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GB-60A LIGHT DETECTING AND RANGING SYSTEM (LIDAR)

M. J. Landry, 7226

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SC-DR-67-115

GB-60A LIGHT DETECTING AND RANGING SYSTEM

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ABSTRACT

Sandia Laboratory has developed a laser light detecting and ranging (LIDAR) system, primarily for use in tracking clouds formed by the ablation of radioactive materials ejected from a SNAP device during atmospheric reentry. This report describes the GB-60A, a first generation LIDAR system which has been used to observe thin atmospheric clouds, retro reflectors, balloons, and discontinuities in the atmosphere. The range equations, system parameters, design details, and operation techniques associated with the system are described.

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SUMMARY

Sandia Laboratory has developed a laser light detecting and ranging (LIDAR) system, primarily for tracking clouds formed by the ablation of radioactive materials ejected from a SNAP device during atmospheric reentry. This report describes the GB-60A, a first generation LIDAR system built at Sandia Laboratory. The GB-60A has been used to observe thin atmospheric clouds, corner reflectors, balloons, and discontinuities in the atmosphere.

The LIDAR is comprised basically of three subsystems: the transmitter, the receiver, and the recorder. The transmitter consists of a ruby laser and a power supply. The laser, which is Q-switched by a total internally reflecting (TIR) prism, is mounted on a rigid base and enclosed in an air-tight housing. The ruby rod is cooled by a refrigerated air conditioner. In normal operation, the laser produces multiple pulses approximately 40 nanoseconds wide.

The receiver consists of the optical system, which contains a 60-inch diameter carbon-arc searchlight mount, a photomultiplier, and a photomultiplier supply. The 60-inch searchlight mirror and a 3-inch mirror are used as the primary and secondary components of a Cassegrainian optical system. A 2 to 4X telescope is mounted on the frame of the searchlight mount and is used to aim the system. A $7\text{\AA}$ interference filter was used in the photomultiplier section for both day and night data acquisition.

The recorder consists of an amplifier, an oscilloscope, and a Polaroid oscilloscope camera. The oscilloscope is triggered by a signal from a photodiode which is placed to the rear of the TIR prism; sufficient light is scattered from the prism during the laser cycle to provide a trigger pulse.

Data were successfully obtained with the GB-60A LIDAR. Both day and night reflections of aerosol clouds have been photographed. As aligning techniques improved, the range of the GB-60A increased. Daytime cloud reflections were photographed at a range of 26 miles; nighttime reflections were recorded at 43 miles. In one instance, a cloud was detected at 92 miles.

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GB-60A LIGHT DETECTING AND RANGING SYSTEM (LIDAR)

Introduction

Sandia Laboratory has developed the GB-60A Light Detecting and Ranging (LIDAR) System, primarily for tracking clouds formed by the ablation of radioactive materials ejected from a SNAP device during atmospheric reentry. The first detection system that was designed demonstrated the possibility of using a laser LIDAR for detecting such clouds and aerosol layers. The position of the radioactive particles and the distribution of their mass and volume densities and their dissipation rates were some of the parameters sought. Initially, nonradioactive sample clouds were to be formed for the purpose of studying atmospheric wind motion at different heights so as to enable more accurate predictions of the dissipative forces.

This report presents the range equations, system parameters, design details, and operation techniques associated with the GB-60A LIDAR System which was a first generation experimental system built at Sandia Laboratory. A block diagram of the GB-60A, which was used to observe thin atmospheric clouds, retro reflectors, balloons, and discontinuities in the atmosphere, is shown in Figure 1.

Light Detecting and Ranging (LIDAR) System

The laser transceiver is comprised basically of three subsystems: transmitter, receiver, and recorder.

LIDAR Transmitter

The LIDAR transmitter consists of a modified Technical Research Group Model TRG 104 ruby laser and a power supply. The standard TRG 104 is Q-switched by a total internally reflecting (TIR) prism assembly which is rotated by a 24,000 rpm motor. The power output of the unit is 10 to 30 megawatts. Magnetic pickoffs synchronize the orientation of the TIR prism and the capacitor bank discharge time. The optical cavity consists of the TIR prism, a 90-degree-oriented ruby rod, an EG&G No. 41 xenon flash lamp, a highly polished aluminum cylindrical cavity, and a seventy-percent transmitting output mirror. The 7.62-cm long, 0.94-cm diameter ruby rod is positioned in the center of the cavity with the flash lamp on the side. The center of the output mirror is positioned below the axis of the ruby rod to allow rotation of the mirror in the event of damage.

