THE LUNAR GROUND SEGMENT: LUNAR GEODESY WITH LLR AND VLBI BEACONS
W. Paul Blase[1], T. Marshall Eubanks[1], Bruce Bills[2], Leonid Petrov[3], Vishnu Viswanathan[4], Scott D. King[5] [1]Space Initiatives Inc, Princeton, WV [2]Jet Propulsion Laboratory, Pasadena, CA [3]NASA Goddard Space Flight Center Code 61A, Greenbelt, MD [4]NASA Goddard Space Flight Center Code 698, Greenbelt, MD [5]Department of Geosciences, Virginia Tech, Blacksburg, VA ; wpb@space-initiatives.com;

Introduction: The Artemis era has the potential to substantially improve the geodetic monitoring of orbital, rotational and tectonic motions of the lunar surface. Here, we describe the scientific return of a geodetic "fiducial point," with collocated Lunar Laser Ranging (LLR) retroreflectors and Very Long Baseline Interferometry (VLBI) lunar radio beacons, on Malapert Mountain near the lunar South Pole.

Lunar Geodesy with Collocated Observations: The present LLR observing system has sufficed to determine the lunar orbit and its recession with a retroreflector array deployed 5 decades ago. Soon, through CLPS and Artemis landings, the LLR array should finally be extended [1]. In addition, Space Initiatives Inc (SII) is developing COMPASS VLBI beacons for the lunar surface [2]. The combination of LLR and VLBI data from collocated retroreflectors and beacons (a geodetic "fiducial point") will significantly enhance the monitoring of station positions, the recession of the lunar orbit and the free lunar librations.

Solution	σ_R	σ_θ	σ_ϕ	σ_a
Malapert Mt. (1 day)				
LLR Only	19516	11683	1525	-
VLBI Only	5145	915	73016	-
LLR + VLBI	324	189	23	-
Malapert Mt. (1 month)				
LLR Only	87.1	71.3	10.0	13.7
VLBI Only	33.5	32.7	240.7	6.4
LLR + VLBI	20.0	16.4	2.7	3.5

Table 1: LLR, VLBI and combined solution formal error estimates (in mm) for a Malapert Mt. fiducial site.

Time Domain Geodesy at Malapert Mountain: Table 1 provides formal errors from solutions with simulated LLR and VLBI data for the site radius, R, longitude, θ, and latitude ϕ, together with the lunar semi-major axis, a. (This parameter was added to judge how well these data determine the orbital recession of the Moon [3].) Figures 1 and 2 show some of the numerical partials. We assumed a fiducial point at the proposed Artemis landing site on Malapert Mt., with LLR observations from the Apache Point APOLLO site, and VLBI observations from the Mauna Kea-Brewster-St. Croix triangle of the VLBA. Normal points are 300 seconds with elevation angle limits of 20° for LLR and 10° for VLBI, and an assumed accuracy of 14 mm for LLR delays [4] and 10 mm for VLBI delays [5].

We conclude that combined solutions using LLR and VLBI data break the geometrical dilution of precision which otherwise hinders short duration determinations of station positions. In addition, combinations of LLR and VLBI data could usefully determine the 38 mm yr^{-1} orbital recession of the Moon [3] on a monthly basis, enabling the study of the interaction of this recession with terrestrial climate cycles.

References: [1] V. Viswanathan, et al. (2021) in *Bulletin of the American Astronomical Society* vol. 53 134 doi.arXiv:2008.09584. [2] T. M. Eubanks (2020) arXiv:2005.09642. [3] J. G. Williams, et al. (2016) *Celestial Mechanics and Dynamical Astronomy* 126(1-3):89 doi. [4] D. A. Pavlov, et al. (2016) *Celestial Mechanics and Dynamical Astronomy* 126(1-3):61 doi. arXiv:1606.08376. [5] J. M. Anderson, et al. (2018) *Journal of Geophysical Research (Solid Earth)* 123(11):10,162 doi.

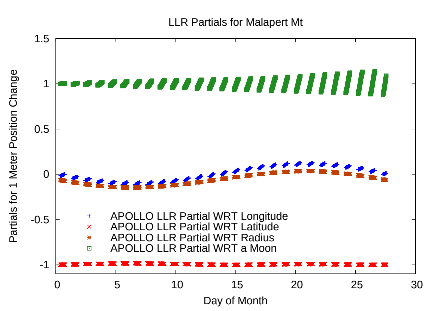

Figure 1: LLR partials for a fiducial site at the top of Malapert Mountain.

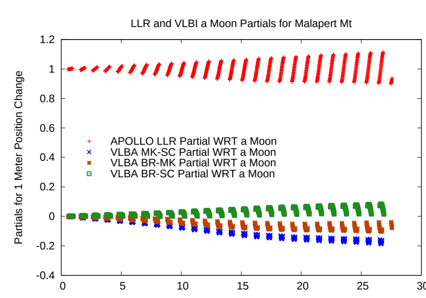

Figure 2: A comparison of LLR and VLBI partials at Malapert Mt. for the lunar semi-major axis, a.