Reduction of ETS-VI Laser Communication Equipment Optical-Downlink Telemetry Collected During GOLD

M. Toyoshima, K. Araki, Y. Arimoto, and M. Toyoda
Communications Research Laboratory, MPT
Koganei, Tokyo, Japan

M. Jeganathan, K. Wilson, and J. R. Lesh
Communications Systems and Research Section

Free-space laser communications experiments were conducted between the laser communication equipment (LCE) on board the Japanese Engineering Test Satellite VI (ETS-VI) and the ground station located at the Table Mountain Facility (TMF) during late 1995 and early 1996. This article describes the off-line data reduction process used to decode LCE telemetry (called E2) downlinked on the optical carrier during the Ground/Orbiter Lasercomm Demonstration (GOLD) experiments. The LCE has the capability of transmitting real-time sensor and status information at 128 kbps by modulating the onboard diode laser. The optical downlink was detected on the ground, bit synchronized, and the resulting data stream stored on a data recorder. The recorded data were subsequently decoded by off-line data processing that included cross-correlation of the known telemetry data format and the downlink data stream. Signals obtained from the processing can be useful not only in evaluating the characteristics of the LCE but also in understanding uplink and downlink signal quality.

I. Introduction

The Communications Research Laboratory (CRL) developed the laser communication equipment (LCE) on board the Japanese Engineering Test Satellite VI (ETS-VI) to demonstrate basic technologies for space laser communications systems [1–4]. The ETS-VI, designed for a geostationary orbit, was launched on August 28, 1994, by the National Space Development Agency (NASDA) of Japan. Due to an apogee kick engine failure, the ETS-VI was put in an elliptical orbit that made possible observation of the satellite from the Table Mountain Facility (TMF) in Wrightwood, California, approximately once every three days. It was believed that a more stable optical communication link could be established from TMF than from Tokyo, owing to better atmospheric conditions. The new orbit thus resulted in a cooperative experiment between CRL and NASA's Jet Propulsion Laboratory (JPL). The joint NASA/CRL optical communications experiment was called Ground/Orbiter Lasercomm Demonstration (GOLD). The GOLD experiments were performed from November 1995 to May 1996.

An overview of the GOLD project, including its objective and major accomplishments, can be found in [5–8]. In this article, we discuss extraction of meaningful data from the optical downlink telemetry. That is, we shall concentrate on the process of decoding the LCE data (E2). The analysis of the extracted data itself will be presented elsewhere.

II. Configuration of the Experiment System

GOLD experiments were performed between TMF and ETS-VI as shown in Fig. 1. First, an argon-ion laser beam, which delivered an average output power of approximately 13.2 W at 514.5 nm, was transmitted from TMF to the LCE. A charge-coupled device (CCD) sensor was used to acquire the uplink beam while a quadrant photodetector (QD) was used for tracking. The uplink laser beacon was tracked using the LCE's two-axis gimbal mirror and a fine-pointing mechanism. Once the tracking system locked on to the uplink, a laser diode (LD), with a wavelength of 830 nm and an output power of 13.8 mW, on board the LCE was turned on and pointed at TMF. The modulated optical downlink from the LCE was collected with a 1.2-m-diameter receiver at TMF and subsequently detected with an avalanche photodiode (APD). The detected signal was reshaped by a comparator, Manchester decoded, bit synchronized, and eventually stored on 8-mm data tapes for further analysis. A block diagram of the downlink data recovery process is shown in Fig. 2.

The downlink modulation mode of the LD was selectable from one of three formats: (1) RX mode—regeneration, and then retransmission, of uplink signal; (2) E2 mode—real-time transmission of telemetry at 128 kbps measured on board the LCE; and (3) PN mode—transmission of repeated 511-bit pseudorandom noise sequences. Regardless of the downlink data format, the signal was transmitted at 1.024 Mbps with a binary pulse position modulation (PPM) (or Manchester modulation). The RX or regeneration mode allowed measurement of overall link performance by comparing the signal received at TMF with the data transmitted from TMF. In the PN mode, the quality of the optical downlink was measurable in real time using bit-error-rate testers (BERTs). The E2 mode, which contained various sensor and status information, provided a means to understand the functioning of the LCE and was most useful in evaluating the LCE's performance.

