Lunar Science and Lunar Laser Ranging

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Abstract: Lunar Laser Ranging studies the Moon's internal structure and properties by tracking the variations in the orientation and tidal distortion of the Moon as a function of time. Future missions to the Moon's surface should include new laser ranging instrumentation capable of improved range accuracy.

1   Introduction: Lunar Laser Ranging and Science

Range and range rate tracking of spacecraft throughout the solar system has provided a wealth of science information on gravity fields, tides, planetary orientation and spacecraft locations. For distant targets this tracking has been done by radio (Asmar et al., 2009), but for the Moon's surface the science technique has been laser ranging to corner cube retroreflector arrays. Radio has the advantage of a strong signal from an active transponder, while the passive laser ranging technique has the advantage of excellent accuracy and longer data spans.

Lunar Laser Ranging (LLR) data are accurate ranges to retroreflector arrays on the Moon from several stations on the Earth. LLR is designed to obtain scientific information about the Moon, the Earth, the lunar orbit, and connected effects such as the nature of gravity (Dickey et al., 1994). Merkowitz et al. (2009) discuss advanced LLR for precision tests of relativistic gravity. Here we shall concentrate on the lunar science that comes from monitoring variations of lunar orientation and tides. Figure 1 shows a ranging observatory on the Earth and a retroreflector corner cube array on the Moon. Figure 2 shows the locations of the retroreflector arrays on the Moon. The Apollo 11, 14, 15 and Lunokhod 2 arrays are ranged operationally. The Lunokhod 1 array is lost. A broader distribution of LLR sites on the Moon would improve the sensitivity to science parameters determined by LLR. New LLR devices would be designed to reduce the scatter of the individual photons used to make a range normal point thereby reducing the number of photons and the duration necessary to make a very accurate normal point. *LLR goals are that new retroreflectors be placed on the Moon and that range data be collected and analyzed*.
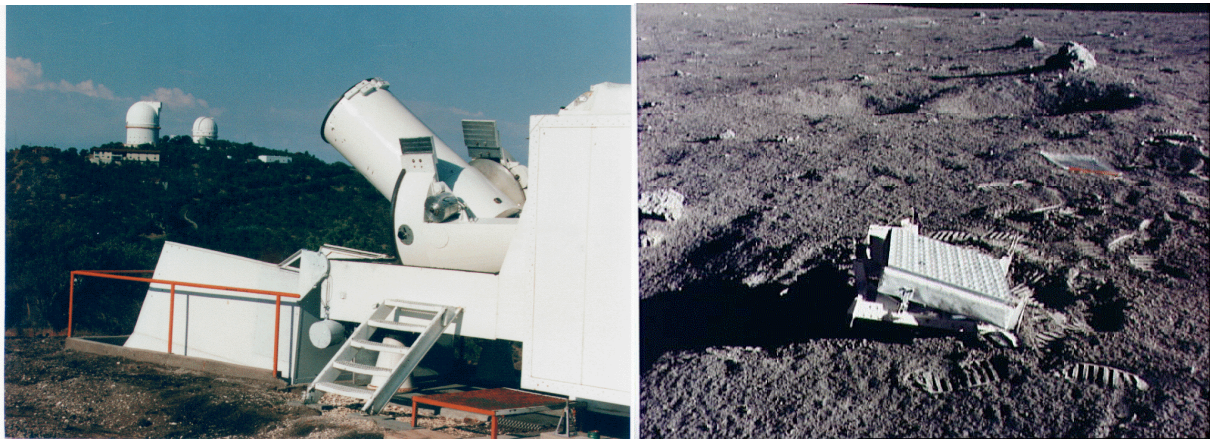

Fig 1 (a) Lunar laser telescope at McDonald Observatory. **(b)** Apollo 14 retroreflector array on Moon.

2   Lunar Science

LLR-determined lunar science depends on monitoring time-varying 3-axis lunar orientation along with solid body tides. The lunar orientation, or three-dimensional rotation, is called physical librations. A recent review of lunar science is in Joliff et al (2006) while recent summaries of LLR lunar science are in Williams et al. (2006, 2009). A summary of important lunar science effects follows.

