ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug1479

A Review of Remote Sensing and In-Situ Methods for Lava Tube Identification and Characterization

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Publication Date: 2026/09/12

Abstract: Lunar lava tubes have emerged as high-priority targets for future exploration and habitation due to their potential to shield astronauts from radiation, thermal extremes, and micrometeorite impacts. This paper reviews current and emerging methods for detecting subsurface cavities on the Moon, spanning gravimetric anomaly mapping, ground-penetrating and orbital radar sounding, passive seismic imaging, and magnetic field surveying. Recent gravimeter-based studies suggest that lava tubes buried more than 26 meters deep could be detected using instruments with resolutions around 25 µGal, based on terrestrial analog modeling. Complementary work has explored ambient seismic noise techniques, including fiber-optic distributed acoustic sensing, as an alternative to dense seismometer networks for subsurface imaging. Gravity field models derived from GRAIL data continue to offer untapped resolution for identifying subsurface voids, while morphological approaches using high-resolution stereo imagery have improved characterization of pit entrances and collapse features. This review synthesizes the strengths, resolution limits, and mission-readiness of each technique, and situates them against magnetometer-based detection to assess complementary roles these methods could play in a multi-instrument approach to confirming and characterizing lunar lava tube networks.

Keywords: *Lava Tubes; Lunar Subsurface; Remote Sensing; Radar Sounder; Gravimetry; Passive Seismic; Distributed Acoustic Sensing; Magnetometry; Pit Morphology.*

How to Cite: Onwuama I. C.; Ozoadibe C.; Nebo N. B.; Gaggah T.; Ibikunle D.; Dabup A.; Idogbe A.; Akpen J.; Ehiwenma E., Balami H. (2026) A Review of Remote Sensing and In-Situ Methods for Lava Tube Identification and Characterization. *International Journal of Innovative Science and Research Technology*,11(8), 3432-3439. https://doi.org/10.38124/ijisrt/26aug1479

I. INTRODUCTION

A. Motivation for Lunar Lava Tube Exploration and Habitation

While the Moon represents the most feasible and viable environment for establishing a permanent human habitat outside of Earth, the lunar surface poses severe technical and biological hurdles for anyone attempting to live there long-term [1]. Astronauts and equipment on the lunar surface are exposed to unshielded galactic cosmic radiation, sporadic solar particle events, meteoroid and micrometeorite bombardment, and diurnal temperature swings of more than 250 K between lunar day and night [1]. Building shelters that protect against radiation using materials brought from Earth involves high expenses and complex delivery requirements. Consequently, there is a growing focus on using the Moon's own underground cavities, specifically lava tubes, as a ready-made solution. Formed during early lunar volcanism, these subsurface lava tubes provide ideal conditions for habitation by shielding inhabitants beneath thick layers of basalt, effectively mitigating extreme thermal fluctuations, ionizing radiation, and micrometeoroid impacts [1], [2], [3]. Additionally, their vast internal dimensions are thought to be capable of supporting the large-scale facilities required for permanent human occupation [4], [5].

B. Historical Evidence and Detection Milestones

Interest in lunar lava tubes is not new, but the evidence base supporting their existence has grown substantially over the past two decades. In 2009, the Terrain Camera on Japan's SELENE (Kaguya) mission captured images of a steep-walled, vertical pit located in the Marius Hills area. This feature, later called the Marius Hills Hole (MHH), provided the first definitive visual evidence of a "skylight" entrance leading into an underground lunar void [3], [6]. Follow-up analysis of data

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug1479

acquired by the Kaguya Lunar Radar Sounder (LRS) revealed distinct subsurface radar reflection patterns surrounding the Marius Hills Hole (MHH), indicating anomalous underground structural features [3], [5]. These findings were initially interpreted by some researchers as radar returns from the ceiling and floor of a preserved, intact lava tube extending for many kilometers from the collapse pit. Following initial discoveries, the Lunar Reconnaissance Orbiter Camera (LROC) identified and catalogued several hundred additional candidate pits and collapse features across both mare and highland terrains [7], [8], [9]. Collectively, these observations transformed lava tubes from a theoretical possibility into a set of concrete, geographically located targets, and motivated a diversified suite of detection techniques capable of confirming their presence, extent, and structural integrity ahead of any future landed mission.

