Expected Impact of the Lunar Lander VLBI Observations on the Lunar Ephemeris Accuracy

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The modern Lunar Ephemerides DE (USA), INPOP (France), EPM-ERA (Russia) have been obtained through the comparison of dynamical models of the Moon orbital and rotational motion with modern highly precise lunar laser observations (LLR) from 1969 to the present time. The main purpose of this paper is to evaluate the impact of adding new types of observations on the accuracy of lunar ephemerides. These types are VLBI and radio ranging observations of a lunar lander equipped with a transponder like the one in the Chinese space project Chang'E-3 with the Yutu rover placed at the Moon's surface [1]. The evaluation was made through the mathematical simulation method for various radio telescopes networks and measurement accuracies. Mathematical models were created by the ERA system developed in the IAA RAS [2]. The results show that VLBI observations processing together with LLR can considerably improve the accuracy of some lunar parameters.

Keywords: Lunar lander VLBI observations, Lunar ephemeris, LLR observations.

1 Introduction

The modern Lunar Ephemerides DE (USA, JPL), INPOP (France, IMCCE), EPM-ERA (Russia, IAA) have been obtained through the comparison of dynamical models of the Moon's orbital and rotational motion with modern highly accurate lunar laser ranging observations (LLR) available since 1969. Equipment and number of LLR stations have been changed since then. Currently, the most active and efficient stations are: Apache (USA), GRASSE (France), and MacDonald (USA). Also, there are the stations Matera (Italy) which works since 2003, and YartRAO (South Africa) which is under construction. The accuracy of modern LLR observations varies from several millimeters at Apache station to several centimeters at other stations, more than 21000 LLR observations are available now. The improvement of modern ephemerides of the Moon is possible in the following directions:

1) improvement of the orbital and rotational model of the Moon's motion. The most precise model of orbital and rotational motion of the Moon is the model of DE430 (USA) ephemeris [3]. Still, this model does not have an adequate accuracy in

comparison with the modern LLR observations, as it is about 2 centimeters, while the Apache station accuracy is several millimeters;

2) the construction of new stations with modern lunar laser devices. Two projects are available currently. One of them is under construction in Russia (Altay station) [4, 5], the second one is in La Silla [6], still not adopted;

3) using new types of observations which have accuracies comparable with LLR, for example: VIBI and radio ranging (LRR) [7] observations of lunar landers equipped with transponders, such as the Yutu rover in the Chinese space project Chang'E-3 [1].

The impact of all factors mentioned above(and LRR observations from point 3 in particular) on the lunar ephemeris accuracy has been studied in sufficient details [3, 4, 5, 6, 7, 10]. The main topic of the paper is to estimate how VLBI observations of lunar landers can improve parameters of Lunar ephemeris.

2 Signal Sources and VLBI Stations

The following signal sources for VLBI observations of the Moon are available or expected:

1) an operating Chinese lunar spacecraft Chang'E-3 equipped with a transponder of X frequency band. It is expected that the next Chinese lunar missions will have the same or advanced capabilities for VLBI and LRR observations;

2) a Japanese project (after 2018) includes a lander with a transponder adjusted for both LRR and VLBI observations [8];

3) Russian lunar projects (2017–2019) where Luna-Glob and Luna-Resourse are planned to be put in near-polar regions of the Moon [9]. Their transponders will operate at X and Ka bands.

It is supposed that all three projects will be coordinated the way that their apparatus and frequency ranges are compatible. VLBI network "Quasar" and IVS stations are used now as ground segment to observe Chang'E-3 lander. Four VLBI sessions took place in 2015 and three sessions in 2016. One additional session is planned in 2016. Both networks are considered to become an observational basis for future intensive programs of VLBI observations of the Moon to improve parameters of lunar ephemeris and give a possibility to obtain more precise values of relativistic parameters and the lunar interior structure.

