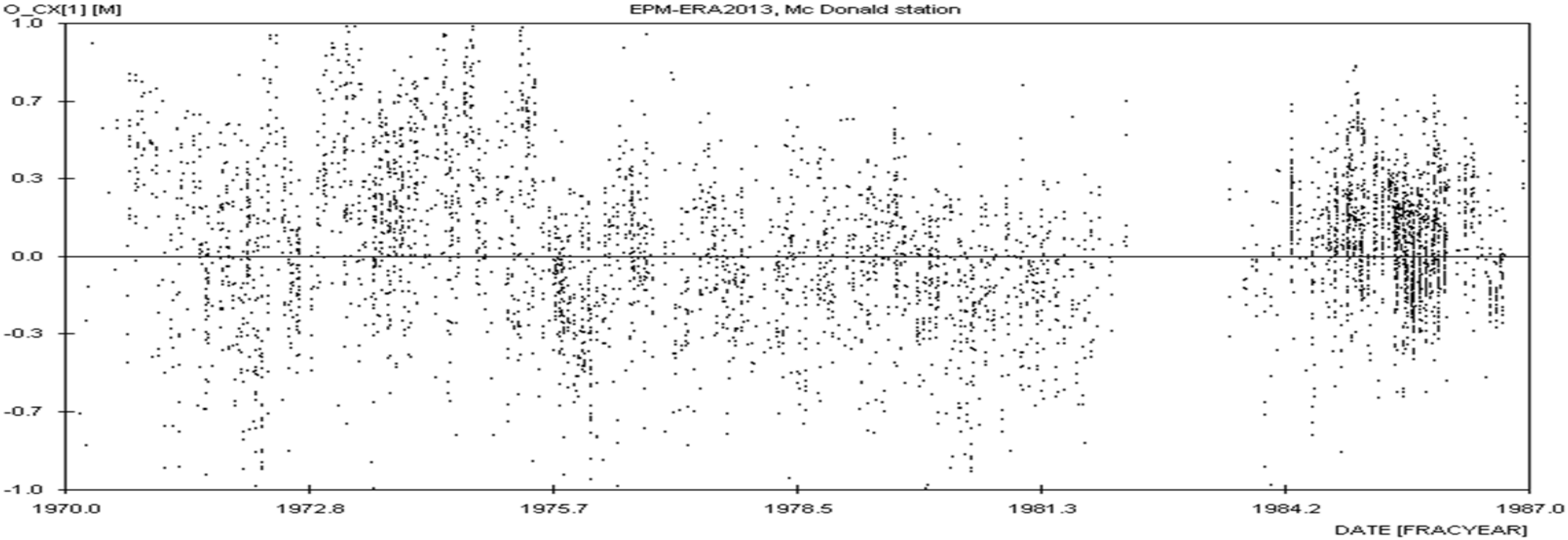
Residuals wrms (cm)	Number of observations	Observational stations	Interval of observations
26.8	3162	McDonald	19700415.0 - 19850630.0
11.6	191	MLRS1	19850301.0 - 19880127.1
18.8	1136	CERGA	19840407.2 - 19860612.2
7.4	3247	CERGA	19871012.2 -19941213.2
4.2	5060	CERGA	19950107.2 -20130219.2
10.9	538	Haleakala	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	(All stations)	19700415.0 -20130202.2

