An Overview of the Galileo Optical Experiment (GOPEX)

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Uplink optical communication to a deep-space vehicle has been demonstrated. In the Galileo Optical Experiment (GOPEX), optical transmissions were beamed to the Galileo spacecraft by Earth-based transmitters at the Table Mountain Facility (TMF), California, and Starfire Optical Range (SOR), New Mexico. The demonstration took place over an eight-day period (December 9 through December 16, 1992) as Galileo receded from Earth on its way to Jupiter, and covered ranges from 1–6 million km. At 6 million km (15 times the Earth–Moon distance), the laser beam transmitted from TMF eight days after Earth flyby covered the longest known range for transmission and detection.

I. Introduction

Optical communications technology is considered a viable contender for future space link applications. This is especially true for mini- and micro-spacecraft applications, where weight and size are the primary driving considerations. System studies, technology development, and deployment planning have been under way for the past 13 years and have resulted in a plan for both the spacecraft and Earth-reception ends [1]. Although there has been significant progress on component technologies, the need for systems-level demonstrations was becoming apparent. The Galileo spacecraft's second flyby of Earth, part of the Venus-Earth-Earth Gravity Assist (VEEGA) trajectory [2], afforded a unique opportunity to perform a deep-space optical uplink with the spacecraft as it receded from Earth on its way to Jupiter. The Galileo Optical Experiment (GOPEX) was conducted over the period December 9–16 from transmitter sites at Table Mountain Facility (TMF), California (see Fig. 1) and at the Starfire Optical Range (SOR), New Mexico (see Fig. 2). The spacecraft's Solid-State Imaging (SSI) camera was used as the optical communications uplink receiver. The experiment had three principal objectives, namely:

(1) Demonstrate laser beam transmission to a spacecraft at deep-space distances.

(2) Verify laser-beam pointing strategies applicable to an optical uplink based solely on spacecraft ephemeris predicts.

(3) Validate the models developed to predict the performance of the optical link.

Galileo's phase angle after its second Earth flyby was approximately 90 deg. Thus, as the spacecraft receded from Earth, it looked back at a half-illuminated Earth image. This geometry allowed laser beam transmission against a dark-Earth background. GOPEX was therefore conducted between 3:00 a.m. and 6:00 a.m. PST. This nighttime uplink had two distinct advantages:

(1) It allowed the uplink to be performed at the frequency doubled neodymium:yttrium-aluminum-garnet (Nd:YAG) laser wavelength of 532 nm, where the responsivity of the SSI camera is high.

(2) Long-exposure camera frames could be taken, which facilitated the identification of the detected laser transmissions. Pre-experiment analysis of the stray-light intensity in the focal plane of the camera showed that the camera shutter could remain open for up to 800 msec before the scattered light from the bright Earth saturated the pixels that detected the laser uplink.[1]

By scanning the camera across the Earth, parallel to the Earth's terminator, during each exposure, the laser signal was readily distinguished from spurious noise counts in the camera frame. With this strategy, the laser uplink appeared as a series of evenly spaced bright dots within the camera frame, quite distinct from other features in the frame.

GOPEX was a very successful experiment. Frames of laser uplink data were received on each of the seven days of the experiment. (The demonstration covered a period of eight days, but other spacecraft activities precluded laser transmission on Day 5.) The laser uplink was unequivocally detected on 48 of the 159 GOPEX frames taken. Because of an unanticipated pointing bias in the scan platform direction, pulses were not detected on any of the frames with exposure times less than 400 ms. Inclement weather, aborted transmissions, and restrictions imposed by regulatory agencies and by the Galileo Project team accounted for the loss of data on the remaining frames.

This article, an overview of the GOPEX demonstration, describes the experiment and presents a summary of the experimental results. An overview of the laser transmitters from the two sites is presented in Section II. A description of the optical receiver is given in Section III, followed by a brief discussion of the telescope pointing strategy in Section IV. The GOPEX results are presented in Section V, and the conclusion is presented in Section VI.

Companion articles included in this issue describe various aspects of the GOPEX demonstration in more detail. The article on telescope pointing [3] describes the process used to develop the Galileo telescope pointing files for the TMF and SOR transmitters and the strategy implemented in pointing the TMF telescope to the spacecraft. The article on the TMF optical train [4] describes the optical train design, laser beam characterization, characterization of the transmitter by using retroreflecting Earth-orbiting satellites in precursor experiments, and the TMF GOPEX uplink procedures. A. Biswas' article [5] describes in detail the characterization of the optical detection system that was used in the precursor experiments. This optical system was used to detect the laser signal retroreflected from the target satellites.

It was important to control the timing of the laser emission to ensure that the pulses arrived at the spacecraft while the camera shutter was open. Pulse-by-pulse monitoring of the laser output during GOPEX, stipulated in the GOPEX concurrence negotiated with the Galileo Project Office, not only satisfied the concurrence requirements but also provided the necessary data for comparing the received signal strengths with theoretical predictions of the optical channel. The article "GOPEX Laser Transmission and Monitoring System" [6] describes the configuration of the transmission and monitoring system at TMF and presents the laser output data recorded at this facility taken during GOPEX. These data were used to improve the estimates of the predicted signal strengths at Galileo. Good agreement was found between the experimental results and the theoretical predictions. The article by Levine, Shaik, and Yan [7] describes the analysis of the GOPEX data.

