An Overview of the GOLD Experiment Between the ETS-VI Satellite and the Table Mountain Facility

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The Ground/Orbiter Lasercomm Demonstration is a demonstration of optical communications between the Japanese Engineering Test Satellite (ETS-VI) and an optical ground transmitting and receiving station at the Table Mountain Facility in Wrightwood, California. Laser transmissions to the satellite are performed for approximately 4 hours every third night when the satellite is at apogee above Table Mountain. The experiment requires the coordination of resources at the Communications Research Laboratory (CRL), JPL, the National Aeronautics and Space Development Agency (NASDA) Tsukuba tracking station, and NASA's Deep Space Network at Goldstone, California, to generate and transmit real-time commands and receive telemetry from the ETS-VI. Transmissions to the ETS-VI began in November 1995 and are scheduled to last into the middle of January 1996, when the satellite is expected to be eclipsed by the Earth's shadow for a major part of its orbit. The eclipse is expected to last for about 2 months, and during this period there will be limited electrical power available on board the satellite. NASDA plans to restrict experiments with the ETS-VI during this period, and no laser transmissions are planned. Posteclipse experiments are currently being negotiated. GOLD is a joint NASA–CRL experiment that is being conducted by JPL in coordination with CRL and NASDA.

I. Introduction

The Ground/Orbiter Lasercomm Demonstration (GOLD) is a joint NASA/Communications Research Laboratory (CRL) optical communications experiment to evaluate one-way and two-way optical communications under a range of atmospheric conditions and to demonstrate optical ranging. GOLD's objectives and goals are outlined below.

The objectives are to

(1) Demonstrate two-way spatial acquisition/tracking of laser beams with a spacecraft

(2) Accomplish one-way and two-way optical data transfer to a spacecraft and measure bit-error rates

(3) Accumulate 10 elapsed hours of transmission/reception experience and 30 Gbytes over a 6-month period

(4) Compare downlink atmospheric transmission losses with similar data from the Table Mountain Facility's (TMF's) atmospheric visibility monitoring (AVM) observatory

The goals are to

(1) Gather atmospheric transmission statistics from an actual space-to-ground link and compare them with corresponding statistics from the AVM system

(2) Build a database for optical link acquisition/reacquisition times

(3) Validate optical communications-link performance prediction tools

(4) Demonstrate optical ranging to 10-m accuracy

GOLD experiments will use the 0.6-m and 1.2-m telescopes located at NASA's TMF to communicate with the Japanese Engineering Test Satellite (ETS-VI). The experiment concept is depicted in Fig. 1. An argon-ion laser coupled to the 0.6-m telescope transmits a 1.024-Mbps Manchester-coded pseudorandom noise (PN) sequence to the spacecraft. The ETS-VI in turn uses its GaAs laser to transmit a similar PN sequence to the 1.2-m ground receiver located approximately 60-m from the transmitter site.

