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Deployment of a communications network to explore a Lunar cave

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Abstract

Lunar caves are subterranean wide and long tubes that could potentially host a human base. These caves are expected to be stable, with small temperature variations and they can protect the base from micrometeorites. The entrance to these tubes, known as pit or skylight, is a small collapse with cliff-like vertical walls.

In this work, the deployment of a communication network is developed: from the pit to the unexplored zone inside the cave. An ad hoc communication network with multiple nodes is foreseen. In order to estimate the data rate of the total communication link, a propagation model has been developed, considering ground, walls and ceiling echoes. This model has been experimentally validated in Earth lava caves in Lanzarote (Spain), for different ground roughness. The measurement campaign has demonstrated that an increment of a few metres in the antenna height can increase the link distance up to 200 metres, due to the positive interference of the ground echo. Moreover, non-line of sight scenarios, like bends and small slopes have been analysed to estimate the increment of the propagation losses.

From this propagation model, the total network behaviour has been analysed. The network shall maximize the coverage distance of the communication link, while remaining a total data rate greater than 25 Mbps. It must be taken into account that a decrease in data rate occurs with each hop between nodes. The geomorphology of the cave and the robotic capabilities have been considered to define network and operation requirements.

Keywords: Lunar caves, communication networks.

Acronyms/Abbreviations

Line of Sight (LOS)
Lunar Reconnaissance Orbiter (LRO)
Mobile ad-hoc network (MANET)
Received Signal Strength Indicator (RSSI)

1. Introduction

On the surface of the Moon there are small collapses with cliff-like vertical walls, known as pits or skylights [1] [2]. Recently, thanks to radar images of the Mare Tranquillitatis pit [3], it has been demonstrated that this collapse provides access to cave conduits with extensive underground volumes. Besides this pit, more than 200 skylights have been identified in numerous locations on the Moon. Lunar caves are potential human settlements, due to their protection to micrometeorites bombing and their stable temperature, around 17 ºC. Exploring these types of lunar caves presents several challenges. Indeed, the European Space Agency launched a campaign for novel ideas at system level to resolve some of these challenges.

It seems clear that the mission will be carried out by a fleet of robots. These robots will have to overcome numerous rocky obstacles, scan both the pit and the cave, and obtain scientific information and send it back to Earth from inside the tube. The best strategy to explore a lava tube is a *mobile ad-hoc network* (known as MANET). In MANETs, all the robots act as relays, so a multi-hop connectivity is established. That is, data packets travel from one robot to another until they reach their objective. A strong coordination between robots shall be developed in order to have connection at every moment.

In this work, the study of the communication system of the robot fleet has been studied in order to ensure a minimum data rate of 25 Mbps. This study is based on the analysis of the cave morphology and on a propagation model validated in lava caves in Lanzarote. Moreover, requirements for this communication system are identified.

2. Propagation Model

2.1 Cave morphology

Estimating the dimensions of the lunar pits and the size of the tubes is important in the context of planning an exploring mission in their interiors and vicinities. Lunar caves are expected to be stable structures much bigger than Earth caves, with a width between 50 and 300 metres and several kilometres long.

Fig. 1 shows a side view sketch of a skylight based on Lunar Reconnaissance Orbiter (LRO) images [3] and on Earth lava pits (Fig. 2). Lunar pits feature a tilted funnel along all or almost their entire circumference, extending inward from the surrounding surface to a nearly vertical wall. The collapse may have a diameter between 20 and 300 metres, with a height between 50 and 200 metres.

In general, the floor of the pit appears to be a collection of blocks of different sizes. The current reconstruction of floor morphology is too uncertain to identify topographic details at scales smaller than ∼20 − 30 metres, although blocks up to 2 metres of diameter can be identified.

The latest discoveries confirm the possibility that there is a cavity connected to the pit via a slope of about 45º. This tube-shaped cavity can be more than 50 meter wide and several kilometres long.

