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Review of the development of Lunar Laser Ranging

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Abstract: This paper provides a comprehensive overview of the development of Lunar Laser Ranging (LLR), covering key components such as ground observatories, lunar retro-reflectors, and data formats. The paper details the evolution of LLR experiments conducted by some major world-class observatories, with a particular focus on addressing critical issues associated with LLR technology. Additionally, the article highlights the latest advancements in the field, elucidating scientific achievements derived from LLR data, including its contributions to gravitational theory, Earth Orientation Parameters, lunar physics exploration, and lunar librations. The review summarizes new challenges in LLR modeling and concludes with prospects for the future development of LLR.

Keywords: Lunar Laser Ranging; Retro-reflectors; Observatories; Gravity

1. INTRODUCTION

The Moon has consistently been a pivotal nexus in humanity's exploration of deep space. With significant achievements in the Chinese Chang'e lunar exploration program and a surge in lunar exploration initiatives worldwide, lunar research has once again become a key area of research. LLR stands as a precise technique for measuring the Earth-Moon distance. In particular, the application of next-generation single solid lunar Cube Corner Retro-reflectors will enable LLR to achieve millimeter-level observational accuracy. The high-precision data obtained from LLR hold crucial scientific value in the realms of astro-geodynamics, the determination of Earth-Moon system parameters, lunar librations, and the validation of the equivalence principle in general relativity[1, 2].

Despite China's successful implementation of LLR, the application of the data acquired is still in its preliminary stages. Therefore, it is of utmost importance to closely follow the latest advancements in the field of international LLR to maximize the utilization of LLR data in scientific research.

2. DEVELOPMENT OF LUNAR LASER RANGING

2.1. History

In 1964, General Electric Company and the Goethe Flight Center successfully measured the distance of the Beacon-B satellite using pulse ruby laser, achieving satellite laser ranging. Subsequently, Alley and others proposed placing laser retro-reflectors on the lunar surface to conduct LLR experiments[3]. On July 21, 1969, the United States' Apollo 11 mission marked the first human landing on the Moon, and astronaut Aldrin placed a retro-reflector on the lunar surface. On August 1 of the same year, the United States' Lick Observatory successfully observed laser ranging echoes from the Apollo 11 retro-reflector using a 3 m telescope. On August 22, the 2.7 m telescope at the United States' McDonald Observatory received echoes[4]. Subsequently, the United States placed retro-reflectors on the lunar surface during the Apollo 14 and Apollo 15 missions, and the Soviet Union also placed retro-reflectors during the Luna 17 and Luna 21 missions, as shown in

Fig. 1. Of the five lunar retro-reflectors, those placed during the Apollo 11, Apollo 14, and Apollo 15 missions consist, respectively, of arrays with 100, 100, and 300 individual corner cube retro-reflectors with diameters of 3.8 cm, as shown in Fig. 2, Fig. 3, Fig. 4[5].

Fig. 1. Retro-reflector positions on the Moon[5].

Fig. 2. Apollo 11 laser retro-reflector arrays.

Fig. 3. Apollo 14 laser retro-reflector arrays.

The Soviet Luna 17 and Luna 21 missions carried retro-reflectors designed by France, each consisting of an array of 14 triangular-faced corner cube retro-reflectors with a side length of 11 cm. Currently, observatories capable of LLR include the McDonald Observatory and Apache Point Observatory (APO) in the United States, the Grasse LLR Station in France, the Matera Laser Ranging Observatory in Italy, Wettzell in Germany, and the Yunnan Observatories, Chinese Academy of Sciences (YNAO) and Sun Yat-sen University in China.

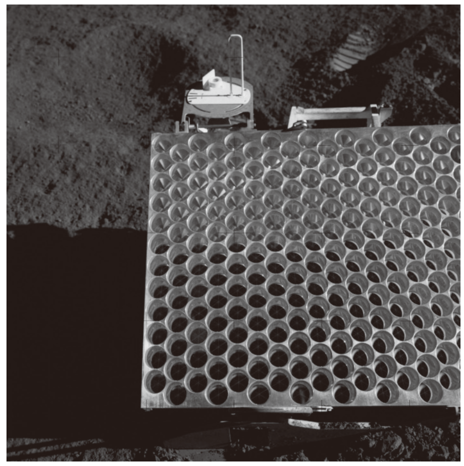

Fig. 4. Apollo 15 laser retro-reflector arrays.

McDonald Observatory in the United States, after successfully receiving the echo signal from the Apollo 11 retro-reflector in 1969, has continuously developed and improved its LLR capabilities, remaining in operation to the present day. The Haleakala Observatory in Hawaii conducted LLR activities between 1984 and 1990. In 1990, France established the dedicated Grasse LLR Station. Matera Laser Ranging Observatory in Italy, constructed in the early 21st century, achieved LLR technology. In 2006, the APO in southern New Mexico, USA, used a 3.5 m telescope and upgraded to a new generation of LLR systems for routine measurements. In 2010, it successfully measured the reflector placed by Lunokhod 1, which lacked precise location information and had been unattainable through LLR for four decades until the reflector's position was identified in Lunar Reconnaissance Orbiter images[6]. The Apache Point Observatory Lunar Laser Ranging Operation (APOLLO) has achieved millimeter range precision in LLR, representing an order of magnitude improvement in various essential tests of gravitational properties and marking the official entry of LLR into the millimeter-level precision era[7]. To date, APO has obtained a total of 3877 standard point data. Additionally, other successful LLR ground stations worldwide include the Wettzell Observatory in Germany.

