Results from the Galileo Laser Uplink;
A JPL demonstration of Deep-space Optical communications

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ABSTRACT

The successful completion of the Galileo Optical Experiment (GOPEX), represented the accomplishment of a significant milestone in JPL's optical communication plan. The experiment demonstrated the first transmission of a narrow laser beams to a deep-space vehicle. Laser pulses 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 experiment 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 uplink from TMF covered the longest known range for laser beam transmission and detection. This demonstration is the latest in a series of accomplishments by JPL in the development of deep-space optical communications technology.

I. INTRODUCTION

JPL's Deep Space Network is singular in its ability to track and communicate with deep-space probes. As we continue to explore and better understand our solar system, there will be demands to return increasing volumes of data from deep-space probes to Earth. Existing 70 meter DSN systems will be unable to support this increased demand, and communication systems at optical and microwave (32 GHz, Ka band) frequencies are considered the most viable emerging technologies for the missions of the twenty-first century. With NASA's directive of faster, better and cheaper, the mini and micro spacecraft are expected to play an ever increasing role in the future, Weight and size are the primary driving considerations for subsystems on mini and micro spacecraft and small light weight optical telescopes coupled to miniature laser transmitters are being favorably considered as an attractive alternative to the large microwave antennae.

Although there has been significant progress in the component technologies for deep-space optical communications, it was becoming apparent that a systems-level demonstration to show the viability of optical communications was needed. The Galileo spacecraft's second flyby of Earth, part of the Venus-Earth-Earth Gravity Assist (VEEGA) trajectory [1], 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 through December 16 from transmitter sites at Table Mountain Facility (TMF), California, see figure 1, and at the Starfire Optical Range (SOR), New Mexico; see figure 2. The spacecraft's Solid State imaging (SSI) camera was used as the optical communications uplink receiver. The experiment had three principal objectives, namely:

- Demonstrate laser beam transmission to a spacecraft at deep-space distances

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, ns	12	15
Beam divergence, μrad		
Days 1-4	110	80
Days 6-8	60	40
Telescope mirror diameter		
Primary, m	0.6	1.5
Secondary, m	0.2	0.1
Optical train transmission	60%	43%

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

SOR's telescope was the 1.5-meter system that is used for adaptive-optics experiments at this facility. A thin-film-plate polarizer served as the aperture-sharing element, and it 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 40 kilometers and 20 kilometers, corresponding to 40-microradian and 80-microradian beam divergence, respectively.

The SOR laser output was transmitted through the full 1.5-meter aperture of the telescope, and the effects of occultation by the 10-centimeter secondary were mitigated by reconfiguring the laser resonator so that it generated a flat-top intensity profile across the beam. This design resulted in less than 10% loss in energy of the outgoing beam due to occultation by the secondary.

III. GOPEX Receiver

The Galileo SSI camera was used to detect the GOPEX uplink. The camera is mounted on the spacecraft scan platform located on the despun section of the spacecraft, It consists of a CCD array of 800 X 800 silicon pixels located at the focal plane of a 1500 mm focal length f/8.5 Cassegrain telescope [2]. The angular resolution per pixel was 10.6 μrad with a full well capacity of 100,000 electrons. The dark current was less than 10 electrons per pixel with readout noise of 8 electrons. Four SSI gain states scale the video analog data to the 8 bit analog-to-digital converter. Over the eight-day experiment window two gain states were used for GOPEX; gain state 2 which has 400 detected photoelectrons per data number (dn) was used on the first two

- Verify laser-beam pointing strategies applicable to an optical uplink based solely on spacecraft ephemeris predicts
- Validate the models developed to predict the performance of the optical link

Galileo's phase angle after its second Earth flyby was approximately 90°. 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, and the experiment was conducted between 3:00 a.m. and 6:00 a.m. Pacific Standard Time. The nighttime transmission had two distinct advantages:

- It allowed the uplink to be performed at the frequency-doubled Nd:YAG laser wavelength of 532 nm, where the responsivity of the solid-state imaging (SS1) camera is high.
- Long-exposure camera frames could be taken. This facilitated the identification of the detected laser transmissions. 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 milliseconds before the scattered light from the bright Earth saturated the pixels that detected the laser uplink.