Fluid Core Moment of Inertia: LLR is sensitive to the fluid core moment of inertia, which depends on core density and radius. This is a new LLR lunar science result for the core. The solution for the ratio of fluid moment to total moment gives $C_f/C = (12\pm4)\mathrm{x}10^{-4}$, where the subscript f indicates the fluid core (Williams et al., 2009). For a uniform liquid iron core without an inner core this value would correspond to a radius of 390±30 km. Lower fluid densities or presence of

an inner core would give larger outer radii for the fluid. Weakly determined at present, an accurate determination of core moment depends on a long time span of high accuracy range data. There is very little information on the core and it is very important to improve this determination.

Whole Moon Moment of Inertia: The whole Moon moments of inertia A<B<C come from combining LLR results for relative moment differences (C-A)/B and (B-A)/C with orbiting spacecraft determined J_2 and C_{22}. The most recent published total value (Konopliv et al., 1998) predates the more recent LLR fluid core moment determination, and is limited by the uncertainty of the earlier adopted fluid core moment. As the fluid core moment improves, so will the whole Moon moment. The lunar moment of inertia constrains model profiles of density vs radius.
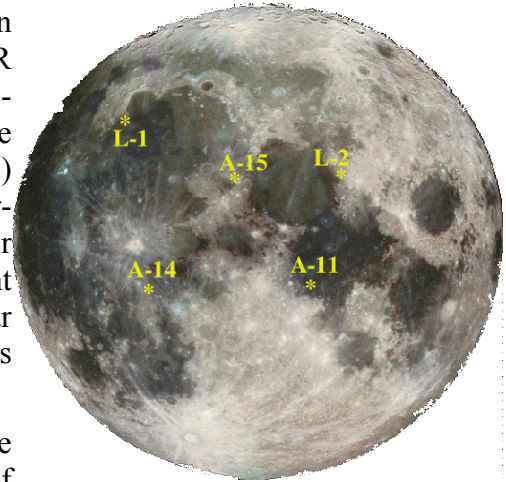
Core Oblateness: LLR detects fluid-core/solid-mantle boundary (CMB) flattening. Currently the product of CMB oblateness f and fluid core moment of inertia is determined more strongly than either factor separately. That product is $f C_f/C = (C_f–A_f)/C = (3\pm1) \times 10^{-7}$ (Williams et al., 2009). The detection of CMB flattening is one of the demonstrations that there is a fluid core.

Fig 2 Retroreflector arrays on the Moon.

Inner Core: A solid inner core might exist inside the fluid core, but it has not yet been detected by any technique. Gravitational interaction between an inner core and the mantle would affect the mantle's three-axis orientation. A future detection would be possible if the effect on mantle rotation is large enough. A detection of the inner core would reveal the frequency of one or more of the three possible resonances plus associated strength parameters. These quantities depend on multiple unknown parameters that describe the inner core gravity and moment of inertia and its gravitational interaction with the mantle.

Elastic Tides: Solid-body tidal displacements depend on the Moon's elastic properties. Typical monthly variations are ±9 cm. The solution parameters are the second-degree Love numbers h_2 and l_2 that scale the global tidal displacements. The existing distribution of LLR sites is weak for determining displacement Love numbers. Future sites with a wider geographic distribution would strongly improve the determination. The physical librations are also sensitive to the Love number k_2 that describes the second-degree tidal variations in potential and moments of inertia. LLR is potentially very sensitive to the Love number k_2, but k_2 correlates with core oblateness, which weakens the determination.

Lunar Tidal Dissipation: The tidal specific dissipation Q depends on the radial distribution of the material Qs. LLR detects tidal dissipation and infers a weak dependence of tidal Q on frequency. The tidal Qs determined from the orientation are surprisingly low, ~30 at a one month period and ~35 at one year. LLR does not distinguish the location of the low-Q material, but at seismic frequencies low-Q material, suspected of being a partial melt, was found for the deep zone above the core. Future LLR sites and very accurate ranges could help increase the frequency span. They could also detect the few mm dissipation effects in the tidal displacements.

