Virtual Research Presentation Conference

Lunar Testbed for Demonstrating Deep-Space Optical Communications with the Hybrid RF/Optical Receiver

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Program: Spontaneous Concept

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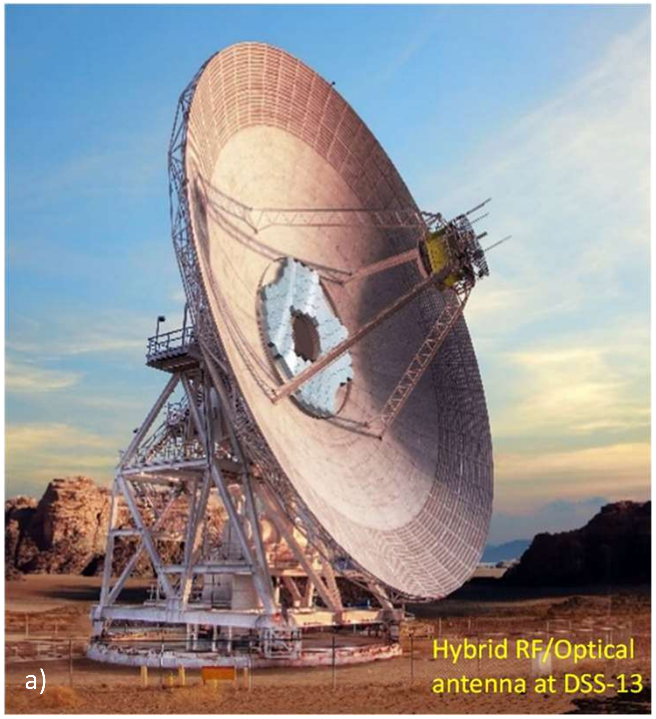
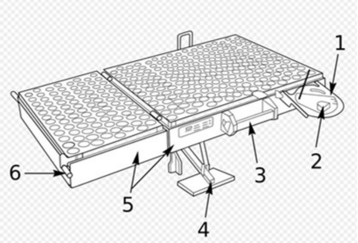
Tutorial Introduction

The objective of this research effort is to develop a conceptual design of an optical Lunar Testbed utilizing the retro-reflector placed on the Moon by the Apollo 15 astronauts.

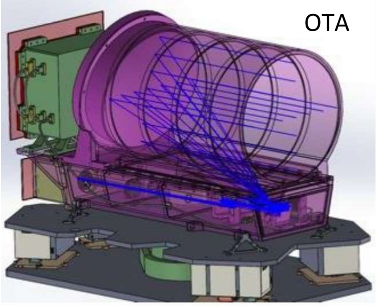
Due to the huge space-loss but short (2.6 s) round-trip light-time (RTLT) between the Earth and the Moon, the Lunar Testbed will be a unique resource that emulates a photon-starved deep-space optical channel with actual orbital dynamics, enabling rapid development and evaluation of deep-space pointing and communications concepts, as well as novel science experiments, under realistic conditions.

A laser transmitter equipped with a 22 cm or larger telescope and roughly 4 watt laser power (similar to the Psyche transceiver) can be used to transmit modulated laser beams from the ground to the retro-reflector, with NASA's new Hybrid RF/Optical Receiver used to collect the reflected photons, after its support of the Psyche mission has concluded.





b) Schematic of the Apollo 15 lunar retro-reflector assembly



c) Flight transceiver showing laser transmitter telescope

Figure 1. Main components of the Lunar Testbed deep-space channel emulator: a) hybrid RF/Optical receiver at DSS-13, with equivalent 8.3 meter effective optical collecting area; b) schematic of Apollo 15 lunar retro-reflector assembly, showing the layout of the 300 corner-cube retro-reflectors; c) diagram of a flight transceiver optical tube assembly (OTA).

Problem Description

a) Context (Why this problem and why now): **The proposed Lunar Testbed will enable rapid development of new optical transmitter and receiver concepts, as well as enabling deep-space optical pointing, communications, ranging and science experiments that benefit NASA's exploration of the solar system.**

b) SOA (Comparison or advancement over current state-of-the-art): **To date, retro-reflector experiments have concentrated on ranging, and were typically carried out at 532 nano-meter (green) or 1064 nm Nd-Yag (near infra-red) wavelengths, due to the availability of powerful laser transmitters and photon-counting detectors. However, the Apollo corner-cubes are made of fused silica, which have excellent optical transmission in the visible and infrared regions, enabling operation at the rapidly emerging 1550 nano-meter wavelength. In addition to providing state-of-the-art ranging, the Lunar Testbed can be used to rapidly develop and test new optical pointing and communications concepts, as well as new algorithms and novel science experiments. To the best of our knowledge, this is a new concept that has not been implemented before, hence represents an advancement over the current state-of-the art.**

c) Relevance to NASA and JPL (Impact on current or future programs): **The Deep Space Network's Hybrid RF/Optical Receiver is an entirely new concept in optical communications, developed by NASA to support the Psyche mission. It is designed for high-rate deep-space optical communications, however after the conclusion of the Psyche mission, this NASA asset will be available for future experiments and development efforts that will benefit NASA's goal of exploring the solar system, the Kuiper belt, and beyond.**