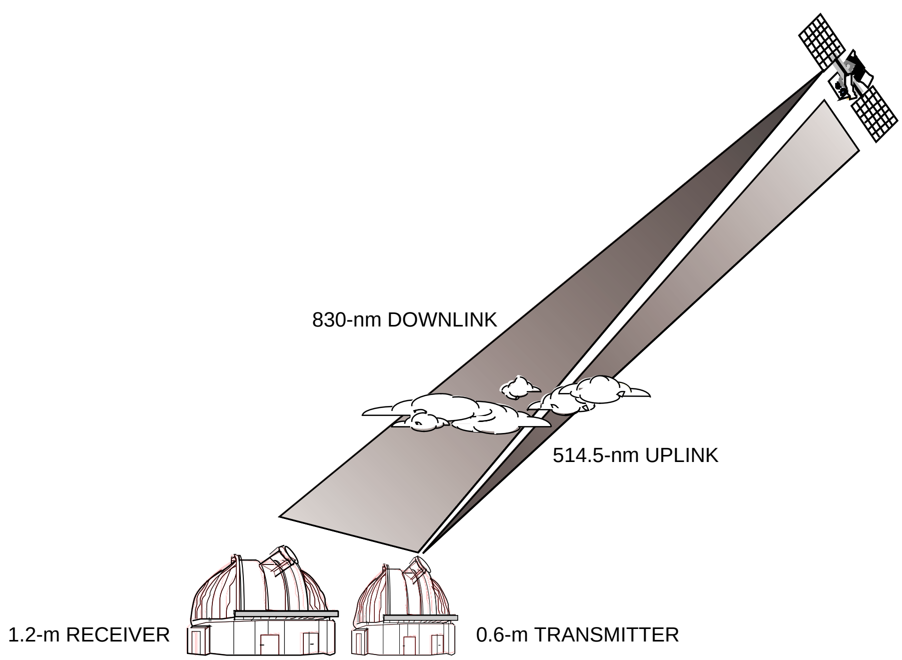

Fig. 1. Conceptual drawing of GOLD. The transmitter at TMF uplinks a 514.5-nm communications signal to the ETS-VI. The satellite downlinks a 830-nm 1-Mbps signal.

The ETS-VI was launched into orbit on August 28, 1994. It was originally intended to be in a geostationary orbit above Japan, but difficulty with one of its motors has resulted in the satellite now being in a geotransfer orbit. To make maximum use of the spacecraft's subsystems in its current orbit, researchers at CRL have encouraged both NASA and European Space Agency (ESA) experimenters to use the optical communications subsystem on board the ETS-VI. In response to this, the National Aeronautics and Space Development Agency (NASDA) has refined the satellite's orbit to facilitate the use of the laser communications equipment (LCE) by experimenters at JPL. Yet, because the satellite's elliptical orbit takes the satellite through the Van Allen belts, its power generation capabilities have been degraded and its expected life reduced. Between mid-January and mid-March 1996, the satellite will go into a 2-month-long eclipse. During this time, very little power will be generated on the spacecraft, and only low-power experiments will be feasible. It is unclear whether optical communications falls into this category of experiments. Posteclipse experiments are not scheduled as yet because of the large uncertainty in whether the satellite batteries will survive the long eclipse.

This article describes the work on the GOLD project to date. The three phases of the GOLD experiment are described in Section II, along with a brief description of the satellite predict generation. The data link between CRL and TMF that is used to confirm the acquisition of the uplink beam and to communicate with CRL experimenters is also described in Section II. The transmitter and receiver optics and electronics are described in Sections III and IV, respectively, and the AVM station that measures the atmospheric transmission at optical wavelengths is described briefly in Section V. Samples of the data collected to date are presented and discussed in Section VI. Conclusions are in Section VII.

II. GOLD Preparation and Operations Phase

A. GOLD Operations and Experiment Phases

The ETS-VI satellite is in a recurrent orbit that makes it visible every 3 days at night from TMF. The GOLD schedule given in Table 1 extends over the period from October 30, 1995, to January 13, 1996. The table shows the laser communications and associated Deep Space Network (DSN) satellite control times. The DSN begins satellite control 2 hours before the laser transmission times and ends 90 minutes after laser transmission.

Table 1 shows the transmission times of the GOLD experiments. The experiment is broken into three phases over the period from November 1995 to January 1996. Phase 1 is a beacon uplink with a 1.024-Mbps downlink detection. The goals of this phase are to

(1) Complete integrated system testing

(2) Measure the uplink optical beam divergence at the satellite

(3) Evaluate the benefits of spatial diversity of the uplink beacon, i.e., single- and dual-beam beacon transmissions

(4) Determine the appropriate uplink power levels to maintain spacecraft closed-loop tracking of the ground station

(5) Evaluate the spacecraft's ability to point to the TMF ground station, and develop appropriate ground-station acquisition strategies

(6) Establish operations procedures for the phases discussed below

Table 1. Laser transmission times for the GOLD experiment.

Date	Start, time UT	End, time UT	Duration, h:min
30 October 1995	11:55	15:00	2:05
2 November 1995	11:45	15:00	3:15
5 November 1995	11:30	14:50	3:20
8 November 1995	11:20	14:40	3:20
11 November 1995	11:15	14:30	3:15
14 November 1995	11:05	14:10	3:05
17 November 1995	11:05	14:10	3:05
20 November 1995	10:45	14:00	3:15
26 November 1995	10:35	13:30	2:55
29 November 1995	9:52	13:55	4:01
2 December 1995	9:36	13:50	4:14
5 December 1995	9:20	13:47	4:27
8 December 1995	9:04	13:43	4:39
11 December 1995	8:48	13:40	4:52
14 December 1995	8:35	13:35	5:00
17 December 1995	8:25	13:24	4:59
20 December 1995	8:14	13:13	4:59
23 December 1995	8:04	13:03	4:59
29 December 1995	7:44	12:41	4:57
4 January 1996	7:24	12:20	4:56
7 January 1996	7:14	12:09	4:56
10 January 1996	7:04	11:59	4:55
13 January 1996	6:54	11:48	4:54

Phase 2 extends over the month of December 1995, and the goals are to demonstrate two-way optical communications, measure the bit-error rate (BER) on the uplink, and evaluate the spacecraft's ability to regenerate an uplinked data sequence.