The modified laser consists of the standard TRG 104 mounted on a rigid base and enclosed in an air-tight housing (Figure 2). The air used for cooling the ruby rod in the modified laser system is supplied by a conventional refrigerant window air conditioner instead of the original blower unit. The cooled, filtered air is forced through the optical cavity and is discharged from the front end of the housing. The air filter prevents dust greater than 0.3-micron from being deposited on the optical components of the laser. During initial testing, it was observed that any dust on optical components onto which laser light was later incident was rapidly burned, and continued exposure to the laser radiation resulted in pitting of the surfaces.

Multiple pulsing and variation in pulse height can be controlled by operating the laser at a lower output energy (near threshold), cooling, and firing at controlled time intervals.¹ It was also observed that the threshold energy

level of the system is critically dependent upon the orientation of the C-axis of the polarized ruby rod relative to the flash lamps, the optical quality of the ruby rod, and the accuracy of the mirror alignment. An operational study of this modified laser system indicated that in normal operation the laser produces multiple pulses approximately 40 nanoseconds wide.

LIDAR Receiver

The receiver consists of the optical system, and the photomultiplier and its power supply. The optical components are contained in a 60-inch diameter carbon-arc searchlight mount (Figure 3). A 2- to 4-power telescope, which is mounted on the frame of the carbon arc mirror structure with its axis parallel to the laser beam, facilitates aiming the system. The 60-inch, 25.6-inch focal length searchlight mirror and a 3-inch, 1-inch focal length mirror are used as primary and secondary components, respectively, in a Cassegrainian optical system.

The photomultiplier section (Figures 4 and 5) consists of an interference filter, converging lens, diaphragm aperture stop, photomultiplier, dynode resistor voltage divider, and power supply. The bandwidth of the 7Å interference filter used to take daytime and nighttime data is shown in Figure 6.

When nonaxial rays are incident onto an interference optical filter, the peak transmission shifts to a longer wavelength. For an optical system with a collecting light cone angle, α , the minimum bandwidth, $\Delta\lambda_{\min}$, needed to transmit the laser wavelength, λ_l , is given by

$$\Delta\lambda_{\min} = \left\{ 1 - \sqrt{\frac{\eta^2 - \sin^2 \frac{\alpha}{2}}{\eta}} \right\} \lambda_l .$$

Figure 7 shows the required $\Delta\lambda$ for cone angles of 1, 2.5, 5.0, and 7.5 degrees for an index of refraction of $\eta = 1.55$. A 7Å filter centered at 6943Å allows only the rays that are included in a 3.68 degree cone to be transmitted. The lens and diaphragm used allow radiation from a cone angle of less than 25 milliradians; therefore, the effective limiting aperture stop is the diaphragm and not the narrow-band-filter. For the system described, the effective diameter of the collector is approximately 45 inches.

The detector used in the LIDAR system was an RCA 7265 photomultiplier (PM). A noise analysis was performed for the particular PM used. The most important single parameter that best describes the performance of the system is the ratio of the signal reflected from the target to that of the system noise signal received. The noise signal can be either external or internal to the detecting system. The external noise is that part of the shot noise resulting from the variation in the photoelectron emission caused by the signal and/or background radiation. The part of the noise signal due to background can be controlled to some extent by choosing the time of day for operating, limiting the field of view of the receiving optics, and by optical filtering. The noise attributed to signal variation, on the other hand, is not as readily controllable, since it is the result of atmospheric effects, such as scattering, diffraction, and refraction. The internal noise is really thermal noise caused by electronic components and by fluctuations in the dark current of the detector, in this case a PM. The thermal noise of PM detectors and their supporting electronic circuits is usually small compared to dark current noise. Dark current noise can be small compared to external noise, i.e., the noise caused by daylight background because of the optical bandwidth used. The probability is small of detecting a dark current noise pulse during the several

microseconds that a gated PM accepts any reflected signal. A laser transmitter operating in a Q-switch mode with energy pulse widths of 20 to 60 nanoseconds further reduces this probability, even though the PM has a large dark count and the cathode is at room temperature.

