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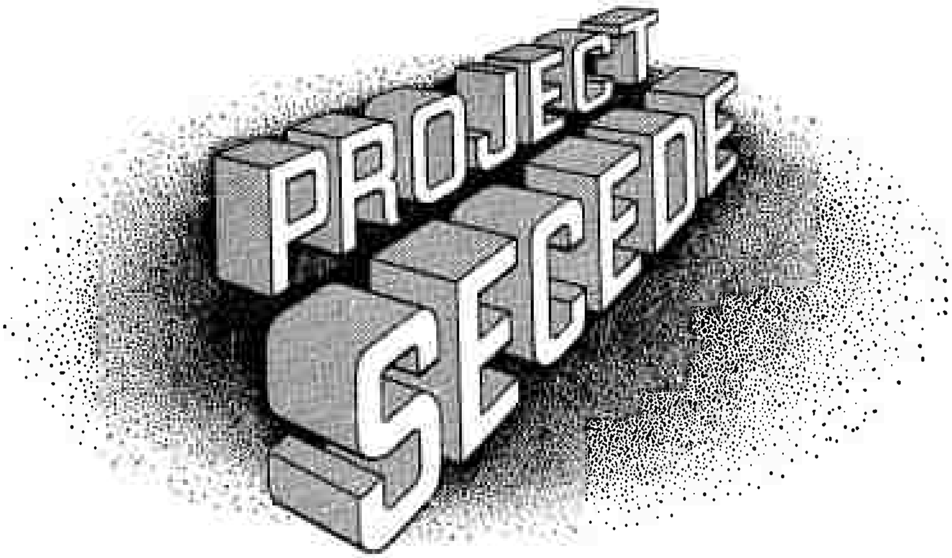

SRI DYE-LASER-RADAR OPERATION FOR SECEDE II

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13. ABSTRACT

A dye laser radar (lidar) developed by Stanford Research Institute with its own resources was operated at a site near Wewahitchka, Florida during the SECEDE II test series, in an attempt to measure barium-ion-density variations within the ion cloud. If present at all, barium ions occur in the natural atmosphere at concentrations much too low to provide resonance backscatter for system-performance evaluation. Therefore, the system was operated before shipment at a 5896-Å sodium resonance line and adequate system performance was obtained. The schedule did not allow complete system tests at the selected 4554-Å barium line prior to shipment. In spite of a tremendous effort, the system sensitivity for the barium line during the test series was in excess of 20 dB below expectation. The resulting signal-to-noise ratio was not sufficient to produce data of significant value in characterizing the cloud. Returns from the SPRUCE cloud have been identified, however, at a range in agreement with cloud position taken from photographs and at a level commensurate with system-sensitivity measurements. These data provide a base for system calculations for any future test. Funding was not obtained for detailed analysis of the data.

PROJECT SECEDE

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
ARPA ORDER No. 1057

January 1972

SRI DYE-LASER-RADAR OPERATION FOR SECEDE II

By

Roy A. Long

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FOREWORD

This Final Technical Report on Stanford Research Institute Project 1001 is reviewed and approved.

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SUMMARY

A dye-laser radar (lidar) developed by Stanford Research Institute with its own resources was operated at a site near Wewahitchka, Florida during the SECEDE II test series, in an attempt to measure barium-ion-density variations within the ion cloud. If present at all, barium ions occur in the natural atmosphere at concentrations much too low to provide resonance backscatter for system-performance evaluation. Therefore, the system was operated before shipment at a 5896-Å sodium resonance line and adequate system performance was obtained. The schedule did not allow complete system tests at the selected 4554-Å barium line prior to shipment. In spite of a tremendous effort, the system sensitivity for the barium line during the test series was in excess of 20 dB below expectation. The resulting signal-to-noise ratio was not sufficient to produce data of significant value in characterizing the cloud. Returns from the SPRUCE cloud have been identified, however, at a range in agreement with cloud position taken from photographs and at a level commensurate with system-sensitivity measurements. These data provide a base for system calculations for any future tests. Funding was not obtained for detailed analysis of the data.

