Lunar Accelerometer Network Gravitational Observatory (LANGO)

Research Campaign White Paper
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Abstract

We propose LANGO (Lunar Accelerometer Network Gravitational Observatory) to detect gravitational waves in the frequency band 1 mHz-10 Hz. The LANGO accelerometers will be 10^5-10^6 times more sensitive than Apollo seismometers. Four superconducting accelerometers (operating at 4 K) deployed on the lunar surface will make the Moon a full-tensor detector with the unique capability of locating the source in the sky. LANGO will detect intermediate-mass black-hole binaries to luminosity distance 10 Gpc and beyond, and coalescing stellar-mass blackhole binaries of the GW150914 size with SNR > 100.

1. Science Enabled by LANGO

Gravitational waves (GWs) offer a unique perspective on fundamental physics. The explosive coalescence of super compact objects such as black holes (BHs) and neutron stars (NSs) allows us to investigate the regime of extreme gravitational fields. These objects create highly curved, nonlinear spacetime environments, which can be explored precisely by measuring the inspiral of compact objects. During the final merger and ringdown phase, these objects approach the speed of light, producing fields that are strong, nonlinear, and highly dynamical – a regime that is only now beginning to be explored by observations, and which can yield new tests of General Relativity (GR) and searches for physics beyond the Standard Model.

1.1 Gravitational-wave astronomy and test of theories of gravitation

The direct detection of GWs in 2015 by Advanced LIGO (Abbott *et al.* 2016) began an era of GW astronomy, as well as for tests of GR. The addition of Advanced Virgo has 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). U.S. and European scientists are advancing plans to construct 3rd-generation ground detectors, Cosmic Explorer (Reitze *et al.* 2019) and Einstein Telescope (Punturo *et al.* 2010). ESA is formulating the LISA mission, with support from NASA, so that LISA could be observing in a lower-frequency band from late 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 to be in this frequency band, such as merging white dwarfs (WDs), NSs and intermediate-mass black holes (IMBHs), as well as type-1a supernovae. 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 and neutrino astronomy communities, enabling more efficient multi-messenger astronomy.

We propose LANGO (Lunar Accelerometer Network Gravitational Observatory) to cover the frequency band from 1 mHz-10 Hz (Paik *et al.* 2021). Figure 1 shows the projected sensitivity of LANGO compared to those of the 3rd-generation ground interferometers and LISA. LANGO will also detect the GW response of the lowest several quadrupole modes of the Moon, allowing narrow-band detection within the LISA band. Some alternative theories of gravity predict the existence of scalar GWs (e.g., Brans & Dicke 1961). By searching for a GW response of the monopole modes of the Moon, LANGO can directly test such theories of gravity.

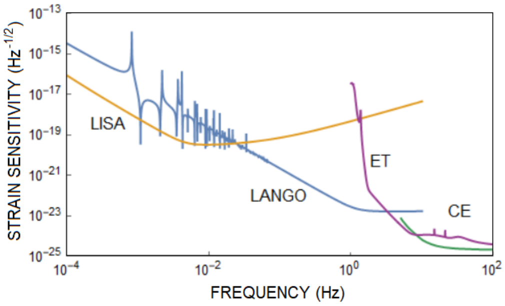


Fig. 1. GW strain sensitivity of LANGO compared to those of proposed ground and space interferometers.

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 the rich geological structure of the Moon. There is, however, still much to learn about the lunar interior. Broadband seismometers with 1 to 2 orders of magnitude better sensitivity than the Apollo seismometers are under development to reach the Lunar Geophysical Network (LGN) target sensitivity (Neal *et al.* 2020). Since accelerometers measure the test mass (TM) 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 investigation of the lunar interior structure must go hand in hand.

The LANGO accelerometer aims at sensitivity 2×10^{-15} m s^{-2} Hz$^{-1/2}$ in the horizontal axes and 10^{-14} m s^{-2} Hz$^{-1/2}$ in the vertical over a frequency band from 1 mHz to 1 Hz, which represents 5-6 orders of magnitude improvement over the Apollo seismometers (see Fig. 2). Such an instrument would be a powerful new tool for lunar geophysics and planetary science. Several 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.

