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USE OF A LASER FOR SATELLITE-RANGE MEASUREMENTS

by

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P. H. Anderson,[2] C. G. Lehr,[3] and L. A. Maestre[4]

Abstract. --A Laser Satellite-Ranging System is being developed at a Smithsonian Observatory astrophysical observing station. Range measurements have been obtained on retroreflector-equipped satellites.

Introduction

The Smithsonian Astrophysical Observatory and the Re-entry Systems Department of the General Electric Company are engaged in a series of experiments using lasers to measure ranges to satellites. These experiments will evaluate an optical ranging system as a supplement to the Baker-Nunn camera for the purpose of increasing the accuracy with which satellite orbits can be determined.

While the Baker-Nunn camera is capable of making highly accurate angular measurements of satellite positions, it cannot measure range directly from a single site; supplemented with a system capable of precise range measurements, it would completely define the position vector of a satellite at a given time.

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A laser system appears to be the most promising to fill this need since it has several advantages over other ranging systems. Among these are:

(1) lower equipment cost,
(2) higher spectral radiant intensity, and
(3) lower ionospheric distortion.

As the work in the evaluation study continues, various experiments are being carried out that eventually will define a laser system to be considered for use at SAO stations. Our previous efforts leading to this experiment are covered in a report by General Electric Co. (1965); this report deals with the recent progress in obtaining range measurements.

<u>System description</u>

The Re-entry Systems Department of General Electric supplied the laser, with its power supply, and the photoelectric receiving system. The Smithsonian Astrophysical Observatory supplied the Baker-Nunn camera, the laser tracking mount, and the satellite predictions, as well as the necessary materiel, personnel, and facilities at the Organ Pass, New Mexico, astrophysical observing station.

The significant characteristics of the GE laser are summarized in Table 1. A combination of rotating prism and RG8 Schott glass was used to obtain the single 50-nanosecond (ns) Q-switched pulse. The passive Q-switched pulse train was achieved by use of only the Schott glass. Figure 1 shows the various laser output pulses.

In the first phase of the experiment, the laser was mounted on the Baker-Nunn camera, as shown in Figure 2(a). The specially designed mounting plate allowed the operator to make vernier adjustments in along-track and cross-track position while sighting through a modified M-17 apogee telescope and tracking with the Baker-Nunn camera drive. Figure 2(b) shows the laser mounted on the surplus 3-inch gun mount used for the second phase of the experiment. To use this mount, two operators were required to turn hand-cranks while viewing through apogee telescopes: one operator controlled elevation; the other, azimuth.

A 60-inch searchlight modified with an RCA 7265 (S-20 surface) photomultiplier and two 70 Å bandpass interference filters served as the receiving system. Figure 2(c) shows how two operators pointed the searchlight while sighting through 6-inch telescopes. Azimuth and elevation velocity controls allowed them to follow the satellite and keep it within the 1/3° receiver beam width.

Figure 3 shows the physical configuration of the experimental equipment. The relative placement of the 3-inch gun mount and searchlight receiver was selected to account for possible velocity aberration effects with the BE-C satellite. The calibration target consisted of a white matte surface, 6-foot square, placed on a hill visible from both the laser (3-inch gun mount) and the searchlight locations. A survey of the combined optical distance from laser to target to searchlight yielded a figure of 5038 feet.

A block diagram showing the electrical connection of the equipment is given in Figure 4. The laser received its firing signal from the station clock, an EECo Precision Time Standard. In the normal, free-running or passive Q-switch modes, the laser fired approximately 0.4 ms after receipt of this signal. In the Q-switch mode, the laser fired the next time the rotating prism was in proper alignment after the firing signal was received. This interval can be up to 4 ms after the clock signal. The relationship between the clock signal and laser firing was, in all cases, recorded from an oscilloscope that displayed a phototube sampling of the laser output on a sweep triggered by the clock signal. Figure 1 represents sample Polaroid photographs of this presentation.

The searchlight received the laser reflection from the satellite, and the output of its photomultiplier was presented on an oscilloscope. The sweep for this trace was expanded and triggered through a delay circuit so as effectively to place a rough range gate around the expected time of the return pulse.

The sampled laser output and the return pulse were each amplified by the oscilloscope preamplifiers and fed into threshold gates for the 10-Mc counter. The "start" gate was triggered by the laser pulse allowing the 10-Mc pulses to accumulate until a stop signal was received from the searchlight receiver. The "stop" gate threshold was variable; it was normally set so that it took a second or more before a noise pulse of sufficient strength came along to stop the counter. The frequency monitor provided a continuous check on the counter's crystal-clock frequency. The satellite range was then computed from the relation

$$\rho = \left(\frac{N_c + 1}{F_c}\right) \frac{C}{2} ,$$

where

ρ = tabulated range (megameters) (Mm),
N_c = cycles counted,
F_c = counter frequency (cps),
C = 299.7928 (Mm/sec).

The only correction contained in the above expression represents the total equipment delays. This delay was determined by the laser being fired at the calibration target and the counter reading of 5.0 μs being noted. This represents a distance of 4918 feet, as opposed to the surveyed distance of 5038 feet. A correction of +0.1 μs, or 1 cycle count at 10 Mc, is thus surmised for equipment delays. The error due to atmospheric refraction can be shown to be small compared to ± 15 m, the resolution of the counter presently in use (see Appendix). When a more precise counter is used, the atmospheric correction will have to be made.

Results

A compilation of the important information pertaining to the observations, including the measured ranges, is found in Table 2. Oscilloscope presentations of the transmitted and received pulses are displayed in Figures 5 through 15. The transmitted pulses for the rotating prism Q-switch mode were always identical in amplitude, time scale, and structure. Therefore, only a single representative photograph is shown.

No oscilloscope pictures are available for success numbers 6, 7, and 8, as listed in Table 2. In these cases, the oscilloscopes did not trigger properly.

The returns obtained can be divided into four separate groups according to the type of Q-switch used for the output pulse and the recording device from which the range measurement was made.

Group I. Successes 1 through 5 resulted from non-Q-switched output pulses of 1-ms duration. Although the returns had sufficient amplitude to stop the range counter, the pulse length and its varying amplitude made it impossible to determine which part of the pulse stopped the counter. More reasonable range values were obtained through a visual correlation of the output and the received pulses.

Group II. Only range-counter measurements were obtained for this group, which includes successes 6 through 8. The output pulse was reduced to 0.5-ms time duration.

Group III. For this group (successes 9 through 11), the counter amplitude threshold was set high to avoid stopping the counter with noise pulses. Unfortunately, the received signals had insufficient strength to stop the counter. Consequently, only oscilloscope presentations of the return signals were possible. The random delay of up to 4 ms in the Q-switched mode required a horizontal oscilloscope scale of 0.5 ms/cm for the transmitted pulse presentation.

Group IV. Altogether, 8 range determinations (successes 12 through 19) were made with the range-counter and a Q-switched pulse. Oscilloscope presentations of the returns were also acquired.

The 10-Mc range counter was monitored by a Hewlett Packard frequency counter during the returns in this group. All of the measured propagation times were then corrected for the frequency offset of the counter oscillator. In addition, the delays arising from the circuitry were identified through use of our system's calibration target, and suitable corrections were made to the measured ranges of the satellite.

The accuracies of the ranges listed in Table 2 for successes 12 through 19 are limited to ± 15 m by the particular range counter which was used for these initial experiments.