Phase 3 extends from January 4, 1995, to January 13, 1996. The primary goal during this period is to use the spacecraft's uplink signal regeneration capabilities to measure the one-way light-time to the spacecraft. These data will be processed through JPL's orbit determination program (ODP) to generate an element set to predict the spacecraft ephemeris.

Table 2 gives a brief description of the results of each night's operations as of the time of writing. Once the required LCE gimbal angle relative to the satellite's orientation was established on November 11, 1995, the uplink was acquired within seconds of transmission on subsequent nights.

B. Satellite Predicts Generation

The satellite predicts for the TMF telescopes are generated from a satellite osculating-element set that is faxed to JPL from NASDA's Tsukuba tracking facility. Ephemeris files are generated at JPL for the transmitter and receiver telescopes, separately with offsets to account for the point ahead angle. The files are electronically transmitted to TMF and are loaded into the telescope control program (TCP). The TCP uses a spline-fitting routine to interpolate between the ephemerides to generate a "smooth" telescope-pointing file to track the ETS-VI satellite.

Table 2. Brief description of results for each night's operations.

Date	Description
30 October 1995	Heavy cloud cover precluded transmission
2 November 1995	Transmitted laser beacon to satellite; no uplink detected
5 November 1995	Transmitted laser beacon to satellite; no uplink detected
8 November 1995	First detection of uplink beacon
	Spacecraft gimball was being scanned
	Downlink detected and recorded
11 November 1995	Uplink detected for 45 min; became sporatic thereafter
	Spacecraft has difficulty tracking the ground station
	Downlink detected and recorded
14 November 1995	Uplink detected, and downlink data recorded
17 November 1995	Spacecraft detector gains adjusted to prevent saturation
	Satellite acquired within seconds of initiating beacon
	Uplink detected for 3 h
20 November 1995	0.6-m telescope malfunction
23 November 1995	Thanksgiving holiday
26 November 1995	Heavy cloud cover over TMF; no transmission

C. Data Links

GOLD requires the simultaneous real-time coordination of experimenters at NASDA, CRL, and the DSN to accomplish the laser transmission from TMF. The command and data flow diagram is shown in Fig. 2. In addition, during the early part of the experiment, the Federal Aviation Administration's (FAA's) Air Traffic Control Center in Palmdale, California, is assisting in aircraft avoidance strategies until an aircraft detection radar system at TMF is installed.

Commands to control the satellite's attitude during the experiment are generated at NASDA. CRL generates commands to control the LCE and sends them to NASDA. These commands are then transmitted from NASDA to DSS 27 at Goldstone, which relays them to the satellite.

The data link between CRL, JPL, and TMF provides near-real-time feedback on the measured onboard laser communications equipment sensors to the experimenters at TMF. The delay between the spacecraft transmission and the TMF reception is approximately 15 s. Spacecraft attitude control system (ACS) data are transmitted along with LCE data via S-band (2.3 GHz) telemetry to DSS 27. The DSN transmits these data to the NASDA Space Center at Tsukuba, where they are demodulated. The LCE data are transmitted to CRL for processing. CRL in turn transmits an ASCII data stream showing time, charge-coupled device (CCD) level, quadrant detector (QD) level, spacecraft laser-diode bias current, and coarse and fine tracking-sensor errors via integrated digital network services (ISDN) link to JPL. Because there are no ISDN links to Wrightwood, a 56-kbps telephone link is used to transmit the data from JPL to TMF.

