INVESTIGATING THE LUNAR INTERIOR USING LONG-LIVED SURFACE MAGNETOMETERS.
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Introduction: We propose to fly flight-ready Vector Helium Magnetometers (VHM) mounted on a boom to characterize the Moon's interior conductivity and investigate the history of the lunar dynamo. Our magnetometer investigation can be integrated on the ARTEMIS lander, or a commercial lander. Its < 3 kg mass and ~3.5 W average power are compatible with expected resource availability.

JPL built two identical VHMs for the Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE) mission, a technology demonstration mission not currently scheduled for launch. An updated version was recently delivered to CubeSat mission to study Solar Particles (CuSP) for flight on EM-1. The VHM's sensitivity (20 pT/√Hz) and stability (25pT /√Hz) make it ideal for measuring crustal and induced magnetic fields at the lunar surface. To reduce magnetic interference from the Lander, the VHM will be deployed at the end of a boom. A dual vector/scalar version of the instrument (SVHM) has been developed for flight on the Europa Clipper mission, but was descoped from the payload due to accommodation issues. Scalar measurements would add a self-calibrating capability to the instrument, which would be especially important to tie network measurements together and reduce the impact of nuisance fields from the lander.

During operations, the VHM will continuously measure the magnetic field at the lunar surface. If the two ARTEMIS (Acceleration Reconnection Turbulence & Electrodynamics of the Moon's Interaction with the Sun) spacecraft [1] now orbiting the moon remain healthy, as expected by NASA and the ARTEMIS PI (Co-I) V. Angelopoulos, our surface magnetic field measurements can be correlated with data from the ARTEMIS orbiters, enabling inference of a conductivity profile that can be inverted for crustal density and temperature profile beneath the lander.

Demonstrating the VHM technology in the lunar surface environment paves the way for future lunar interior investigations that employ spatially distributed networks of [S]VHM magnetometer 'stations' to characterize lunar interior properties down to the Moon's core, with an order-of-magnitude better accuracy and resolution than the best Apollo data allows. Locally distributed networks can reveal underlying local or regional structures; a globally distributed network can provide global-scale characterization of the lunar interior, bounding models for core formation and evolution. Such networks could be deployed as small landed stations, or placed on the surface by humans.

The current VHM design needs few modifications to be used on any lunar lander. It needs to be repackaged so it can interface mechanically and electrically with the boom and Lander (which could be a commercial lander or the Artemis lander), and its firmware needs to be updated so it can receive commands from the Lander and return data. Many spare components and parts are available for these modifications, along with all needed I&T, calibration, and V&V facilities. Work is ongoing to integrate the VHM into a thermal enclosure being developed at JPL [2] that would allow long-lived operations through the lunar night. Such long-term data sets provide unique insights into the lunar interior.

Science Objectives: The primary science objectives of the investigation would be to characterize the Moon's internal structure, seismic activity, global heat flow budget, bulk composition, and magnetic field. These objectives could be investigated non-invasively with the use of a magnetometer instrument aboard a single lander or network of landers. The magnetic field measurements acquired could be used to better understand the origin and nature of the magnetic fields measured at the surface. These measurements would help provide insight into the thermal evolution of the lunar crust, mantle, and core, as well as the physics of magnetization/demagnetization processes that tend to occur in basin-forming impacts. If selected for integration with the lunar lander, the goals of the investigation are to 1) perform an electromagnetic induction study to investigate the internal lunar composition; and 2) help constrain the timeline of the ancient lunar dynamo.

The interior structure of the Moon provides key constraints on its origin and evolution. Electromagnetic (EM) sounding techniques determine the conductivity profile of the lunar interior providing major insights on its physical properties (e.g., radius of lunar core, [3]) or the allowable mineralogy and temperature profile of the mantle [4]. Although major strides were made using EM during the Apollo era, limitations of those data sets (e.g., zero level drifts for Apollo and its companion Explorer 33) has hampered accurate inversion (see [5] for a modern review). Thus, the lunar core remains compatible with either metallic or silicate composition. Additionally, tens of ppm of H_2O [6] in the lunar interior could also explain the deep mantle conductivity, in lieu of high-alumina pyroxene [7].