C. Overview of Detection Methods

Accurately determining the three-dimensional layout of subsurface voids is a complex challenge that requires the integration of diverse observational methods, as no individual instrument, whether operating from lunar orbit or stationed on the surface, can definitively map these structures on its own [7], [8], [9]. The methods reported in the literature to date fall broadly into four complementary families:

- Gravimetric anomaly mapping, which identifies negative gravity anomalies resulting from the mass deficit created by empty subsurface cavities [4], [8];
- Orbital and surface radar sounding, encompassing both orbital low-frequency sounders and surface-deployed ground-penetrating radar (GPR), used to capture subsurface dielectric discontinuities [2], [5], [10];
- Active and passive seismic imaging and distributed acoustic sensing (DAS), which infers void geometry from the propagation and scattering of ambient seismic energy [9]; and
- Magnetometer-based surveying, which detects localized perturbations caused by the lack of magnetized basaltic material within a lava tube's interior [7].

This review evaluates the current and operational states, spatial resolution limits, and lunar mission-readiness of each of these approaches.

D. Gravimetric Anomaly Mapping

Gravimetric sensing is based on the physical principle that an empty underground void creates a localized area of mass deficit, or a negative density anomaly, compared to the higher-density host rock [3], [4], [8]. Using gravity gradient data from NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission, Chappaz et al. [4] identified several elongated mass-deficit signatures that strongly suggest the presence of vast, hollow subsurface conduits. Their analysis indicates that these intact lava tubes may reach widths of several kilometers, and several of these detected anomalies are directly associated with known sinuous rilles and skylight pits, such as the Marius Hills Hole, providing independent geophysical evidence for their existence [4]. Because the GRAIL spacecraft collected gravity field data at orbital altitudes, the resulting measurements primarily detect regional, high-mass geological structures, leaving smaller, human-scale lava tube conduits beyond the instrument's spatial resolution [4], [9]. Montañez Muñoz et al. [8] used a high-resolution three-dimensional model of Ape Cave, Washington, to demonstrate that gravimeters with resolutions below 25 μGal can reliably detect analog lava tubes buried more than 26 m deep, and that larger, more lunar-realistic tube geometries produce detectable signals even at coarser instrument sensitivities. Collectively, these findings establish that orbital gravity surveys are ideal for detecting large-scale subterranean voids and estimating their primary volumetric bounds. Conversely, mapping smaller or shallow conduit segments suitable for infrastructure deployment requires high-resolution ground-based or near-surface gravimetric surveys.

E. Orbital Radar Sounding

Radar sounding represents the most direct geophysical method for visualizing subsurface dielectric interfaces and currently stands as the most mature and extensively developed detection technique [2], [5]. Orbital low-frequency sounders exploit the transition in dielectric properties between solid rock, an air-filled void, and rock again, which produces a characteristic pair of reflections from the tube's ceiling and floor, specifically identified by a 180-degree phase inversion at the roof interface that allows researchers to distinguish legitimate subsurface conduits from surface clutter [2], [5], [10]. Kobayashi et al. [3] re-examined multi-orbit Kaguya LRS observations over the Marius Hills region and established a consecutive-detection criterion for distinguishing genuine lava tube echoes from surface clutter. Building upon these predecessors, Carrer et al. [2] designed and simulated a dual-frequency radar sounder purpose-built for lava tube detection, showing through a coherent three-dimensional electromagnetic simulator that an orbiting instrument could reliably detect the majority of lunar lava tubes wider than approximately 250 m, with the roof echo's characteristic phase inversion serving as a robust discriminator against clutter. Donini et al. [10] proposed an unsupervised, fuzzy-rule-based method for automatically extracting linear subsurface features from simulated radargrams, reducing reliance on a priori geometric assumptions when screening large volumes of sounder data. In their review of radar technologies for lunar and Martian exploration, Qiu and Ding [5] examined the application of ground-penetrating radar (GPR) into surface-based platforms like rovers and landers, including the Chang'e-3/4 lunar GPR and the RIMFAX and RoSPR instruments flown to Mars, concluding that surface-deployed GPR offers finer resolution than orbital sounding at the cost of spatial coverage.