The YNAO, achieved LLR for the first time domestically in 2018 using a 1.2 m horizontal telescope, receiving echo signals from the Apollo 15 retro-reflector[8]. The YNAO's laser ranging system, developed for Sun Yat-sen University's Tianqin project, successfully detected all reflectors on the lunar surface in 2019 and received echo signals, achieving centimeter-level ranging accuracy[9].

The International Laser Ranging Service (ILRS) has accumulated over 50 years of LLR observation data, and the Crimean Astrophysical Observatory accumulated an additional 103 normal point data between 1973 and 1981, totaling 31 351 normal point data. Data from each observation station are presented in Table 1. Fig. 5 shows the distribution of lunar reflectors in the LLR dataset. Most LLR data are derived from observations of Apollo 15, and the development of data precision is shown in Fig. 6 using the root mean square (RMS) of the fitted residuals. The highest precision has been achieved by APOLLO, reaching the millimeter level.

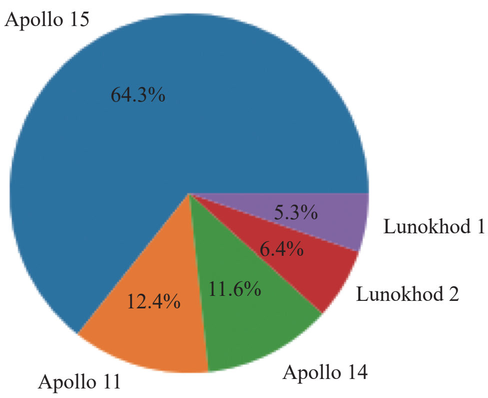

Fig. 5. The distribution of retro-reflectors in the LLR dataset.

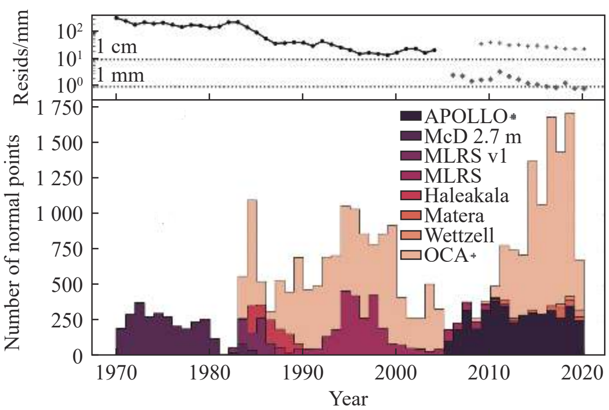

Fig. 6. Top panel: Data-Model agreement (line with points) as quantified by the RMS of the post-fit residuals of LLR data with the JPL solar system ephemeris model. Bottom panel: A stacked histogram that displays the annual count of normal point data generated by each LLR station[10].

Table 1. Normal point data for major observatories

Observatory	Observation time	Normal point data
McDonald	1969–2015	7 905
Grasse	1986–2021	18 201
Haleakala	1984–1990	770
Apache Point	2006–2021	3 877
Wettzell	2018–2021	115
Crimean Astrophysical	1973–1981	103
Matera	2003–2021	380
ALL	1969–2021	31 351

2.2. LLR Data Format

During LLR observations, each session is dedicated to a single retro-reflector and typically lasts for 5–15 min. The distribution of LLR session duration in LLR dataset acquisition is shown in Fig. 7 and Fig. 8. During this time, the recorded signals may range from a few echo photons to several thousand echo photons. LLR data are uniformly released by the ILRS and is usually organized into normal point data, representing the averaged results from multiple observation points within a single observation session. The LLR data are recorded in coordinated universal time (UTC), and include the laser emission time, the time delay between laser emission and reception, information about the lunar retro-reflector and observation station, atmospheric pressure, temperature, humidity, and laser wavelength.

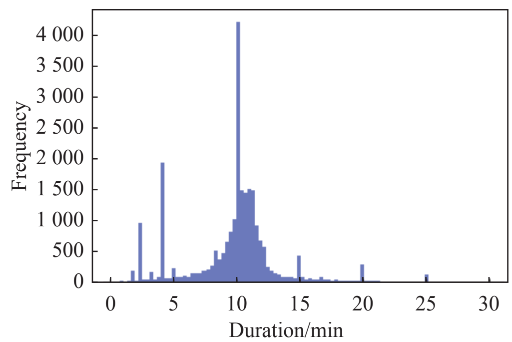

Fig. 7. Distribution of LLR session duration.

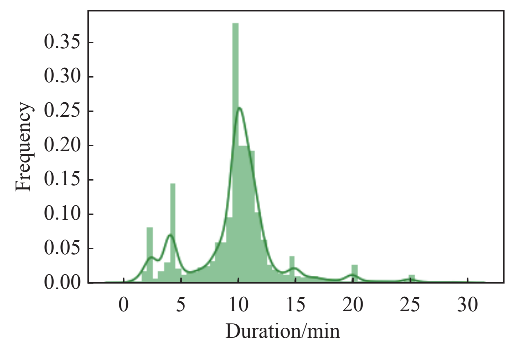

Fig. 8. Probability density distribution of LLR session duration.