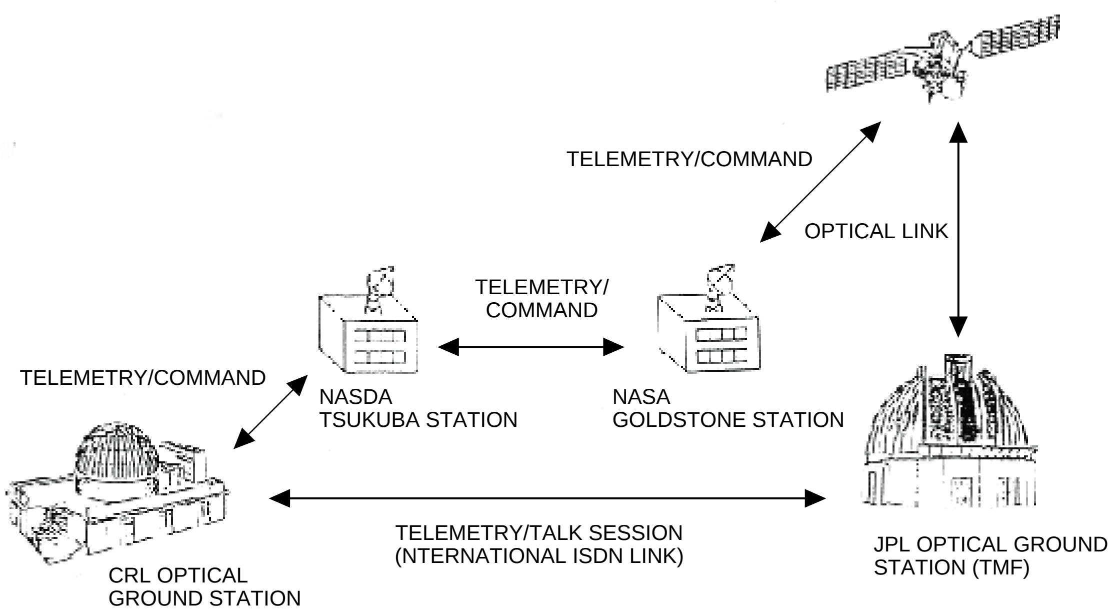


Fig. 1. Configuration of the GOLD experiment.

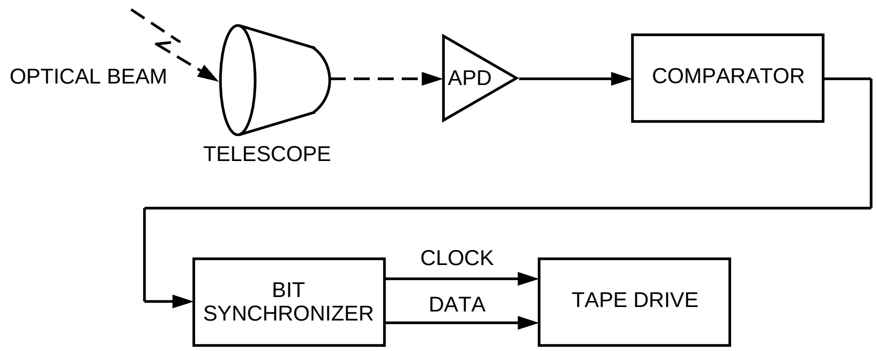


Fig. 2. Block diagram of the optical receiver at TMF.

During the 3- to 5-hour duration of the GOLD experiments, data measured by LCE sensors were sent on the S-band (2.3-GHz) telemetry link to the command terminal at CRL by way of the Deep Space Network (DSN) and NASDA. The telemetry received at the CRL was converted to appropriate engineering units and then sent to JPL and TMF via an international integrated services digital network (ISDN) link. The S-band downlink provided only 1-Hz sampled data. The optical E2 telemetry data, however, were capable of providing high-frequency (up to 500-Hz) sampled sensor data. No attempt was made to decode the E2 telemetry in real time during the experiments. These optical downlink data were stored on tape for future analysis. Postdetection off-line processing of the LCE real-time optical telemetry is the subject of this article and will be discussed in the following sections.