I INTRODUCTION

The technique of probing the atmosphere with lidar has been in use since 1963, when suitable lasers first became available. The relatively recent development of tunable laser sources has permitted the goals of lidar probing to be widened immensely. This experiment was based on the great enhancement of backscattering coefficient that occurs when the illuminating laser is tuned exactly to a resonance frequency of an atmospheric component. The laser operated during the SECEDE II experiments had sufficiently small beamwidth, bandwidth, and pulse duration and sufficiently high design sensitivity and stability to allow the gathering of high-definition data that would contribute to the determination of the morphology and ion-density variations of the barium-ion clouds. However, a number of difficulties were encountered during the final development and fielding of the equipment, with the result that data meeting these objectives were not obtained.

II SYSTEM DESCRIPTION

The basic components of the lidar are depicted in Figure 1. The output of a tunable dye laser is directed toward the target at range d, where the scattering takes place. Energy scattered into the acceptance cone of the receive telescope is detected by a photomultiplier tube, the output of which is recorded. With pulsed laser operation, the range

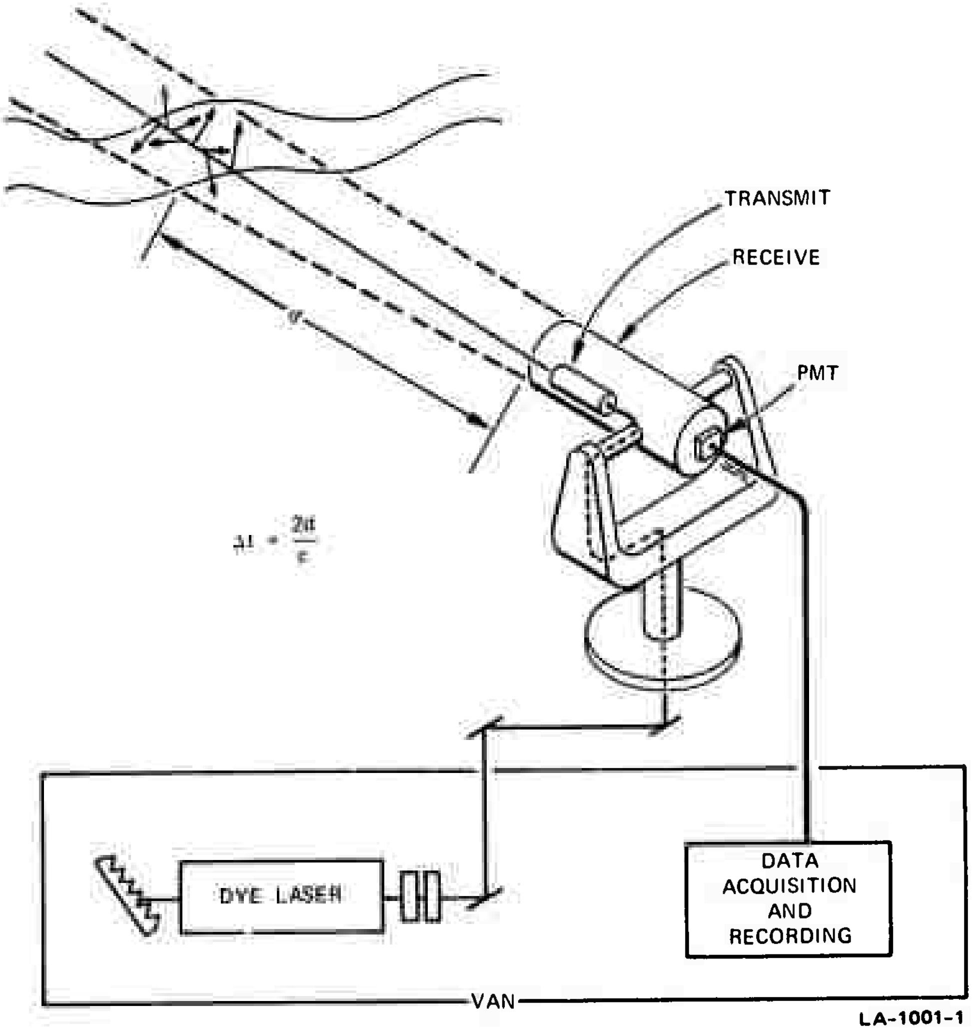

FIGURE 1 DYE-LIDAR OPERATION

to the target is determined by the time delay between the generation of the laser transmit pulse and the reception of the laser scattered energy, according to the range equation included in the figure.