III. The Transmitter

The transmitter consists of an argon-ion laser coupled to the 0.6-m telescope at TMF. The telescope is located in Building TM-12 at TMF, and its surveyed position is as follows:

Parameter	Position
Longitude	117° 40′ 52.55″
Latitude	34° 22′ 53.49″
Altitude	2.286 km

The telescope is used in the coude mode, which allows light to be coupled from large, high-power lasers into the telescope. The uplink laser is a prism-tuned coherent Innova-100 argon-ion laser that delivers a maximum 14.5-W linearly polarizer laser-light output power at 514.5 nm. At maximum power, the laser output is multimode. The laser is typically operated at an output power of about 13 W to achieve good beam quality. Coalignment of the laser beam with the telescope axis was achieved by adjusting the position of the telescope's secondary mirror until the focus was brought to a position on the optical bench. At this setting, the telescope's focal ratio was f/41, i.e., a focal length of 26.4 m.

A schematic of the optical train is shown in Fig. 3. A Conoptics electro-optic modulator impresses the uplink data stream on the optical carrier. The modulator consists of four potassium–dihydrogen–phosphate crystals and a polarizer. A data formatter—a Firebird 6000 bit-error rate tester (BERT) is used to generate a basic data pattern that is amplified—generates 0- to 1-V square-wave modulation that is amplified to the modulator's half-wave voltage in the driver, with 0 V corresponding to maximum transmission through the modulator.

After modulation, the beam is incident on a concave/convex lens pair that sets the beam divergence out of the telescope. This is nominally set at 20 μrad. A beam splitter separates the beam into two

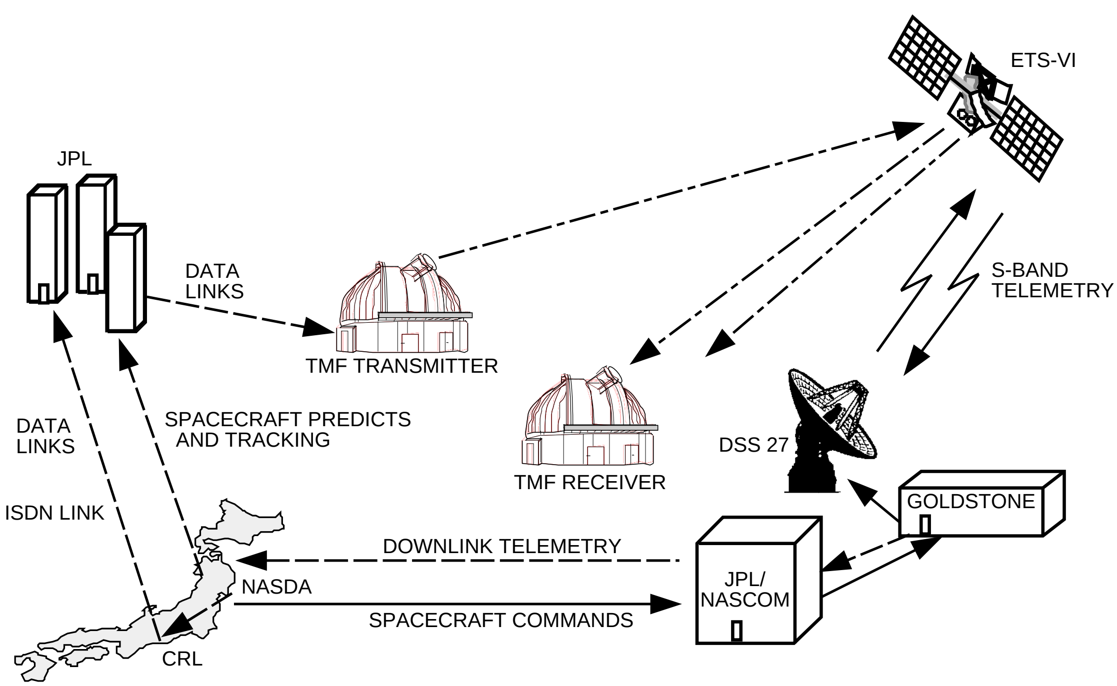

Fig. 2. Real-time coordination of several organizations is needed to accomplish the GOLD experiment. NASDA transfer commands to the DSN, which uplinks them to the ETS-VI. The spacecraft attitude and LCE sensor status are downlinked via S-band telemetry to Goldstone. The telemetry is demodulated by NASDA and forwarded to CRL for processing. During the optical uplink, CRL transmits LCE sensor data to JPL and TMF.

