Lunar Laser Interferometer Gravitational-Wave Observatory Postprint

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Abstract

Gravitational waves are an important prediction of general relativity, and gravitational wave detection is one of the most active frontier fields in contemporary physics. The discovery of gravitational waves has enabled gravitational wave astronomy to complete the historic transition from searching for gravitational waves to studying them, ushering in a new era of vigorous development for gravitational wave astronomy. Ground-based laser interferometer gravitational-wave observatories and space-based gravitational wave detectors have rapidly developed around the world. With the advancement of lunar exploration programs, the construction of lunar-based laser interferometer gravitational-wave observatories has increasingly attracted attention. This paper provides a brief introduction to lunar-based laser interferometer gravitational-wave observatories: first reviewing their history, describing their advantageous conditions and the basic parameters and optical configuration of the detectors, and prospecting their future development.

Full Text

Preamble

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PROGRESS IN ASTRONOMY

Lunar-Based Laser Interferometer Gravitational-Wave Observatory

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Abstract: Gravitational waves represent a crucial prediction of general relativity, and their detection stands as one of the most active frontiers in contemporary physics. The discovery of gravitational waves has catalyzed a historic transition in gravitational-wave astronomy—from merely searching for these signals to conducting systematic astronomical studies—ushering in a new era of vigorous development. Earth-based laser interferometer gravitational-wave observatories and space-based detectors have proliferated worldwide. With the advancement of lunar exploration programs, constructing a lunar-based laser interferometer gravitational-wave observatory has garnered increasing attention. This paper provides a concise overview of such observatories, reviewing their history, favorable conditions, basic detector parameters, optical architecture, and future prospects.

Keywords: gravitational waves; gravitational wave detection; lunar base; laser interferometer

1 Gravitational Waves and Astronomy

Astronomical research fundamentally relies on celestial radiation, which falls into two primary categories: electromagnetic radiation and gravitational radiation, corresponding to electromagnetic-wave astronomy and gravitational-wave astronomy, respectively. Electromagnetic-wave astronomy—conventional astronomy—employs electromagnetic waves (radio, infrared, visible, ultraviolet, X-ray, γ-ray, etc.) as its observational medium, utilizing "image-like" detection methods and image analysis techniques. For millennia, our ancestors studied celestial phenomena through electromagnetic radiation, creating a rich and splendid ancient astronomy. Over the past three centuries, astronomers have established hundreds of observatories worldwide and in Earth's orbital vicinity, achieving remarkable success in astronomical research and mapping the distribution of celestial bodies across the cosmos. The discovery of gravitational waves has opened a new epoch for gravitational-wave astronomy, providing humanity with a novel window for studying the universe.

1.1 Gravitational Waves and Gravitational-Wave Astronomy

Gravitational-wave astronomy uses gravitational radiation as its observational medium. Gravitational radiation possesses distinct characteristics: its wavelength can be comparable to the scale of gravitational-wave sources, making it neither visible to the eye nor capturable through photography or electronic displays. Its detection methodology belongs to the "sound-like" category, employing waveform analysis analogous to acoustic signal processing. Both "sound" and "image" represent two manifestations of cosmic entities, each carrying detailed information about celestial bodies and concealing cosmic secrets. Compared to electromagnetic-wave astronomy, gravitational-wave astronomy remains in its infancy. The "gravitational-wave sky map" remains a blank canvas awaiting exploration and research. This emerging interdisciplinary science will acquire information unattainable through other astronomical observations, enabling the discovery of unknown celestial objects, investigation of their structure and evolution, and revelation of cosmic mysteries. It represents a tremendous expansion and complement to traditional electromagnetic-wave astronomy.

1.2 Gravitational Wave Frequency Ranges and Detection Methods

The discovery of gravitational waves has spurred vigorous development across the field. Gravitational waves span an extremely broad frequency range from 10^{-16} to 10^{4} Hz (Figure 1 [Figure 1: see original paper]), making full-band measurement with a single detector and method impossible. Consequently, various gravitational-wave detection devices with different structures and principles have emerged, including laser interferometer detectors, pulsar timing arrays, and cosmic microwave background B-mode polarization detectors. Space-based gravitational-wave detectors are also being planned and constructed, with research fervor sweeping the globe.

