LUNAR LASER RANGING ON ARTEMIS III: OPERATION AND SCIENCE GOALS

CO-AUTHORS: J. G. Williams, D. H. Boggs, D. G. Currie, S. Dell'Agnello, D. D. Wellnitz, C. S. Wu, G. Bianco, D. Dequal, R. Vittori, J. Müller, J-M. Torre, U. Schreiber, Y. LI, S. Kopeikin, M. Eubanks .

A Lunar Laser Ranging Retroreflector LLR array was deployed by the Apollo 11 astronauts during the first crewed landing on the Moon in the Early Apollo Scientific Experiment Package (EASEP)[1,2]. After successfully determining the distance to this LLR array, additional arrays were deployed by the astronauts during the Apollo 14 and 15 missions.

Lunar Laser Ranging Observatories (LLROs) in various countries project short laser pulses toward the LLR arrays which reflect the laser pulses directly back to the LLRO. The LLRO measures the difference between the time of transmission and the time of the return of the laser pulse. Using the known speed of light, this is then converted to the distance at that instant of time. These measurements are repeated numerous times a day and week at present.

Ranging to these three Apollo LLR arrays as well as the two LLR arrays deployed by the Soviet Union has continued over the past five decades primarily from LLROs located in the US McDonald [MCD][3], [MLRS][7], Hawaii [Hall][7] Apache Point [Apollo][4], France [MeO][5], Italy [Matera][6], Germany [Wettzell][7]. These long-time series of lunar laser ranges, which are publicly available, have been analyzed by the Jet Propulsion Laboratory as well at other analysis centers.

Science Results

The analysis of the LLR data to date has provided unique new results in science and technology, that is, in lunar physics, gravitation, General Relativity and Earth science, illustrating a strong and wide-ranging scientific heritage.

The advances in **Lunar Science and Technology** lie in the areas of measurements of the liquid lunar core, the evaluation of the Love numbers and the Lunar Orbit. In addition, the locations of the landing sites to sub-meter accuracy form the basis of the two fundamental selenodetic coordinate frames. Additionally, the dissipation of the fluid core-solid mantle boundary (CMB), the tidal dissipation at several periods, the CMB flattening and the following combinations of the moments of inertia (C−A)/B and (B−A)/C are evaluated.

The demonstrated areas of **Astrophysical Science** include the Weak Equivalence Principle and the inertial properties of gravitational energy, the strong equivalence principle, the spatial and temporal variation of the gravitational constant, gravitomagnetism and geodetic precession.

The demonstrated areas of **Earth Physics** include the location of LLROs, Continental Plate Motion, GM(Earth+Moon) and variations of the Length of Day.

The five retroreflector arrays are composed of multiple small Cube Corner Retroreflectors (CCRs). Due to lunar optical librations, the arrays tilt w.r.t. Earth and spread the return laser pulse, degrading the single photon range accuracy. Single Big Retroreflectors (SBRs) deployed during the Artemis III missions would not be subject to such spreading and each range would be more accurate than single ranges to the LLR arrays by a factor exceeding 100.

Simulation solutions that include 6 years of simulated Lunar Laser Ranging (LLR) data show degrees of improvement in the uncertainties of many science parameters.

The achieved accuracy of a normal point by the LLROs will depend upon their hardware and observing procedures. Thus, we now wish to consider how the improved ranging accuracy translates into improved science results as a function of the status of the LLROs. To address the expected improvement in the science that deployment of SBRs during the Artemis III missions w.r.t. the science results that have been obtained using the LLR arrays, one of us (JGW) at Jet Propulsion Laboratory (JPL) has run simulations using the programs that are normally used to extract the science from the LLR range measurements.

