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MENLO PARK, CALIFORNIA

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August 1968

UCRL-13358

Final Report

MASTER

LIDAR OBSERVATIONS OF THE EXHAUST PLUME
OF A NUCLEAR-POWERED ROCKET ENGINE

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Contract AT (04-3)-115
Project Agreement Number 68

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FRONTISPIECE

EXHAUST PLUME FROM NRX-A6 NUCLEAR
ROCKET ENGINE STATIC TEST

ABSTRACT

Lidar (laser radar) observations of the particulate matter within the exhaust plume of a nuclear-powered rocket engine are described. The observations were made by a ruby lidar 5.5 km from the NRX-A6 engine operating at full power in a static test mount on 15 December 1967 at the Nuclear Rocket Development Station, Nevada.

The observational data were analyzed to obtain:

- (1) Volume backscatter coefficient of the exhaust plume as a function of time
- (2) Values of volume backscatter coefficient of the plume and the attenuation through the plume
- (3) Relative density variations of the particulate matter within the plume.

These analyses are presented and discussed. It is concluded that the experiment has demonstrated the feasibility of lidar for the remote, real-time monitoring of the particulate matter within a nuclear-rocket exhaust plume.

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ACKNOWLEDGMENT

The SRI team that carried out the field observations consisted of Messrs. Ron Collis, John Oblanas, Norman Nielsen, and Albert Smith. The lidar data were reduced and analyzed by Albert Smith. Calculations of lidar backscatter from turbulent refractive-index fluctuations of the plume were made by Dr. Warren B. Johnson, Jr. Ron Collis contributed helpful suggestions regarding data analysis and interpretation.

The interest and assistance of Messrs. Robert Rohrer of Lawrence Radiation Laboratory and Ron Nelson of the Nuclear Rocket Development Station are gratefully acknowledged.

I INTRODUCTION

This final report presents the results obtained from the lidar (laser radar) observations of the particulate matter contained in the exhaust plume of the nuclear-powered NRX-A6 rocket engine, operating at full power in a static test mount. Lidar observations were made from a ground-based site 5.5 km away. The observations were made on 15 December 1967 at the Nuclear Rocket Development Station, Jackass Flats, Nevada.

The primary objectives of this program were to: (1) obtain optical backscatter data of the particulate matter in the plume, and (2) analyze the resulting data to obtain as much information as possible regarding the envelope of material as it was transported downwind.

This exploratory program is one of a continuing series of experiments investigating the feasibility of lidar techniques for the monitoring of debris clouds produced by nuclear cratering detonations. Information concerning the location, dimensions, and rate of movement of the cloud resulting from a nuclear cratering detonation is of prime importance in assessing the radiological safety aspects of the detonation. One of the difficulties with visual or photographic tracking is that once the cloud becomes tenuous it is indistinguishable from the background. It is believed that the use of lidar techniques would significantly improve the ability to track the sub-visible cloud and determine its dimensions and location at late times following detonation.

References 1 and 2* describe previous ground-based and airborne lidar observations of the debris clouds produced by large-scale, chemical explosive cratering detonations.

Apart from its immediate significance in monitoring rocket-test operations, the lidar observations described here are of particular interest for debris-cloud monitoring, for it is estimated that the rocket engine effluent would resemble late-time concentrations of nuclear explosion debris.

* References are listed at the end of the report.

Lidar is a radar apparatus operating in the optical rather than the microwave portion of the electromagnetic spectrum. Because of its very short wavelength compared to that of microwave radar, the lidar is capable of detecting energy backscattered from the visually clear atmosphere (and from discontinuities therein) as well as from natural and man-made clouds. However, the lidar cannot detect the presence of nuclear radiation in any of its forms. The SRI Mark V 1967 lidar (Fig. 1) consists of a pulsed ruby laser source operating at a wavelength of 6943 Å, an energy detector, the necessary beam-defining optics, and data display and recording equipment.

FIG. 1 MARK V RUBY LIDAR

II SUMMARY AND CONCLUSIONS

A. Program Summary

The lidar equipment (which was already at the Nevada Test Site for the Cabriolet experiment) was taken to the Nuclear Rocket Development Station (NRDS) in preparation for a rocket test that was to take place on 17 February 1967. Owing to difficulties with the safety and operational plans, the lidar observation program was excluded from this particular rocket test and the equipment was returned to Menlo Park.