The eight returns of Group IV were made during seven passes of 6532A over the New Mexico tracking station. Bright sky/poor satellite visibility conditions prevented additional measurements from being secured.

The Baker-Nunn camera was synchronized with the laser firing times for returns 9 through 19, so that the laser beam would appear on the film while the sunlit satellite was being photographed. This expedient allowed simultaneous laser Baker-Nunn observations to be effected, with times recorded on the Baker-Nunn film to 0.1-ms accuracy.

A noteworthy accomplishment was that for success numbers 13 through 19, doppler range-rate measurements on 6532A were made simultaneously with Baker-Nunn photography of the sunlit satellite and laser-range determinations. This constitutes what is probably the first set of simultaneous measurements made on a satellite by three accurate tracking systems. (The doppler range-rate measuring system, owned by the Navy, is collocated at the New Mexico station for the purpose of a systems comparison with the Baker-Nunn camera.)

Acknowledgments

We thank Mr. J. T. Williams and his staff at the Organ Pass, New Mexico tracking station for the assistance they provided in acquiring the measurements listed in this paper. Mrs. Bea Miller of SAO Data Division was helpful in supplying the required satellite predictions. Gratitude is also due Mr. Gordon Snyder of the Re-entry Systems Department, General Electric Company, without whose equipment and services this work could not have been performed.

APPENDIX

The Correction for Atmospheric Refraction

Veis (1960) gives the following expression for the refractive index of the atmosphere as a function of altitude:

$$n - 1 = Ke^{ah} , \tag{A1}$$

where $K = 292 \times 10^{-6}$, $a = -0.1385 \text{ km}^{-1}$, and h is the altitude in km.

For an atmospheric correction to laser-range measurements, the difference between the optical path in the atmosphere and the optical path in the vacuum is desired. This difference is the following:

$$d = \int_0^R (n - 1) \, d\rho , \tag{A2}$$

where R is the slant range to the satellite. Assuming a flat earth, we may let $h = \rho \sin \theta$, where θ is the elevation angle of the satellite. Substituting this expression and equation (A1) into (A2), we obtain

$$d = \int_0^R Ke^{a\rho \sin \theta} \, d\rho ,$$

which yields

$$d = \frac{K}{a \sin \theta} \left[e^{aR \sin \theta} - 1 \right] ,$$

$$\approx \frac{K}{a \sin \theta} \quad .$$

The lowest elevation for which range was measured in this experiment was 41°. Using this value of θ, and the constants given above, the correction to the range measurement would be

$$d = \frac{2.1}{\sin 41^\circ} = 3.2 \text{ m} \quad .$$

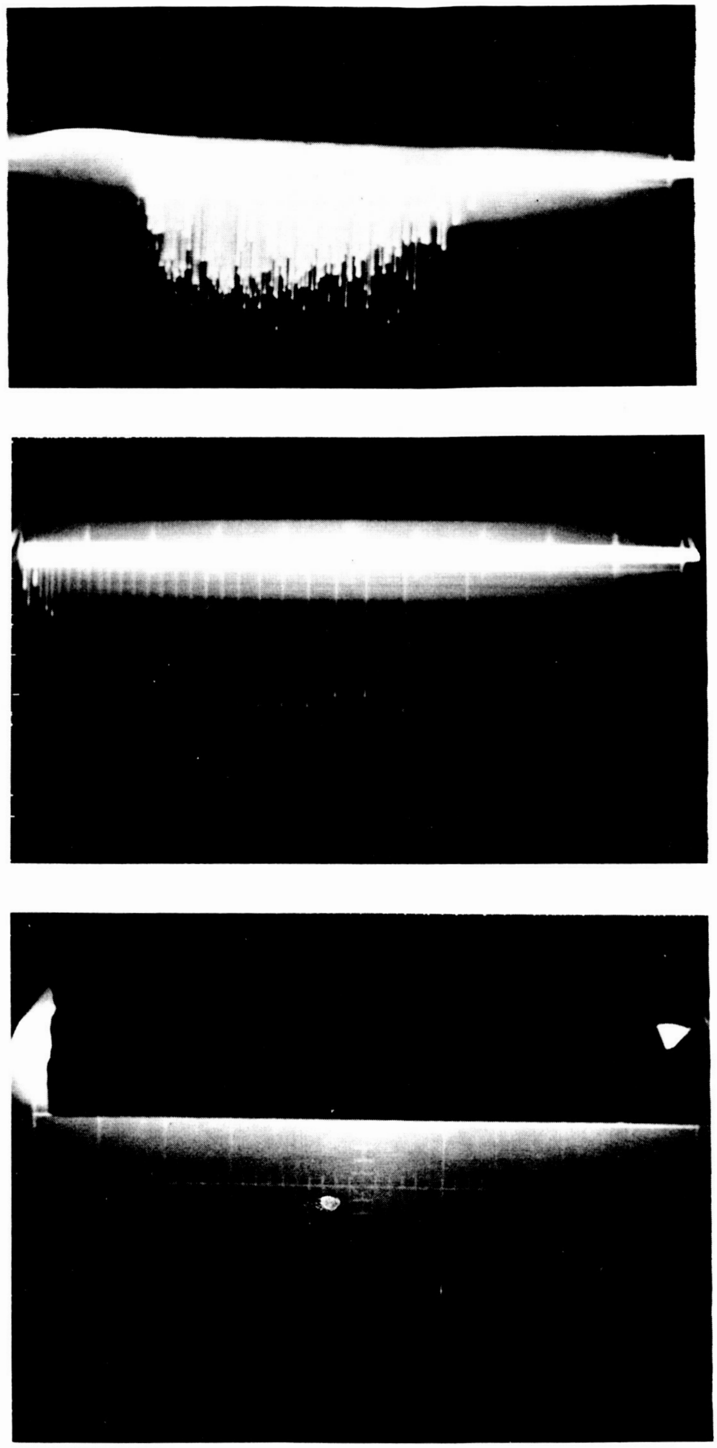
References

GENERAL ELECTRIC COMPANY

1965. Laser experiments with a Baker-Nunn camera. Final Report on Contracts SI-715 and SI-718 with the Smithsonian Astrophysical Observatory, Cambridge, Massachusetts.

VEIS, G.

