Lunar Accelerometer Network Gravitational Observatory (LANGO)

Topical white paper in response to BPS Decadal Survey 2023-2032

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1. Science Enabled by LANGO

Gravitational waves (GWs) offer a unique perspective on fundamental physics. The intensely explosive coalescence of super compact objects such as black holes (BHs) and neutron stars (NSs) allows us to investigate the regime of the extreme gravitational field characterizing these events. With these objects reaching speeds comparable to the speed of light, collision events such as these create harsh spacetime environments where the fields are strong, nonlinear, and highly dynamical – a regime that is not yet explored by fundamental physics.

1.1 Gravitational-wave astronomy and test of theories of gravitation

The direct detection of GWs, first achieved in 2015 by the Advanced LIGO detectors (Abbott *et al*. 2016), began an era of GW astronomy which is continuing to blossom. Instrumentation improvements and the addition of the Advanced Virgo detector have enabled the detection and systematic study of dozens of GW signals from merging BHs and NSs, including the spectacular multi-messenger event GW170817 (Abbott *et al*. 2017). The global GW detector network will be further enhanced this decade by commissioning of KAGRA and LIGO-India. U.S. and European scientists also are advancing plans to construct third-generation ground-based interferometers, Cosmic Explorer (Reitze *et al*. 2019) and Einstein Telescope (Punturo *et al*. 2010), which could begin observing in the 2030s. Meanwhile, ESA has proceeded through the Mission Formulation phase of the LISA space-based GW interferometer, with support from NASA, so that LISA should be observing in a lower-frequency (10^{-4} to 0.1 Hz) band from the second half of 2030s.

With all these exciting developments, there will still be a missing frequency band, 0.1-10 Hz, left between the ground and space interferometers. Many astronomical sources are expected in this frequency band, such as merging white dwarfs (WDs), NSs and intermediate-mass black holes (IMBHs). Direct observation of 10^3-10^5 solar-mass IMBHs would shed light on the puzzle of how supermassive black holes (SMBH), primary target sources for LISA, are formed. Further, mid-frequency detectors would detect coalescing stellar-mass BHs days before merging and could alert the GW as well as optical, X-ray, γ-ray astronomy communities enabling more efficient multi-messenger astronomy.

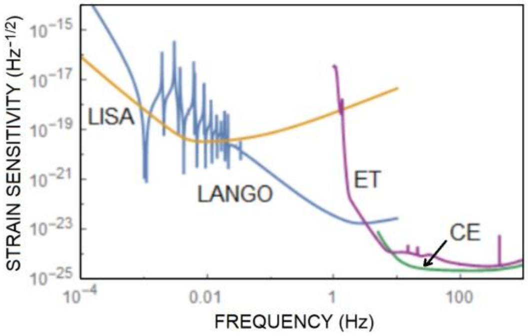

Fig. 1. GW strain sensitivity of LANGO compared to those of ground- and space-based interferometers.

We propose LANGO (Lunar Accelerometer Network Gravitational Observatory) to cover frequency band 1 mHz-10 Hz. Figure 1 shows the frequency band and the projected sensitivity of LANGO compared to those of the third-generation ground-based interferometers and LISA. In addition to mid-frequency detection, LANGO will also detect the GW response of the lowest several quadrupole modes of the Moon, allowing narrow-band detection within the LISA band. LANGO, therefore, has synergies with both the ground and space interferometer detectors. Some alternative theories of gravity (e.g., Brans & Dicke 1961) predict the existence of scalar GWs. By searching for a GW response of the monopole modes of the Moon, LANGO can directly test such theories of gravity.

1.2 Lunar geophysics and seismology

The seismic experiments on the Moon during the Apollo era and the gravity measurements by the recent GRAIL mission show rich geological structure of the Moon. There is, however, still much to learn about the lunar interior. Broadband seismometers with one to two orders of magnitude better sensitivity than the Apollo seismometers are under development to reach the Lunar Geophysical Network (LGN) target sensitivity (Erwin *et al*. 2020).

