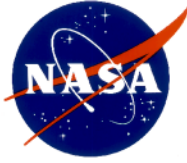# Pisgah Lava Cave Communication Test
*Science Case Study for the
Networked Constellations Initiative*

K. Belov
D. Ellison
A. Fraeman
Jet Propulsion Laboratory

CONTENTS

1   INTRODUCTION

As part of the science case study for the Networked Constellations initiative, a team of JPL scientists explore the possibility of a mission to study the lava caves on Mars. Natural caves on Mars and the Moon present a unique opportunity to learn about the planetary geology and to provide a shelter for human explorers. Due to power and communication challenges, a network of assets has significant advantages over a single asset sent inside a cave.

However, communication between the assets and the data downlink present significant difficulties due to the presence of rough walls, boulders, and other obstacles with unknown dielectric constant inside a typical cave, disturbing the propagation of the radio waves. A detailed study is needed to establish the limitations of the current communication technologies and to develop requirements for the new communication technology applicable to the cave environment.

On May 4 of 2017, Konstantin Belov, Doug Ellison, and Abby Fraeman visited a lava cave in Pisgah, CA. The purpose of the visit was to build a 3D map of the cave, which could be used to create a model of radio wave propagation, and to conduct a series of communication tests using off-the-shelf equipment to verify the in-cave communication challenges. This experiment should be considered as a simple "proof of concept" and is the subject of this report.

2   EQUIPMENT

The following equipment was used during the test:

- Netgear R7000 2.4/5 GHz router
- USB3 portable hard drive
- Li-ion 44 Wh rechargeable battery
- Different antennas tuned to 2.4 and 5 GHz bands
- MacBook Pro laptop
- Different antenna adapters

The Netgear R7000 is a robust flexible network router supporting 2.4 and 5 GHz WiFi bands. It has 3 antennas, allowing us to change the signal polarization if needed, as well as a USB3 port to connect the external storage. We used a traditional spinning USB3 hard drive with 1 TB capacity. The power to the router and the attached hard drive was supplied by a 44 Wh Li-ion rechargeable battery. The battery has a standard 12 V outlet socket and a cable with the standard 12 V plug. The router is rated at 3.5 A max current at 12 V. No modification to the battery, the router, or the power cable was needed. The battery was able to supply the power during the whole duration of the test, which lasted more than 5 hours.

Although several additional antennas were available for the test, the limited manpower combined with the difficult terrain inside the cave made switching the antennas cumbersome, and only the standard antennas were used for most of the experiment.

The router with the attached hard drive powered by the Li-ion battery formed one communication station, while a MacBook Pro laptop was used as the second station for the experiment. The stations were placed at different locations inside the cave and the two tests were conducted at 2.4 and 5 GHz frequencies at each location: 1) a ping test to check for the packet loss, and 2) a data speed transfer test. The total of 14 locations were tested.

3 RESULTS

The results of the tests together with the description of the signal paths are summarized in Table 1 below. The distances between the checkpoints are shown in Table 2, while the map of the cave with the checkpoints marked is shown in Appendix A. The following are some examples of the tests conducted:

3.1 TEST 1

The router was placed at Checkpoint E, under the cave ceiling between the first and second room (see Figure 1). Two 5 GHz chip antennas were connected. Since only two such antennas were available, the router's third antennas input was terminated by a 50 Ohm plug. The laptop was located 4 m from the router in direct field of view. The communication was established initially at 5 GHz, but then the connection was lost.

After changing the antennas back to the standard ones, it was decided to conduct the rest of the tests with the standard antennas because the more advanced directive antennas on hand would require careful tuning and only one team member was available for the communication tests. The rest of the team was busy with 3D mapping, which also proved to be very labor intensive.
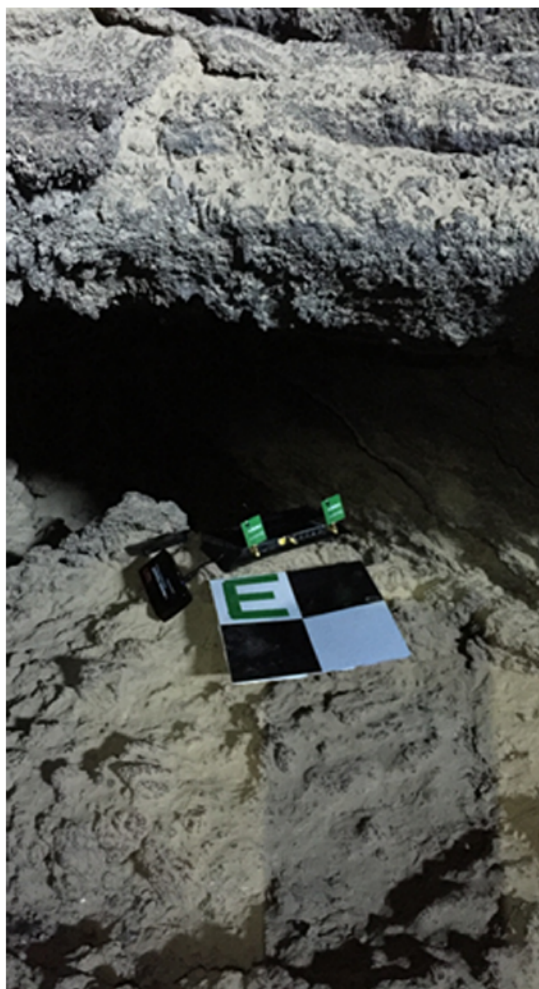

Figure 1. Router location for Test 1.