1960. Geodetic uses of artificial satellites. Smithsonian Contr. Astrophys., vol. 3, pp. 95-161.



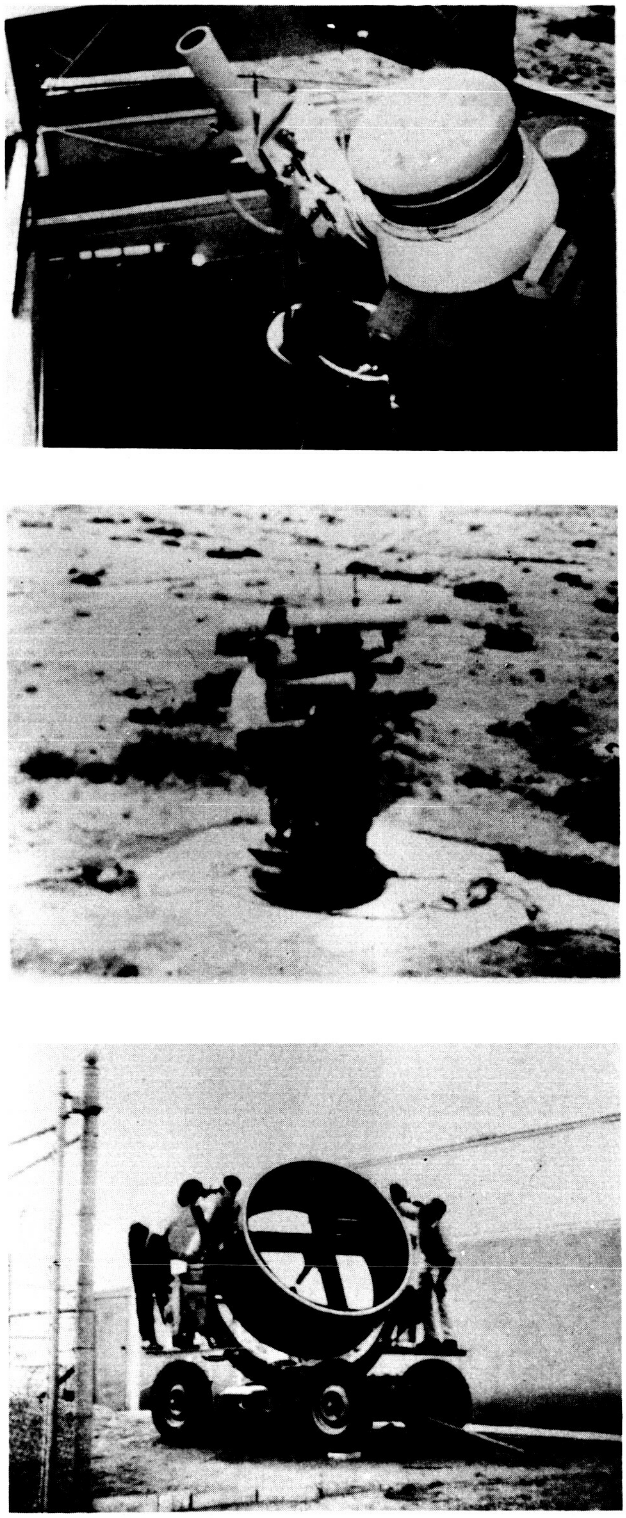
0.1 V/cm (a)

0.2 V/cm (b)

0.2 V/cm (c)

0.5 ms/cm

Figure 1. --Laser output pulses: (a) Normal, free-running mode; (b) Passive Q-switched mode; (c) Single-pulse Q-switched mode.



(a)

(b)

(c)

Figure 2. --Polaroid photos of (a) Laser mounted on Baker-Nunn camera; (b) Laser mounted on 3-inch gun mount; and (c) Searchlight receiver.

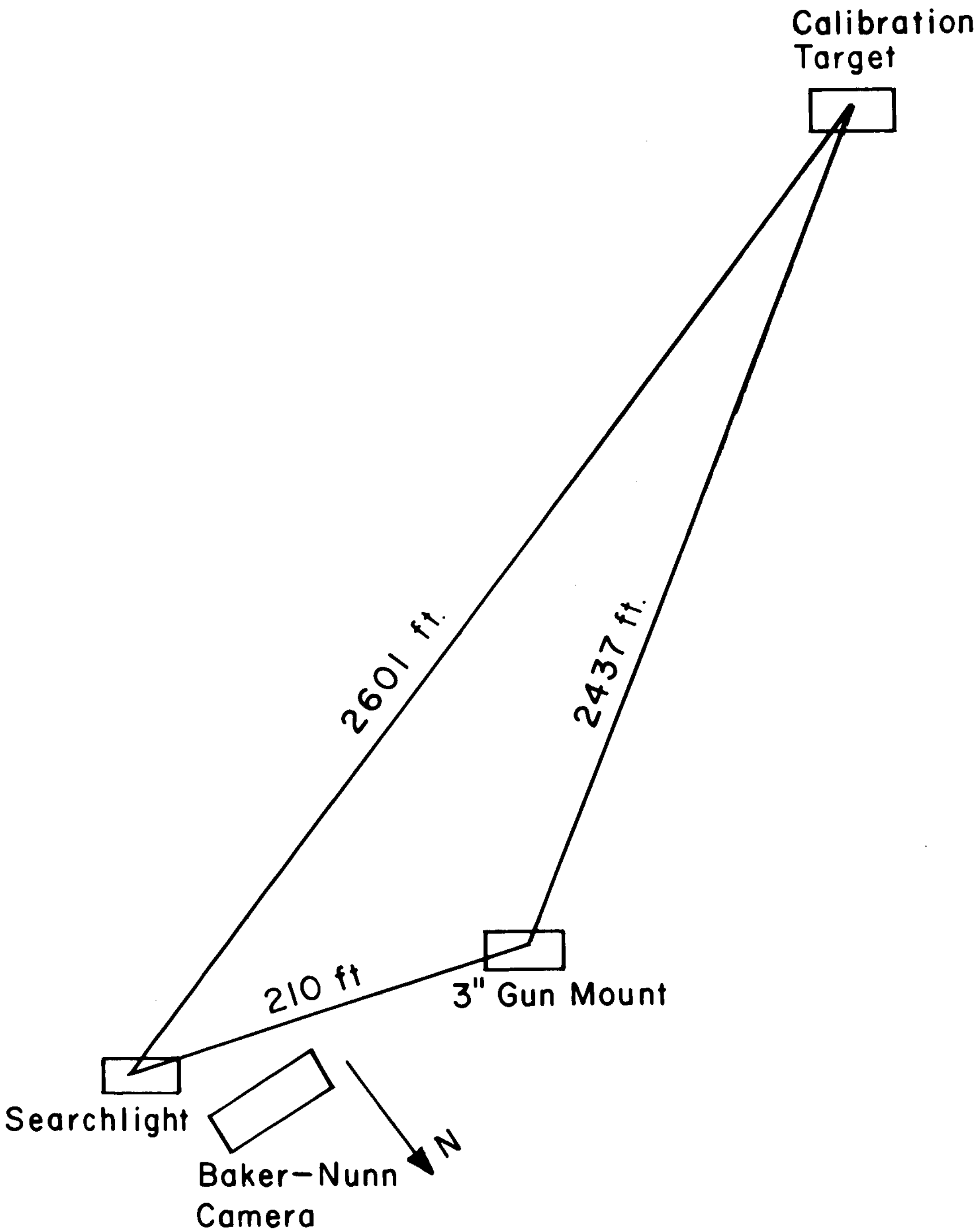


Figure 3. --Physical configuration of experimental equipment. The distances are _not_ to scale.

