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A multi-frequency radar sounder for lava tubes detection on the Moon: Design, performance assessment and simulations

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ABSTRACT

Lunar lava tubes have attracted special interest as they would be suitable shelters for future human outposts on the Moon. Recent experimental results from optical images and gravitational anomalies have brought strong evidence of their existence, but such investigative means have very limited potential for global mapping of lava tubes. In this paper, we investigate the design requirement and feasibility of a radar sounder system specifically conceived for detecting subsurface Moon lava tubes from orbit. This is done by conducting a complete performance assessment and by simulating the electromagnetic signatures of lava tubes using a coherent 3D simulator.

The results show that radar sounding of lava tubes is feasible with good performance margins in terms of signal-to-noise and signal-to-clutter ratio, and that a dual-frequency radar sounder would be able to detect the majority of lunar lava tubes based on their potential dimension with some limitations for very small lava tubes having width smaller than 250 m. The electromagnetic simulations show that lava tubes display an unique signature characterized by a signal phase inversion on the roof echo. The analysis is provided for different acquisition geometries with respect to the position of the sounded lava tube. This analysis confirms that orbiting multi-frequency radar sounder can detect and map in a reliable and unambiguous way the majority of Moon lava tubes.

1. Introduction

In the last years, there has been a renewed interest in the exploration of the Moon. Our satellite is a potential strategic outpost with significant raw materials reserves (Crawford, 2015). Lunar lava tubes are considered to be one of the main candidates for a future human outpost (Horz, 1985). They are natural subsurface conduits which are the result of volcanic activity (Greeley, 2013). A lava tube is formed when the upper part of a given lava stream cools down and crusts while the lower part of it continues to flow, which results in the formation of an empty cave.

Moon lava tubes are considered to be important and useful structures since they can offer shelter against meteorite impacts, radiation (De Angelis et al., 2002) and strong thermal variations taking place on the Moon surface (Horz, 1985). Recent studies based on gravity measurements (Blair et al., 2017; Chappaz et al., 2017) and experimental evidence based on terrain mapping camera (Arya et al., 2011; Haruyama et al., Ohtakeet al) suggest the hypothesis that there is an abundance of lava tubes on the Moon and their dimensions are consistently larger than the ones found on the Earth. The main reason for their large size, is that the Moon gravity is considerably lower than the terrestrial one.

A complete map of the lava tubes dimension and location will provide important information in view of the exploration and colonization of the Moon. However, the mapping of lava tubes with optical camera has limitations. This is due to the fact that lava tubes are essentially subsurface structures. Radar observations at 70-cm wavelength of the region near Bessel crater in Mare Serenitatis show dark-radar lineaments. This can be interpreted as locally deeper regolith filling voids which might be collapsed portions of once subsurface lava tubes (Campbell et al., 2014). Unfortunately, radar waves at centimeter scale cannot penetrate through the regolith.

Planetary radar sounders instruments are low-frequency spaceborne ground penetrating radars which are particularly suitable for revealing the presence of lava tubes concealed under the Moon surface. Their signal wavelength is in the order of metres. These types of instruments are capable of transmitting pulsed electromagnetic energy and recording any reflection generated by dielectric discontinuities in the target terrain. In particular, by analysing the electromagnetic characteristic of the echo signals generated from both the Moon surface and subsurface, it is possible to understand the physical composition of the lava tube (*e.g.*, whether it is empty or not), its size and shape and the nature of the material forming the lava tube roof and floor.

Two radar sounding missions already probed the Moon surface,

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NASA's Apollo lunar radar sounder experiment (ALSE) and JAXA's LRS instrument onboard the Kaguya spacecraft (Porcello et al., 1974; Ono and Oya, 2000) but they were not specifically designed for lava tubes detection. Very recently, an intact lava tube was detected in the data acquired by the Lunar Radar Sounder (LRS) (Haruyama et al., 2017). On the one hand, this confirms the potentiality of sounders to detect lava tubes, but on the other hand, LRS has not been specifically designed for the detecting them. Thus, due to its very low spatial resolution (due to a relatively small carrier frequency), it can only detect very large lava tubes. A recent paper has nevertheless highlighted the possibility of detecting lava tubes of sub-resolution size (LRS resolution is 75 m) (Kaku et al., Yokotaet al). However, in the paper there are two different interpretation of the lava tube detection results namely (i) the lava tube roof echo is buried in the surface response or (ii) the lava tube echo floor is buried in the roof radar echo. A dedicated, higher-frequency radar, however, would be able to make more conclusive detections of such small and shallow tubes, which are of special importance since they are easier to explore either by manned or unmanned missions.

Sood et al. (2016). highlighted the scientific value of a radar sounder mission specifically designed for lava tubes detection. However, they did not provide an assessment analysis on how an hypothetical sounder system will be able to perform for this specific task and how to interpret the returning data. The studies performed on terrestrial lava tubes with ground penetrating radar (Miyamoto et al., Crownet al; Rowell et al., 2010; Olhoeft et al., 2000) are of marginal relevance in terms of system design for the planetary radar sounding case. This is due to the very different acquisition geometry and very different radar system technological implementations.

This paper addresses the problem of detecting lava tubes on the Moon from orbit by using radar sounders. To this extent, the main goals of this paper are (i) the understanding of the design requirements that the sounding system should have for effective lava tube sounding, (ii) a performance assessment as function of the radar, geometric and terrain parameters and (iii) extensive simulations and analysis of the lunar lava tubes electromagnetic responses. The evaluation of the electromagnetic signatures is needed for providing a better understanding of the potential recorded data and thus greatly aiding its scientific interpretation. In our analysis, the allowed lava tube sizes are the ones provided in the recently published structural stability analysis based on gravity measurements presented by Blair et al. (2017), which also envelopes the lava tube sizes provided by Coombs et al. (Coombs and Hawke, 1992).