Figure 1 Gravitational wave frequency distribution and corresponding detection methods

As lunar exploration programs advance, lunar-based laser interferometer gravitational-wave detection has attracted significant scientific attention, becoming a new frontier in gravitational-wave astronomy research.

1.2.1 Ultra-Low-Frequency Gravitational Wave Detection (10^{-16}–10^{-12} Hz) The standard method for detecting ultra-low-frequency gravitational waves in the 10^{-16} to 10^{-12} Hz range involves searching for B-mode polarization patterns in the cosmic microwave background radiation.

(1) Basic Principle: The cosmic microwave background is an extremely faint electromagnetic radiation permeating the entire universe, a relic of the Big Bang. Theoretical physicists posit that our universe originated from a sudden explosion of an extremely hot, dense singularity 13.7 billion years ago, marking the beginning of space and time. To refine the "hot Big Bang cosmological model," Guth et al. [2] proposed the "inflation theory" in 1981, suggesting that 10^{-35}

seconds after the Big Bang, the universe underwent an unimaginably rapid expansion—inflation—during which its volume increased by more than 10^{78} times in less than one second. Primordial gravitational waves generated during inflation would distort spacetime, compressing it in one direction while stretching it in the perpendicular direction. When ancient light from the Big Bang passes through this distorted space, it produces a unique polarization pattern called B-mode polarization—a distinctive imprint of primordial gravitational waves. B-mode polarization exhibits vortex-like features in cosmic microwave background polarization observations. Since B-mode polarization can only arise from tensor perturbations, which electromagnetic fields cannot produce, its detection would unequivocally confirm the existence of primordial gravitational waves.

(2) Experimental Apparatus: Representative experiments using B-mode polarization to detect gravitational waves include BICEP [3–5] and China's Ali Project [6]. BICEP (Background Imaging of Cosmic Extragalactic Polarization) is implemented through a radio telescope located on the Antarctic ice sheet (Figure 2 [Figure 2: see original paper]), which scans the sky to observe cosmic microwave background radiation and search for the unique B-mode polarization signature. Initiated in 2005, BICEP has evolved to its third generation (BICEP3 [5]), with experiments ongoing.

Figure 2 The BICEP experiment

1.2.2 Nanohertz Gravitational Wave Detection (10^{-10}–10^{-6} Hz)

Pulsar timing arrays serve as the experimental "apparatus" for nanohertz gravitational wave detection.

(1) Basic Principle: Millisecond pulsars are neutron stars with rotation periods in the millisecond range, exhibiting exceptional rotational stability (10^{-18} to 10^{-21}). Due to their highly predictable pulse periods, an array of such pulsars can function as a precise timing array for detecting extremely low-frequency gravitational waves. When gravitational waves pass between Earth and a pulsar, they stretch or compress the distance, causing the propagation path of radio pulses to lengthen or shorten accordingly. This results in the arrival time of radio pulse signals on Earth being earlier or later than predicted. Detecting this characteristic variation in pulse arrival times constitutes gravitational wave detection.

The effect of gravitational waves on a single pulsar's pulse arrival times is minuscule and difficult to distinguish from observational noise. Even ignoring noise, various parameters in pulsar timing models are obtained through optimization and fitting of large datasets, introducing significant uncertainties and model correlations. These errors resemble gravitational wave effects, making single-pulsar detection extremely difficult and impractical. Consequently, gravitational wave detection using pulsars typically employs an array of stable pulsars observed simultaneously over extended periods. By exploiting correlations in pulse arrival times across different pulsars, various error sources can be suppressed to extract the gravitational wave signal—hence the name "pulsar timing array gravitational wave detection" (Figure 3 [Figure 3: see original paper]). Multiple pulsar timing arrays now operate worldwide, forming the International Pulsar Timing Array (IPTA [9]).

