

## Recent progress in deep space optical communications

James R. Lesh

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

### ABSTRACT

Progress in the NASA-funded optical communications program at the Jet Propulsion Laboratory (JPL) is described. This description includes a system-level breadboard for an optical communications flight package, the planning for the Earth-reception facilities, and the results of a recent optical communications experiment to deep space with the Galileo spacecraft.

### INTRODUCTION

Past NASA missions have been starved for communications capacity and missions of the future will require even more of that capacity while, taxing the spacecraft less in terms of mass, size and power consumption. For example, the Voyager mission extracted more space-acquired data at the Saturn, Uranus, and Neptune encounters than was planned at launch due to improvements implemented in the Deep Space Network (DSN) during the interplanetary cruise period. These improvements included arraying of the antennas within a given DSN complex, arraying of multiple DSN complexes, and finally the arraying of the DSN with the 27 antennas at the Very Large Array (VLA) at Socorro, NM. The data return requirements for the Galileo mission resulted in a spacecraft design with an antenna too large to launch erected, and drove the decision to utilize the spare unfurlable TDRSS antenna. Furthermore, NASA has made preliminary exploratory visits to most of the major bodies in the solar system and subsequent missions will be expected to perform more in-depth studies using sensors that require even larger volumes of data return (such as multispectral imagers and synthetic aperture radars).

At the same time, the emphasis in NASA is away from the larger, less frequent missions, and toward more frequent launches of lower-cost mini- or micro-spacecraft. Such missions would be faster, better and cheaper than previous missions since, a higher degree of calculated risk could be accepted on an individual mission. Live launches of multiple spacecraft from a single, expendable launch vehicle are being contemplated. Such missions will place very stringent constraints on all the spacecraft subsystems in terms of size, mass and power. Thus, figures-of-merit like kbps/kg or Mbps/cubic centimeter may become important system engineering trade, variable, .

Laser communications has long been envisioned as an extremely promising technology for use under these conditions. NASA has concentrated its optical communications program at JPL for the development and testing of this important technology. The program was started 13 years ago with an emphasis on the planetary mission applications, since the needs were clearly evident in the deep space missions. The program has grown to the point where both the spacecraft and ground reception technologies are being developed, system-level deployment planning is in place, and an exciting new deep-space optical communications demonstration has just been completed.

In this paper we will describe the overall NASA optical communications program at JPL. We will begin by examining the base technology development for the spacecraft side of the link. This will emphasize the development of a laboratory breadboard system called the Optical Communications Demonstrator (OCD). The OCD is being used as the basis for an experimental flight package with applications to both planetary microspacecraft and higher data rate Earth crosslink applications. Next we will discuss the development and planning associated with the Earth-reception end of the link. This includes the use of existing optical telescope facilities for near-term flight experiments, the development of a more permanent RFI reception station, and a study for an eventual orbital reception satellite. Finally, we will briefly describe a recently completed optical communications experiment with the Galileo spacecraft that successfully transmitted and received pulsed laser signals over a distance of 6 million km.

## SPACECRAFT TECHNOLOGY DEVELOPMENT

Over the past 12 years various technological ingredients have been developed in support of the spacecraft side of optical communications links. These ingredients include lasers, acquisition and tracking subsystems, modulators and detectors. Additionally, the funding for these technologies was spread across multiple offices at NASA Headquarters. Two years ago the separate technology programs were merged under a single office. This provided the opportunity to more easily establish a coordinated development program around a common deliverable. The resulting program is a laboratory demonstration system called the Optical Communications Demonstrator (OCD) Program.

The OCD program is a laboratory demonstration of a spacecraft optical communications transmitter system. It contains three separate hardware/software systems as shown in Fig. 1. Each will be described below.

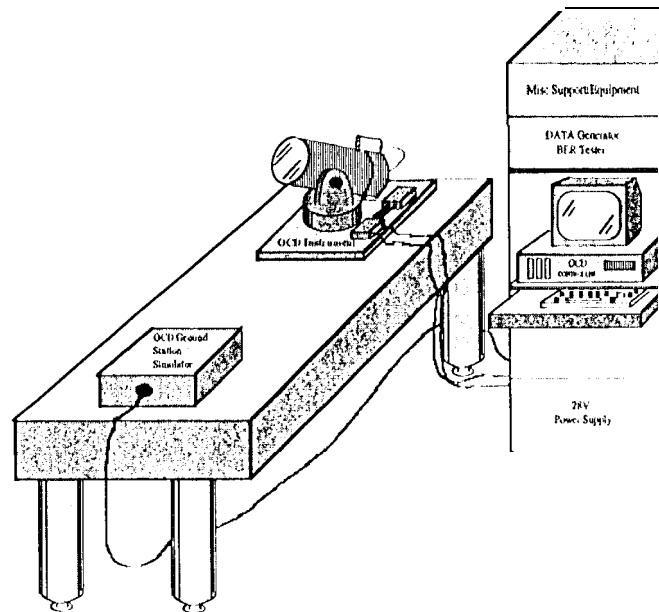


Fig. 1. The Optical Communications Demonstrator Program.