Since accelerometers invariably measure the test mass displacements relative to the ground, the response of the Moon to GWs as well as to moonquakes and meteorite impacts must be measured or modeled in order to extract GW signals. Hence, measurement and modeling of the Moon’s eigenmodes from 1 mHz to 10 Hz would be necessary. GW detection and improvement of the lunar interior structure must go hand in hand.

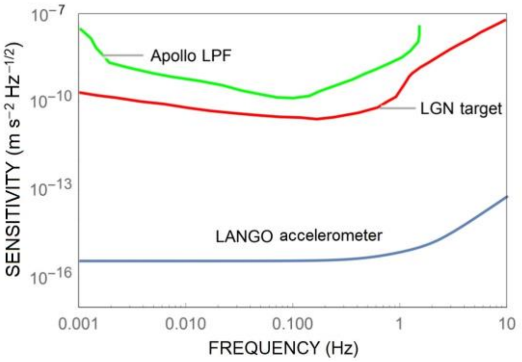

Fig. 2. Projected sensitivity of LANGO accelerometer compared to the sensitivity of the Apollo seismometers and the LGN target sensitivity.

The LANGO accelerometer aims at sensitivity $\leq 10^{-15}$ m s^{-2} Hz$^{-1/2}$ over frequency band from 1 mHz to 2 Hz, which represents six to seven orders of magnitude improvement over the Apollo seismometers (see Fig. 2). The instrument will also measure gravity changes as a vector gravimeter with six orders of magnitude better sensitivity than the GWR superconducting gravimeter (Goodkind 1999). Such an instrument would indeed be a powerful new tool for lunar geophysics and planetary science. Six globally deployed LANGO accelerometers may be able to detect deep moonquakes occurring anywhere inside the Moon, and make a significant contribution to the improvement of the lunar interior model.

2. Design Concept of LANGO

LANGO consists of six three-axis superconducting accelerometers (operating at 4 K) deployed in an octahedral configuration on the surface of the Moon, for example, one at the north pole, one at the south pole, and four on the equator, as shown in Fig. 3. Each accelerometer has a magnetically levitated superconducting test mass with resonance frequency $f_0 \sim$ 1 mHz in both the horizontal and vertical axes. The test mass displacement relative to the lunar surface is sensed by a capacitance bridge coupled to a low-noise two-stage dc SQUID (Superconducting Quantum Interference Device).

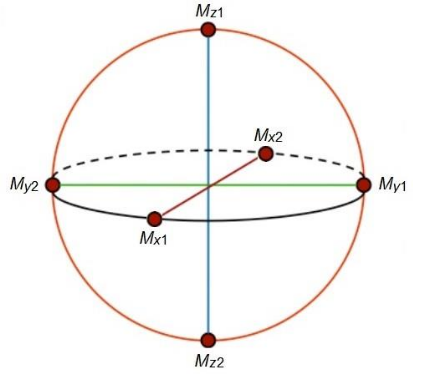

Fig. 3. Six superconducting accelerometers are symmetrically located on the surface of the Moon. As a spherical detector, LANGO has uniform sky coverage and can determine the sky location of the source and the polarization of the wave.

According to general relativity, GWs couple only to the spheroidal quadrupole modes of the Moon. Unlike the laser interferometer detectors on earth and in space, the Moon, as a spherical antenna instrumented with six accelerometers, has uniform sky coverage with the unique capability of determining the sky location of the source and the polarization of the wave (Forward 1971; Wagoner & Paik 1977). The six accelerometers overdetermine the Moon's response to GWs. The extra degrees of freedom can be used to veto non-GW events such as due to seismic motion of the Moon or electromagnetic disturbances.

LANGO is a far advanced version of the lunar gravimeter experiment that Weber attempted in the 1970's (Giganti *et al*. 1977) and is an extension of the lunar GW experiments proposed by Paik & Venkateswara (2009) and by Harms *et al*. (2021). Superconducting accelerometers have heritage. The superconducting accelerometer was first developed as a sensor for the motion of cryogenic resonant-mass GW antennas in the 1970s (Paik 1976). More and more sensitive superconducting gravity gradiometers have been developed over the past four decades with NASA support for gravity mapping missions for the earth and planets (Moody *et al*. 2002; Griggs *et al*. 2017). The same technology is now applied again to detect GWs.