Currently, commonly used LLR normal point data formats include MINI, Coordination Space Techniques for Geodesy-Geodynamics (CSTG), and Consolidated laser Ranging Data format (CRD). The distribution of LLR data format in the LLR dataset is shown in Fig. 9. The MINI data format was initially used by the McDonald Observatory, Haleakala Observatory, and Grasse Observatory, and is still employed by the Apache Point Observatory. The CSTG data format was officially adopted by ILRS in 1999 as the recording format for both satellite laser ranging and LLR observation data. It underwent revisions in 2004 and continues to be used. CSTG normal point data records header information and data record information. The header information includes laser emission and reception time delays, station and retro-reflector identification, echo photon count, and meteorological parameters. The CRD format is a flexible and expandable data format. Currently, there are limited CRD format LLR data in the ILRS.

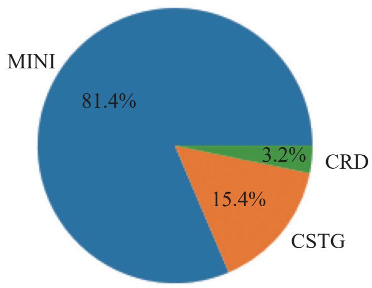

Fig. 9. The distribution of LLR data format in the LLR dataset.

2.3. Development of LLR at APOLLO

In 2006, APOLLO represented a novel venture in the field of LLR. Fig. 10 shows the APOLLO telescope at the APO. It employs a 3.5 m telescope located at Apache Point in the southern region of New Mexico. The combination of the telescope's large aperture and the favorable atmospheric conditions at the observatory site has yielded a new domain which can now detect multiple photons returning from each laser pulse. This is a significant improvement over previous LLR installations, which typically averaged only 0.01 photons per pulse. APOLLO has since delivered range measurements with millimeter-level precision[7, 10].

Fig. 10. Looking north along the escarpment at APO, the prominent dome silhouetted against the sky contains the LLR 3.5 m telescope. Behind and to the right of it stands the white, cone-shaped SUNSPOT solar telescope[11].

The high precision of APOLLO data relies on the development of an absolute calibration system (ACS) to eliminate system errors in the data. Since APOLLO became operational, it has been responsible for the majority of LLR measurements globally, routinely capturing data from 4-5 reflectors during each hourly observing session, as shown in Fig. 11. The distribution of uncertainty in the APOLLO dataset is shown in Fig. 12, The range measurements conducted by APOLLO, starting from 2006, have demonstrated a median uncertainty of 6.14 mm, outperforming the uncertainty levels achieved by other LLR stations. This substantial enhancement in measurement precision should theoretically advance tests of relativistic gravity to a precision of approximately 0.01% in a short time frame. However, LLR science depends on a complex and specialized model that can accurately replicate all physical factors affecting measurements, from an Earth-based telescope to a retro-reflector. Currently, only a handful of such models exist globally[12].

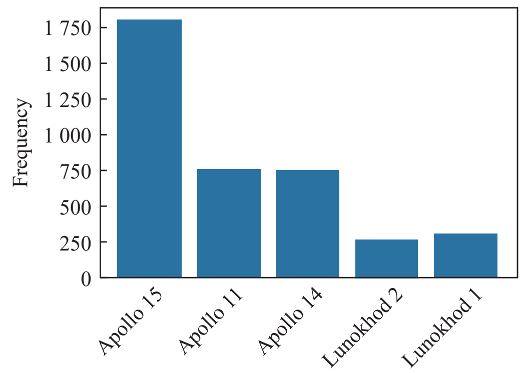

Fig. 11. The distribution of lunar retro-reflectors in the APOLLO dataset.

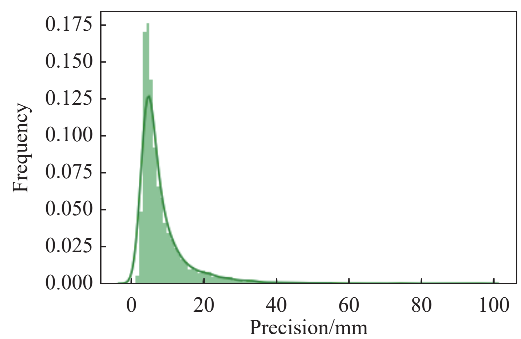

Fig. 12. The distribution of uncertainty in the APOLLO dataset.

The discrepancy between measured and calculated ranges generates residuals, which are progressively minimized through an iterative least-squares approach by adjusting the model's unknown parameters. If measurement uncertainties are accurately evaluated and the model encompasses all necessary physics (and is accurately coded), then the residuals should be centered around zero, in accordance with uncertainties. None of the currently existing LLR models show this behavior. The discrepancies in residuals for APOLLO's approximately 2 mm scale measurements vary from around 15 mm in the most accurate model to roughly twice that in others[12]. Consequently, the introduction of LLR data, with precision improved by an order of magnitude compared with previous standards, has notably advanced gravitational testing.

The APOLLO data boast high precision, but the errors in the models are an order of magnitude larger than those in the measurements. Possible reasons for this issue are incomplete or incorrect models, or imprecise ranging data. Although endeavors to enhance models persist, considerable time has elapsed without a definitive determination regarding whether the substantial residuals stem from model deficiencies or data inconsistencies. The evidence remains inconclusive. Scientists believe that the measurement of the local corner cube may be affected by rapid discharge of the laser, which involves a switch of approximately 3 000 V in just a few nanoseconds, thereby generating electromagnetic interference (EMI) that could affect nearby detectors and timing electronics[11].

