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September 1968

**LASER LIGHT DETECTING AND RANGING (LIDAR)
SYSTEMS GB-60A AND GB-60B**

M. J. Landry, 7271
J. R. Lochner, 2316

SANDIA LABORATORIES

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SC-DR-67-850

LASER LIGHT DETECTING AND RANGING (LIDAR) SYSTEMS GB-60A AND GB-60B

M. J. Landry, 7226*
J. R. Lochner, 2316

Sandia Laboratories, Albuquerque

September 1968

ABSTRACT

Sandia Laboratories has developed a laser light detecting and ranging (LIDAR) system, primarily for use in tracking and diagnosing clouds formed by the ablation of simulated SNAP heat source materials during atmospheric reentry tests. This report briefly describes the GB-60A, a first generation LIDAR, and describes in detail the GB-60B LIDAR which provides more real time tracking than does the GB-60A.

*Formerly of 9232, work performed for Department 9510.

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Please make the attached corrections to your copy of the referenced report.

LLA:3412:rw

Page Line

- 4 26 Change 83 miles to 52.5 miles
- 4 27 Change 57 miles to 26.6 miles
- 9 16 Change 10 μm to 20 μm
- 11 6 Change to read "Instantaneous cloud depth,
 $l = 20$ ft for 20 nanosecond laser pulse"
- 11 Eq. (3) Correct denominator to read: $N_v p d^2 D^2 N_t l$
- 22 21 Change 4 joules to 2.8 joules
- 23 21 Change phonton to photon
- 53 6 Change ± 0.05 degree to ± 0.1 degree
- 53 7 Change ± 0.05 degree to ± 0.1 degree
- 64 11 Insert a superscript 8 after the word "skin"
- 67 Eq. (9) Equation 9 should read as follows:

$$P_R = P_T \eta_T \rho \left[\frac{D^2}{8R^2} \right]$$

- 70 3 Insert a superscript 17 after the " $6943\text{\AA}$ "
- 92 24(last) Change Table XX to Table X
- 109 Eq. (D-4) Change α^2 to a^2
- 127 Ref. 7 Change "Harris" to "Hams"
- 127 Ref. 10 Change "Shuster" to "Schuster"
- 128 Add following reference:
17. Ross, M., Laser Receivers, John Wiley
and Sons, Inc., New York, p. 288 (1966).
- 128 Ref. 4 Delete

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SUMMARY

In early 1964 a working group was established at Sandia Laboratory to review the feasibility of and the requirements for developing a laser LIDAR (Light Detecting and Ranging) system. The first generation LIDAR (GB-60A) was designed and built; it consists basically of a transmitter, receiver, and recorder. The transmitter consists of a Q-switched ruby laser and a power supply. The receiver consists of the optical system, a photomultiplier, and a photomultiplier supply. The recorder consists of an amplifier, an oscilloscope, and an oscilloscope camera. Data were successfully obtained with the GB-60A LIDAR. Daytime cloud reflections were photographed at a range of 26 miles, and nighttime reflections were recorded at 43 miles. In addition, retroreflectors, balloons, and discontinuities in the atmosphere were observed.

The successful detection of targets by the GB-60A LIDAR indicated that a second generation laser LIDAR should be constructed which would provide more real time tracking. To accomplish this, the GB-60B laser LIDAR was developed; it consists of a transmitter, a receiver, data and control electronics, and support equipment. The transmitter, the receiver, and some of the data and control electronics are mounted on a modified ME-16 tracking mount.

The transmitter is a dual-head ruby laser. The receiver is composed of a 300-inch focal length Cassegrainian telescope, a temperature-controlled interference filter and a photomultiplier detector. The data and control electronics are made up of the following subsystems: master timer, two range

systems, angle control and readout, and data recording instruments. The master timer provides pre-laser-fire operations for the visicorder, two 35 mm cameras, two printers, and personnel alarms in the control trailer; it also provides a laser fire signal coincident with the laser shot number. There are two range systems in the GB-60B; Range system No. 1 provides a coarse and a fine range trigger plus interval markers for the dual trace oscilloscope; Range system No. 2 provides a single range gate and 20 one-microsecond gated intervals in which the video signal is integrated. The angle control and readout subsystem provides seven searching and tracking modes. A synchro-system and a Decitrack system are used for angle readout. The data recording equipment consists of a visicorder, two 35 mm oscilloscope cameras, two 12-channel printers, and an X, Y, and H plotter which records the position of the tracking mount.

The support equipment for the GB-60B LIDAR consists of a modified ME-16 tracking mount and an instrument trailer which houses most of the electronic, data processing, and control equipment.

Clouds, retroreflectors, and terrain were successfully detected by the GB-60B LIDAR. The maximum range from which energy was reflected from atmospheric clouds is 75.8 miles (122 km); this is approximately 1.7 times the range attained with the GB-60A. A 2.25-inch diameter retroreflector was detected at a range of 83 miles. Mountainous terrain was detected at a range of 57 miles.

TABLE OF CONTENTS

	<u>Page</u>
DEFINING THE PROBLEM	7
LASER THEORETICAL CONSIDERATIONS	10
GB-60A LIDAR	13
Alignment	18
Data From GB-60A	19
GB-60B LIDAR	21
Transmitter	21
Receiver	28
Cassegrainian Telescope	28
Interference Filter	31
Photomultiplier Detector	33
Optical Alignment and Calibration	33
Data and Control Electronics	33
Sequence of Events	34
Master Timer	36
System Power and Photomultiplier Monitor	39
Temperature Monitors	40
Laser Shot Number Generator	40
Laser Power Control	40
Range Systems	43
ME-16 Angle Control and Readout	47
Data Recording Instruments	50
Plotting Board Display	51
Data Output	53
Auxiliary Data Inputs and Outputs	54

TABLE OF CONTENTS (Continued)

	<u>Page</u>
Support Equipment	54
ME-16 Tracking Mount	54
Control Trailer	56
Safety Considerations	60
Data From GB-60B	66
Introduction	66
Detection of Clouds	76
Detection of Retroreflectors	77
Detection of Terrain	83
Attenuation Due to Backscattering	85
Pulse Stretching	88
Correlation Between Retroreflector Data and Atmospheric Transmission Theory . .	89
Conclusion	94
APPENDIX A -- Development of Laser	95
APPENDIX B -- Radiation Detectors	97
APPENDIX C -- Aligning the GB-60B	99
APPENDIX D -- Calculation of Minimum Number Density Detectable by GB-60B	103
APPENDIX E -- Atmosphere Attenuation Due to Water, Carbon Dioxide, and Ozone	113
APPENDIX F -- Molecular Attenuation in the Atmosphere	121
REFERENCES	127
REFERENCES NOT CITED	128

LASER LIGHT DETECTING AND RANGING (LIDAR) SYSTEMS GB-60A AND GB-60B

DEFINING THE PROBLEM

In early 1964 a working group was established at Sandia to review the feasibility of and the necessary requirements for developing a LIDAR (Light Detecting and Ranging) system for locating and tracking an ablation cloud formed by the ablation debris from a SNAP (Systems for Nuclear Auxiliary Power) device. The original specification of this type of cloud was outlined in "Flight Test Experiment Plan for Sampling Ablation Debris Proposal," which was written by Division 9311 and is recapitulated here. The exact geometry and specifics of these clouds cannot be predicted; they can only be theorized.

Theoretical and experimental studies show that ablation material may shear from the reentry body as liquid droplets. These droplets may be further decreased in size due to physical and/or thermochemical effects. It is possible to predict, from the Weber number, the size of the maximum stable liquid drop formed of a particular material. It is not possible to predict the final size of the drop since aerodynamic forces acting on the liquid drop could further reduce the size of the drop. It does seem reasonable to assume that the size of the drops will be smaller than that predicted using the Weber number. A brief example will illustrate the specifics of the proposed sample cloud. Consider a cloud with the specifications listed in Table I.

TABLE I
Cloud Specifications

Material = Zirconium

Burnup altitude = 150,000 feet

Reentry velocity, $V_p = 20,000$ feet/second

Air density at altitude burnup, $P_g = 1.149 \times 10^{-4}$ lb/ft³

Surface tension of molten zirconium, $T_p = 9.25 \times 10^{-2}$ lb/ft

Cloud dimension = 5,000 ft diameter by 50,000 ft long

Cloud mass = 400 lbs (181.44 Kg)

Zirconium density = 6.4 g/cm³

Zirconium reflectivity = 0.6

$G =$ Gravitational constant = 32.3 (lb-ft)/sec²

The maximum size that liquid droplets can sustain is given according to the Weber number, WN:

$$WN = \frac{V_p^2 P_g D_m}{12 T_p G} \quad (1)$$

Rearranging Equation (1), the maximum diameter of the zirconium droplet is

$$\begin{aligned} D_m &= \frac{12 T_p G}{V_p^2 P_g} WN \\ &= 775 \times 10^{-6} \text{ ft} = 236 \text{ } \mu\text{m} \end{aligned} \quad (2)$$

under the conditions itemized above and assuming the critical Weber Number to be 1. It is therefore reasonable to assume that the diameter of the droplets will be $\lesssim 200$ micrometers. For 400 pounds of zirconium distributed entirely in monosized particles of either 200, 20, 2, or $0.2 \text{ } \mu\text{m}$, the density in a 5,000 foot diameter by 50,000 foot long cloud would be as indicated in Table II.

TABLE II
Cloud Density

Size of particles (cm)	Volume of 1 particle (cm ³)	No. of particles in cloud	No. of particle/ ft ³
200 x 10 ⁻⁴	4.19 x 10 ⁻⁶	6.7 x 10 ⁹	6.7 x 10 ⁻³
20.0 x 10 ⁻⁴	4.19 x 10 ⁻⁹	6.7 x 10 ¹²	6.7
2.00 x 10 ⁻⁴	4.19 x 10 ⁻¹²	6.7 x 10 ¹⁵	6.7 x 10 ³
0.200 x 10 ⁻⁴	4.19 x 10 ⁻¹⁵	6.7 x 10 ¹⁸	6.7 x 10 ⁶

It is probably not too realistic to assume that the particles in the clouds are monosized; but at present reentry physics does not allow even calculated guesses about particulate specifics, especially particle size distribution. It was suggested by Division 9511 that particle size distribution range from 2 to 20 μm might be valid. For calculation purposes, nominal monosized particles of 10 μm diameter are considered.

LASER THEORETICAL CONSIDERATIONS

After the problem was defined, Division 9232 initiated a theoretical feasibility study of the possible use of a laser LIDAR to detect and track the type of cloud described by Division 9511. It is apropos to discuss briefly the principles involved in detecting and tracking a cloud with a LIDAR system. The system should consist of two main sub-systems, a transmitter and a receiver. The transmitter emits radiation in the visible spectrum with a restricted divergence. After attenuation by the atmosphere, the energy incident onto the cloud particulate will be diffracted, scattered, and reflected by the particulate. For a transmitter and receiver at the same location, only a fraction of the energy reflected in a solid angle subtended by the diameter of a target will be collected by the receiver, because the radiation contained in this solid angle is again attenuated by the atmosphere as it returns. Due to the beam divergence of the transmitter, the finite area of the particulate, and the atmospheric attenuation, large amounts of energy are needed. If the particular characteristics of the cloud, e.g., time variables, cloud depth, density distribution, etc., are required, the transmitter radiation must be switched at rates sufficient to resolve these variables. At the time the LIDAR Project was initiated, pulsed lasers had a pulse rate of 1 pps at a maximum of 200 megawatts for 15 minutes; CW lasers allow a maximum of 100 milliwatts of power for hours of operation. A simple calculation, illustrated below, shows that only Q-switched lasers were worth considering.

Consider a transmitter-receiver system and a cloud with the characteristics listed in Table III.

TABLE III

Transmitter-Receiver and Cloud Characteristics

Cloud density, $N_v = 6.7$ particle/ft³

Particle diameter, $d = 20\mu\text{m} = 6.55 \times 10^{-5}$ ft

Reflectivity, $p = 0.5$

Instantaneous cloud depth = 20 ft for 20 nanosecond laser pulse

Diameter of receiver collector, $D = 5$ ft

Atmospheric and optical transmission, $N_t = 0.1$

Range, $R = 50$ miles = 2.64×10^5 ft

Minimum detectable power $P_{\min} = 10^{-9}$ watts

Laser beam divergence = 10^{-2} radians

For a cloud with dimensions greater than the dimensions of the laser beam, the required power of the transmitter, in order to detect the reflection from the particulate, must be

$$P_t = \frac{R^2 P_{\min}}{N_v p d^2 D^2 N_t} = 20 \times 10^6 \text{ watts.} \quad (3)$$

It is obvious that only a Q-switched laser could be used as the transmitter. Due to the large output power required, very few crystalline materials are suitable for LIDAR applications. The large majority of existing laser frequencies occur in the infrared where the sensitivity and response time of available detectors is relatively poor, even with cryogenic cooling. The use in receivers of low-noise, high-sensitivity, uncooled detectors such as photomultipliers limits the output wavelength to less than about $10,000 \text{ \AA}$. The only crystalline materials with proved laser action and sufficient power that fall in this category are ruby ($6943 \text{ \AA}$) and neodymium-doped glass ($10,600 \text{ \AA}$).

Although the pumping requirements for neodymium are much lower than for ruby, the sensitivity of the best available detector at 10,600 Å is two orders of magnitude lower than the best available detector at 6943 Å. Ruby is also thermally easier to Q-spoil than neodymium-doped materials. Thus, from the standpoints of overall efficiency, e.g., detection sensitivity and pumping requirements, linewidth, and ease of Q-spoiling, ruby is the best material available.

GB-60A LIDAR

The first generation laser LIDAR system (GB-60A) was built around a carbon-arc searchlight frame and its 60-inch diameter mirror. The system and the data collected are described in detail in SC-RR-67-115.¹ We will present a brief description of the system, some of the problems encountered, and the more pertinent results.

The first generation LIDAR system is comprised basically of three subsystems: the transmitter, the receiver, and the recorder and control (Figure 1). Figures 2 and 3 show front and rear views of the converted searchlight mount with the transmitter and receiver sections mounted on it. Figure 4 shows the recorder and control section.