LIDAR Recorder

The recorder consists of an amplifier, an oscilloscope, and a Polaroid camera; these record the energy collected (Figure 8). The output of the Tektronix Model 555 dual beam oscilloscope is recorded by a Beattie oscilloscope Polaroid camera. The oscilloscope is triggered by a signal received from an ITT FW 114 photodiode which is placed to the rear of the TIR prism. Sufficient light is scattered from the TIR prism during the laser cycle to provide a trigger pulse. One beam of the oscilloscope is used as a course range from the cloud to the receiver, and the other is delayed and expanded to give fine ranging information.

Alignment of GB-60A LIDAR

The system was optically aligned prior to use. A Watkins-Johnson Model 145 He-Ne multimode gas laser with a nominal 1.5-milliwatt output was placed on a line-of-sight hill located six miles from the LIDAR System. The 60-inch reflector was pointed in the direction of the He-Ne laser beam. The secondary mirror shown in Figure 3a was adjusted until the focused beam filled the interference filter which is positioned in front of the PM. It was necessary to change the position of the primary and secondary mirrors to obtain the best alignment. Three retro reflectors were placed at the vertices of an isosceles right triangle on the 6-mile hill, with the He-Ne aligning laser at the mid-point on the base of

the triangle (Figure 9). This configuration was held throughout the remaining alignment. The TRG 104 laser was fired into the retro reflectors, and both the laser and the retro reflectors were adjusted in position until the three retro reflectors were positioned on the edge of the beam incident from the laser. This assured that the TRG 104 laser axis was parallel to the optical axis of the receiving optics.

Prediction of Radiation Reflected from Aerosol Cloud

This section presents the calculations which predict the radiation reflected from an aerosol cloud. The effect reflection depth, d_r , of a cloud illuminated by a Q-switch laser with a pulse width, t , is

$$d_r = \frac{c}{t} . \quad (1)$$

The reflective volume, V_r , of this effect depth is

$$V_r = A_r d_r = (\Delta\theta_s R_s)^2 \frac{\pi}{4} d_r, \quad (2)$$

where A_r is the projected area of the laser beam at the cloud, $\Delta\theta_s$ is the solid angle at the cloud, and R_s is the distance to the cloud. The number of aerosol particles in the cloud which are illuminated during one pulse width is

$$N_r = n_r V_r = n_s d_r (\Delta\theta_s R_s)^2 \frac{\pi}{4} . \quad (3)$$

Instead of the rigorous electromagnetic theory, the geometrical optical approximation can be used in determining the intensity of the light scattered from the aerosol particles in the cloud, providing

$$\frac{b}{\lambda} > 1.5 , \quad (4)$$

where b is the diameter of the aerosol particles. For $\lambda = 6943\text{\AA}$, the geometrical approximation is applicable for $b > 1$ micron. Therefore, the total monochromatic power scattered by a single particle is given by

$$P_s(\lambda) = \int_0^{4\pi} E_s(\lambda) dw, \quad (5)$$

where $E_s(\lambda)$ is the scattered radiant intensity integrated over the surface of the scattering particle. For spherical particles

$$\begin{aligned} P_s(\lambda) &= \int_0^{2\pi} d\theta \int_0^\pi E_s(\lambda) \sin \phi d\phi \\ &= 2\pi \int_0^\pi E_s(\lambda) \sin \phi d\phi, \end{aligned} \quad (6)$$

where $P_s(\lambda) = 0$ in the direction of the incident radiation (Figure 10). The scattered radiant intensity $E_s(\lambda)$ for a spherical particle according to Kruse² is given by

$$E_s(\lambda) = E_r(\lambda) + E_t(\lambda) + E_d(\lambda) + E_c(\lambda), \quad (7)$$

where

$$\begin{aligned} E_c(\lambda) &= \frac{2 \cos^2 \phi/2}{\sin \phi} J_1 \left\{ \frac{2\pi b \sin \phi}{\lambda} \right\} p^{1/2} b^2 H_i(\lambda) \\ &\quad \sin \left\{ \frac{4\pi b \sin \phi}{\lambda} \right\} \end{aligned} \quad (8)$$

and

- $E_r (\lambda)$ = reflected radiant intensity
- $E_t (\lambda)$ = refracted radiant intensity
- $E_d (\lambda)$ = diffracted radiant intensity
- $E_c (\lambda)$ = coherent effect radiant intensity.

