National Aeronautics and Space Administration

FY24 R&TD Innovative Spontaneous Concepts (ISC)

Synthesizing a Direct Detection Telescope Array for the Early DSOC Mission

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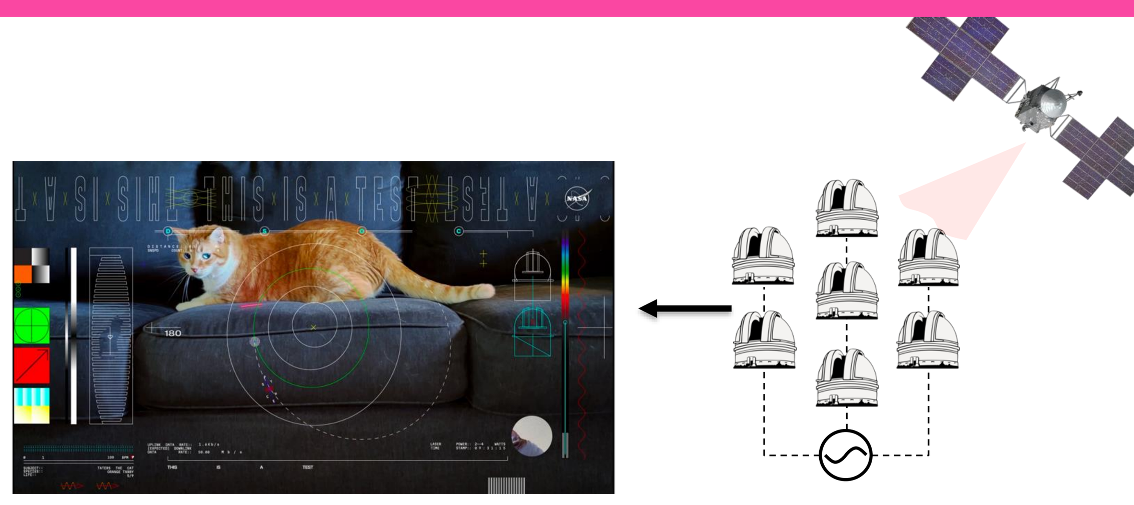
Strategic Focus Area: Innovative Spontaneous Concepts



Objective: Our objective was to leverage three existing telescopes (the DSOC Ground Laser Receiver (GLR) at Palomar Mountain, CA, the Optical- to-Orion (O2O) receiver at Table Mountain, CA, and the RF- Optical Hybrid (RFO) at Goldstone, CA) to simultaneously record the downlink signal from the Deep Space Optical Communication (DSOC) project, and synthesize a telescope array with post-processing software. This provided valuable information about Psyche/DSOC's pointing stability, measurements of the timing statistics across ground stations, insight into the operational challenges of running an array, validated analytical predictions of link performance, and demonstrated the feasibility of this technology for proposal to NASA.

Background: There are currently no large telescopes (> 2-m diameter) dedicated to the Earth-based reception of free space optical communication from deep space. The DSOC project is using the storied Palomar Hale 200-inch telescope for its primary ground station, but since it remains an important and actively-used astronomical instrument, its use as an optical communication asset is possibly limited to the lifetime of DSOC. Our proposed technical solution to this programmatic problem is the use of many relatively small-aperture ground telescopes that are arrayed together to aggregate the total collecting area of an equivalent large-aperture telescope. Thus with a smaller initial investment, NASA can establish a preliminary foothold in optical communication capabilities, while the supportable downlink rates can be expanded with additional telescopes as demand grows.

Approach and Results: The first demonstration of a long baseline optical communication array from deep space was performed on Jan. 15-16, 2024 from 0.42 AU. The spacecraft was configured to transmit at data rates ranging from 1.3 Mbps to 200 Mbps, with the spacecraft pointing approximately half-way between Table Mountain and DSS13 (Figure 1).

After accounting for the time of arrival difference and reference frequency offsets at each ground station, we were able to combine the signals with almost the ideal power gain. Figure 2 shows received signal power for the three stations. Combining loss is defined as the ratio of the signal power of the combined signal over the sum of the individual signal powers. We were able to achieve < 0.01 dB of combining loss. This can be seen heuristically in Figure 2, where the measured combined power (purple line) lies on top of the ideal combined power (green line).

The time of arrival of each photon at each ground station is recorded relative to UTC using GPS clocks and can be used to infer link geometry. For example, the time of arrival of this signal at Table Mountain occurred 31 ns before it arrived at Palomar, indicating that the signal was traveling nearly perpendicular to the baseline between the two sites. Additional analysis of this data is ongoing to determine its utility for navigation.