On 4 December 1967, the lidar equipment was returned to NRDS by LRL personnel and installed in an enclosed van by a four-man SRI team in preparation for a rocket test originally scheduled for 6 December. Observations were attempted during the abortive operation of the reactor at low power on 6 December, but without success. SRI personnel left the site on 8 December and returned (as a three-man team) on 13 December. The effective observational program was carried out on 15 December during a 60-minute full-power run of the NRX-A6 engine between 1100 and 1200 PST.

The lidar was scanned horizontally across the plume according to a predetermined sequence. The return signal amplitude versus time resulting from each lidar firing was displayed on an oscilloscope and photographically recorded on 35-mm film. Table I summarizes the data obtained. Each run consists of a scan across the plume, made up of a number of lidar shots.

The basic data for this report consist of 43 lidar "A-scope" recordings showing signal amplitude vs. slant range along with the corresponding azimuth and elevation pointing angles and the time of each laser firing. From the basic data, the height above ground and the plan range of any selected point on a particular lidar return can be determined along with the return signal amplitude for that point. By considering a group of recordings produced when the lidar was scanned across the plume, an estimate of the shape and extent of the plume can be obtained. A detailed discussion of the data-analysis technique is presented in Sec. III.

Table I
SUMMARY OF LIDAR OBSERVATIONS

Run	Start Time (PST)	End Time (PST)	Elevation Angle (degrees)	Number of shots Fired	Number of shots With Returns
1	1119:20	1122:55	2	6	6
2	1123:55	1126:20	4	4	0
3	1128:05	1133:05	3	7	1
4	1136:00	1143:30	3	9	0*
5	1144:45	1149:15	4	6	0
6	1150:00	1150:45	Vertical Scan	2	1
7	1151:15	1153:25	2	4	0
8	1154:35	1156:20	2.5	3	2
9	1156:55	1159:00	2.0	2	2
			TOTALS	43	12

* Returns from snow flurries obscured any valid data.

B. Conclusions

It is concluded that this experiment has successfully demonstrated the potential of lidar for detecting and tracking very tenuous, subvisible clouds of particulate matter in the lower atmosphere. The results show that within the limits of performance of the equipment, the lidar is able to reliably detect particulate matter concentrations whose reflectivity is within a factor of two of the reflectivity of the clear, unpolluted atmosphere. With the experimental equipment used, these concentrations could be detected to ranges of 5.5 km. The results of this experiment complement the findings of previous work (Refs. 1 and 2), which have demonstrated the feasibility of lidar for the tracking of sub-visible clouds of considerably higher particulate concentration.

Moreover, this experiment has shown the feasibility of lidar for the remote, real-time monitoring of particulate matter expelled from a nuclear-powered rocket engine.

Specifically, the lidar was able to monitor the particulate matter concentrations in the plume, with an average time resolution of 60 seconds. In one instance, the lidar was able to detect the plume at a maximum distance of 750 meters downwind of the reactor. The lidar was able to detect the plume at a maximum height of 151 meters above Test Cell "c". The data from one run was analyzed to obtain relative density contours of the reactor plume. These results were obtained in spite of the fact that the experiment was conducted under less than optimum meteorological conditions.

It is important to recognize that the lidar used in this experiment is a research instrument, designed to be readily adapted to a variety of uses, and not an instrument designed for the specific requirements of this program. An instrument optimized for a particular application would, in general, exhibit performance superior to the results described in this report.

C. Recommendations

The original purpose of this experiment was to demonstrate the feasibility of lidar to detect and track tenuous clouds of particulate

matter in the lower atmosphere. Accordingly, the experiment was designed to provide data applicable to nuclear cratering research. However, if the kind of data presented here is of sufficient value to the nuclear rocket program to justify further work along these lines, a number of meaningful experiments could be designed using existing or improved lidar equipment.

For example, as an immediate input along these lines, one could monitor, in real time, the time variability of particulate matter in the plume in the region directly above the reactor nozzle. The monitoring could be accomplished by two methods simultaneously: (1) the measurement of optical backscatter from the plume, and (2) the measurement of optical extinction through the plume.

In addition, it might be possible to make some estimate of particle-size distribution vs. time using multiple-wavelength lidar. This concept has by no means been established, but preliminary calculations are in progress at SRI.

Both the above possibilities have the added advantage of paralleling very closely the work being done at SRI in connection with the AEC nuclear cratering program.