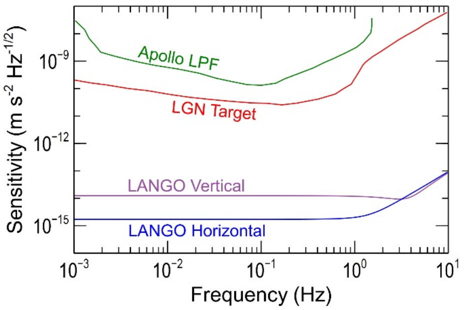


Fig. 2. Sensitivity of LANGO accelerometer compared to that of Apollo seismometers and LGN target sensitivity.

2. Design Concept of LANGO

2.1 Accelerometer network

We have investigated both an octahedral and a tetrahedral configuration of accelerometers on the Moon. Due to gravity bias, the vertical axis of the LANGO accelerometer is 5 times less sensitive than the horizontal. The octahedral configuration of 6 horizontal-only accelerometers fails to form a full-tensor detector, but the tetrahedral configuration of 4 horizontal accelerometers, does form a full-tensor detector. Figure 3(a) shows the tetrahedral configuration of 4 accelerometers deployed on 4 of the 8 vertices of a cube inscribed in the Moon. Figure 3(b) shows an alternative arrangement of 4 accelerometers occupying the 4 vertices of the cube face facing the Earth. Either option yields the same GW strain sensitivity and antenna pattern shown in Figs. 1 and 4. The square configuration has the advantage of not requiring a relay satellite to communicate with the accelerometer on the back side of the Moon. If the budget permits, 4 more accelerometers could be added so that 8 accelerometers occupy all 8 vertices. This will improve the strain sensitivity by factor $\sqrt{2}$ and increase the instrument's capability to reject local noise sources.

In the baseline configuration, we assume that only 4 accelerometers are deployed. Each accelerometer has a magnetically levitated superconducting TM with resonance frequency $f_0 = 0.1$ Hz in horizontal and ~ 5 Hz in vertical directions. The TM displacement relative to the lunar surface is sensed by a capacitance bridge coupled to a low-noise 2-stage dc SQUID (Superconducting Quantum Interference Device). Commercial cryocoolers, such as SHI RDE-418D4 4-K cryocooler, appear to be adequate to cool the LANGO accelerometers to 4 K on the Moon (SHI webpage).

According to GR, GWs couple only to the spheroidal quadrupole modes of the Moon. Unlike the laser interferometer detectors, the Moon, instrumented with 4 accelerometers, has nearly uniform sky coverage (to $\leq 17\%$) with the unique capability of determining the sky location of the source and the polarization of the wave (see Fig. 4). The 8 horizontal acceleration outputs overdetermine the Moon's response to GWs. The extra degrees of freedom can be used to veto non-GW events such as those due to seismic motion of the Moon or electromagnetic disturbances.

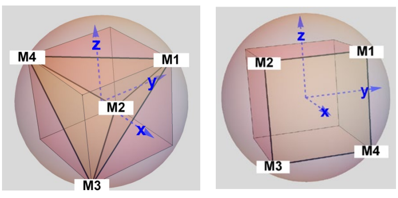
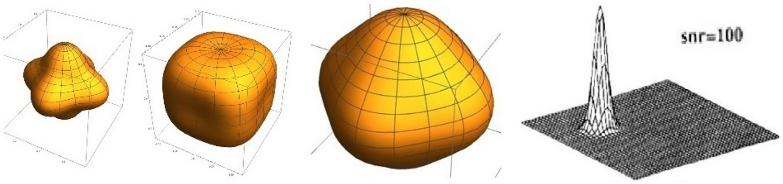


Fig. 3. Four superconducting accelerometers deployed on the Moon (a) in a tetrahedral configuration and (b) in a square configuration.



3 diagonal 3 off-diagonal Full tensor Sky location

Fig. 4. Antenna pattern of LANGO. As a full-tensor detector, LANGO has full-sky coverage with nearly equal sensitivity to waves coming from any direction with any polarization, and can locate the source in the sky.

2.2 Accelerometer design

Figure 5 shows a cross-sectional view of the LANGO accelerometer. The TM consists of two parts, the inner part made out of niobium (Nb, density 8.57 g/cm^3) and the outer part, tungsten-copper (W90-Cu10, density 17.0 g/cm^3). The purpose of this design is to produce a compact TM with a total mass of 10 kg, and to be able to replace the W-Cu part with a structure made out of titanium Ti6Al4V alloy, so as to reduce the total mass by a factor of 6 to 1.66 kg and simulate the lunar gravity environment.