The main element is the Optical Communications Demonstrator Instrument (OCDI). It is a form, fit and function replica of a spacecraft optical communications transmitter package. The package provides for uplink beacon acquisition and tracking, and transmission of a retro-directed beam back in the beacon source direction, offset by a programmable point-ahead angle. The OCDI consists of a 10-cm-diameter Telescope Optical Assembly, a Tracking Detector Assembly for measuring the received beacon direction and calibrating the transmit direction, a Tracking Preprocessor Assembly for deriving the necessary spatial pointing error signals, a Coarse Pointing Assembly for pointing the telescope, a Laser XMTR Assembly for providing a fiber-coupled optical signal to the telescope, and a Control Processor Assembly for conditioning the error signals for the spatial actuators, as well as for implementing the appropriate modulation signals for the transmit laser, and interfacing with the demonstration system controller. Interface to the other major systems in the demonstration program is via an unregulated 28-VDC power supply line, some elementary control lines, and, of course, the optical beams. A photograph of a one-to-one sized mock-up of the, OCDI is shown in Fig. 2.

The OCDI is supported by two other systems, the OCD Controller/Power Supply, and the OCD Ground Station Simulator. The OCD Controller/Power Supply emulates the host spacecraft by providing the unregulated 28-VDC power, and the necessary mode control lines to operate the OCDI, as well as to specify the initial pointing direction. It also provides the demonstration console for operator interface and presentation of the instrument's status and performance. The OCD Ground Station Simulator generates the simulated uplink beacon signal, and provides the optics, detectors and electronics to measure and characterize the OCDI's output transmit beam performance. Both the OCD Controller/Power Supply and the OCD Ground Station Simulator will be implemented using general-purpose laboratory instruments wherever appropriate and cost-effective.

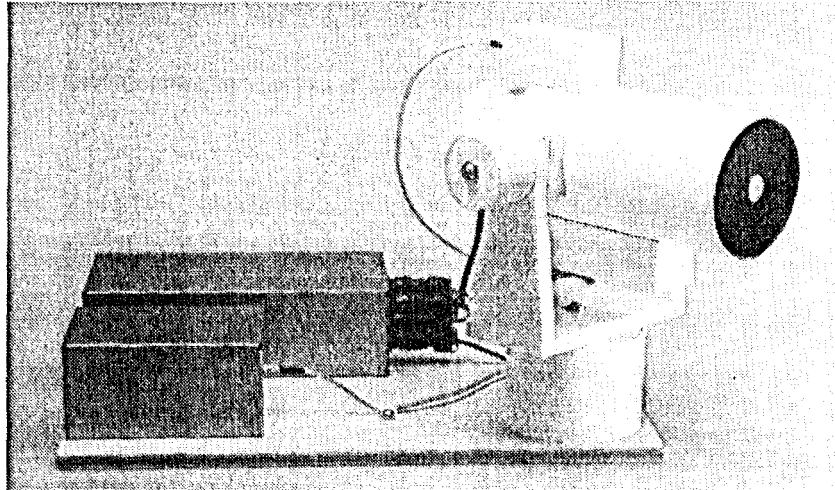


Fig. 2. The Optical Communications Demonstrator instrument Mock-Up.

The OCD program will serve as the breadboard phase for a Space Shuttle-to-ground flight experiment. The OCDI is capable of transmitting more than 100 Mbps from Earth orbit to the ground. Additionally, the OCDI is being designed as a precursor to a deep space microspacecraft optical communications package. The only changes needed to convert the Shuttle terminal to a microspacecraft terminal are the removal of the Coarse Pointing Assembly (assuming the microspacecraft has 3-axis attitude control and the communication terminal will be body mounted) and the replacement of the fiber-coupled high-data-rate Laser XMTR Assembly with an appropriate lower-data-rate version. Several studies have been performed to estimate the performance and mass/size/power impacts for such microspacecraft optical communications terminals. These studies include proposed missions like the Pluto Flyby and the Discovery class of missions. The OCDI architecture appears well suited for such applications.

The OCD development program commenced in 1992, and is scheduled for completion in 1995. Following this, plans call for the architecture to be space qualified for a future flight on the Shuttle, whereupon operational flight terminals for deep space microspacecraft, or for Earth-crosslink applications would be developed. The breadboard development is currently funded under the NASA Base Technology program. Resources for the flight demonstration are currently being sought.

#### EARTH RECEPTION SYSTEM PLANNING

To perform optical communications demonstrations with terminals in space one needs an Earth-reception capability. This includes the ability to transmit an uplink beacon signal to the spacecraft, and to receive its downlink modulated beam for data extraction. Eventually, deep space missions will require reception telescope facilities with substantial collecting apertures. However, for most of the remainder of this decade, optical communications reception will be from flight experimental packages in Earth-orbit. This will permit the use of much more moderate-sized receivers. At one time the 11'1", optical communications plan called for the development and deployment of an interim optical communications support terminal housed in a transportable trailer. It would be built and tested at JPL, and then deployed to appropriate, temporary locations for supporting specific flight experiments.