III DETAILED DISCUSSION

A. Operational Plan

1. Observation Sites

To accomodate a wide range of wind conditions, three lidar sites were prepared and surveyed in the vicinity of the reactor location at Test Cell "c." The sites were located near the A & E Building, ETS #1, and the R-MAD Building. The three available sites allowed optimum location of the lidar based on the low-level wind predicted for the test. The site chosen was approximately 400 meters northeast of the A & E Building; the reactor was 5.5 km away on a bearing of 7.5° from the lidar (see Fig. 3).

2. Laser Safety

The closed van containing the lidar equipment was oriented at the observation site so that its back opened toward the reactor. The lidar was positioned inside the van pointing out of the open back. The van was aligned so that its sides made it impossible for the lidar to be fired outside the safe operating sector designated in the laser safety plan. In addition, mechanical azimuth and elevation stops were applied to the lidar to further define the safe operating sector. These safety stops were applied under the supervision of the attendant safety officer to comply with both the LRL and U.S. Air Force safety plan (Ref. 3). Safety ropes delineated safe access limits for personnel in the vicinity of the van. Red warning lights located on the safety barriers were illuminated when the lidar was operative. A rotating amber beacon was mounted on the roof of the van. The lidar was fired only with the specific permission of the test director. All lidar operations were made in strict compliance with the previously agreed-upon safety plan, which provided for the sequencing of laser observations between passes of a B-57 sampling aircraft that was originally scheduled to make a number of flights through the rocket engine plume.

3. Observational Plan

The observational plan, which had been rehearsed on the afternoon

of 14 December, called for the systematic azimuth scanning of the engine exhaust plume. The first scan would begin at a two-degree elevation angle (the minimum angle permitted by the laser safety plan), with subsequent scans made at 0.5° increments of elevation angle.

The optimum weather conditions for the lidar observations would be a day with high visibility, overcast sky, and a light wind in a direction perpendicular to the optical line of sight from the lidar to the rocket. The requirement for high horizontal visibility is particularly important to avoid the possibility of ambiguous lidar returns from precipitation.

B. Results

1. Weather Conditions--15 Dec. 1967^{*}

The 1000 PST meteorological observations for 15 December indicated a low-pressure center approximately 100 miles off the coast near San Diego, California with a trough of low pressure extending northward along the Pacific Coast. A high-pressure cell was centered in eastern Idaho. Both high- and low-pressure centers were nearly stationary during and immediately following the full-power run.

Deteriorating weather conditions were evident during the early morning hours associated with the closed low-pressure system off the southern California coast. By the time of the test (1100-1200 PST), overcast skies prevailed over the test site, with mountain tops obscured by snow showers. Precipitation consisting of light rain showers began about 1230 PST and continued throughout the day.

Moderate north-northeasterly winds prevailed over Test Cell "c" during the full-power run. Local surface winds surrounding the immediate area were moderate northeasterly to north-northeasterly.

The 1120 PST temperature sounding taken at the NRDS weather

^{*}Weather data provided by Environmental Science Services Administration, Air Resources Laboratory, Las Vegas, Nevada.

station showed a near adiabatic or neutral lapse rate from the surface to 1860 meters MSL. Slightly more stable lapse rates were indicated for 1860 to 2790 meters, followed by an isothermal layer between 2790 and 3240 meters.

2. Lidar Observations

The reactor was operated at low power level for approximately 10 minutes, and at full power for approximately 60 minutes from 1058 to 1159 PST. A total of 43 lidar observations of the reactor plume were taken during the full-power run. Because of triggering problems associated with the data-recording equipment, the scanning of the lidar beam across the reactor plume did not begin until approximately 1119, and ended when the reactor was shut down at 1159. Because of marginal weather conditions, the plume-sampling aircraft was not flown, thus allowing uninterrupted operation of the lidar during the full-power run.

The observations were conducted according to the plans worked out the previous day; a total of nine systematic scans were made at various elevations across the plume. With the exception of Run 6, all the runs consisted of scans made at fixed elevation angles. In addition, nine observations were made of the clear-air return prior to the reactor run. These data were subsequently used for calibration of the lidar.

The terrain geometry as viewed from the lidar site near the A & E Building was such that when the lidar beam was positioned at a minimum elevation angle over the reactor 5.5 km away, a lidar return could also be obtained from a mountain range 11.5 km away. This situation afforded an opportunity to measure both the backscatter from, and the transmission through, the reactor plume. The maximum firing rate of the lidar was approximately two pulses per minute, and the average rate was approximately one pulse per minute.

