Multi-Gigabit Data-rate Optical Communication Depicting LEO-to-GEO and GEO-to-Ground Links

H. Hemmati, M. Wright, B. Sanii, N. Page, G. G. Ortiz, A. Biswas and K. Wilson
Jet propulsion Laboratory, California Institute of Technology[1]

ABSTRACT

Communication links with multi-giga-bits per sec (Gbps) data-rates depicting both LEO-GEO and GEO-to-Ground optical communications were characterized in the laboratory. A 5.4 Gbps link, with a capability of 7.5 Gbps, was demonstrated in the laboratory. The breadboard utilized a 13 cm diameter telescope as the transmit aperture that simulates the LEO terminal. The receiver is a 30-cm telescope that simulates the GEO terminal. The objective of the laboratory breadboard development is to validate the link analysis and to demonstrate a multi-gigabit link utilizing off-the-shelf or minimally modified commercially available components (optics and opto-electronics) and subsystems. For a bit-error-rate of 1E-7, the measured required received signal is within 1 to 2 dB of that predicted by the link analysis.

INTRODUCTION

It is anticipated that the next generation of remote sensing spacecraft (mostly in LEO orbit) will gather enormous quantities of data. Making this volume of data available for use on the ground in near real time is challenging. The work presented here describes the use of optical communications as a viable and attractive technology for meeting the former requirement, namely streaming data from space based sensors to ground stations in near real time. Using GEO relay satellites is the favored strategy for transferring large data volumes from space to ground for reasons elaborated below. It will be possible to relay such data to the ground advantageously, at the rate of multiple-Gbps, by using a lasercomm relay terminal located on a geo-stationary (GEO) relay spacecraft [1]. The two key subsystems for successful multi-Gbps data-rate free-space optical communication between LEO and GEO and GEO and ground are the communications physical layer and the acquisition, tracking and pointing (ATP) subsystem. All the link measurements reported here are based on the direct-detection technique. The related ATP experiments will be reported separately.

The high-data-rate laser-communication technology can uniquely enable the required relay of significant data volumes, largely due to the following features: availability of very large and unregulated bandwidths at optical frequencies; the legacy of fiberoptic communication system technologies that now routinely operate in global telecommunications links at 1-10 Gbps data-rates. Much of this technology is directly pertinent to the free-space lasercomm systems.

LEO-TO-GEO CROSSLINK

LEO-GEO links are of interest since the atmospheric effects, as well as, reduced link availability due to cloud cover that is associated with LEO-to-ground links, is mitigated. From a single mid latitude ground-based receiver station, a LEO spacecraft is typically observable for less than 15 minutes in a 24-hour period. Even sites with favorable atmospheric visibility typically display availability in the 60% to 70% range. By contrast the line-of-sight (LOS) to a GEO terminal is maintained nearly continuously. Moreover, in the event of sustained cloud cover, the data may be re-broadcast or transmitted to alternative ground receiver(s) located within the GEO satellite's LOS but in a diverse weather cell that does not have simultaneous cloud cover. Analysis shows that site diversity can increase availability from 60-70% to greater than 95%.

[1] 4800 Oak Grove Drive, Pasadena, CA 91109. Contact author at: hamid.hemmati@jpl.nasa.gov, phone 818-354-4960

Architecture - The acquisition, tracking and pointing (ATP) architecture for the JPL-developed OCD (Optical Communication Demonstrator, shown on Figure 1) is a simple yet scalable architecture that can be adapted for the LEO-GEO cross-links being discussed and is adopted for the remainder of this study [2].