The camera was scanned across the Earth, parallel to the Earth's terminator, during each exposure to facilitate the identification of the laser uplink from spurious noise counts in the camera frame. Using this strategy, the laser uplink appeared as a series of evenly spaced bright dots within the camera frame, and was quite distinct from other features in the frame. Laser uplink data were received on each of the seven days of the experiment with detections on 50 of the 159 GOPEX frames taken, The demonstration covered a period of eight days, but other spacecraft activities precluded laser transmission on Day 5. Because of an unanticipated bias in the scan platform pointing , pulses were detected on only two of the frames with exposure times less than 400 milliseconds. inclement weather, aborted transmissions, and restrictions imposed by regulatory agencies and by the Project Galileo team accounted for the loss of data on the remaining frames.

The two GOPEX laser/telescope transmitters and SS1 camera receiver are discussed in Section 11 and III of this paper. Section IV describes the telescope pointing strategy which used bright stars in the vicinity of Galileo as references, and the GOPEX results are presented in Section V. Conclusions are discussed in Section VI.

II. GOPEX Laser Transmitters

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

A 0.6-meter equatorial-mount astronomical telescope was used for the TMF transmitter. This is the same telescope that was 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, figure 3, to achieve the required laser beam divergence. See Table 1. The optical train was designed so that the transmitted laser beam illuminated a 1 S cm sub-aperture of the primary mirror. The principal benefit of this technique over full aperture illumination was that it eliminated the large loss in transmitted energy that would have been caused by occultation from the 0.2-meter secondary.

days, and the more sensitive gain state 3 with 160 detected photoelectrons per dn was used on subsequent days.

Field correction elements, an eight position filter wheel, and a two blade shutter are positioned along the optical train between the telescope primary and the focal plane of the SS1 camera, The latter two elements were inherited from the Voyager program, The filter wheel contained one clear filter, one infrared transmitting filter and six 20 nm bandpass color-filters. These were rotated into the optical train, as required, to enable the color reconstruction of an imaged scene. The green color-filter with 50 % transmission at 532 nm (the peak transmission was 90% at 560 nm) was used for GOPEX.

The SS1 shutter is operable in any one of 28 exposure times ranging from 4.16 milliseconds to 51.2 seconds. Exposure time selection 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 to confirm the laser uplink. improved estimates of the scattered light intensity were made using data taken at the Gaspra encounter. Final estimates of the scattered light rates due to Earth-shine 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. On the basis of these estimates, the GOPEX imaging sequence was designed with shutter times ranging from 133 msec to 800 msec. Actual scattered light rates measured during GOPEX ranged from 8 to $10\,e^-$/msec. The low actual scatter levels would have allowed longer camera exposure times and the accumulation of more data.

IV. GOPEX telescope-pointing strategy

Telescope-pointing files for TMF and SOR were generated from updates of the spacecraft ephemeris files that were provided to the GOPEX team on December 8 and December 11. The strategy was to off-point the telescope from reference stars located within 0.5° of the spacecraft 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. Here, 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-minute 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-thee experiment was conducted when the spacecraft’s elevation from TMF was greater than 30 —and the proximity of the reference stars to Galileo’s position obviated the need to implement atmospheric refraction compensation techniques while pointing to the spacecraft.

The beam width of the rf beam to Galileo was approximately forty times that of the laser beam, 2 millirad versus 60 microrad. To verify the accuracy of the pointing predicts SOR dithered the laser beam in a 85 microrad radius circle about the spacecraft’s predicted position while the TMF transmitter pointed directly to Galileo’s predicted position. This strategy was implemented for several of the long-duration frames (frames with exposure times greater than 400 milliseconds) on the first day. The results from one of the dithered uplinks are shown in Figure 4. Nine pulses can be clearly discerned in the figure; seven are from the 15-hertz TMF transmitter, and two are from the 10-hertz 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 of seven from TMF clearly demonstrates that the error in the telescope pointing predicts was significantly less than 85 microradians. This was further confirmed by the successful use of a 60-microradian beam from TMF for laser transmissions on the last three days of GOPEX.

V. GOPEX RESULTS

Table 2 gives a summary of the detected GOPEX laser transmissions over the duration of the experiment.

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	1[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	1
	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 Observatory precluded laser transmission on this day, and it was cloudy at Starfire Optical Range,

Over the eight-day period, transmissions to the spacecraft were made over a range beginning at 600,000 kilometers on the morning of December 9 and ending at 6,000,000 kilometers 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. (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 resulted in the lack of detection on several frames. Final results show that the laser uplink was successfully detected on 50 camera images during the experiment window. Figures 4 and 5 show two representative images of the detected laser pulses.