With the exception of the triggering problem noted earlier, the lidar equipment operated without malfunction during the test. Erratic triggering of the video disc recording equipment occurred at approximately 1045 PST, and could not be corrected in the time remaining. The primary purpose of the disc recorder in these observations was to record and play back each lidar signal on an oscilloscope for visual monitoring of the

progress of the experiment. Because of the unreliable operation of the disc recorder, the back-up data-display system was used. This technique consisted of displaying each transitory lidar signal on an oscilloscope and photographing it on polaroid film. The photographs were examined during the run for the presence or absence of significant lidar returns associated with the plume.

While malfunction of the disc recorder was annoying, it did not affect the course of the experiment, because the prime data were collected by an independent data system consisting of a 35-mm recording camera mounted on a second oscilloscope.

The data on the polaroid photographs were analyzed and a preliminary report was submitted on 20 December 1967. The 35-mm film containing the high-resolution data was subsequently processed, and the preliminary analysis enlarged upon.

C. Analysis and Interpretation of the Data

1. Lidar Returns

Fig. 2 shows the azimuth and elevation coverage of the lidar observations superimposed on a sketch of Test Cell "c" and a portion of the mountain range directly behind. The specific azimuth and elevation angles at which lidar observations were made are indicated by the circles. The angles at which lidar returns were obtained are indicated by the solid dots. All the horizontal scans were begun directly over the reactor at various elevation angles and proceeded from right to left in the direction of the wind. Run 6 consisted of two lidar observations above the reactor, one at 2° and one at 2.5° elevation angle. Run 9 consisted of two observations at minimum elevation angle directly above the tip of the visible flame.

Figs. 3 through 11 show the graphical plots of the lidar observations in plan view. The sector consisting of two light radial lines originating at the lidar site indicate the region scanned by the lidar. Lidar returns are indicated by the heavier lines within this sector. The lidar returns in the vicinity of the reactor for Runs 1, 3, 6, 8, and 9

FIG.2 AZIMUTH AND ELEVATION COVERAGE OF THE LIDAR OBSERVATIONS

FIG. 3 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME -- RUN 1

FIG. 4 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME -- RUN 2

FIG.5 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME -- RUN 3

FIG.6 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME-- RUN 4

FIG. 7 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME -- RUN 5

FIG. 8 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME-- RUN 6

FIG. 9 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME -- RUN 7

FIG.10 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME -- RUN 8

FIG.11 PLAN VIEW OF LIDAR OBSERVATIONS OF THE PLUME -- RUN 9

are clearly related to the reactor plume. The returns show a consistency from shot to shot (as in Run 1), or the individual returns occur at a position in space that correlates with the reactor location and wind direction (Runs 3, 6, 8, and 9).

The returns obtained in Run 4 are believed to be from snow showers because a brief flurry of precipitation was reported by one of the lidar crew members immediately after the end of this run.

Runs 1, 2, and 3 contain returns of uncertain origin occurring within 3 km of the lidar. These returns are not obviously connected with the reactor plume since the position of the returns is not compatible with the wind direction. The best explanation at this time seems to be that these returns were caused by snow showers. No extraneous returns were detected on Runs 5 through 9.

Runs 2 and 3 contain returns that are classed as marginal on the basis of their extremely low signal amplitude. These marginal signals are marked with a question mark.

Comparison of the lidar observations with the clear-air observations made prior to the reactor run indicate that no measurable change occurred in atmospheric extinction during the course of the observations.

2. Information Regarding Plume Envelope

The following information regarding the lidar returns from the exhaust plume may be derived from the reduced data:

- (1) With the exception of Runs 1 and 3, all of the returns from the plume occurred within 100 meters horizontal distance of the nozzle. On Run 1, the plume could be detected 750 meters downwind of the nozzle, when the plume width was 380 meters. On Run 3 a return was detected 550 meters downwind.
- (2) In the vertical plane, returns were received from horizontal scans made at heights of 55, 103, and 151 meters above the terrain of Test Cell "c." No returns were received from two scans made at a height of 247 meters above terrain.

3. Plume Reflectivity

For a given particle-size distribution, the aerosol concentration

at a particular point within the cloud is proportional*, in a complicated way, to the backscatter coefficient (reflectivity) of the cloud at that point.