The TM has cylindrical symmetry about the central axis. The TM is levitated by the levitation coils (red) located under 2 Nb disks and centered by a solenoid (red) in the middle. Two vertical sensing capacitors (dark blue) are located above each Nb disk and 4 horizontal sensing capacitors (dark blue) surround the TM. The housing dimensions are 11.4 cm in diameter and 17.8 cm in height.

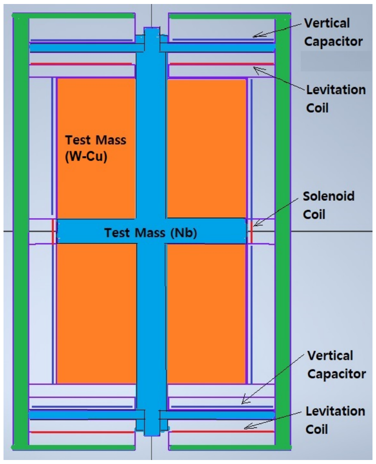


Fig. 5. Cross-sectional view of LANGO accelerometer. TM is levitated by levitation coils and centered by a solenoid.

2.3 Justification for lunar experiment

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 Harms *et al*. (2021). Superconducting accelerometers have heritage. A superconducting accelerometer was first developed for cryogenic resonant-mass GW antennas in the 1970s (Paik 1976). More and more sensitive superconducting gravity gradiometers have been developed since then with NASA support for gravity mapping missions for Earth and planets (Moody *et al*. 2002; Griggs *et al*. 2017). The same technology is now applied again to detect GWs.

Spherical resonant-mass GW detectors have been proposed, and prototypes 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 were all ultimately discontinued 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 10^6 times the diameter of these antennas, and, with the absence of plate tectonics, oceans and winds, its seismic background is 10^6 times quieter than Earth. Therefore, with proper instrumentation, the Moon could become an ideal GW observatory. Unlike space interferometers, LANGO could be operational for ≥ 20 years.

LANGO would be an excellent supplement to the LGN mission (Neal *et al*. 2020). LGN proposes to globally distribute 4 landers around the Moon, with each lander containing laser retroreflectors, seismometers, electromagnetic sounders, and heat flow probes. The plan is to have each lander continuously gathering data for 6 years with a goal of 10 years. The primary goal of LGN is to *understand the initial stages of terrestrial planet evolution*. If the LANGO network is active simultaneously with LGN, both missions would benefit each other. LANGO would yield data that would add fidelity to LGN. Conversely, LGN would inform LANGO regarding the detected signals – are they internal to the Moon or induced by meteoroid impact or other external sources?

3. LANGO Mission Description

3.1 Deployment of accelerometers

To reduce the cost of LANGO deployment, the 4 accelerometers are deployed pairwise from 2 different lunar orbits using the same lunar transfer stage. Once the first pair of spacecrafts with accelerometers is deployed, the stage changes its inclination to deploy the second pair.

The LANGO spacecraft configuration is fairly simple. The box-like main structure would have 4 legs rigidly attached for landing on the Moon. All 4 spacecraft will fit within the fairing of a Falcon 9 launch vehicle. The 2 spacecrafts deploying the first 2 accelerometers will separate from the launch vehicle and continue their flight toward the Moon. The 2 spacecrafts deploying the remaining 2 will share a space tug that will be capable of placing them on a perpendicular orbit. Each spacecraft has small solar panels and a high-gain antenna, and will be capable to store on-board power enough to keep the instruments in survival mode through the 14-days lunar night.

Following a 2-week cruise, when the spacecraft arrives at the Moon, propulsive maneuvers will place it into a nearly circular low lunar orbit. Landing on the Moon will be done semi-autonomously using onboard landing capabilities. All propellant tanks will be vented once on the Moon. Nominal science operations would continue for 3 years. Since there are no expendables during science operations, further observations could occur in an extended mission phase.

3.2 Flight systems

The LANGO spacecraft includes all equipment necessary to deliver and support the 3-axis superconducting accelerometers on the Moon. The mass by subsystem is ~200 kg. A typical power required is ~50 W. With Falcon 9 as the launch vehicle, mass and volume capabilities are much greater than necessary, so subsystems can be optimized to minimize cost rather than mass.

Attitude control will be done using thrusters since there is no stringent pointing requirement for the spacecraft. Attitude control sensors will include standard star trackers, inertial measurement units, coarse sun sensors, optical navigation camera, terminal descent camera, terminal descent laser altimeter, and electronics for driving the laser range instrument pointing gimbal. Propulsion will be done using a monopropellant to minimize cost of tanks and thrusters.