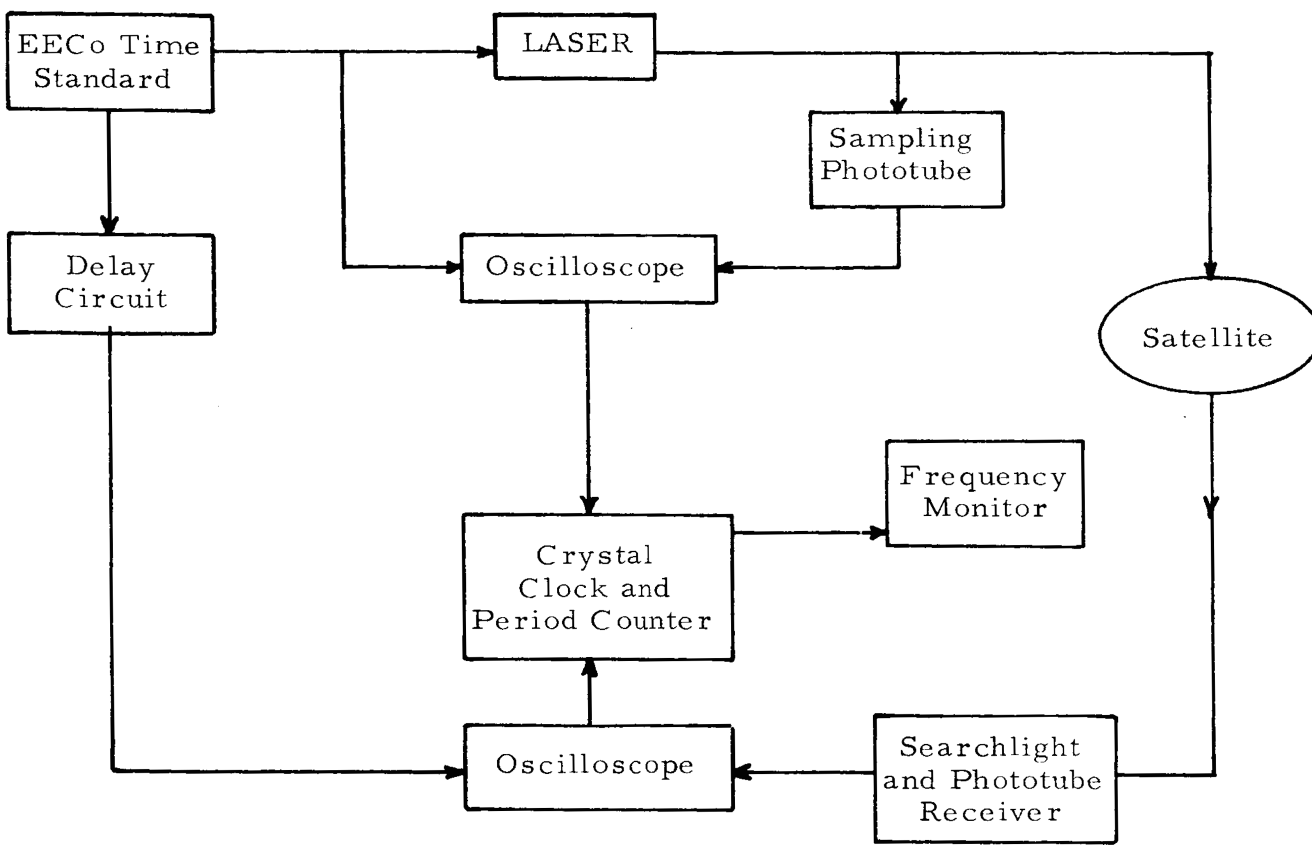
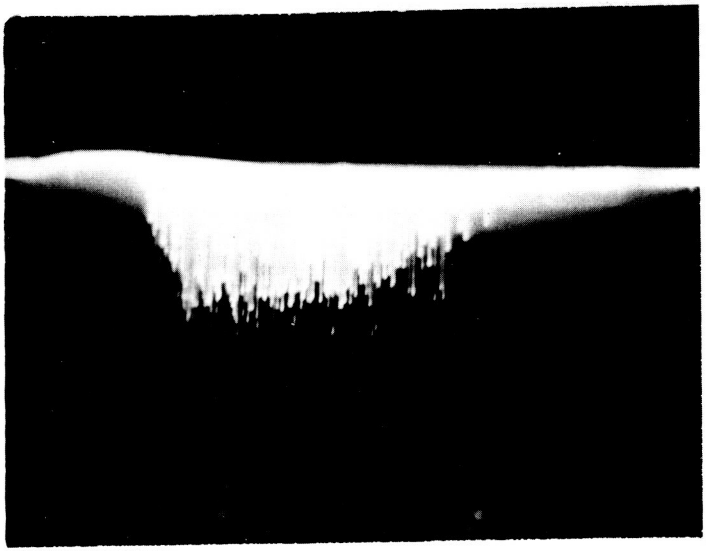


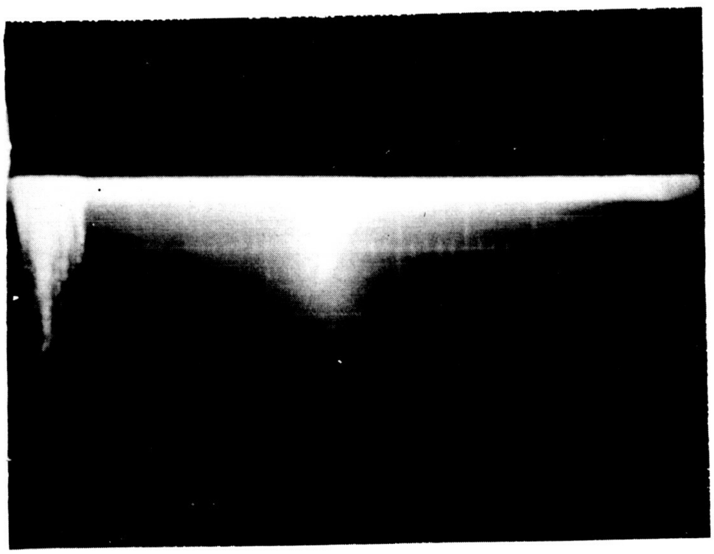
Figure 4. --Block diagram of laser-ranging system.

