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Geodesy on the Moon

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Abstract

Several techniques are available to make range measurements to the Moon, active or passive, radio or laser based. All of them require the placement of hardware on the surface of the Moon. Owing to technological advances over the years, the measurement resolution could be improved by more than an order of magnitude. We propose the deployment of a set of geodetic instruments in order to improve the ranging measurements to the Moon and in addition, to improve the reference frame realizations.

1. Introduction

While the use of passive Laser reflectors on the lunar surface appeared to be most attractive in the Apollo era, the next generation of LLR experiment should aim at a substantial improvement.

Hence, we propose to deploy an advanced Laser beacon / Laser receiver experiment on the Moon, used for highly accurate ranging measurements. A particular strength of this proposed experiment is given when several stations are ranging to the Moon simultaneously and/or when several geodetic stations on the Moon are used simultaneously, as this is expected to improve the modelling geometry and data quality. The proposed experiment may well initiate the installation of new observing stations on Earth – perhaps within the infrastructure of existing astronomical observatories. In the case of the beacon mode, only passive optical receivers are needed on the ground. We will fully explore the requirements and make recommendations for the instrumentation of such a ground station.

In addition, we propose to deploy and operate a microwave receiver/transmitter with precisely known mechanical local ties to the Laser beacon, which will permit observations of the tangential position of the Moon with respect to the celestial frame.

We also propose to include a GNSS microwave transmitter into the proposed equipment realizing a "GPS/Galileo satellite on the Moon" that is tracked together with GNSS satellites by receivers on the ground and possibly on the future generation of GNSS satellites. The ultimate objectives of our proposal are twofold, the improvement of the reference frames for the Earth and a better understanding of the Moon's interior.

A limited number of measurements have been collected during the years, and the distribution of measurements within the lunar cycle is strongly biased, since the equipment cannot cope with the close proximity of the solar light background at new Moon or with the maximum brightness at full Moon. A next generation Lunar Laser Ranging (LLR) experiment should aim at a substantial improvement of the link budget, to overcome these limitations, as well as integrate the passive laser ranging with active radio measurement by placing on the surface of the Moon radio transponders of the latest generation.

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2. Technical concept

We propose to deploy an instrument block on the Moon with the following components:

1. an optical transponder for laser reflection,
2. a low-power microwave pseudo random code beacon and coherent transponder,
3. a GPS/Galileo type space qualified Cesium clock and P-code transmitter.

The optical transponder would improve the Laser link budget substantially. While in the reflector case, the signal strength decreases with lunar distance r to the fourth power ($1/r^4$), for transponders, signal strength decreases with only $1/r^2$. It would be ideal to place transmitters and receivers at both ends of the ranging leg, one on the Moon and several on Earth; however, the complexity of the hardware on the Moon would be too large. Therefore, we propose to employ a one-way ranging concept. There are two ways in which this can be realized: through a "Laser Beacon" concept or an "Inverted Beacon" concept. In the *laser beacon concept*, a pulse Laser beacon is placed on the Moon, slaved to a sufficiently stable clock. In the second concept, the *inverted beacon*, a defocused small receive telescope and a highly sensitive wide-bandwidth photo detector are deployed on the Moon. Both concepts have advantages and disadvantages.

The second element, the microwave beacon/coherent transponder, will be recorded by the terrestrial DSN (Deep Space Network) and ESTRACK (ESA Tracking) ground stations as well as by the VLBI stations, which would allow the high precision mapping of the Moon with its complex motion into the static quasar reference frame.

The third component, the GPS/Galileo transmitter, would make the Moon in its drag-free orbit a "natural GPS satellite" within the global navigation satellite system. The entire block will represent a tight link point to the Lunar, terrestrial, and celestial reference systems.

3. Moon ephemeris improvements

A Laser transponder on the Moon will greatly increase our knowledge on the variation of lunar range. More measurements at higher accuracy, from observatories in both Northern and Southern Hemisphere and without observational bias will be available. The new range data would then be the basis for comprehensive models of the dynamics of the Earth/Moon system and will give stronger determinations of lunar ephemeris, rotation, and tidal deformation, and therewith also information on the deep interior of the Moon. They will also contribute to a much better realizations of the various reference systems, i.e. the terrestrial and selenocentric frame, but also the dynamic realization of the celestial reference system. New reflectors on the Moon will provide additional accurate surface positions for cartographic control.

The microwave transmitter/transponder will permit us to carry out observations of the tangential motion of the Moon in the quasi-inertial space with accuracy in the range of 100-300 microarcseconds (which translates to the sub-meter level). It will also permit us to measure relative velocity of the Moon with respect to the Earth at better than a few hundredths of mm/s. Together with the radial information from Laser ranging, the tangential component from VLBI will push the insight into the Moon's orbital behaviour including its libration to as yet unknown frontiers and there with obtain information on the core of the Moon.

4. Reference frame improvements

At the same time, it is highly desirable to combine all the currently available high precision space geodetic techniques, like Very Long Baseline Interferometer (VLBI) and compatibility with the Global Navigation Satellite System (GNSS) at the location of the landing sites on the Moon, to match the currently available equipment at geodetic observatories on the Earth.

With the inclusion of a GNSS (Global Navigation Satellite System) microwave transmitter in the package, three of the major space geodetic techniques will be co-located on the lunar surface supporting the efforts for a rigorous combination of these techniques. This will eventually allow us to define a unified reference frame rather than a measurement-biased frame as today.

A "GPS/Galileo satellite on the Moon" or the "Moon as a natural GPS/Galileo satellite" that is linked to VLBI will make it possible to directly refer the GNSS satellite constellations (and thus GNSS-determined station coordinates) to the ICRF (International Celestial Reference Frame). This will allow us to measure UT1, i.e., the rotation angle of the Earth, as well as components of nutation with high temporal resolution (and there with obtain information on the deep interior of the Earth) while today GNSS is capable to provide only mean rates of Earth orientation and nutation. A "local tie" between GNSS and VLBI on the Moon would allow for a consistent interpolation of VLBI derived UT1 data with high rate GNSS derived values. A link to the Moon may also improve the sensitivity of GNSS to components of the geocenter. The identification and monitoring of possible geocenter variations by GNSS is currently limited by satellite radiation pressure modelling deficiencies, a restriction that does not apply to the Earth's natural neighbour.