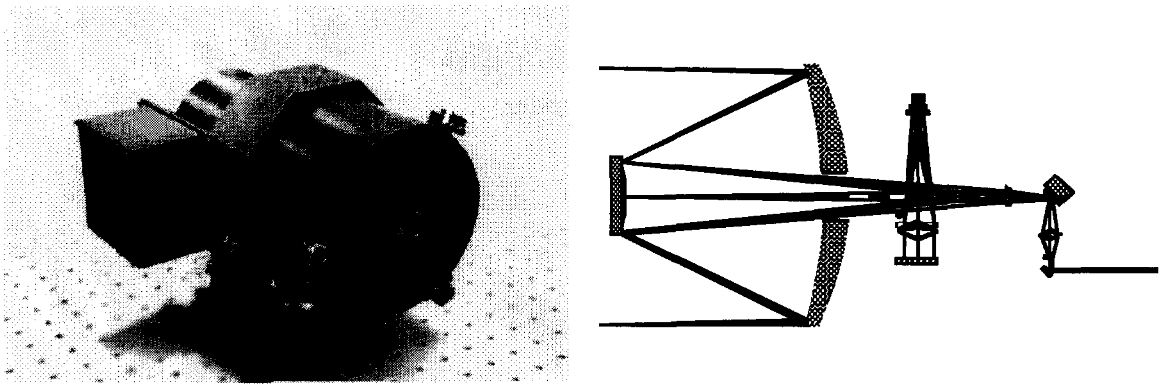

Fig. 1. Picture of the JPL-developed laser-communication terminal and schematic layout of the OCD terminal showing the optics, laser transmitter beam, fine-pointing mirror, and focal plane array (for ATP).

ACQUISITION & TRACKING

The ATP is one of the most challenging aspects of establishing a communication link. Various scenarios for ATP between LEO and GEO spacecrafts are discussed. It is assumed that the computers onboard each spacecraft initiate the normal acquisition between the lasercomm system elements, utilizing previously defined clock and position references. Use of GPS and inertial navigation systems (INS) based reference system will aid the acquisition process by providing the LEO spacecraft precise knowledge of its position at all times. For a given spacecraft, the following factors contribute to the magnitude of location and orientation knowledge (position in orbit) uncertainty: (1) the spacecraft stabilization technique (3-axis, reaction wheels, spinner...); (2) quality of inertial measurement sensors (gyros, star-sensors...); (3) attitude control system; (4) attitude estimation software; and (5) the disturbance environment to which the lasercomm payload is exposed.

All of these directly affect the orientation of the laser communication transceiver is instantaneous line-of-sight (LOS) relative to the acquisition uncertainty cone. For purposes of communication, acquisition is defined as the time required for LEO-terminal to receive tracking data and lock-on to the beacon broadcast from the GEO-terminal. A proposed acquisition technique for inter-satellite links typically begins with one of the terminals, for example the LEO terminal, turning on a beacon for the second terminal (for example the GEO-terminal) to detect and lock onto. Thus, the GEO-terminal acquires the beacon from LEO-terminal. The requirements on the beacon pointing are that it successfully illuminates the GEO-terminal. This may be done with a beacon that instantaneously fills the entire angular error volume associated with the location of the GEO-terminal relative to LEO-terminal, or it may be done with a smaller beam that scans the error volume. Another possibility is a beacon at the GEO orbit only and no beacon on the LEO terminal. It is possible for the communication laser itself to serve as the beacon also. However, some beam broadening (defocus) may be required. The complexity of a scanning technique is avoided if the error volume is small enough so that the beacon can provide an adequate power density over the entire volume, thus providing for a good signal to GEO-terminal to detect the incoming beacon (most likely difficult to accomplish). It is possible that the LEO-terminal beacon cannot fill the entire error volume of the GEO-terminal detector field-of-view (FOV). In that case, both terminals will have to scan their beacon beams within their respective error volume. Typically, there is a finite amount of time available to perform the acquisition process. In certain acquisition scenarios both terminals may be transmitting and receiving, simultaneously. For the experiments conducted so far, it is assumed that the ATP subsystem has performed its task and has accurately pointed the two terminals together. Experiments that simulate ATP between LEO and GEO terminals in the laboratory using the JPL's OCD ATP architecture are now underway. The work described here concentrates on the communications aspects of the link.