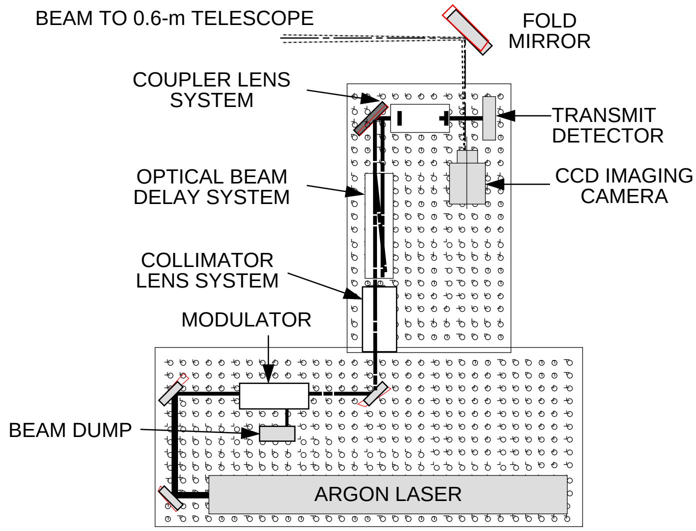

Fig. 3. Schematic of the optical train for the GOLD experiment showing the laser, the modulator, and the optical beam delay system used to provide temporal and spatial diversity of the optical beams transmitted to the satellite. Also shown are the detector used to monitor the modulated wave form and the CCD camera used to image the satellite.

equal parts, one of which goes through a 25-cm optical delay line with a path length difference greater than the laser's coherence length; $\lambda^2/\Delta\lambda$ is 10 cm. Both beams are reflected from a high-power dichroic beam splitter and are brought to a focus at the iris that is located at the f/41 focus of the telescope. From there the beams diverge and are reflected by the third coude flat and into the telescope. The beams are made incident on opposite sides of the 0.6-m telescope's primary mirror, a distance greater than the size of an atmospheric coherence cell. The use of spatial and temporal diversity mitigates the effects of atmospheric scintillation on the uplink beacon, thereby allowing the satellite's tracking system to better track the uplink beacon.

The CCD was a Pulnix camera and image intensifier with sensitivity down to 10^{-6} lux. This high-sensitivity camera has enabled us to track the satellite around apogee, where its brightness has varied from that of a magnitude 12 to a magnitude 14 star, depending on the phase angle of the solar panels. The avalanche photodiode (APD) transmitter detector monitors the modulation of the transmitted signal. In the ranging phase of the GOLD experiment, this detector will monitor the modulation sequence sent to the satellite, and these data will be transmitted to the receiver facility to initiate the timing sequence.

IV. The Receiver Facility

The optical receiver weighs approximately 30 kg and is mounted at the flange of the 1.2-m (f/29.5) telescope's bent Cassegrain focus. It consists of two CCD cameras and a 3-mm diameter low-noise APD (see Fig. 4). The cameras are a wide-field Cohu with an image intensifier for satellite acquisition and tracking and a Spectra Source CCD for atmospheric seeing measurements. These detectors are coaligned on an optical bench assembly to ensure that the downlink transmission is incident on both the tracking and communications detectors.

Satellite acquisition at the receiver is accomplished in a series of steps. It begins with calibration of the telescope's pointing direction relative to a 0.25-m Meade and a 0.4-m guiding telescope attached to the telescope's frame. A bright calibration star is acquired in the wider-field Meade and is transferred to the satellite CCD tracking detector in the smaller 1.2-m telescope field. Because the blind point accuracy of