Ground-based deep-space optical communications of the future will employ a strategy of site diversity in ground transceiver deployment to ensure good line-of-sight visibility between the spacecraft and the transceiver station. A study of the December weather statistics for TMF over a four-year period, 1988 to 1991, showed that for 77 percent of the time the cloud cover at this facility lasted for more than two days.[2] The threat of inclement weather at TMF during GOPEX posed an unacceptably high risk to the demonstration. A dual-site transmitter strategy was therefore implemented to mitigate this risk. The selection of SOR as a second uplink site was based on a set of selection criteria with geographical location, (i.e., proximity to the TMF site) and the capabilities of site personnel as the principal considerations. The final article in this series [8] describes the SOR optical system along with the GOPEX and the precursor experiment operations as they were conducted from SOR.

[1] K. E. Wilson, "GOPEX Second Transmission Site" briefing to GOPEX Advisory Board (internal document), Jet Propulsion Laboratory, Pasadena, California, May 19, 1992.

[2] Ibid.

II. GOPEX Laser Transmitters

The laser transmitters at both sites consisted of a frequency-doubled Nd:YAG laser (532 nm) coupled to a Cassegrain telescope through a coudé mount arrangement. The transmitter characteristics are given in Table 1.

The TMF telescope used was the 0.6-m equatorial-mount astronomical telescope that had been used in 1968 to perform the laser transmission to the Surveyor 7 spacecraft on the Moon. The telescope is f/36 at the coudé focus, and the appropriate beam-forming lens set was inserted into the optical train, Fig. 3, to achieve the required laser beam divergence. The divergences used are given in Table 1. In the optical-train design, the laser beam reflected off the 0.2-m secondary mirror and illuminated a 15-cm subaperture on the telescope primary. The advantage of this subaperture illumination over full aperture was that it eliminated the large loss in transmitted signal strength that would have resulted from occultation by the 0.2-m secondary.

The two beam-forming lens sets, one for the 110-mrad divergence and a second for the 60-mrad divergence, were designed so that the laser beam was brought to a focus at a distance of 1.3 km when the telescope was focused at infinity. Light from the reference stars that was used to point the telescope to Galileo was collected across the full 0.6-m collecting aperture of the instrument.

The SOR telescope used for GOPEX was the 1.5-m system that is used for adaptive-optics experiments at this facility. A thin-film-plate polarizer served as the aperture-sharing element and coupled the laser output to the telescope optical train while allowing reference stars to be observed by the charge-coupled device (CCD) camera positioned in the orthogonal leg of the optical train. The required laser beam divergence was achieved by focusing the outgoing laser beam at ranges of 38km and 19km in the atmosphere. This corresponded to 40-μrad and 80-μrad beam divergences, respectively.

The output from the SOR laser was transmitted through the full 1.5-m aperture of the telescope. The effects of occultation by the 10-cm secondary were mitigated by reconfiguring the laser resonator so that it generated a flat-top intensity profile across the beam. With this design, occultation by the secondary accounted for less than 1 percent of the transmission loss in the optical train.

III. GOPEX Receiver

The GOPEX receiver was the Galileo SSI camera. The camera was mounted on the scan platform located on the despun section of the spacecraft. It consisted of a 12.19 x 12.19-mm CCD array composed of 800 $\times$ 800 silicon pixels and was located at the focal plane of a 1500-mm focal length f/8.5 Cassegrain telescope [9]. The angular resolution per pixel was 10.6 μrad, and the full well capacity per pixel was 100,000 electrons. The dark current was less than 10 electrons per pixel with 8-electrons readout noise. The camera has four gain states that are used to scale the video analog data to the 8-bit ADC. Over the eight-day experiment window, two gain states were used for GOPEX. Gain state 2, in which a data number (dn) of 255 corresponded to 100,000 detected photoelectrons, was used on the first two days; gain state 3, where the maximum dn corresponded to 40,000 detected photoelectrons, was used on the subsequent days.

Field correction elements, an eight-position filter wheel, and a two-blade shutter are positioned in the intervening space between the telescope primary and the focal plane of the SSI camera. The latter two elements were inherited from the Voyager program. The filter wheel contained six 20-nm bandpass color filters, one clear filter, and one infrared transmitting filter that were rotated into the optical train as required to enable the color reconstruction of an imaged scene. For GOPEX, the green color-filter with 50-percent transmission at 532 nm (the peak transmission was 90 percent at 560 nm) was used to reduce the effects of Earth-shine.