The dye laser constructed at SRI employs flash-lamp pumping. This gives a greater power output per pulse but a smaller tuning range than laser pumping. The laser is shown schematically in Figure 2, as configured for operation during the SECEDE series. It is a two-stage device with identical oscillator and amplifier heads. Each head as indicated in Section AA contains a dye cell symmetrically surrounded by six flash lamps and six spark-gap/capacitor combinations in a folded coax configuration to reduce inductance. Six lamps have been used in order to obtain uniform illumination of the dye cell, resulting in high temporal and spectral-pulse stability, and to improve reliability. The cavity reflectors are circular cylindrical sections of polished aluminum. The dye solution is pumped through the dye cell at about four liters per minute. Cold N_2 gas is passed through tubes surrounding the flash lamps for cooling. The oscillator cavity utilizes a diffraction grating and reflector and an electrically controlled output etalon.

By tuning the cavity the wavelength can be varied over a small range with a given dye. Rhodamine 6G, the best known laser dye, is ideally suited for tuning to the sodium resonance lines at 5890 and 5896 Å. Umbelliferone, the dye used during this series, tunes to peak output very near the 4554-Å barium line, but has proved to be much more difficult to control.

After leaving the amplifier head, a small portion of the beam is diverted for the various monitoring functions inside the van. Wavelength positioning within about 0.05 Å can be obtained by visually comparing the frequency of the output pulse with that of a hollow-cathode source via a 12-meter spectrometer. Precise wavelength