F. Passive Seismic Imaging and Distributed Acoustic Sensing

Passive seismic methods, though not as established for characterizing lava tubes, have gained attention as low-mass alternatives and easily deployable compared to the logistical

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug1479

burden of deploying traditional, high-density sensor arrays [1], [9]. Ambient seismic noise on the Moon is dominated by thermally induced moonquakes rather than the human-made or tectonic activity typically analyzed in Earth-based studies, and these temperature-driven vibrations restrict the available frequency range to mostly above 1 Hz, which limits the sensitivity of passive recordings primarily to shallow structures within the upper 10 metres of the subsurface [9]. Keil et al. [9] used two-dimensional numerical simulations of the shallow lunar subsurface, including a realistic model of the Marius Hills skylight, to evaluate seismic interferometry, horizontal-to-vertical spectral ratios, distributed acoustic sensing (DAS), and rotational measurements as candidate lava tube imaging techniques. Their results show that while all four methods are effective at detecting underground voids and determining the thickness of their roofs, they are primarily sensitive only to features within the upper 10 metres of the lunar subsurface, and visualising conduits at greater depths would require lower-frequency energy (below 1 Hz), which is not well represented by natural lunar seismic activity [9]. The study concludes that achieving reliable three-dimensional mapping of these structures will likely require the integration of multiple ambient-noise techniques alongside other complementary geophysical datasets, rather than relying on a single standalone seismic method [9].

G. Magnetometer-Based Detection

Magnetometer-based sensing identifies lava tubes by detecting localized disruptions in the magnetic field created by the structural boundaries of either a preserved or collapsed conduit [1], [7]. Bell et al. [7] conducted a high-resolution magnetic survey using a proton-precession magnetometer over an area exceeding 100,000 m² within the Modoc Crater lava tube complex at California's Lava Beds National Monument. Their findings established that the most significant negative magnetic anomaly produced by a conduit is directly related to its geometric ratio, specifically the relationship between its cross-sectional area and the depth to its center [7]. Additionally, the researchers determined that the spatial gradient of the magnetic signature provides a precise method for delineating the lateral boundaries and positions of the lava tube's walls [7].

H. Scope and Organization of This Review

While individual progress across geophysical method families such as gravimetric anomaly mapping, radar sounding, and seismic imaging has been significant, no single technique currently offers a viable, standalone solution for fully resolving the three-dimensional extent of lunar lava tubes [2], [9]. Gravimetry and orbital radar sounding may provide vast spatial coverage but suffer from poor vertical resolution and have difficulty resolving smaller, human-scale subsurface structures [4], [5]. In contrast, surface-deployed instruments such as ground-penetrating radar (GPR) and passive seismic arrays deliver high vertical resolution but are restricted by minimal lateral coverage and the logistical challenges of increased payload mass and deployment [5], [9]. This review examines four detection families, evaluating their physical mechanisms, resolution constraints, and flight readiness for near-term lunar exploration missions. Ultimately, it aims to define a multi-instrument architecture capable of effectively verifying and mapping subsurface lava tube networks for potential habitat sites.

The remainder of this paper is organized as follows: Section II reviews and analyzes comparative methods; Section III discusses key technical gaps identified in current literature; and Section IV summarizes the synthesized conclusions and reference framework.

II. METHODS ANALYSIS

A. Gravimetric Anomaly Mapping (e.g., GRAIL Bouguer / free-air gravity, gradiometry)

- Strengths: Only method with existing, global, high-resolution lunar coverage today (via GRAIL data)—no new mission required to start analysis [11], [12]. Directly sensitive to the physical signature that matters most: a mass deficit, which is exactly what an air-filled void produces [11]. Has already produced the strongest candidate evidence for large tubes (e.g., Marius Hills, Rima Sharp, Vallis Schröteri) [11], [13], [15]. Works purely from orbit—safe, repeatable, no landed hardware required [11].

B. Orbital Radar Sounding (e.g., SELENE/Kaguya LRS, Apollo ALSE, proposed dual-frequency sounders)

- Strengths: Can penetrate several kilometers into the subsurface and detect sharp dielectric discontinuities (rock/void boundaries) at a tube's roof and floor [16]. Enables broad or even global mapping from orbit [16], [18], unlike surface-bound techniques. Existing missions have already returned candidate echo signatures that align with gravity anomalies [16] (mutual corroboration).