Core/Mantle Boundary Dissipation: LLR first demonstrated that the Moon has a fluid core by detecting the energy dissipated by the flow of the fluid along the boundary (Williams et al.,

2001). The CMB dissipation remains strong in LLR solutions (Williams et al., 2009) and is determined in addition to, but correlated with, the tidal dissipation. The CMB dissipation depends on fluid core size, fluid viscosity and CMB roughness.

Free Physical Librations: Normal modes of the rotation may be stimulated by internal or external mechanisms, but they are subject to damping which is short compared to the age of the Moon. Two of the free libration amplitudes are observed by LLR to be large (>10 m) which implies active or geologically recent stimulation (Newhall and Williams, 1997; Chapront et al., 1999; Rambaux and Williams, 2009). The 2.9 yr longitude mode with an 11 m amplitude is stimulated, at least in part, by resonance passage (Eckhardt, 1993). The wobble mode, analogous to the Earth's Chandler wobble, is a large elliptical (28x69 m) 74.6 yr motion of the pole direction. If wobble is stimulated by eddies at the CMB as suggested by Yoder (1981), then ongoing activity might be revealed by future LLR measurements as irregularities in the path of polar wobble. The third mantle mode, a free precession in space, and the liquid core free core nutation are small (<1 m). The former may be detected, but it appears to be sensitive to the interior model.

Site Positions: The Moon-centered locations of four retroreflectors are known with submeter accuracy (Williams et al., 1996, 2008). Positions for existing and new LLR sites can be used as control points for lunar cartographic networks, as was done by Davies et al. (1987, 1994, 2000). The four site radii are a valuable check on altimetry from orbit (Fok et al., 2009).

Tidal Acceleration and Orbit Evolution: LLR is very sensitive to tidal acceleration of the lunar orbit. Tides on Earth dominate the energy and angular momentum transfer to the orbit and the Moon's evolution outward. Tidal effects on the Moon are separable from Earth tide effects in the LLR solutions (Chapront et al., 2002; Williams et al., 2009). The total tidal acceleration in orbital mean longitude from Earth and Moon tides is -25.85 arcsec/century^2, which corresponds to a 3.81 cm/yr recession of the Moon (Williams et al., 2009). Eccentricity rate is also detected. Evolving the lunar orbit backward in time is an important and surprisingly difficult goal. LLR provides numerical values for two sources of dissipation on Earth and two for the Moon.

Synergies: LLR is one of several instruments suitable for geophysical exploration of the lunar interior (Neal et al., 2009). Some synergies between the geophysical techniques follow.

Seismology: The Apollo seismic network determined the structure of the Moon down to the middle mantle and we anticipate that a broadly distributed future network could identify rays through the lower mantle and core regions. The LLR-determined fluid core moment of inertia could be compared with seismic travel times through the fluid, which depend on radii, fluid density and bulk modulus. Does the low LLR tidal Q come from a partial melt in the lower mantle? A seismic determination of lower mantle seismic dissipation could answer that question. An inner core seismic detection would be valuable since any LLR or lunar orbiting spacecraft detection is sensitive to interior gravity fields, very different from the seismic sensitivities.

Gravity: Radio tracking of lunar orbiting spacecraft is sensitive to tidal variation of the gravity field and hence Love number k_2 (Konopliv et al., 2001; Goossens and Matsumoto, 2008). The GRAIL mission should improve k_2 accuracy by more than an order of magnitude over the LLR determination allowing an improved CMB flattening. The improved gravity field from GRAIL will aid the physical libration computation. Both LLR and GRAIL will be looking for evidence of a solid inner core (Williams, 2007). LLR determined lunar orbit and physical librations (Williams et al., 2008) will be used by GRAIL and other lunar missions.

Magnetic field: Magnetic induction measurements from orbit indicate a small conducting core is present (Hood et al., 1999). The derived core size depends on conductivity, and it can be compared with the LLR moment.