The LIDAR transmitter is a modified TRG 104 ruby laser. The optically excited ruby emits 10 to 30 megawatts of power in pulse widths of 20 to 60 nanoseconds. The Q-switching element is a 24,000 rpm spinning prism which is synchronized with the flash lamp power circuit. The modified TRG 104 laser is encased in a dust tight box with a rigid base to protect the optical surfaces from dust and help keep the optical cavity aligned. It is cooled by refrigerated air instead of ambient air to lower the threshold of the laser; the input cooling air is filtered through a 0.3 μm dust filter.

The LIDAR receiver consists of a Cassegrainian telescope, which is made up of a 60-inch diameter primary and a 3.00-inch diameter secondary, and a detector. The detector section consists of 7 Å bandwidth interference filter, a collecting lens, diaphragm stop, photomultiplier, dynode resistors, and power

Figure 1. Block diagram of the GB-60A LIDAR

Figure 2. Front view of GB-60A laser LIDAR mount

Figure 3. Rear view of GB-60A laser LIDAR mount

Figure 4. Recorder and control section of GB-60A laser LIDAR

supply. The Cassegrainian telescope system has a 25-milli-radian field of view. A noise analysis of different photomultiplier tubes² showed that the sky noise background is the limiting noise in daytime operation. Even for night operation, it is not necessary to cool the photocathode surface of the PM tubes. The number of noise pulses per unit time is sufficiently small so that the probability of detecting a noise pulse during the observation period is small.

The LIDAR recording section consists of a Tektronic Model 555 oscilloscope, Beattie-Coleman Polaroid oscilloscope camera, and timer. The laser is fired at the rate of 1 ppm, while the voltage output of the photomultiplier, which represents the reflected energy received from the cloud, is displayed on the oscilloscope and photographed by the camera. The oscilloscope is triggered by a zero time signal from an ITT FW 114 photodiode which is placed to the rear of the spinning prism of the laser cavity. Scattered light from the prism is intense enough to provide the required signal.

Alignment

The most difficult problems encountered in working with this first generation system were: (1) the signal to noise ratio and (2) aligning the laser output ray parallel to the optical axis of the Cassegrainian telescope. A sufficient signal-to-noise ratio was obtained by limiting the field of view of the PM to essentially the beam divergence of the laser output. The method of aligning the axes of the Cassegrainian telescope and the laser ray is discussed in detail in SC-RR-67-115.¹ Essentially, an He-Ne gas laser was positioned on a 5-mile hill pointing toward the LIDAR system. The receiver was positioned for maximum signal out of the PM. Three retro-reflectors were placed at the tips of two intersecting lines.

The horizontal line was placed at the top of the hill and was twice the length of the vertical line which was directed down the hill. The He-Ne laser was placed at the midpoint of the base. The retroreflectors were moved outward equidistant from the intersection along the lines until an observer at the transmitter could barely see the reflections of the 104 laser beam from each reflector.

Data From GB-60A

Data were collected from atmospheric clouds, balloons, and retroreflectors. The detection of atmospheric clouds in the daytime at a distance of 26 miles and at night at 43.2 miles (Figure 5) along with the tracking of a radar retro-reflector from 3.8 to 4.5 miles (Figure 6) demonstrated that the system could be used to detect and track low density, slow velocity targets. The results also demonstrated that the varying density of a cloud 14.66 miles downrange, with a characteristic thickness of 2000 feet, could be recorded (Figure 7).

Range 26 miles
daytime

Range 43.2 miles
nighttime

Figure 5. Reflections from atmospheric clouds - GB-60A

3.8 miles range
0.034 volt

4.5 miles range
0.015 volt

Figure 6. Tracking a radar retroreflector from 3.8 to 4.5 miles

A trace 20.0 $\mu\text{sec}/\text{cm}$
B trace 1.0 $\mu\text{sec}/\text{cm}$
14.66 miles slant range
Cloud ~2000 feet thick
Amplitude of B trace =
0.17 v nighttime

Figure 7. Detection of a thick atmospheric cloud

GB-60B LIDAR

The successful detection of targets by the GB-60A LIDAR indicated that a second generation laser LIDAR could be constructed which would provide more real time tracking. To accomplish this, the GB-60B laser LIDAR was developed. It consists of the following subsystems:

1. Transmitter
2. Receiver
3. Data and Control Electronics
4. Support Equipment

The transmitter is a Raytheon LH8 ruby laser head.* The receiver was developed at Sandia Laboratory. The data and control electronics were developed and/or assembled at Sandia. Of the support equipment, the control trailer and the ME-16 tracking mount were fabricated at Sandia; the remainder of the support equipment consists of commercial equipment.

Transmitter

The transmitter used in the GB-60B LIDAR system is a dual-head Raytheon LH8 ruby laser which is mounted on the tracking mount. Each laser head consists of a liquid-cooled elliptical cylinder reflecting cavity, a liquid-cooled flash lamp, and a liquid-cooled laser crystal. Each 90-degree

*See Appendix A for a discussion of the problems encountered during laser development.

polarization-oriented ruby crystal is 6-5/8-inches long by 3/8-inch diameter and is coated with an anti-reflection coating at the end closest to the Pockels cell. The rubies are Al_2O_3 crystals and are doped with 0.05-percent triply ionized chromium. The transmitter specifications are listed in Table IV.

TABLE IV

GB-60B Laser Transmitter Specifications

Electrical energy input - up to 2800 joules
Maximum optical energy output - 200 megawatts, each head
Maximum repetition rate - 1 pps
Crystal size - 6-5/8-inches long by 3/8-inch diameter
Flash lamp - FX - 47B (EG&G)
Coolant - water-alcohol mixture
Coolant flow rate - 1.70 gallons/minute
Output wavelength - $6943 \text{ \AA}$ ($0.6943 \mu\text{m}$)
Pulse width - 12-28 nanoseconds, Q-spoiled
0.5 millisecond, non-Q-spoiled
Beam divergence - 4.5 milliradians at 30 MW
8.5 milliradians at 100 MW
8.5 milliradians at 200 MW
Energy output - 4 joules, Q-spoiled
50 joules, non-Q-spoiled
Q-Switch - Pockels cell Model LA12A
Dimension - 61-inches long x 10-inches wide x
13-inches high
Weight - Approximately 90 pounds
Lamp life time - 2000 shots at 2800 joules input

The ruby rod is optically pumped by a xenon flash lamp. The laser head is shown in Figure 8. The flash lamp is fired by a pulse from an inline saturable trigger transformer which ionizes the gas inside the flash lamp. A charged 900 μfd capacitor bank which is capable of a maximum charge of 3000 V, is connected to the ends of the flash lamp and discharges through the lamp. A maximum of 15,000 amperes discharges through the lamp which has an effective discharge resistance of 0.2 ohm. The optical flash of the xenon in the lamp causes the chromium ions in the ${}^4\text{A}_2$ levels to be excited to the ${}^4\text{F}_2$ band (1000 $\text{\AA}$ wide) (Figure 9). This transition corresponds to a 5600 $\text{\AA}$ wavelength. The high transition probability S_{32} non-radiative transition to ${}^2\text{E}$ level populates that state. The $2\bar{\text{A}}$ and $\bar{\text{E}}$ to ${}^4\text{A}_2$ transition corresponds to the R_2 and R_1 emission lines, respectively. The long lifetime of the $2\bar{\text{A}}$ and $\bar{\text{E}}$ (labeled the metastable states) enables the population in these states to build up and eventually surpass that of the ${}^4\text{A}_2$ (ground state); if a sufficient inversion of population occurs between the $\bar{\text{E}}$ and ${}^4\text{A}_2$ states such that the losses of the cavity are surpassed, then the laser oscillates. The spontaneously emitted photon creates a radiation field that allows induced emission from the $\bar{\text{E}}$ to ${}^4\text{A}_2$ state to occur. This emission corresponds to the 6943 $\text{\AA}$ laser line used in the LIDAR system. The radiation emitted from both ends of the rod is essentially fluorescent radiation ($\Delta\lambda \cong 800 \text{\AA}$) until the "lasing" threshold is reached. At this time, the following occur:

1. The spectrum of the R_1 emission line (the laser line) becomes narrower (the spectral line width changes from 6.0 cm^{-1} to 0.2 cm^{-1}),^{2,3}
2. The lifetime of the $\bar{\text{E}}$ state shortens from 3 to 0.6 msec,⁴
3. The intensity ratio⁵ $\text{R}_1:\text{R}_2$ increases from 2:1 to 50:1,

Figure 8. GB-60B laser head

Figure 9. Energy level of the GB-60B laser ruby

4. The directionality³ of the emitting radiation sharpens, and
5. The coherence of the emitting electromagnetic field increases.³

The light emitted from the Pockels cell end of the ruby (Figure 10), which is polarized 90° relative to the optical axis of the rod, is transmitted through the Pockels cell and the polarizer plates, and is reflected by the 100-percent reflecting end mirror back through the polarizer plates, the Pockels cell, and the ruby. Seven percent of the light emitting from the output end of the ruby rod is reflected back into the rod to be reamplified and transmitted out the internal end of the rod through a path identical to the path outlined above. The light is transmitted through the Pockels cell and the polarizer plates, providing the polarization axis of the ruby is properly oriented relative to the polarizer plates and provided the proper voltage is placed on the Pockels cell. The Pockels cell rotates the axis of the polarized light which is incident from either side. This is accomplished by altering the birefringence of the KDP material. The birefringence is altered by changing the electric field to which the cell is subjected. One value of electric field will allow the polarized light to be properly oriented so that it will traverse the polarizer plates and be reflected by the end mirror, while another value will not. The polarizer plates act as an analyzer to reject the light transmitted by the Pockels cell if the polarization is not properly oriented.

The ruby and Pockels cell are provided with Brewster angle dust covers. The scattering from the ruby dust cover is piped to a ITT FW 4000 photodiode. The output of this diode provides a "zero" time pulse for the range gating and is also calibrated to provide continuous monitoring of the energy output of the laser.

Figure 10. Diagram of laser head

The Raytheon laser transmitter proved to be extremely reliable. One of the laser heads has operated at least twice the length of time required in the specifications at the 100 megawatt level without changing any optical components. The mirrors of the optical cavity require frequent alignment. We found that operating with a 60-40 water-alcohol mixture provided ample protection against freezing and did not adversely affect the performance of the cooled optical surfaces, i.e., the flash lamp and ruby. It was observed that after 45 minutes of operation at 100 megawatts, a thin black film barely visible to the eye is deposited on the flash lamp envelope. The film is carbon from the carbon chain in the alcohol.

Two modifications were made to the laser head. After a few weeks of use, it was found that when the alignment telescope was placed on one end of the base plate of the laser head, the weight of the telescope twisted the plate and misaligned the cavity. A thicker plate was designed, and cross members were provided to prevent the plate from twisting when the scope was placed on it. The ruby holder and cooling jacket were modified to accept a 6-1/2- by 5/8-inch ruby rod instead of the 6-5/8- by 3/8-inch rod which was originally supplied.

Receiver

The laser LIDAR receiver consists of a Cassegrainian telescope (Figure 11), and a temperature-controlled interference filter and photomultiplier detector (Figure 12).

Cassegrainian Telescope

The telescope, which has an effective focal length of 300 inches, is mounted on a modified ME-16 tracking mount which was developed at Sandia Laboratory. The 60-inch diameter primary mirror is attached to the modified front end of the cylindrical tube which formerly held a 16-inch diameter Newtonian telescope. The rhodium-coated bronze parabolic primary mirror has a focal length of 25.6 inches. The secondary mirror is 8-inches in diameter and is held to the long cylinder tube of the ME-16 mount by three spider legs; it can be moved along a geometrical axis which is parallel to the geometrical axis of the mount and can also be tilted relative to this axis. The secondary was aluminized according to specification Number 1058 of the Liberty Mirror Division of Libby-Owens-Ford and has a reflectivity of approximately 95 percent. The hyperbolic surface of the secondary is curved according to

$$x^2 - 36.238x - 2.4509y^2 = 0$$

where x is along the axis of the mirror and y is normal to the axis as defined in P11563. The surface was pitch-polished to within 0.0003 inch of the above equation. The overall efficiency of the optical system is approximately 6.3 percent; this indicates that the figure of the primary mirror surface is not very good.

Figure 11. Cassegrainian telescope

Figure 12. Photomultiplier detector and interference filter

A field stop was inserted along the optical axis to limit the field; this helps reduce unwanted background radiation noise. All components, except the face of the photomultiplier tube, through which energy is transmitted are coated with an anti-reflection coating to minimize reflection losses.

Interference Filter

A temperature-controlled interference filter, which has a bandpass as shown in Figure 13 is placed within 5 inches of the focal point of the telescope. The filter bandwidth of $\Delta\lambda = 20 \text{ \AA}$ allows the $6943 \text{ \AA}$ rays from a light cone of 12.6° (or the rays contained in an angle 6.3° from the normal to the filter) to pass through the filter. Theoretically, the light cone angle is 11.7° , or 5.7° from the normal to the surface, and would require a $15.5 \text{ \AA}$ filter. This means that unwanted background noise corresponding to $4.5 \text{ \AA}$ is passing through the filter and is received by the detector. This limits the range of the LIDAR during daylight but does not affect nighttime operation. The lower wavelength of the filter is positioned with the upper half-power point at $6943 \text{ \AA}$ at 130°F and with a $20 \text{ \AA}$ wide bandpass positioned on the lower wavelength side of $6943 \text{ \AA}$. The reflected laser ray that enters the filter at the normal incident angle of zero enters at the $6943 \text{ \AA}$ side of the filter. Reflected waves which enter at an incident angle greater than zero will enter at an effective wavelength shorter than $6943 \text{ \AA}$. For a specific incident angle, θ , the required bandwidth of the filter is

$$\Delta\lambda = \left[1 - \frac{\sqrt{n^2 - \sin^2 \theta}}{n} \right] \lambda_0 \quad (4)$$

where n is the index of the filter and λ is the wavelength to be filtered. The bandwidth is from λ_0 to short wavelength.