The shutter was operable in any one of 28 exposure times, ranging from 4.16 msec to 51.2 sec. The selection of exposure times was based on the estimate of the best balance between the conflicting requirements of short duration, to reduce stray light effects, and long duration, to ensure that enough pulses were detected across the image to confirm the laser uplink. Data taken at the Gaspra encounter were used to improve the original estimate of the scattered light intensity. Estimates of the scattered light rates for the GOPEX transmitter sites ranged from a high of 110 e-/msec on the end of the first day for the SOR location to 32 e-/msec on day 8 for both sites.[3] Based on these estimates, the GOPEX imaging sequence was designed with shutter times ranging from 133 to 800 msec. Actual scattered light rates measured during GOPEX ranged from 8 to 10 e-/msec [7]. These low scatter levels would have allowed longer camera exposure times and the accumulation of more data.

[3] K. Klaasen, "Scattered Light Predictions for GOPEX Observations," JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, July 15, 1992.

IV. GOPEX Telescope-Pointing Strategy

The telescope-pointing files for both transmitter sites were generated from updates of the spacecraft ephemeris file that were provided to the GOPEX team on December 8 and December 11. The strategy was to off-point the telescope from reference stars that were located within 0.5 deg of the spacecraft's position. Over the eight-day period, six guide stars of magnitudes 6 to 10 were used to point the TMF telescope at Galileo.

Transmission to Galileo was accomplished by using a "point and shoot" approach. In this technique, the telescope was set to track the reference star in the intervals between the three-second bursts of laser transmissions. Two and one-half minutes before laser transmission, the reference star was positioned in the center of the field of view of the focal plane aperture at coudé and the telescope was calibrated. Ten seconds prior to transmission, the telescope was pointed to Galileo's predicted location and set to track the spacecraft for the next thirteen seconds. This procedure was repeated during the three- to six-minute intervals between the laser transmissions. Because the telescope calibration was performed just before transmission, the pointing errors introduced by mount sag were reduced significantly. In addition, the high elevation of the spacecraft during the uplink—the experiment was conducted when Galileo's elevation from TMF was greater than 30 deg—and the proximity of the reference stars obviated the need to implement atmospheric refraction compensation techniques while pointing to the spacecraft.

To test the accuracy of the telescope-pointing predicts, SOR dithered the laser beam in a circle of 85-mrad radius about the predicted position of the spacecraft, while the TMF transmitter pointed directly to the predicted spacecraft position. This was done on the first day of GOPEX for several of the long-duration frames (frames with exposure times greater than 400 msec). The results are shown in Fig. 4. Nine pulses can be clearly discerned in the figure; seven are from the 15-Hz TMF transmitter, and two are from the 10-Hz SOR transmitter. Without beam scanning, a total of four pulses would have been detected from the SOR transmitter. The presence of only two pulses from SOR and seven from TMF clearly demonstrates that the error in the telescope pointing predicts was significantly less than 85 mrad. This was further confirmed by the successful use of a 60-mrad beam from TMF for laser transmissions on the last three days of GOPEX.

V. GOPEX Results

A summary of the detected GOPEX laser transmissions over the duration of the experiment is given in Table 2. Over the eight-day period, transmissions to the spacecraft were made over a range beginning at 600,000 km on the morning of December 9 and ending at 6,000,000 km on the morning of December 16. Signals were successfully detected on each of the experiment days, although not on all frames within a given day. There were several reasons for the lack of detection on all frames. These included unfavorable weather (which caused outages), regulatory agency restrictions on transmissions, temporary signal-to-noise anomalies on the downlink, and an unexpected camera-pointing bias error. Final results show that the laser uplink was successfully detected on 50 camera images during the experiment window. Two representative images showing the detected laser pulses are shown in Figs. 4 and 5.

Although transmitted laser pulses were detected on each of the seven days of the uplink, adverse weather at the sites and not telescope pointing was the most severe impediment to successfully detecting the laser transmissions. Winter storms at TMF and SOR brought snow, heavy clouds, and ground fog to these facilities. Transmission from TMF was most affected on the first and fourth days of the experiment. The last seven frames obtained on the first day were taken with TMF completely overcast and SOR in daylight. On the fourth day, falling snow at TMF precluded transmission from this facility; also on that day, during only one of the ten transmissions there was clear sky between the SOR transmitter and the spacecraft. Falling snow and heavy cloud cover prevented transmission from SOR on the last three days.

Restrictions from regulatory agencies were also responsible for data outages. Transmission of the GOPEX laser beam into space required the concurrence of the U.S. Space Defense Operations Center (SPADOC). On the first day, SPADOC restrictions prevented TMF from transmitting during four frames. An additional frame was lost because the ground receiving station (at Goldstone, California) momentarily lost lock on the Galileo spacecraft downlink signal. Owing to the loss of downlink signal, the orientation of the spacecraft could not be confirmed, and since one of the GOPEX concurrence conditions was that laser uplink would proceed only if the spacecraft orientation was known, no laser transmissions were sent during this data outage.

