Detection Capability Analysis of Lunar Retroreflector

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ABSTRACT

The Lunar Laser Ranging (LLR) System is a part of the Lunar Exploration. It is used to detect the photons reflected by the retroreflector on the moon, and to accurately calculate range from the earth to the moon at a certain time, so as to improve the pointing precision of the telescope and correct the lunar orbit. The data is indispensable for other research about the moon. This paper not only analyses the main factors (the performance of chosen telescope, the power of laser used in LLR, the capability of detector) in affecting the detection capability of the Lunar Laser Ranging system, but also analyses the whole detection capability under the situation of all parts of an apparatus that could be attainable around the international areas. At last, the economic, feasible, with high performance-to-price ratio supporting programs are presented.

Keywords: Lunar Laser Ranging, Feasibility Study, Detection Capability

1 INTRODUCTION

LLR experiment had its origins in the late 1950's in the gravitational research program at Princeton University. R.H.Dicke and his co-workers were considering ways to look for possible slow changes in the gravitational constant G by precise tracking of a very dense artificial satellite in a high-altitude orbit. Then, ruby laser were developed, the laser ranging measurements to retroreflectors on artificial satellites and on the moon would provide much more accurate tracking information. LLR is used to detect the photons reflected by the retroreflector on the moon, and to accurately calculate range from the earth to the moon at a certain time, so as to improve the pointing precision of the telescope and correct the lunar orbit. The data is indispensable for other research about the moon.

The analyses of LLR measurements contribute to a wide range of scientific disciplines, and are solely responsible for production of the lunar ephemeris. An independent analysis gives geodetic and astronomical results. The interior, tidal response, and physical librations (rotational variations) of the Moon are all probed by LLR, making it a valuable tool for lunar science.

LLR data provides science results: gravitational physics and ephemeris information from the orbit, lunar science from rotation and solid body tides, and Earth science.

(i)Science from the orbit: Sensitive tests of gravitational physics include the Equivalence Principle, limits on the time variation of the gravitational constant G, and geodetic precession. Lunar ephemerides are a product of the LLR analysis used by current and future spacecraft missions. The analysis is sensitive to astronomical parameters such as orbit, masses and obliquity.

(ⅱ)Lunar science: Lunar rotational variation has sensitivity to interior structure, physical properties, and energy dissipation.

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2011 International Conference on Optical Instruments and Technology: Optoelectronic Measurement Technology and Systems, edited by Xinyong Dong, Xiaoyi Bao, Perry Ping Shum, Tiegen Liu, Proc. of SPIE Vol. 8201, 820114
© 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.913047

(iii)Earth science: Station positions and motion, Earth rotation variations, nutation, and precession are determined from analyses. Future: Extending the data span and improving range accuracy will yield improved and new scientific results. Adding either new retroreflectors or precise active transponders on the Moon would improve the accuracy of the scientific results.

Several countries begun researching LLR project for the following scientific objectives: (i) a much improved lunar orbit; (ii) determination of the location of the retroreflectors with respect to the lunar center of mass; (iii) study of the lunar physical librations (angular motions about the center of mass due to gravitational torques on the moon); and (iv) an accurate check on gravitational theory, through at that period a search for deviations from the calculated range after all known parameters in the problem had been adjusted.

2 THE CONSTITUTION OF LLR SYSTEM

Two independent parts assemble the LLR measurements: the retroreflectors on the lunar surface and the observatory on the Earth. To range the Moon, the observatories on the Earth fire a short laser pulse toward the target retroreflector array; the outgoing laser beam is narrow and the illuminated spot on the Moon is a few kilometers across; the returning pulse illuminates an area around the observatory which is a few tens of kilometers in diameter; the observatory has a very sensitive detector which records single photon arrivals. Photons from different laser pulses have similar residuals with respect to the expected round-trip time of flight and are thus separated from the widely scattered randomly arriving background photons.

2.1 The retroreflector

The retroreflectors are made up of arrays of corner cubes: 100 for Apollo 11 and 14, 300 for Apollo 15, and 14 for the Lunokhods. At each corner cube the laser beam enters the front face and bounces off of each of the three orthogonal faces at the rear of the corner cube. The triply reflected pulse exits the front face and returns in a direction opposite to its approach.