Figure 13. Bandpass of the interference filter used in the LIDAR receiver

Photomultiplier Detector

The detection of small signals requires the use of a photomultiplier (PM) tube (Appendix B). The International Telephone and Telegraph FW 130 and the RCA 7265 PM's, both with S-20 photoemissive surfaces, have been used successfully; either PM can be used in the GB-60B. These tubes are particularly useful in laser LIDAR work because of their very low dark pulse rate and high S/N characteristics. With these PM's, there is a very high probability of successfully detecting a small number of photoelectrons.

The photomultiplier tube, which is located at the focus of the Cassegrainian telescope, is properly supported to isolate shocks and is shielded against both electrostatic and magnetic fields. The resistor-diode network is mounted directly on the PM tube base to minimize inadvertent signal pickup.

Optical Alignment and Calibration

The primary mirror, secondary mirror, and the filter mount can be tilted relative to the geometrical axis of the ME-16 tracking mount. These adjustments are provided to facilitate the optical alignment of the receiver. This alignment presented a challenging problem and is discussed in Appendix C. A procedure for calibrating the optical efficiency of the Cassegrainian telescope is discussed later. This procedure was used to determine the optical efficiency factor which was used in the Data Discussion section of this report.

Data and Control Electronics

The sequence of events for controlling major functions and recording data is complex. Almost all of the equipment for this portion of the LIDAR was developed at Sandia Labora-

tory. The basic system functions will be discussed and then the major circuits will be described briefly. The data system functions are shown in Figure 14.

Sequence of Events

The master timer provides pre-laser-fire operations for the visicorder, two 35 mm cameras, two printers, and personnel alarms in the control trailer and ME-16; and a laser fire signal coincident with the laser shot number signal. The laser pulse fires the laser, setting two distinct processes into operation. A pulse of light is emitted into the atmosphere, and the laser pulse is detected by the "0" time circuit. The laser pulse from the "0" time detector is directed to the pulse stretcher and driver circuit. The fast pulse is stretched to 15 milliseconds and 10 milliseconds. The 15 millisecond pulse is used as the range start pulse for both range systems. The 10 millisecond pulse, which has a height proportional to the power output of the laser, is recorded on the visicorder. The range systems are digital circuits. Either system may be used to start the data and "A" type oscilloscope traces. Range system No. 1 is controlled by two sets of digital thumbwheel switches and has a maximum allowable range of 700,000 yards. One group of switches is used to set the course range gate, and the other is used to set the fine gate. The course range gate starts the upper trace, and the fine range gate starts the lower trace on the data and "A" type oscilloscopes. Range system No. 2 is controlled by a single slewing switch and has a maximum range of 1,999,999 yards (1,938,799 meters). At present, the first range output of Range system No. 2 can be used to start both the upper and lower traces of the oscilloscopes. The traces of the oscilloscopes are started at the proper time to observe the desired signal.

Figure 14. LIDAR system functions

The video signal is transformed from photon energy to an electrical signal in the high gain photomultiplier tube. Next, a circuit monitors the photomultiplier DC current and couples the AC component to the gain switching unit. The gain switching unit is a video amplifier with an RF coaxial switching arrangement that allows the video signal to be amplified by a factor of either 1, 10, or 100. The signal can be coupled from a distribution panel to either a counter or, during normal operation, the oscilloscope in Rack 2. The video signal is then distributed to the various high input impedance oscilloscopes. The video signal terminates in a 50-ohm load in Range system No. 2. Each signal return can be photographed by a 35 mm camera. The range to the target is determined by the setting on the range system being used and the elapsed time on the photograph from trace start to target signal. Each microsecond of ranging time is equivalent to 164 yards of range.

Figure 15 is a diagram of the angle control and readout subsystem. In general, angle information is obtained by measuring shaft rotation of the azimuth and elevation axes of the ME-16 mount. Two angle readout systems are used. A synchro-system is used to give the control trailer tracking operation a reasonable angle position. This system is coupled to the control trailer tracking control mode. A Decitrak angle readout system gives a direct reading with accuracies of ± 0.1 degree. An X, Y, and H plotter is also available to record the position of the tracking mount relative to the target.

Master Timer

The master timer (shown in Rack 4 of Figure 16) is a transistorized digital system. It provides basic control for the laser system and the recording devices. A variable firing interval of one shot per second to one shot per one hundred

Figure 15. Angle control and readout

Figure 16. Master control and data recording console

seconds allows adequate rates for system check-out and field test operations. The number of seconds remaining until fire is displayed on nixie tubes. The master timer operation controls are automatic mode, hold, count, manual mode, manual fire, and reset. The controls for cameras include ON-OFF for four cameras and a pre-fire start pulse that opens the camera shutters 0.01 to 0.10 second in ten steps before laser fire. A similar control is used to furnish a pre-fire start pulse for the visicorder. The pulse-timing may be varied in ten steps from 0.1 to 1.0 second before laser fire. In conjunction with the timing switch, a switch provides either visicorder continuous operation or visicorder automatic operation. A pre-fire signal is available to activate personnel warning bells. The signal can occur from 9.0 to 1.0 seconds, in one second steps, before laser fire. Two ON-OFF switches are provided for the warning bells, one for ME-16 personnel and one for the control trailer personnel. Another safety device that is controlled at the master timer panel is the laser shutter. This is a solenoid-operated shutter that is placed in the exit path of the laser beam. The master timer uses a precision crystal-controlled 1000 Hz oscillator as the master clock. Coarse, medium, and fine synchronizing switches are provided to allow the digital system to be operated in time phase with an external test range reference signal. Also, an external master clock may be used if the polarity and amplitude of the signal are correct.

System Power and Photomultiplier Monitor

This is a simple and easily read array of meters which monitors the important operating voltages and currents. Expanded scale meter systems, which monitor a small range of voltage about the required voltage, are used for the more sensitive voltages. The functions monitored are: +80 and +175 v nixie power; -18, -6, and +12 v master timer transistor

power; -28 v system power (+28 v system power is monitored by the meter lights being on or off on the System Power and PM Monitor); +205 v master timer clock supply; 0 to 3.0 kv "0" time biplanes diode power; 0 to -3.0 kv photomultiplier power; 0 to 0.1 ma and 0 to 1.0 ma DC photomultiplier current; -18, -6, and +12 v range systems power; and frequency and 115 v AC for main power.

Temperature Monitors

Temperature monitors are available for equipment Racks 3, 4, and 5; optical bandpass filter; photomultiplier tube; and two other locations. All of the monitor circuits are of the same basic balanced-bridge type with a thermistor located in one leg. All meters read in degrees Centigrade except the optical filter monitor which indicates degrees $\times 10^{-1}$ above 100°F. The only switch on the temperature monitor panel allows 115 v AC power to be applied to the heating element in the temperature controller.

Laser Shot Number Generator

The laser shot number generator provides for recorded data correlation. It is a transistorized, binary-coded logic system that provides both serial and parallel output sequences. Data correlation numbers are furnished to: (1) nixie tubes in both 35 mm cameras, (2) printers A and B, (3) nixie tubes in the visual display for operator information, and (4) the visicorder. The number generator counts from 0 to 9,999 and can be reset to any number within that range.

Laser Power Control

The laser power supply rack is shown in Figure 17. Two control panels contain functions that must be activated before control is relinquished to the master timer control panel.

Figure 17. Laser power supply rack

There are eight basic controls on the laser power supply panel. The power ON-OFF switches control the primary three-phase voltage. These switches allow the cooler to operate in a closed circuit, no flow through the laser heads, and all electronics to be activated. Monitor lights indicate the status of electrical interlocks, water interlocks, local or remote control, and circuits closed to laser head No. 1 or No. 2. The high voltage ON switch must be activated to allow the flash lamp energy storage capacitors to be charged. The voltage to which these capacitors are charged is determined by the setting of the charge level switch; three levels, low, medium, and high, are available. The fire mode switch has three positions. In the repetitive mode, the laser control electronics fire the laser at a one-shot-per-second rate. The single shot mode is self-explanatory. In the center position, which presently has no markings, the master timer controls the laser firing. The local-remote control switch allows basic laser system control to be switched from the panel in the laser power supply rack to the control panel mounted on the ME-16 tracking tube. The head selector switch determines which laser head on the tracking mount will be used. The remaining two switches provide refrigeration cooling control. The cooling system switch has a normal and a standby position. In the normal position, with the power switch on, the cooler operates in a closed cycle with no flow through the laser heads. The high voltage must be turned on to get complete system flow. In the standby position, there is cooling flow through the heads without the high voltage on. This allows the cooling system to temperature stabilize without the danger attendant on high voltage. The standby cooling ON-OFF switch is functional only when the system cooling switch is in the standby position. The standby cooling switch allows

the refrigeration unit to be turned on or off while maintaining flow through the laser heads. This function is provided primarily to enable the optical components in the head to warm up and to allow replacement without condensation problems.

The functions of the remote control panel are identical to the identically named functions on the laser power supply control panel with the exception of one control. There is a system interlock switch on the remote panel that disables the high voltage charging circuit. This is basically a safety function.

The integrated laser modulator panel provides control for the Pockels cells and variable high voltage control with various delayed switching times. A remote trigger input is provided, and sync-outputs are provided to that trigger when Pockels cell switching occurs.

Range Systems

A ranging system for the LIDAR must perform much the same function as an RF radar range gate system. The two range systems in the LIDAR were built to perform two different functions; however, either can be used as a true range system. Range system No. 1 provides coarse and fine range triggers plus interval markers for the dual-trace oscilloscope. Range system No. 2 provides a single range gate and 20 one-micro-second gated intervals in which the video signal is integrated.

Since the laser transmitter pulse is asynchronous, standard ranging systems were not applicable. The ambiguous delay between the trigger pulse and the laser output made it necessary to trigger the ranging system from the "0" time biplanar diode rather than triggering the transmitter from the main time base, as is usually done. This method of operation seriously complicates analog systems but was handled reasonably with digital circuitry.

Figure 18 is a block diagram of Range system No. 1. The system contains a series of digital thumbwheel switches by which the desired range to the start of the coarse gate is entered. A second set of switches adjusts the delay between the coarse gate and the start of the fine gate. A 1.64 MHz oscillator is the master-digital-clock, and when the "0" time pulse is received, a gate opens which permits these pulses to enter a four-decade main counter. This counter is continuously compared with the number set into the switches, and when parity is reached, an output pulse is generated which triggers the coarse gate scope. This pulse also opens a second clock gate which permits the pulse into the fine gate counter. When the fine range counter is running, pulses may be picked off between its decades to provide 100 and 1000 yard markers for the range scopes. The main counter also continues to count. When parity is reached between the fine counter and the fine gate delay switches, a second pulse is generated which triggers the fine gate scope. This pulse also shuts off the main counter gate, which stops the count at a number which indicates yards delay to the start of the fine sweep. This number is presented to the operator by a nixie tube display. The range system is reset by the next laser trigger pulse, which occurs at least 0.4 ms before the laser output pulse. One other function is required: an analog output for the plotting board range information. It is obtained by incorporating a modified Wolff-Poggendorf divider into the digital switches, and, in effect, provides a range potentiometer for the plotting board. In practice, the operator maintains the video return pulse in the fine gate by manipulating the digital switches while observing the "A" type oscilloscope.

Range system No. 2 (Figure 19) was designed as a real-time data processor. It is also a transistorized digital system, but it is more sophisticated than Range system No. 1 in that it samples and integrates the return video signal.

Figure 18. Range system No. 1

Figure 19. Range system No. 2

The range is set by a single slewing switch and a visual display. This basically operates an up-down counter in the digital circuits. A comparator circuit designates when the desired range is reached. At this time, 20 serial one-microsecond gates sample, integrate and store the video signal until the range system is reset. While the signals in the 20 intervals are stored, each is read out in a 20 millisecond interval with 20 milliseconds between pulses. At this slower rate, the information is recorded on the visicorder.

A switch on the tracking operator's console allows either Range system No. 1 or Range system No. 2 to trigger the dual-trace oscilloscopes. Presently, the leading edge of the first one-microsecond sampling interval triggers both traces when Range system No. 2 is being used. It would be possible to get a pseudo-fine range gate trigger by using the leading edge of any of the remaining 19 one-microsecond intervals. However, this fine gate would be fixed in relation to the coarse range gate.

ME-16 Angle Control and Readout

A block diagram for the angle control and readout for the tracking mount is shown in Figure 15. The system provides the following tracking and searching modes:

1. Optical tracking - the mount is controlled by the operator on the ME-16.
2. Manual - the mount is manually controlled by an operator in the control trailer.
3. Sector scan - the mount is automatically controlled to scan a vertical path; the length and time of the scan are variable.
4. Circle scan - the mount is automatically controlled to scan a circular path; the diameter of the circle and time rates are variable.

5. Horizontal or vertical raster scan - the mount is automatically scanned to produce a raster pattern, with size and time variable.
6. Designate - the mount is positioned by a remote source (such as an RF radar); all of the scan functions can be superimposed upon the information.

Figure 20 shows the ranging and tracking console in the control trailer. The azimuth and elevation angles of the mount are monitored with an accuracy of approximately 0.5-degree by using synchro dial readouts. These dial readouts and the control handwheels are identical to those used in an SCR-584 radar. A precise angle and azimuth readout of ± 0.1 -degree is provided by the Decitrak system. However, the Decitrak system is primarily for the data system and secondarily for tracking operator control. The angle control panel and angle control unit contain the automatic scan circuitry and the operating mode switching circuits. The electrical signals that the automatic scan circuits develop can be observed on a memoscope. A beam-intensified circuit could be added to the memoscope to intensify the trace when a return video signal is received. This would be a variable level, peak detecting circuit.

Modified M-33 radar data converters are used on the ME-16 for both azimuth and elevation reference signals. The 400 Hz in the data converter synchros in the data converter were replaced by 60 Hz synchros. The sine-cosine potentiometers are for the computer-plotter and are also contained in the data converters. None of the original ME-16 synchros are used. The laser radar tracking control system provides a phase signal and a reference signal for azimuth and elevation control of the ME-16 for each mode of operation except optical track.