2.2 Image model

Three different propagation links can be identified in Fig. 1. On top of the lunar pit, a rover acting as a base station between the mission control and the robot fleet is foreseen [4]. This rover will establish a vertical link with the explorer robots on the pit floor. One of these explorers will act as a relay, placed at the entrance of the cave and giving coverage to the robots inside the cave. Two different propagation links can be defined here: one between the robot on the pit floor, in a higher elevated position, and the robot inside the cave, and the other when both robots are inside the cave.

A model based on image theory will be used as a first approximation to the estimation of the received power in the third propagation link, that is, between two robots inside the cave. It is a very simple model accounting only for reflections on the ground, ceiling and both side walls. Furthermore, all the surfaces are assumed to be flat. Nevertheless, it is useful to get a first impression of the effect of the floor and walls, and to try to figure out which would be the most suitable propagation model to use initially for a worst-case link balance.

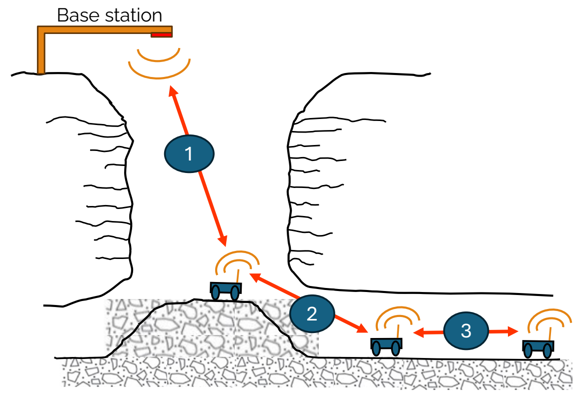


Fig. 1. Possible model for a lunar skylight and cave conduit.

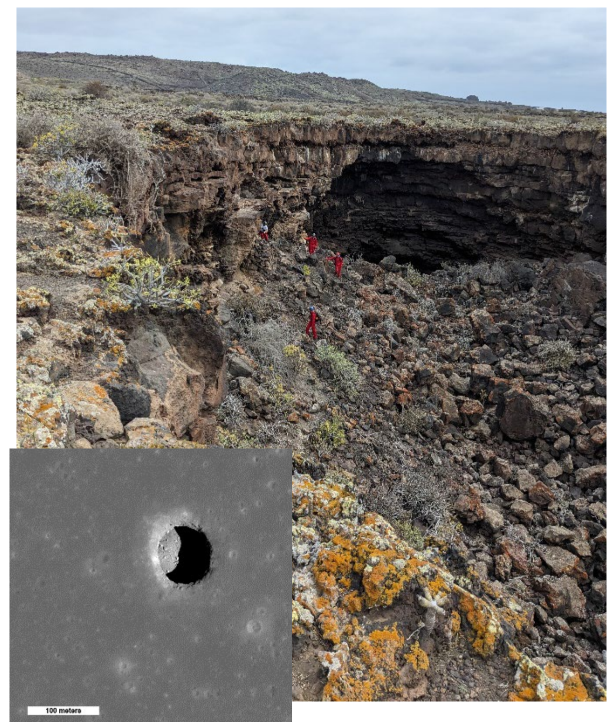


Fig. 2. Jameo de la Gente (Lanzarote) and Marius Hill Pit

3. Experimental Results

Two set of tests have been carried out in analogue caves in Lanzarote, specifically in Los Naturalistas cave, (14 m width × 4 m high), see Fig. 3, and in La Corona lava tube (7 m width x 5 m high), shown in Fig. 4. Measurements were carried at two different frequencies, 2.4 and 5 GHz, and antennas were placed at 35 cm above floor level.

Fig. 3. Naturalistas cave (Lanzarote).

Fig. 4. La Corona lava tube (Lanzarote).

3.1 Received Signal Strength tests

Into the caves, the image model was applied considering four images, to account for simple reflections on ground, ceiling and walls. The geometrical model consisted of flat, smooth surfaces, electromagnetically characterized by their relative permittivity and conductivity. In practice, however, the possible roughness of the surfaces will generate a diffuse reflection phenomenon, which will decrease the reflectivity in the direction of the main beam. The irregularities in the surface can be taken into account considering the height of the irregularity Δh, and the angle φ between the incident ray and the mean surface [5]. Then, the quantity g is defined, which represents the phase difference between the path without and with irregularity,

$$g = \frac{4\pi \Delta h sin\varphi}{\lambda} \quad (1)$$

being λ the wavelength at the frequency of interest. Then, the reflection factor of the surface will be multiplied by a factor ρ_f given by

$$\rho_f = exp\left(-{}^1/_2\, g^2\right) I_0\left({}^1/_2\, g^2\right) \quad (2)$$

where I_0 is a modified Bessel function of order zero.