There are 5 lunar reflector arrays which were placed on the lunar surface at different direction towards the earth (Fig.1). The Apollo 11 retroreflector array, consisting of 100 corner-cube prisms in a 10×10 array. Each corner cube is made of fused silica (quartz) and is 3.8 cm in diameter. The palette is 0.45 meters square and carefully designed to minimize thermal gradients across the corner cubes as the array is slammed into and out of the sun's rays as the moon's phase changes. This prevents thermal distortions from seriously degrading the amount of light returned by the reflectors. The Apollo 14 retroreflector array is very much like the Apollo 11 array in design: 100 3.8 cm reflectors in a 10×10 square pattern. Unlike the picture of the Apollo 11 array, this one has sunlight on its face, enabling a better view of the array of corner cubes. The Apollo 15 (Fig.2) array has 300 3.8 cm corner cubes in a hexagonal array. Because this reflector is three times larger than the previous two, it gets preferential treatment by the photon-challenged LLR stations currently in operation.

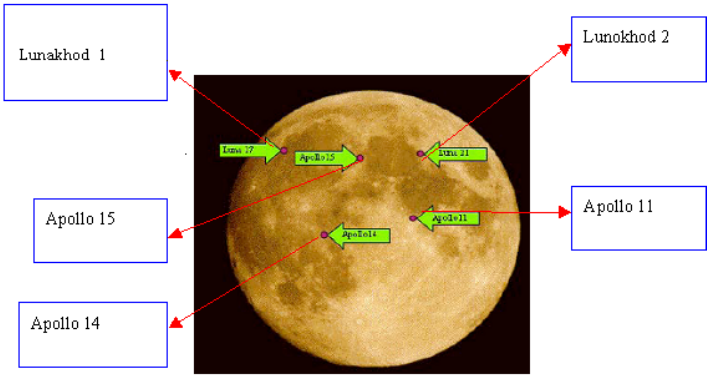

Fig. 1 shows the five retroreflectors on the moon surface

Until now, most of the return pulse the observatories got are from Apollo 15. The Apollo 15 array deployment on 31 July 1971, returns were obtained at McDonald within a few days.

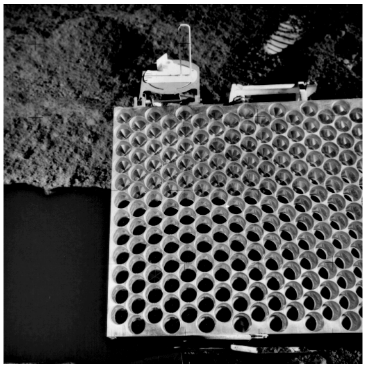

Fig.2 shows Apollo 15 on lunar surface

2.2 The constitution of the LLR system

In order to measure the range from the retroreflector on the moon to the ground, the reasonable, effective and economical lunar laser ranging system should be built up. Just as satellite laser ranging system which is familiar to us, LLR system could be divided into five parts: (i) controlling subsystem, (ii) timing subsystem, (iii) transmitting subsystem, (iv) receiving subsystem and (v) data processing subsystem. The whole system frame is shown in Fig. 3.

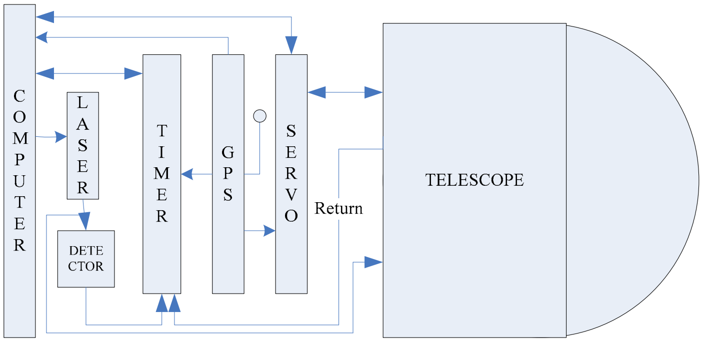

Fig. 3 LLR System Frame

(i) Controlling subsystem is made up of microcomputer, tracking software and the servo. It could transmit the injunction to all the equipment; keep the telescope tracking the object on real time; obtain the original data and save to certain memory medium.