On February 12-13, the highest data rate decodable by either the O2O or RFO receivers was 1.3 Mbps. However, the combined signal was sufficiently large to decode DSOC's 4.17 Mbps data rate, demonstrating a 3x increase in data volume capability for this two-station array (Figure 3).

On March 18-19, DSOC transmitted at 50 Mbps from 1.18 AU, but due to light cloud cover the Palomar ground station could not close the link with < 1e−4 frame error rate (the threshold used by the project to declare link closure). By combining the signals from all three ground stations, a frame error rate < 1e−4 was achieved, demonstrating operational utility for the mission.

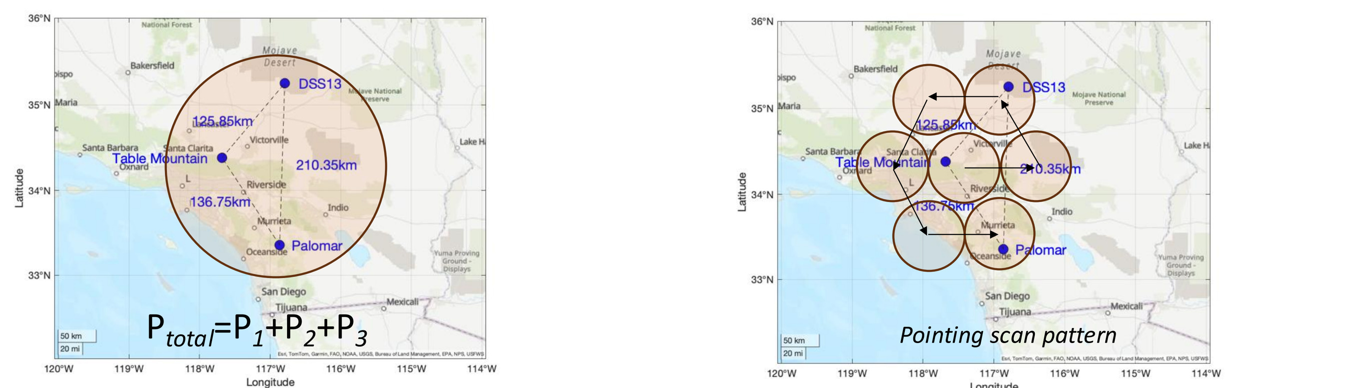


Figure 1: The three telescopes across Southern California used for the demonstration. Left: when the spacecraft is far from Earth and the laser spot is large relative to the telescope spacing, arraying provides a power gain for the simultaneous reception of the signal. Right: When the spot size is small relative to telescope spacing, arraying can provide a diversity gain (having a strong signal at some telescopes while it is weak or absent at others).

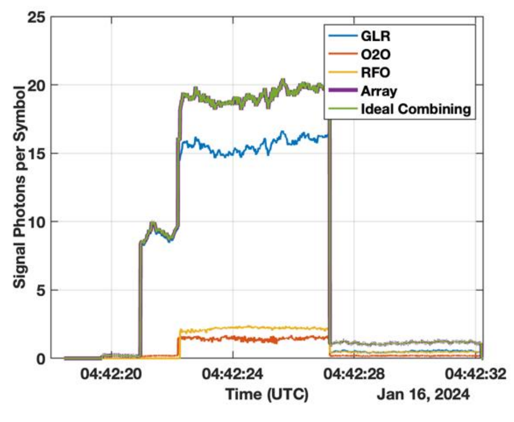


Figure 2: Array gain comes from the coherent addition (at the slot clock, not optical wavelength) of the signal across each telescope. Here we illustrate the actual received power after synchronizing and combining the signals (purple) compared to the ideal achievable array gain (green). The quantitative evaluation of this idea is called combining loss, which measures the average ratio of these two curves. In this demonstration, we routinely achieved better than 0.01 dB of combining loss. The significant difference in received signal power between GLR and O2O/RFO is due to the difference in aperture size (GLR: 5m diameter, O2O: 1m diameter, RFO: 1.2m diameter).