COMMUNICATIONS

Some of the key parameters for communications are: required data rate and bit-error-rate (BER). Various internal and external noise sources in the receiver contribute to the bit error. BER is typically driven by the average/peak signal power and RMS noise power during a bit interval. However, optical communication can provide 2.5 Gbps without much additional complexity since the bulk of the work is in acquisition, tracking and pointing. A data-rate of 2.5 Gbps is analyzed here and demonstrated experimentally. The required laser power may be determined by assuming the following link parameters: wavelength = 1550 nm, link range = 4.3E4 km; data-rate = 2.5 E6 kbps; BER = 1E-7; transmit aperture = 13 cm; receive aperture = 30 cm, and a link margin of 3 dB. Table [1] summarizes important parameters of the link budget.

Parameter	Value	
Transmit power	3.35 W average	38.25 dBm
Transmit losses	64.5% trans.	1.90 dB
Transmitter gain	(9.2 urad beam)	113.51 dB
Pointing losses		-2.01 dB
Space loss		-290.85 dB
Atmospheric losses		0 dB
Receiver gain		115.5 dB
Receiver losses	46% transmission	-3.36 dB
Received signal	2570 photons/pulse	-30.85 dBm
Background	6.66E-9 photons/s	0 dB
Required signal	1.29E3 photons/pulse	-33.85 dBm
Link Margin		3.00 dB

Table 1. Summary of the LEO-GEO link budget

On-off keying modulation without coding was assumed here. Inclusion of coding will enhance the link margin. The required average laser power of 3.25 Watt is well within the range of commercially available Er-doped fiber amplifiers (EDFAs). For higher data-rates, the transmit channel may be a single transmitter or could, for example, utilize a four (4) wavelength coarse division multiplexer (CWDM) to form four separate channels. Polarization coupling provides another means of increasing the data-rate by providing an additional channel. The 1550 nm wavelength WDM technology is very well developed by fiberoptic industry. The technology of high power high-data-rate lasers at 1550 nm is maturing as well. Among other properties associated with the 1550 nm wavelength for free-space communication use is a lower level of background sunlight at that wavelength.

EXPERIMENTS

The 2.5 Gbps transmitters, receivers, electronics, and characterization equipment were assembled to validate the functionality of each component. Optics (telescopes and multitude of lenses and mirrors) were assembled onto their respective breadboards. A 13 cm diameter telescope was used in the transmitter optical assembly and was aligned using a Zygo interferometer. An (available) all-Silicon-carbide telescope with a 30-cm aperture was used in the receiver system. Optical throughput (transmission) was measured upon integration of the optics with the telescopes. A modulated fiber coupled laser transmitter was integrated with the 13-cm telescope and a high bandwidth receiver was integrated with the 30-cm telescope.

Figure (2) shows a schematic of the experimental setup with Fig. (3) showing a photograph of the current setup.