LANGO utilizes the lossless Meissner effect suspension of the test masses, which eliminates the structural damping that limits the low-frequency sensitivity of mechanical spring suspension devices (Griggs *et al*. 2017). Another critical technology that makes LANGO sensitive over the entire bandwidth from 1 mHz to 10 Hz is superconducting negative spring that reduces the test mass frequencies to near zero, which was demonstrated decades ago (Moody *et al*. 1986).

3. Justification of Lunar GW Experiment

Spherical resonant-mass detectors were proposed, and prototypes were constructed and tested by a number of groups (Johnson & Merkowitz 1993; Coccia *et al*. 1995; Aguiar *et al*. 2008). Although the spherical antenna has many advantages over the Weber-bar antenna, its development efforts all folded because, with the maximum diameter of ~ 3 m that could be cast with aluminum, its sensitivity could not compete with long-baseline laser interferometers. Here comes the Moon! The Moon has a million times larger diameter and, with the absence of plate tectonics, oceans and winds, its seismic background is a million times quieter than the earth. Therefore, with proper instrumentation, the Moon could become an ideal GW observatory.

Recently, Paik *et al*. (2016) revived the spherical antenna by proposing a "split sphere" antenna for SOGRO (Superconducting Omni-directional Gravitational Radiation Observatory), with the diameter effectively increased to 50 m. Figure 4 shows a perspective view of SOGRO. Six superconducting test masses are levitated magnetically from a common platform. The acceleration of each test mass is measured in all three axes. By combining the responses of the six accelerometers, a full-tensor GW detector is formed with the same detector characteristics as a solid sphere. SOGRO was designed to be a mid-frequency (0.1-10 Hz) GW detector. As such, its platform must be rigid enough to prevent the Brownian motion of low-frequency platform modes from compromising the detector sensitivity. This rigidity requirement limited the platform length to 50 m.

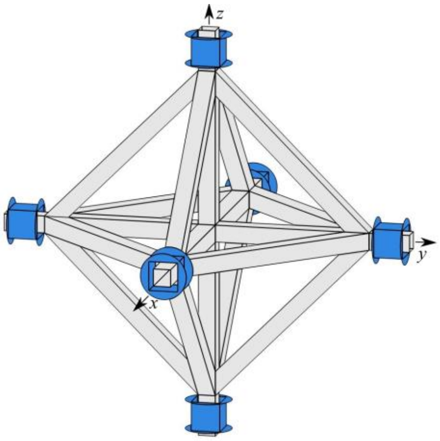

Fig. 4. SOGRO consists of six superconducting accelerometers mounted on a common platform. SOGRO is a full-tensor GW detector with the same detector characteristics as a solid sphere.

LANGO is a gigantically enlarged version of SOGRO with the Moon serving as its platform, with the diameter increased by a factor of 7 × 10^4. The Moon is not rigid in the signal frequency band; rather, it will respond to the GWs but with an amplitude different from that of the weakly suspended test masses. Our calculation shows that the signal attenuation by their tandem "fall" in the GW field is by about a factor of 3. Hence the GW signal for LANGO is still over four orders of magnitude greater than that for SOGRO. This signal gain allows us to construct LANGO with strain sensitivity two orders of magnitude better than SOGRO with 500 times lighter test masses (10 kg each) than SOGRO (5 metric tons each). This makes transport to and operation on the Moon a feasible proposition. Unlike space interferometers, LANGO could be operational for twenty years or longer like the Apollo seismometers.