The definition of lidar backscattering cross section for a volume target is identical to that for microwave radar. The volume backscatter coefficient β'_{180} is defined as "the scattering cross section of an isotropic scatterer returning as much power to the lidar as a unit volume of the particles actually present." β'_{180} is expressed in dimensions of area/unit volume.

The volume backscattering coefficient of the target cloud is a component of the lidar range equation, which describes the behavior of the return signal in terms of equipment constants and the characteristics of the atmosphere and the target. The lidar equation is fundamental to the analysis techniques employed to extract useful information from the signal, and may be written as follows:

$$P_r = P_t \frac{A_r C \tau}{R^2 8\pi} \beta'_{180}(R') T_o T_a \exp -2 \int_0^{R'} \sigma dR' \quad (1)$$

where

P_r = Received power

P_t = Transmitted power

A_r = Effective area of receiver aperture

C = Velocity of light

τ = Transmitter pulse length

$\beta'_{180}(R')$ = Volume backscattering coefficient at range R'

T_o = Transmission efficiency of all optical components

R = One-way distance to target

R' = Penetration distance into target

T_a = Atmospheric transmission factor accounting for total attenuation to and from the target

σ = Extinction coefficient within target region.

* The exact relationship is defined by Mie scattering theory, which is presently under study at SRI.

The backscatter-coefficient data can be obtained from the solution of Eq. (1) for $\beta'_{180}(R')$:

$$\beta'_{180}(R') \exp -2 \int_0^{R'} \sigma dR' = K_1 \frac{P_r R'^2}{T_a} \quad (2)$$

where

K_1 is a constant, dependent on the lidar parameters:

$$K_1 = \frac{8\pi}{P_t A_R C T_o \tau} \quad (3)$$

Equation (2) can be evaluated directly in terms of $\beta'_{180}(R')$ for the special cases where the penetration distance R' into the cloud is small, or the value of extinction coefficient σ is small. This latter condition applies particularly when the target is too tenuous to be visible.

Since the test sites were removed from any major sources of atmospheric pollution, Elterman's model of a clear atmosphere (Ref. 8) may be used to estimate the value of atmospheric attenuation T_a , and its rate of increase with increasing range R . For a wavelength of 6943 Å and an altitude of 1000 meters above sea level, this model gives an extinction coefficient of 0.063 km^{-1} , which corresponds to a two-way attenuation T_a of 0.56 dB per kilometer.

The maximum variation in range during these observations was approximately 0.6 km, resulting in a variation of T_a of 0.336 dB or a factor of 1.07. T_a was therefore assumed to be constant for this analysis. Fig. 12 summarizes the plume backscatter data as a function of time. Plume backscatter $\beta'_{180}(R')$ is expressed as a ratio:

$$\frac{\text{Backscatter from the plume at range } R'}{\text{Backscatter from clear atmosphere at range } R'}$$

The RMS errors attributed to equipment calibration and data reading are indicated in Fig. 12 by the bar labeled "RMS error." The error associated with the determination of the volume backscatter coefficient from plume backscatter is presently estimated to be $\pm 60\%$. The great majority of this error is attributed to an imprecise knowledge of the backscatter coefficient of the clear atmosphere. From the limited data sample available,

RUN	1	2	3	4	5	6	7	8	9
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FIG. 12 PLUME BACKSCATTER vs. TIME

it appears that the particulate concentration of the plume consisted of four pulsations, the largest occurring near the beginning of the lidar observations at 1120 PST. The amplitude of the pulsations decreased smoothly with time.

4. Plume Attenuation

The data from Run 9 included lidar returns from both the reactor plume and the mountain range 11.5 km away from the lidar. Run 7 yielded no detectable signal from the plume but it did contain a lidar return from the mountain. Using these data, the one-way attenuation through the plume was calculated at 1.5 dB or a transmission of 0.71 through the plume.

The measured value of transmission is abnormally high when compared to a corresponding value of transmission obtained from plume backscatter data. The primary reason for the lack of agreement is the error associated with the determination of the volume backscatter coefficient discussed in the previous section.

5. Relative Density Contours

The data of Run 1 were reduced to obtain relative density contours of the plume (Fig. 13). The contours represent values of return signal in dB (a logarithmic scale)* referenced to the signal obtained from the clear atmosphere at the same range.