Only a limited subset of the full set of simulations is considered here. In particular, the current focus will be upon the nominal landing site of Artemis III near the South Pole (SPL). The analysis in Table 1 also assumes current range accuracies and that the data from the SBR deployed by Artemis III will be analyzed in conjunction with the data from the existing arrays. A second set of simulations (shown in the row labeled CRS WST SW SPL) addresses the results for an Artemis III mission, during which the SBRs currently under construction in the NASA/LSITP program[8] have been deployed at Mare Crisium (CRS, Long 59, Lat 17), a Western Site region (WST -50,20), a south western site (SW -55, -45) and the Artemis III site (SPL 0, -88). The improvements to be addressed are for a limited set of science parameters: in particular, moment combinations β=(C−A)/B and γ=(B−A)/C, the distortions of the lunar crust in response to the tidal forces (Love Numbers h_2 and l_2), a parameter (cos D) that addressees the General Relativistic weak equivalence principle, the total mass of the Earth-Moon system that depends on the mean semimajor axis <a>, and the longitude librations (Tau) at 815 days. The Post-Newtonian Parameter β and γ sensitivities are the same as cosine(D). The GM (Earth+Moon) sensitivity is the same as <a>.

The basic SBR package can support very high accuracy ranging[8]. Thus Table 1 addresses the science improvements when the LLROs have no upgrades, using the current uncertainties in the normal points of the LLRO (MeO) in Grasse, France, one of the major contributors to the data base used for the analysis of the range data to extract the scientific products. MeO has also pioneered the use of an infrared wavelength laser that appears to provide many advantages.

The improvements in the science results that would be achieved if the accuracy of a single range would reach the capability of the basic SBR package[8], that is, less than a millimeter can also be explored. In order to reach this goal, the horizontal gradient in the Earth's atmosphere must be determined either by modeling or by direct measurement as is currently routinely done in GPS and VLBI data analysis. The laser pulse length must be in the 10-picosecond domain and the electronics should have an accuracy of pico-seconds. On the Moon, the thermal expansions over a lunation must be calibrated. However, all but the last item are performed at the LLROs and thus can take advantage of developing technology over the years, as has occurred for the ranging to the Apollo arrays where the accuracy of a normal point has improved by more than a factor of 100. The results of this latter set of simulations are indicated in Table 2 where the improvements in the science results are factors of hundreds w.r.t. current Apollo results. Range accuracies better than present accuracies would be between the two tables.

Conclusion and Recommendations: By the deployment of the Single Big Retroreflector (SBR), the Artemis III mission would make a very significant contribution to Lunar Physics, Astrophysics and Earth Physics. This would greatly extend the accuracy the scientific objective and would continue to contribute decade after decade as has the Apollo retroreflector arrays. The history behind the SBR shows a very strong scientific and technological heritage.

References: [1] C. Alley, R. Chang, D. Currie, et al. 1970, Science, 167, 3917, 368 [2] P. L. Bender, D. G. Currie, S. K. Poultney, et al, Science 19 Oct 1973: Vol. 182, Issue 4109, pp. 229-238 [3] E. Silverberg, and D. Currie, 1971 Journal of Optics Soc. America, Vol. 61, p. 692 – 693 [4]T. Murphy J. D. Strasburg, C. W. Stubbs et al., 14th International Workshop on Laser Ranging (2005) [5] J. Chabé , C. Courde1, J-M. Torre, et al ESS. 7. [6] T. Varghese, K. Thomas, W. M. Decker, et al., 8th International Workshop on Laser Ranging Instrumentation (1993) [7] https://ilrs.gsfc.nasa.gov/network/stations/index.html. [8] D. G. Currie, S. Dell'Agnello, G. O. Delle Monache, et al. Nucl. Phys. B V.243, p.218-228. (2013)

Case	Beta	Gam	*h*_2	*l*_2	cos*D*	<*a*>	Tau S 815 d
SPL	11%	0%	60% 2.5x	56% 2.3x	5%	25%	0%
CRS WST SW SPL	22%	32%	64% 2.8x	60% 2.5x	12%	31%	23%

Table 1 Factors and percentages of improvement with the Artemis III mission and the assumption that ranging by the LLROs is simulated at the current accuracy level of the LLRO at Grasse, France.

Case	Beta	Gam	*h*_2	*l*_2	cos *D*	<*a*>	Tau S 815 d
SPL	92% 13x	74% 3.9x	87% 7.9x	70% 3.3x	98% 56x	98% 50x	7% 40x
CRS WST SW SPL	99% 111x	99.8% 420x	99.5% 212x	99.8% 570x	99.4% 162x	99.3% 147x	99.7% 330x

Table 2 Factors and percentages of improvement with the Artemis III mission and the assumption that ranging by the LLROs is performed at the ultimate levels of accuracy supported by the basic SBR package.