# Precision Lunar Laser Ranging for Lunar and Gravitational Science

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Laser ranging to retroreflector arrays placed on the lunar surface by the Apollo astronauts and the Soviet Luna missions over the past 39 years have dramatically increased our understanding of gravitational physics along with Earth and Moon geophysics, geodesy, and dynamics. Significant advances in these areas will require placing modern retroreflectors and/or active laser ranging systems at new locations on the lunar surface. Ranging to new locations will enable better measurements of the lunar librations, aiding in our understanding of the interior structure of the moon. More precise range measurements will allow us to study effects that are too small to be observed by the current capabilities as well as enabling more stringent tests of Einstein's theory of General Relativity [1].

Setting up retroreflectors was a key part of the Apollo missions so it is natural to ask if future lunar missions should include them as well. The Apollo retroreflectors are still being used today, and nearly 40 years of ranging data has been invaluable for scientific as well as other studies such as orbital dynamics. However, the available retroreflectors all lie within 26 degrees latitude of the equator, and the most useful ones within 24 degrees longitude of the sub-earth meridian. This clustering weakens their geometrical strength.

A new instrument, APOLLO, at the Apache Point facility in New Mexico recently became operational and promises nearly an order of magnitude improvement in ranging precision [2]. However, this system will ultimately be limited by systematic errors associated with the Apollo retroreflectors. In addition, this system is located at a similar latitude to the other active lunar ranging stations so it does not improve the geometric coverage of ranging measurements.

New retroreflectors placed at locations other than the Apollo sites (such as a pole or limb) would enable the study of additional effects, particularly those that rely on the measurement of the lunar librations. In addition, more advanced retroreflectors are now available that will reduce some of the systematic errors associated with using the Apollo arrays, resulting in more precise range measurements. Retroreflectors are extremely robust, do not require power, and will last for years. This longevity is important for studying long-term effects such as a possible time variation in the gravitational constant. New retroreflectors with higher cross-sections would also enable more laser ranging stations to be used for lunar measurements.

An active laser ranging system may be a simple laser transponder or a full optical communication system with ranging capability. An active system is advantageous over a retroreflector in that the amount of light returned to an Earth ground station goes as the inverse of the distance squared rather than the inverse of the distance to the fourth power. This stronger signal will enable the use of most of the more than 40 existing satellite laser ranging stations to make nearly continuous range measurements, even during the daytime. An active system is also potentially more accurate as advanced ranging techniques, like laser phase locking, may be implemented. This type of system could also be adapted for use on Mars where an active laser ranging system may be the only way to exceed the meter level accuracy of current Mars ranging data.

We report here on results from our Lunar Sortie Science Opportunities concept study. This study consists of several parts. First, we define the science and measurement requirements that can be achieved by adding additional lunar ranging sites with more advanced ranging capabilities. This provides the motivation for placing additional ranging instruments on the lunar surface. We then describe several instrument options that are capable of achieving these requirements. These include:

- A high cross-section retroreflector array using advanced hollow corner cubes,
- Several smaller retroreflector arrays distributed near a landing site with separation sufficient to distinguish their ranging returns,
- An asynchronous laser transponder,
- A laser communication system with ranging capability.

The advantages and disadvantages of each system will be discussed along with an estimate of the resource requirements including cost, mass, power, etc.

[1] S. M. Merkowitz *et al.*, Int. J. Mod. Phys. D **16**, 2151 (2007).

[2] T. W. Murphy *et al.*, Publ. Astron. Soc. Pac. **120**, 20 (2008).