Figure 20. Ranging and mount control console

Data Recording Instruments

A list of the various data recording equipment is given in Table V. Recording devices record necessary data for angle, range, necessary operating parameters, and video signal signature. The plotting board is a real time data system that is also a typical radar analog system. Slant range is obtained from Range system No.1 by operation of the plotting board range potentiometer. Sine-cosine potentiometers are mechanically positioned by rotating the azimuth and elevation axes of the ME-16. The voltage inputs to the polar-to-cartesian coordinate computer appear across these potentiometers. The computer corrects for earth curvature and origin parallax, and the data are referenced to the desired scale factor. The target position is then plotted in real time, and at the conclusion of the operation a time history of the target is available for later analysis.

TABLE V
Data Recording Equipment

- I. Visicorder
 - A. Shot number
 - B. Laser output energy
 - C. 20 segments of signal return
 - D. Video amplifier gain
 - E. Range for real time data processors
- II. Oscillograph Cameras
 - A. Shot number
 - B. Signal returns (coarse and fine)
- III. Printers
 - A. Shot number
 - B. Decimal azimuth and elevation
 - C. Range to start of oscilloscope sweep
 - D. PM voltage setting (ths. and hds.)
- IV. Plotting Board
 - A. X versus time
 - B. Y versus time
 - C. H versus time

The visicorder is a Honeywell Model 1508. Five channels are used to record: (1) a serial binary-coded laser shot number, (2) real time data processor range from Range system No. 2, (3) video amplifier and gain, (4) 20 integrated segments of relative return density from Range system No. 2, and (5) relative laser shot energy which is obtained from the pulse stretcher and integrated power circuit.

The 35 mm oscillograph cameras record the signal return, on both a normal and expanded sweep, and the laser shot number. If desired, one of the traces can be used to record the laser pulse shape instead of the video signal. The mechanically actuated counters in the cameras were replaced with miniature nixie tubes. The nixie tubes are controlled by the laser shot number generator to provide data correlation.

The printer section is comprised of two Beckman 12-channel printers. Printer A records the laser shot number; it also records the azimuth and elevation from the Decitrak system. Printer B records laser shot number, range from Range system No. 2, gain of the video amplifier, and the thousandth and hundredth digits of the photomultiplier high-voltage reading. The printers are located in Rack 3 in the master control and recording console shown in Figure 16.

Plotting Board Display (Figure 21)

Analog signals taken from the azimuth and elevation sine-cosine potentiometers and the slant range potentiometers are fed to an analog coordinate converter. Intermediate analog voltages are corrected for the earth's curvature, and final voltages are obtained which represent the X, Y, and H coordinates of the target. These voltages are applied to a 30-inch by 30-inch plotting board, and a plot of these functions is constructed in real time.

Figure 21. X, Y, and H computer plotting board

Data Output

The data acquired by the laser LIDAR are presented as follows.

1. Digital Printout
 - a. Slant range - ± 300 feet
 - b. Azimuth angle - ± 0.05 degree
 - c. Elevation angle - ± 0.05 degree
 - d. Shot number
2. Oscillograph
 - a. Return histogram
 - b. Shot number
 - c. Calorimeter output (long integrator)
 - d. Range readout
3. Oscilloscopes (2)
 - a. Calorimeter output (short integrator)
 - b. Either short range gate video or fine range gate video
 - c. Shot number
4. ME-16 Tracking Mount Camera
 - a. Photograph of laser LIDAR target
 - b. Shot number

Auxiliary Data Inputs and Outputs

The following auxiliary data inputs and outputs are available.

1. Input: Synchro information from a tracking radar so that the laser tracking mount can be remotely positioned for acquisition purposes.
2. Output: Synchro information so that a remote tracking mount can be controlled by the laser LIDAR.

Support Equipment

ME-16 Tracking Mount

The mobile Sandia-designed ME-16 (Figure 22) was chosen as the tracking mount for the GB-60B LIDAR system. It provides its own electrical and hydraulic power. The ME-16 was designed originally to track aircraft and/or objects dropped from aircraft and to take motion pictures through its 16-inch telescope. It has maximum azimuth and elevation tracking rates of approximately 20 degrees per second. The telescope can travel through 95 degrees of elevation and 360 degrees of azimuth, either clockwise or counterclockwise, before limit stops are tripped. Detailed information on the ME-16 is available in SM ME16-2, Field Test Series, Operation and Maintenance Instruction, ME-16 Telescope.

In order to use the ME-16 in the LIDAR system, the following modifications were made.

1. The rear-mounted 16-inch diameter reflector was removed. A new front tube casting was made, as was the hardware required to mount a 60-inch diameter reflector. A secondary mirror was mounted to form a Cassegrainian telescope.

Figure 22. Original Sandia-designed ME-16 tracking mount

2. Castings were designed for mounting M-33 radar azimuth and elevation data converters. Each converter contains the necessary synchros and sine-cosine data potentiometers.
3. A tube-top mounting base, which contains the necessary collimation controls, was designed for the lasers.
4. New cabling was built as necessary.
5. Mechanical design changes were made to allow precise manual movements of the telescope tube in both azimuth and elevation. This was necessary for optimum optical alignment and to maximize the signal return from a small stationary target.

Figure 23 shows the right and left sides of the modified ME-16 mount and laser transmitting system. There is a clam shell type door on each side; these close over the instrument mount during transit under adverse weather conditions and when the unit is not in use.

Control Trailer

The Control Trailer houses the major portion of the electronic, data processing, and control equipment (Figure 24). The trailer is 40 feet long and 10 feet wide. A raised floor was added to provide air-conditioning and cabling access to any point in the trailer. Two refrigerated air-conditioners provide cooling for equipment and personnel. A work and dark-room area was constructed in one end. An ultraclean area, which filters particles 0.3 micrometer and larger in size, is used for maintenance, repair, and cleaning of the laser heads. Storage space, including a refrigerator for film, is provided for replacement parts. Two draw curtains are provided in the operations and control section of the trailer so that different light levels can be used simultaneously.

Figure 23a. Right side of MC-16 tracking mount modified for GB-60B LIDAR

Figure 23b. Left side of MC-16 tracking mount modified for GB-60B LIDAR

Figure 24. Configuration of Control Trailer

The ME-16 and the Control Trailer are connected by an intercom system. There are two stations and two speakers on the ME-16 and four stations and one speaker in the Control Trailer.

Safety Considerations

Much has been said about laser safety.* There appear to exist three areas of concern when using a laser: (1) high voltage, (2) pumping radiation, and (3) laser output radiation. Since the laser unit used in the GB-60B LIDAR is a Q-switched system, only that type of laser is considered. The energy for the flash lamp, which is the exciter of the laser head, is obtained from a capacitor bank. As mentioned earlier, thousands of amperes at up to 3000 volts are available. The nonrestrictive current regulation on the power supply makes the charge lethal, and care must be taken when near the HV terminals. Since the laser is optically excited and since the output radiation from the laser is very directional and contains up to ≈ 3 joules of energy, which is switched in a very short time, the pump radiation and the output power can also create problems. The duration of the flash lamp pulse is approximately a millisecond, and unlike the laser its output is polychromatic and omnidirectional. To an observer, the flash from the pump lamp and the laser emission appear to occur simultaneously. Both the lamp and the laser flashes are potentially hazardous. Either flash can cause damage to both eyes and skin, with the laser output being more hazardous. Experimental work by Dr. W. T. Hams⁷ of the Department of Biophysics, Medical College of Virginia, established that a

*See Reference 6 for a discussion of laser safety at Sandia.

20 to 50 nanosecond pulsed energy density of 0.07 joule per square centimeter causes irreversible ocular damage to the retina of a rabbit's eye. Experimental work demonstrated that the rabbit's eye is an acceptable model for evaluating the effects of laser radiation on the human eye. Safe threshold levels of 0.01 and 0.018 joule per square centimeter have been used by other laboratories.^{8,9} The Industrial Hygiene Division at Sandia Laboratory set 0.001 joule per centimeter as a safe level at which to operate.

The energy density incident on the retina of a human when viewing the laser beam directly is given by

$$I_R = \frac{4 J D_E^4 p e^{-\mu R}}{\pi (2.44 \phi f \lambda R)^2} \quad \text{joules cm}^{-2} \quad (5)$$

where

I_R = energy density on retina (joules/cm²)

J = energy of laser (joules); 0.9 joule minimum and 2.8 joules maximum

D_E = pupil diameter; typical daytime value is 0.15 cm; nighttime is 0.7 cm

P = transmission of eye (use 0.98 for worst case condition for ruby)

μ = atmospheric attenuation coefficient (cm⁻¹); equals 3.9/ R_V , where R_V is the meteorological visual range; R_V = 60 miles for Albuquerque (nominal)

R = laser/eye range (cm)

ϕ = laser beamwidth (radians); 8 mr at 2.8 joules; 3 mr at 0.9 joule

f = focal length of eye (cm); average for human eye is 2.29 cm

λ = laser wavelength (cm); 6.943×10^{-5} cm

The energy density that a human receives when looking directly into the laser output is given in Figure 25 as a function of range for both daytime and nighttime operation of the two extreme laser energy outputs of 0.9 and 2.8 joules; Figure 25 was obtained from Equation (5). Table VI gives the safe ranges for the different safe thresholds mentioned earlier and the laser outputs of 0.9 and 2.8 joules, as obtained from Figure 25.

TABLE VI
Safe Range for GB-60B LIDAR

<u>Safe Energy density (joules/cm²)</u>	<u>Laser output (joules)</u>	<u>Time of Operation</u>	<u>Safe range (miles)</u>
10^{-3} (Sandia)	2.8	day	2.7
	0.9	day	3.8
	2.8	night	25.5
	0.9	night	32.0
10^{-2} (Martin)	2.8	day	0.8
	0.9	day	1.3
	2.8	night	12.4
	0.9	night	16.5
1.8×10^{-2} (Eglin)	2.8	day	0.6
	0.9	day	0.9
	2.8	night	9.8
	0.9	night	13.7

As can be seen in Table VI, the safe range can vary greatly depending upon the safe energy threshold assumed. The Sandia Laboratory choice requires that control over a very large range be maintained in order to assure safe operation. If the higher energy density safe threshold were acceptable, it would definitely reduce the operational problems encountered when the

Figure 25. Laser output energy as a function of range

LIDAR is fired. It is obvious that more detailed study is required to determine the safe energy density levels a human eye can endure.

The effects of both single and repeated laser shots incident on normal and pathologic skin were studied. These studies indicate that the degree of damage to the skin depends on the type of laser, the energy level, and the duration of the irradiation. The amount of regeneration at the damaged area depends upon the degree of burn. The skin injury threshold shown in Figure 26 is from a theoretical comparison study of injury to human and pig skin. The graph can be used to determine the diameter of the damage threshold zone (the cross-hatched area in the graph) for a specific energy output in joules.

The distance at which direct irradiation of the skin is safe is given by the following equation

$$R = \frac{D}{\theta} , \quad (6)$$

where

D = the diameter of the damaged spot in centimeters

θ = the beam divergence in radians

R = the distance in centimeters

The maximum energy emitted from the GB-60B LIDAR is 2.8 joules. From Figure 26 a diameter of 0.48 to 0.6 cm corresponds to 3 joules. This means that after a range of 1.85 ft (56.5 cm) for the 0.48 cm spot and 2.3 ft (70.5 cm) for the 6.0 cm spot, the GB-60B LIDAR will not produce burn damage to human skin.

Safety during any LIDAR experiment is the responsibility of the operating personnel at the LIDAR station. One man is always at the master control panel in the control trailer and

Figure 26. Skin injury threshold from laser radiation (from Reference 8)

can stop laser firing on a one second notice from the laser safety man on the ME-16 tracking mount. The man on the tracking mount has primary laser safety control. His job is to watch for any airplanes, vehicles, etc., in the broad general vicinity of the laser firing area. Besides intercom facilities to the control trailer, the safety man on the ME-16 has a remote laser control panel. This panel has an interlock control that will stop the firing of the laser transmitter system. There will also be a two-way radio link between the tracking mount safety man and a Sandia representative in the test area. All personnel in the test area will wear neutral density type filters or approved goggles to ensure that the received laser light density will be well within the safety level established by Sandia Laboratory.

Data From GB-60B

Introduction

The objects detected using the GB-60B LIDAR include clouds, terrain, and retroreflectors. The objects are both diffuse and specular reflectors. In all cases, except for the retroreflector, the objects are larger in angular extent than is the divergence of the laser beam. For these targets (L-targets) the intensity at the receiver is proportional to $1/R^2$ for the retroreflectors (S-targets) the intensity is proportional to $1/R^4$.

For the first case, consider the power diffusely reflected from an infinite wall into 2π steradian. The power received at the detector is proportional to the ratio of the solid angle subtended by the receiver and the hemisphere into which it reflected and is given by

$$P_R = P_T \eta_T \rho (\Omega_R/2\pi) \quad (7)$$

for

$$\Omega_R = \pi (\alpha/2)^2 \quad (8)$$

where

α = angle subtended by the receiver (for small angles,
 $\alpha = D/R$)

D = diameter of the receiver

R = one way range

ρ = reflectivity of the wall

η_T = attenuation of atmosphere (η_A) and optics (η_O) =
 $(\eta_A)^2 \eta_O$

P_T = power submitted by the laser

Equation (7) then becomes

$$P_R = P_T \eta_T \left[\frac{D^2}{8R^2} \right] \quad (9)$$

as the power received for a diffuse reflecting infinite wall
L-target.