Methodology

- A conceptual design of the Lunar Testbed was developed using models of the Psyche 1550 nm transmitter to generate the pulse position modulated (PPM) uplink signals, the Apollo 15 retro-reflector, and the Hybrid RF/Optical receiver at DSS-13.
- The impact of atmospheric turbulence on the uplink laser-beam was considered, and it was shown that fading due to beam-steering can be minimized by matching the laser beamwidth to the turbulence conditions [1].
- Background and laser backscatter effects were evaluated assuming a dark Apollo 15 site observed at night, and also assuming a brightly illuminated full Moon. It was shown that laser backscatter from the lunar surface can be ignored at the ground receiver, but that solar light scattered from the full Moon contributes significant background photons even when narrowband (1 angstrom) filters are used [2].
- The reflected signal power collected by the Hybrid RF/Optical Receiver was calculated, assuming the cornercubes are not aligned to a small fraction of the 1550 nm laser wavelength, hence independent diffraction applies.
- Polarization of the retro-reflected laser light was considered using Jones matrix analyses, which showed that constraints imposed by the cornercubes must be taken into account for experiments that depend on polarization states (BB84 Quantum Key Distribution protocol). More work is required to fully understand polarization effects.
- Examples of communications, ranging and Secret Key Distribution algorithms were developed and their performance evaluated in the presence of background with strong, medium and weak turbulence [3,4,5].

Results

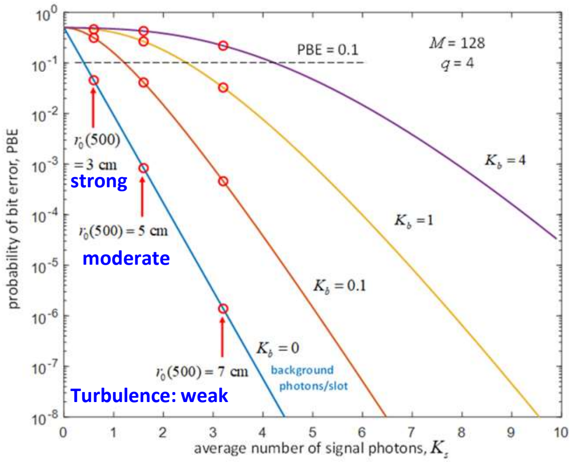


Figure 2. Uncoded PPM bit error probability as a function of average detected signal photons per slot, for a range of background energies in strong, moderate, and weak turbulence, with PPM repetition factor of 4

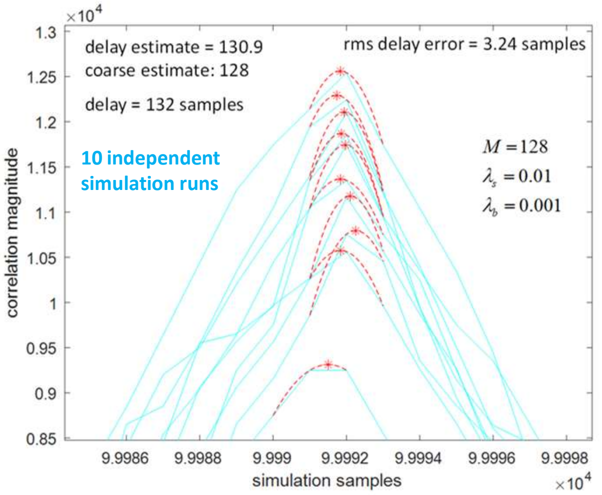


Figure 3. Delay estimation via cross-correlation, using 2176 PPM symbols. Coarse delay is the peak of the correlation function (blue), fine estimate is the peak of the quadratic approximation (red). The rms delay error of 3.24 samples corresponds to 4.7 mm range accuracy

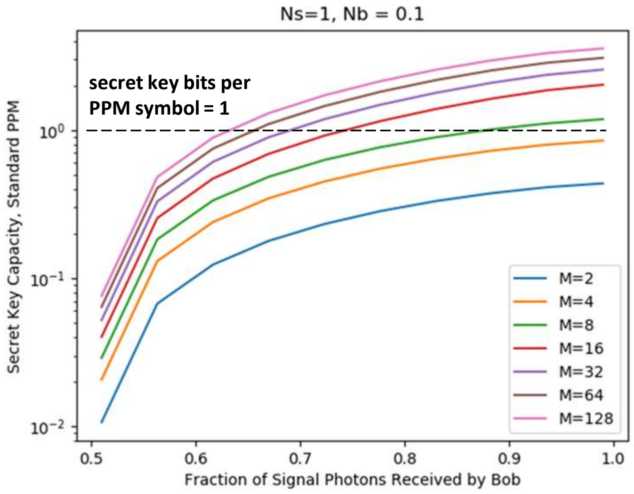


Figure 4. Maximum rate at which Alice can send secret key bits to Bob per channel use (or PPM symbol), assuming standard photon counting detection with moderate background interference

- **In the above Figures we selected signal detection, delay estimation, and secure key distribution algorithms that are general enough to apply reasonably well to a large number of different implementations.**
- **Finally, it was shown that high average photon rates can be achieved with a 4 watt transmitter, when the reflected photons are collected by the large aperture Hybrid RF/Optical receiver, suggesting that this proposed concept is indeed feasible.**

Publications and References

PUBLICATIONS

[1] Victor Vilnrotter, Joseph Jao, Jon Giorgini, Dennis Lee, Philip Tsao, “Lunar Testbed for Demonstrating Deep-Space Optical Communications, Ranging and Science Applications with the DSN’s New Hybrid RF/Optical Receiver,” to be published in The Interplanetary Network Progress Report, volume 43-233, November 15, 2020.

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[3] A. D. Wyner, "The wire-tap channel," in *The Bell System Technical Journal*, vol. 54, no. 8, pp. 1355-1387, Oct. 1975.

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[5] I. Devetak, "The private classical capacity and quantum capacity of a quantum channel," in *IEEE Transactions on Information Theory*, vol. 51, no. 1, pp. 44-55, Jan. 2005