C. Ground-Penetrating Radar (GPR) (Surface / rover-deployed)

- Strengths: Much higher spatial resolution than orbital radar since it operates close to the target. Can directly confirm or refute a candidate identified by gravity or orbital radar. Already demonstrated on the Moon (Chang'E-3 / Chang'E-4 rover radar), including detection of shallow layering and small (~3 m) voids [20].

D. Active and Passive Seismic Imaging

- ➢ *Active Seismic (reflection, refraction tomography, MASW, backscatter methods):*
- Strengths: Well-proven on Earth for cavity detection; new backscatter techniques can resolve small voids (10–20 m) at

shallow depth (5–15 m) without dense sensor arrays [20]; potentially transferable to GPR datasets too.

- Resolution Limits: Signal enhancement from a cavity is not by itself a definitive indicator (nonuniqueness, same issue as gravity/magnetics) [20]; requires deploying an active source plus receivers on the surface [20], [22].
- Mission-Readiness: Medium—methods and instruments are mature terrestrially, but deploying an active seismic source on the Moon adds logistical/engineering complexity [20], [22] beyond passive alternatives.

➢ *Passive Seismic (ambient noise methods):*

- Strengths: No active source needed—just listens to natural background vibrations (moonquakes, thermal cracking, micrometeorite impacts), which is logistically far simpler; simulations show it can both detect a tube and estimate ceiling thickness [21].
- Resolution Limits: Still mostly at the simulation/proof-of-concept stage rather than flight-validated; the Moon's naturally scattering, heterogeneous shallow subsurface (known from Apollo-era data) produces long, ambiguous seismic coda that complicates clean interpretation [21].
- Mission-Readiness: Medium-low—conceptually simple to deploy (a seismometer array) but the analysis techniques are newer and less field-tested on the Moon [21] than gravity or radar approaches.

Table 1 Comparative Method Summary

Method	Detects	Best Feature Scale	Key Weakness	Mission-Readiness
Gravimetric Mapping	Mass deficit	Large (km-scale)	Nonunique; low resolution for small tubes	High (data exists)
Orbital Radar Sounding	Dielectric contrast	Large, and deep	Clutter / echo misinterpretation	Medium (concept mature; dedicated instrument pending)
Ground-Penetrating Radar (GPR)	Dielectric contrast, near-surface	Small–medium, shallow	Local only, limited depth	High (already flown, but confirmatory only)
Active Seismic	Reflected / backscattered elastic waves	Small–medium	Needs active source; nonunique	Medium
Passive Seismic	Ambient elastic wave scattering	Small–medium (in simulation)	Immature; scattering-heavy environment	Medium-low
Magnetometer Surveying	Magnetic anomaly contrast	Small–medium (terrestrial analog scale)	Needs magnetic host rock; minimal lunar-specific validation	Low-medium

F. Rationale for a Multi-Instrument Approach

Every method above shares the same fundamental problem: nonuniqueness [21], [23]. A gravity low, a radar echo, a seismic scattering anomaly, and a magnetic anomaly can each be produced by more than one kind of subsurface structure—not just a lava tube [12], [17], [20]. A layered workflow—gravity for broad discovery [11], [12], orbital radar for independent cross-check [16], [17], and GPR/seismic/magnetometry for landed confirmation [18], [20], [21], [17]—lets each method's strengths compensate for another's blind spot, following the same cross-validation logic already used at Marius Hills [11], [16], [17].

A layered, complementary workflow addresses this by having each method compensate for another's blind spot [16]:

- Gravity mapping (broad discovery)—scan wide regions using existing GRAIL data to flag candidate mass-deficit zones. This is the cheapest first-pass filter since no new mission is needed.

✓ Orbital radar sounding (independent cross-check)—check whether the same candidate zone also produces a dielectric-contrast echo consistent with a void. Agreement between gravity and radar substantially raises confidence, since the two methods have unrelated failure modes (density contrast vs. dielectric contrast).