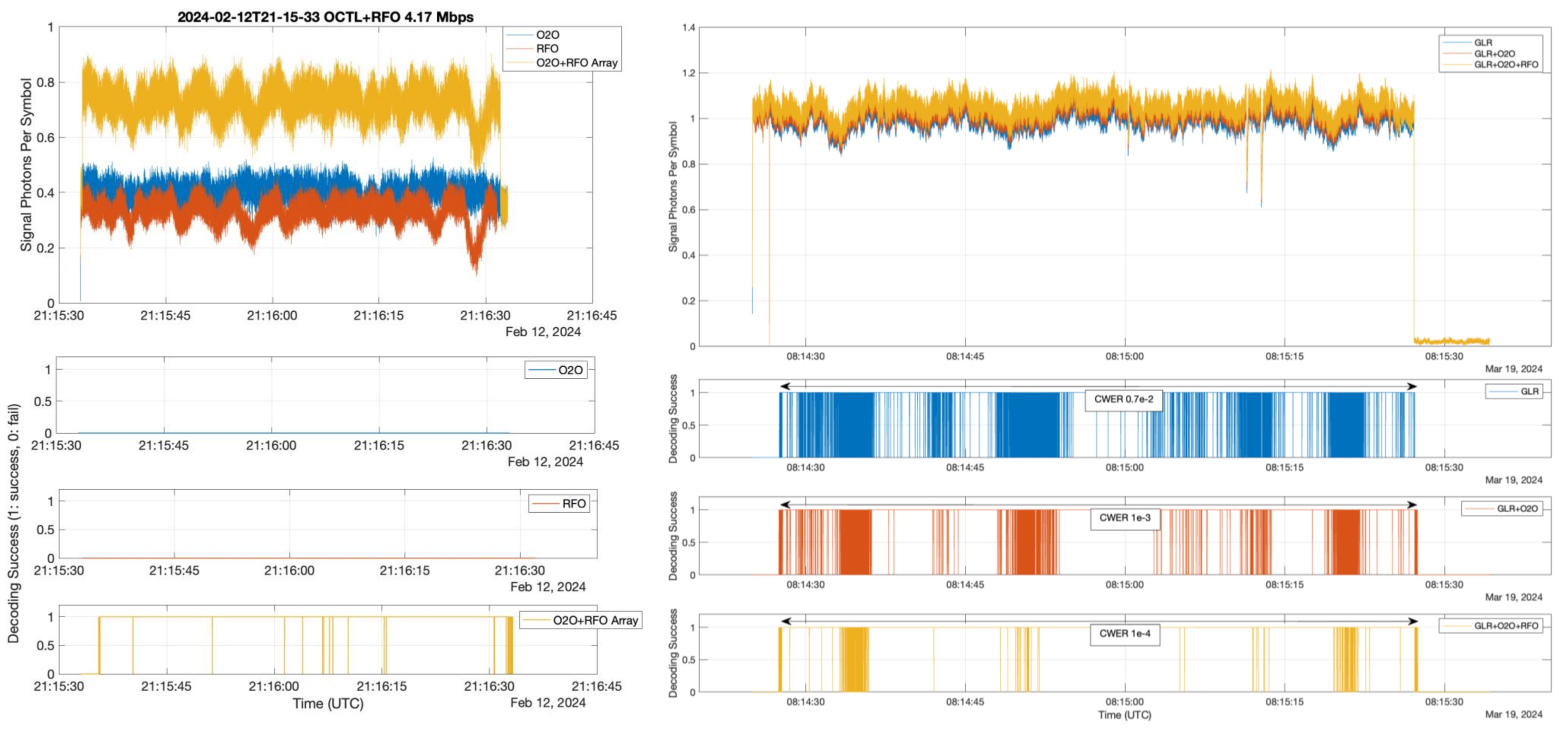


Figure 3: Left: omitting the large Palomar telescope, we show the array gain principle wherein neither O2O nor RFO has sufficient power to decode individually, but their combined signal can be decoded. Right: a track on March 19 in which there was not enough power to decode 50 Mbps at < 1e-4 frame error rate (the project's definition of link closure) at Palomar, but the minor additional power introduced by the two small apertures was sufficient to achieve link closure.

Significance/Benefits to JPL and NASA: This was the first time that arraying was demonstrated for an optical communication signal from deep space, indicating that the signal processing algorithm development is sufficiently mature to enable this technology for future demonstrations and operational deployment. With COTS telescopes on the order of 2m, it is imminently feasible for NASA to fund the development of a low-complexity ground station with modest initial capabilities that can be scaled up to a 5-8m-equivalent telescope as funding becomes available.

Publications:

R. Rogalin, "Telescope Arrays for Deep Space Optical Communication: Preliminary Operational Results," 2024 IEEE Photonics Society Summer Topicals Meeting Series (SUM), 2024, pp. 1-2, doi: 10.1109/SUM60964.2024.10614531.

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