Tests of optical communications for deep space show promise

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A free-space optical beam can reliably transfer more than one bit of data per photon received, even in the presence of background light.

Communication is vital for any spacecraft. After all, an instrument is of little use if it cannot return data. Space communications is currently dominated by radio-frequency (RF) links. Optical communication, however, promises higher data rates while adding less mass and volume to the spacecraft and consuming less power. Optical links have two main advantages over radio communications. First, the beam's shorter wavelength means less diffraction, so it spreads less as it travels through space and can be more tightly directed towards the receiver. Second, the optical system's available modulation bandwidth is much larger than that of an RF system, especially when considering the regulatory restrictions on RF allocation.

While spacecraft optical-communications systems have been demonstrated in Earth orbit,¹⁻³ links to deep space at interplanetary distances have yet to be deployed. The improved optical-link performance is highly beneficial for these mass- and power-constrained spacecraft, yet the extreme distances involved pose a new set of challenges. For example, a link from Mars orbit to Earth would operate at up to 10,000 times longer range than one from geosynchronous orbit to the ground, corresponding to an additional loss of 80dB. Deep-space optical communications therefore require new paradigms and innovative technologies.⁴

To reduce mission risk prior to flight operations, we have used elements of the Jet Propulsion Laboratory's deep-space optical-communications technology for a series of demonstrations aimed at validating subsystem models and operations. They evolved from initial in-fiber laboratory validations to current day-and-night operational free-space links that functionally validate transmitter and receiver systems in real time at data rates of over 44Mbps with efficiencies of approximately two bits per detected photon.⁵ We have also found that testing with pseudo-random data is not always sufficient to validate robust

Figure 1. End-to-end testbed receiver. The receiver telescope (top) collects signal light through the sunlit window (top left). The digital receiver and decoder electronics are on the short rack to the right. Power supplies, amplifiers, and monitoring equipment are on the short rack to the left.

system operations, e.g., temporal acquisition and tracking issues may be masked by repetitive data sequences. Thus, we included a channel for live transmission of high-definition television at a compressed nominal data rate of 30Mbps.

The testbed implements a building-top to building 100m-range link with the receiver placed indoors behind a window (see Figure 1). A custom telescope, used to test prototype low-cost, large-aperture optics, collects a small part of a wide

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signal beam sent from the transmitter. The telescope's field of view allows us to vary the sky-background light level on the detector (depending on the sun angle). The link is typically operated under daytime conditions with suitable bandpass, spatial, and neutral-density filters to provide the desired detector signal and background levels that emulate a Mars-to-Earth link. The link achieves high photon efficiency using pulse-position modulation along with state-of-the-art error-correcting codes to encode multiple bits of information in each optical pulse's arrival time. Pulses are measured by a hybrid photodiode, a photon-counting detector, and the signal is processed by custom field-programmable gate-array-based hardware. The digital receiver and decoder hardware provide standard network interfaces and can be scaled up to gigabit-per-second data rates using a parallel approach.

Future work will include validating a prototype spacecraft terminal currently under development. A brassboard model, to be completed this year, has an innovative low-complexity design,⁶ a robust high-peak-power fiber laser, compact optics, and a novel vibration-isolation system. Once completed, the spacecraft terminal can be tested in a bidirectional link with the existing (or an upgraded) high-efficiency ground receiver. Planned improvements in the ground system include superconducting photon-counting detectors with higher efficiency and lower noise, and an active tracking and pointing system using feedback from the digital receiver. With successful tests minimizing the major risks in the end-to-end system, the promise of optical communications for deep space could soon be realized.

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