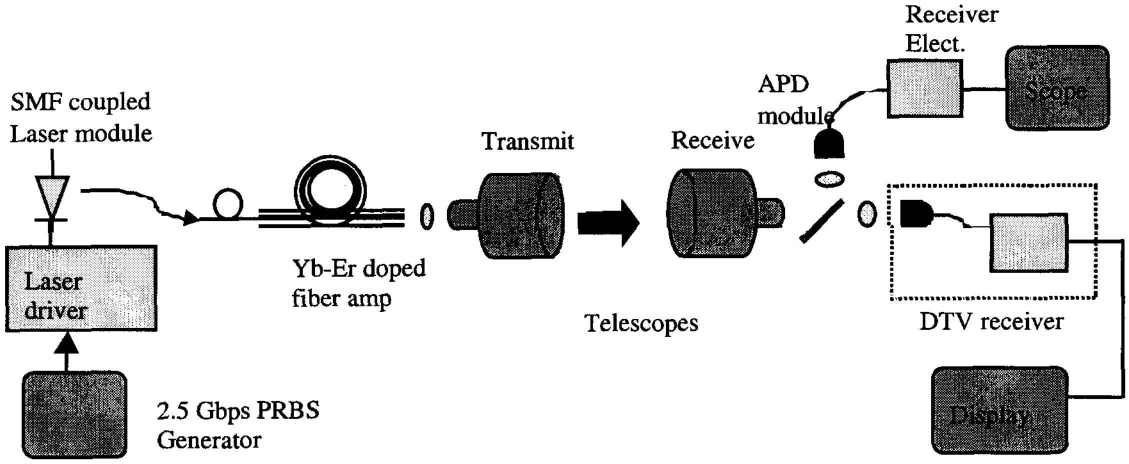

Figure 2. Schematic of the communication experiments

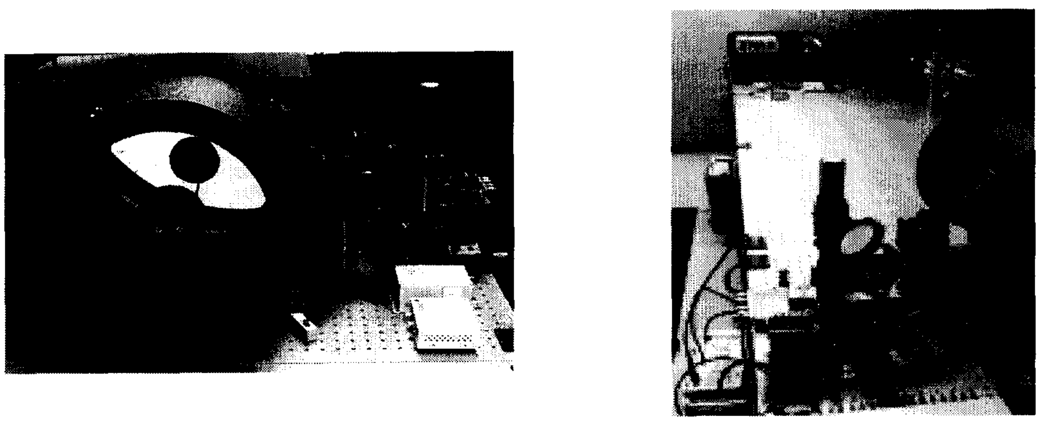

Fig. 3. Pictures of the setup showing the two telescopes and associated transmitters and receivers

Initially, an optical link was established across an optical table while the laser transmitter was modulated up to a maximum of 2.5 Gbps. In the laboratory, a fraction of a milli-Watt (mW) of laser transmit power is sufficient to establish a link. However, to simulate the final system, an optical amplifier, capable of providing 2 W of saturated laser power at 1550 nm, was attached to our laser transmitter and attenuated to obtain the required power levels at the receiver. Bit-error-rate testers and high- speed oscilloscopes were used to measure the BER (bit error rate) and to observe eye patterns. A clock and data recovery (CDR) unit was also used in the receiver system. Several receivers were tested including fiber coupled and uncoupled APD detectors. Eye patterns reveal the quality of modulation and potential sources of errors as the received power is decreased. Our goal is to experimentally match, as closely as possible, the link performance predictions assuming measured and known characteristics of the components utilized in the end-to-end link. Sample experimental data on the characterization of different transmitters, the amplified transmitter, and different receivers is shown in Figures 4 through 6.

Measured throughput power of the laboratory optical system, which includes non-optimized optics and coatings in each of the transmit and receive telescopes, is approximately 21 % compared to 27 % used in the theoretical link analysis. The required received signal is also within 1-2 dB of that predicted by the link analysis. Thus the preliminary setup demonstrates the feasibility of the predicted links.