(ii) Timing subsystem is made up of Global Positioning System (GPS) and the Timer. The purpose of this subsystem is following: (1) to provide accurate on station epoch timing to simplify and accelerate the acquisition and tracking of the targets; (2) to provide an accurate frequency source for the pulse time-of-flight measurements; and (3) to lock the epoch the pulses leaving and arriving the ground. The unit uses timing information from the GPS constellation of satellites to automatically constrain the long term frequency drift in a crystal oscillator, which has excellent short term stability, and provides clock outputs at both 1 Hz and 10 MHz. The Event Timer with high precision and low drift will be used to memorize the epoch records.

(iii) Transmitting subsystem is made up of the laser and the transmitting beam path. The laser used in the LLR system should own predominant performances: generate a pulse with high energy, narrow FWHM, high repetition, and low radiation angle. Owning these performances, the pulses generated by the laser would be transferred through the transmit beam path to the lunar with the highest energy it can take.

(iv) Receiving subsystem is made up of the telescope, the detector, and the receiving beam path. The purpose of this subsystem is following: (1) to receive the return pulse flight back telescope (2) to transfer the back photon pulses into electronic pulses in very short time. The larger the telescope's effective area is, the more photons the system can get.

(v) Data processing subsystem is made up of microcomputer and software. The software runs on the microcomputer provides curve fitting and other processing methods, it could pick up the "real" data from the original data according to prediction orbits.
The five subsystems talked above work together to accomplish LLR measurements.

3 MAIN FACTORS AFFECTING LLR SYSTEM PRECISION

The high photon rate expected from LLR System is the key to achieving substantial gains in precision. The principal factors enabling LLR to accomplish its precision are the large telescope aperture and the excellent atmospheric seeing experienced at the site. A bottom-up calculation of the expected photon return rate based on the familiar link efficiency equation is also illuminating.

3.1 Radar equation

Radar equation shows the relationship among lunar detector photon numbers and parameters of devices.

$$N_s = \frac{16 \bullet E \bullet S \bullet A_s \bullet A_r \bullet K_t \bullet K_r \bullet T^2 \bullet \eta \bullet \alpha}{\pi^2 \bullet R^4 \bullet \theta_t^2 \bullet \theta_s^2} \tag{1}$$

N_s	Detection photon number per pulse
E	Laser pulse energy
S	Photon number per Joule
A_s	Effective area of the lunar retroreflector
A_r	Effective area of the receiving mirror
K_t	Transmitter efficiency
K_r	Receiver throughput (dominated by narrow-band filter)
T	Atmospheric transmissivity (double trip)
η	Detector quantum efficiency
α	Attenuation factor
R	Range from the Earth to the moon
θ_t	The beam divergence
θ_s	The lunar retroreflector divergence

In the LLR system, each device assembled the system places a special role during it works. Some performances of these devices are the main factors which affect the system performances, such as pulse energy of the laser, the effective area of retroreflector on the moon, the effective area of receiving mirror, quantum efficiency of detector, radiation angle of the laser.

3.2 The main factors of LLR

Analysis of the equation, we could find that detection number of LLR system is determined by many factors: the laser, the receiver, the detector, the beam divergence, and so on. The signal returning from the Moon is so weak that single photons must be detected. Not all ranging attempts are successful and the likelihood of success depends on the conditions of observation. Observational effects may influence the strength of the signal, the background light which competes with the detection of the returning laser signal, the width of the outgoing or returning beam, and the telescope pointing. Some of these observational influences select randomly and some select systematically, e.g. with phase of Moon, time of day, or time of year. So, detector and laser play important role. The detector should be single photon detected, sufficient sensitivity to be triggered, time walk for compensated, and etc. The laser should produce high power, small divergence pulse on condition that it provides perfect wave shape.

As the far distance would waste energy of laser, the narrow laser beam must be accurately pointed at the target. Seeing, a measure of the chaotic blurring of a point source during the transmission of light through the atmosphere, affects both the outgoing laser beam and the returning signal. The beam's angular spread, typically a few seconds of arc (″), depends on atmospheric seeing so the spot size on the Moon is a few kilometers across at the lunar distance. The amount of energy falling on the retroreflector array depends inversely on that spot area. At the telescope's detector both a diaphragm restricting the field of view and a (few Angstrom) narrow-band color filter reduce background light.

3.3 Detection Probability of LLR system

According to the equation talked above, we could calculate the detection probability of LLR System. The device performances which we expected are listed below.