During the first two days of GOPEX, the spacecraft orientation resulted in the low-gain antenna being pointed away from Earth. This resulted in a low signal-to-noise ratio (SNR) of the spacecraft downlink and was evidenced by the numerous burst errors in the downlinked data. See also [7]. The GOPEX images for these days showed numerous streaks across the frames, which made it difficult to discern successful laser transmissions on the images. Just after the GOPEX uplink on day 2, a planned spacecraft maneuver was executed. This maneuver increased the SNR of the radio frequency downlink and resulted in clearer GOPEX images for the remainder of the demonstration.

The GOPEX demonstration required that the SSI camera be operated in a mode for which it was not designed (that is, slewing the camera during imaging). To get the GOPEX transmitter sites in the field of view during the slew, the camera was initially pointed to a position above or below the targeted direction and the shutter was opened at a prescribed time after the start of the slew. Uncertainties in the stray-light intensity in the focal plane of the SSI camera dictated the shutter times used for GOPEX. The times chosen ranged from 133 to 800 msec, and these were loaded into the spacecraft sequence of events prior to GOPEX. As the experiment progressed, it was observed that laser transmissions were consistently detected only on frames with greater than 400-msec exposure times; on days 4 and 7, laser pulses were detected in one of the 200-msec exposure frames.[4] The consistent absence of detections on the shorter duration frames was traced to a pointing error caused by the scan platform acceleration being slower than predicted. As a result, no clear evidence of laser transmission was observed on 88 of the 90 frames taken with exposure times less than 400 msec.

The remaining 69 frames were analyzed to determine the detected pulse energy statistics and to compare those statistics with theoretical predictions. Figure 6 shows a typical comparison. The histogram of the detected pulse energies is plotted along with the theoretical distribution using atmospheric turbulence data and the appropriate turbulence model. A log-normal intensity distribution based on statistics of the measured data is also shown. As the figure shows, there is good agreement between the measured and theoretically predicted distributions.

VI. Conclusion

The results of the first deep-space optical transmission to a spacecraft in flight have been presented. The transmission was performed from transmitters located at TMF, California, and SOR, New Mexico. The laser uplink was detected on every day of the experiment—out to a range of 6,000,000 km for the TMF transmission. The camera images returned from Galileo and the analysis of the data show that the distribution of the detected signal strengths is consistent with theoretical predictions. All experiment objectives were achieved.

[4] B. M. Levine, "GOPEX Data Products Summary," JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, December 22, 1992.

Acknowledgments

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[8] R. Q. Fugate, "GOPEX at the Starfire Optical Range," *The Telecommunications and Data Acquisition Progress Report 42-114, vol. April–June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 255–279, August 15, 1993.

[9] K. P. Klaasen, M. C. Clary, and J. R. Janesick, "Charge-coupled Device Television Camera for NASA's Galileo Mission to Jupiter," *Optical Engineering*, vol. 23, no. 3, pp. 334–342, May/June 1984.

Table 1. GOPEX laser transmitter characteristics.

Characteristic	Table Mountain Facility	Starfire Optical Range
Wavelength, nm	532	532
Pulse energy, mJ	250	350
Repetition rate, Hz	15–30	10
Pulse width, nsec	12	15
Beam divergence, μrad	110	80
Days 1–4	60	40
Days 6–8		
Telescope mirror diameter	0.6	1.5
Primary, m	0.2	0.1
Secondary, m		
Optical train transmission, percent	60	43

Table 2. Summary of detected laser signals.

Day	Shutter speed, ms	Frames received	Frames with detections
1	133	9 of 10	0
	200	24 of 25	0
	400	19 of 20	6
	800	5 of 5	4
2	200	5 of 5	0
	267	15 of 15	0
	533	15 of 15	11
	800	5 of 5	5
3	200	5 of 5	0
	267	10 of 10	0
	533	5 of 5	5
4	200	3 of 3	0[b]
	267	4 of 4	0
	533	3 of 3	2[b]
5		No activity planned	
6[a]	133	3 of 3	0
	267	6 of 6	0
	533	3 of 3	3
7[a]	200	3 of 3	0
	400	3 of 4	3
	800	3 of 3	3
8[a]	267	2 of 2	0
	533	4 of 4	4
	800	2 of 2	2

[a] Adverse weather at Starfire Optical Range precluded laser transmission on this day.

[b] Adverse weather at Table Mountain Facility precluded laser transmission on this day, and it was cloudy at Starfire Optical Range.

