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Lunar Impactor: Investigating lunar magnetism and swirls with a cubesat

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Abstract

Magnetized 100-km-scale patches of the lunar crust were first observed by the Apollo 15 and 16 subsatellites. Despite several decades of study, the origin of these magnetic "anomalies" remains unknown. Part of the difficulty in determining the origin of these features has been the relatively high altitude of orbiting lunar spacecraft. Ideally, one would send a rover to measure the surface magnetic field, but the costs are prohibitive. Instead, small spacecraft can be sent on low-angle impact-trajectories into the hearts of these features. The spacecraft transmit measurements to the Earth in real-time, until the last milliseconds, enabling measurements at < 100 m altitude. To perform this mission, we have designed a fully-independent 3U cubesat capable of reaching the Moon from geosynchronous orbit. We will describe the mission science, the cubesat design, and a magnetometer for making high-frequency magnetic field measurements.

1. Magnetic anomalies and swirls

Figure 1 shows the horizontal component of the magnetic field at the Reiner Gamma anomaly [1]. The dominant hypotheses for forming magnetic anomalies are either an ancient dynamo that magnetized the underlying rock, or processes related to meteoroid impacts. Determining the origin of these features would have implications for the dynamo history of the Moon and how the Moon fits into the spectrum of planetary magnetism.

Many lunar magnetic anomalies are also correlated with bright markings on the surface, known as "swirls" (Figure 1). The dominant hypothesis for swirl formation is that the solar wind, normally a darkening agent, is being deflected from the underlying surface. However, the actual origin of swirls is unknown. Therefore, a major goal of Lunar Impactor is to also determine the origin of swirls. The result would also have implications for understanding space weathering and solar wind interactions with other airless bodies in the solar system.

Near-surface measurements of the magnetic field at Reiner Gamma would provide important information about the coherence of the underlying magnetization, helping to constrain its origin. In addition, the structure of the magnetic field can help test the solar wind deflection hypothesis, since it is likely the dark inner lanes at swirls correlate with nearly vertical fields, where the solar wind can reach the surface [1]. To perform the necessary measurements, we estimate that impact angles of < 20° from the horizontal are required, with data collected at < 3 km over dark lanes [2]. Ideally, a solar wind sensor would also be flown, but here we focus on a magnetometer payload.

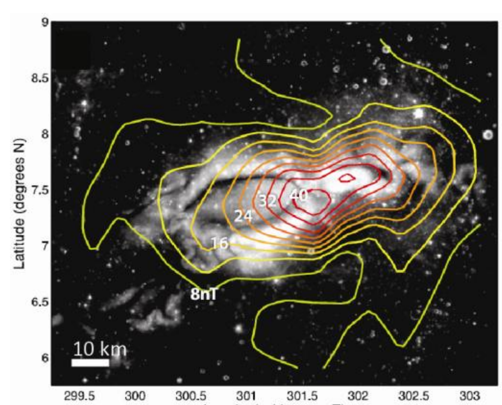

Figure 1: Horizontal component of the magnetic field at 18 km at Reiner Gamma [1].

2. Mission architecture and enabling technology

To obtain near-surface measurements of the magnetic field, we have developed an architecture that sends a 3U cubesat on a low-angle impact trajectory above the surface (Figure 2). During its descent, it transmits measurements in real-time to the Earth up until impact. At impact, the spacecraft velocity is 2 km/s, which places requirements on the instrument measurement frequency (Section 3).

To achieve the impact trajectory, the cubesat is released from geosynchronous orbit (GEO), and spirals slowly to the Moon using a micro-fabricated ion electrospray propulsion system [3] (Figure 3). The system, which has been developed by the MIT Space Propulsion Laboratory, provides nearly 2 km/s of delta-*v* over ~105 days, assuming near-continuous thrusting and body-fixed solar panels with a peak output power of 30 W [2]. Starting from GEO, instead of geostationary transfer orbit, is more expensive, but significantly reduces the radiation exposure, delta-*v*, and flight time (Figure 4). Three-axis attitude control is provided by sets of orthogonal thrusters. In all, < 400 grams of propellant are required, and the total propulsion system volume including electronics is < 1U.

For communication, an X-band omnidirectional antenna and 1 W spacecraft transmitter power provide a downlink rate of 32 kbps with 10.8 dB of link margin, assuming a 34 m Deep Space Network (DSN) ground station [2]. Navigation (Doppler and range) is enabled by a DSN compatible transponder now being developed by the Jet Propulsion Laboratory for cubesats (volume < 0.5U) [4].

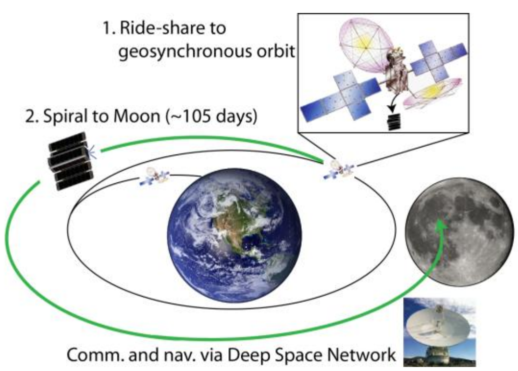

Figure 2: Summary of the mission architecture [2].