Fig. 5 and Fig. 6 show some results at 2.4 GHz in Naturalistas cave and La Corona respectively.

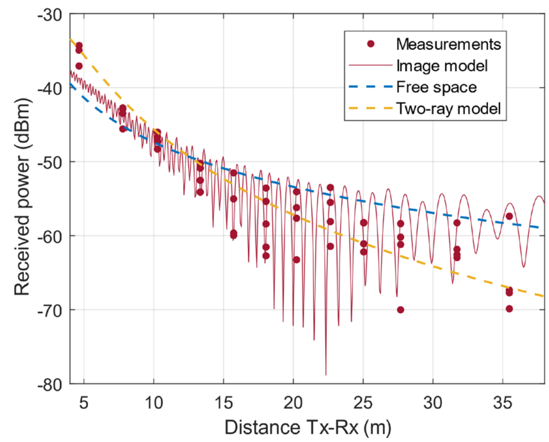


Fig. 5. Measurements in Naturalistas cave (2.4 GHz) and comparison with propagation models.

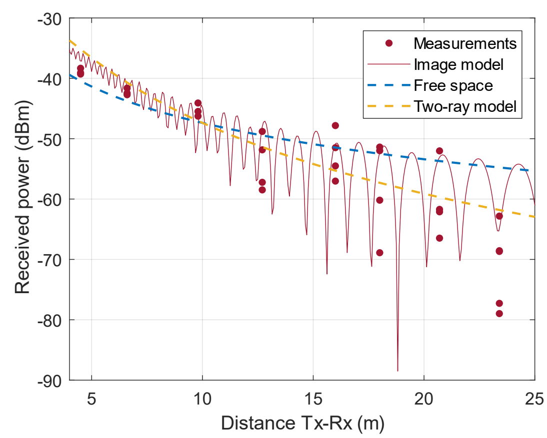
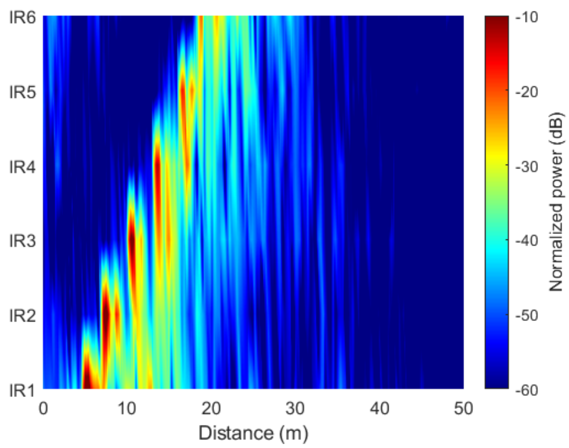


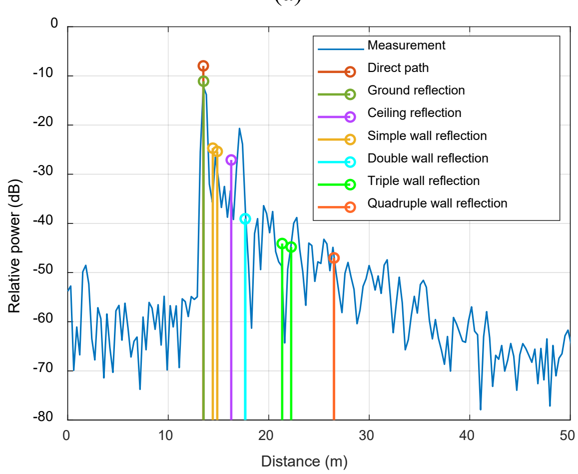
Fig. 6. Measurements in La Corona tube and comparison with propagation models.