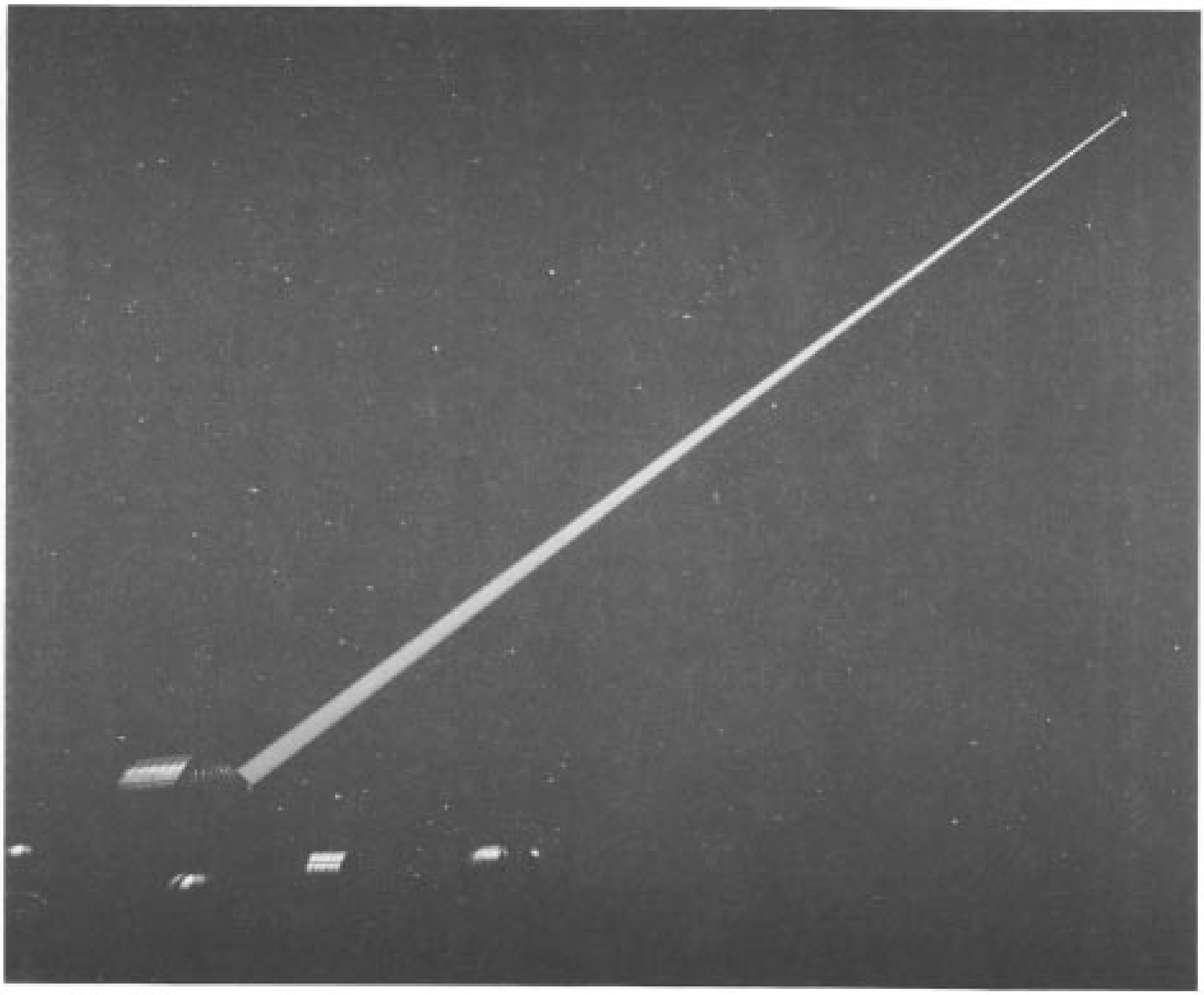

Fig. 1. Laser transmission from the 0.6-m telescope at the Table Mountain Facility, Wrightwood, California.