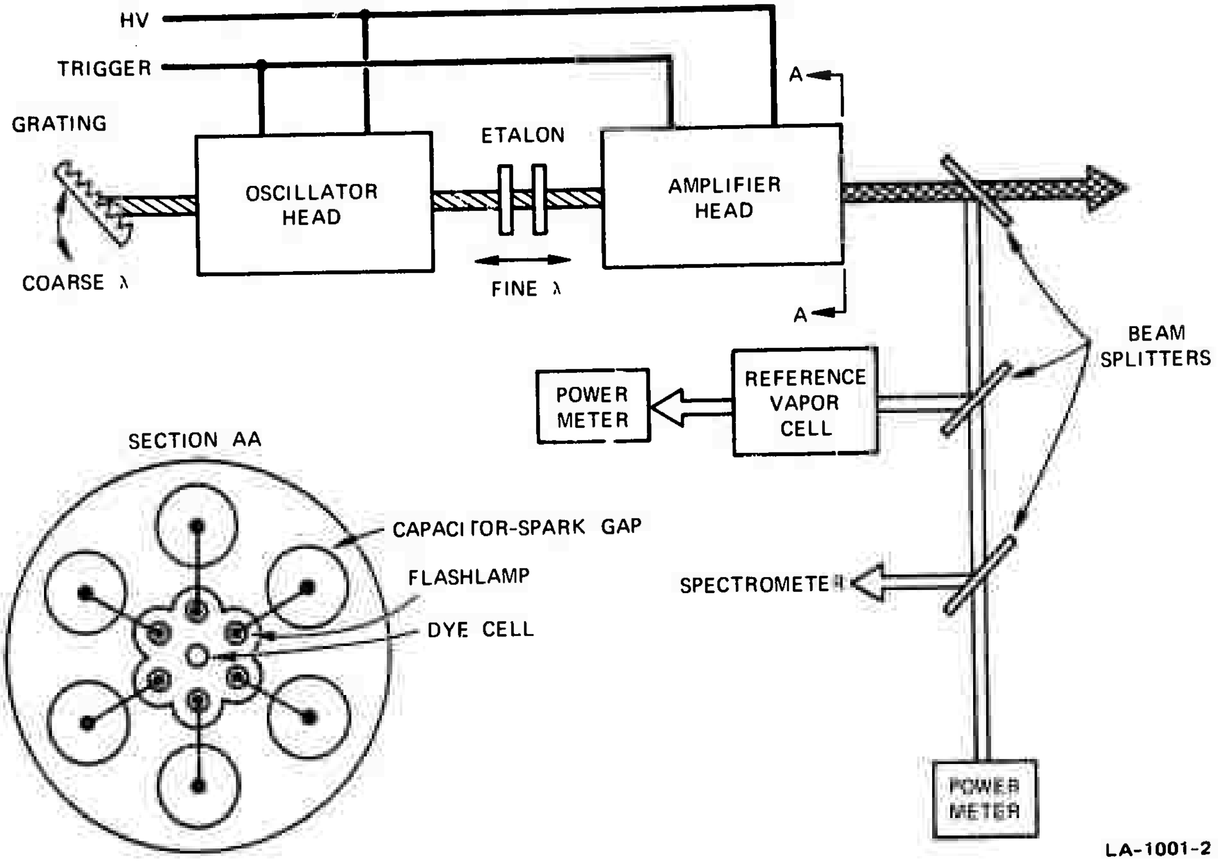

FIGURE 2 SRI SECEDE DYE LASER

positioning is achieved by monitoring the portion of the diverted beam that is directed through a cell containing barium vapor. The barium-vapor density is fixed (by controlling the temperature of the cell) at a value such that light on the resonant frequency is appreciably attenuated, while off-frequency light is transmitted. The output etalon spacing (and hence, the output wavelength) is then adjusted to minimize the energy-meter reading and thus tune to the dip that occurs when the wavelength is at the desired resonance frequency. The remaining portion of the diverted beam impinges on a second power meter to monitor the laser's total output energy.

The laser is mounted in a van on an optical bench supported by posts that extend through the floor and down to a stable pad at ground level. The beam is directed by a series of mirrors through the azimuth and elevation axes of a telescope mount located outside the van and is then collimated by a five-inch telescope mounted on the side of the 16-inch Celestron receiving telescope. The Schmidt optical system of the receiver is used to focus the intercepted light through a narrowband interference filter and onto the ITT FW-130 star-tracker photomultiplier tube. The optics are normally set to accept a receive beam having a full angle of 0.5 milliradians, but can be adjusted in the 0.2-to-1.0-mrad range. The active area of the photomultiplier cathode is electronically controlled to provide dynamic convergence of the transmit and receive beams. During the period in which clear-air returns are being received from an altitude of 15 to 20 km the receive beam is steered briefly off center in each of the four quadrature directions. By observing the received signal level during that interval, the operator can study the convergence on a pulse-to-pulse basis. Proper convergence of the two beams is characterized by equal reductions of the return signal during each of the four excursions of the receive beam.

Primary data recording was accomplished by a high-speed digital data-acquisition system utilizing a Hewlett Packard 2114 minicomputer. Figure 3 shows the system as utilized during the SECEDE II series. The receiver output was sampled with an 8-bit A/D converter at a 10-MHz rate. Four thousand samples corresponding to 60 km of range were temporarily stored in a recirculating MOS memory and then recorded on magnetic tape along with time, range, laser power, and other housekeeping data. The content of the recirculating memory was also D/A converted and displayed continuously in real time on an oscilloscope.

A magnetic video-disc recording system specifically developed for the laser radar data was also employed to provide "instant replay" as well as permanent storage of acquired data. Voice comments, time, and the video data were also recorded on an Ampex VR-7500 video tape machine.