A specular S-target reflects backward at 180-degrees only a fraction of the energy emitted by the laser. For example, although a retroreflector reflects all the energy it intercepts, it intercepts only a fraction of the incident energy, i.e., the ratio of its area to the area of the laser beam; this ratio is usually small for long ranges. The power collected by the receiving optics for this type of specular S-target is

$$P_R = \frac{\eta_T \rho P_T A_M}{A_L} \quad (10)$$

where the area illuminated, A_L , and the area of the retro-reflector, A_M , are

$$A_L = \frac{\pi D^2}{4} = \frac{\pi \alpha_L^2 R^2}{4} \quad (11)$$

and

$$A_M = \frac{\pi d^2}{4} . \quad (12)$$

Substituting Equations (11) and (12) in Equation (10) results in

$$P_R = P_T \eta_T \rho \left[\frac{d_{\text{ret}}^2}{\alpha_L^2 R^2} \right] , \quad (13)$$

where d_{ret} is the diameter of the specular reflector and α_L is the divergency in the laser beam. Equation (13) holds providing the diameter of the reflected beam at the receiver is less than the diameter of the receiver. If the reflected solid angle of the retroreflector is larger than the solid angle subtended by the receiver from the retroreflector, Equation (13) must be modified and is given by

$$P_R = P_T \eta_T \rho \left[\frac{D^2 d_{\text{ret}}^2}{\alpha_L^2 \alpha_{\text{ret}}^2 R^4} \right] \quad (14)$$

where α_{ret} is the effective beam divergency of the retroreflector due to diffraction and/or atmospheric scattering.

If the S-target is a diffuse reflector reflecting into a hemisphere, Equations (9), (13), and (14) do not predict the power received at the receiver. For a diffuser, only a small portion of the energy reflected backwards will be in the direction of the collector, i.e., the solid angle ratio again. The power received for a diffuse S-target is given by

$$P_R = P_T \eta_T \rho \left[\frac{d_d^2 D^2}{8 \alpha_L^2 R^4} \right] \quad (15)$$

where d_d is the diameter of the diffuse S-target and the rest of the parameters are as defined earlier.

If the target is three-dimensional, e.g., a cloud, Equation (15) must be modified to include the total number of particles instantaneously illuminated in the cloud. The cloud is an S-target regardless of its size, since the reflection is by the individual particles, which are S-targets. Under these conditions, the reflected power collected by the receiver would be

$$P_R = P_T \eta_T \rho \left[\frac{N d_p^2 D^2}{8 \alpha_L^2 R^4} \right] \quad (16)$$

where N is the total number of particles from which power is reflected and d_p is the diameter of each particle. The minimum number of particles that can be detected using the GB-60B LIDAR is discussed in Appendix D.

The usefulness of the GB-60B LIDAR system is impaired by certain parameters in Equations (7) through (16); the most important parameters are transmittance in the atmosphere and background noise. It is of paramount importance that scattering from normal concentrations of dust and aerosol in the atmosphere be measured over the data path at the time observations are made. It is important also to define the background conditions when the reflected signals are comparable to the signal from the background.

At the operating wave length of $6943 \text{ \AA}$, the atmosphere is an excellent window. The main losses are by absorption of radiation by the main constituents of the atmosphere: water vapor, carbon dioxide, and ozone (Appendix E); and also to molecular backscattering (Appendix F). At $6943 \text{ \AA}$, ozone and carbon dioxide have 100 percent transmitting windows. Water vapor, on the other hand, does absorb some of the incident radiation. Figure 27 shows the molecular absorption

Figure 27. Molecular absorption lines in the vicinity of the LIDAR laser output wavelength

lines in the vicinity of $6943 \text{ \AA}$.⁹ As can be seen, H_2O and O_2 are the only major absorbers in this region, with only H_2O absorbing on either side of the laser output which is centered at $6943 \text{ \AA}$. For an 85 km - 45° slant range path, the absorption is equivalent to 1.1 cm of water. This path, therefore, transmits only 90 percent of the incident power, P_T . The effective transmission for the combination of backscattering and atmospheric attenuation for altitudes up to 30 km can be taken as 50 percent for a worse case situation. However, for accurate calibration on the data path, backscattering experiments should be performed to obtain more accurate atmospheric transmission function.

Another parameter that must be determined is the efficiency of the receiver section of the LIDAR. This efficiency is the combined efficiency of the photomultiplier, filter, and

receiving optics. The RCA 7265 photomultiplier, with its S-20 surface, has a quantum efficiency of approximately 2 percent (and a sensitivity of 6.012 amperes/watt at $6943 \text{ \AA}$, the laser wavelength. This unit should be calibrated also. The transmittance of the filter was shown in Figure 13 and is approximately 60 percent. Lastly, the calibration of the optical efficiency of the receiver system was carried out on a first try basis.

The procedure used to calibrate the optical efficiency of the mirror surfaces will now be considered. The center of of the primary was positioned 277.5 feet from a tungsten ribbon lamp, Serial No. E 186. The test was conducted with the optical filter removed from in front of the PM tube. The spectral radiance of the lamp as a function of wavelength for two operating currents is listed in Table VII and illustrated in Figure 28. The circular aperture stop which defined the area of the source was 0.00501 square inches, or 3.232 square millimeters. An 8 percent loss resulted at the source from reflection of the lens surfaces.

The DC output of the PM was measured using a Keithley microvoltmeter, Model 150A, and the circuit used is shown in Figure 29. The defining diameter of the aperture of the receiver was 60 inches, or 1.52 meters, and the photomultiplier diameter was 1.2495 inches or 3.078 cm. The data collected using the above described set-up are shown in Table VIII. The data shown in Table VIII were used to calculate the optical efficiency of the GB-60B LIDAR system. For a constant incident radiance, the ratio of the current output on the PM tube using the complete Cassegrainian telescope with the secondary removed is related to the optical efficiency of the telescope and the ratio of the effective collector areas by the equation:

TABLE VII

Spectral Radiance in Microwatts per (Steradian-
Nanometer-mm² of Source) of Lamp E-186
Operated at 25 and 30 Amperes

<u>λ, μ</u>	<u>25 Amperes</u>	<u>30 Amperes</u>
0.5	1.81	8.50
0.55	3.80	15.6
0.6	6.80	24.5
0.65	10.5	34.9
0.7	15.0	45.5
0.75	19.9	55.7
0.8	24.7	64.6
0.9	32.8	77.5
1.0	38.9	84.3
1.1	43.0	85.6
1.2	44.5	83.7
1.3	43.9	79.8
1.4	42.4	74.6
1.5	40.1	68.5
1.6	37.2	61.6
1.7	33.8	54.4
1.8	30.2	47.5
1.9	26.9	41.3
2.0	23.9	35.9
2.1	21.2	31.4
2.2	18.8	27.7
2.3	16.7	24.7
2.4	15.0	22.1
2.5	13.5	19.8
2.6	12.1	17.7

0.653 λ optical pyrometer center of band

Figure 28. Spectral radiance of lamp E-186 as a function of wavelength

Figure 29. Circuit used to measure the DC output of the PM

TABLE VIII

Calibration Data for the Optical Receiver

<u>Current (micro amps)</u>	<u>PM (kilovoltage)</u>	<u>Current source (amps)</u>
<u>With Telescope</u>		
37.00	2.4	0.00 Background
77.00	2.4	20.00
268.00	2.4	25.00
500.00	2.4	28.00
800.00	2.4	30.00
<u>Without Telescope</u>		
25.5	2.4	00.00
25.5	2.4	20.00
26.5	2.4	25.00
27.5	2.4	28.00
29.0	2.4	30.00
40.00	2.4	0.00 Background
24.50	2.3	
15.00	2.2	
8.40	2.1	
4.60	2.0	
2.48	1.9	
1.25	1.8	
0.81	1.7	
0.44	1.6	

$$\frac{I_1}{I_2} = E_t \frac{A_1}{A_2} \quad (17)$$

where

E_t = optical efficiency of the Cassegrainian telescope

I_1 = current of the PM tube with telescope

I_2 = current of the PM tube without telescope

A_1 = area of the 60-inch diameter telescope
($1.83 \times 10^6 \text{ mm}^2$)

A_2 = area of the PM aperture (79.5 mm^2)

Equation (17) holds so long as the PM tube does not exhibit saturation effects. As an example, consider the PM current reading of 800 ma with telescope and 29 ma with no telescope and the lamp operating at 30 amperes. The efficiency is

$$\begin{aligned} E_t &= \frac{I_1}{I_2} \cdot \frac{A_2}{A_1} \\ &= \frac{800}{29} \cdot \frac{79.5}{1.83 \times 10^6} \\ &= 12.5\% \end{aligned} \quad (18)$$

This appears to be a low value for the optical efficiency; however, the primary mirror tested has many raised points on the surface, and these affect the efficiency of the collector quite remarkably. The total efficiency E_T of the telescope, four glass surfaces, and interference filter is given by

$$\begin{aligned} E_T &= (E_f) (E_t) (E_g) \\ &= (0.6) (0.125) (0.84) = 0.063 \end{aligned} \quad (19)$$

where

E_f = efficiency of the filter (0.6)

E_t = efficiency of the telescope (0.125)

E_g = efficiency of the four glass surfaces (0.84)

It is obvious that the optical efficiency of the Cassegrainian telescope can and should be increased by changing the primary mirror.

Detection of Clouds

Very little concrete data were obtained from laser reflections from clouds using the GB-60B LIDAR. As mentioned earlier, the bandpass filter is too wide by $4.5 \text{ \AA}$, thereby allowing a large amount of background noise through the filter and into the PM tube. The maximum range from which energy was reflected from atmospheric clouds is shown in Figure 30a to be 75.8 miles (122 km). It should be noted that the signal is in a large amount of noise due to the wide $20 \text{ \AA}$ filter used. A $15.5 \text{ \AA}$ filter would allow the reflected rays to pass through the filter and reduce the background noise. The noise in the lower trace occurred only when the laser was fired; therefore, it must be attributed to backscattering of laser fluorescence and not to PM tube or star background noise. The 75.8 mile range attained with the GB-60B is essentially 1.7 times that attained using the GB-60A LIDAR. Figure 30a does not represent the maximum signal-to-noise ratio attainable; it is simply one signal return from atmospheric clouds recorded at this distance. Narrowing the bandwidth of the optical filter reduces the general sky-background noise but does not reduce that portion of the noise caused by the fluorescence of the ruby or the pump light.* Figure 30b shows the reflection obtained from a cloud 18.4 miles distant under daytime conditions. Except for range, the actual amount of information obtained from such traces is small unless the atmospheric transmission between the cloud and the LIDAR is known.

*Using a bleachable cell at the output end of a ruby laser would reduce the fluorescence by 65 percent.¹⁰

a. Range - 75.8 miles
nighttime

b. Range - 18.4 miles
daytime

Figure 30. Reflections from atmospheric clouds

Detection of Retroreflectors

The idea of using retroreflectors positioned on mountain tops to monitor the real-time atmospheric attenuation function promoted the study of reflecting energy from retroreflectors. Figure 31 shows a 2.25-inch diameter retroreflector positioned on a 6-foot high aluminum stand which was secured on top of five mountains at various distances: 5.35, 26.5, 47.8, 52.5, and 83+ miles. For convenience, these will be referred to as the 5-, 26-, 47-, 52-, and 83-mile targets. Figure 32 shows signal returns from the 5-, 26-, 47-, and 52-mile targets. The emitted laser pulse is approximately 40 ns wide (lower trace), while the return pulse is approximately 60 ns wide (upper trace) for all targets except the 5-mile target which has a much wider return pulse. The 5-mile target

Figure 31. Retroreflector mounted on 6-foot stand

trace in Figure 32 shows a definite depression on the leading edge of the top trace. As the transmitter is elevated and pointed skyward, this part of the return decreases. Therefore, the depression is attributed to laser light reflected by the hilly terrain on which the retroreflector was positioned. In this and other pictures, the lower trace is used to calibrate the output of the laser transmitter. The time scale of the photographs of the signal from the 5-, 26-, and 52-mile targets, with neutral density filters (ND) of 4, 4, and 2, respectively, inserted in front of the optical filter, indicates that the time lengthening effect in the received beam is a saturation effect. By using an ND of a value which would sufficiently attenuate the collected signal, the received pulse width could be the same as the transmitted pulse width.

The specific reflections obtained from the different retroreflector locations are given in Table IX. Table IX gives the exact location of the retroreflectors to within

0.5 v/cm; 0.2 μ s/cm - Top trace - 2.0 v/cm; 0.2 μ s/cm
 1.0 v/cm; 0.1 μ s/cm - Bottom trace - 1.0 v/cm; 0.1 μ s/cm
 ND 4

a. 5-mile target

0.5 v/cm; 0.2 μ s/cm - Top trace - 2.0 v/cm; 0.2 μ s/cm
 1.0 v/cm; 0.1 μ s/cm - Bottom trace - 1.0 v/cm; 0.1 μ s/cm
 ND 4

b. 26-mile target

Figure 32. Signal returns from retroreflectors

Top trace - 2.0 v/cm; 0.2 μ s/cm
 Bottom trace - 1.0 v/cm; 0.1 μ s/cm

c. 47-mile target

5.0 v/cm; 0.2 μ s/cm - Top trace - 0.05 v/cm; 0.2 μ s/cm
 1.0 v/cm; 0.1 μ s/cm - Bottom trace - 1.0 v/cm; 0.1 μ s/cm
 ND 2

d. 52-mile target

Figure 32. Signal returns from retroreflectors (cont)

TABLE IX

Retroreflector Data Obtained by GB-60B LIDAR

5-Mile Target (Elevation 5624 Feet)