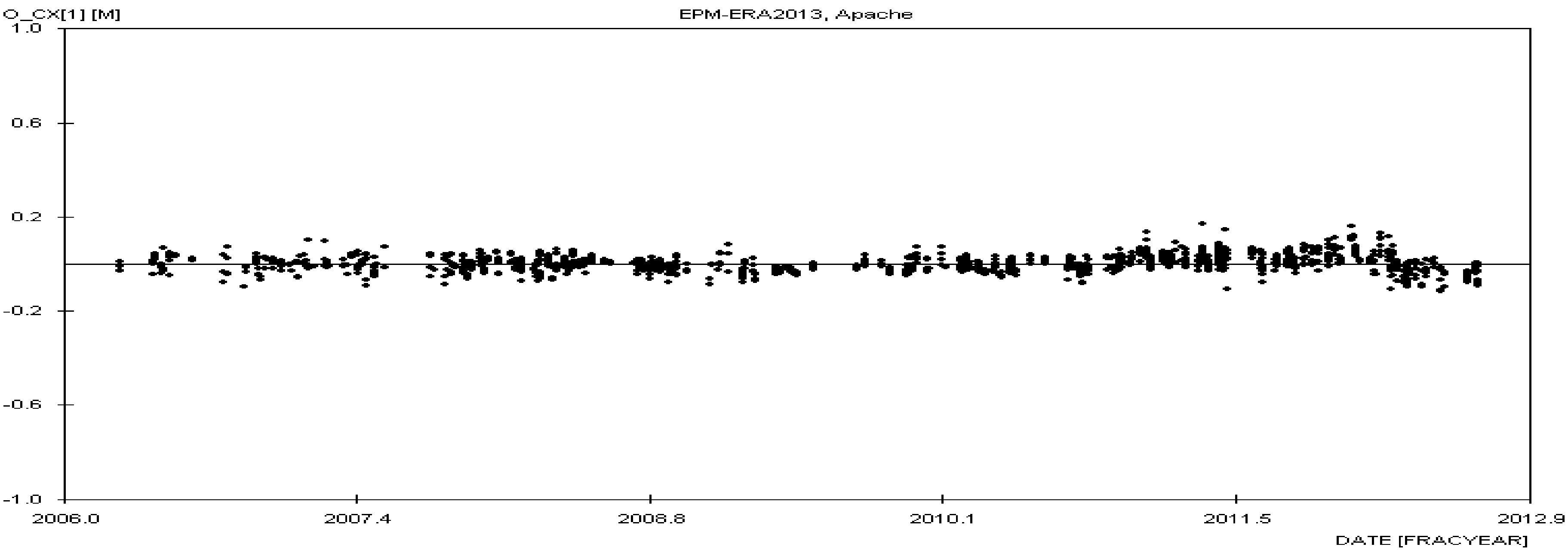
EPM-ERA2013 ephemeris, statistics of residuals

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(4.4)	5060(4973)
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	989
MLRS2	1996-2012	5.6	1972	1996-2012	6.1	1775
Haleakala	1984-1990	8.1	733	1984-1990	10.9	538
Apollo	2006-2010	5.2	935	2006-2012	3.5(5.0)	1564(915)
Matera	2003-2012	29.5	33	2003-2012	_	_



EPM-ERA2013 ephemeris, residuals (laser ranging)


O_CX[1] [M]
EPM-ERA2013, Mc Donald station
1.0
0.7
0.3
0.0
-0.3
-0.7
-1.0
1970.0
1972.8
1975.7
1978.5
1981.3
1984.2
1987.0
DATE [FRACYEAR]


O_CX[1] [M]
EPM-ERA2013, Apache
1.0
0.6
0.2
-0.2
-0.6
-1.0
2006.0
2007.4
2008.8
2010.1
2011.5
2012.9
DATE [FRACYEAR]

Residuals for DE and INPOP10e ephemerides compared with EPM-ERA2013

Ephemeris	Residuals Wrms (cm)	Number of observations	Number of deleted observations
DE405	4.5	18121	579
DE421	3.8	18154	546
DE423	3.8	18141	559
DE430	3.6	18144	556
INPOP10e	4.4	18214	586
EPM-ERA 2013	4.9	17662	1038

Conclusions

- The inner accuracy of EPM-ERA 2013 was increased to 4.9 cm from 6.0 cm in previous version

- Most likely EPM-ERA 2013 provides the upper limit of accuracy in case when model of lunar rotation described by Krasinsky is used

- Nevertheless, Lunar rotation model requires further improvements, more sophisticated model than Krasinsky one. The work is in the way.

Thank you very much for your attention!