For backscattering, the solid angle subtended by the targets is $\Delta\theta_r = 10^{-6}$ radians; $\theta \rightarrow 0$ and $\phi \rightarrow \pi$, so that all but the first term in Equation (7) can be disregarded. The reflected intensity is given by

$$E_s (\lambda) \approx E_r (\lambda) = p b^2 H_i (\lambda), \quad (9)$$

where

$$H_i (\lambda) = \int_{\Delta\lambda_\ell} \left\{ \frac{\tau_{op} P_i (\lambda) \tau_a (\lambda)}{\frac{\pi}{4} (4 \theta_s R_s)^2} \right\} d\lambda \quad (10)$$

and

- p = reflectivity of the particles
- $\tau_{op} (\lambda)$ = transmission of the receiving and transmitting optics
- $\tau_a (\lambda)$ = transmission of the atmosphere
- $\Delta\theta_s$ = the solid angle subtended by the source
- R_s = distance from the particles to the source
- $\Delta\lambda_\ell$ = effective bandwidth of the laser radiation.

The reflected power from Equation (6) is then

$$P_s(\lambda) = P_r(\lambda) = \frac{pb^2}{2} H_i(\lambda) \int_{\text{limit}} \sin \phi d\phi. \quad (11)$$

The limits on the integration of Equation (11) is from $\pi - \frac{\Delta\theta_r}{2}$ to π . Since $\Delta\theta_r \approx 10^{-6}$ radians, the small angle approximation can be made for the integrated results

$$\cos \frac{\Delta\theta_r}{2} \approx 1 - \frac{\left(\frac{\Delta\theta_r}{2}\right)^2}{2!}. \quad (12)$$

The reflected power is then

$$P_r(\lambda) = \frac{\pi pb^2}{2} H_i(\lambda) \left(\frac{\Delta\theta_r}{2}\right)^2 / 2 \quad (13)$$

$$= \frac{pb^2}{4R_s} \left(\frac{\Delta\theta_r}{\Delta\theta_s}\right)^2 \int_{\Delta\lambda_\ell} \tau_{op} P_i(\lambda) \tau_a(\lambda) d\lambda \quad (14)$$

For N_r reflecting particles, the reflected power would be

$$P_r(\lambda)_{\text{total}} = N_r P_r(\lambda). \quad (15)$$

When Equations (3) and (14) are substituted into Equation (15), the result is

$$P_r(\lambda)_{\text{total}} = \frac{\pi N_s p b^2 d_r \Delta\theta_r^2}{8} \int_{\Delta\lambda_\ell} \tau_{op}(\lambda) P_i(\lambda) \tau_a(\lambda) d\lambda. \quad (16)$$

The signal-to-noise ratio is given by

$$\frac{S}{N} = \frac{P_r(\lambda) \text{ total}}{P_r(\lambda) \text{ photo noise}} \cdot \quad (17)$$

The main atmospheric losses result from molecular Rayleigh backscattering and absorption of radiation by the main constituents of the atmosphere: water vapor, carbon dioxide, and ozone. At the operating wavelength of 6943Å, the absorption due to ozone and carbon dioxide is negligible. On the other hand, water vapor does absorb radiation near this wavelength. The backscattering in the atmosphere was previously analyzed by Elteman,³ and others. For a different slant path, the actual absorption can be calculated using either Allshuler's method⁴ or the standard atmosphere from the Geophysical handbook.

During operation, the output wavelength of the LIDAR transmitter may vary because of thermal changes.⁵ There exist specific absorption bands at 6940.2, 6941.2, 6942.2, 6943.8, and 6945.2 in the atmosphere which should and can be avoided by thermal-tuning the LIDAR transmitter to minimize atmospheric absorption (Figure 11). The decrease in intensity is essentially an exponential function with distance and is caused largely by Rayleigh scattering. This type of scattering is wavelength dependent, and the coefficient of scattering, k , is given by

$$k = \frac{32 \pi^3}{3 \lambda^4 N} (\eta - 1)^2$$

where N = number of dipoles per unit volume,

η = the index of refraction of the medium.

This close-range backscattering effect is discussed later in this report.