3   New Retroreflectors on the Moon

Lunar retroreflectors are simple devices in concept, for which no power is needed. The existing arrays of small corner cubes (Fig. 1b) can spread the reflected pulse by ±3-5 cm because the array face is not always normal to the Earth's variable direction. This broadening requires a large number of laser shots to accurately locate the center of the pulse. Technology is available to produce large single cornercube retroreflectors, both hollow and solid, which do not spread the pulse. Including the mounting, the mass is a few kilograms. Detailed thermal design is critical to making large corner cubes for the Moon. After delivery to the lunar surface these instruments would be pointed toward the Earth. Since these proposed new retroreflector instruments would be both smaller and lighter than their Apollo counterparts, they could be placed on the lunar surface by both manned and unmanned lander missions. Retroreflectors should be placed far enough away from any activity that they would not become contaminated by dust. Although the present set of retroreflector arrays has operated on the Moon for four decades, some degradation is suspected. New retroreflectors optimized for pulse spread, signal strength, and thermal effects will be valuable at any location on the Moon.

Overall, the separation of lunar 3-dimensional rotation, the rotation angle and orientation of the rotation axis, and tidal displacements depends on a good geographical spread of retroreflector positions. The current three Apollo sites plus the infrequently observed Lunokhod 2 are close to the minimum configuration for separation of rotation and tides, so that unexpected effects might go unrecognized. A geographic distribution of new instruments on the lunar surface wider than the current distribution (Fig. 2) would be a great benefit. A wider spread of retroreflectors could improve the sensitivity to rotation/orientation angles and the dependent lunar science parameters by factors of up to 2.6 for longitude and up to 4 for pole orientation. The present configuration of retroreflector array locations is quite poor for measuring lunar tidal displacements. Tidal measurements would be very much improved by a retroreflector near the center of the disk, longitude 0 and latitude 0, plus several retroreflectors further from the center than the Apollo sites (Turyshev and Williams, 2007).

New retrorefllectors capable of high accuracy ranges must be matched by accurate ranging stations and accurate data analysis. The Apache Point station is capable of millimeter ranging (Murphy et al., 2008; Battat et al., 2008; Murphy et al., 2009a) and the French station (OCA) has been recently upgraded. Range accuracy, data span, and distributions of Earth stations and retroreflectors are important considerations for future LLR data analysis. Improved range accuracy helps all solution parameters of the Earth-Moon system including lunar interior and geophysics. Data span is very important for some parameters. The passive nature of retroreflectors will naturally result in a long time span of LLR range data.

New retroreflectors would have benefits beyond lunar science. LLR is sensitive to Earth geophysics and geodesy including the positions and rates for LLR stations, Earth rotation, precession rate, nutation, and tidal influences on the orbit. Precise tests of the Einstein's general theory of relativity include tests of the equivalence principle, search for a time variability of the gravitational constant, G, and measurement of relativistic geodetic precession (Merkowitz et al., 2009). New retroreflectors would have a wide benefit.

Laser Ranging Beyond the Moon: At interplanetary distances, active techniques are required to achieve good signal strength (a benefit of $1/r^2$ energy transfer). Passive retroreflectors work well at the lunar distance, but at larger distances a laser signal would need to be boosted through the use of a transponder. Active ranging to a transponder makes ranging to the surfaces of Mars, Phobos or other solid solar system bodies practical. The development of active laser techniques would extend the accuracies characteristic of passive laser ranging to interplanetary distances. Technology is available to conduct such measurements (Murphy et al., 2009b).

4   Summary and Goals

LLR goals include placing new retroreflectors on the Moon plus collecting and analyzing accurate range data. A geographic distribution of retroreflectors wider than the current retroreflector distribution would be a great benefit. Passive retroreflectors will operate for a long time. The accuracy of the lunar science parameters would improve from new retroreflectors.

The anticipated science impact includes lunar science, gravitational physics, geophysics, and geodesy. Lunar science interior information includes tidal response, tidal dissipation, fluid core moment of inertia, and core boundary oblateness and dissipation. Compared to the existing distribution of LLR sites, new LLR sites on the Moon could increase the north-south spread by a factor of up to 4 and the east-west spread by a factor of up to 2.6. Sensitivities to lunar science effects would increase by these factors. Extending the spread in both directions is valuable.

New retroreflectors can be made to return narrower pulses allowing more rapid accurate ranges. This benefits the entire set of parameters of the Earth-Moon system. Retroreflectors with improved performance will allow Lunar Laser Ranging to continue to provide valuable lunar science results in the future.

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