Adverse weather at the sites and not telescope pointing was the most severe impediment to successful detection of 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 was there 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 also caused data outages. Transmission of the GOPEX laser beam into space required the concurrence of the US. 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 data files. The GOPEX images for these days showed numerous streaks across the frames and made it difficult to discern successful laser transmissions on the images. On the second day, just after the GOPEX uplink, a planned spacecraft maneuver that increased the SNR of the radio frequency downlink was executed. This resulted in clearer GOPEX images for the remainder of the demonstration.

The GOPEX demonstration required that the SS1 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 SS1 camera dictated the shutter times used for GOPEX. The times chosen ranged from 133 milliseconds to 800 milliseconds, 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-millisecond exposure times; laser pulses were detected in one 200 msec exposure frame taken on day 4 and again on day 7. 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 milliseconds.

After determining the reasons for the missing pulse detections on selected frames, the remaining frames were analyzed to calculate 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 was constructed from a total of 51 pulses received on this day, and it is plotted along with the theoretical distribution using atmospheric turbulence data and the appropriate turbulence model. The error bars in the histogram heights are large because of the small data set. They show the expected range of the relative frequency of detections for the GOPEX demonstration performed again under the similar atmospheric conditions. The poor fit near the lower laser energies is due to the difficulty in estimating low detected laser energies. The log-normal intensity distribution, based on statistics of the measured data, is also shown. The data show good agreement between the measured and theoretically predicted distributions.

VI. CONCLUSION

GOPEX represents the achievement of a significant milestone in deep-space optical communications, The laser 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 kilometers for the TMF transmission. The camera images returned from Galileo and the analysis of the data show that all the experiment objectives were achieved.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

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2, K. P. Klaasen, M. C. Clary. 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.