III. The E2 Data Format

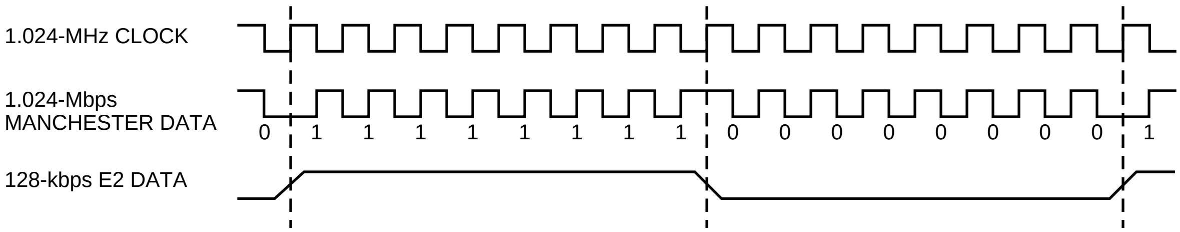
As mentioned earlier, E2 data were the real-time telemetry downlinked to the ground station via the optical carrier that contains values measured on board the LCE. The format of the modulated waveform of the 1.024-Mbps Manchester-coded E2 data stream is shown in Fig. 3(a). To arrive at the desired communication data rate of 1.024 Mbps, each bit in a 128-kbps telemetry data stream was repeated 8 times. The 1.024-Mbps E2 data stream was made up of 2048-bit-long "frames." Each frame lasted 2 ms, resulting in a frame rate of 500 Hz. From the high degree of redundancy of the E2 data bits, it was possible to correct for bit errors in the 1.024-Mbps E2 data stream as well as compute bit-error rates.

The structure of the E2 data format is given in Fig. 3(b), and its contents include information such as the uplink bit-error count, the output of the APD detector, the variation of the satellite attitude, the received optical power, etc. Each of the E2 data fields is 8-bits wide and, thus, the values range from 0 to 255. Proper conversions are required to translate the 8-bit number to a physical quantity. Since each bit is repeated 8 times, a field occupies 64 bits. The frame header is a sequence of 128 ones. The header is followed by 12 sets of data values and separators. The separators are 64 bits of ones. The last part of the frame contains 6 fields without separators. Each frame, therefore, consists of 18 8-bit-wide fields with headers and separators embedded between them. In fact, there are only 144 information bits (18 bytes) in the 2048-bit frame, representing an engineering information content rate of only about 7.2 kbps. It must be noted that it was possible for all the bits stored on tape to be reversed depending on whether the "invert" switch on the bit synchronizer was turned on or off.

IV. Off-Line Processing

The data stream stored on tapes at 1.024 Mbps amounts to a few gigabytes for each GOLD experiment, which typically lasted from 3 to 5 hours. An example of the stored data stream is shown in Fig. 4. As can be seen from the E2 format in Fig. 3, the data show successive 8 bits, as expected. An error bit can be found in the first line in Fig. 4. The bit-error rate (BER) for the displayed data in Fig. 4 can be estimated to be less than 9.8×10^{-4}.

(a)



(b)

