LUNAR SCIENCE FROM LASER RANGING – PRESENT AND FUTURE J. T. Ratcliff, J. G. Williams and S. G. Turyshev[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109 (e-mail Todd.Ratcliff@jpl.nasa.gov, James.G.Williams@jpl.nasa.gov).

Introduction: The interior properties of the Moon influence lunar tides and rotation. Three-axis rotation (physical librations) and tides are sensed by tracking lunar landers. The Lunar Laser Ranging (LLR) experiment has acquired 38 yr of increasingly accurate ranges from observatories on the Earth to four corner-cube retroreflector arrays on the Moon. Lunar Laser Ranging is reviewed in [1]. Recent lunar science results are in [4,5]. In this abstract present LLR capabilities are described followed by future possibilities.

Moments of Inertia: Analyses of tracking data on orbiting spacecraft give the second-degree gravity harmonics J_2 and C_{22}. LLR data analysis gives the moment of inertia combinations (C-A)/B and (B-A)/C. Combining the two sets gives lunar C/MR^2, the polar moment C normalized with the mass M and radius R [2]. LLR is also sensitive to the fluid core moment, indirectly through the dissipation at the fluid-core/solid-mantle boundary and directly through the dynamics [3]. The latter approach requires a decades long data span, is just now starting to yield significant results [4], and will improve in the near future. Uncertainty in the fluid core moment is the main limitation to the uncertainty in the total moment.

Elastic Tides: Elastic tidal displacements are characterized by the lunar second-degree Love numbers h_2 and l_2. Tidal distortion of the second-degree gravity potential and moments of inertia depends on the Love number k_2. Love numbers depend on the elastic properties of the interior including the deeper zones where the seismic information is weakest. LLR detects tidal displacements and determines h_2 with a 20% uncertainty with l_2 fixed, but k_2 is more accurately determined (12%) through rotation [3,4]. The distribution of the Apollo retroreflector arrays is weak for determining tidal displacements.

Tidal Dissipation: The tidal dissipation Q is a bulk property that depends on the radial distribution of the material Qs. LLR detects four dissipation terms and infers a weak dependence of tidal Q on frequency [3,4]. The tidal Qs are surprisingly low, ~30 at a one month period, but LLR does not distinguish the location of the low-Q material. At seismic frequencies low-Q material, suspected of being a partial melt, was found for the zone below the moonquakes and above the core [6].

Dissipation at a Liquid-Core/Solid-Mantle Interface: A fluid core does not share the rotation axis of the solid mantle. While the lunar equator precesses along the ecliptic plane, the fluid core can only weakly mimic this precession. The resulting velocity difference of ~2.5 cm/sec at the core-mantle boundary (CMB) causes a torque and dissipates energy. Dissipation terms are detected at several periods in the LLR analysis allowing dissipation from core and tides to be separated. The fluid core is inferred to have a radius of roughly 350 km for molten iron or larger for a lower density material such as Fe-FeS. The separation of tide and core dissipation should improve in the future, but a more accurate core size is limited by possible topography on the CMB and the application [3] of Yoder's theory [7].

Core Oblateness: A fluid core also exerts torques if the core-mantle boundary (CMB) is oblate. LLR detects CMB flattening [4], but it is difficult to separate from fluid core moment of inertia. CMB flattening contributes the major uncertainty to solutions for the Love number k_2.

Inner Core: A solid inner core might exist inside the fluid core. Gravitational interaction between an inner core and the mantle would affect the three-axis rotation. The size of the potentially observable effect depends on unknown quantities. A future detection may be possible if the perturbation of rotation is large enough.

Evolution and Heating: Both tidal and CMB dissipation would have significantly heated the Moon when it was closer to the Earth [3,8]. Early dynamical heating would have added to radiogenic heating helping to promote convection and a dynamo. The evolution of the orbit and rotation and the heating of the early Moon may be linked problems. We currently do not understand all of the contributions to the observed eccentricity rate [3], and this is a problem that needs to be solved for orbit evolution studies.

Free Librations: Normal modes of the rotation correspond to resonances in the rotation dynamics. These lunar free librations may be stimulated by internal or external mechanisms, but they are subject to damping. Two of the free libration amplitudes are observed by LLR to be large (>1") which implies active or geologically recent stimulation [5,9]. The wobble mode, which is analogous to the Chandler wobble, is a large (3"x8") 75 yr motion of the polar body axis with respect to the rotation axis. If wobble is stimulated by eddies at the CMB as suggested by Yoder [10], then any ongoing activity might be revealed as irregularities in the path of polar wobble. Fluid and inner cores introduce additional free libration modes.

Site Positions: The Moon-centered locations of four retroreflectors are known with submeter accuracy [11]. These positions have been used as control points for past lunar control networks [12,13] and are available for future networks. However, currently available high resolution images do not include all of the LLR sites [12].

Future Lunar Laser Ranging: Three retroreflector array locations on the Moon are the minimum needed to determine rotation about two axes. Physical libration about the third axis is related to the other axes through the dynamics. While there are four LLR sites on the Moon, the three Apollo sites get 97% of the ranges. The fourth site, on the Lunokhod 2 rover, can be used only during lunar night, gives a weak reflection, and may be fading. So the current configuration has little, if any, redundancy. Further, the geographical spread of LLR sites north-south, currently 25% of the diameter, and east-west, 38% of the diameter, determines the sensitivity to small rotation angles. A wider spread of LLR locations would improve the determination of three-dimensional rotation and tides to the benefit of lunar science. In addition to retroreflector arrays, laser transponders are a future possibility. Transponders would give much brighter signals, but they require power and pointing.

Important time scales for lunar science observations span 1/2 month to decades. A useful position for a new array or transponder could be determined with one to several months of tracking, though spans of years give the highest accuracy. Data spans of years are optimum for most lunar science applications but that would include continued accurate tracking of the four existing lunar retroreflector arrays.

Future Complementary Data: Gravity field determinations from orbiting spacecraft [2,14] have been useful in combination with LLR results for lunar moment of inertia [2] and rotation [3]. We look forward to accurate gravity field and Love number k_2 results from Kaguya, GRAIL and other missions in progress or planned. Very high accuracy gravity missions may be able to detect an inner lunar core [15].

A future lunar network of seismometers is an important way to probe the lunar interior. The sizes, densities and elastic properties of the fluid core and the possible inner core are of great interest. Also of interest are the properties, including damping vs radius, of the attenuation zone between the deep focus moonquakes and the fluid core [6].

The lunar dynamical and thermal evolution may be connected since heat is generated by both tidal and CMB dissipation, and the Moon's former molten interior affected its tidal response. Information pertaining to the past magnetic field and thermal history is of great interest.

The highest resolution images of the past do not include all of the LLR retroreflector array sites limiting their use as control points for lunar control networks. High-resolution images of the Apollo and Lunokhod sites should be obtained from orbiting spacecraft. Nearby altimetry is also of interest. Future LLR sites, either retroreflector arrays or laser transponders, and landed spacecraft with high quality radio tracking can be used to expand the number and distribution of control points in the future [16].

Finally, we note that there is a "lost" fifth retroreflector array on the Moon on the Lunokhod 1 vehicle. While there were reports of early ranges to this array, those ranges were not distributed and the operational ranging sites never acquired ranges. The problem may be lack of a sufficiently accurate position for the Lunokhod 1 rover and the Luna 17 landing stage [17,18]. High-resolution images taken from orbit should be able to locate these vehicles.

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