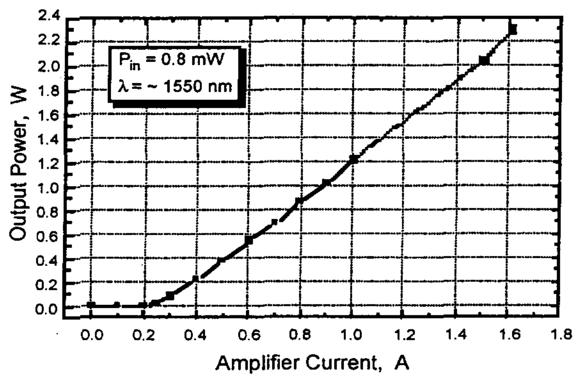

Fig. 4. Fiber amplifier output power as a function of the pump diode current. The fiber amplifier is capable of greater than 2 W average power with a channel bandwidth of 40 nm around 1550 nm

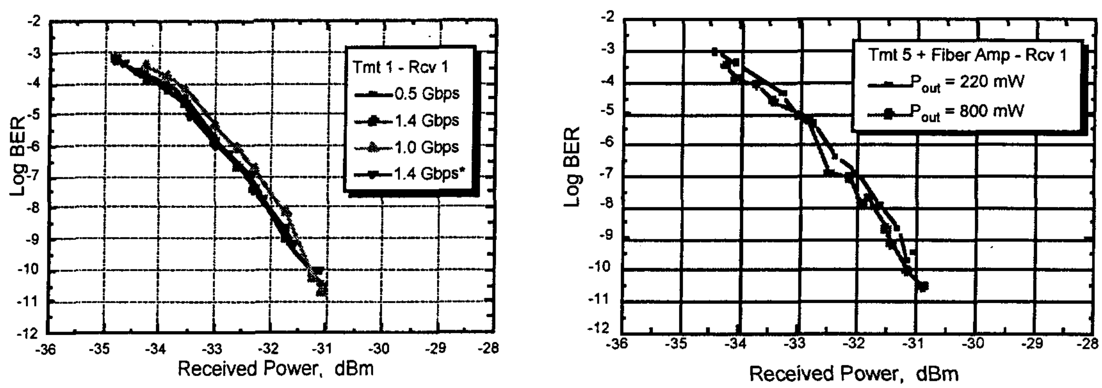

Fig. 5. (a) Data rate dependence of BER as a function of received power for an APD based receiver with external CDR and (b) BER as a function of received power at 1.4 Gbps with the fiber amplifier at varying pump intensities.

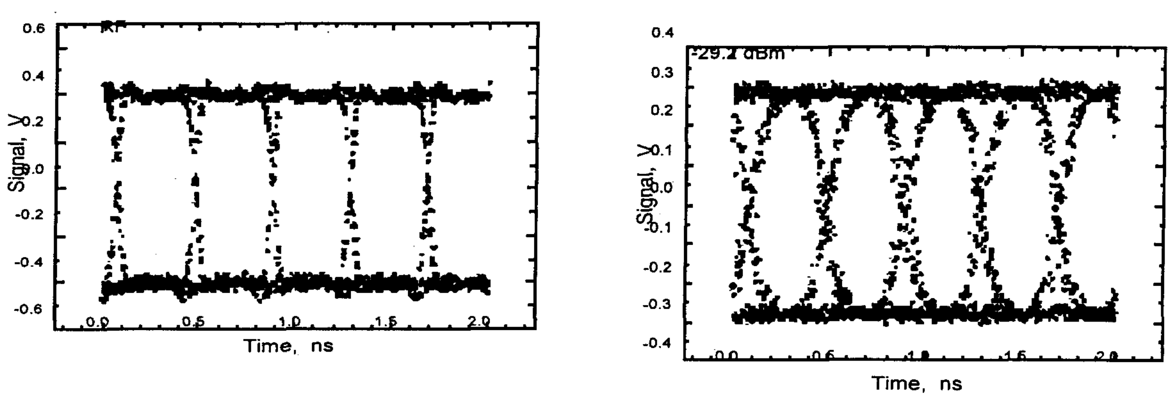

Fig. 7. "Eye diagram" of RF source modulation to transmitters at 2.5 Gbps (left) and "Eye diagram" for Transmitter 1 to Receiver 1 at 2.5 Gbps. Output is directly from the receiver without CDR to reveal the quality of modulation at low BER (w/ -29 dBm of input signal)

