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A Lunar Laser Ranging Retroreflector Array for the 21st Century: Review of the History, Science, Status and Future

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Abstract

Lunar Laser Ranging (LLR) [1] has produced unique new lunar science (e.g., the discovery of the liquid core of the moon) and some of the best tests of Gravitation and General Relativity [2]. Ground stations have improved by a factor of 200 over the past four decades so the Apollo hardware now limits the single photo-electron ranging accuracy. We describe challenges and status of the next generation of Lunar RetroReflector (LRR) that is currently being developed.

1. Historical Review of LLR

A brief history of the background of the existing Apollo arrays [1] will be presented. In particular, this will review the role of Robert Dicke of Princeton, one of the first modern experimentalists to address testing General Relativity and Carroll Alley, Principal Investigator of the team that developed Apollo LLR. The early ranging stations, in particular at the McDonald Observatory [9] developed by the author, and the continuing analysis of the data by various groups, especially James Williams at JPL will be described. Finally, the history of the development of the "Lunar Laser Ranging Retroreflector Array for the 21st Century" (LLRRA-21) [3] centered at the University of Maryland will be reviewed.

2. Current LLR Science Results

The Apollo arrays, along with the Lunahod arrays, have resulted in a wealth of unique new results. In particular, in Lunar Physics (e.g., the discovery and determining the properties of the liquid core of the moon, the Properties of the Core-Mantle Boundary, etc.), Gravitational Physics (e. g., the temporal and spatial constancy of the Gravitational Constant) and General Relativity Tests (e. g., the Strong Equivalence Principle and the inertial properties of gravitational energy) will be described.

3. Challenges w.r.t. Current LRRs

The ranging accuracy of the single photo-electron returns from the Apollo arrays remains the same after four decades, although the ground stations have improved the ranging accuracy by a factor of 200. Lunar liberation causes the panel of 100/300 Cube Corner Reflectors to tilt. As a result, the combination of the design of the Apollo arrays and the lunar libration means that the existing Apollo arrays now limit the accuracy of the single photo-electron return. Thus the current limitation on the accuracy of a single shot is the lack of knowledge of whether the photon came from the near corner or the far corner. Finally, we will address the reasons for the ability of the next generation of retroreflectors to overcome these problems in the form of the "Lunar Laser Ranging Retroreflector Array for the 21st Century" (LLRRA-21) [3]. The latter is being developed by an international team led by the University of Maryland in collaboration with the INFN-LNF.

4. Current Status of the LLRRA-21

This project, centered at the University of Maryland, is being conducted within an Italian collaboration with INFN and the Italian Space Agency (ASI). A nominal design, at TRL 6, is currently being refined. A detailed optical/thermal simulation [4] has been developed and is being used to refine the package design and to define the optimal thermal-control coatings. Finally, several thermal/vacuum simulations have been performed at the unique testing facility that has been jointly developed at the INFN-LNF in Frascati, Italy [6].

5. Apollo Simulation

Although the Apollo arrays are still in operation after four decades and are still providing the same level of ranging accuracy, the magnitude of the return signal has very significantly decreased over the four decades [7]. A detailed family of simulation programs [4] has been developed to identify the causes of the degradation. The recent observations of the magnitude of the returns during a lunar eclipse [8] have been particularly useful, since the time constant of the changes in the solar illumination are similar to the time constants of the CCRs. These results are being used in order to minimize their impact in the design of the LLRRA [5].

6. Future Directions

The main issue at present is determining how to transport the LLRR-21 to the moon. We are presently working with two of the Google Lunar X Prize groups, Moon Express and Astrobotics. In addition, a formal collaboration including Japan is addressing the optimal type of retroreflector for the future Japanese lander. Further discussions with other possible contributors are of critical interest, since at least three new retroreflectors are needed to accomplish the next generation science.

The stability of the emplacement on the lunar surface is a critical factor. The stability and thus the ultimate ranging accuracy can vary from a few millimeters to 0.1 mm depending upon a mounting on the lander on an anchored deployment using the pneumatic drilling technique of Honeybee Corporation [10]. Further emplacements will provide an improved selenodetic coordinate system and will improve the science products, especially the Lunar Physics.

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