The command and data handling subsystem is based on the architecture used for the landers available from either Masten Space Systems or Astrobotic. It includes RAD750 processors, interfaces to the attitude control, telecommunication, power, and payload subsystems, with sufficient memory storage to accumulate up to 2 weeks of instrument data. The power subsystem includes 5.3 m^2 solar panels. LANGO will rely on onboard RHU units for power and thermal management.

Thermal control will be done using multi-layer insulation and heaters. Spacecraft and electronics will be in a thermally isolated box that will be kept warm during dark periods on the Moon. Telecommunications will utilize standard X-band transponders and traveling-wave tube amplifiers with a deployed pointable high-gain antenna 0.5-m diameter for sending instrument data to Earth.

3.3 Mission operations

Science operations of the LANGO accelerometers will be done on a continuous basis. The data will be stored onboard to communicate back to Earth. The spacecraft will have 3 view periods each day to select for operations. The tracking pass time will be selected to accommodate available tracking stations for that day. Once per week the spacecraft will communicate with a dedicated ground-based receiver network to download the previous week of science data.

4. Activity schedule

To meet the anticipated launch date of July 2028, the official LANGO project would begin in July 2023, starting a 60-month development effort. Following launch, a 2-week cruise and a 1-month Orbit Phase precede a lunar landing in September 2028. The landers then start their 3-year primary mission. The only anticipated technology development effort is for the accelerometer. At project start, the LANGO will be at TRL 4. The plan will advance the instrument maturity to TRL 6 by the project's Preliminary Design Review (PDR) in November 2026.

The 10 months of Phase A will be dedicated to project formulation. A comprehensive set of requirements will be generated during this time. The 10 months of Phase B will focus on preliminary design. Refinements to requirements will be made, with special emphasis on interfaces. Project governing documents will be baselined. The goal is to achieve TRL 6 for a successful PDR.

Phase C and D together will last 40 months. The goal of phase C is to reach the maturity to pass a critical design review. At the end of Phase C, the detailed design should be complete, all interfaces must be finalized, manufacturing processes will be in place, certain long-lead items must be fabricated/procured, and a verification and validation plan will be available to execute.

Phase D is dedicated to assembly, test, and launch. The spacecraft will be brought to a recognizable shape, integrated with LANGO and all subsystems, and subjected to a battery of system-level tests. Tests will be conducted on the flight hardware, as well as on a representative spacecraft simulator, which will be used throughout the remainder of the mission to validate incremental software developments and test operational activities before they are executed in the mission itself.

5. Cost Estimates

The cost estimates were generated as part of a Pre-Phase-A preliminary concept study and were prepared without consideration of potential industry participation. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, typically Pre-Phase A, and should be viewed as indicative rather than predictive. The estimate adds 30% reserves for development (Phases A-D) and 15% for operations (Phase E). During Phase E, 10% of the operation costs will be allocated to science.

The project cost is roughly \$150M FY21 with appropriate contingencies, including 3 years of science operations (see Table 1).

Table 1. LANGO Cost Estimate Summary.

Item	Cost (\$M 2021)
Management, Systems Engineer-	12
Payload System	36
Flight System	40
Mission Ops/Ground Data System	15
Assembly, Test, Launch Opera-	8
Science	10
Education and Public Outreach	3
Mission Design	6
Reserves	20
Total Project Cost	**150**

6. Conclusions

The Moon, with its low-noise environment, provides a unique opportunity to deploy a GW observatory capable of harnessing the information encoded within GWs to probe fundamental physics from an entirely new perspective. This new observatory will allow us to test Einstein's GR in previously inaccessible regimes. While observationally confirmed in every spacetime region reachable over the last century, it has yet to be accurately probed in extreme gravity environments, such as those produced by binary BH mergers. By considering inspiral and merger-ringdown GW signals, we can find strong constraints on several alternative theories of gravity as well.

Analysis of binary BH merger observations will allow us to put theory-agnostic bounds on modifications of GR, 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 4 orders of magnitude with respect to present GW constraints, while multiband observations can yield improvements of up to 6 orders of magnitude. This represents a truly unique opportunity to advance our understanding of the universe. With a crewed lunar landing scheduled as early as 2025 under the Artemis program, it is high time to return to the Moon and build a lunar GW observatory to advance fundamental physics, as well as astrophysics.

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