64 bits

	DATA FIELD	8 bits bit 7	8 bits bit 6	8 bits bit 5	8 bits bit 4	8 bits bit 3	8 bits bit 2	8 bits bit 1	8 bits bit 0
1	HEADER								
2	HEADER								
3	SEPARATOR								
4	HIGH-FREQUENCY FPM MIRROR ANGLE (X-AXIS)								
5	SEPARATOR								
6	HIGH-FREQUENCY FPM MIRROR ANGLE (Y-AXIS)								
7	SEPARATOR								
8	POINT AHEAD (PA) (PZT VOLTAGE) X								
9	SEPARATOR								
10	POINT AHEAD (PZT VOLTAGE) Y								
11	SEPARATOR								
12	LD PA MONITOR ANGLE X (8-kHz MODULATION)								
13	SEPARATOR								
14	LD PA MONITOR ANGLE Y (8-kHz MODULATION)								
15	SEPARATOR								
16	LD POWER LEVEL MONITOR (8-kHz MODULATION)								
17	SEPARATOR								
18	RECEIVED ANGLE X (315-Hz MODULATION)								
19	SEPARATOR								
20	RECEIVED ANGLE Y (315-Hz MODULATION)								
21	SEPARATOR								
22	RECEIVED POWER LEVEL (315-Hz MODULATION)								
23	SEPARATOR								
24	APD CURRENT (40-Hz BANDWIDTH)								
25	SEPARATOR								
26	APD RECEIVED POWER (400-Hz BANDWIDTH)								
27	CCD X1 (HIGHER 8 BITS)								
28	CCD X2 (LOW 1 BIT)								
29	CCD Y								
30	UPLINK BER								
31	YAW ANGLE								
32	E2 STATUS								

1 FRAME (64 x 32 = 2048 bits)

Fig 3. The E2 data : (a) format of the data stream and (b) the telemetry data format showing contents of one 2048-bit-long frame. The shaded regions indicate known constant bit values.

The algorithm shown in Fig. 5(a) was used to extract the E2 telemetry data from the stored data stream. First, the stored data stream was loaded into a temporary buffer [Buff2 in Fig. 5(b)]. The buffer size was set to twice the size of a frame for performing correlation. The buffer shift process wrote the data in Buff2 to Buff1, and the next data stream was loaded again into Buff2. A masking process that retained header and separator bits and removed those telemetry data bits that varied with time was used to keep the maximum correlation value constant. Cross-correlation was performed between the known E2 telemetry format and the buffered data stream. The cross-correlation process performed the logical

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Fig. 4. Digital output of a segment of data stream downlinked on the optical carrier over a distance of about 40,000 km at 1.024 Mbps. The BER is less than 9.8 x 10^{-4} for the time interval shown.

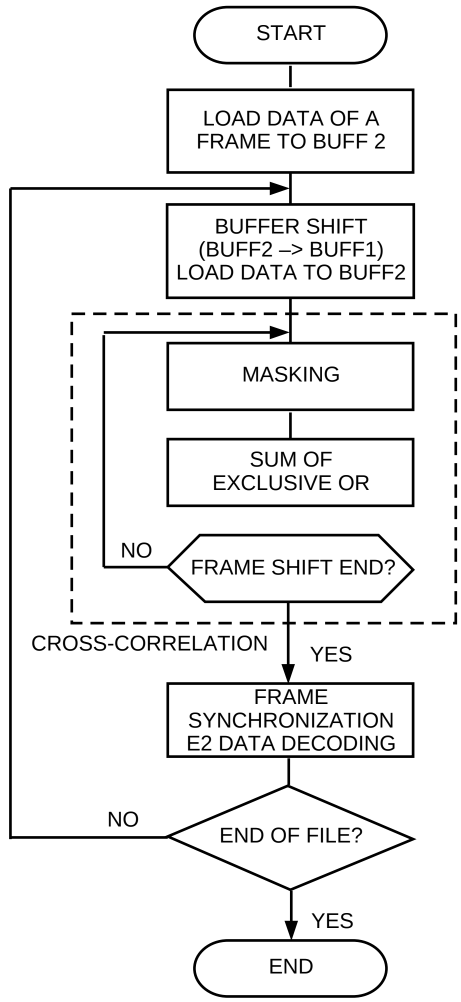
exclusive-or (XOR) operation between the E2 format and the stored data stream for every bit shift. If the correlation was maximum, frame synchronization was completely established at the appropriate point in the data stream. After the correlation process, the next frame from the data stream was loaded into the Buff2 buffer. An example of the cross-correlation result between the known E2-format data and the stored data stream is shown in Fig. 6. The maximum value during each period corresponds to the position where frame synchronization is established. The figure clearly shows that the cross-correlation has a periodic component. This periodicity is, of course, due to the fact that the correlation peaks every 2048 bits (or 2 ms), which represents E2 frame synchronization. The 8-times repetition of the data bits results in a broadening of the correlation peak. Unusually low correlation values in the plot are the result of burst errors (typically due to downlink power degradation caused by laser-beam-pointing errors on the LCE).

