Moon geodesy with radio beacons

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The fundamental geodetic reference frame on the Earth's surface is determined by a network of ground fundamental stations. The fundamental selenodesy network on the Moon's surface is determined by five retroreflectors: three brought by Apollo 11, Apollo 14, and Apollo 15, and two brought by the Soviet landers Lunokhod 1 and Lunokhod 2. Lunar Laser Ranging (LLR) allows us to measure the distance from a ground station to a retroreflector with a precision up to one millimeter although the scatter of post-fit residuals is one order of magnitude greater. The LLR is sensitive to the radial component of the vector from the ground station to the retroreflector.

We propose to augment the fundamental selenodesy network on the Moon by placing radio-beacons on the Moon's surface. In the simplest form such a radio beacon emits narrow-band signals with a power of several watts. In a more advanced form a beacon has a battery that allows it to operate during lunar nights. Such a beacon can be considered as a primitive version of a cell phone lying on the Moon's surface fed by a solar panel or a battery. The existing network of the fundamental very long baseline interferometry (VLBI) stations is able to detect such a signal. The network of the radio telescopes will perform so-called nodding observations by switching every several minutes between a radio beacon and a well-known background extragalactic radio source located within several degrees of the Moon. A similar technique employed by the Deep Space Network, Delta-Differential One-Way Ranging (Delta-DOR), is widely used for tracking interplanetary spacecrafts. The precision of the phase-referencing observations is at a level of 0.03 milliarcseconds, or 5 cm on the Moon's surface. Its accuracy is limited primarily by the accuracy of source positions. Positions of extragalactic radio sources can be determined with a level of 0.05 milliarcseconds.

Such observations will be complimentary to LLR. Unlike to LLR, VLBI is sensitive to the tangential component of the vector from the ground station to the radio beacon. Unlike to LLR, VLBI is a kinematic technique. Beacon positions derived with VLBI do not depend on the dynamic models and provide a direct tie to the inertial coordinate system defined by positions of natural extragalactic sources at gigaparsec distances. Unlike to LLR, VLBI observations can be performed at any weather and anytime when the beacon is powered on.

The main science case of putting radio beacons on the Moon is to improve the results provided by the LLR through the synergy of two techniques. One of them (LLR) is sensitive to the radial component of the vector between a ground based geodetic fundamental stations and the Moon-based fundamental station and another (VLBI) is sensitive to the tangential components. Adding an observable that is sensitive to the component of the beacon position that is orthogonal to the radial direction helps to separate variables and reduce correlations between parameter adjustments when processed in a combined solution. When processed separately, comparison of estimates of the parameters evaluated using a totally independent techniques will provide us a measure of their disagreement. This will give us an insight on systematic errors of both techniques and therefore, on reliability of the inference we make from LLR and VLBI results.

At the moment, the Moon-centered positions of retroreflectors are known with a sub-meter accuracy. Observations with more than one well-known extragalactic source used as a phase calibrator allows very precise determination in the Moon reference frame. VLBI phase-referencing observations of the radio beacons will determine position of the beacon with a millimeter level of accuracy.

Ground VLBI observation of radio beacons will improve our knowledge of the fluid core of the moment of inertia, core oblatness, Lunar tidal dissipation and the core/mantle boundary dissipation. These observations of radio beacons will improve measurements of the free Lunar librations and Love numbers or Lunar tides.

Putting beacons at the 2nd, 3rd and other location will provide us an opportunity to use phase differences between signals emitted by beacons trough nodding observations without observations of an extragalactic source. Such observations are very sensitive to the parameters of the Lunar rotation and Lunar tides. The differential phase delay between beacons can be measured with an accuracy of 0.01 mas, which corresponds to 1.5 cm on the Moon.

The availability of a reference beacon or beacons on the Moon with a precisely known position allows us to determine the position of another space vehicle on the Moon or in the cislunar space bearing the same beacon with respect to the reference one with a precision of 2–5 cm. This will provides us an additional channel for precise position determination that is totally independent from the Doppler measurements that is expected to be used as a primary channel. Thus, placing radio beacons on the Moon and space vehicles improves safety of operations in the cis-lunar space by providing a redundant and independent check of the main channel for precise positioning. Radio beacons can be considered as a reincarnation of lighthouses that were used in the past for maritime navigation. The simplicity of the radio beacon design makes it very reliable.

We recommend the Science Definition Team to consider a deployment of radio beacons on the Moon and on space vehicles. These beacons will both contribute to science and improve reliability of precise positioning on the Moon and in the cis-lunar space. The main scientific objective is to improve our knowledge of the Moon's interior through synergism with LLR by measuring the variations in the Moon's rotation and lunar tides. VLBI observations of the network of beacons will provide us an independent channel for measuring precise position of the beacons utilizing the existing network of ground VLBI stations.

References

Efroimsky M., "Tidal viscosity of Enceladus", Icarus, 300: 223–226.

Klopotek, G. Hobiger, T. and Haas, R., "Geodetic VLBI with an artificial radio source on the Moon: a simulation study", (2018) J. Geodesy, 92:457–469.

Kurdubov, S.L., Pavlov, D.A., Mironova, S.M., Kaplev, S.A., "Earth-Moon very-long-baseline interferometry project: modelling of the scientific outcome", (2019) MNRAS, 486(1), 815–822.

Liu, S., Yan, J. He, Q, Cao, J., Ye, M., Barriot, J.-P., "Precise positioning of Chang'e 3 lander based on Helmert-VCE-aided weighting method using phase delay data from Chinese VLBI Network", (2020) ASR, 66, 1485–1494.

Williams, J.G. and Boggs, D.H., "Tides on the Moon: Theory and determination of dissipation", (2015) JGR, 10.1002/2014JE004755.