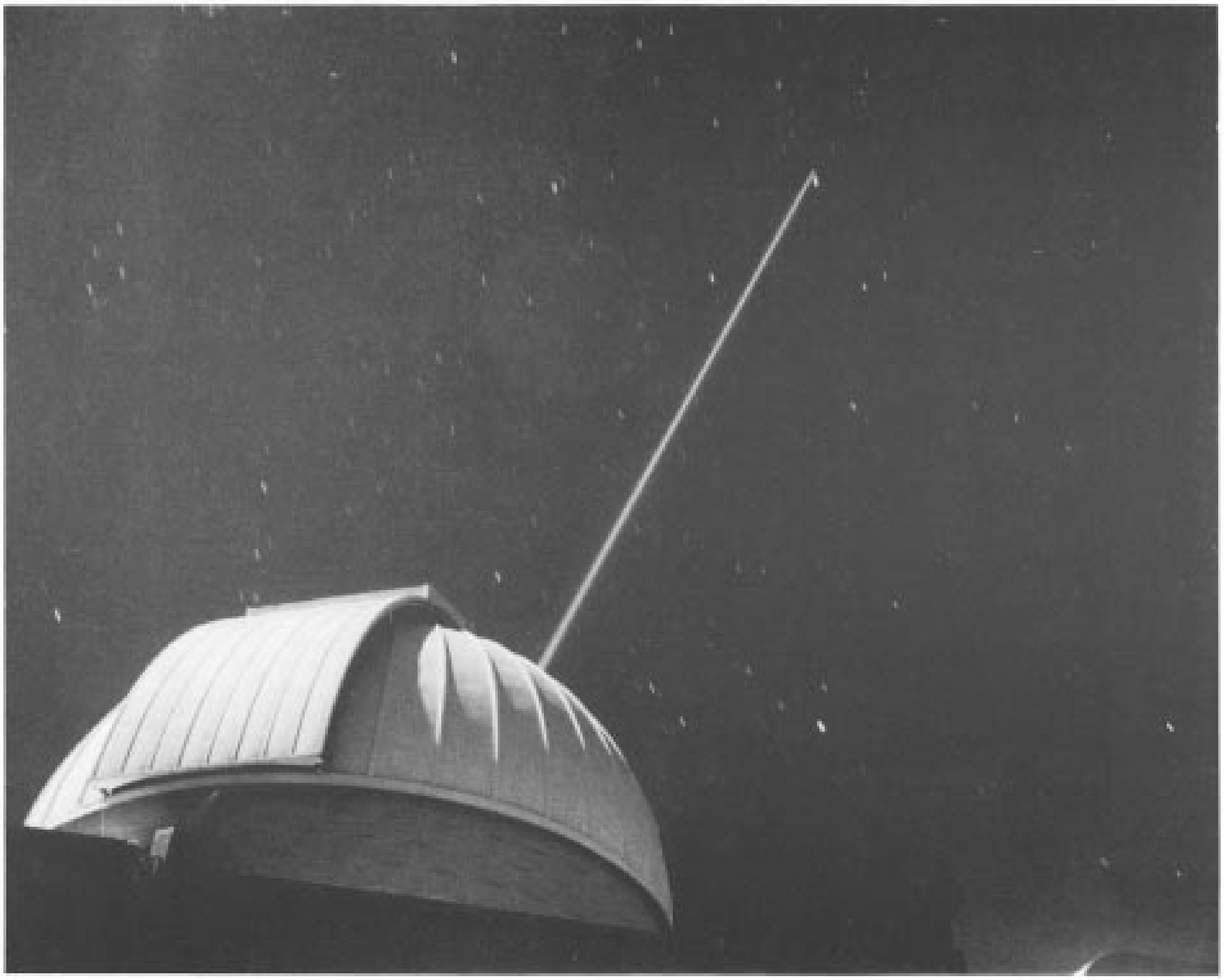

Fig. 2. Laser Transmission from the 1.5-m telescope at Starfire Optical Range, Albuquerque, New Mexico.

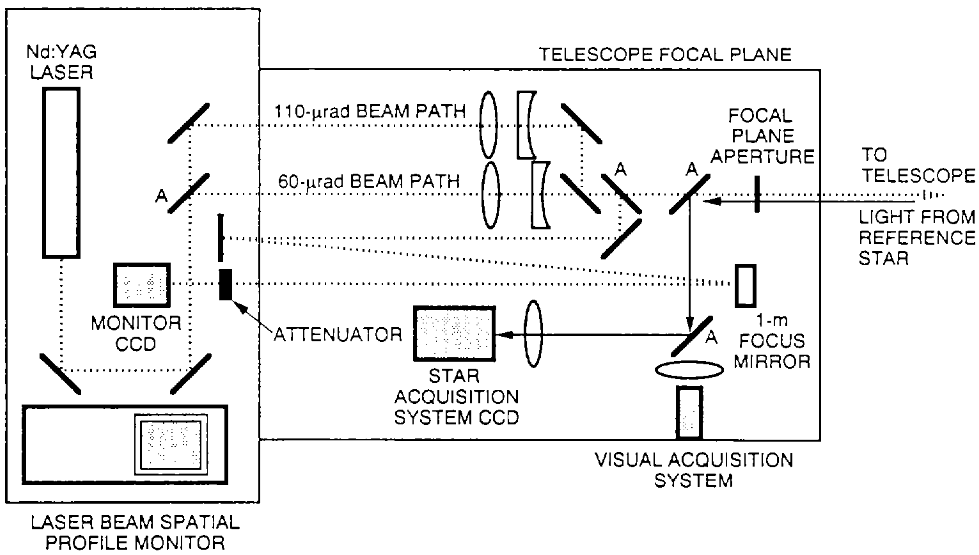

Fig. 3. GOPEX optical train, at the Table Mountain Facility. Relay mirrors (labeled "A" in the figure) are appropriately inserted into the optical train to obtain the required beam divergence.