The bit-error count during 2-ms intervals for a segment of the downlink data stream is shown in Fig. 7. During stable optical link, there were very few bit errors in the received data. The BER in Fig. 7 was 1.6×10^{-5} at best. Occasional beam-pointing errors, as mentioned earlier, resulted in burst errors lasting several ms. After frame synchronization was established, the contents of the E2 telemetry were error corrected and decoded. Physical values with scientific units were then obtained by appropriate engineering conversions based on laboratory measurements of the flight hardware before launch.

V. Results of the E2 Telemetry Data Reduction

Examples of decoded E2 telemetry data are plotted in Figs. 8(a) and (b). Figure 8(a) shows the azimuth and elevation components of the mirror angles of the spacecraft terminal fine-pointing mechanism (FPM), sampled at a frequency of 500 Hz. The variation in Fig. 8(a) includes compensation for both the satellite attitude variation and, in this case, the coarse tracking error of the gimbal mirror. The coarse tracking loop in the autotracking mode has an operational frequency of about 2 to 3 Hz. It follows, therefore, that the low-frequency envelope (around 2 to 3 Hz) of the angles in Fig. 8(a) corresponds to the coarse tracking error of the gimbal mirror. Because the optical link already was established, the fine-tracking error, that is, the measurement error of the angles in Fig. 8(a), is considered to be much less than the 30-μrad downlink beam divergence. Figure 8(b) shows the received optical power in nW at the APD

(a)



(b)

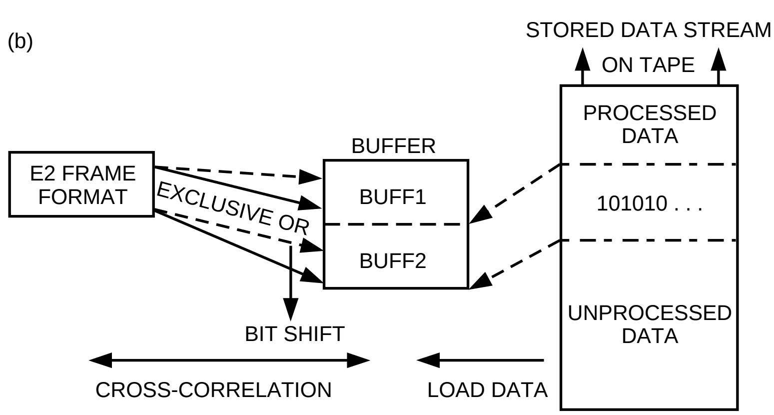


Fig. 5. The E2 data (a) flowchart, describing off-line data processing of E2 data, and (b) the E2 data-processing algorithm.

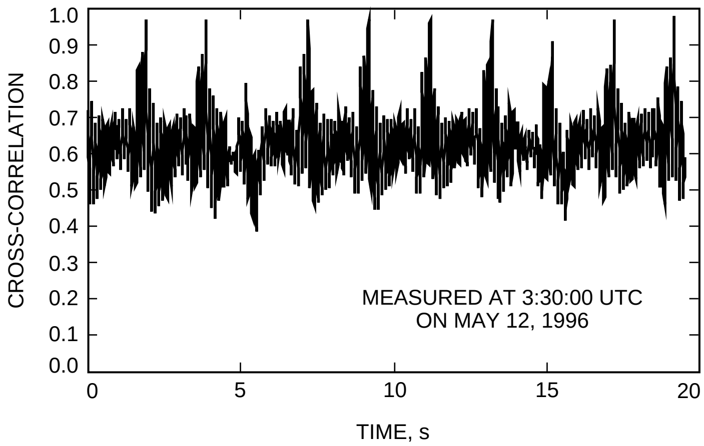


Fig. 6. Cross-correlation between the known E2 frame format and the stored data stream. The correlation peaks corresponding to frame synchronization occur every 2 ms.