Retroreflector: Effective area: Apollo-11(1134cm^2), Apollo-14(1134cm)^2, Apollo-15(3402cm)^2

Laser: wavelength: 532nm; Pulse energy: 0.1J, 0.2J, 0.5J

Telescope: Radius: 0.8, 1.5m, 1.8m, 2.0m (effective area estimated); Divergence angel: 2″, 3″

Table 1. Parameters of devices.

Parameters of devices

E	Laser pulse energy,0.1J, 0.2J
S	Photon number per Joule, 532nm 2.7×10^{18}
A_s	Effective area of the lunar retroreflector ,Apollo-15(3402cm^2)
A_r	Effective area of the receiving mirror, Caliber 1.5m，1.8m，2.0m，2.4m
K_t	Transmitter efficiency,0.7
K_r	Receiver throughput (dominated by narrow-band filter), 0.21
T	Atmospheric transmissivity-double trip, 0.49
η	Detector quantum efficiency, 0.2
α	Attenuation factor, 0.1
R	Range from the Earth to the moon, 385,000km
θ_t	The beam divergence, 2"，3"
θ_s	The lunar retroreflector divergence, 10"

The successful probability of detection:

$$P_d = 1 - e^{-N_s} \tag{2}$$

Table 2.Photon numbers and detection probability results

Photon numbers and detection probability results

Num.	Caliber	Energy	Divergence	Photon numbers	Detection probability
1	1.5 m	0.1 J	2"	0.077	7.41%
2	1.5 m	0.1 J	3"	0.0342	3.36%
3	1.5 m	0.15 J	2"	0.1155	10.90%
4	1.5 m	0.15 J	3"	0.0513	5.0%
5	1.5 m	0.2 J	2"	0.154	14.27%
6	1.5 m	0.2 J	3"	0.0684	6.61%
7	1.8 m	0.1 J	2"	0.1091	10.34 %
8	1.8 m	0.1 J	3"	0.0485	4.73%
9	1.8 m	0.15 J	2"	0.1637	15.1%
10	1.8 m	0.15 J	3"	0.07275	7.02%
11	1.8 m	0.2 J	2"	0.2182	19.6%
12	1.8 m	0.2 J	3"	0.0970	9.24%
13	2.0 m	0.1 J	2"	0.1333	12.48%
14	2.0 m	0.1 J	3"	0.0593	5.76%
15	2.0 m	0.15 J	2"	0.20	18.12%
16	2.0 m	0.15 J	3"	0.089	8.51%
17	2.0 m	0.2 J	2"	0.2667	23.4%
18	2.0 m	0.2 J	3"	0.1185	11.17%
19	2.4 m	0.1 J	2"	0.191	17.39%
20	2.4 m	0.1 J	3"	0.085	8.15%
21	2.4 m	0.15 J	2"	0.2865	24.91%
22	2.4 m	0.15 J	3"	0.1275	11.97%
23	2.4 m	0.2 J	2"	0.383	31.82%
24	2.4 m	0.2 J	3"	0.17	15.63%

Table 3.The gradual arrangement of detection probability

The gradual arrangement of detection probability

Num.	Detection probability	Num.	Detection probability	Num.	Detection probability
1	3.36%	9	8.51%	17	15.1%
2	4.73%	10	9.24%	18	15.63%
3	5.0%	11	10.34%	19	17.39%
4	5.76%	12	10.9%	20	18.12%
5	6.61%	13	11.17%	21	19.6%
6	7.02%	14	11.97%	22	23.4%
7	7.41%	15	12.48%	23	24.91%
8	8.15%	16	14.27%	24	31.82%

From the results listed in the table above, we could find that: the detection probability in Line 1 is too low for us to detect the return pulse; the detection probability in Line 2 is also not very easy to get the return signal; the detection probability

31.82% is really nice, while the cost of telescope is too high. So, considering the cost of manufacture, the 1.8m telescope, laser with 0.2J energy, Divergence angel 2″would be a reasonable choice for LLR System.

4 CONCLUSIONS

LLR measurement becomes more and more important for the scientific research to the moon. From this paper, we could find that the foundation of LLR System is feasible and significant. Still, the existence of active stations is a limitation. If more stations with wide distribution are founded, I'm sure LLR will exert more impact in Earth sciences.

ACKNOWLEDGMENTS

Thanks: Supported by National Natural Science Foundation. No.60927010.

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