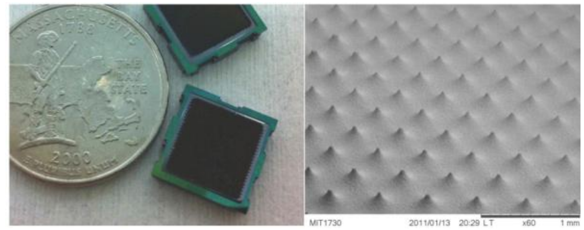

Figure 3: Ion electrospray thruster modules (left) and a close up of individual emitter cones (right) [2].

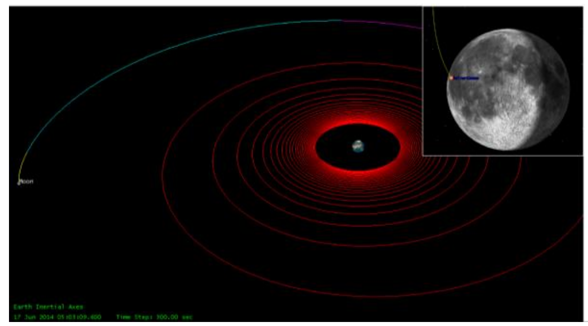

Figure 4: STK simulation of the spiral trajectory to lunar impact from geosynchronous orbit [2].

3. Magnetometer payload

The mission architecture places strong requirements on the spacecraft's primary instrument, the magnetometer. Its mass must be low enough to be compatible with the small size of a cubesat. In addition, if measurements are made every ~10 meters along the flight path, and the impact velocity is ~2 km/s, the magnetometer must be capable of measurements at high frequency (200 Hz).

Imperial College London has developed a magnetometer that can satisfy these requirements. The sensor is based on anisotropic magnetoresistance (AMR), which exhibits high detectivity in the DC-100 Hz range due to its low 1/*f* noise characteristics. Noise levels can be as low as 30 pT/√Hz at 1 Hz, which is competitive with top end fluxgates (<10 pT/√Hz at 1 Hz) [5]. In addition, AMR sensors maintain excellent sensitivity with increasing frequency, unlike fluxgates which tend to roll off sharply above 100 Hz. The instrument contains two tri-axial AMR sensors (based on the three single axis HMC1001 sensors from Honeywell Inc., Figure 5), with one triad mounted on the electronics card, and the other designed for mounting at a remote location (e.g. on a boom) and connection to the electronics via a lightweight harness (Figure 6). This design is currently flying on the CINEMA cubesat [6], and similar technology is flying on the Tatiana-2 spacecraft.

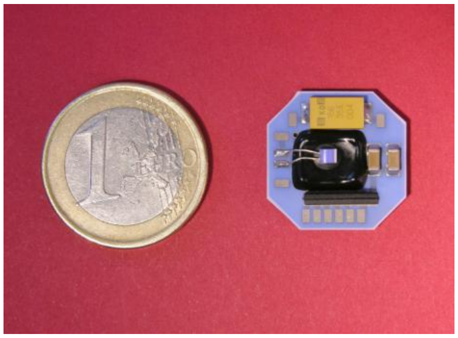

Figure 5: Photo of the hybrid magnetoresistive sensor.

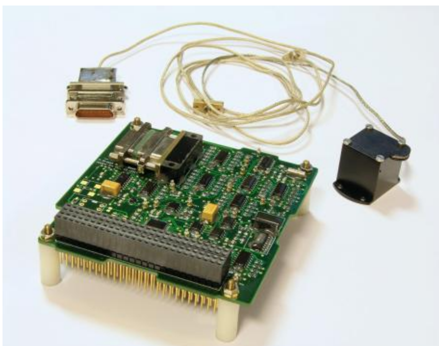

Figure 6: The CINEMA magnetometer (MAGIC), composed of a PC104 card and hybrid sensor connected by a 1 m harness.

For the Lunar Impactor mission, we anticipate a boom length of order maximum 15 cm, which will place the sensor closer to the bus than on CINEMA (where the sensor is 1 m away from the platform). If a boom is not possible we may consider arrangements of multiple sensors, which could be used in a differential mode to reject background noise and isolate the lunar signal. Some modification to the electronics is required to increase the measurement cadence from the current 10 vectors/s up to 200 vectors/s. However, this is not expected to be significantly complex, requiring only some modification to the demodulator and associated filter blocks. Ranging is not likely to be required. In the CINEMA design using a 24 bit ADC filtered to 19 bit transmission we achieve 0.25 nT digital resolution in a single ±55,000 nT range, which will be more than enough for lunar field studies (a maximum field range of ±10,000 nT will be easily sufficient). Radiation susceptibility of the externally mounted sensors is not anticipated to be a problem, as the HMC1001 sensors do not show significant degradation of sensitivity in radiation dose testing [7].

In all, the magnetometer package will have a mass < 150 grams, require < 0.5 W of power, and have a sensitivity < 2 nT.

4. Conclusions

The propulsion, communication, and navigation hardware are expected to be ready for flight for this mission profile in less than two years. The significant challenges that remain include long-duration testing of the electrospray thrusters, approaches to radiation tolerance, in-depth studies of the trajectory, and details of the navigation procedures.

While the 3U Lunar Impactor platform can provide first-of-a-kind measurements of lunar magnetism, it is also a versatile platform capable of other near-Earth missions, such as investigations of the magnetosphere and close-approaching asteroids.

References

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