Moon's vibration modes in the mHz band and the Lunar Gravitational-Wave Antenna

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Introduction

With Apollo 17, the Lunar Surface Gravimeter was deployed on the Moon with the main scientific goal to observe gravitational waves (GWs) through the vibrations they cause of the Moon. A technical failure prevented the experiment to be carried out, and today, we believe that the gravimeter would not have had sufficient sensitivity to observe GWs. Nonetheless, the concept to observe GWs on the Moon is intriguing, and we propose a new detector concept, the Lunar Gravitational-Wave Antenna (LGWA) [1], to make GW observations possible in the near future. We propose that the Artemis crew deploys a geophysical station to provide crucial insight about the seismic, thermal and electromagnetic environment of the Moon near its south pole as an important step in the planning of LGWA.

Scientific targets

Gravitational waves passing the Moon excite its quadrupolar vibrational modes [2]. These vibrations can be observed with seismometers deployed on its surface. Using terrestrial and lunar seismometer and gravimeter networks, a series of papers demonstrated that state-of-the-art analysis pipelines developed by the LIGO and Virgo collaborations can be applied to GW analyses of data from seismic networks leading to greatly improved GW sensitivities between 1 mHz and 1 Hz compared to past experiments [2–4].

These studies focused on the detection of stochastic GW backgrounds. More complicated, but also more probable with LGWA, would be the observation of long-lasting signals from compact binaries in the range 1 mHz – 1 Hz composed, for example, of white dwarfs, neutron stars and black holes. Such observations require the modeling of a response curve as shown in figure 1. It shows the amplitude of surface vibrations caused by a GW per unit GW strain. It features resonant amplifications of the response in the mHz band where GWs hit resonances of the vibrational modes (only spheroidal modes included in this plot). This curve is based on a very simple homogeneous model of the Moon, and a more accurate model is required to assess LGWA's sensitivity to GWs and to develop GW data-analysis methods. The accuracy of such a response model hinges on our ability to predict the properties of quadrupolar lunar vibrations. These properties can be deduced from a model of the Moon's internal structure as revealed by observations of seismic events supported by direct observations of vibrational modes at mHz frequencies.

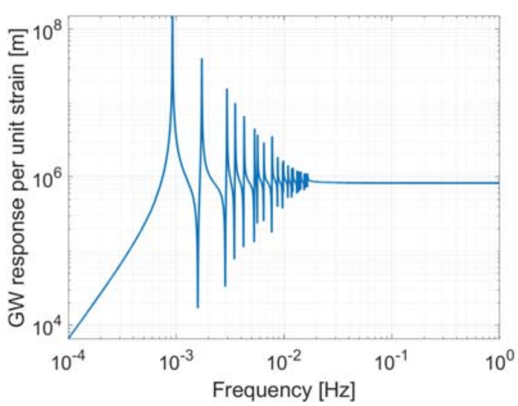

FIG. 1. Moon's response to gravitational waves.

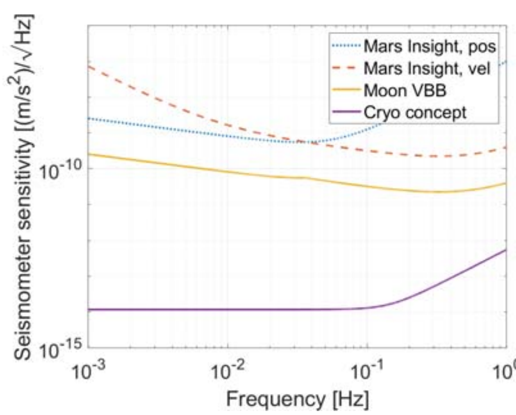

FIG. 2. Models of seismometer sensitivities.

Meteoroid impacts produce a stationary noise background enforcing an ultimate sensitivity limit to how precisely surface vibrations caused by GWs can be measured. The analyses done with the Apollo data need to be extended to lower magnitudes of impact events and to lower frequencies to produce an updated noise model made possible by available modern seismometers. Such a noise model when extended to mHz frequencies requires a model of the Moon's internal structure, which, in turn, can be provided by using seismic signals from meteoroid impacts as probes.