Results and Discussion

The data described in this section date back to the summer of 1964. The initial data were obtained using a $10\text{\AA}$ -wide optical filter instead of the $7\text{\AA}$ filter mentioned in the description of the apparatus. Figures 12(A) and (B) are the oscilloscope traces corresponding to the energy received from the aerosols in atmospheric clouds. Figure 12(A) is a photograph of a cloud reflection recorded on the night of July 1, 1964, using the system previously described. As can be seen, the signal is distinctly greater than the noise.

The results of this initial nighttime cloud reflection study were sufficiently encouraging to warrant a daytime test. The $10\text{\AA}$ optical filter was replaced by a $7\text{\AA}$ filter to decrease the incident background power, P_b . Figure 12(B) is representative of the initial data obtained in the daytime.

As aligning techniques were improved, the range of night and daytime cloud reflections increased as shown in Figures 12(C), (D), (E), and (F). The reflections recorded in Figures 12(C) and (D) (nighttime) show that the depths of the clouds can be recorded for long ranges. Figures 12(E) and (F) show definite reflection in the daytime up to a range of 26 miles. The maximum range signals of 30.5 and 43.2 miles that were recorded at night are shown in Figures 12(G) and (H). The upper trace of Figure 12(G) shows the characteristic cloud distribution as represented by the reflected energy received. The cloud at 43.2 miles was not recorded on the expanded trace; however, the upper trace shows that this cloud also had a varying density distribution.

Figures 12(I) and (J) show the reflections received from a range of 95 miles at 2-minute intervals. Figure 12(I) shows no reflected energy received. Figure 12(J) shows that

2 minutes later the atmosphere changed drastically, and signals were obtained over an extended range. This indicates a high probability of detection at a range of 95 miles.

Included in the results are also some reflections received from a standard radar kite (quasi-corner reflector) secured to a balloon. The data were taken at dusk on August 24, 1964. The sequence of photographs demonstrates the ability to manually track a moving target with the system. Figure 13 shows the reflected signal recorded at one minute intervals. Figure 13(G) shows that a cloud at 8.26 miles reflected a stronger signal than the kite; before and after this shot, the reflection received from the kite was much higher. The reduction in signal for shot (G) was due to the mount being inaccurately adjusted.

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

Figure 2. TRG laser transmitter in dust-proof box

Figure 3(A). Front view of GB-60A Laser Transceiver System mount

Figure 3(B). Rear view of GB-60A Laser Transceiver System mount

Figure 4. Photomultiplier detector and associated optical and electronic components

RCA 7265

Figure 5. Dynode resistor voltage divider

Figure 6. Light transmission versus wavelength for 7⁰ interference filter

Figure 7. Required optical bandwidth for specific incident cone angles at different wavelengths

Figure 8. Electronic system for recording laser data

Figure 9. Retro reflector and He-Ne gas laser configuration for optically aligning the GB-60A

Figure 10. Geometric consideration for total monochromatic power scattered by a spherical particle

Figure 11. Atmospheric absorption near the ruby laser wavelength

$5 \mu\text{sec/cm}$
 $+0.25 \mu\text{sec delay}$
 0.05 v/cm
 Range 5930 yds
 Nighttime

Figure 12(A)

Daytime

Figure 12(B)

Figure 12. Energy reflected from atmospheric clouds at different ranges during both daytime and nighttime

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

Figure 12(C)

1 $\mu\text{sec/cm}$
 Range = 18 miles
 Cloud ~2500 feet thick
 Nighttime

Figure 12(D)

50 μ sec/cm
Range 26 miles
Daytime

Figure 12(E)

Range 13.1 miles
Daytime

Figure 12(F)

Range 30.5 miles
Nighttime

Figure 12(G)

Range 43.2 miles
Nighttime

Figure 12(H)

Some evidence of
signal return at a
distance of 95 miles

Figure 12(I)

High probability of a
return from something
at a distance of 95
miles. Picture taken
2 minutes after 12(I)

Figure 12(J)

20,050 feet range
0.034 volt

Figure 13(A)

20,950 feet range
0.04 volt

Figure 13(B)

21,210 feet range
0.02 volt

Figure 13(C)

Figure 13. Energy reflected from a radar kite.
The kite was acquired and tracked.

Not tracking

Figure 13(D)

18,600 feet range
0.015 volt
not tracking?

Figure 13(E)

21,350 feet range
0.015 volt

Figure 13(F)

22,200 feet range
0.0075 volt
cloud at 8.26 miles

Figure 13(G)

23,800 feet range
0.015 volt

Figure 13(H)

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