4. Sensitivity Calculation

In the frequency space, the accelerometer response to a GW signal, $h(f)$, is given by

$$\left(\omega_0^2 - \omega^2 + \frac{j\omega\omega_0}{Q}\right)[x(f) - X(f)] = \omega^2\left[\frac{1}{2}h(f)R - X(f)\right], \tag{1}$$

where ω_0 and Q are the resonance frequency and the quality factor of the test mass, $x(f)$ and $X(f)$ are the displacements of the test mass and the lunar surface with respect to the unperturbed metric. $X(f)$ has components coming from two different origins, a GW-driven component, which is coherent with $h(f)$, and a seismically driven component, which is incoherent with $h(f)$. The coherent part of $X(f)$ can be written as

$$X_c(f) = \frac{1}{2}h(f)R'(f), \tag{2}$$

where $R'(f)$ is the equivalent radius of the Moon that would produce the same signal in the accelerometer, if the Moon were completely rigid at this frequency so that the lunar surface were not perturbed by the GW field. To compute $R'(f)$, we need to assume a lunar interior model. We then calculate its spectrum of elastic eigenmodes, and the coupling of each of these modes to a GW, then use a weighted sum to determine the motion of the Moon's surface caused by the GW. For the simplest model with uniform density, we find $R'(f) = 0.66\ R$ for f between 0.1 and 1 Hz. We do not expect $R'(f)$ to change drastically when an improved lunar interior model is used.

Applying the accelerometer noise calculation derived for SOGRO (Paik *et al*. 2016), we obtain the intrinsic detector noise power spectral density of LANGO:

$$S_h(f) = \frac{4}{M(R-R')^2\omega^4}\left[\frac{k_B T\omega_0}{Q} + |\omega^2 - \omega_0^2|\left(1+\frac{1}{\beta^2}\right)^{\frac{1}{2}} E_A(f)\right], \tag{3}$$

where the first term in the square bracket comes from the thermal Brownian motion noise of the test mass and the second term from the amplifier noise. Here β is the transducer energy coupling constant and $E_A(f)$ represents the amplifier noise. Substituting the values of detector parameters listed in Table 1, which are more modest than SOGRO, we obtain the instrument-limited GW sensitivity of LANGO plotted in Fig. 1.

Table 1. Proposed detector parameters and intrinsic detector noise of LANGO.

Parameter	Design value
Each test mass M	10 kg
Temperature T	4.2 K
Resonance frequency f_0	1 mHz
Quality factor Q	10^6
Pump frequency f_p	5 MHz
Amplifier noise $E_A(f)$	$250\hbar$
Detector noise $S_h^{1/2}(1\ \text{Hz})$	$7 \times 10^{-23}\ \text{Hz}^{-1/2}$

To be able to reach this instrument-limited sensitivity, the accelerometer must be designed carefully and data processed properly to minimize the coupling of seismic and other environmental noise to the instrument. The tensor nature of LANGO will be fully utilized to reject any noise that do not satisfy the conditions that a GW must satisfy.

5. Conclusions

The Moon, with its low-noise dynamic environment, provides us a new unique opportunity to deploy a GW observatory capable of harnessing the information encoded within GWs and to probe fundamental physics from an entirely new perspective. We can probe nuclear physics by way of the tidal information encoded within GWs from binary NS mergers. The new observatories will also allow us to test Einstein's general theory of relativity. While observationally confirmed in every spacetime region reachable over the last century, it has yet to be probed in extreme gravity environments, such as those outside binary BH mergers. By considering inspiral and merger-ringdown GW signals, we can find strong constraints on several alternative theories of gravity with both current and future observations.

Analysis of binary BH merger observations will allow us to put theory-agnostic bounds on modifications of general relativity, as well as bounds on specific theories. For theory-agnostic bounds, ground-based observations of stellar-mass BHs, LISA and LANGO observations of massive BHs can each lead to improvements of up to four orders of magnitude with respect to present GW constraints, while multiband observations can yield improvements of up to six orders of magnitude. This is truly unmatched opportunities.

The BPS Decadal has the unique opportunity to influence the fundamental physics investigation in the next decade. We urge Decadal Committee to embrace the opportunity for exciting fundamental physics investigations offered by lunar landing opportunities that are planned for this decade within the Artemis program. If built within the decade, LANGO will join a network of ground-based and in-space GW observatories and bridge the gap between these observatories.

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