As discussed in Sec. III-C-3 above, the values of signal returns do not correspond directly to plume reflectivity owing to the effects of attenuation within the plume. Also, the exact relationship between optical reflectivity and the particulate matter concentration of the plume is not precisely known. As a first approximation, however, the contours of relative signal intensity provide a very good basis for inferring the spatial and time variations of particulate matter within the plume because the attenuation through the plume is low. Due to the limited amount of

* dB (decibel) is here used as an expression of power ratio:

$$n \text{ dB} = 10 \log_{10} \frac{P}{P_{\text{ref}}}, \text{ where } P = \text{backscatter from the plume at a given range, } P_{\text{ref}} = \text{backscatter from the clear atmosphere.}$$

FIG.13 RELATIVE DENSITY CONTOURS OF THE REACTOR PLUME -- RUN I

data, it was not possible to obtain relative density contours of Runs 3, 6, 8, and 9.

6. Lidar Performance

With few exceptions, the lidar returns from the plume were of relatively low signal amplitude, indicating that the lidar was operating very near its maximum range for this specific kind of volume target. In practice, larger values of signal amplitude would be preferred, in order to increase the reliability of signal detection. This could be accomplished by the simple expedient of locating the lidar closer to the reactor, at a range of 2 to 3 km instead of the 5.5 km as in this experiment. Also, the lidar parameters described in Eq. (1) that are amenable to modification (such as: P_t , T_o , and to some extent A_r) could be optimized to yield the maximum possible return signal. Alternatively, the peak power output of the transmitter could be raised to increase the received signal with the lidar located at 5.5 km away from the reactor.

7. Estimates of Particulate Matter in the Plume

Information regarding particulate matter expelled from the reactor during the high-power run was obtained by NRDS personnel from a network of ground-based particle samplers located downwind of the reactor.

The following data was provided by Mr. Van Vleck of Pan-American Airways, a NRDS contractor:

- (1) Median diameter of measured particles: 80 μ
- (2) Geometric deviation: 2.2
- (3) The particle-size data within $\pm$ one standard deviation about the median value were closely approximated by a log-normal distribution.
- (4) An estimated total of 1.8×10^8 particles were released during the entire 70-minute run of the reactor.
- (5) In addition, an unknown amount of fine particles (from 0.04 μ to 4 μ in diameter) were released during the reactor run.

8. Lidar Returns from Other Physical Properties of the Plume

In addition to lidar returns from the particulate matter within the plume, there are three other physical mechanisms present in the exhaust stream that could possibly reflect optical energy sufficiently to produce a lidar return.

These mechanisms are:

- (1) The turbulent boundary layer separating the relatively stationary cold atmosphere and the high-velocity exhaust jet
- (2) The significant density and index of refraction change that the lidar beam encounters in passing from the atmosphere, through the hot, high-velocity hydrogen jet, and back to the atmosphere again
- (3) Shock waves produced by supersonic flow from the nozzle.

Pertinent theoretical or experimental data regarding the conditions within the plume are not readily available; however, some very general conclusions may be made regarding the three reflection mechanisms listed above.

In order for optical reflection to occur at an index-of-refraction discontinuity, the thickness of the discontinuity must be on the same order as the wavelength of the light in question (Ref. 5). In the case of the turbulent boundary layer, it seems unlikely that the boundaries of the turbulent "cells" would have an abrupt discontinuity of a thickness in the order of 0.7μ . The turbulent cells could be clearly seen visually in the region above the reactor because of the refractive effects on the light passing through the turbulent region. A very slight index of refraction change (in the order 10^{-6}) is required to produce these refractive effects. Also, the thickness of the boundary of the turbulent cells is not as critical for refraction as it is for reflection. The lidar was scanned through the region where turbulence cells could be seen (Runs 2 and 5). Lidar returns were not detected. The ratio of turbulent backscatter to molecular backscatter was calculated using the method developed by Munick⁶ based upon the work of Tatarski.⁷ The calculations were based upon a temperature of 4400°R and a velocity of 6100 m/sec at the nozzle.

A triangular temperature and velocity profile was assumed across the plume. The calculation showed the expected turbulent backscatter to be at least 20 times less than the molecular backscatter from the clear atmosphere. The extreme temperature gradient (and hence the large index of refraction change) experienced at the hydrogen jet boundary could cause lidar reflections if the thickness of the boundary was sufficiently small. Although the temperature gradient is extreme, it is believed that the thickness of this gradient is large compared with the wavelength of light. Lidar returns are not expected from a relatively gradual change in index of refraction vs. penetration into the plume.