Table 1. Communication test summary. P - ping, R - data transfer rate.

#	SETUP	RESULTS: Ping (ms) Rate (MB) 2.4 / 5 GHz
1	R: "E". 10.7 m in cave. On top of the rock. Under low ceiling. L: "D" at entrance. Direct FOV. Liard 5 GHz.	Initially connected. Connection dropped. Moved laptop to ~4 m from Router. No luck connecting.
2	R: Center of room 1 on the rocks. R7000 antennas connected. HDD disconnected. Laptop at "E" on the rocks.	Could only connect at 2.4 GHz initially. Then connected at 5 GHz. P: 22.8/14.8. R: 8.3/16.1
3	R: "E" on top of the rock. R7000 antennas. HDD connected. L: Center of room 1. ~4 m from Router. Direct FOV	Good connection. P: 11.2/17.1. R: 8.3/12.7
4	R: "E". Same as previous test. L: "D" at the cave entrance. ~10.7 m from R. Direct FOV	Good connection. P: 23.0/14.6. R: 9.7/18.6
5	R: In front of "F" on top of the rock in room 2. L: Middle of room 1. Direct FOV through cave narrowing.	Good connection. P: 12.6/14.7. R: 9.0/18.6
6	R: In front of "F" on top of the rock in room 2. L: "D" at the cave entrance. No direct FOV. Router is obstructed by ceiling.	Good connection. P: 15.8/15.0 R: 3.4/1.9
7	R: Behind mark "F", below the rock. L: "D" at the cave entrance. Double obstruction: ceiling + rock.	No connection.
8	R: Behind mark "F", below the rock. L: "E" on top of the rock. Single obstruction by the rock only.	Good connection. P: 14.8/14.3. R: 6.5/14.2
9	R: At "G" on top of the rock in room 2. L: At "F" on top of the rock in the same room. Direct FOV.	Good connection. P: 10.9/18.5. R: 8.3/14.2
10	R: At "G" behind the rock in room 2 on the floor. L: At "F" on top of the rock in the same room. No direct FOV.	Good connection. P: 19.9/15.7. R: 6.9/16.1
11	R: At "G" at same location. Now it is in front (relative to laptop) of the rock in room 2 on the floor. L: On rock next to "I" in room 3. ~25 cm from the floor. No direct FOV. Obstruction due to cave turn and elevation change.	Good connection. P: 16.7/12.0. R: 4.9/10.5
12	R: Same location at Tests 10 and 11. L: On the floor next to "J". Deeper into corridor. More obstruction by turn.	Good connection. P: 18.0/8.5. R: 4.1/1.0
13	R: Same location at Tests 10 and 11. L: At mark "A2" in room 4. On top of high rock.	Can only see 2.4 GHz network, but cannot join it. No ping or data transfer possible.
14	R: Next to mark "H" on the floor. Closer than Test 13, still obstructed by turn and elevation change. L: At mark "A2" in room 4. On top of high rock.	Can see 2.4 and 5 GHz networks. Can only join 2.4 GHz. P: 20.1/N. R: 3.6/0.0

Table 2. Distance between the checkpoints inside the cave. Stations were placed near the checkpoint. Checkpoint A2 is the one inside the cave, but uses the same sign as Checkpoint A outside the cave as the signs were reused.

Between Checkpoints	Distance (m)
D ↔ E	10.7
E ↔ F	5.4
F ↔ G	9.5
G ↔ H	12.7
H ↔ I	12.5
I ↔ J	10.8

3.2   TEST 10

The router was placed behind a boulder at Checkpoint G. The laptop was on the rock next to Checkpoint F with no direct FOV to the router. See Figure 2.

Table 3. Ping test roundtrip (ms):

	min	avg	max	stddev
5 GHz	0.833	15.736	144.206	31.842
2.4 GHz	1.031	19.864	254.168	45.998

Table 4. Data transfer: 10 files, 120.9 MB total size

	size per sec
5 GHz	16.13 MB/sec
2.4 GHz	6.19 MB/sec

3.3   TESTS 11 AND 12

For Tests 11 and 12, the router was placed in the next room inside the cave. In both tests, the router was not in the field of view of the laptop. Test 12 goes deeper into the cave behind the turn. See Figure 3. The results of the tests are in Table 1.

Figure 2. Test 10 setup.

3.4   TESTS 13 AND 14

These tests were conducted with the router in the same location as in Tests 11 and 12, but the laptop was placed in the last room of the cave, Room 4. In addition to the previous obstruction by the turn and the elevation change, the narrow passage into the room created an additional obstacle for the signal. For Test 14, the router was moved closer to the laptop, to Checkpoint H, but the wall obstruction was still present.

The results of the test are provided in the Table 1, while the laptop location is shown in Figure 4.

Figure 3. Laptop location for Test 11 (left) and Test 12 (right).

4   DISCUSSION

The field experiment showed that it is possible to establish a reliable communication inside the lava cave using commercial equipment utilizing the standard WiFi protocols. The communication range was about 10–30 m depending on the cave geometry.

The experiment also showed that complicated cave geometry and obstructions does not necessarily prevent high rate of data transfer; however, the data rate is reduced if obstructions are present. Double obstructions proved problematic for establishing any communication. Further analysis of the electric field properties is required to understand how various geometry features affect the link quality and to develop an advanced protocol to mitigate the communication challenges in the presence of complicated geometry that obstructs the signal.

Figure 4. Laptop location for Tests 13 and 14.

APPENDIX A.   PISGAH LAVA CAVE MAP