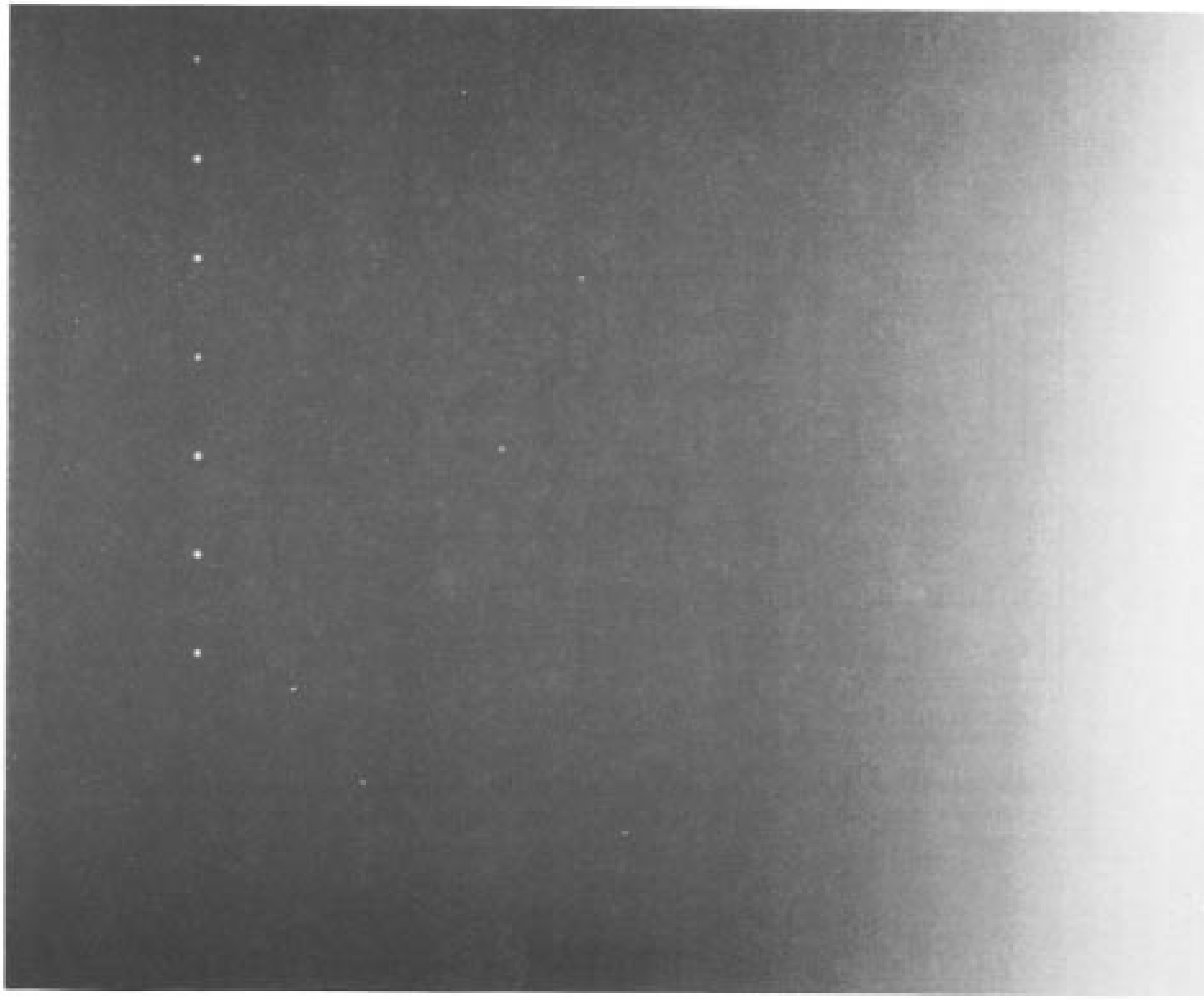

Fig. 4. Camera image showing detected pulses from TMF and SOR. To the right of the figure is the blurred image of the portion of the Earth illuminated by sunlight. Detections of the TMF laser pulses are shown on the left and of SOR pulses closer to the right. The missing pulses are due to the spatial scanning of the SOR beam.