However, recent changes in the political climate have resulted in a number of telescope facilities, particularly those operated or supported by the Department of Defense, becoming available for supporting civil space programs. Recent trade studies have concluded that a more cost-effective way to perform space-to-ground experiments in the 90's is to arrange for use of these existing facilities, and to only develop the additional equipment necessary to adapt them to the specific experiment conditions. For example, support for a flight experiment was successfully obtained from the Air Force Phillips Laboratory for the use of the Starfire Optical Range's 1.5-meter-diameter telescope (see below). It is envisioned that such facilities will support these early demonstrations, as well as possibly some early phases of deep space missions, out through the year 2000.

Beyond the year 2000, deep space missions will require a dedicated operational network similar to the current DSN which provides for radio frequency reception. This network will be developed as a result of experience gained on a deep space R+D station that will be used to support mission-enhancement flight experiments aboard future deep space missions. JPL has, for the last several years, been defining a 10-meter Deep Space Optical Reception Antenna (DSORA). This facility will use a segmented, advance-composite primary reflector, and will operate as a millicollector photon bucket for receiving deep space optical signals. DSORA is in the NASA Construction-of-Facilities development plan with construction planned to begin in 1999.

Eventually, the Deep Space optical reception network is expected to be a spaceborne network, both to eliminate the visibility outages due to clouds and to permit daytime operation without the high levels of daylight background characteristic of ground-based reception. However, the time frame for deploying an orbital facility, let alone a network, is highly dependent on the cost and reliability of orbiting receivers vs. ground-based ones. Indeed, it might be much more cost-effective to implement more ground stations and use the spatial diversity to mitigate the effects of clouds. To quantify the performance/cost trade space better, JPL is funding a set of parallel feasibility studies, one by TRW and the other by Stanford Telecommunications, for an orbiting receiver. These two-year studies are a little more than half completed. The study results will permit the evaluation of the viability of orbital receiving facilities in the near future. A companion assessment of a ground-based network is also in progress.

### AN EXPERIMENT TO DEEP SPACE

In order to send optical communications signals back from deep space, an uplink beacon laser signal must first be transmitted to the spacecraft. Last December an optical communications experiment was conducted with the Galileo spacecraft as it sped on its way toward Jupiter after passing by the Earth for gravity assist. The objectives of the Galileo Optical Experiment (GOPX) were to demonstrate that an uplink laser beam could be successfully pointed to a distant spacecraft based only on the spacecraft's trajectory predictions and nearby calibration reference stars; that the disturbance effects of the turbulent Earth's atmosphere could be adequately predicted and accommodated; and that the optical communications link theoretical models used to predict the link performance were valid.

The GOPX experiment involved a pair of simultaneous uplink laser transmission sites, one at Table Mountain Observatory near Wrightwood, CA, and the other at the Starfire Optical Range at Kirtland Air Force Base in Albuquerque, NM. Transmissions were made to the Galileo spacecraft at distances ranging from 600,000 km to 6,000,000 km. The Galileo imaging camera, with its CCD-based detector, was used to detect the optical signals. Pulsed laser signals were sent up from both sites at pulse rates ranging from 101 Hz to 30 Hz. The spacecraft's camera was opened while the camera was spatially scanned over the direction from which the uplink signals were generated. This scanning caused the temporally modulated laser signals to show up on the camera images as spatially modulated patterns across the CCD detector. The camera images were then relayed back to Earth via the normal radio frequency downlink for analysis.

The experiment was performed on the mornings of December 9-12 and 14-16, 1992. Nearly 50 images with confirmed detections were obtained. The number of detected pulses per frame ranged from 2 to 17 depending on the shutter opening durations, the laser pulse rates, and the cloud conditions at the sites. Successful detections were made on every one of the seven experiment mornings, although not always from both sites due to storm activities. Signal detections were very repeatable, and demonstrated that the pointing predictions and beam divergences (adjusted to compensate for atmospheric turbulence and pointing uncertainties) were extremely accurate. Preliminary analysis of the detected signal intensities indicates that they were well within the expected signal fluctuation limits. The demonstration results show that uplink beacon transmission to deep space is well understood and clears the way for more challenging follow-on experiments in the future. (A detailed discussion of the GOPX experiment and its results is contained in a separate paper in this proceedings.)

### CONCLUSIONS

In this paper we have provided an update of the status of the NASA-funded optical communications program at JPL. We first discussed the factors that motivate the development of the technology, both from a historical perspective, and from the constraints imposed by the new emphasis on microspacecraft. We then discussed the development of the Optical Communications Demonstrator, a laboratory breadboard terminal that, with follow-on flight-qualification and Space Shuttle demonstration, will validate the architecture for either Earth-crosslink terminals or small microspacecraft terminals for deep

space. Ground reception station planning, both for the near-term as well as the more distant future, was then discussed, followed by a summary of a recently completed deep-space optical communications experiment with the Galileo spacecraft.

Progress in the development of optical communications technology has been very steady, both for the space segment and for the Earth reception systems. The success of the recent GOPEX experiment will further bolster confidence that the technology is rapidly coming of age.

#### ACKNOWLEDGMENT

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