Figure 3 Schematic diagram of pulsar timing array gravitational wave detection

A pulsar timing array can be considered a galaxy-scale gravitational wave detector. By analogy with laser interferometers, pulsars in the array act as "test masses," their emitted radio pulses serve as "lasers," and the distance between pulsars and Earth-based observatories functions as an interferometer "arm."

(2) Pulsar Timing Arrays: Currently operational arrays include:
1) Australia's PPTA [10], established in 2004, monitoring 20 millisecond pulsars;
2) Europe's EPTA [11], operational since 2004/2005, comprising radio telescopes from France, Germany, Italy, the Netherlands, and the UK, monitoring 22 millisecond pulsars;
3) The North American Nanohertz Observatory for Gravitational Waves (NANOGrav [12]), operational since 2007, using Arecibo and Green Bank telescopes to monitor 45 millisecond pulsars;
4) China's CPTA [13, 14], including the FAST radio telescope, monitoring 57 pulsars.

1.2.3 Low-Frequency Gravitational Wave Detection (10^{-4}–10^{-1} Hz)

Space-based gravitational-wave detectors are the preferred instruments for low-frequency gravitational waves, particularly in the millihertz band. Theoretical calculations show that for sinusoidal gravitational waves, interferometer output signals reach maximum when the arm length equals one-quarter of the gravitational wavelength. Thus, longer interferometer arms correspond to lower optimal detection frequencies. In principle, space-based detectors can have arbitrarily long arms, making them ideal for low-frequency gravitational waves.

Planning for space-based detectors began in the mid-20th century and remains in the pre-research stage, though substantial progress has been achieved. Current representative proposals include Europe's eLISA [15], China's Taiji program [16], and Tianqin program [17]. These aim to study millihertz gravitational waves, requiring extremely long arms: eLISA's arms are 2.5×10^6 km with a detection band of 10^{-4}–10^{-1} Hz; China's Taiji program features 3×10^6 km arms covering 10^{-4}–10^{-1} Hz. Low-frequency gravitational waves carry rich physical information, revealing deeper cosmic and astrophysical mysteries. Detection in this band constitutes an important component of gravitational-wave astronomy, powerfully complementing ground-based observatories and greatly expanding the research field.

Space-based detectors are extremely large and complex. The Taiji program, for example, consists of three satellites forming an equilateral triangle constellation with 3×10^6 km sides. Its center of mass follows Earth's orbit around the Sun at approximately 5×10^7 km from Earth, deviating about 20° from the Sun-Earth line (Figure 4 [Figure 4: see original paper]).

Figure 4 Schematic diagram of the Taiji space gravitational wave detector

1.2.4 Gravitational Wave Detection (3–2×10^4 Hz) Earth-based laser interferometer gravitational-wave observatories are optimal for the 3–2×10^4 Hz band. As the mainstream detection equipment, they have flourished globally [18], enabling humanity's first direct detection of gravitational waves. Their development spanned decades of challenging progress. Laser interferometer detectors offer high sensitivity, broad frequency bands, long service life, and ease of maintenance and upgrades, making them the international standard.

Currently, five major second-generation laser interferometer detectors are operational (Figures 5–9 [Figure 5: see original paper]–[Figure 9: see original paper]), achieving design sensitivity of 10^{-23} across approximately 10–10^4 Hz:

1) Advanced LIGO in Livingston, Louisiana, USA (4 km arms, Figure 5);
2) Advanced LIGO in Hanford, Washington, USA (4 km arms, Figure 6 [Figure 6: see original paper]);
3) Advanced VIRGO near Pisa, Italy (3 km arms, joint Italian-French construction, Figure 7 [Figure 7: see original paper]);
4) GEO-600 in Hanover, Germany (600 m arms, joint British-German construction, Figure 8 [Figure 8: see original paper]);
5) KAGRA in Kamioka, Japan (3 km arms, Figure 9 [Figure 9: see original paper]).

Additionally, LIGO-India (4 km arms), a US-India collaboration, is under construction.

1.3 Fruitful Research Results

During their commissioning phase, Advanced LIGO and Advanced VIRGO conducted three observing runs, detecting over 90 gravitational wave events. These include dozens of binary black hole mergers, two binary neutron star mergers, two neutron star-black hole mergers, and two candidate neutron star-black hole mergers—yielding abundant results (Figure 10 [Figure 10: see original paper]). After three years of upgrades, they began their fourth observing run in May 2023, promising further exciting discoveries.