✓ Landed/rover follow-up: GPR + seismic + magnetometer (local confirmation and characterization)—once a site is prioritized, in-situ instruments resolve what orbital data cannot: precise depth, roof thickness, lateral extent, and internal structure. GPR nails down shallow geometry; passive seismic can estimate ceiling thickness with minimal hardware; active seismic/backscatter can resolve smaller voids missed by radar; magnetometry adds an independent, physically unrelated line of evidence (density- and dielectric-independent) that helps rule out non-void explanations.

✓ Cross-validation loop—because each technique's weaknesses differ (gravity: low resolution; radar: clutter misinterpretation; seismic: scattering ambiguity; magnetics: host-rock dependency), a candidate that is corroborated by two or more independently-failing methods is far more likely to be a genuine cavity than one flagged by any single technique. This is the same logic already used in the Marius Hills case, where gravity and radar signals were compared directly against each other.

In short: gravity and orbital radar are best used as global search tools, while GPR, seismic, and magnetometry are best used as local confirmation and characterization tools once a candidate has been narrowed down. No single method is currently mission-ready enough to stand alone as definitive proof of a lava tube—confirming and mapping an actual navigable lunar cave network will require this kind of staged, multi-instrument strategy.

III. DISCUSSION (GAPS IDENTIFIED IN CURRENT LITERATURE)

Despite significant progress in the remote detection and characterization of lunar lava tubes, several important technical and scientific gaps remain. These limitations arise not only from the capabilities of individual sensing techniques but also from the difficulty of integrating observations acquired at different spatial scales, depths, and levels of certainty. Consequently, current approaches are generally more successful at identifying candidate surface expressions or subsurface anomalies than at providing definitive, three-dimensional characterization of complete lava-tube systems.

First, the spatial resolution and sensitivity of gravity observations from the GRAIL mission constrain the detection of relatively small or deeply buried lava tubes. GRAIL gravity data have provided important evidence for large subsurface voids and possible lava-tube structures, including interpretations in the Marius Hills and other regions of the Moon [27], [28]. However, gravity measurements respond to variations in subsurface mass distribution rather than directly imaging cavities. The resulting gravity anomaly therefore depends on the size, depth, geometry, and density contrast of the structure. Large cavities can generate detectable mass deficits, whereas smaller tubes or complex networks may produce weak signals that become difficult to distinguish from regional geological variations [27], [31], [28]. Consequently, current gravity-based investigations may preferentially identify larger or more favorably oriented structures, potentially causing the smaller-scale components of lunar lava-tube networks to remain unresolved. This is particularly important because a lava-tube system may consist of interconnected passages with variable dimensions rather than a single large, uniform cavity. Thus, improving the interpretation of gravity observations will require higher-resolution measurements, improved geological constraints, and integration with complementary subsurface sensing techniques.

Second, radar sounding provides one of the most direct remote-sensing approaches for investigating the subsurface, but its effectiveness is constrained by signal propagation and interpretation ambiguities. Observations from the SELENE/Kaguya Lunar Radar Sounder have provided evidence for intact lava tubes, particularly in the Marius Hills region [32], [35], while radar simulations demonstrate that appropriately selected frequencies could improve the detectability of subsurface cavities [33], [34]. Nevertheless, radar measurements are sensitive to surface topography, subsurface dielectric properties, layer interfaces, and observation geometry. Surface clutter can generate returns that obscure or complicate the interpretation of deeper reflections, while attenuation and scattering can reduce the strength of signals propagating through heterogeneous or highly complex subsurface materials [33], [34]. Furthermore, a radar reflector does not necessarily constitute unambiguous evidence of a lava tube because subsurface geological interfaces may generate similar responses. This creates a fundamental challenge: increasing radar detection capability does not automatically eliminate geological ambiguity. Future radar systems therefore need optimized frequency selection, improved signal processing, and potentially multi-frequency observations capable of distinguishing cavity-related signatures from other subsurface reflectors.