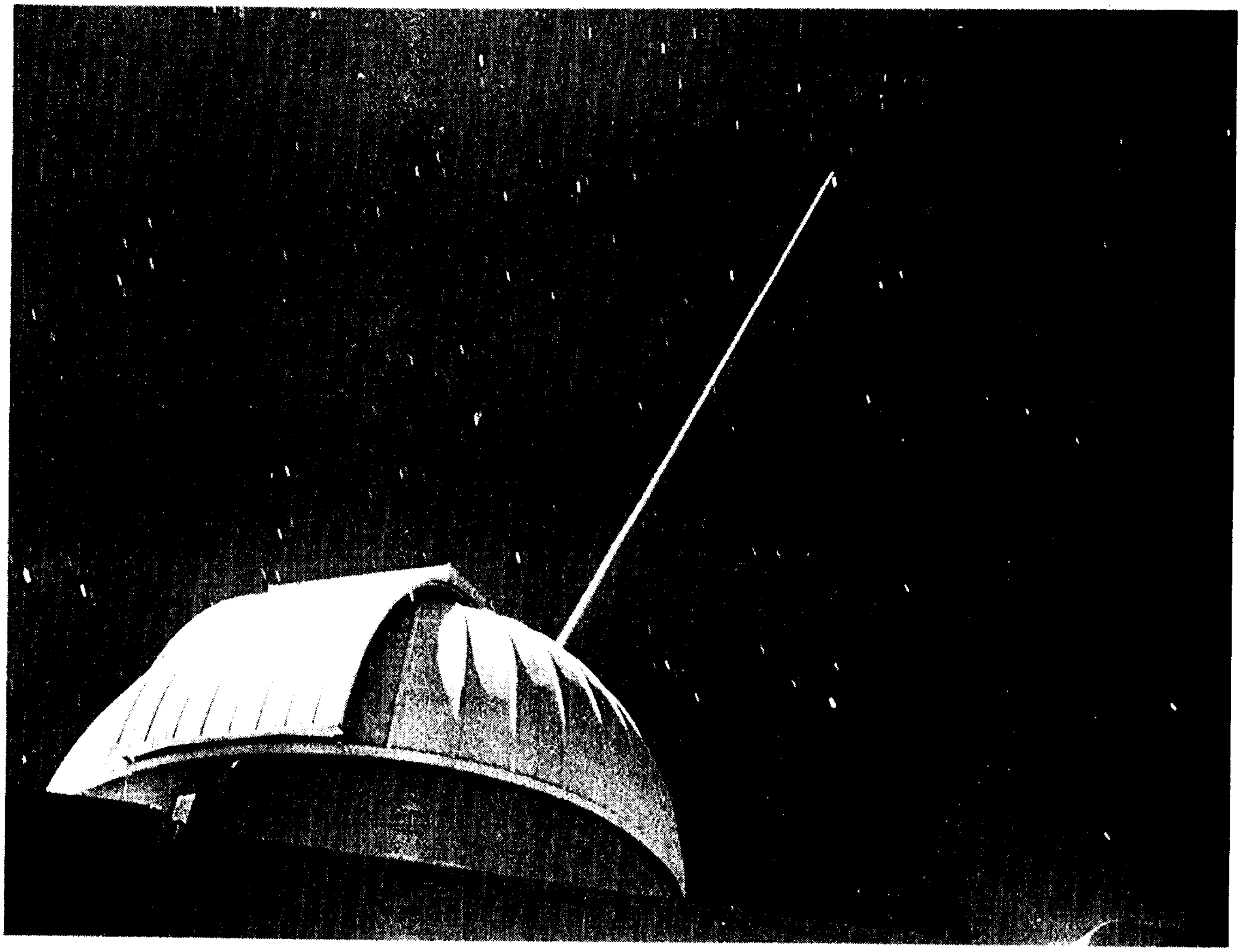

Figure 1. Laser transmission from 0.6-meter telescope at TMF, Wrightwood, CA.

Figure 2. Laser Transmission from 1.5-meter telescope at SOR, Albuquerque, NM.