Figure 10 Mass distribution of discovered gravitational wave events

1.4 Third-Generation Laser Interferometer Gravitational-Wave Detectors

As second-generation detectors flourish, planning for third-generation observatories such as Europe's Einstein Telescope (ET) [25] and America's Cosmic Explorer (CE) [26] is underway. These aim for sensitivity of 10^{-24} across 1–10^4 Hz, establishing true gravitational-wave observatories for routine astronomical research (Figures 11 [Figure 11: see original paper] and 12 [Figure 12: see original paper]). Improving sensitivity, particularly at low frequencies, represents the primary development direction.

Figure 11 Conceptual diagram of Europe's third-generation detector "Einstein Telescope" (10 km arms)

Figure 12 [Figure 12: see original paper] Conceptual diagram of America's third-generation detector "Cosmic Explorer" (40 km arms)

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2 Lunar-Based Laser Interferometer Gravitational-Wave Observatory

With deepening lunar exploration, constructing gravitational-wave observatories on the Moon has attracted intense interest. Multiple nations have proposed schemes for long-baseline interferometers on the lunar surface [29, 30], gradually evolving into a new field of gravitational-wave astronomy.

2.1 Importance of Lunar-Based Observatories

Theoretical studies show gravitational waves span an extremely broad frequency range, with each band containing rich physics requiring different detection methods. As shown in Figure 1, third-generation ground-based interferometers ET and CE can extend detection to approximately 3 Hz, while space-based detectors like Taiji and eLISA operate around 10^{-3} Hz. The gap between them, particularly the 0.1–10 Hz range, represents a "blind spot" where ground-based detectors are limited by low frequencies and space-based detectors by high frequencies. A lunar-based observatory can eliminate this blind spot, complementing existing detection systems.

The 0.1–10 Hz band encompasses numerous important astrophysical phenomena [31]. Notably, for certain processes, this represents the *only* observational window:

(1) Intermediate-mass black hole mergers: Black holes are categorized as supermassive (10^5–10^{10} M), intermediate-mass (10^2–10^5 M), or stellar-mass (1–10^2 M). While supermassive and stellar-mass black holes have been confirmed, intermediate-mass black holes—crucial for understanding black hole formation and evolution—remain largely unconfirmed (despite some candidates). Since LIGO's first detections, ground-based observatories have discovered numerous stellar-mass binary black hole mergers (Figure 10). As gravitational wave frequency during merger is inversely proportional to total system mass, detecting intermediate-mass black hole mergers requires coverage of the 0.1–10 Hz band.

(2) Double white dwarf mergers: Type Ia supernovae serve as standard candles, providing direct evidence for the universe's accelerated expansion. While consensus exists that their progenitors are binary systems, the specific configuration remains mysterious. Binary evolution theory centers on whether they are single- or double-degenerate systems [32]. In either case, the merger process accompanies the supernova explosion, releasing violent electromagnetic radiation, neutrinos, and gravitational waves in the 10^{-4}–10 Hz band [33]. Detecting these waves could unveil the nature of Type Ia supernova progenitors, profoundly impacting stellar physics and cosmology.

(3) Core-collapse supernovae: The core-collapse model explains Type II supernovae. Massive stars (>8 M) may collapse directly into black holes or neutron stars late in their evolution, ejecting material and releasing energy across multiple wavelengths. The explosion also generates low-frequency gravitational waves (0.1–10 Hz) from aspherical mass ejection (dominated by neutrinos) [34]. Detecting these signals would reveal internal structures and explosion details of Type II supernovae.

The latter two processes, with their violent energy release, provide excellent multi-messenger astronomy opportunities combining electromagnetic waves, gravitational waves, and neutrinos.