APOLLO has developed an ACS to detect and eliminate systematic errors, which also serves as a means for direct calibration of the ranging data[13]. The structure of the ACS is shown in Fig. 13. APOLLO's timing precision has been investigated, including attempts to pinpoint the origins of systematic errors, by initiating the injection of short pulses into the detector at tightly controlled intervals. This method has since advanced to employ a high-repetition-rate fiber laser that is locked to a cesium clock. The laser pulses are currently guided to the APOLLO system through an extended fiber, which effectively protects the system from any electromagnetic interference generated by APOLLO. Most importantly, these calibration photons can be overlaid onto the lunar ranging measurements, acting as a finely calibrated "optical ruler" that supplies photon reference points to the detector, concurrent with the lunar return photons. As a result, measurements can be calibrated directly, even if the systematic error sources remain undetermined and unresolved. This procedure converts APOLLO from an instrument with millimeter precision to one that achieves millimeter accuracy.

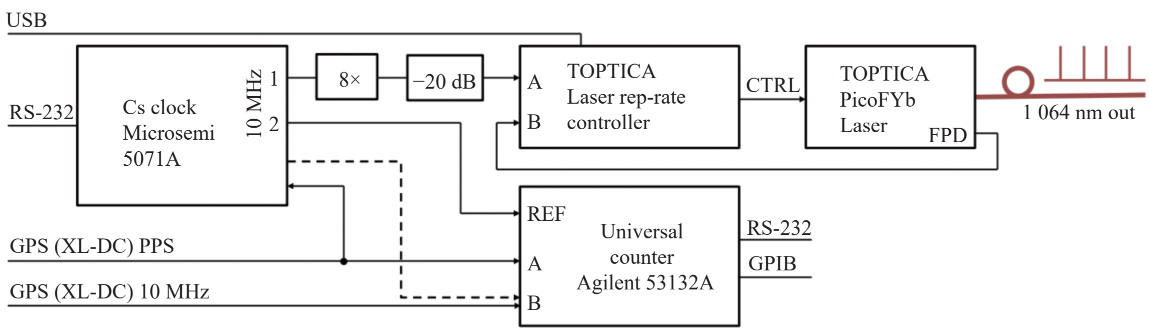

Fig. 13. The ACS enclosure houses a laser, which emits a sequence of 1064 nm pulses, each lasting 10 ps, into an optical fiber. The laser repetition-rate controller, specifically the Microsemi 5071A, synchronizes the fiber laser with a cesium frequency standard. A universal counter, the Agilent 53132A, is used to compare the frequency of the cesium clock with that of a clock regulated by Global Positioning System (GPS) data, the TrueTime XL-DC. The dashed line in the diagram indicates temporary and intermittent adjustments made to observe the growing phase discrepancy between the two clocks[13].

Preliminary analysis indicates that there is no inaccuracy in the APOLLO data at the 3 mm level, suggesting that the historical APOLLO data quality has been high, and this encourages us to continue improving the capa bilities of the models. The ACS also offers a means to provide accurate and precise APOLLO data at levels below 2 mm[13].

2.4. Development of LLR at Grasse

The Grasse station is the observatory that has measured the most LLR data in the world. The uncertainty of the LLR data from the Grasse station is illustrated in Fig. 14, which shows that the overall data precision is at the centimeter level.

LLR measurements at the Grasse station commenced in 1981, which operates a 1.54 m telescope, employing a ruby laser with a wavelength of 684.3 nm to emit 3 ns wide pulses of 3 J energy at 6 s intervals. Over a span of 4 years, the station conducted 1 188 observations, achieving a residual RMS error of approximately 16.4 cm[14]. In 1986, an infrared neodymium-doped yttrium aluminum garnet (Nd:YAG) laser was adopted, emitting at a wavelength of 532 nm, which allowed for the use of more precise, and less noisy, detectors. The available energy per pulse was around 75 mJ in the green spectrum, emitted at a rate of 10 Hz, resulting in a return rate of about one photon every 10 s. From 1984 to 2005, the Grasse station produced 9512 normal points of data. In 2005, the station was upgraded to extend the operational capabilities of the telescope and enhance the stability of the station's timebase for time transfer experiments. Multiple upgrades were made to the electronics, and new event timers and a fiber-based calibration system were installed[14]. In 2012, the Grasse station saw its laser pulse duration extended

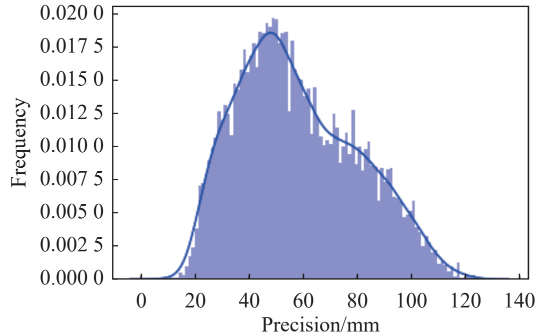

Fig. 14. The distribution of precision of returned photons in the Grasse dataset.

from less than 70 ps to 150 ps.