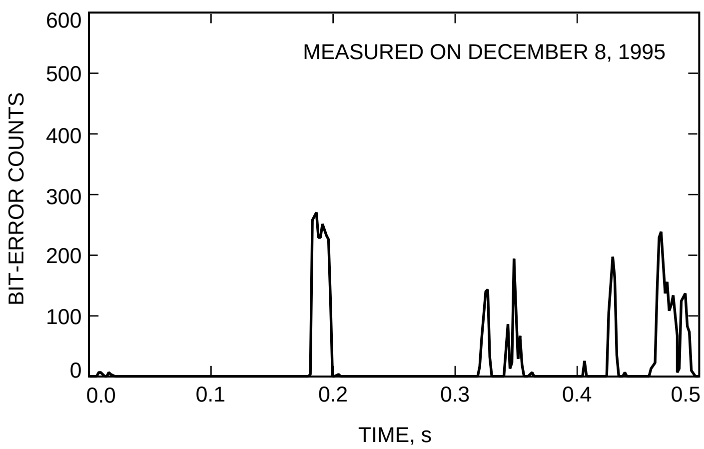


Fig. 7. Bit error counts during 2-ms (or one-frame) intervals obtained from a segment of the optical downlink. Burst errors are apparent.

for the same time interval as shown in Fig. 8(a). The two lines in Fig. 8(b) represent the wideband (400-Hz-bandwidth) data, or "propagation," and narrowband (40-Hz-bandwidth) data, or "APD current." The discontinuity in the plots in Fig. 8 corresponds to a loss of signal caused by burst errors as shown in Fig. 7. These telemetry data can be very useful in analyzing the operation of the LCE in detail. For example, since a BER of better than 10^{-5} can be achieved with an optical power greater than 0.63 nW at the APD receiver of the LCE, it can be confirmed from Fig. 8(b) that an optical uplink with a BER of less than 10^{-5} was established intermittently. In addition, it can be confirmed from the above results that the E2 circuitry in the LCE worked well in orbit.

VI. Conclusion

Stable ground-to-satellite optical communication links with a low BER were successfully established for the first time during the GOLD international cooperative experiment. The high data rate telemetry that was downlinked on the optical carrier was processed to gain better insight into the LCE's operation. Information on the in-orbit operation of the E2 electrical system in the LCE was obtained from the processed data. These significant results will be useful not only to evaluate the LCE but also to develop the next generation of free-space optical communication payloads. Analysis of the high-frequency sampled data extracted from E2 telemetry is in progress to understand, for example, the effects of atmospheric turbulence and the causes of satellite pointing error.