Beyond these unique windows, 0.1–10 Hz detection offers: 1) Early warning observations of stellar-mass binary black hole inspirals, breaking parameter degeneracies; 2) Early warning for black hole-neutron star and binary neutron star systems, enabling prepared multi-messenger observations; 3) Complete coverage of the 10^{-4}–10^{4} Hz stochastic background spectrum alongside ground and space interferometers, crucial for early universe studies; 4) Cosmological studies using large gravitational-wave source samples.

This band is most likely to integrate with electromagnetic observations, becoming a window for large-sample multi-messenger astronomy!

2.2 Emergence of Lunar-Based Observatories

NASA's Artemis program, succeeding Apollo, aims to establish a long-term human presence on the Moon. As part of this initiative, scientists Jani and Loeb [35] proposed a lunar-based laser interferometer observatory. Italian scientists Harms et al. [36] presented similar proposals, culminating in the first international lunar gravitational-wave detection conference in Florence, Italy, in October 2021.

In March 2021, China and Russia announced collaboration on the "International Lunar Research Station" (ILRS), signing a memorandum of understanding to build permanent habitats for lunar exploration, resource utilization, and fundamental space science experiments. This program is progressing systematically.

Chinese lunar exploration scientists, including Academicians Ouyang Ziyuan, Yu Dengyun, and Wu Weiren, have emphasized establishing a lunar research station with human presence to exploit lunar resources and conduct fundamental research. Public information indicates China plans crewed lunar landing by 2030, with the China National Space Administration actively promoting ILRS for broader international cooperation.

As a key ILRS component, lunar-based gravitational-wave observatories have attracted strong Chinese scientific interest. Led by Professor Zhang Xiaomin of Beijing Institute of Technology, Chinese scientists organized a series of workshops from 2021–2023 to explore lunar-based interferometer schemes.

2.3 Advantages of Lunar-Based Construction

Constructing laser interferometer gravitational-wave observatories on the Moon offers numerous advantages:

(1) Extended service life: Gravitational-wave astronomy is a generational scientific endeavor, not merely a short-term experiment. While conventional astronomy has developed over centuries with hundreds of observatories, gravitational-wave astronomy will follow a similar trajectory. Space-based detectors like eLISA have design lifetimes of only a few years before solar system gravitational perturbations disrupt their geometry. Lunar- and Earth-based interferometers can operate for decades, continuously upgraded with new materials, components, and technologies, making them suitable for long-term stable operation.

(2) Ease of adjustment and maintenance: Laser interferometers are complex facilities requiring extensive commissioning to optimize parameters and performance. Operational failures, damage, and component aging necessitate continuous maintenance. The Hubble Space Telescope, at 569 km altitude, required five servicing missions. While such maintenance is impossible for detectors millions of kilometers away in space, lunar-based facilities can be serviced by resident astronauts.

(3) No complex vacuum system required: All Earth-based interferometers require elaborate vacuum systems comprising vacuum pipes and chambers housing test masses, optics, and vibration isolation systems (Figure 13 [Figure 13: see original paper]). Required vacuum levels exceed 10^{-7} Pa, where laser phase noise matches thermal, seismic, and shot noise. Achieving and maintaining such vacuum over large volumes demands massive, complex pumping, measurement, and maintenance systems (mechanical, turbomolecular, ion, and cryogenic pumps; high-vacuum gauges; sealed valves). Vacuum systems represent the most expensive component—accounting for nearly one-third of LIGO's total cost, with proportionally higher costs for longer baselines.

Lunar surface vacuum reaches ~10^{-8} Pa during lunar day and ~10^{-10} Pa during lunar night [37], fully satisfying interferometer requirements (10^{-7} Pa [38]). Eliminating vacuum systems saves enormous construction and operational costs, as well as maintenance resources.

(4) Natural outgassing of vacuum materials: Earth-based interferometers require pre-outgassing vacuum materials to meet release rate standards. Stainless steel vacuum pipe walls are primary outgassing sources, typically wrapped in insulation and heated to 140°C for ~30 days to achieve water molecule release rates of 10^{-17} $\mathrm{Pa \cdot L \cdot s^{-1} \cdot cm^{-2}}$. Lunar surface temperatures range from -130°C at night to 120°C during day [40]. Leveraging these conditions for pre-assembly material outgassing saves substantial resources.