0.1 V/cm



0.2 ms/cm
Transmitted Pulse
for Success #1

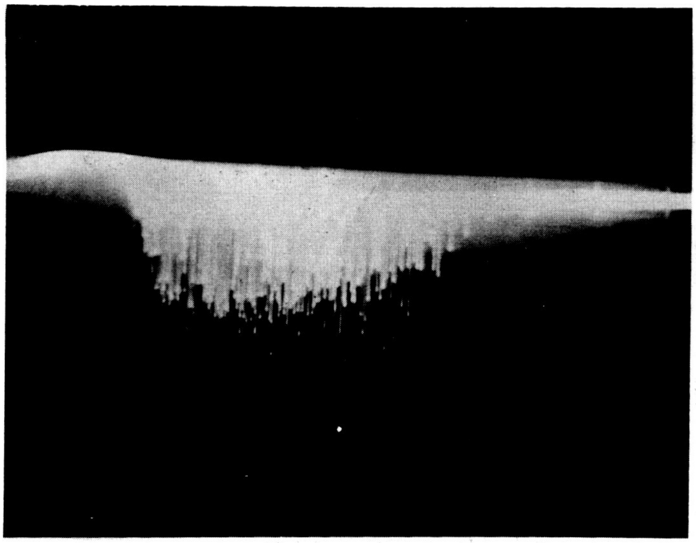
5 mv/cm



1.0 ms/cm
Success #1
Received Pulse

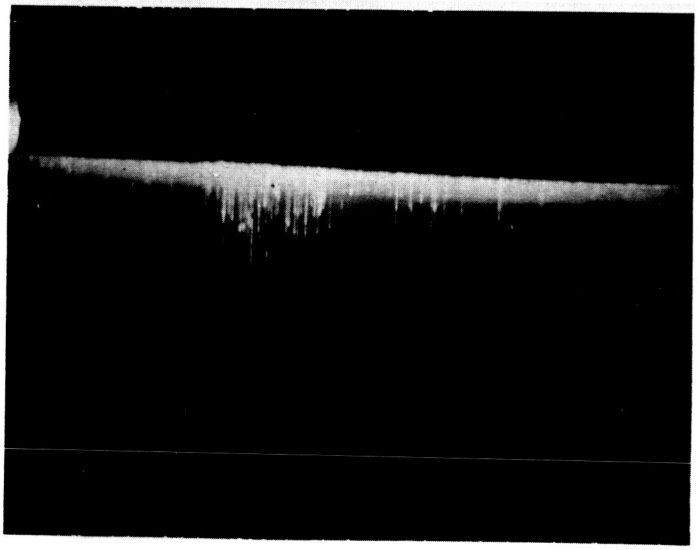
Figure 5

0.1V/cm



0.2 ms/cm
Transmitted Pulse
for Success #2

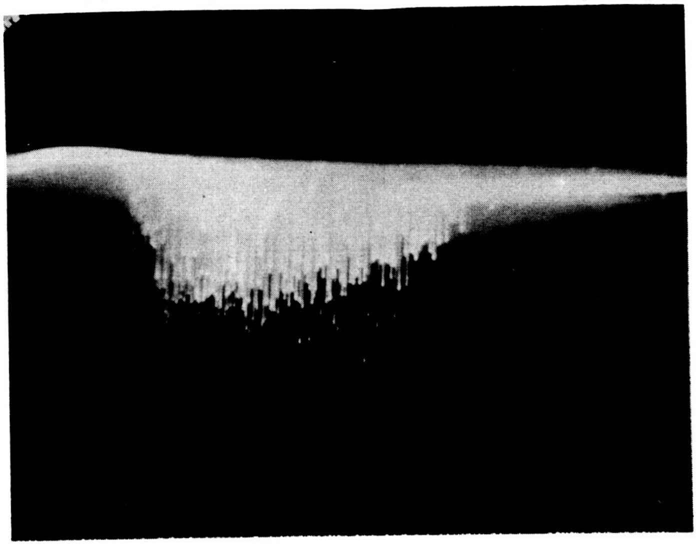
5 mv/cm



0.2 ms/cm
Success #2
Received Pulse

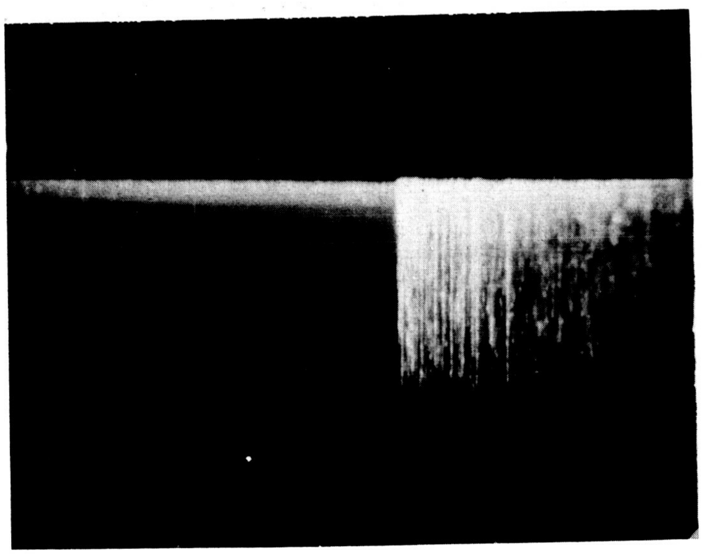
Figure 6

0.1 V/cm



0.2 ms/cm
Transmitted Pulse
for Success #3

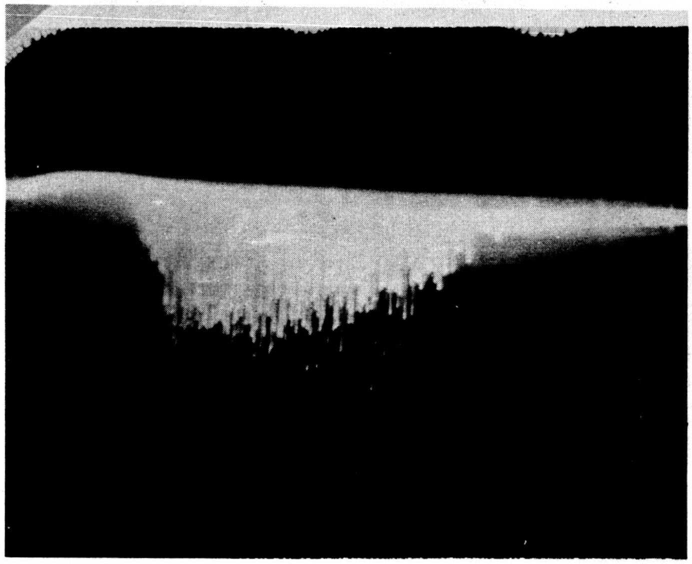
5 mv/cm



0.2 ms/cm
Success #3
Received Pulse

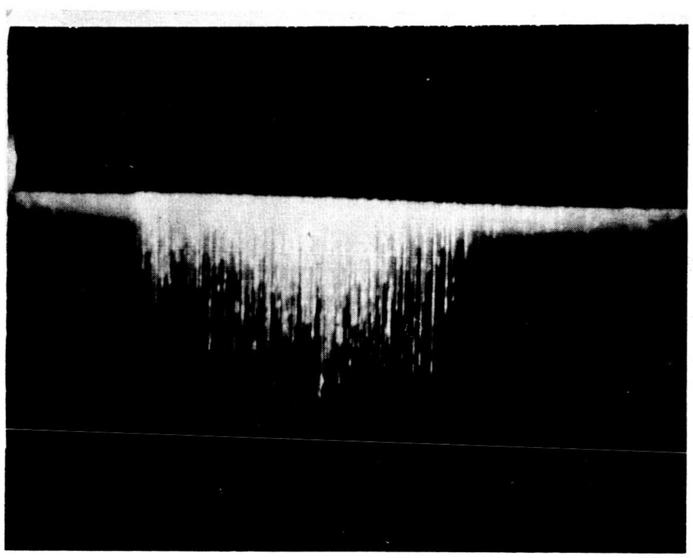
Figure 7

0.1V/cm



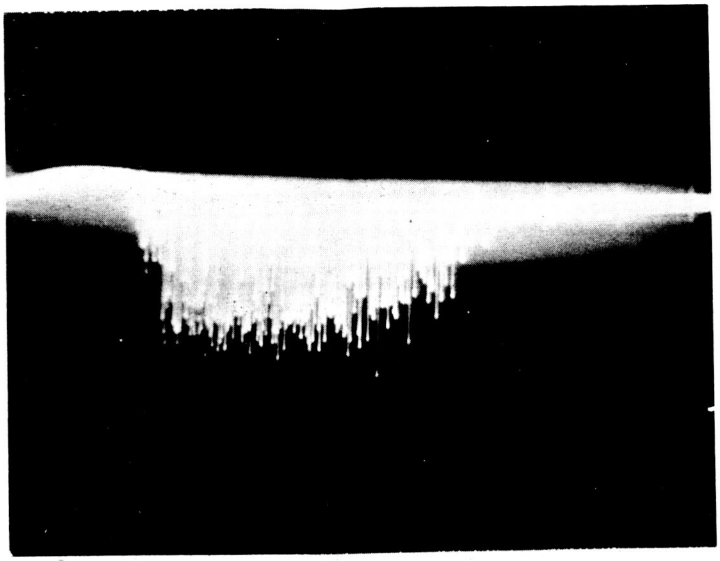
0.2 ms/cm
Transmitted Pulse
for Success #4