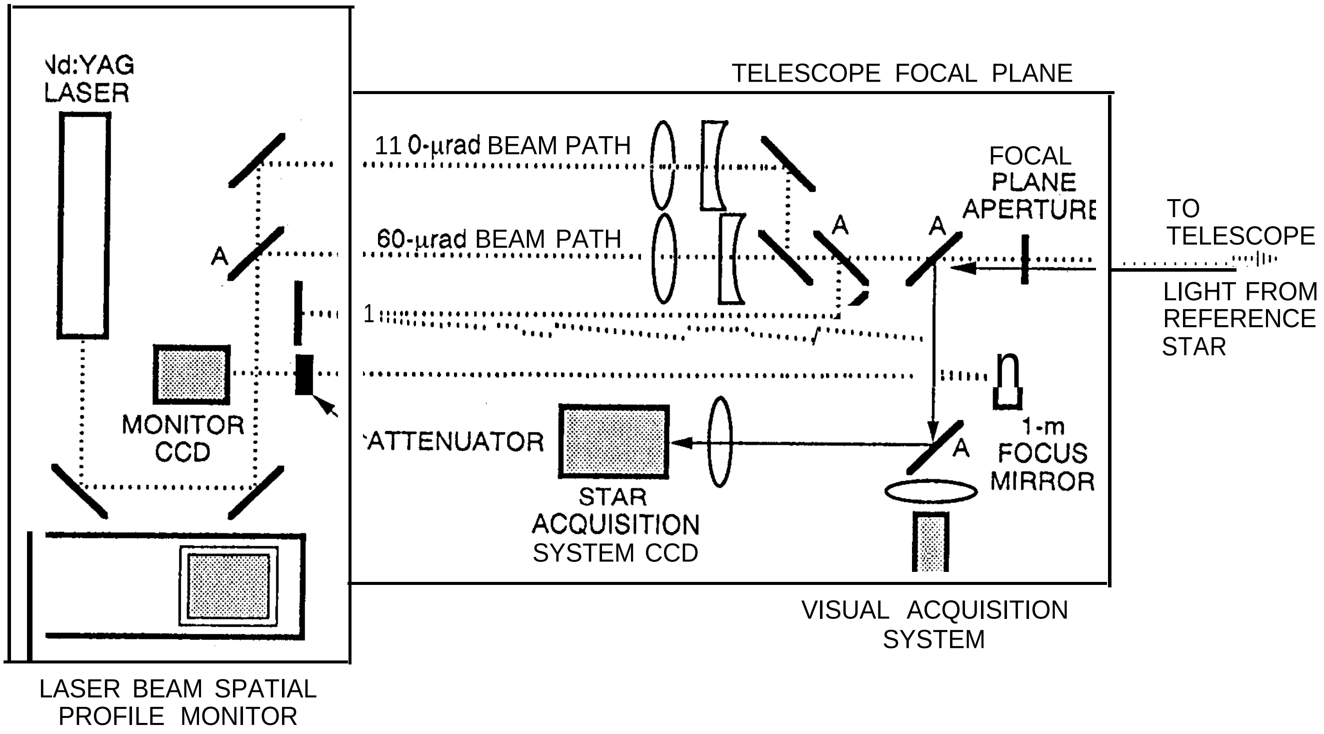

Figure 3. GOPEX optical train, at TMF. Relay mirrors (labeled "A" in the figure) are appropriately inserted into the optical train to obtain the required beam divergence.

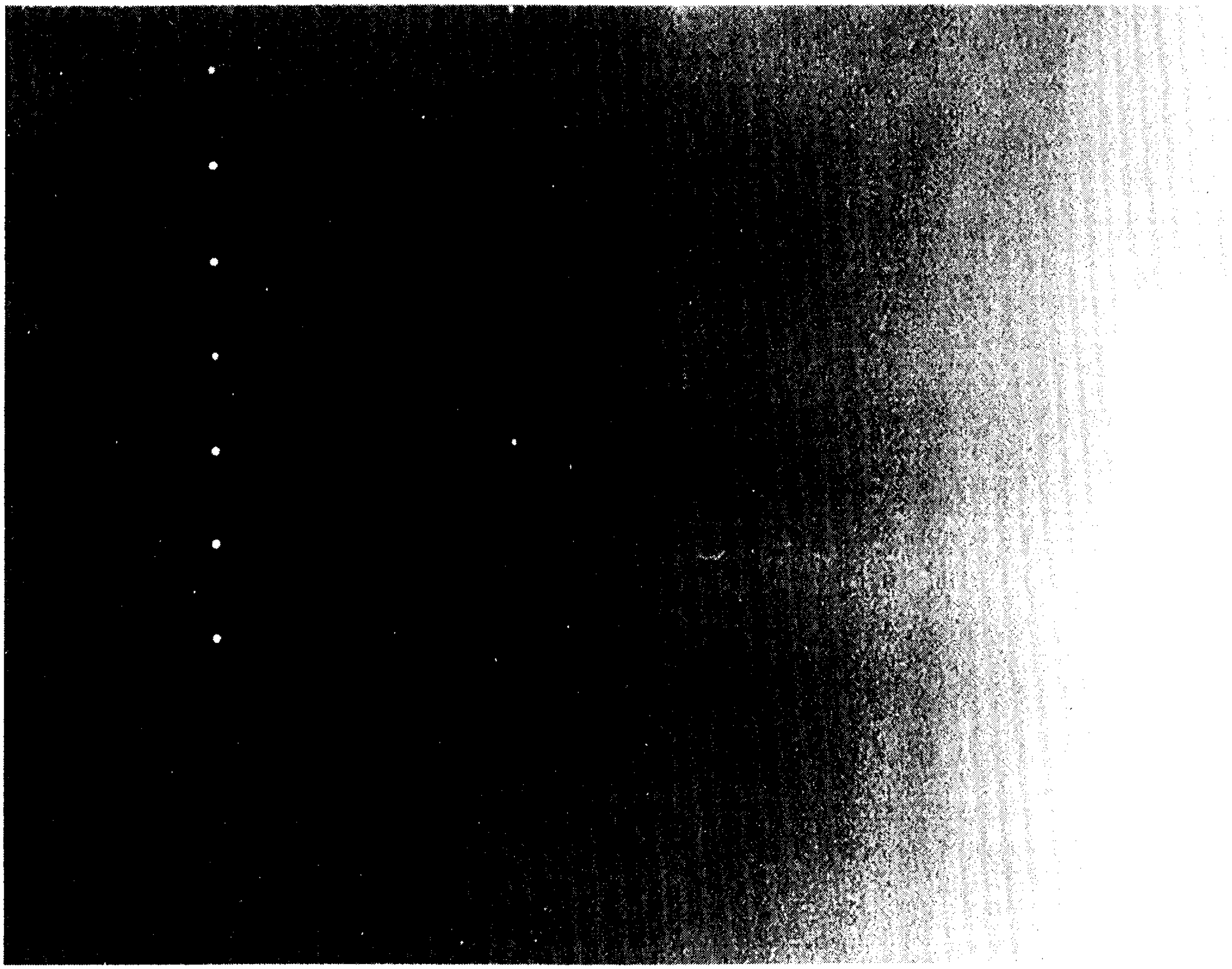

Figure 4. Camera image showing detected pulses from TMF and SOR. To the right of the figure is the blurred image of the portion of the Earth illuminated by sunlight. Detections of the TMF laser pulses are shown on the left and of SOR pulses closer to the right. The missing pulses are due to the spatial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