The velocity of sound in hydrogen at a temperature of 4400°R is approximately 3360 m/sec. Accordingly, the gas velocity of 6100 m/sec at the mouth of the nozzle is only slightly supersonic, which suggests that a weak, conical shock structure may have existed close to the mouth of the nozzle during the full-power run. It is not believed that shock waves would extend to a distance of approximately 50 meters downstream from the nozzle, the maximum distance at which lidar observations were taken.

In addition, the shock-wave thickness is usually estimated to be 10 times the molecular mean free path of the fluid in question. At the temperature and pressures existing at the mouth of the nozzle, the estimated mean free path is 10^{-4} cm, yielding a shock thickness of $10\ \mu$. Lidar returns would not be expected from a shock wave occurring close to the rocket nozzle. No evidence of a shock wave was seen from the lidar site during the full-power run.

Appendix

LIDAR EQUIPMENT AND INSTRUMENTATION

APPENDIX

LIDAR EQUIPMENT AND INSTRUMENTATION

1. Lidar

The Mark V 1967 lidar transmitter consists of a Q-switched, ruby laser radiating at a wavelength of $6943 \text{ \AA}$. The laser produces pulses of coherent radiation of 15-nanoseconds duration, with a peak power of 18 megawatts. The laser output beam is collimated by a 6-inch Newtonian reflecting telescope (see Fig. A-1) and is transmitted in a beam normally having a divergence of 0.34 milliradians. For this experiment, the beam divergence was intentionally increased to 0.9 milliradians to comply with the laser safety plan. The corresponding two-dimensional spatial resolution of this beam is 5 meters at a range of 5.5 km. The pulse-repetition rate (PRR) of the Mark V lidar is primarily limited by the ambient air temperature, which determines the cooling rate of the laser head. For the relatively cool temperature encountered during the observations discussed here, the maximum PRR attained was approximately two pulses per minute.

The lidar receiver consists of a 6-inch-diameter Newtonian reflecting telescope, identical to the transmitter optics. An adjustable field stop at the focal plane limits the receiver acceptance angle to a maximum of 6 milliradians. A multi-layered interference filter with a wavelength interval (bandwidth) of $15 \text{ \AA}$ is inserted in the receiver optical path to reduce noise due to solar radiation scattered into the receiver's field of view. The detector consists of an RCA 7265 photomultiplier that has an S-20 Spectral Response.

A detailed discussion concerning lidar detection of atmospheric targets and lidar equipment design features is beyond the scope of the present report. These topics are treated extensively in Refs. 8, 9, and 10.

Table II summarizes the pertinent characteristics of the Mark V lidar.

FIG. A-1 MARK V LIDAR OPTICAL DIAGRAM

Table II

MARK V RUBY LIDAR CHARACTERISTICS

Transmitter	
Laser	Ruby
Wavelength	6943 Å
Beamwidth	0.9 milliradian
Optics	6-inch f/4 Newtonian reflector
Peak Power Output	18 megawatts
Pulse Length	15 nanoseconds
Q-Switch	Rotating prism and saturable dye
Receiver	
Optics	6-inch Newtonian reflector
Field of View	1.5 milliradian (normal setting)
Pre-Detection Filter	15 Å
Wavelength Interval	
Detector	RCA 7265 Photomultiplier (S-20 cathode)
Post-Detection Filter	6 MHz
Bandwidth	

2. Data Display and Recording Equipment

See Fig. A-2 for a block diagram of the Mark V lidar electronics. The output of the photomultiplier in the lidar receiver is fed to an amplifier having a logarithmic transfer function, and then to a video disc recorder. The output of the video recorder is applied to a Tektronix 453 oscilloscope, the display of which is visually monitored during the scanning.

FIG. A-2 BLOCK DIAGRAM OF MARK V ELECTRONICS

The video disc serves two purposes:

- (1) To play back the recorded signal repetitively immediately after the lidar firing, for visual monitoring during cloud tracking.
- (2) To record the signal for analysis at a later time.

An independent data-recording system, consisting of a 35-mm recording camera mounted on a second oscilloscope, automatically photographs each lidar trace.

The lidar and data-recording equipment were temporarily installed in a large van. A telephone line connecting the lidar team members facilitated communication during the observations. An audio tape recorder connected to the telephone party line was used to record various equipment settings and lidar pointing angles, as well as a running commentary on the details of the observations.

35-mm Kodachrome photographs were taken at various times during the lidar observations with a camera attached to, and coaligned with, the lidar.

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