In 2015, a significant upgrade was implemented at the Grasse station to enhance LLR observational efficiency, Courde et al. proposed the use of laser beams at the 1 064 nm infrared (IR) wavelength as an alternative to the widely used 532 nm wavelength for LLR observations. The use of 532 nm wavelength lasers for LLR has long been plagued by issues of temporal and spatial non-uniformity, and the introduction of the infrared wavelength laser has addressed this concern[15]. Simultaneously, the incorporation of infrared observations in LLR has the potential to amplify the scientific output of LLR data. As shown in Fig. 15 and Fig. 16, using a 1 064 nm wavelength for LLR results in a significant improvement in number of returned photons and data precision compared with using 532 nm. This indicates that infrared LLR increases site efficiency by eight times during new moon and full moon periods. This not only significantly augments the normal point data for all lunar retro-reflectors, but also results in a more even distribution of observations across all retro-reflectors, as shown in Fig. 17. Observations have also shown that the degradation in the performance of Lunokhod 2, noted in infrared LLR, appears to be chromatic, as the substantial differences observed in green light by Grasse and APOLLO are not present in the infrared[15, 16]. This phenomenon offers new insights for analyzing the performance of lunar retro-reflectors.

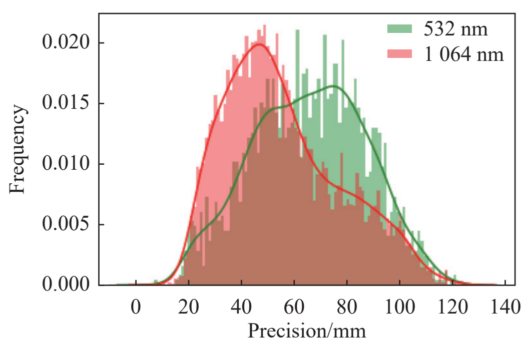

Fig. 15. The distribution of uncertainty in the Grasse dataset for LLR using different laser wavelengths.

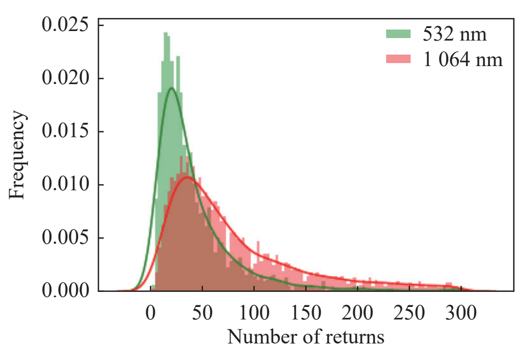

Fig. 16. The distribution of number of returned photons in the Grasse dataset using different laser wavelengths.

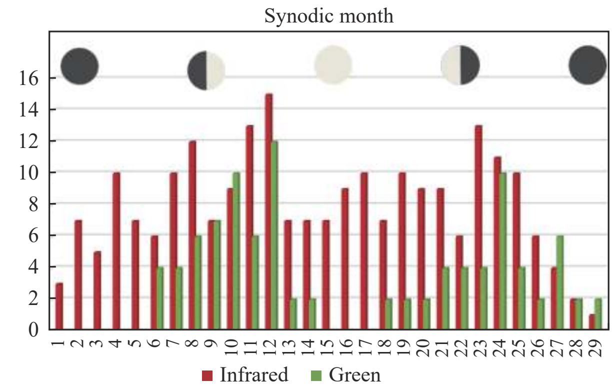

Fig. 17. Repartition of normal points during the synodic month[16].

2.5. LLR in the Crimean Astrophysical Observatory

The Crimean Astrophysical Observatory (CrAO) served as the sole institution within the Soviet Union engaged in LLR activities. In 1960, a 2.6 m telescope was installed at CrAO, which remains an operational and valuable astronomical instrument to this day. Commencing in 1963, the observatory initiated LLR experiments using a ruby laser developed by the Lebedev Physical Institute (LPI), characterized by a wavelength of 694.3 nm, a pulse duration of 30 ns, and an energy output of 2 J. Ongoing technological advancements have led to a significant improvement in the precision of lunar distance measurements, culminating in an accuracy of 25 cm in 1984, which is on par with contemporary LLR observations conducted at the McDonald Observatory, the Haleakala Observatory in Hawaii, and the Grasse Observatory in France. Between 1973 and 1984, the CrAO amassed a total of 176 photons and 103 normal points of data in its LLR endeavors[17]. Notably, the three observations of Lunokhod 1 obtained in 1974 were instrumental in pinpointing the location of the robotic rover on the lunar surface. The LLR observations conducted by CrAO have been validated as authentic and reliable, offering a rich resource for comparative analysis with LLR data from other observatories. This comparative approach aims to enhance the precision of lunar dynamic models.

As for the development of planetary and lunar ephemerides, the Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS) has developed the EPM-ERA lunar ephemeris, a sophisticated mathematical model designed to predict the position and motion of the Moon[18]. Using a comprehensive dataset of 17 580 LLR observations, spanning from 1970 to 2012, this ephemeris incorporates various factors such as lunar orbital dynamics, rotational motion, Earth tides, and the lunar gravitational field. While it demonstrates slightly lower accuracy compared with the DE403, DE405, DE421, and INPOP10 ephemerides in representing LLR observations, the precision of EPM-ERA is sufficient for addressing numerous practical challenges in astronomy, including ephemeris support for the Global Navigation Satellite System (GLONASS) and orbit refinement for near-Earth asteroids. Future research aims to refine the mathematical model of lunar rotation to better accommodate millimeter-precision LLR observations from APOLLO.