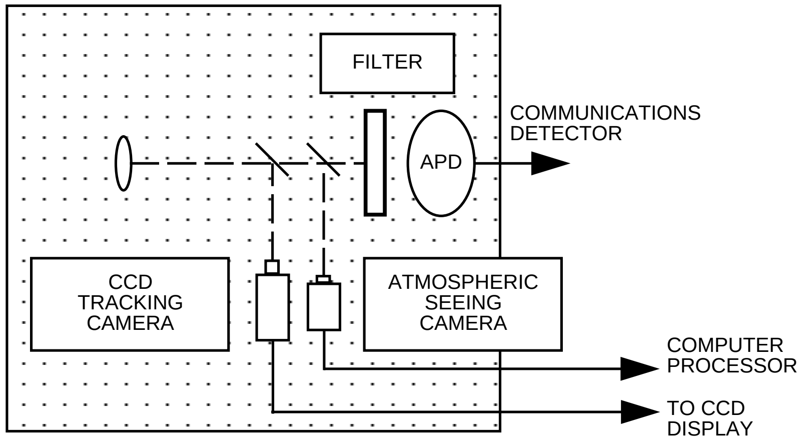

Fig. 4. Schematic of the optical receiver located at the focus of the 1.2-m telescope. CCD detectors in the optical train track the satellite and measure atmospheric seeing. The APD detects the 1.024-Mbps optical downlink data stream.

the telescope depends on separation between the calibration star and the satellite positions, the telescope is moved to a star in the vicinity of the satellite and the pointing offsets are noted for calibration. Near apogee, the satellite brightness ranges from the 12th to the 14th magnitude. Because of the large dynamic range between the third- to fifth-magnitude calibration stars and the satellite, an optical density no.-2 filter is placed in an electronically switchable holder located in front of the tracking camera. The filter is placed in the optical beam during the calibration and is switched out to acquire the satellite.

Atmospheric seeing measurements provide essential data for evaluating the optical link performance. The predictions of theoretical models that incorporate scintillation effects into the link performance will be compared with experimental results to validate the models. The data are taken at 15-min intervals and are reduced and transferred to the data analyst at the end of each night's run.

Downlink data-recovery electronics starts with the APD amplifier and signal conditioner. Depending on the mode of operation, the downlinked data are recovered through a bit synchronizer to recover the clock and then stored on a digital data recorder. This is shown in Fig. 5. When operating in the ranging or regeneration modes, before storage, the data are correlated with the transmitted data from the BERT located in the transmitter facility.

V. AVM Observatory

The atmospheric attenuation during the experiment is measured using the AVM observatory located at TMF. The AVM measures and records the intensity of selected stars over the course of the experiment. Star intensities are measured using three Johnson standard [V (100-nm wide centered at 560 nm), R (200-nm wide centered at 700 nm), and I (200-nm wide centered at 860 nm)] astronomical filters and three 10-nm-wide interference filters centered at the 532-nm, 860-nm, and 1064.2-nm wavelengths. The attenuation measurements made at 532 nm and 860 nm are used to estimate the atmospheric transmission at the uplink (514.5-nm) and downlink (830-nm) laser wavelengths. Transmission data at these wavelengths are calibrated using data taken through the astronomical V and I filters.

VI. Data Recovery and Data Processing

Data recovery from the satellite is accomplished using both S-band and optical downlinks. The uplink signal power is sampled at the CCD and QD at 1 Hz and transmitted on S-band telemetry. A 1-h

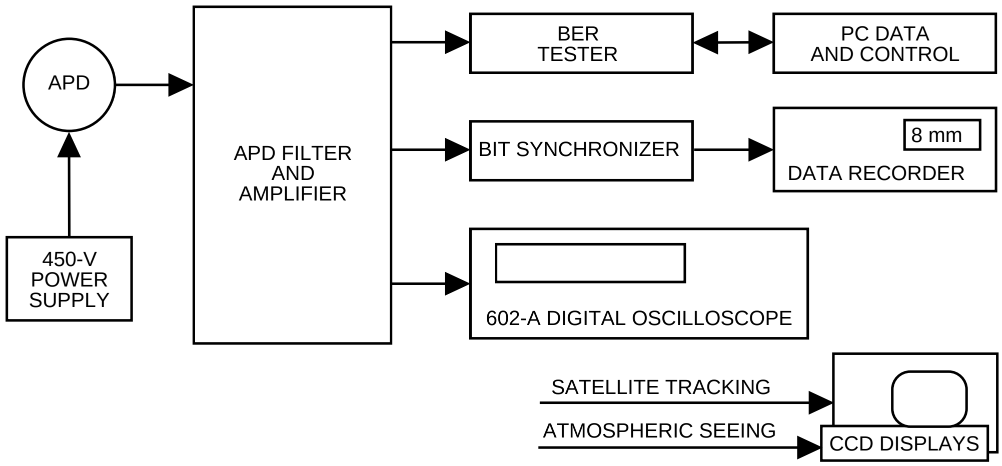

Fig. 5. Schematic of downlink data recovery. The APD output is bit synchronized and recorded for later processing. The 602-A digital oscilloscope monitors the low-pass-filtered downlink signal for long-term signal amplitude variations.