3 Mathematical Simulation

The method of mathematical simulation is used to estimate a potential influence of the VLBI observations of the lunar lander on the accuracy of the Moon's ephemeris parameters. The VLBI observations of Chinese landing apparatus Chang'E3 were simulated from 2006 to 2013 for different IVS stations. It was supposed that an interval between two consecutive VLBI observations was 2 hours. Precision of simulated observations was 0.06 meters, assuming that atmospheric and clock errors were excluded by simultaneous quasar observations. It was agreed

Table 1

Adjusted parameters of Lunar epmemeris EPM-ERA2014

N	Par.	N	Par.	N	Par.	N	Par.
1	X Moon	18	A14 Py	35	MLRS1 Px	52	C_{33}
2	Y Moon	19	L2 long	36	MLRS1 long	53	S_{33}
3	Z Moon	20	L2 Px	37	MLRS1Py	54	T*sidt
4	Vx Moon	21	L2 Py	38	Apache Px	55	T*sidtMoon
5	Vy Moon	22	A15 Px	39	Apache long	56	T*deps
6	Vz Moon	23	MCD Px	40	Apache Py	57	T*dpsi
7	Libration θ	24	MCD long	41	Lag Earth	58	deps
8	Libration ϕ	25	MCD Py	42	C_{20}	59	dpsi
9	Libration ψ	26	MLRS Px	43	C_{21}	60	Lag Moon
10	Libration dθ/dt	27	MLRS long	44	S_{21}	61	k2 Moon
11	Libration dϕ/dt	28	MLRS Py	45	C_{22}	62	A15 long
12	Libration dψ/dt	29	Cerga Px	46	S_{22}	63	A15 Px
13	A11 long	30	Cerga long	47	C_{30}	64	A15 Py
14	A11 Px	31	Cerga Py	48	C_{31}	65	L1 long
15	A11 Py	32	Haleak Px	49	S_{31}	66	L1 Px
16	A14 long	33	Haleak long	50	C_{32}	67	L1 Py
17	A14 Px	34	Haleak Py	51	S_{32}		

that coordinates of VLBI stations were sufficiently accurate and it was not necessary to improve them during processing of VLBI observations of the Moon's lander. 18700 real LLR measurements from 1970 to 2013 were used simultaneously with the simulated observations. Several scenarios under described conditions were considered:

1) the mentioned real LLR observations and simulated VLBI observations of the Moon's lander using only two stations of "Quasar" VLBI network: Zelenchukskaya (Zc) and Badary (Bd) ones;

2) the mentioned real LLR observations and simulated VLBI observations of the Moon's lander using "Quasar" VLBI network;

3) the mentioned real LLR observations and simulated VLBI observations of the Moon's lander using all IVS stations.

The latest version of Moon's ephemeris EPM-ERA 2014 [10] was used for simulations. In the table 1 the list of adjusted parameters of EPM-ERA ephemeris are presented.

4 Results

The results obtained under the scenarios described above can be seen in Fig. 1, 2, 3. Relative improvement (expressed in percentages) in the accuracy of the EPM-ERA 2014 ephemeris parameters are shown in all pictures. Scenarios 1 and 2 give almost the same results, where maximal differences are less than half a percent. It shows that VLBI observations using a single baseline or even a local VLBI network are not sufficient enough.

Simulation of the whole IVS network (scenario 3) for lunar lander VLBI observations demonstrates a remarkable improvement of lunar ephemeris parameters, es-

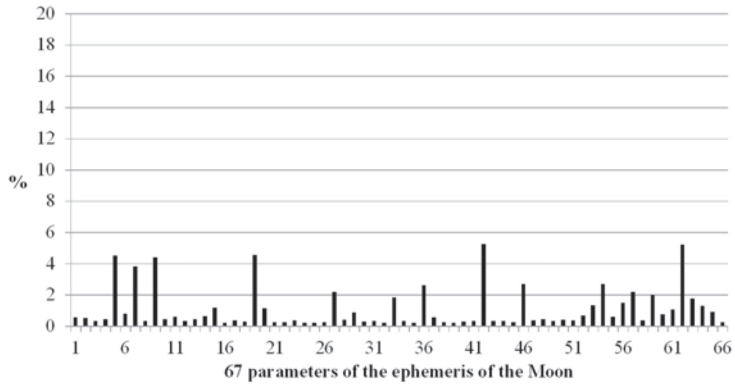

Fig. 1. Expected impact of VLBI observations on the Moon's ephemeris accuracy, scenario 1, 2