Shot No.	"A" Trace		"B" Trace		Max & min peak volts return signal (volts)	Max & min peak power pulse (volts)	Power pulse (mw)	Power pulse (joule)	Shots on film (No.)	Max range (ft)	Min range (ft)	"A" Trace start (yards)	Flash lamp voltage (kv)	PM's voltage (kv)	Date & time
	Time (μ s/cm)	Ampl. (v/cm)	Time (μ s/cm)	Ampl. (v/cm)											
1-A	0.2	0.5	0.1	0.5	1.53	2.25	4.0	0.14	1	28,680	-	9,300	2.250	1.130	4:00 PM
2-A	↓	↓	↓	↓	1.55	1.75	↓	↓	1	28,060	-	↓	↓	↓	7-6-67
3-A	↓	↓	↓	↓	1.55	1.60	↓	↓	1	27,910	-	↓	↓	↓	↓
4-A	↓	↓	↓	↓	1.55	2.20	↓	↓	1	28,330	-	↓	↓	↓	↓
5-A	↓	↓	↓	↓	1.58	2.30	↓	↓	1	28,240	-	↓	↓	↓	↓
6-A	↓	↓	↓	↓	1.48	2.50	↓	↓	1	28,220	-	↓	↓	↓	≈4:00 PM
7-A	0.2	0.5	0.1	0.5	1.58	2.20	4.0	0.14	1	28,250	-	9,300	2.250	1.130	7-6-67
1-C	0.2	1.0	0.1	1.0	1.75	2.80	5.0	0.18	1	28,395	-	9,300	2.340	1.200	4:30 PM
2-C	↓	↓	↓	↓	1.75	2.75	↓	↓	2	28,260	28,140	↓	↓	↓	7-6-67
3-C	↓	↓	↓	↓	1.80	2.30	↓	↓	2	28,410	28,280	↓	↓	↓	↓
4-C	0.2	1.0	0.1	1.0	1.80	2.90	↓	↓	2	28,410	28,280	↓	↓	↓	≈4:30 PM
1-CC	0.2	1.0	0.1	1.0	1.75	2.35	5.0	0.18	5	28,310	28,000	9,300	2.340	1.200	7-6-67
					1.65	1.50									10:55 AM
1-Y	0.2	0.2	0.1	1.0	0.40	2.80	6.0	0.225	1	28,330	-	9,200	2.400	2.000	8:45 PM
2-Y	0.2	0.2	0.1	1.0	2.50	2.50	~6.0	0.225	5	28,370	28,090	9,200	2.400	2.000	7-11-67
					1.90	1.95									7-11-67

26-Mile Target (Elevation 9369 Feet)

1-B	0.2	0.5	0.1	1.0	1.05	2.00	↑	↑	1	139,560	-	46,400	2.340	1.130	4:15 PM
2-B	↓	↓	↓	↓	1.48	1.95	4.0	0.1	1	139,460	-	↓	↓	↓	7-6-67
3-B	↓	↓	↓	↓	0.60	2.40	to	to	1	139,680	-	↓	↓	↓	↓
4-B	↓	↓	↓	↓	1.38	1.90	5.0	0.18	1	139,540	-	↓	↓	↓	4:15 PM
5-B	0.2	0.5	0.1	1.0	1.00	2.45	↓	↓	1	139,480	-	46,400	2.340	1.130	7-6-67
1-E	0.2	5.0	0.1	1.0	6.00	2.80	↑	↑	1	139,500	-	46,400	2.340	2.400	9:15 PM
							4.0	0.14							7-6-67
2-E	0.2	5.0	0.1	1.0	6.00	2.90	to	to	3	139,590	139,540	46,400	2.340	2.400	9:15 PM
					5.75	2.90	5.0	0.18							7-6-67
3-E	0.2	5.0	0.1	1.0	6.50	3.00	↓	↓	3	139,585	139,350	46,400	2.340	2.400	9:15 PM
					4.00	1.90	↓	↓							7-6-67

TABLE IX (cont)

47-Mile Target (Elevation 7259 Feet)

Shot No.	"A" Trace		"B" Trace		Max & min peak volts return signal (volts)	Max & min peak power pulse (volts)	Power pulse (mw)	Power pulse (joule)	Shots on film (No.)	Max range (ft)	Min range (ft)	"A" Trace start (yards)	Flash lamp voltage (kv)	PM's voltage (kv)	Date & time
	Time (μ s/cm)	Ampl. (v/cm)	Time (μ s/cm)	Ampl. (v/cm)											
1-X	0.2	2.0	0.1	1.0	2.40	2.70	↑	↑	1	252,380	-	84,000	2.400	2.000	8:40 PM 7-11-67
2-X	0.2	2.0	0.1	1.0	6.00 4.20	2.80 2.30	5.0 ↓	0.18 ↓	4	252,190	252,380	84,000	2.400	2.000	8:40 PM 7-11-67
3-X	0.5	2.0	0.1	1.0	5.40 3.40	2.70 2.40	↓	↓	3	252,650	252,425	84,000	2.400	2.000	8:40 PM 7-11-67

52-Mile Target (Elevation 9183 Feet)

1-D	0.2	5.0	0.1	1.0	7.50	2.70	↑	↑	1	278,360	-	92,700	2.340	2.400	9:00 PM
2-D	↓	↓	↓	↓	6.75	2.50			1	278,460	-	↓	↓	↓	7-6-67
3-D					7.75	2.90	5.0	0.18	3	278,540	278,320	↓	↓	↓	↓
4-D	0.2	5.0	0.1	1.0	7.00 7.75 7.25	2.70 2.95 2.84	↓	↓	3	278,590	278,440	92,700	2.340	2.400	9:00 PM 7-6-67
1-AA	0.2	0.5	0.1	1.0	0.15	3.00	↑	↑	1	278,460	-	92,700	2.340	1.200	10:30 AM
2-AA	↓	↓	↓	↓	1.48	2.40			3	278,480	278,360	↓	↓	↓	7-10-67
3-AA					0.30	2.10									
4-AA					0.125	2.60			2	278,520	278,410	↓	↓	↓	↓
5-AA	0.2	0.5	0.1	1.0	0.100	2.00	5.0	0.18	4	278,400	278,205	↓	↓	↓	↓
					0.80	2.90									
					0.35	2.10	↓	↓	3	278,570	278,300	92,700	2.340	1.200	10:30 AM
					1.65	2.90									7-10-67
					0.15	2.35	↓	↓							
1-Z	0.2	2.0	0.1	1.0	6.20	2.00	↑	↑	1	278,320	-	92,700	2.400	2.000	8:50 PM
2-Z	0.2	2.0	0.1	1.0	6.40 3.00	2.90 2.50	5.0 ↓	0.18 ↓	9	278,530	278,280	92,700	2.400	2.000	8:50 PM 7-11-67

20 feet. It should be noted that the laser was operating at a very low power level (≈ 4 to 6 MW); normally, it would be operated at > 30 MW. The low power output is attributed to aging of the flash lamp and depositing of film on the glass covers of the water jackets around the flash lamp and the ruby laser rod.

Detection of Terrain

The final targets that were detected were various mountain terrains. Figure 33 shows reflections from mountains at ranges of 3.75 to 26.6 miles. Terrains at greater ranges were detected but were not recorded; the signals are well above the noise level even at these extreme distances. Figures 33b and 33c are of the same terrain; 33c shows some overdriving of the oscilloscope, but it also shows more detail of the initial reflection of the terrain. Figure 33d shows some ringing at the very end of the signal, along with some very high peak reflection during the signal pulse. It would be extremely difficult to determine the surface of the target from signals such as these. At times, reflections are collected from the many sections of the terrain that are optically equidistant from the LIDAR. The strength of the return with time depends upon the orientation of these sections of the target, along with their reflectivity. Since the reflectivity of terrain can vary from zero to over 90 percent, it is impossible to deduce exact target detail. If the target were more homogeneous, i.e., all trees or all rocks, its reflectivity might be uniform, and the target parameters could possibly be deduced. However, mixed targets do not display uniform reflectivity.

a.

b.

c.

d.

		<u>Top Traces</u>				
		<u>Range</u>	<u>(v/cm)</u>	<u>(μs/cm)</u>	<u>ND</u>	<u>PM (kv)</u>
a.	3.75-miles	6,600	0.2	0.5	1	2.4
b.	17.3 -miles	30,400	0.2	1.0	1	2.4
c.	17.3 -miles	30,400	0.5	1.0	1	2.4
d.	26.6 -miles	46,800	0.2	1.0	0	2.1

All bottom traces are 1 v/cm, 0.1 μ s/cm.

Figure 33. Signal returns from mountain terrain

Attenuation Due to Backscattering

A common feature in LIDAR signals is attenuation due to severe backscattering during the initial 20,000 to 50,000 feet of path-length. A preliminary literature search¹¹ was conducted, and some rather generalized data are presented in Appendix F.

Three photographs were used to produce Figure 34 which is a plot of signal amplitude as a function of time for the first 60 microseconds after laser fire. The experimental curve can be approximated by the exponential decay equation

$$A_x = A_o e^{-ax} \quad (20)$$

where

A_x = amplitude at distance x

A_o = amplitude at $x = 0$

a = optical density per unit length (ft^{-1}).

The dashed curve on Figure 34 was drawn using a value of $a = 2.5 \times 10^{-4} \text{ ft}^{-1}$. The physical significance of a is complex, but its value will, in general, be determined by the number density of particulate matter suspended in the atmosphere.

A reflection from a cloud at a distance of 10 miles can be seen in Figure 34. The amplitude is plotted on the same scale as the original backscatter. Using Equation (20)

$$\begin{aligned} A_{\text{nuclei}} &= 3.7e^{-(2.5 \times 10^4)} (5.28 \times 10^4) \\ &= 9.25 \times 10^{-7} \end{aligned} \quad (21)$$

$$A_{\text{cloud}} = 3.6 \text{ (from Figure 34)}. \quad (22)$$

Figure 34. Signal amplitude as a function of time for 0 - 60 μsec after laser fire

The cloud altitude was approximately 5000 feet above terrain; according to Table F-II in Appendix F, a number density of 2.5×10^3 can be assigned to the area adjacent to the cloud. The ratio of the amplitudes of the cloud to the adjacent atmosphere should be proportional to the ratio of the cloud number density to the nuclei number density as

$$\frac{A_c}{A_n} = K \frac{N_c}{N_n} \quad (23)$$

which becomes

$$N_c = \frac{1}{K} \frac{A_c N_n}{A_n} . \quad (24)$$

The number density of the cloud is then

$$\begin{aligned} N_c &= \frac{1}{K} \frac{3.6}{9.25 \times 10^{-7}} 2.5 \times 10^3 \\ &= \frac{1}{K} 9.6 \times 10^9 . \end{aligned} \quad (25)$$

The proportionality constant K could be proportional to temperature, pressure path length, etc. It could be that atmospheric monitoring of the initial backscattering would give insight to this constant K.

The change in the atmospheric transmission, or the effective atmospheric attenuation with time, can also be detected by the LIDAR system. Figure 35 shows nine continuous reflections from the retroreflector at 52-miles; the repetition rate was 1 pulse every 2 seconds. The output of the laser was constant to within ± 1 megawatt, yet the detected signal varied over a factor of 2. This indicates that the refraction in the atmosphere changed drastically during these 18 seconds. The LIDAR could be used to monitor the average change in atmospheric refraction which affects the attenuation.

Top Trace $\left\{ \begin{array}{l} 2.0 \text{ v/cm} \\ 0.2 \text{ } \mu\text{s/cm} \end{array} \right.$

Bottom Trace $\left\{ \begin{array}{l} 1.0 \text{ v/cm} \\ 0.1 \text{ } \mu\text{s/cm} \end{array} \right.$

Figure 35. Nine laser reflections from a retroreflector;
one shot every two seconds

Traces $\left\{ \begin{array}{l} 0.1 \text{ v/cm} \\ 20 \text{ ns/cm} \end{array} \right.$

6.9 ft of RG-8 cable

Figure 36. System response to a 20 nanosecond,
10,000 photon pulse

Pulse Stretching

As previously mentioned, the discrepancy in width between the laser output pulse and the reflected pulse recorded could be caused by saturation effects in the PM tube. This phenomenon is not completely understood. The reflections from the 5-to 52-mile targets (left column of Figure 32) show that the 40 ns transmitted pulse was stretched to a 60 ns pulse width after being received. Figure 36 shows the effect which the optical filter, PM tube, cables, and 555 oscilloscope

have on a 20 ns pulse of light containing 10,000 photons. As can be seen, the electronic system handles this 20 ns pulse light level with no stretching. The strength of the signal incident to the PM photocathode was attenuated by placing neutral density filters in front of the optical filter. As the density was increased, the pulse width decreased until, with an ND filter of 4, the reflected pulse recorded was essentially the same width as the one transmitted as shown in Figure 37 for the 26-mile target. For up to an ND of 2, the output of the PM tube increased with increasing ND filter density.

As the gain of the PM tube was decreased from 2100 volts to 1200 volts, a reduction in PM amplification from 2.2×10^6 to 1.2×10^4 or a 10^2 reduction in gain, the pulse width narrowed from 120 ns to 60 ns; however, the reduction in amplitude was not 100, but rather from 6.8 volts to 4 volts (Figure 38). This indicates that both amplitude saturation and pulse stretching are also related to gain saturation. The time stretching could be related to space charges developing within the PM tube when it saturates.