Third, seismic techniques represent a promising but comparatively less mature approach to lunar lava-tube detection. Recent work on enhanced seismic backscattering demonstrates that seismic waves can potentially interact with subsurface voids in ways that produce detectable signatures [36]. However, the application of such techniques to actual lunar lava tubes remains constrained by the limited availability of empirical lunar seismic measurements specifically associated with known subsurface cavities. This creates a validation problem: numerical and laboratory models can demonstrate that a lava tube should produce a particular seismic response, but the reliability of those signatures under realistic lunar conditions remains insufficiently established. The problem is further complicated by the Moon's heterogeneous crust, strong scattering environment, and limited distribution of seismic instrumentation. Consequently, future investigations should focus on experimentally validating seismic signatures using terrestrial lava-tube analogues and numerical simulations before applying the methodology to lunar exploration. The development of dedicated seismic arrays around suspected lava-tube sites could ultimately provide a complementary means of constraining cavity geometry and depth [36].

Fourth, magnetic methods offer another potentially valuable source of subsurface information but remain limited by instrumentation, spatial coverage, and the complexity of interpreting magnetic anomalies. Terrestrial investigations have demonstrated that lava tubes can produce measurable magnetic anomalies associated with variations in the magnetic properties and thermal history of volcanic materials [43]. Such observations provide an important analogue for lunar exploration. However, transferring terrestrial magnetic-prospecting techniques to the Moon is not straightforward. The magnitude and spatial distribution of lunar magnetic signatures can differ substantially from terrestrial volcanic environments, and effective detection may require high-sensitivity instruments operating close to the surface. The limited deployment of dedicated magnetic surveys on lunar missions therefore restricts the present validation of this technique [43]. Future low-altitude or rover-based magnetic measurements could potentially overcome some of these limitations, particularly when magnetic observations are spatially correlated with optical, topographic, and radar evidence.

Fifth, the detection of a cavity does not necessarily establish that the structure is stable or suitable for exploration. Structural studies have demonstrated that the geometry of lunar lava tubes strongly influences their mechanical stability [37], [26]. Earlier simplified models frequently represented lava tubes using idealized cross-sectional geometries, whereas more recent work has shown that variable cross sections and layered roof structures can substantially influence stress distributions and failure behaviour [37], [38]. These findings reveal an important limitation in current detection-oriented studies: identifying a subsurface void is only one component of the exploration problem. The structural condition of the roof, its thickness, internal layering, geometry, and potential failure mechanisms must also be assessed. Moreover, real lava tubes may contain irregularities, fractures, collapses, and other geological discontinuities that are difficult to represent using simplified numerical models. Therefore, future lava-tube characterization should move beyond simple cavity detection toward three-dimensional structural characterization and stability assessment.

Finally, the absence of direct in situ observations from confirmed lunar lava-tube interiors remains one of the fundamental limitations affecting the entire field. Existing investigations rely heavily on orbital observations, numerical modelling, and terrestrial analogues [25], [39], [43]. Mission concepts such as the Leto concept illustrate the potential value of deploying robotic systems to investigate lunar pits and obtain direct information about their subsurface environments [39]. However, until such observations are obtained, uncertainties remain concerning the actual internal morphology, geological composition, surface conditions, accessibility, and environmental characteristics of lunar lava tubes. These uncertainties also affect assessments of their potential suitability for human habitation, because theoretical models of pressurized lava-tube habitats necessarily depend on assumptions regarding structural integrity and internal environmental conditions [42]. Consequently, habitability assessments should be regarded as prospective rather than empirically validated until direct measurements from lunar subsurface environments become available.

Taken together, these limitations reveal a broader research gap: current lava-tube detection techniques tend to operate independently and provide complementary but incomplete evidence. Gravity can constrain mass deficits, radar can probe subsurface interfaces, seismic methods can potentially characterize cavity-induced wave responses, magnetic observations can provide geological constraints, and optical/topographic data can identify surface expressions. However, differences in spatial resolution, penetration depth, measurement geometry, and uncertainty make it difficult to combine these observations systematically. A promising direction is therefore the development of integrated multi-sensor detection and characterization frameworks in which optical, topographic, gravity, radar, seismic, and magnetic observations are jointly analyzed rather than interpreted independently. Reviews of lunar lava-tube exploration and mission concepts similarly emphasize the importance of integrated exploration architectures and terrestrial analogue testing [25], [41]. Such an approach could improve candidate discrimination, reduce false interpretations, quantify uncertainty, and ultimately provide a more reliable transition from candidate identification to subsurface confirmation and structural characterization.

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