3.2 Impulse Response tests

Frequency responses were measured under Line of Sight (LOS) conditions in both caves for different distances between the transmitter and the receiver, and measurements were processed to obtain the channel impulse response. In both caves, similar conclusions have been extracted. Fig. 7(a) shows the six impulse responses (IR1 to IR 6) measured in La Corona. It can be seen that there is a clear dominant path for all the measured positions and the relevant presence of reflection on walls after this main path. The dominant path will be the sum of the direct path, and the ground reflected path, since this cannot be resolved due to its proximity to the direct one. Fig. 7(b) shows the estimation given by the image model for one of the measures. In this case, multiple reflections on walls have been included in the model. Due to their low amplitude, double and higher effects are not relevant when estimating the RSSI (Received Signal Strength Indicator), but they will be in the estimation of the wideband parameters of the channel (delay spread, coherence bandwidth) form the impulse response.



(a)



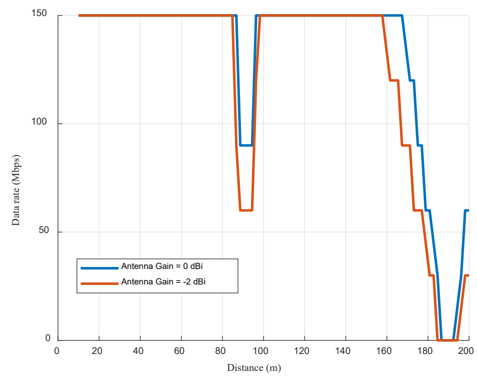
(b)

Fig. 7. Measurements in La Corona lava tube. (a) impulse responses, (b) comparison of measurements and image model.

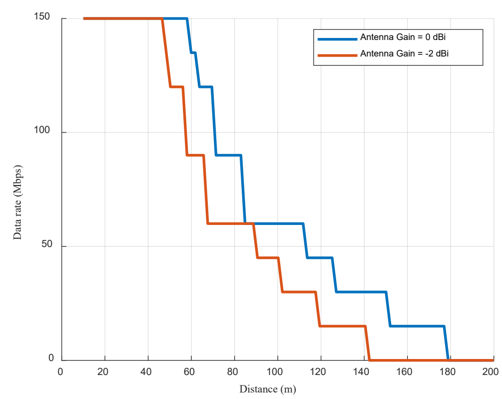
4. Link Budget Analysis

Based on this model, a link budget analysis has been carried out. In this analysis, omnidirectional antennas and a low power consumption Wi-Fi network card [6] has been taken into account.

Fig. 7.a. shows the data rate for a possible link when an explorer acts as relay on top of the collapse and the other robot is exploring (link 2). This location allows a wider coverage than the situation when both robots are at the same height (as in link 3).



(a)



(b)

Fig. 8. Data rate of a Wi-Fi link, (a) when one of the robot is at a height of 30m. and (b) both antennas of the robots are at the same height (30 cm).

5. Communications system requirements

Finally, some system requirements have been identified. Some of them are similar to requirements for rescue in disaster areas [7,8].

- The network must provide and maintain essential services under adverse conditions as well (resilience requirement).
- Mobile nodes facilitate the deployment and redeployment of the network, making it possible to tailor the network topology to the incident zone conditions. Moreover, the positions of the nodes can be modified to improve network performance (mobility requirement).
- Any robot shall act as a communication relay.
- The communication subsystem shall have an algorithm capable to monitor the link quality.

6. Conclusions

The habitat in a lunar cave is a real possibility for human settlement. To explore these caves, a stable communication network among robots must be deployed. In this work, a propagation model for caves has been developed. This model has been validated in lava caves similar to lunar caves. Thanks to this model, the link budget has been analyzed for various situations. The most advantageous situation, that is, the one that provides the greatest coverage, occurs when one of the exploring robots is positioned on top of the collapse, acting as a link between the rest of the robot fleet and the base station at the cave entrance. To achieve this, the robots must be able to estimate the quality of the communication link to avoid getting left out the coverage area.

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