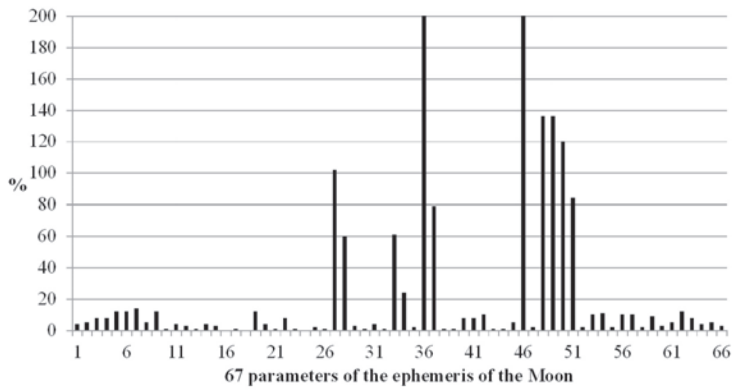

Fig. 2. Expected impact of VLBI observations on the Moon's ephemeris accuracy, scenario 3

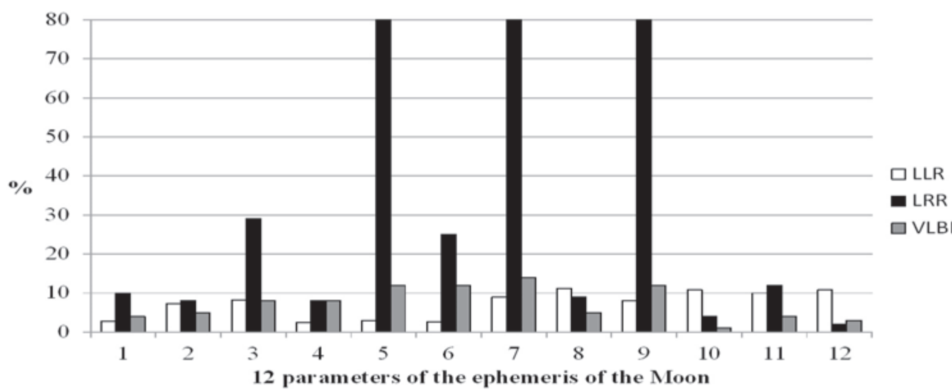

Fig. 3. Expected impact of LLR, LRR and VLBI observations on the Moon's ephemeris accuracy

pecially when it concerns the gravitational potential of the Moon and coordinates of LLR stations.

The last picture (Fig. 3) provides an opportunity to estimate how the new observational facilities may improve the accuracy of the ephemeris of the Moon. One can see that observations of the IVS network and a developing LLR station give almost the same relative improvement of the Moon ephemeris parameters, but not as impressive as in the case of LRR observations. It means that VLBI observations of the lunar landers could produce a visible impact only if a global VLBI network and intensive program of observations are used. So, VLBI observations of lunar landers may be considered as a good addition for LLR observations to improve lunar ephemeris, to investigate the interior structure of the Moon and, probably, to estimate relativistic parameters. Note also that real VLBI and LRR measurements are in the preliminary stage of processing, and the simulation results may be further adjusted after completion of the processing.

5 Conclusion and Plans

1. The special programs were developed to evaluate the influence of VLBI observations of lunar landers on the accuracy of lunar ephemeris.

2. It is shown that VLBI observations of Lunar landers can be a considerable addition to modern high precision LLR observations and give a result comparable with the best LLR modern stations.

3. Well-known advantages of radio method of measurements, such as independence of weather, large volume of data and high accuracy may be taken into consideration for LRR and VLBI observations to become the main sources of data in investigations of the Moon.

4. Differential VLBI observations of lunar lander Chang'E-3 are under correlation processing now. The next stage planned is to use them for analysis and adjustment of the Moon's orbital and rotational theory of motion.

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