2.6. Development of LLR at YNAO

LLR represents the pinnacle of single-photon detection technology, and after more than 50 years of development, it remains a highly challenging and complex task. Constrained by factors such as telescope aperture and laser technology, LLR started relatively late in China. YNAO initiated LLR research in the 1980s with a 1.2 m horizontal telescope. This telescope was the largest aperture ranging telescope in China at the time, and held the greatest potential for achieving LLR[1]. After years of exploration and technological upgrades, the telescope's performance has greatly improved. In particular, with the upgrade to the third-generation laser ranging system, an independently developed Common Path Kilohertz laser ranging system was implemented, significantly enhancing the accuracy of ranging for high-orbit satellites. In 2010, daylight satellite laser ranging was achieved, and a 4.5 J high-energy laser was used for space debris ranging[19, 20]. Li et al. studied the impact of the detector's position on the detection probability of reflected photons, achieving precise control of the detector's position[21]. Tang et al. investigated the distribution characteristics of the photons reflected in laser ranging and conducted an analysis of the influence of atmospheric turbulence on the number of reflected photons in laser ranging[22, 23]. These developments have significantly enhanced the ranging capabilities at YNAO and made LLR a possibility.

After years of research and exploration, YNAO successfully detected the reflection from the APOLLO 15 retroreflector using its 1.2 m telescope and a 10 Hz common-path LLR system on January 22, 2018, achieving LLR technology. The images and range residual during LLR conducted by YNAO are presented in Fig. 18 and Fig. 19. YNAO, based on the specifications of the International Earth Rotation and Reference Systems Service (IERS) and the data from the French INPOP19a ephemeris, conducted an analysis of the primary influencing factors of LLR. Factors were modeled with magnitudes exceeding 1 cm, established an observational model for the Yunnan Observatories' LLR, and the results indicate that the precision of the acquired normal point data has reached the order of 10 cm[24]. The current precision is primarily influenced by the laser pulse width and with the use of new narrow-pulse-width lasers, there is potential to improve LLR accuracy to the centimeter level.

2.7. Trends in LLR Development

Noticeable degradation in the performance of lunar retro-reflectors has been identified with LLR. Among the most likely explanations is the gradual accumulation of an extremely thin layer of dust on the front surface of the retro-reflectors by electrostatic suspension, impacting the efficiency of photon reflection[25, 26].

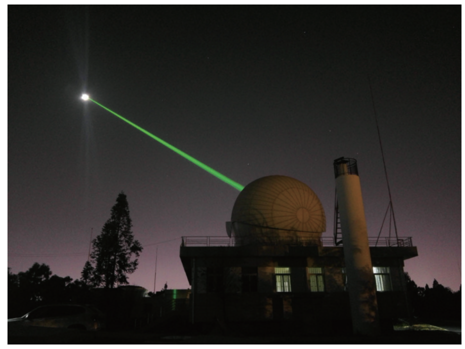

Fig. 18. LLR being performed at YNAO.

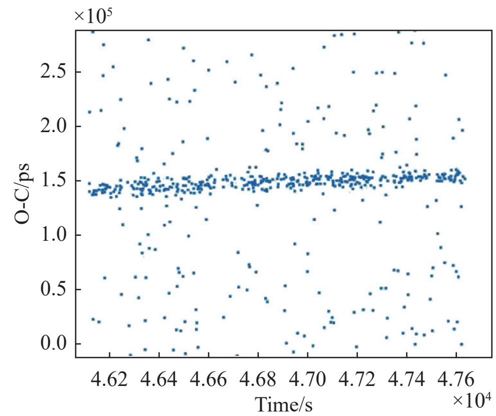

Fig. 19. Residuals of the measurement data of the YNAO LLR.

Another primary factor limiting the accuracy of LLR is Earth's atmosphere, with its impact on accuracy not exceeding 5 mm. To better mitigate the atmospheric impact on LLR accuracy, the establishment of a facility at Table Mountain Observatory operated by the NASA Jet Propulsion Laboratory (JPL) will facilitate a novel form of LLR known as differential lunar laser ranging (DLLR). This approach introduces a distinctive observable, termed the lunar range difference, which involves the difference between two consecutive ranges, obtained by a single station rapidly alternating between two or more lunar reflectors. This previously inaccessible observation is expected to achieve an exceptionally high level of accuracy (around 30 μm), primarily attributed to a reduction in atmospheric error from Earth[27]. In addition to the planned improvements for lunar investigations, it will contribute to advancements in tests of relativity, such as the equivalence principle.

3. SCIENTIFIC RESEARCH IN LLR

3.1. Testing General Relativity and Beyond

Long-term LLR data have extremely high scientific value and have yielded many scientific achievements. Despite gravity being one of the most prominent forces in nature, it is the weakest among the fundamental forces. Consequently, experimental tests of gravity are less comprehensive compared with other forces. Einstein's theory of General Relativity currently stands as our most accurate description of gravity; however, it is fundamentally incompatible with quantum mechanics. Therefore, the validation of General Relativity remains a crucial topic in modern physics[28].

The Moon, as the natural satellite of Earth, possesses a considerable gravitational mass. Its gravitational environment is relatively similar to Earth's, and because of its larger scale and spatial extent compared with artificial celestial bodies, the gravitational effects are more pronounced. Therefore, lunar orbit serves as a natural laboratory for testing General Relativity[29]. The latest observations from LLR have achieved millimeter-level precision, making this the most accurate technique internationally for verifying the equivalence principle of General Relativity.