The remainder of the paper is organized as following. Section 2 introduces the acquisition geometry and the subsurface structure assumptions. This serves as a basis for the performance analysis and lava tubes detectability results of Section 3. Section 4 presents the lava tubes electromagnetic signature analysis for different scenarios. Finally, Section 5 addresses the conclusions of this paper.

2. Radar sounding acquisition geometry and subsurface structure assumptions

In this section, we introduce the radar sounding geometry and the main assumptions regarding the Moon's lava tubes structure. This forms the basis for the next sections of the paper.

Let us consider a radar sensor with carrier frequency assumed to be in the range between 1 MHz and 100 MHz positioned at certain height h from the surface as shown in Fig. 1. We define a coordinate reference system composed by three orthogonal axes which are denoted as (i) along-track (*i.e.*, in the direction of the sensor movement), (ii) across-track (*i.e.*, in the direction orthogonal to the sensor movement) and (iii) height/depth direction (which is perpendicular to the other ones previously defined).

We consider the surface substrate to be covered by a regolith layer with average thickness denoted as r_t. We assume the base of the regolith (*i.e.*, the interface between the regolith and the substrate) to be rough. The slope of this rugged base is poorly constrained in the literature. The best piece of evidence available for estimating its order of magnitude (at least in Maria regions) is an optical image of the regolith base on Rima Hadley at Apollo 15 landing site (Howard et al., 1972) and the pit rims features exposing layered walls of basalt below the regolith (Robinson et al., 2012). Such optical clues suggest that the regolith base relief is in the order of metres. This is also suggested by the earth-based radar mapping observations at 70-cm wavelength scale (Campbell et al., 2014). Due to this uncertainty, we follow the same approach described in (Fa et al., 2011), where the base of the regolith roughness is assumed to be of the same magnitude as the one measured by the Lunar Orbiter Laser Altimeter (LOLA) (Rosenburg et al., Zuber). A given lava tube is geometrically described by (i) its depth of the roof, denoted as h_r, (ii) its width, denoted as w, and (iii) its height, which is set equal to $w/3$. These assumptions are based on the structural analysis of Blair et al. (2017). The work by Coombs et al (Coombs and Hawke, 1992). on lunar rilles suggests lava tubes of dimension far smaller than the possible maximum dimension specified by Blair et al. (2017). In any case, the numbers given in (Coombs and Hawke, 1992) are covered by the provided lava tube dimensions in (Blair et al., 2017) and therefore included in our analysis.

The length of a lava tube is not specified and it is assumed to be in the order of kilometres (Horz, 1985; Coombs and Hawke, 1992). For what pertains the surface and subsurface materials we denote as ε_1, ε_2 and ε_4 the real part of the dielectric constant of the regolith, the lava tube roof, and lava tube floor (*i.e.*, cave bottom), respectively. The dielectric constant of the cave interior ε_3 is assumed to be the one of vacuum and is thus equal to 1.

3. Radar sounder design and lava tubes detectability analysis

In this section we study the requirements on the parameters of a radar sounder for detecting lava tubes and perform an analysis of the expected performances and detection capabilities. In Subsection 3.1, we assess the regolith contribution to echo power losses. Subsection 3.2 discusses the different resolution parameters. In subsection 3.3 the model for the echo power received by the lava tube is presented. Subsections 3.4 and 3.5 are devoted to the assessment of the signal-to-noise ratio (SNR) and signal-to-clutter ratio (SCR), respectively. Finally, Subsection 3.6 illustrates the results on the lava tube detectability by combining the analyses presented in the previous sections of this chapter. The final assessment provides information on whether a lava tube with given width and depth of the roof can be detected as a function of the probing central frequency.

3.1. Assessment on the regolith contribution to echo power losses

Radar sounders propagation losses are classified in three different types namely (i) geometric losses due to the radial distance between the target and the sensor, (ii) attenuation losses induced by the terrain electric properties, and (iii) scattering losses due to heterogeneous inclusions in an otherwise homogeneous medium. In this section we investigate the impact of lunar regolith on both the attenuation and scattering losses, as well as on the dispersion of wide bandwidth waveforms.

Lunar surface is covered by a mantling layer composed of fragmented heterogeneous material denoted as regolith. Its average thickness is estimated to be 5 m in Maria regions and 12 m in Highland regions (Shkuratov and Bondarenko, 2001). Being formed by an ensemble of objects (*e.g.*, rocks) of various sizes and shapes, they could potentially give rise to volume scattering phenomena. In general, for longer wavelength the scattering mechanism is dominated by the base of the regolith, whereas, for shorter ones, scattering on and within the regolith is an important factor contributing to losses (Campbell, 2002). Let us analyse a scenario of a regolith with thickness $r_t = 8.5$ m (*i.e.*, global average over the Moon surface) and rock inclusion modelled as dielectric spheres of radius comprised between $0.6\lambda/(2\pi\sqrt{\varepsilon_1})$ and $10\lambda/(2\pi\sqrt{\varepsilon_1})$ where $\varepsilon_1 = 2.7$ is the average dielectric constant of the soil enclosing the rocks (Shkuratov and Bondarenko, 2001; Olhoeft and Strangway, 1975) and λ