The most sensitive concepts of surface-vibration sensors for LGWA foresee superconducting electronics and magnetic levitation, which require cryocooling [5]. The sensitivity of such a device, compared to, e.g., the Mars Insight very broadband (VBB) instrument and its sensitivity projection for a Moon deployment (Moon VBB) is shown in figure 2. This cryo concept is based on SQUID readout of the position of a magnetically levitated 1 kg test mass at 40 K. Since active cryocooling of a system deployed on the Moon would pose a major hurdle, investigation of permanent low-temperature regions on the Moon can open a crucial opportunity to boost the sensitivity of seismic sensing and therefore of LGWA's science case. Such a seismometer concept would also be susceptible to its electromagnetic environment, which is why we include the monitoring of the electromagnetic field in the science targets of this project.

Concept

We propose that the Artemis crew deploys a geophysical station in one of the permanently shadowed regions (PSRs) near the lunar south pole shown in figure 3. The

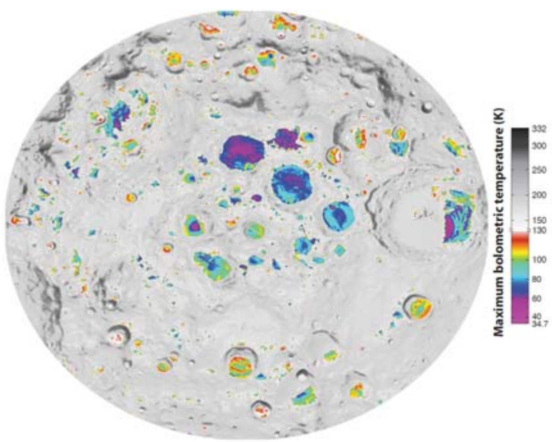

FIG. 3. Maximal temperatures in PSRs at Moon's south pole (image from [6]).

station needs to be equipped with a VBB seismometer designed for measurements of vertical and horizontal surface displacements in the frequency range 1 mHz to 10 Hz. Additional monitors of the thermal and electromagnetic environment are required to assess the feasibility of LGWA's most sensitive seismometer concepts.

The low-temperature environment of a PSR might provide a natural cryocooling system for a cryo concept of LGWA seismometers if temperatures are sufficiently stable. A crater with maximal temperatures below 100 K needs to be selected to be interesting to LGWA, but selection will be constrained by the requirement of a data-transfer link to Earth with earth-facing PSRs typically having higher temperature. The station is meant to remain operative for several years, which requires a special power source in PSRs as for example a nuclear power system or a separate deployment of a solar panel.

The proposed experiment exploits the advanced technological readiness of the instrumentation for the Lunar Geophysical Network (LGN) and builds on the success of the SEIS experiment of the Mars Insight mission, which includes VBB and short-period seismometers. It is important to note that the proposed seismic studies to improve our understanding of Moon's interior require additional seismic stations, which we assume to be provided by the robotic deployment of LGN stations (the LUNETTE lander concept is shown in figure 4). In this

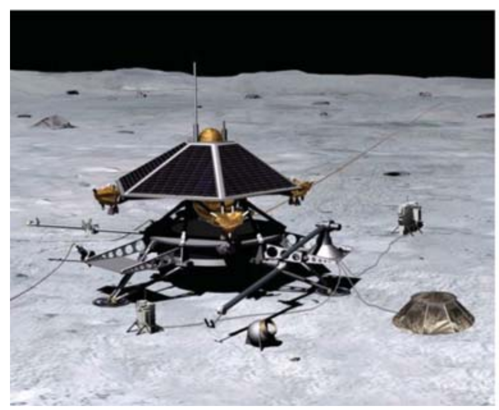

FIG. 4. JPL Lunette mission concept [7].

configuration, our experiment supports a much wider science case as envisioned for the LGN.

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