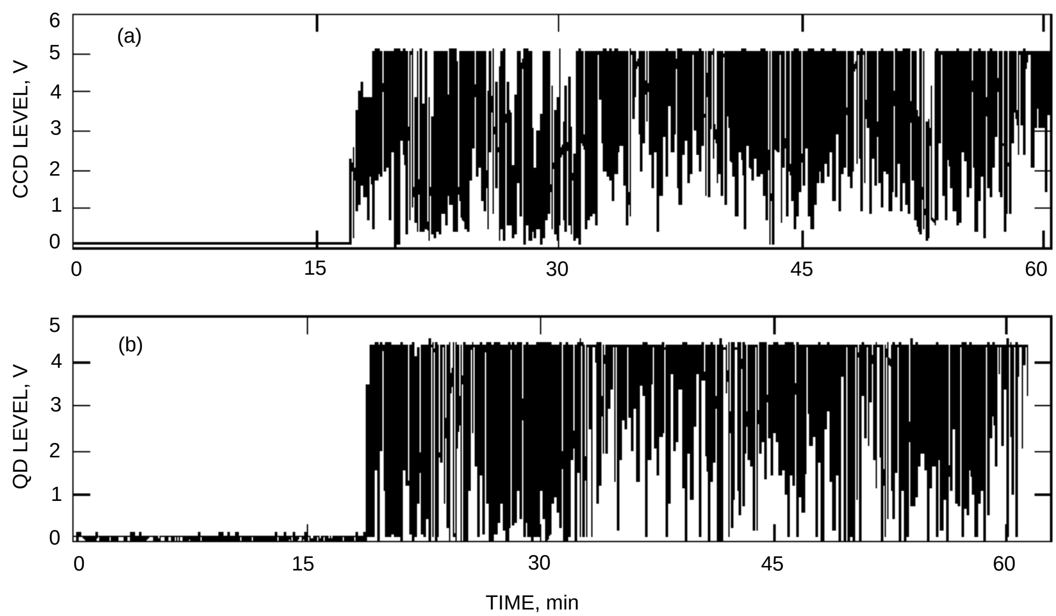

Fig. 6. A 1-hour sample of the uplink beacon as measured by the onboard CCD and QDs: (a) satellite coarse-tracking CCD sensor and (b) satellite fine-tracking QD sensor. The data show that the uplink signal is strong enough to saturate these detectors. In subsequent experiments, improved tracking performance was achieved by reducing both the transmitted intensity and the detector gain.

section of the uplink laser signal measured on the November-14 pass is shown in Fig. 6. The data clearly show saturation of the uplink power measurement on both the CCD and the QD. The coarse-pointing tracking system that is servoed around the CCD camera acquires the uplink first. The detected signal is then centered in the camera's field of view and tracked by the fine-tracking loop servoed around the QD's output. The delay between acquisition and tracking is on the order of minutes and can be clearly discerned in the two traces presented in Fig. 6. The dropouts seen in the data file are due to a combination of scintillation on the uplink beam and satellite and LCE pointing.

The LCE can impress three different data types on the downlink optical carrier. The first is the PN mode, in which an onboard PN sequence is transmitted to the ground station. This is shown in Fig. 7, where the random bit flips of the modulation that make up the 1.024-Mbps PN data stream are clearly evident. The second is the telemetry mode, where the LCE data are transmitted at 128 kbps (with redundant transmission and Manchester modulation up to the 1.024-Mbps channel rate). Included in this data stream are the laser diode levels, the CCD and QD signal levels, the fine- and coarse-tracking levels, the APD communication detector signal levels, and the measured uplink BER data. A sample of this data stream is shown in Fig. 8. The data show bit flips occurring in multiples of eight, consistent with the $\times 8$ multiplication of the 128-kbps data stream to achieve the 1.024-Mbps data rate.

The third mode, the regeneration mode, is shown in Fig. 9. In this mode, a 1-MHz square-wave uplink is detected by the communications detector and then retransmitted back to the ground station. Figure 9 clearly shows the regenerated 1-MHz uplink. It also shows the signal fades at a frequency inconsistent with atmospheric effects. We believe that these effects are caused by distortion in the modulated uplink beam. The causes of this distortion are being investigated. This regeneration feature will be used to perform the turnaround optical ranging experiments.