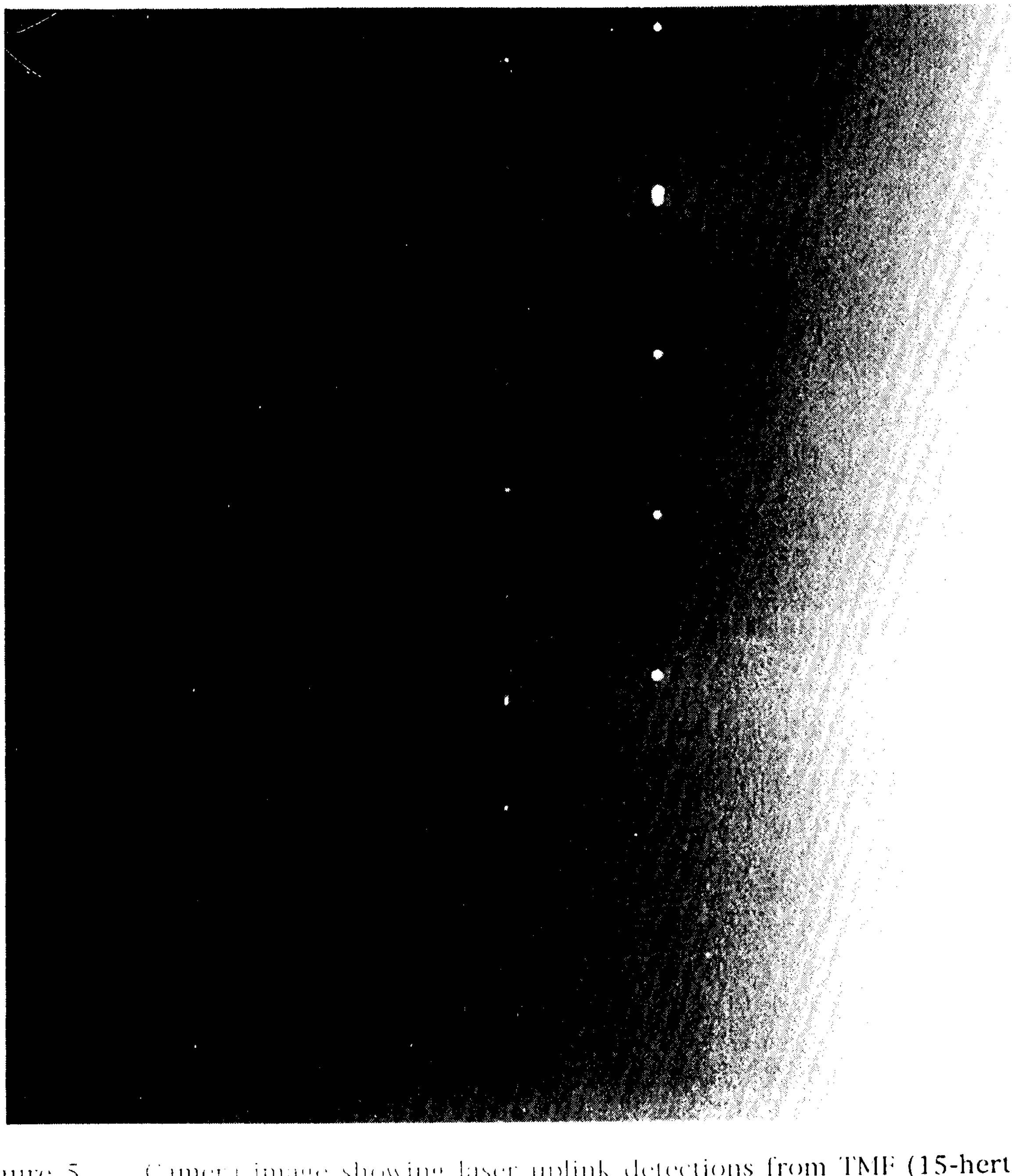

Figure 5. Camera image showing laser uplink detections from TMF (15-hertz repetition rate) and SOR (10-hertz repetition rate) on Day 2 of GOPEX. SOR scanning was off.

