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Detection of Lunar Lava Tubes with Orbiting Radar Sounder Systems

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Abstract

Lunar lava tubes are subsurface structures which are potential candidates for future human outposts on the Moon. Recently, remote sensing observations of the Moon based on optical cameras and gravitational field mapping have detected features which can be directly related to the presence of lava tubes. However, the potential for global lava tubes mapping using these types of sensors is very limited. In order to accurately detect lava tubes it is necessary to perform direct subsurface measurements of the shallow lunar subsurface. This can be done by radar sounders which are electromagnetic instruments specifically designed to detect and classify subsurface features from orbit. However, past Moon radar sounder missions were not aiming for for lava tubes exploration, and had thus limited capability to detect them. In this paper, we have studied the optimal type of orbiting radar instrument that would be needed to detect the majority of lunar lava tubes, based on their expected properties. To define this instrument, we conducted both a performance assessment versus different parameters of the radar sounder and an electromagnetic signature analysis to determine the possibility to detect lava tubes having different sizes from orbit.

1. Introduction

Lunar lava tubes are considered to be one of the main candidates for future human outposts [1] as they can offer shelter against meteorite impacts, radiation, and strong thermal variations taking place on the Moon surface. They are natural subsurface conduits which are the result of past volcanic activity. Recent studies based on gravity measurements [2] and experimental evidence based on terrain mapping cameras [3] suggest that there is an abundance of lava tubes scattered across the Moon. However, lava tube mapping with an optical camera has limitations due to the fact that they are essentially subsurface structures. In this context, spaceborne radar sounder instruments are particularly suitable for revealing the presence of lava tubes due to their ability to remotely probe the subsurface of a planetary body. By analyzing the electromagnetic characteristic of the echo signals received by a radar optimized for lava tube detection we expect that it is possible to infer the physical composition of a lava tube, its size and shape as well as the nature of the material forming the lava tube roof and floor.

Very recently, researchers detected in the data acquired by the Lunar Radar Sounder (LRS) an intact lava tube [4]. On the one hand this confirms the capability of sounders to detect lava tubes. On the other hand, LRS has not been specifically designed for the detection of lava tubes. Thus, due to its very low carrier frequency (and thus spatial resolution), it can only detect very large lava tubes. Accordingly, the detection of small and shallower lava tubes appears to be very unlikely with LRS. Moreover, shallow lava tubes are of high importance since it is easier to explore them either by manned and unmanned missions.

In this paper we present a study for the design of an orbital radar sounder optimized for detecting lunar lava tubes of various dimensions. This is done by providing a detailed perfomance analysis versus different radar parameters. Our analysis is complemented by extensive simulations of the lunar lava tubes electromagnetic responses by means of a 3D coherent multilayer radar echo simulator. In our study, the allowed lava tube sizes in terms of roof height and width are those provided in the recently published structural stability analysis by Blair et al. [2]. Accordingly, structurally unstable lava tubes have not been considered in our analysis.

2. Radar Sounder for Lava Tubes Detection

The study on a radar sounder for lava tubes detection was performed considering realistic parameters such as the ones on orbital configuration of the spacecraft and transmitted power by taking into account the heritage of previous radar sounding missions. Regarding the surface and subsurface parameters, we assumed a representative yet challenging scenario which implies a large radar signal attenuation. To this extent, we considered a regolith mantling layer covering the lava tube roof of variable thickness and consisting of basaltic material. The lava tube floor is considered basaltic as well. The analyses on Signal to Noise Ratio (SNR) and Signal to Clutter Ratio (SCR) highlight that the main driving factor affecting the radar performance is the attenuation of the radar signal for fixed subsurface properties in terms of complex dielectric constant. It mainly depends on the lava tube roof height and on the radar central frequency. The capability to detect lava tubes with thin roof improves as the radar central frequency increases due to larger achievable radiated pulse bandwidth resulting in improved range resolution. The same behavior is found for the detection of lava tubes with small widths as horizontal resolution improves by increasing the central frequency. The detection of lava tubes having large roofs degrades as the central frequency increases due to attenuation in