VII. Conclusions

GOLD is an international cooperative experiment that has demonstrated two-way optical communications between a satellite at a geostationary distance and an optical ground receiver. GOLD's thrust is to measure and understand the performance of the two-way optical link under a variety of atmospheric attenuation and turbulence conditions. The data accumulated from this experiment will enable better definition of the performance of optical communications systems for mission designers. Satellite ranging by detection and retransmission of an uplinked code is a time-tested approach in rf communications systems. A key goal of GOLD is to demonstrate this capability at optical frequencies for the first time.

To date we have amassed several gigabytes of data and videotapes of the optical links, along with measurements on the uplink scintillation. These data will be processed and the findings reported in future articles.

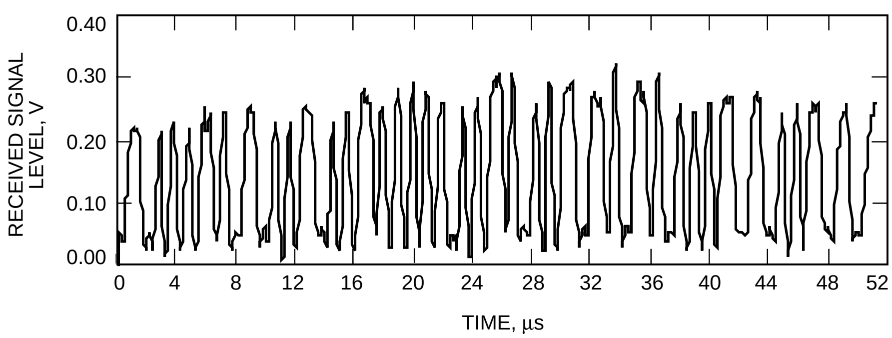

Fig. 7. Sample of 1.024-Mbps Manchester-coded PN sequence downlink telemetry from the LCE showing random bit flips.

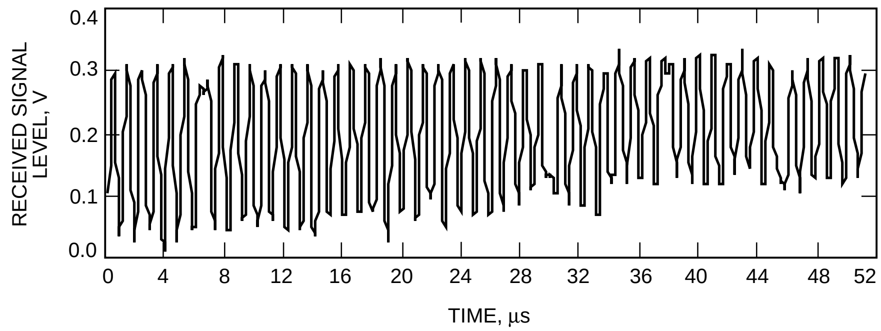

Fig. 8. Downlinked satellite telemetry at 128 kbps. The data show bit flips in multiples of eight consistent with 8X repetition of the bit pattern.

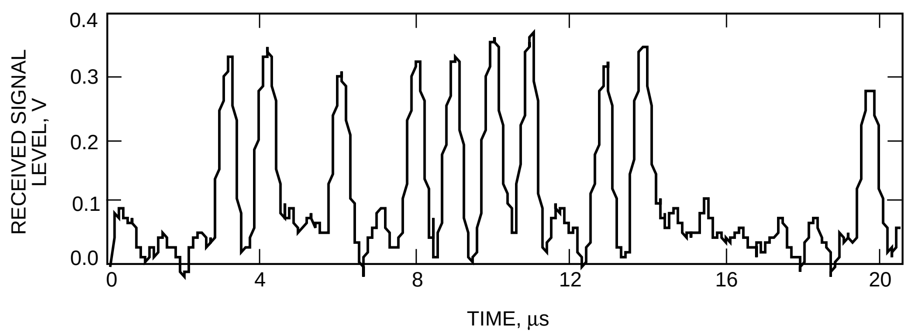

Fig. 9. Section of a 1-MHz square-wave regenerated from a 1-MHz uplink to the satellite.

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