LLR measurements are crucial for testing and refining our understanding of gravity, providing data for estimating gravitational parameters and studying the dynamics of the Earth-Moon system. At the current stage, LLR has achieved remarkable results in the verification of General Relativity, including:

- To test the strong equivalence principle, LLR data demonstrate a sensitivity to the equivalence principle parameters of approximately 3×10^{-4} [30-32].
- Through the analysis of LLR data over an extended time span, the rate of change of the gravitational constant $\dot{G}/G$ has been constrained to the level of 6×10^{-12} per year[33-35].
- Earth's precession, obtained through the analysis of LLR data, is determined to be 19.2 milliarcseconds per year, with a difference of less than 0.3% from the prediction of general relativity[32, 36, 37].
- The inverse-square law $1/r^2$, integral to Newtonian gravity, predicts a specific precession of orbit perigees for celestial bodies. The lunar orbit, positioned at a height of 10^8 m, undergoes scrutiny through LLR analysis to constrain deviations from the inverse-square law to an impressive level of 5×10^{-11}. This represents one of the strongest experimental constraints on the inverse-square law currently achievable[38, 39].
- In additionally, LLR data find applications in various aspects, such as testing Newton's third law[40-42]. LLR may also provide insights into the possible existence of extra dimensions through cosmic expansion[43, 44]. Beyond the strong equivalence principle, LLR tests the weak equivalence principle at the level of $\Delta a/a < 1.3\times10^{-13}$. It achieves a precision level similar to laboratory tests for the weak equivalence principle[45, 46].
- LLR data can and have also been used to put constraints on new gravitational physics beyond General Relativity. Such data can be used to study Spacetime Torsion by analyzing the motion of the Moon and calculating the corrections to perihelion precession and orbital geodetic precession, exploring new gravitational phenomena[47]. Furthermore, LLR data play a significant role in the study of Planck-scale Effective Field Theories of Gravity, Nonminimally Coupled Gravity, and Lunar Gravitational Wave Detection[48-50].

3.2. Research on the Earth-Moon System

The total inertia moments of the Moon can be determined through the analysis of LLR data. With the advancement of laser ranging technology and the improvement of observational accuracy, there is a significant enhancement in the precision of the lunar core inertia moments (A, B, C). This improvement allows for better constraints on the density distribution model of the Moon, facilitating the determination of physical parameters such as lunar oblateness, solid tide, and other relevant factors. These refinements contribute to the enhancement of the internal structure model of the Moon. In their research, Williams et al. observed pronounced dissipation effects in the lunar tides and determined the lunar dissipation factors. The study indicates the presence of a fluid core with approximately 20% of the lunar radius, as the rotation of the Moon is influenced by its internal characteristics. This advancement contributes to an improved understanding of the Moon's origin and evolutionary processes[51-53]. In addition, LLR can be used to determine the dynamical model parameters of the Earth-Moon system, such as the measurement of Earth-Moon mass and lunar librations[54, 55].

3.3. Earth Orientation Parameter (EOP) Reference Frame and Ephemeris

LLR is highly sensitive to Earth's orientation parameters, allowing them to be investigated using LLR data. Biskupek and Müller, among others, utilized LLR data to determine Earth's nutation, precession, polar motion, and Universal Time (UT0)[56, 57]. The Shanghai Astronomical Observatory has conducted research on Earth's orientation parameters using publicly available LLR data from ILRS[58, 59].

LLR data also play a crucial role in determining coordinate frameworks and can be used for establishing the coordinates of ground observation stations and lunar retro-reflectors. The transformation from the lunar-fixed frame to the lunar-centered celestial frame depends on the lunar rotation Euler angles. LLR data are employed to model the lunar rotation, providing a sequence of high-precision lunar rotation Euler angles. Standish and Folkner provide detailed descriptions of JPL integration models for both orbit and lunar rotation[60, 61]. Pavlov elaborates on the application of the Institute of Astronomy's model[53], while the model for the Intégrateur Numérique Planétaire de l'Observatoire de Paris (INPOP) ephemeris is expounded upon by Viswanathan et al.[62].

Another crucial role of LLR data is its use in constructing lunar ephemerides. Numerical ephemerides are indispensable tools for deep space exploration, and the high precision of LLR provides the foundational data for generating lunar numerical ephemerides. The generation of lunar ephemerides is a complex process, generally requiring high-precision lunar dynamical models. Integrators are employed to calculate a series of celestial body state data, which are then fitted using Chebyshev polynomials to create ephemerides files stored in the form of Chebyshev polynomial coefficients.

Currently, nations such as the United States, Russia, and France have established their own numerical ephemerides. Taking the example of the DE (Development Ephemerides) series ephemerides: NASA-JPL has developed the DE/lunar ephemerides (LE) series planetary and lunar ephemerides. The latest in the DE series is DE441[63]. The DE ephemerides has seen widespread use, starting with DE96 in 1975. With the implementation of numerous deep space exploration missions and the acquisition of actual measurement data for major celestial bodies in the solar system, subsequent versions such as DE403 and DE405 were produced, becoming the foundation for various astronomical almanacs. In later research, with the increase in LLR data and further refinement of lunar models, scientists established a two-layer elastic lunar model, leading to the creation of DE421 and DE430. Notably, DE430 used the Gravity Recovery And Interior Laboratory (GRAIL) lunar gravity field model, significantly improving the precision of lunar orbit and rotation parameters[61].

4. LLR MODEL

Currently, there are multiple LLR models worldwide, located at NASA-JPL, the Harvard-Smithsonian Center for Astrophysics (CfA), Leibniz University in Hannover, Germany, and Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE) in Paris, France[11]. Among them, only the Planetary Ephemeris Program (PEP) at CfA is made available to the community and provided in the form of open-source code. Presently, the JPL model exhibits the best performance, with a weighted RMS residual of approximately 18 mm for the APOLLO and Observatoire de Côte d'Azur (OCA) data, roughly twice the current level of other models. Clearly, there is a gap between the estimated APOLLO uncertainty and the model residuals, with the former being on the order of a few millimeters.