Correlation Between Retroreflector Data and Atmospheric Transmission Theory

A correlation between the data collected from retro-reflector targets and atmospheric transmission theory led to initially satisfactory results. Equation (14) instead of Equation (15) is used to calculate the current output of the PM tube since the reflected solid angle (due to diffraction of the aperture, 1.48×10^{-5} radians) is less than the solid angle subtended by the receiver (3.77×10^{-5} radians). The atmospheric attenuation for a single path to the retro-reflector target is then given by

$$\eta_A = \frac{\alpha_L R}{d_{ret}} \left(\frac{I}{\mu q P_0 \eta_0 \eta_{ND} \rho} \right)^{1/2} . \quad (26)$$

Top trace is 5 v/cm, 0.2 μ s/cm
a. ND 0

Top trace is 5 v/cm, 0.2 μ s/cm
b. ND 1

Top trace is 5 v/cm, 0.2 μ s/cm
c. ND 2

Top trace is 2 v/cm, 0.2 μ s/cm
d. ND 3

Top trace is 1 v/cm, 0.2 μ s/cm
e. ND 4

Bottom trace in each case is 1.0 v/cm and 0.2 μ s/cm

Figure 37. Photomultiplier output as a function of signal attenuation for 46,800 yard range

a. PM voltage = 2100 v

b. PM voltage = 1800 v

c. PM voltage = 1500 v

d. PM voltage = 1200 v

Top traces are 2 v/cm and 0.2 μ s/cm

Bottom traces are 1 v/cm and 0.1 μ s/cm

PD = 1000 v

Figure 38. Photomultiplier output as a function of PM gain for 46,800 yard range

When $\alpha = 8.5 \times 10^{-3}$ radians, $d_{\text{ret}} = 0.1875$ ft, $\alpha_L = 1.4 \times 10^{-2}$ amp/watts, $\eta_0 = 0.063$, $\eta_{\text{ND}} = 10^{-4}$, and $\rho = 0.80$, the values of Range R, amplification μ , and recorded Current I are as given in Table X. The appropriate measured effective one-way atmospheric transmissions for the 26- and 52-mile targets, as calculated using Equation (26) and the data collected, are also listed in Table X. The transmission through the atmosphere for the path length between the targets and the LIDAR is really along a slant range from h_1 , the LIDAR altitude, to h_T , the target altitude. The theoretical calculation¹² for a clear Standard Atmosphere at a given altitude h, which is not a slant range, is given by

$$\eta_a = \exp - \left[\beta_t(h) \ell \right], \quad (27)$$

TABLE X
Measured Atmospheric Transmission

<u>Target</u>	<u>Range (km)</u>	<u>Alt (amp)</u>	<u>I (amp)</u>	<u>μ</u>	<u>η_A</u>
26-mile	42.4 (139,920 ft)	2.816	4×10^{-2}	$\left\{ \begin{array}{l} 7 \times 10^7 \\ 10^7 \end{array} \right.$	$\left\{ \begin{array}{l} 26.0 \\ 68.0 \end{array} \right.$
52-mile	84.0 (277,580 ft)	2.780	1.18×10^3	$\left\{ \begin{array}{l} 7 \times 10^7 \\ 10^7 \end{array} \right.$	$\left\{ \begin{array}{l} 08.7 \\ 23.0 \end{array} \right.$

Two calculations were made with Equation (27), one with the path length positioned at the target altitudes and the other with the path length at the LIDAR altitude (Table XI). If the theory agrees with the data, the transmission to each target listed in Table XX should lie between the transmissions

TABLE XI

Transmission Measured at Target and Transmitter Altitudes

<u>Location</u>	<u>h</u> <u>(km)</u>	β_t <u>$(\text{km}^{-1}) \times 10^{-2}$</u>	<u>Range</u> <u>(km)</u>	η_a <u>(%)</u>	<u>μ</u>	η_A <u>(%)</u>
47-mile target	2.20	2.949	76.6	10.4		
52-mile target	2.78	1.726	84.0	23.4	10^7	23.0
26-mile target	2.82	1.543	42.4	52.2	10^7	68.0
83-mile target	3.04	1.402	-	-		
Transmitter	1.7	3.812	42.4	19.88	7×10^7	26.0
Transmitter	1.7	3.812	76.6	05.39		
Transmitter	1.7	3.812	84.0	04.08	7×10^7	08.7

calculated for the same path lengths at the altitudes shown in Table XI. The atmospheric transmission to both sites for the maximum amplification of 7×10^7 is bounded by the upper and lower calculation values, e.g., for the 26-mile target the 26.0 percent measured is between the 19.8 and 52.2 percent calculated and the 8.7 measured is between the 4.08 and the 23.4 percent calculated. For the median amplification of 10^7 , only the 52-mile target has the measured value bound by the calculated values. This does not indicate the degree of fit between theory and data; only an integration along the data path between the altitudes h and h_T would give the degree of fit. However, the above discussion does indicate that the LIDAR/retroreflector system could be used to determine actual atmospheric transmission over long paths.

Conclusion

In order to analyze the data collected by the GB-60B LIDAR, it will be necessary to perform the following field tests:

1. Determine thresholds for varying particulate sizes at different altitudes, elevation angles, and slant ranges.
2. Determine meteorological conditions for each of the tests indicated in (1), in particular the atmospheric attenuation.
3. Determine variation in thresholds for varying geographical locations; this implies that entirely different conditions can exist between, e.g., Wallops Island and Cloudcroft.
4. Each test should be run using both the LIDAR and an FPQ-6 or FPS-16.

Results from the above items will be of scientific as well as engineering interest, and are a must if the LIDAR is to be used to determine the density and dispersion rates of particulate distributions.

APPENDIX A

Development of Laser

After several months of investigating laser system companies, the Raytheon Company was chosen as the laser supplier for Sandia Laboratories. On December 4, 1964, the contract was finalized with Raytheon to design, develop, fabricate, and test a Q-switched laser system, using Brewster angles on the ruby, Kerr cell, polarizer, and prism. The system was to be delivered to Sandia by October 31, 1965. Due to technical problems at Raytheon and a Sandia change order, the first laser was shipped approximately April 1, 1966. On October 13, 1966, Sandia ran the final laser head qualification tests on a Pockels cell Q-switching system with anti-reflection coating.

The major technical problems that Raytheon encountered during development and testing were:

1. irreparable damaging of the Brewster angle Kerr cells by the high power, high repetition rate pulses,
2. the 95 feet separation of the flash lamp cavity from the energy storage capacitor,
3. the 10,000 feet altitude requirement necessitated several redesigns of the high energy pulse transformer and corrections for the high voltage Pockel cell connections,
4. a good coolant for the flash lamp cavity was never found, and
5. deterioration of optical surfaces at high energy levels.

Some minor problems were initial deletion of required control functions and sync-circuit, and charging of energy storage capacitors at the high firing rates and power levels required. Table A-I lists the major systems requirements and how each laser head met these specifications.

TABLE A-I
Major System Specifications

Requirements	Laser Head No. 1 met specifications	Comments Head No. 1	Laser Head No. 2 met specifications	Comments Head No. 2
1. Continuous operation at 1 pps for 1 hr and 30 min	No	Realignment of optical compo- nents and rear mirror changed.	No	Realignment of optical compo- nents.
A. 30 mw for 1 hr	Yes		No	Output varied from 10 to 50 mw. Missed approxi- mately 20 shots. Master power breaker turned off 10 times.
B. 100 mw for 15 min	No	Output down to 75 mw at end of test.	Yes	
C. 200 mw for 15 min	No	160 mw maximum output at the be- ginning and output down to 140 mw at end of test. 200 mw could only be obtained by firing every 2 sec.	No	15 min run at 190 mw.
2. Beam divergence				
A. 2 mr at 30 mw	No	4.5 mr (Raytheon's method of measur- ing was worst- case).	No	
B. 10 mr at 10 mw	Yes	8.5 mr	Yes	
C. 10 mr at 200 mw	Yes	8.5 mr	Yes	
3. Stable operation while Sandia tracking mount is in operation	No	Output decreased at least 15% when mount was pointed 85° to 90° up.	No	Output decreased 36% when mount was pointed 85° up.

APPENDIX B

Radiation Detectors

Many physical processes exist--thermal and photoelectric are the most important--in which some change in the state of a material occurs as a result of radiation. The thermal detector converts incident radiation into heat and records the temperature change. From a knowledge of the heat capacity (or electrical resistance versus temperature) of the radiated material, an absolute determination can be made of the total light energy of the input. In fact, other types of detectors are usually calibrated by thermal devices. On the other hand, the response time of thermal detectors is long, and they can be used only for the interpretation of signal amplitude modulated at an impractically slow rate; their sensitivity is also rather low.

The type of radiation detector of primary interest is based on the photoelectric effect, in which the energy of the incident radiation is converted to the energy of electrons contained in the detection element. A photoelectric detector is also called a quantum detector because each quantum, or photon, of light incident on the detector results in a change in state of one and only one electron. More quantitatively, light exists only in bundles of energy such that the energy = $h \nu$, where h is Planck's constant and ν is the frequency of the light. When a single photon is absorbed by an appropriate surface, the photon ceases to exist and the energy it contained is transferred to a single electron.

In the visible part of the spectrum, one photon generally imparts enough energy to an electron so that the electron has sufficient energy to leave certain detector materials. We will define this effect as an external photoelectric effect. When an appropriate bias is applied between the detector material and some other surface, the emitted electron can be collected directly. Materials to carry out this process in the infrared region are not available, but materials are available in which the photon is absorbed. The energy of the photon is still transmitted to the electron, but since the frequency is now considerably less, the electron does not have sufficient energy to escape the material. However, the electrons so affected have additional energy, manifested as kinetic energy, which can be detected microscopically by the conductivity change of the material or by the change in potential difference between different points in the material. Detectors of this type are defined as operating on the internal photoelectric effect.

In all photoelectric devices, the voltage or current output of the device is proportional to the intensity (power) of the input signal which is the amplitude squared; therefore, photoelectric devices are termed "square law" devices.

APPENDIX C

Aligning the GB-60B

There are three optical axes that must be aligned parallel: (1) the Cassegrainian telescope, (2) the ME-16 viewing telescopes, and (3) the ruby lasers. The elements of the Cassegrainian telescope are aligned first, then the viewing telescopes, and lastly the axes of the ruby lasers. Figure C-1 shows the locations of the five points involved in this alignment. A Davidson alignment telescope is located at A, a laser target is positioned at B which is approximately 10 miles down-range and approximates an infinity target, the secondary of the telescope is at C, the photocathode of the photomultiplier is at D, and the center of the 60-inch primary mirror is at E. The laser target at B consists of a Spectra Physics He-Ne 130 laser and a 40X telescope which have parallel optical axes. A retroreflector at the front of the secondary reflects the beam back 10 miles to the 40X telescope. Using this technique, the laser can be pointed to within the beam width of approximately 100 feet at the receiver. A cross hair reticle is centered at the geometrical center of the holder of the secondary, C. The cylinder that holds the rod, on which the secondary is mounted, is geometrically centered to the spider holders. A similar reticle is fastened at the photocathode surface position, D. With the alignment scope at A focused at infinity, the ME-16 tube is pointed toward B. The scope is then focused at C. The cylinder holding the reticle at C, and the scope at A and the ME-16 mount are moved until the reticle in the scope, the reticle at C, and the infinity target are in line. At that time, the reticle at D is also placed in line at the proper distance from the center of the primary, E. The rim of the primary is held normal to the mechanical axis of the

ME-16 tube to within ± 0.001 inch. At this time, the secondary mirror holder plate and rod are placed inside the cylinder. The secondary is adjusted along the axis and tilted until a clearly focused image of the 130 laser exit beam is seen at D; the secondary is then secured. The photomultiplier is then slipped into its holder at D; this completes the alignment of the Cassegrainian telescope and the PM cathode surface.

Figure C-1. Setup for aligning GB-60B

The axes of the wide angle and telephoto viewing telescopes are then aligned parallel to the axis of the Cassegrainian telescope. This is done by looking at the He-Ne target laser beam through each scope without moving the ME-16 mount. The telescopes are adjusted until their reticles are centered on the He-Ne target laser beam.

The axis of each of the ruby laser transmitters is aligned in the following manner. A Davidson aligning telescope placed in a special mount is positioned on the laser head between the laser output end and the back of the primary mirror of the Cassegrainian telescope (Figure 23). The optical axis of the aligning telescope is aligned perpendicular to the front face (output end) of the ruby rod. Simultaneously, the reflection of the reticle of the aligning scope is centered on the face of the ruby rod. With the scope mount locked in this position, the aligning scope is rotated 180 degrees relative to a vertical axis. It now points in the direction the ruby laser beam travels when fired. The base on which the laser head is mounted is then adjusted until the reticle of the aligning scope (focused at infinity) is centered on the He-Ne laser beam (the target). The entire system is now optically aligned.

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APPENDIX D

Calculation of Minimum Number Density Detectable by GB-60B

A more accurate calculation of the minimum number density which can be detected by the GB-60B LIDAR system might be in order. This minimum number density is given by

$$N = \frac{2 R^2 P_{\min}}{P_o \pi a^2 r^2 n_o n_p \sigma \ell} \quad (D-1)$$

where

- N = number density, particles/ft³
- R = slant range, feet
- P_{min} = minimum power detectable, 10⁻⁹ watts
- P_o = power output, watts
- a = particulate radius, feet
- r = primary mirror radius, 2.5 feet
- n_o = system optical efficiency = 0.20
- n_p = path transmittance, transmitting and receiving = 0.5
- σ = reflectivity of the particulate, 0.6
- ℓ = depth of cloud illuminated instantaneously, 20 feet

The GB-60B has essentially the following characteristics:

Peak power output = switchable: 30, 100, and 200 megawatts

Wavelength = 6943 ± 2 angstroms (6.943 x 10⁻⁵ cm)

Pulse length (Q-switched) = 20 nanoseconds

Repetition rate = 1 pulse per second maximum

Diameter of primary mirror = 60 inches

Optical bandpass filter width = 20 angstroms (0.5 transmission points)

Efficiency of optical system = 0.3

Transmitter beam divergence = 4.5 milliradians (30 mw)
8.5 milliradians (100 mw)
8.5 milliradians (200 mw)

Equation (D-1) requires that the diameter of the particulate cloud always be greater than that of the laser beam illuminating the cloud, and that the cloud be at least 20 feet thick. The equation also assumes that the particles reflect energy diffusely into a hemisphere.

Figure D-1 indicates the diameter, d , of the laser beam for both 4.5×10^{-3} - and 8.5×10^{-3} -radian divergences as a function of slant range, R . Figure D-2 shows the instantaneous volume, V , illuminated by the laser as a function of range, again for both divergences. These parameters are dependent upon the beam divergence, α , and the Q-switch laser pulse length, τ , by

$$d = \alpha R \quad (D-2)$$

and

$$V = \frac{\pi}{4} (\alpha R)^2 \tau . \quad (D-3)$$

A particulate dispensed from a point source can be tracked until it diffuses beyond the boundary indicated. If particulates are formed during reentry ablation, the graphs indicate that some cloud size restrictions must prevail to aid in acquisition. A large cloud of particulate whose number density is several times above threshold can be mapped by scanning around the edges, and hence, cloud growth (diffusion rates)

Figure D-1. Diameter of the cloud intercepted by the laser beams versus slant range. The divergence for the different power outputs are 30 mw = 4.5×10^{-3} radians and 100 and 200 mw = 8.5×10^{-3} radians

Figure D-2. Volume of the cloud instantaneously illuminated by the different divergent laser beams versus slant range. The diameter of the cloud is assumed to be greater than that of the laser beams

can be established. Figure D-3 shows the threshold particulate number density versus slant range for the parameter depicted by Equation D-1. Three power outputs (30, 100, and 200 mw) and three particle sizes (10, 100, and 1000) μm are shown.