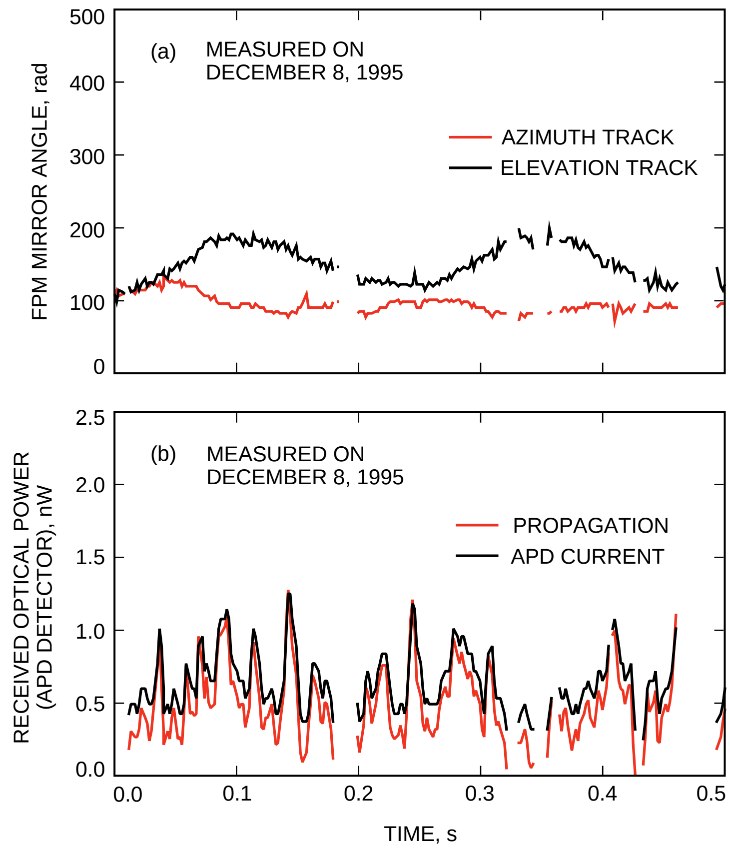


Fig. 8. Examples of decoded E2 telemetry data: (a) FPM mirror angles in outer space obtained from the optical link at the sampling frequency of 500 Hz, which include the residual error in coarse tracking angle under the satellite attitude dynamics, where the azimuth and elevation tracks correspond to the roll and pitch of the satellite coordinate system, respectively, and (b) the received optical power level as seen by the APD detector. Propagation refers to 500-Hz sampling of a 400-Hz-bandwidth signal, while APD current refers to 500-Hz sampling of a 40-Hz-bandwidth circuit.

References

[1] Y. Arimoto, M. Toyoshima, M. Toyoda, T. Takahashi, M. Shikatani, and K. Araki, "Preliminary Result on Laser Communication Experiment Using ETS-VI," *SPIE Proceedings*, vol. 2381, San Jose, California, pp. 151–158, 1995.

[2] K. Araki, Y. Arimoto, M. Shikatani, M. Toyoda, M. Toyoshima, and T. Takahashi, "Performance Evaluation of Laser Communication Equipment Onboard the ETS-VI Satellite," *SPIE Proceedings*, vol. 2699, San Jose, California, pp. 52–59, January 1996.

[3] M. Toyoda, M. Toyoshima, T. Takahashi, M. Shikatani, Y. Arimoto, K. Araki, and T. Aruga, "Ground to ETS-VI Narrow Laser Beam Transmission," *SPIE Proceedings*, vol. 2699, San Jose, California, pp. 71–80, January 1996.

[4] M. Toyoshima, T. Fukazawa, M. Toyoda, T. Takahashi, M. Shikatani, T. Takahashi, K. Araki, Y. Arimoto, and T. Aruga, "Measurements of Background Noise from Earth Surface Using the ETS-VI/LCE," *SPIE Proceedings*, vol. 2699, San Jose, California, pp. 93–102, January 1996.

[5] K. Wilson, "An Overview of the GOLD Experiment Between the ETS-VI Satellite and the Table Mountain Facility," *The Telecommunications and Data Acquisition Progress Report 42-124, October–December 1995*, Jet Propulsion Laboratory, Pasadena, California, pp. 8–19, February 15, 1996.
http://tda.jpl.nasa.gov/tda/progress_report/42-124/124I.pdf

[6] M. Jeganathan, K. Wilson, and J. R. Lesh, "Preliminary Analysis of Fluctuations in the Received Uplink-Beacon-Power Data Obtained From the GOLD Experiments," *The Telecommunications and Data Acquisition Progress Report 42-124, October–December 1995*, Jet Propulsion Laboratory, Pasadena, California, pp. 20–32, February 15, 1996.
http://tda.jpl.nasa.gov/tda/progress_report/42-124/124J.pdf

[7] K. Wilson, J. Lesh, K. Araki, and Y. Arimoto, "Preliminary Results of the GOLD (Ground/Orbiter Lasercomm Demonstration) Experiment Between Table Mountain and the ETS-VI Satellite," *SPIE Proceedings*, vol. 2699, San Jose, California, pp. 121–132, January 1996.

[8] K. Wilson, "Preliminary Results, Analysis, and Overview of Part I of the GOLD Experiment," paper invited to the CRL International Symposium on Advanced Technologies in Optical Communications and Sensing, Tokyo, Japan, March 13, 1996.