(5) Reduced seismic noise: Ground vibration is a major noise source for Earth-based detectors [39], arising from natural phenomena (volcanic activity, earthquakes, ocean tides, wind, precipitation) and human activities (transportation, industry, mining, construction). Typical ground vibration amplitudes are ~10^{-6} m, while expected gravitational wave amplitudes are ~10^{-19} m, requiring vibration isolation systems with attenuation $>10^{13}$. This seismic noise fundamentally limits low-frequency sensitivity, with next-generation detectors barely reaching ~3 Hz [41].

The lunar surface is far quieter. In the 0.1–4 Hz band, lunar vibration noise is 3–4 orders of magnitude lower than Earth's [42–44], enabling simplified vibration isolation systems and reduced construction costs. This could lower the minimum detection frequency to 0.1 Hz, greatly expanding astrophysical research capabilities.

(6) Reduced gravity gradient noise: Newtonian gravitational attraction between test masses and surrounding objects creates gravity gradient noise from local mass distribution variations (atmospheric density changes, personnel, vehicles, wind). This noise "short-circuits" isolation systems, directly affecting mirrors and is unavoidable. Studies show gravity gradient noise scales with frequency squared, severely impacting low-frequency detection. The most effective Earth-based mitigation is underground construction at hundreds of meters depth, dramatically increasing costs and technical challenges.

The lunar surface is exceptionally quiet [40], with no human activity or atmospheric weather phenomena. Consequently, lunar gravity gradient noise is negligible, eliminating the need for underground construction and substantially reducing costs.

(7) High duty cycle: Continuous, stable operation is crucial for maximizing data acquisition. Earth-based detectors suffer frequent interruptions from earthquakes, transportation, lighting, storms, and other environmental factors, requiring time-consuming re-locking and resulting in low duty cycles. The lunar surface experiences minimal human interference and negligible Earth tidal effects. Lunar seismic frequencies are much lower than Earth's [44], essentially not affecting the relevant detection band. This ensures excellent long-term stability and high duty cycles.

(8) Enhanced source localization: Joint observations with ground-based observatories can improve gravitational-wave source localization by nearly 30 times [35, 45], providing precise pointing information for rapid electromagnetic follow-up observations and laying the foundation for multi-messenger astronomy.

3 Basic Parameters and Optical Structure of Lunar-Based Detectors

Lunar-based laser interferometer gravitational-wave detectors comprise mechanical, electronic, and optical components. Their basic parameters and optical architecture are described below.

3.1 Main Parameters

Key parameters and their values are: sensitivity, 10^{-24}; detection frequency, 0.1–10^4 Hz; arm length, 100 km; overall configuration, L-shaped; laser power, 200 W; squeezed light field compression, 15 dB.

3.2 Basic Optical Structure

The basic optical structure is shown in Figure 15 [Figure 15: see original paper], comprising the following systems:

Figure 15 Basic optical structure of lunar-based laser interferometer gravitational-wave detector

(1) Laser: Requires high output power (200 W), excellent power stability ($<10^{-9}$), frequency stability ($<10^{-12}$), pure TEM_{00} transverse mode, linear polarization, and low intrinsic noise (Δ / well below total interferometer noise).

(2) Faraday isolator: Since optical paths are reversible, laser light returning from the interferometer could damage the laser source. Faraday isolators, made from magneto-optical materials, function as optical one-way filters, allowing forward transmission while blocking reflected light.

(3) Frequency modulator: Electro-optically modulates the laser frequency to generate sidebands around the carrier. By finely tuning Fabry-Pérot cavity length for carrier resonance, the two sidebands have equal amplitude. When interferometer arms stretch or compress due to disturbances, the cavity detunes, shifting the carrier from resonance and causing operational failure. The resulting sideband amplitude imbalance provides an error signal for Pound-Drever-Hall techniques to automatically restore cavity resonance.

(4) Mode cleaner: Laser beam intensity distributions are described by Hermite-Gaussian polynomials. Interferometers require pure fundamental

Hermite-Gaussian mode (TEM_{00}); mode cleaners eliminate harmful higher-order modes.