5 mv/cm



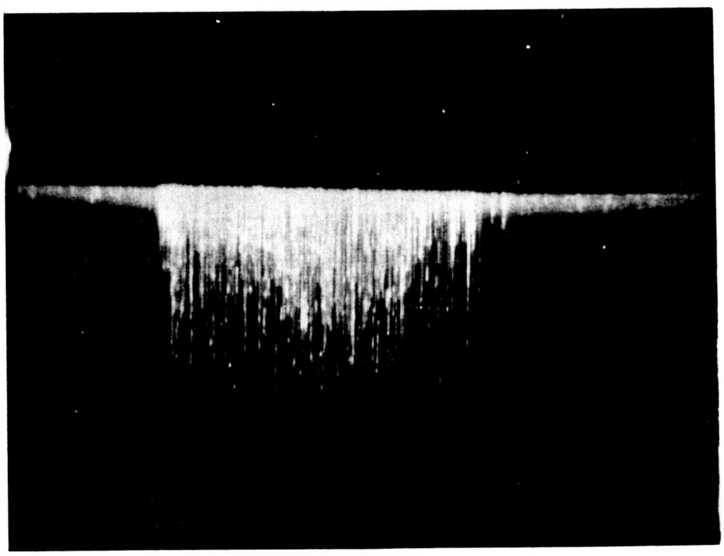
0.2 ms/cm
Success #4
Received Pulse

Figure 8



0.1V/cm

0.2 ms/cm
Transmitted Pulse
for Success #5

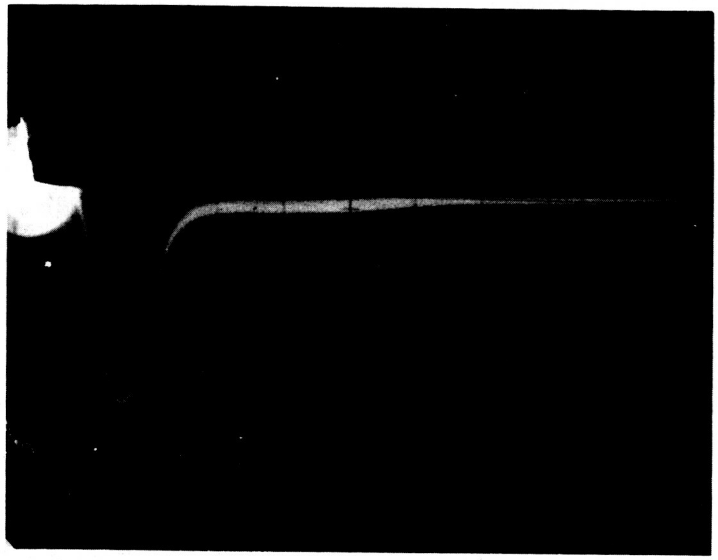


5 mv/cm

0.2 ms/cm
Success #5
Received Pulse

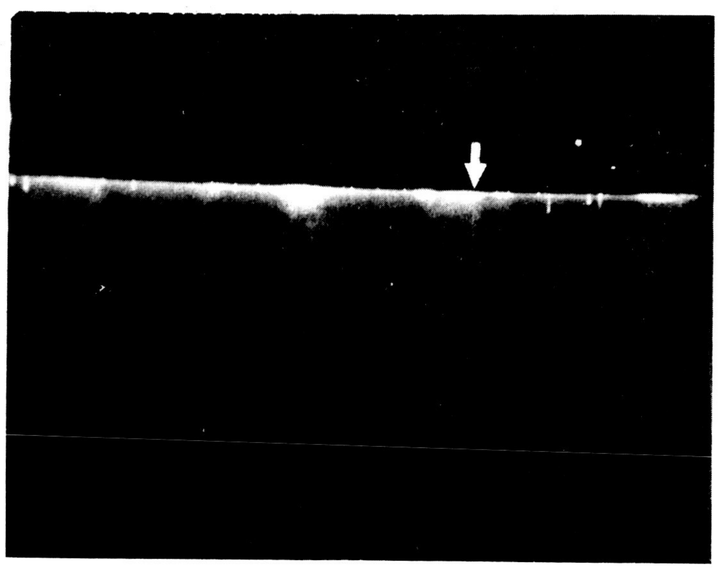
Figure 9

0.2V/cm



0.1 μs/cm
Typical Transmitted Pulse
for Rotating Prism Q-Switch

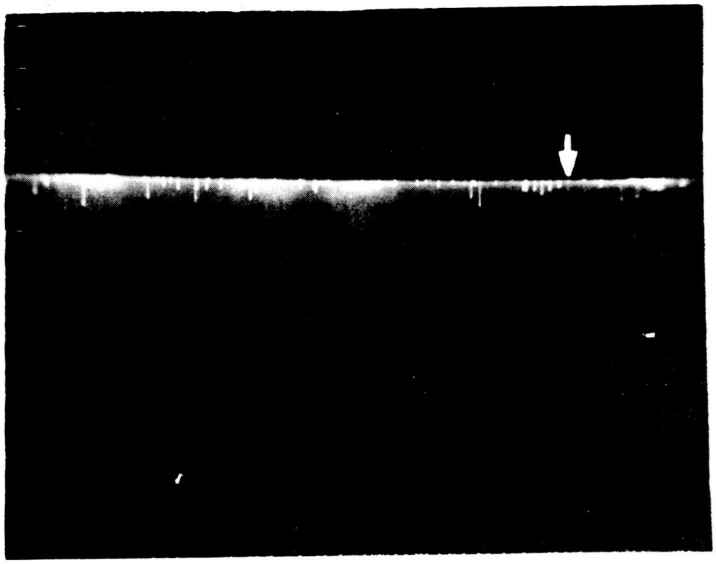
5 mv/cm



0.1 ms/cm
Success #9
Received Pulse

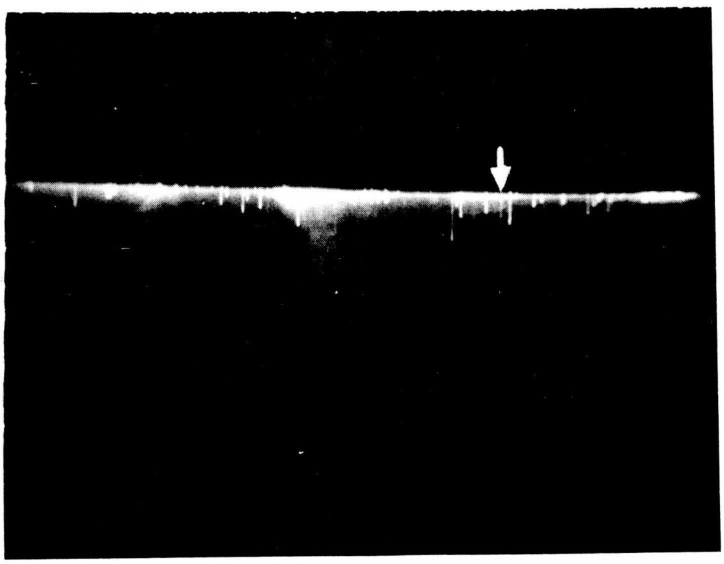
Figure 10

5 mv/cm



0.1 ms/cm
Success #10
Received Pulse

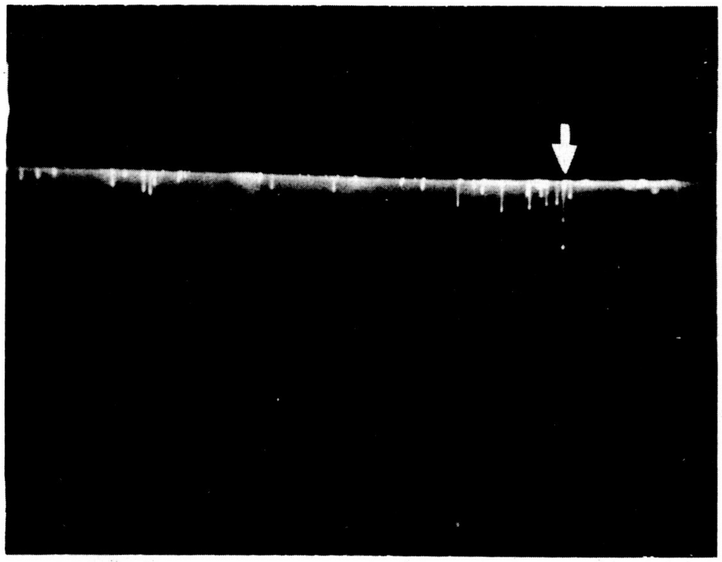
5 mv/cm



0.1 ms/cm
Success #11
Received Pulse

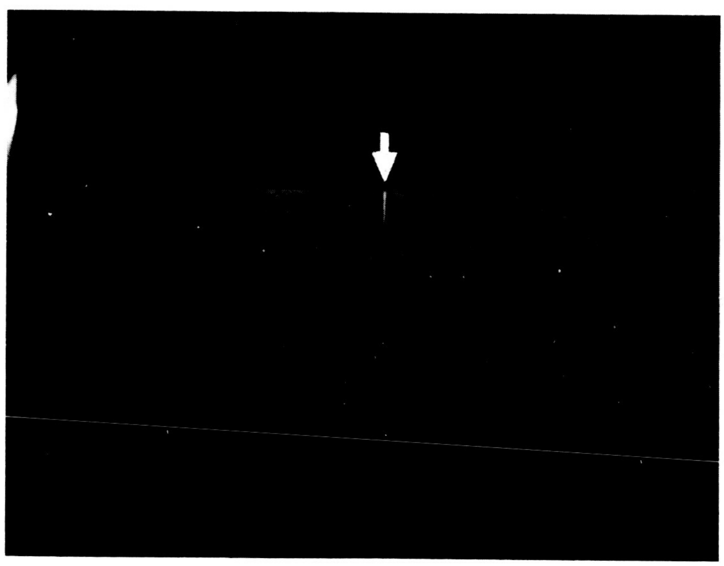
Figure 11

5 mv/cm



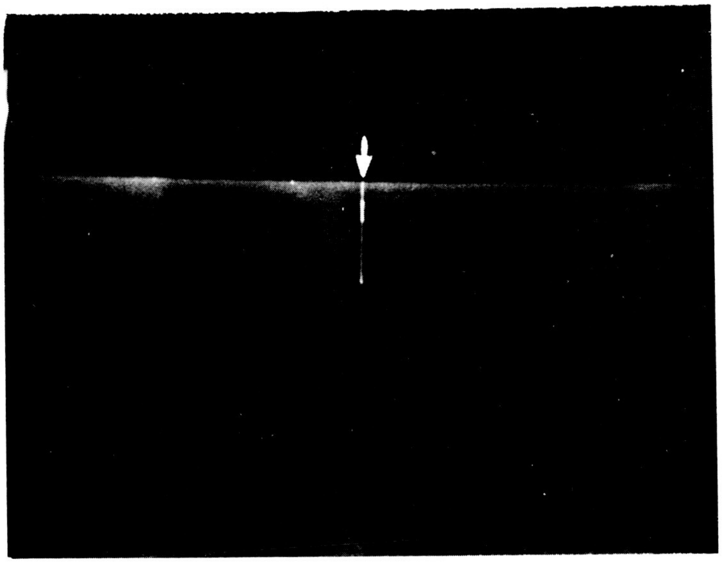
0.1 ms/cm
Success #12
Received Pulse

10 mv/cm

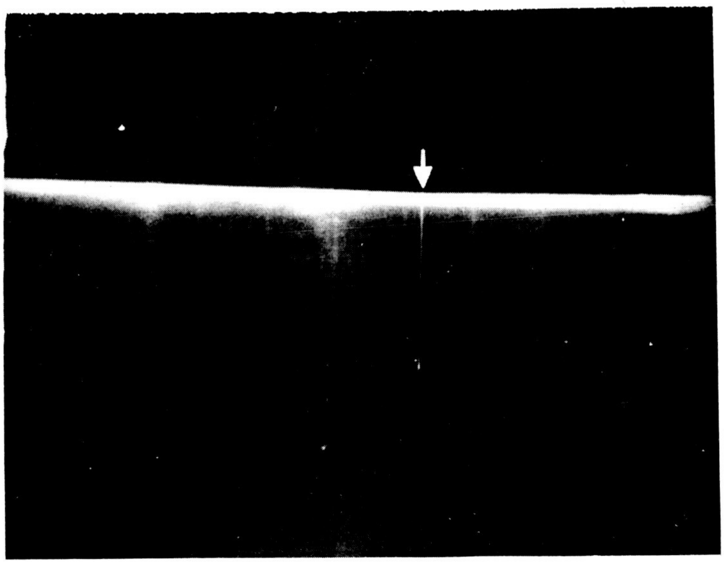


0.1 ms/cm
Success #13
Received Pulse

Figure 12



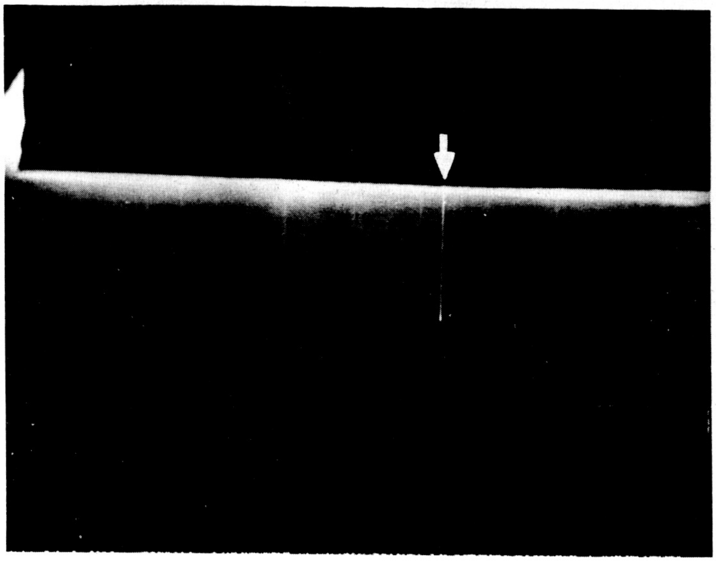
0. 1 ms/cm
Success #14
Received Pulse



0. 1 ms/cm
Success #15
Received Pulse

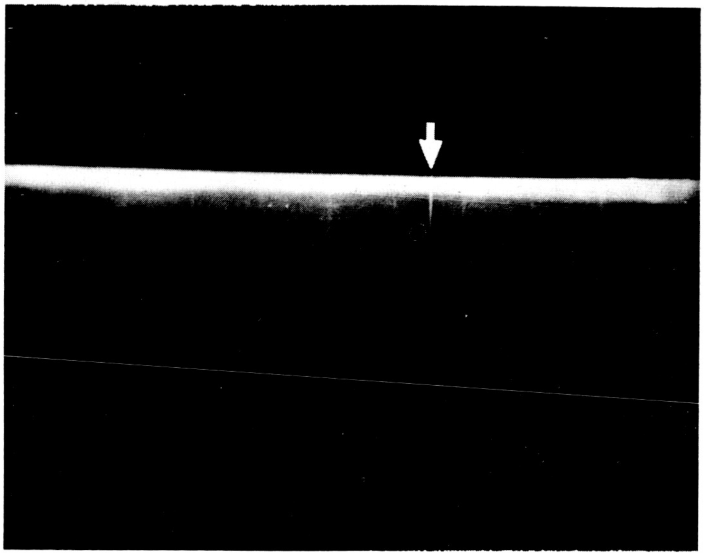
Figure 13

20 mv/cm



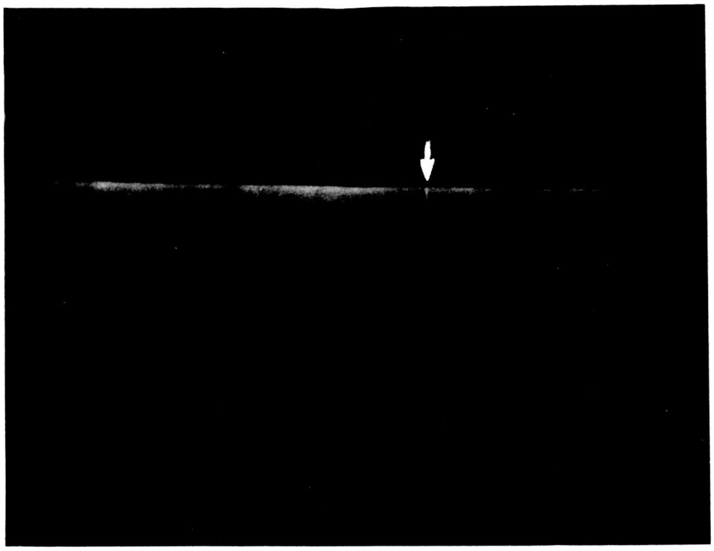
0.1 ms/cm
Success #16
Received Pulse

20 mv/cm



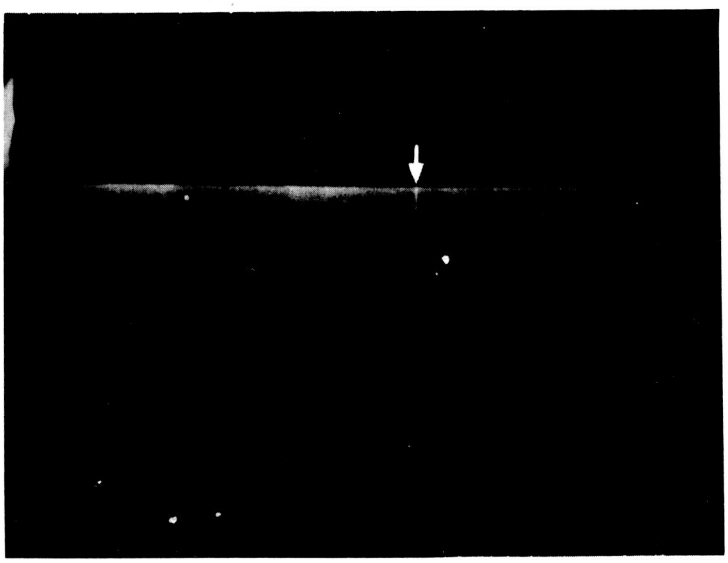
0.1 ms/cm
Success #17
Received Pulse

Figure 14



20 mv/cm

0.1 ms/cm
Success #18
Received Pulse



20 mv/cm

0.1 ms/cm
Success #19
Received Pulse