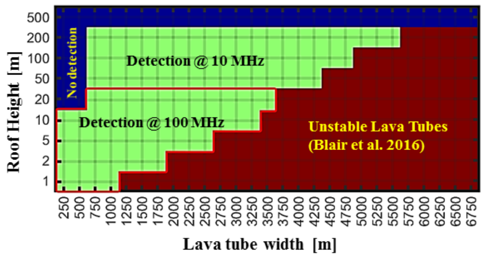

Figure 1: Detectable lava tubes matrix with dual carrier frequency sounding (10 MHz and 100 MHz).

the medium. By combining all these observations, we are naturally led to the conclusion that a radar sounder operating with a low central frequency (e.g. 10 MHz to 20 MHz) is suitable for detecting large lava tubes while a system with higher frequency (e.g. 80 MHz to 100 MHz) is suitable for detect small ones. Consequently, a multi-frequency radar sounder is needed to map the vast majority of stable lava tubes in terms of dimensions, as shown in the example of Fig. 1. The detection matrix is displayed in the same fashion as the structural stability one presented in [2].

3. Electromagnetic Signatures of Lava Tubes

We have analyzed the radar returns for different lava tubes geometries using a coherent 3D simulator we developed. The simulations were performed for different radar system parameters and for different crossing angles of the sensor over the investigated scene. Four representative lava tubes were selected, with dimensions based on the stability analysis of [2]: $w = 4000\,\text{m}$, $h = 200\,\text{m}$; $w = 3000\,\text{m}$, $h = 10\,\text{m}$; $w = 1250\,\text{m}$, $h = 50\,\text{m}$; and $w = 250\,\text{m}$, $h = 1\,\text{m}$, where w represents the lava tube width and h the roof depth. Simulations the surface terrain and the target lava tube were carried out at two different central frequencies, 10 MHz and 100 MHz. The bandwidth was set equal to half the central frequency in both cases. Procedurally generated fractional brownian motion surfaces were used to reproduce the lunar surface topography and subsurface roughness.
The electromagnetic simulations confirmed the conclusions of the performance analysis and were able to provide realistic examples of lava tube electromagnetic signatures acquired from lunar orbit with a dedicated radar sounder system. Electromagnetic signatures of small lava tubes are generally made of two vertically-aligned hyperbola sections, one for the lava tube roof and one for the lava tube floor. Large lava tubes show thicker and more linear contributions when compared to small ones (see Fig. 2) due to the wider scattering area.
Because of the relatively strong attenuation in the material composing the lava tube roof, the deeper lava tubes were only visible by the lower frequency

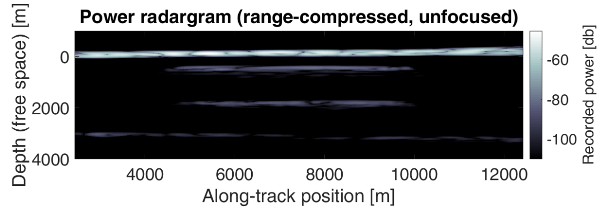

Figure 2: Example of simulated signature for a Moon lava tube with a width of 4 km and a roof height of 200 m as seen by a radar with a central frequency of 10 MHz and a bandwidth of 5 MHz. The sensor crossing direction is perpendicular to the lava tube axis. The fBm surface parameters are $H = 0.75$ and $T = 355\,\text{m}$.

radar. On the other hand, the upper hyperbola of the shallower lava tubes could be unambiguously distinguished from the surface return only with the high-frequency radar. The difference in signal intensity between the returns from lava tube roof and floor was never more than a few dBs in all cases, as it is only due to geometrical effects (there is no attenuation in the lava tube cavity).

4. Summary and Conclusions

Recent evidence based on optical camera surveys and gravity measurements suggest that there is a considerable number of lava tubes concealed under the surface of the Moon. In this paper we investigated the feasibility of detecting them from orbit with a radar sounder specifically designed for this task. To this extent, our performance analysis shows that a multi-frequency sounding system is the best option for detecting lava tubes of very different dimensions. The electromagnetic simulations show that lava tubes have unique electromagnetic signatures, which can be detected from various crossing configurations of the sensor when orbiting over the lava tube.

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