(5) Power recycling mirror: Recycles light exiting the interferometer input port back into the system.

(6) Beam splitter: Divides the laser beam into two equal-intensity beams reflected into perpendicular arms.

(7) Fabry-Pérot cavity: Gravitational-wave-induced phase shifts are proportional to arm length. Increasing arm length enhances sensitivity. Fabry-Pérot cavities, composed of input and end mirrors, resonate incident light for multiple passes, repeatedly sampling mirror displacement from gravitational waves. This effectively folds ultra-long interferometer arms for practical construction, representing a revolutionary advancement in detector capability.

(8) Signal recycling mirror: Forms a Fabry-Pérot cavity with the interferometer's equivalent mirror to resonantly enhance output signals.

(9) Cryogenic interferometer: Thermal noise arises from Brownian motion of optical components or temperature fluctuations. Cryogenic detectors place test masses in low-temperature environments to reduce thermal noise. Cryostats made of stainless steel maintain interior walls at ~8 K and mirror bodies at ~20 K.

(10) Squeezed light injection system: For next-generation detectors targeting 10^{-24} sensitivity, the standard quantum limit poses the primary barrier. Squeezed light injection is crucial for surpassing this limit [46]. Pure amplitude or phase squeezing (Figure 16a [Figure 16: see original paper]) only reduces quantum noise at low or high frequencies, not across the entire band. Frequency-dependent squeezing (or frequency-dependent squeezing) rotates the squeezing ellipse as a function of detection frequency, enabling optimal quadrature squeezing across all frequencies and improving sensitivity throughout the band.

Figure 16 Squeezed light field injection system

In Figure 16b, curve (1) represents the standard quantum limit, curve (2) shows conventional interferometer quantum noise without squeezing, curve (3) depicts pure phase squeezing, and curve (4) illustrates frequency-dependent squeezing. The ellipses at the bottom show squeezing ellipses at different frequencies.

Additional components include vibration isolation systems, control systems, pipe shielding, wave plates, and environmental monitoring systems.

3.3 Noise Issues in Lunar Environment

The 0.1–10 Hz band contains rich physics and important astrophysical phenomena, offering a new window between ground and space detection with significant scientific value. While lunar construction offers many advantages, the unique lunar environment introduces different noise and error characteristics compared to ground-based detection.

After decades of research, ground-based interferometer noise sources are well understood, with effective mitigation methods [39] providing valuable lessons for lunar systems. Primary noise sources include seismic noise, thermal noise, gravity gradient noise, quantum noise, and stray photon noise.

(1) Seismic noise: A major noise source arising from natural phenomena and human activities. Typical Earth vibration amplitudes are ~10^{-6} m. The lunar surface is much quieter, with no human activity or terrestrial natural phenomena. Literature indicates lunar vibration noise is 3–4 orders of magnitude lower than Earth's in the 0.1–4 Hz band [42–44]. However, frequency and amplitude distributions must be measured in preparatory studies.

(2) Thermal noise: Caused by Brownian motion of optical components or environmental temperature fluctuations. The "violin modes" of suspension fibers and "drum modes" of mirrors are primary concerns. Large lunar temperature variations require placing Fabry-Pérot cavity end mirrors and suspensions in cryogenic environments. Experimental halls (Figure 13) need temperature control, preferably located in thermally stable lava tubes.

(3) Gravity gradient noise: Local mass distribution variations cause gravitational field fluctuations (Newtonian noise). The lunar surface lacks large-scale mass changes and atmospheric weather, making this noise negligible.

(4) Quantum noise: Originates from light's quantum nature, limiting sensitivity across nearly all frequencies. It manifests as shot noise (intensity quantum noise at the photodetector) and radiation pressure noise (mirror displacement from photon momentum transfer). Shot noise dominates at high frequencies, while radiation pressure noise dominates at low frequencies. Lunar detectors operating at 0.1–10 Hz are primarily limited by radiation pressure noise, mitigable through moderate laser power and squeezed light technology [39].