These curves are quite meaningless for the shorter ranges (less than 50,000 feet or so) and at low elevation angles. If the particulate cloud is formed at low altitudes or at positions demanding low elevation angles relative to the tracking mount, the following problems arise.

1. The particulate cloud might easily be imbedded in a medium whose content (aerosol, particulate, water vapor, etc.) might be many orders of magnitude greater than that illustrated by the curves of Figure D-3. These atmospheric parameters are meteorologically dependent and will vary considerably in time at a given geographic location; the variation with geographic location is likewise considerable.
2. In the absence of temperature inversions, smog, and clouds, normal humidity can easily be a limiting factor in determining the threshold. In addition to creating backscatter, which the receiver picks up, the water vapor acts as an attenuator. The amount of attenuation depends upon the total water content in the optical path.

The effective thickness of water can vary from a few tens of millimeters to a few tens of centimeters, depending upon atmospheric conditions and optical path length.

Figure D-3. Threshold number density versus slant range for output powers 30, 100, and 200 mw

At the longer ranges (more specifically, at the higher altitudes) these background problems are minimized, and the threshold number density approaches the values shown in Figure D-3. The attenuation due to the water content in the observation path remains. This attenuation could possibly influence the threshold results by a factor of ten. Many papers have tried to treat these kinds of problems analytically; however, data from field experimentation are much more meaningful.

The total minimum or threshold number of particles required for detection of a specific laser beam divergence of α is given by

$$n = K \frac{\alpha^2 R^4}{\alpha^2 P_o} \quad (D-4)$$

for

$$K = \frac{P_{\min}}{2r^2 n_o n_p \rho} = 1.32 \times 10^{-9} \frac{\text{watts}}{\text{ft}^2} \quad (D-5)$$

which are the parameters defined in Equation (D-1). Using Equation (D-5), Equation (D-4) becomes

$$n = 1.32 \times 10^{-9} \frac{\alpha^2 R^4}{a^2 P_o} . \quad (D-6)$$

Figure D-4 depicts the threshold number of particles versus range for the 30 megawatt laser LIDAR output with a beam divergence of 4.5 milliradians when a volume of the particulate is created as defined in Figure D-2. Figure D-5 shows the threshold number of particles versus slant range for the 100 and 200 megawatt laser output with a beam divergence of 8.5 milliradians when a volume as defined in Figure D-2 is created.

Figure D-4. Threshold number of particles versus slant range for 30 mw of power and beam divergence of 4.5×10^{-3} radians

Figure D-5 Threshold number of particles versus slant range for 100 and 200 mw of power and a beam divergence of 8.5×10^{-3} radians

The threshold number of particles dependent on the fourth order of range is apparent in both Figures D-4 and D-5. What was stated for Figure D-3 as pertaining to short ranges or low elevation angles applies equally well to Figures D-4 and D-5.

APPENDIX E

Atmosphere Attenuation Due to Water, Carbon Dioxide, and Ozone

In order to predict the performance of laser ranging and dust measurement equipment, it is necessary to evaluate the character of the target and background radiation and the atmospheric absorption of the laser beam. In this appendix, an attempt is made to provide the necessary elements to calculate or analyze these parameters.

Detailed procedures for evaluating atmospheric attenuation have been described. The procedure of Altshuler¹³ is used as the basis for the calculations. The vapors and gases primarily responsible for atmospheric attenuation are water vapor, carbon dioxide, and ozone. Since Q-switched lasers exist only in the visible and near infrared, e.g., $< 2 \mu\text{m}$, the discussion is restricted to wavelengths between 0.3 and $1.4 \mu\text{m}$ where water vapor is the main attenuator. Any estimate of water vapor as a function of altitude is weather dependent. Therefore, either the weather conditions along the path in question must be known, or an average weather assumption must be made. For our purposes an average weather is assumed, i.e., the smooth curve of Figure E-1. The effects due to haze, fog, or rain are not considered in the initial calculations because they increase the complexity of the calculations. The method described by Altshuler is best demonstrated by an example. Consider a transmitter at sea level, (altitude 0 km), a target at an altitude of 60 km, and a slant range of 85 km. The operating wavelength is $6943 \text{ \AA}$. From Figure E2, read $\bar{W}_1$ (from 0 to 24 km altitude):

$$\bar{W}_1 = 0.0303 \frac{\text{cm water}}{\text{km air}} .$$

Figure E-1. Humidity mixing ratio versus altitude

Figure E-2. Observer altitude versus average value of precipitable water vapor corrected to sea level (from WADC Technical Report 54-581, Dayton) AD-54-347

The slant range, R_1 (from 0 to 24 altitude), is $24 \frac{85}{60} = 34$ km. Hence, the total amount of water in the slant range R_1 is

$$W_1 = R_1 \bar{W}_1 = 1.2 \text{ cm water.}$$

From Figure E-3 read W_v (from 24 to 60 km altitude):

$$W_v = 3.8 \times 10^{-4} \text{ cm of water in a vertical column;}$$

therefore,

$$W_2 = W_v \frac{\text{Slant Range}}{\text{Altitude}} = 3.8 \times 10^{-4} \frac{(85-34)}{(60-24)}$$

$$= 5.4 \times 10^{-4} \text{ cm water}$$

and

$$W_{\text{Total}} = W_1 + W_2 = 1.2 \text{ cm water.}$$

From Figure E-4 for $W_T = 1.2$ cm water at $6943 \text{ \AA}$, the percent transmission of the one way path is 90, so the percent transmission for the round trip is 81. The assumption of average weather implies some error in atmospheric attenuation. However, if we assume a 50 percent error in the calculation of W_T (total number of centimeters of water in the path), then, as W_T changes from 0.6 to 2.4 cm of water, the round trip percent transmission drops from 86 to 77 percent, or about a 5 percent error from this cause. It is believed that a 5 percent error is acceptable. Calculations based on specific weather conditions also were made but are not reviewed here.

One expects turbulons throughout the atmosphere which will vary the path attenuation by scattering. In order to make an absolute measurement of particle densities, it will be necessary to have an estimate of the absolute atmospheric attenuation.

Figure E-3. Maximum altitude versus average value of precipitable water vapor. The curves remain horizontal beyond their right ends as $h_{\max}$ increases

$W_r = \text{cm precipitable H}_2\text{O vapor}$

Figure E-4. Wavelength versus transmission

Background radiation sources, such as erroneous light reflected from the target (caused by satellites and moon-, earth-, or sunlight), other direct light sources (e.g., moon, earth, sun, and stars), and scattering from geophysical phenomena (e.g., the dust belt around the earth, etc.) may all interfere significantly with most of the applications intended for the GB-60B LIDAR system. The radiances from typical sources are shown in Table E-I; the radiances for ground level are the worst cases.

The sky radiance exhibits a strong polarization relative to the sun's position. For polarized reflected light, definite advantages exist if it could be polarized normal to that of the sky radiance. However, if the reflected light from the target is unpolarized and a properly oriented polarizer is used to eliminate the polarized sky radiance, the improvement in signal to noise ratio is at most 1.5, a not too significant increase.

TABLE E-I

Radiances From Typical Sources

Wavelength (Å)	Daylight sky radiance [watts - (cm ² -Å- steradian) ⁻¹]	Night sky radiance [watts - (cm ² -Å- steradian) ⁻¹]	Direct viewing of the moon** [watts - (cm ² - Å-steradian) ⁻¹] (x 10 ⁻⁶)	Direct viewing of sunlit earth [watts - (cm ² - Å-steradian) ⁻¹] (x 10 ⁻⁶)	Direct viewing of moonlit earth [watts - (cm ² - Å-steradian) ⁻¹] (x 10 ⁻¹²)	Direct viewing of a 0 magni- tude star *** [watts - (cm ² - Å-steradian) ⁻¹] (x 10 ⁻¹⁵)
3000		1.4 x 10 ⁻¹⁴	0.12	0.01	0.0126	0.34
4000	8.2 x 10 ⁻³	1.3 x 10 ⁻¹⁴	0.34	1.18	1.64	0.83
5000	4.4 x 10 ⁻³	2.0 x 10 ⁻¹⁴	0.47	1.70	2.22	1.16
6000	2.2 x 10 ⁻³	5.0 x 10 ⁻¹⁴	0.41	1.73	2.28	1.04
7000	1.6 x 10 ⁻³	*8.0 x 10 ⁻¹⁴	0.33	1.57	2.08	0.8
8000	1 x 10 ⁻³		0.26	1.32	1.75	0.63
9000	9.3 x 10 ⁻⁴		0.20	1.10	1.42	0.5
10000	1.0 x 10 ⁻⁴		0.16	0.875	1.16	0.41

*Believed to be lower than number quoted.

**For direct viewing of entire moon, consider that the moon subtends 6×10^{-5} steradians.

- ***1. If we maintain a field of view of less than 1 degree and avoid having planets in our field of view, this is indeed a worst case.
2. If we wish to consider direct viewing of a -5 magnitude (brightest) planet, multiply above results by factor of 100.

APPENDIX F

Molecular Attenuation in the Atmosphere

The molecular attenuation in the atmosphere follows an exponential function. This attenuation is due to particulates, generally called "nuclei of condensation,"¹⁴ which are of two types. One type has an affinity for water vapor and is a fog-former; the other type requires supersaturation for the initiation of condensation and is a haze-former. The radii of both types of nuclei have been measured and range in value from 0.5 to 30 μm . Number densities on land vary from $1.5 \times 10^5/\text{cm}^3$ to $4 \times 10^6/\text{cm}^3$ in urban areas, and from $5 \times 10^4/\text{cm}^3$ to $4 \times 10^5/\text{cm}^3$ in unpopulated areas (Table F-I). The range is $1 \times 10^3/\text{cm}^3$ to $4 \times 10^4/\text{cm}^3$ over ocean areas.¹⁵

Nuclei concentration has been correlated with visibility, air mass, wind direction and force, etc. The important question of the variation of the concentration of nuclei with elevation has not been thoroughly studied because of the difficulties of making such measurements. Most of the measurements were made in mountainous regions at various elevations and showed a rapid decrease in concentration with elevation. A few determinations were made from free balloons. These showed a more rapid decrease of concentration of nuclei with increasing elevation than did the mountain observations. The average vertical distribution of nuclei from the balloon ascents showed a count of $2.23 \times 10^4/\text{cm}^3$ in the layer from 0 to 500 meters, decreasing to $80/\text{cm}^3$ above 5000 meters (Table F-II). This information shows that the source of condensation nuclei is at or near the surface, with the nuclei being carried aloft by turbulence and convection.

TABLE F-I

Horizontal Distribution of Nuclei

Location	Number of		Nuclei per cm ³				
	Localities	Observations	Average	Mean (max)	Mean (min)	Absolute (max)	Absolute (min)
Large city	28	2500	1.41×10^5	3.79×10^5	4.9×10^4	4×10^6	3.5×10^3
Town	15	4700	3.4×10^4	1.14×10^5	5.9×10^3	4×10^5	6.2×10^2
Open country	25	3500	9.5×10^3	6.6×10^4	1.05×10^3	3.36×10^5	1.8×10^2
Ocean	21	600	9.4×10^2	4.68×10^3	8.4×10^2	3.9×10^4	2

TABLE F-II

Vertical Distribution of Nuclei

Altitude (ft)	1.5×10^3	$1.5-3 \times 10^3$	$3-6 \times 10^3$	$6-9 \times 10^3$	$9-12 \times 10^3$	$12-15 \times 10^3$	15×10^3
Nuclei (per cm ³)	2.23×10^4	1.1×10^4	2.5×10^3	780	340	170	80

It is seen that the initial backscatter is the result of too large concentrations of nuclei of somewhat even distribution horizontally but with rapidly decreasing vertical concentration. The variance in nuclei size is most significantly influenced by humidity, and above a certain level of humidity a rain drop size is formed.

Clouds

Many thousands of measurements of droplet size have been made of mountain fog, and stratus, stratocumulus, and altocumulus clouds.¹⁶ The absolute range of mean drop diameter was about 5 to 70 μm . The most frequent diameter was about 17.6 μm .

The range of the most frequent diameter was smaller for altocumulus and stratocumulus clouds than for fog and stratus clouds. A large amount of data on drop size, size distribution, and liquid water content in clouds was collected at Mount Washington, New Hampshire; the mean drop diameter was 13 μm , with an observed range of about 5 to 40 μm .

Table F-III below summarizes observed drop sizes in various types of clouds.¹⁶

TABLE F-III
Drop Sizes in Clouds

<u>Cloud type</u>	<u>Mean Diameter (μm)</u>	<u>Range (μm)</u>
Dense Cumulus	14.5	3-40
Cumulus	8.5	2-20
Stratocumulus	7.9	2-24
Nimbostratus	13.2	2-42
Stratus	12.9	2-42
Altostratus	10.6	2-30

Fog drops exhibit ranges from 25 to 75 μm , with an average of 45 μm ; a rare drop is as large as 120 μm . The most frequent value for the liquid water content of clouds is 0.24 g/m^3 , and the most frequent value for fog is 0.13 g/m^3 . A rainfall rate of 0.05 inch/hour has a median drop diameter of 1.1 mm; for 0.5 inch/hour, the median diameter is 1.9 mm; for 4.0 inch/hour, the median is 2.8 mm. Information on the number density of nuclei in clouds was not found during the brief literature search.

In summarizing the foregoing information, it is seen that particle size distributions in haze, fog, and various types of clouds are not significantly different. Therefore, to a first approximation, the amplitude of a return pulse from a cloud can be related to the amplitude of the backscatter from the nuclei (number density known approximately) adjacent to the cloud. The difference in amplitude should be in some way proportional to the ratio of number density of the cloud to the nuclei.

Conclusions

The following conclusions were reached based on the above discussion.

1. The choice of a proper operating site will reduce significantly the energy loss from the initial backscatter.
2. The number density of backscattering nuclei at a given site can be determined to within a reasonable limit with proven instruments (Aitken's Method).
3. Once calibrated, the laser radar probably can determine the number densities of nuclei at any time.

4. If Item (3) proves to be correct, the LIDAR system could be used to:
- (a) Study air pollution,
 - (b) Study debris dispersal and fallout, and
 - (c) Study cloud formation and dispersion.

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