Figure 15

Table 1. --Laser characteristics

Wavelength	6943 Å
Beam Divergence (at output optics)	1 mrad
Repetition Rate	One pulse per minute

	Normal	Passive Q-Sw.	Q-Switched
Energy	36 joules	11 joules	0.5 joule
Pulse Width	1 ms	1 ms (total)	50 ns

Table 2. --Successful laser-range measurements.

Success No.	Date UT	Time UT	Satellite	Elevation (degrees)	Q-Switch*	Laser Transmitter Position	Range (Megameters)	Remarks
1	9/27/65	$11^h44^m00^s$	65032-01	53	No	B/N	1.134	
2	9/28/65	$11^h02^m20^s$	65032-01	44	No	B/N	1.281	
3	9/28/65	$11^h03^m20^s$	65032-01	47	No	B/N	1.214	Ranges determined from oscilloscope presentation.
4	9/28/65	$11^h05^m20^s$	65032-01	37	No	B/N	1.446	
5	9/28/65	$11^h06^m20^s$	65032-01	26	No	B/N	1.691	
6	9/29/65	$10^h26^m00^s$	65032-01	22	passive	B/N	1.835	
7	10/01/65	$10^h56^m40^s$	65032-01	59	No	3" gun mount	1.082	No oscilloscope presentation; Ranges determined from range counter.
8	10/01/65	$10^h57^m40^s$	65032-01	41	No	3" gun mount	1.288	
9	10/08/65	$02^h18^m50^s$	65032-01	49	Yes	3" gun mount	1.6110	
10	10/08/65	$02^h20^m50^s$	65032-01	57	Yes	3" gun mount	1.4415	Range counter amplitude threshold set too high; Ranges from oscilloscope presentation.
11	10/08/65	$02^h21^m50^s$	65032-01	52	Yes	3" gun mount	1.4925	
12	10/08/65	$02^h22^m50^s$	65032-01	44	Yes	3" gun mount	1.628566	Ranges determined from range counter.