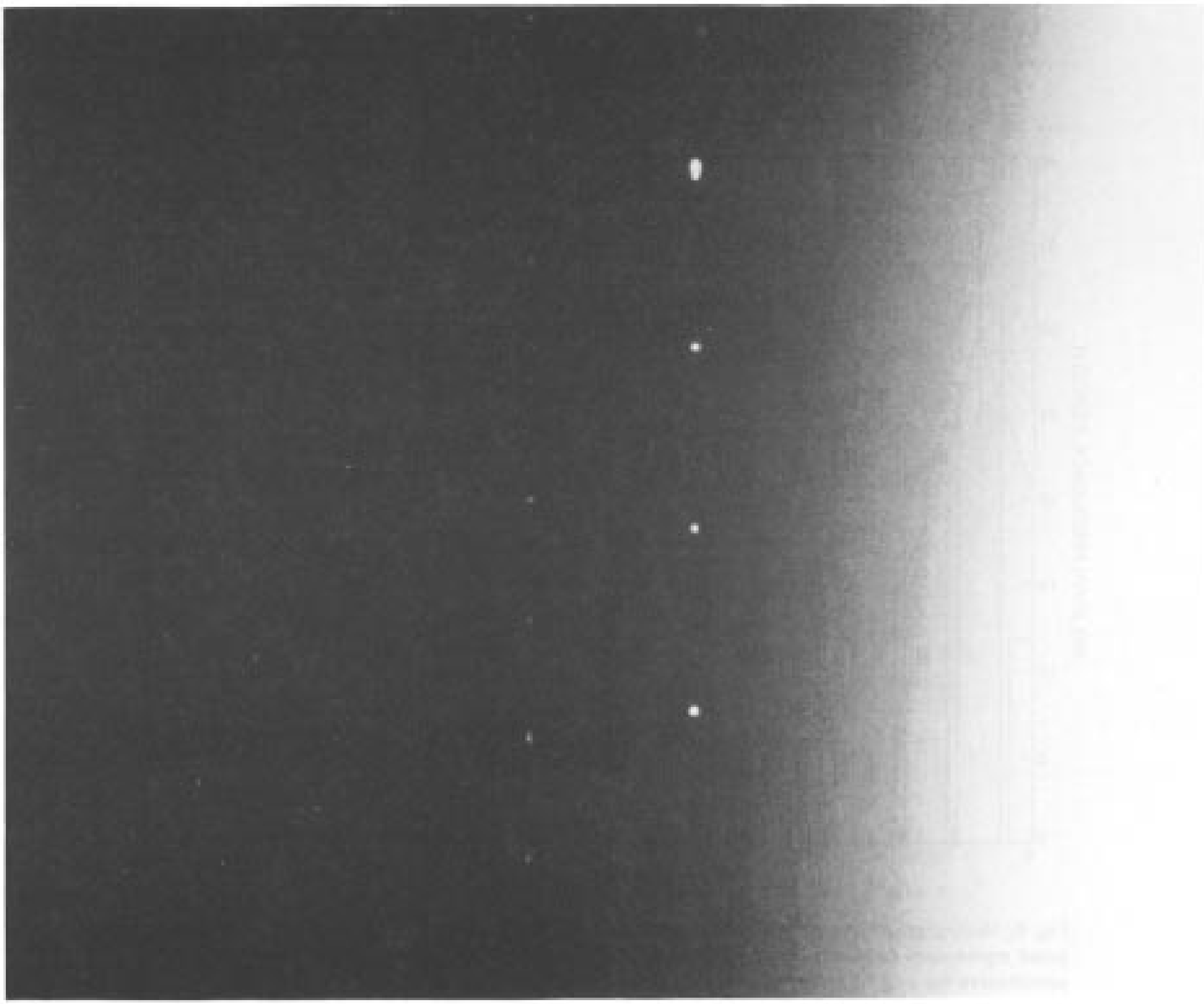

Fig. 5. Camera image showing laser uplink detections from TMF (15-Hz repetition rate) and SOR (10-Hz repetition rate) on Day 2 of GOPEX. SOR scanning was off.

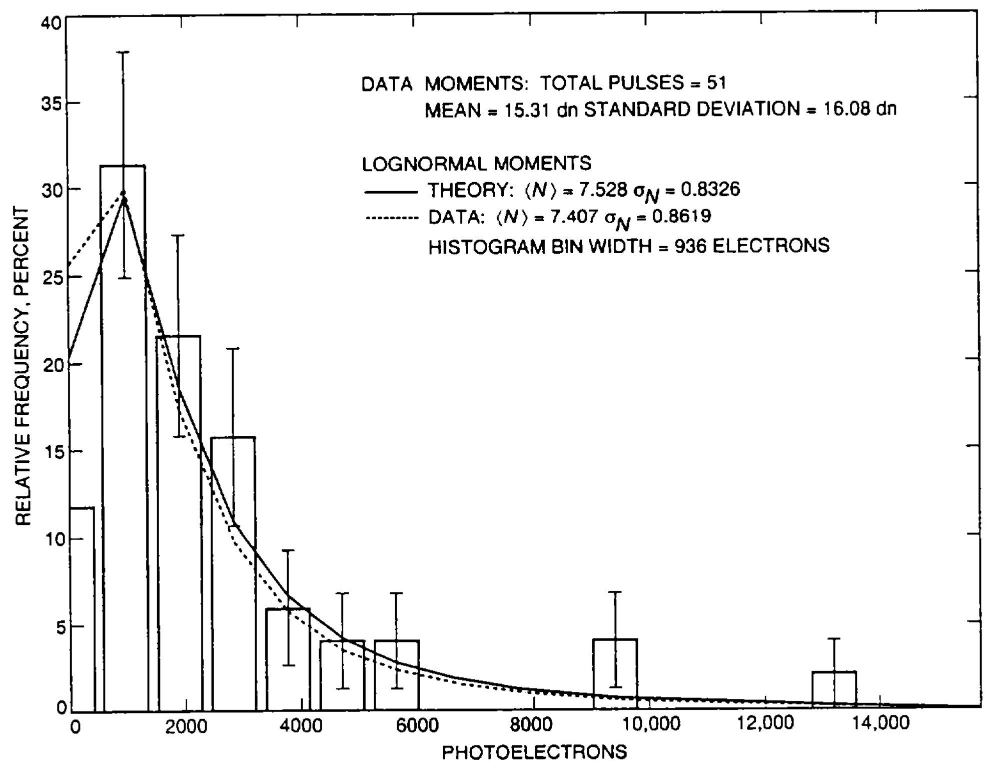

Fig. 6. Histogram of detected signal strengths from TMF on Day 8 of GOPEX. The data show good agreement between the experimental and the theoretical lognormal distribution using parameters for strong turbulence theory.