Every LLR analysis team maintains a catalog of known effects that have not been accounted for in the model, with many of these effects only becoming noticeable at the millimeter scale. Using PEP at CfA as an illustration, the following outlines a list of recognized effects that have yet to be integrated into the model. Other groups may be at various stages in addressing these factors. For PEP, specific enhancements required encompass:

● A more comprehensive treatment of internal dissipation in the Moon.

● A more rigorous tidal model, employing Love numbers dependent on frequency and spherical harmonics.

● Utilization of the latest data from the GRACE and GRAIL missions to update the gravity fields of the Eart and Moon.

● Improved Earth orientation handling, including feedback of LLR residuals into data determined by Very Long Baseline Interferometry (VLBI) and GPS data.

● For APOLLO sites, considerations such as approximately 3 mm horizontal RMS and 5 mm vertical RMS ocean tide.

● Atmospheric loading, with an impact of approximately 1 mm per 3 mbar pressure anomaly.

● Earth center-of-mass motion observed through satellite laser ranging, with an amplitude of about 1 cm at annual frequency.

5. SUMMARY AND PROSPECTS

Since it was first employed, LLR has been established as the cornerstone for precision measurements related to gravitational research, lunar-terrestrial system physics, and coordinate system considerations. The fundamental measurements conducted by LLR have diverse applications in physics. In the field of gravity, LLR serves as a powerful tool for detecting the equivalence principle, variations in gravitational constants, gravitational magnetic fields, Earth's nutation, the inverse square law, and preferred reference frames, among other crucial aspects. Furthermore, LLR is applicable to testing new concepts in physics.

Despite a significant decrease in signal strength from reflectors caused by lunar dust, LLR data accuracy continues to improve, approaching millimeter-level precision. However, the current configuration of lunar retro-reflectors constitutes a major source of ranging errors[64]. Adding single solid lunar Cube Corner Retro-reflectors to the lunar surface could significantly enhance ranging precision[5, 65]. Next-generation laser retro-reflectors have been developed over the years, and some have been built and space qualified for imminent lunar landing missions. A lab-simulated performance test and analysis demonstrates that the next-generation lunar retro-reflector, Moon Laser Instrumentation for General relativity/geophysics High-accuracy Tests (MoonLIGHT-2), exhibits excellent thermal and optical performance and is unaffected by lunar libration[66]. This suggests that MoonLIGHT-2 has the potential to significantly improve the precision of LLR. Williams et al. indicate that the new retro-reflectors are single 10 cm corner cubes that do not disperse the laser pulse during reflection as existing arrays do, and larger corner cubes necessitate careful handling to ensure that the potential spread of velocity aberration displacements is optimally accommodated within the diffraction pattern[67]. The work of Haviland et al. introduces the network applications of laser retro-reflectors and Porcelli et al. provide a comprehensive review of next-generation laser retro-reflectors and their imminent lunar mission opportunities[2, 68]. The latter paper also describes a useful recent evolution of lunar laser retro-reflector payloads: the integration of dual Earth pointing actuators into the optical instrument itself, MoonLIGHT Pointing Actuators (MPAc).

Simultaneously, installing active laser responders on the lunar surface could have a greater impact on LLR science, replacing the $1/r^4$ signal loss mechanism with a better $1/r^2$ mechanism. This would allow widespread participation of Satellite Laser Ranging networks in LLR on a routine basis. Studies by Yang et al. optimized the deployment direction of single large-aperture new retro-reflectors to enhance the effective diffractive area and increase the return photons[69]. The introduction of new reflectors or active laser responders on the lunar surface could extend LLR to dozens of satellite laser ranging stations worldwide, significantly increasing data volume, global distribution, and scientific contributions.

Moreover, another significant limitation on the accuracy of LLR is the Earth's atmosphere. To mitigate this, Table Mountain Observatory has proposed DLLR to significantly reduce the influence of the Earth's atmosphere, resulting in an accuracy approximately 200 times better than regular LLR. Additionally, dual-frequency LLR, which simultaneously uses laser wavelengths of 1064 nm and 532 nm, is effective in reducing the impact of the atmosphere during LLR. However, there are currently no reported implementations of this technology.

Because of the complexity of the LLR model, unmodeled components contribute to lower model accuracy compared with LLR observational precision. Ongoing improvements are necessary in existing models to adapt to millimeter-level LLR data. As models adapt to millimeter-level data, LLR is expected to provide even greater scientific value in the future.

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AUTHOR CONTRIBUTIONS

Kai Huang conceived the idea for the review, conducted the literature search, drafted the manuscript and organized the structure of the review. Yongzhang Yang helped draft sections of the manuscript and provided feedback on the overall structure and content. Yuqiang Li supervised the review process and provided guidance on the selection of topics and the interpretation of the literature. Marco Muccino, Luca Porcelli and Simone Dell'Agnello reviewed and edited the manuscript, ensuring its academic rigor and clarity. Rufeng Tang and Jin Cao contributed to the literature search and provided critical insights on the topics covered in the review. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

Yuqiang Li is an editorial board member for Astronomical Techniques and Instruments and he was not involved in the editorial review or the decision to publish this article. The authors declare no competing interests.

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