13	10/09/65	$01^h40^m40^s$	65032-01	46	Yes	3" gun mount	1.638627	"
14	10/09/65	$01^h41^m40^s$	65032-01	41	Yes	3" gun mount	1.727432	"
15	10/12/65	$01^h35^m00^s$	65032-01	41	Yes	3" gun mount	1.768592	"
16	10/12/65	$03^h25^m30^s$	65032-01	50	Yes	3" gun mount	1.551090	"
17	10/13/65	$02^h47^m20^s$	65032-01	46	Yes	3" gun mount	1.586799	"
18	10/14/65	$02^h05^m40^s$	65032-01	57	Yes	3" gun mount	1.447215	"
19	10/14/65	$02^h06^m40^s$	65032-01	50	Yes	3" gun mount	1.581404	"
--	10/14/65	--	Calibration target	6	Yes	3" gun mount	0.001500	"

*See text for system description.

NOTICE

This series of Special Reports was instituted under the supervision of Dr. F. L. Whipple, Director of the Astrophysical Observatory of the Smithsonian Institution, shortly after the launching of the first artificial earth satellite on October 4, 1957. Contributions came from the Staff of the Observatory.

First issued to ensure the immediate dissemination of data for satellite tracking, the Reports have continued to provide a rapid distribution of catalogs of satellite observations, orbital information, and preliminary results of data analyses prior to formal publication in the appropriate journals. The Reports are also used extensively for the rapid publication of preliminary or special results in other fields of astrophysics.

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