As a demonstration of science data transmission capability, a three-CCD full color High Definition television (HDTV) camera was used as the data source with an optical receiver connected to a HDTV monitor to display the signal. The data format was 1080i comprising 1920 x 1080 pixels at 60 Hz to give the SMPTE 292M HDTV standard. The HD serial digital interface (SDI) from the camera outputs the uncompressed 1.48 Gbps data stream that directly drives a laser transmitter. Varying the transmitted power and comparing to the BER with the identical transmit/receive power could quantify the quality of transmission quantified from the observed signal on the monitor. It was found that the BER had to be better than 10^{-8} to obtain very minimal signal degradation. Below that level the picture quality deteriorated, first with intermittent loss of lines, then overall 'snow effect' and finally loss of synchronization at around a BER of 10^{-5}.

To access greater than 2.5 Gbps data rates, multiple high-speed sources can be multiplexed together into a single transmitter. Wavelength division multiplexing (WDM) is routinely done in fiber optic based telecommunications with several transmit laser sources each shifted slightly in frequency or wavelength, coupled through a WDM with low insertion loss into a single amplifier [3]. The amplifier gain is then divided over the number of channels, depending on the gain spectra. On the received side, each channel is similarly split off using a WDM demultiplexer. To avoid the stringent control of each source wavelength and hence coupling ratio, CWDM is typically used when only a few channels are required. Here the channels are spaced 10-20 nm apart. For the receiver to be used in a GEO to ground system, the detectors are non-fiber coupled due to the larger atmospherically blurred spot size in the detection channel. Thus, multi-coated micro-optic filters are required to split the CWDM channels with low loss and high throughput. These filters centered at 1540 and 1560 nm were angle tuned and cascaded so that their 18 nm optical band pass could be optimized for the individual laser source wavelengths. Based on the available sources and filters, a three-channel system was setup in the laboratory with the schematic shown in Fig. (8). By appropriate choice of wavelength of the laser sources, more channels could easily be accommodated. The three channels simultaneously demonstrated transmission of a 2.5 Gbps PRBS signal at λ_1 = 1558 nm, a 1.48 Gbps uncompressed HDTV signal at λ_2 = 1546 nm and a 1.4 Gbps PRBS signal at λ_3 = 1552 nm to give an aggregate data rate of 5.4 Gbps. BER's of better than 10^{-9} were measured with no cross talk or channel interference apparent in the received signals. Due to the available source wavelengths, a 1 x 3 fiber coupler was used to multiplex the three sources into a single transmitter. Compared to the desired CWDM system, each input channel has a much higher insertion loss.

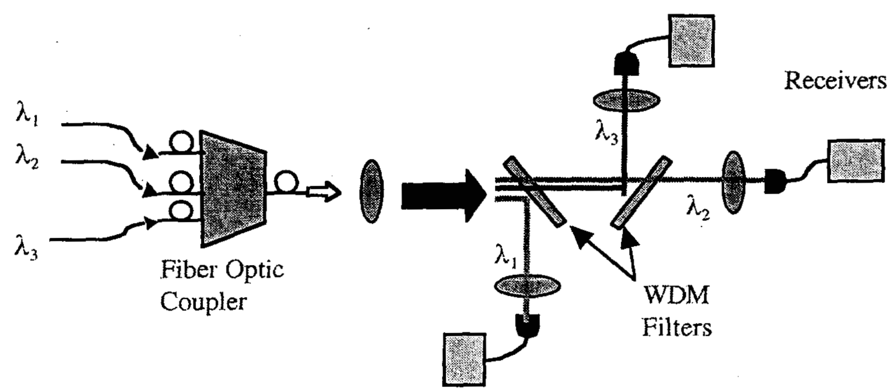

Fig. 8. 3 Channel free space WDM system.

SUMMARY

A multi-Gbps optical communication link depicting LEO-GEO and GEO-ground scenarios has been demonstrated in the laboratory using predominately commercial components. The link analysis has been validated while the full system design, including the ATP architecture, is in progress and will be reported at a later date.

ACKNOWLEDGEMENTS

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