Because the Moon has a very thin atmosphere, solar wind plasma is able to strike the lunar surface. The plasma carries the interplanetary magnetic field (IMF) which causes small perturbations of the direction and magnitude of the local magnetic field. Resulting variations in lunar surface fields, which typically range from 1 to 5 nT, could be as high as several 10s of nT [8]. To accurately measure both the crustal magnetic field and the perturbation induced by the solar wind plasma, the required sensitivity of the magnetometer is < 0.1 nT at a cadence of about 0.1 seconds. The required specifications are met by the VHM.

Drift-free VHM surface magnetic field measurements and point measurements from the ARTEMIS orbiters can be used to sound the lunar interior. A broad spectrum of frequencies is available for sounding in the ambient solar wind such as turbulent waves, shocks and other structures. Additionally, for ~4 days each month, the Moon passes into the Earth's geomagnetic tail, consisting of two near-vacuum magnetic lobes, sandwiching a dense sheet of plasma moving at subsonic speeds. This results in very low frequency (50µHz to 50mHz) external drivers, ideal for probing at great depths.

The Moon does not currently have an internally generated magnetic field. However, measurements of crustal magnetism made from orbit by Apollo-era and Lunar Prospector magnetometers and laboratory measurements of rocks from the Apollo missions indicate that the Moon once had an internal self-sustaining dynamo [9] with surface field intensity reaching that of the present Earth (i.e., tens of µT) from at least 4.25 to 3.56 billion years ago (Ga). Following this high-field epoch, the field declined at least an order of magnitude by 3.2 Ga, but then persisted in a weakened state (~5 µT) until at least 2.5 Ga [10]. Measurements of young breccias indicate the field had declined to <0.1 µT by ~1-0.5 Ga, suggesting that the dynamo had ceased by this time [11]. One of the major unknowns about the lunar dynamo is when it ceased, as knowledge of its lifetime would constrain its power source. Only precession and core crystallization are currently thought to be capable of powering a dynamo beyond ~3.4 Ga, while only core crystallization is thought to a viable mechanism after ~0.6 Ga. Establishing which dynamo mechanism operated would constrain the lunar thermal and orbital evolution. A key problem in determining the lifetime of the lunar dynamo is that there are very few Apollo samples with ages younger than 3 Ga. Measurements acquired on surface locations younger than 2.5 Ga could establish whether the dynamo persisted at the time these surfaces formed. There are numerous locations with such young mare scattered around the Moon.

Resources: Table 1 summarizes the VHM's mass, volume, and power requirements. Mass values are based on INSPIRE and CuSP actual values. The INSPIRE and CuSP development activities resulted in a compact instrument with a sensor mass of 95 g and electronics board mass of 380 g (Figure 1). The mass of the boom is 600g and the anticipated thermal mass is estimated to be up to 500g. Total mass of the entire package with cabling and packaging is estimated to be no more than 3kg. The total volume of the electronics is or order 0.5U. The volume of the sensor is ~4cm x 4cm x 5cm and can be housed in the 1U volume that the 0.75m stacer boom occupies. With cabling and packaging, we do not anticipate the volume of the entire unit to exceed 3U. The maximum power is driven by the diode laser thermoelectric control (TEC) – the actual peak power depends on the thermal environment in the chassis, but typically runs at 3.5W. These metrics are not expected to change significantly once the instrument is integrated with the thermal enclosure. Constant operation at the 1s rate would generate up to 4 Mbits per day, which can be downlinked at 1 kbps in just over an hour.

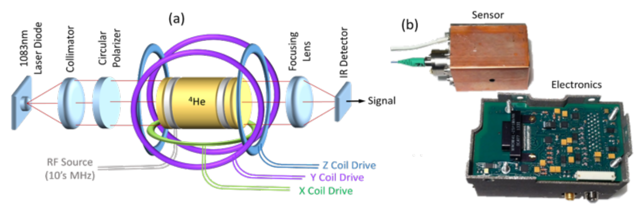

Figure 1. (a) Block diagram of the VHM sensing unit and (b) image of INSPIRE sensor and electronics

Param.	Projected Performance
Range	+/- 2,000 nT
Stability	25 pT over 2 weeks
Sensitivity	20 pT/√Hz
Resolution	4 pT (20-bit vectors)

Param.	Projected Performance
Mass	1.25 kg (with boom)
Power	3.5 W
Volume	1 U (stowed boom)
Cadence	1s (0.1s min)

Table 1. Projected performance of VHM integrated to a short boom.

Acknowledgments: Part of this work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Government sponsorship acknowledged.

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