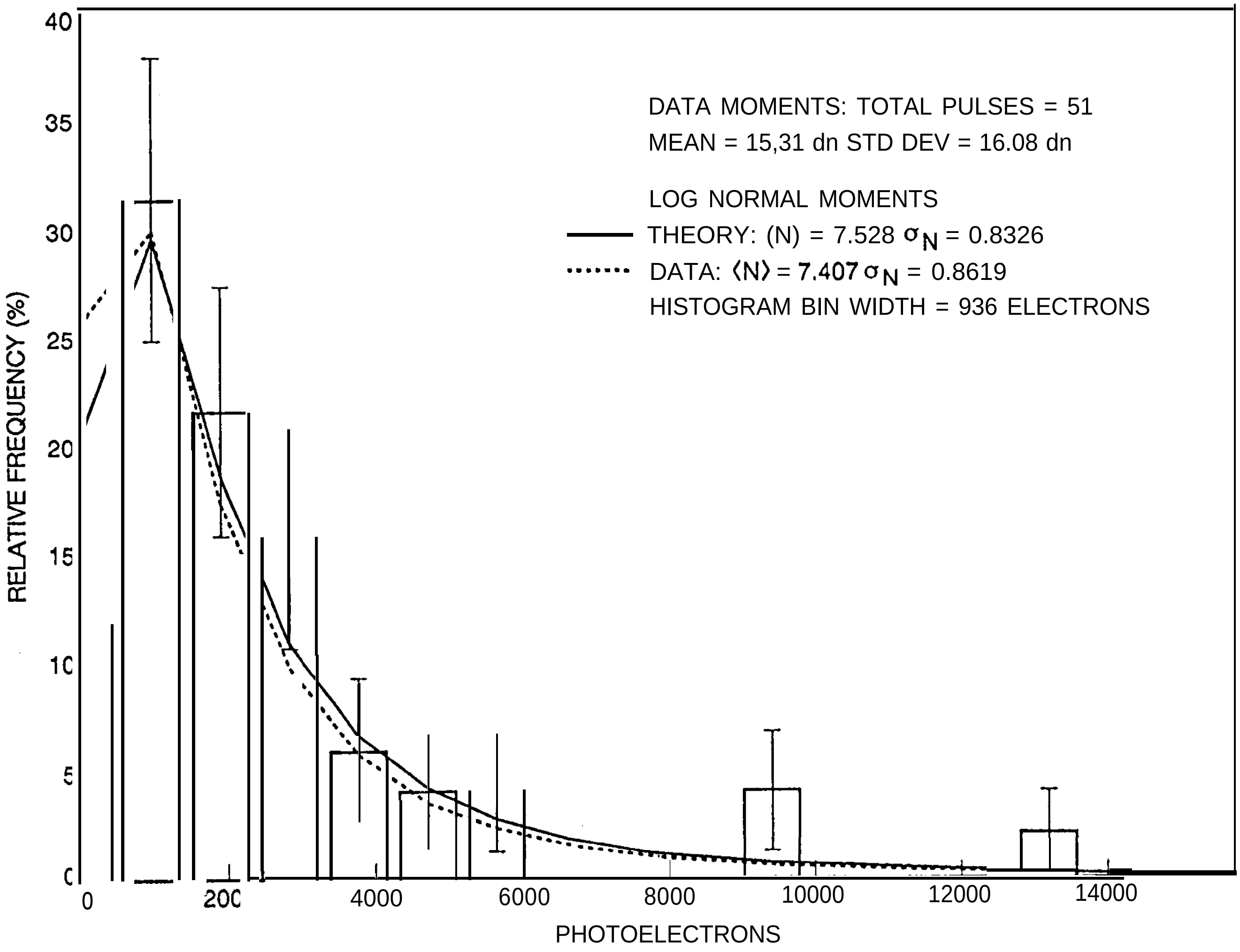

Figure 6. Histogram of detected signal strengths from TMF on Day 8 of GOPEX. The data show good agreement between the experimental and the theoretical lognormal distribution using parameters for strong turbulence theory.