(5) Stray photon noise: Scattered photons leaving and re-entering the main beam couple into the interferometer, contaminating signals. Lunar dust (regolith) near the surface is a significant source. Measuring dust concentration and particle distribution, plus developing reliable filtering methods and deploying apertures, are important preparatory research topics.

3.4 Preparatory Research

Before detailed design, extensive preparatory studies are needed to determine detector parameters and architecture:

(1) Non-Gaussian noise: Primary sources include cosmic ray bombardment and solar flares. Mitigation methods must be studied, such as magnetic shielding in test mass vacuum chambers to block scattered light from charged particles and regolith, or cosmic ray discriminators.

(2) Extreme temperature variations: With lunar surface temperatures of -130°C at night and 120°C during day, research is needed on thermal coating materials and methods, or active cooling systems to maintain stable temperatures and minimize thermal expansion effects.

(3) Lunar curvature: The Moon's curvature is much greater than Earth's—a 40 km baseline produces ~450 m height deviation. Ideal terrain must be selected or alternative solutions developed.

Additional challenges include solar radiation effects, dust impacts, and data communication difficulties requiring solutions in subsequent studies (see reference [47]).

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4 Site Selection for Lunar Observatories

The lunar surface is covered with impact craters whose ring structures can largely offset or eliminate curvature effects for large interferometers.

Craters are characterized by two parameters [48] (Figure 17 [Figure 17: see original paper]): diameter D (average length through the crater center connecting rim points, up to hundreds of kilometers) and depth d (average height difference between deepest point and rim, typically tens to thousands of meters).

Figure 17 Schematic diagram of crater diameter D and depth d

Generally, larger craters have greater depths, but the depth-to-diameter ratio (d/D) decreases with increasing diameter [49, 50]: average d/D ratios are 1/20 for 28–90 km craters, 1/30 for 90–120 km craters, and 1/40 for craters >120 km. This distribution implies a theoretical maximum crater diameter for completely eliminating curvature effects by mounting interferometers on crater rims. Simple calculations yield a maximum diameter of ~250 km, corresponding to arm lengths of ~180 km (L-configuration) and ~220 km (equilateral triangle configuration)—perfectly meeting the requirement for hundred-kilometer-scale interferometers!

Based on lunar crater statistics [51], 72 large craters have diameters of 200–250 km (corresponding to L-configuration arm lengths of 140–180 km). Considering geological irregularities, local seismic conditions, and signal transmission factors, truly suitable craters are limited. We recommend preliminary screening using lunar surface data, followed by environmental monitoring with small vibration sensors to prepare for future observatory construction.

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5 Summary and Outlook

As lunar exploration advances, lunar gravitational-wave observatories have become a new research field attracting intense interest. Proposals fall into two categories: (1) laser interferometer schemes similar to LIGO; (2) lunar seismometer schemes analogous to Weber bars (e.g., Harms et al.'s LGWA [30], Jani and Loeb's GLOC [35], and Beijing Normal University's "Moon as a string" proposal [52]). These schemes remain in early discussion stages.

The lunar-based laser interferometer detector proposed herein features high sensitivity, broad development prospects, long service life, advanced technology, and convenient maintenance and upgrades—capable of becoming a true observatory for long-term operation. The lunar surface offers abundant craters of various scales, no atmosphere, no human activity, and low seismic noise, enabling simplified interferometer designs, reduced costs, and enhanced performance. Arm lengths can be customized from kilometers to hundreds of kilometers based on astrophysical targets, broadly covering gravitational-wave frequency bands and opening new frontiers.

Particularly, large-arm (hundred-kilometer-scale) interferometers with high-precision Fabry-Pérot cavities offer unique advantages for 0.1–10 Hz gravitational-wave astronomy. This unique band not only provides the best opportunity for multi-messenger astronomy combined with electromagnetic observations but also eliminates the "blind spot" between space and ground detectors, establishing a complete 10^{-4}–10^{4} Hz detection system.

We firmly believe that with advancing lunar exploration and continuous optimization of detection schemes, lunar gravitational-wave detection will usher in a new era of rapid development, making the Moon humanity's most important platform for gravitational-wave astronomy.

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Note: Figure translations are in progress. See original paper for figures.