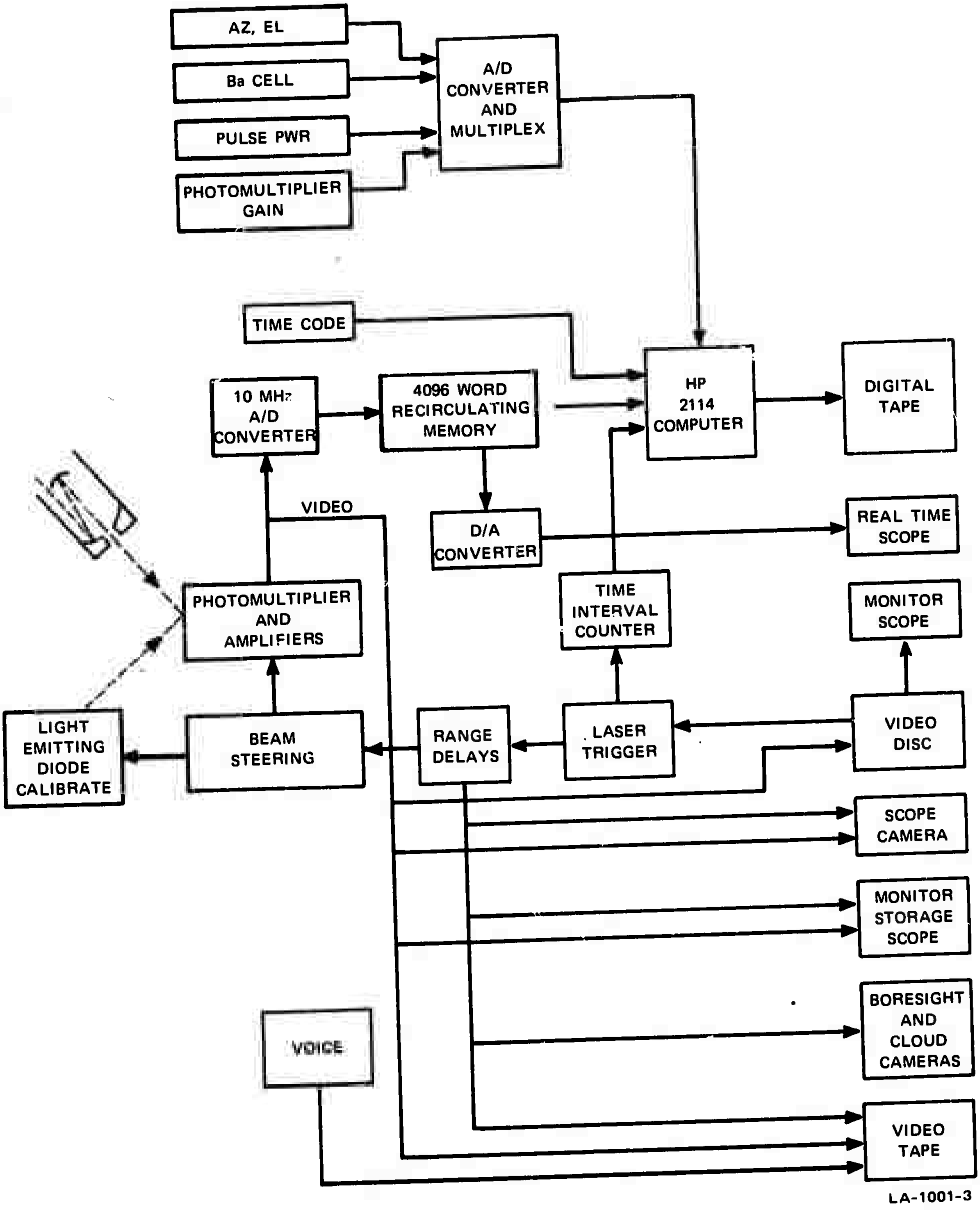

FIGURE 3 SRI SECEDE LIDAR DATA SYSTEM

It is essential to know precisely where the laser is pointed with respect to the cloud. The telescope pointing angles were recorded on a pulse-by-pulse basis on digital tape. However, more accurate and readily used pointing data were obtained from boresight and outrigger cameras mounted at right angles with respect to the transmit/receive optics. When the films from these cameras are aligned using the star field, the two images of the outgoing pulse converge to show where the system was pointed.

III PRE-SERIES PERFORMANCE TESTS

Barium in either neutral or ion form is not detectable in the natural atmosphere by traditional upper-atmospheric probing methods. These methods (mainly twilight spectrometry) are sensitive enough to set an upper limit on the concentration that is far too low to be useful for evluation of lidar system performance. Accordingly, the system was operated at the 5896-Å resonance line of atomic sodium in order to test performance by probing the sodium layer at 90 km. This layer is a well established feature of the natural atmosphere, with a column density normally between 1 and 4×10^{9} cm^{-2}, or an optical depth between 0.01 and 0.04. Since this represents the same sort of optical depth that should be used for probing a barium-ion cloud (operation in the optically thin wings of the line), it was felt that operation on natural sodium would be a fair simulation of operation on a barium-ion cloud. Several runs were made during various nights in the fall of 1970. A sample of the data obtained is shown in Figure 4. The layer is easily distinguished, and the returns are at a signal level that would result in useful data for operation on a barium cloud.

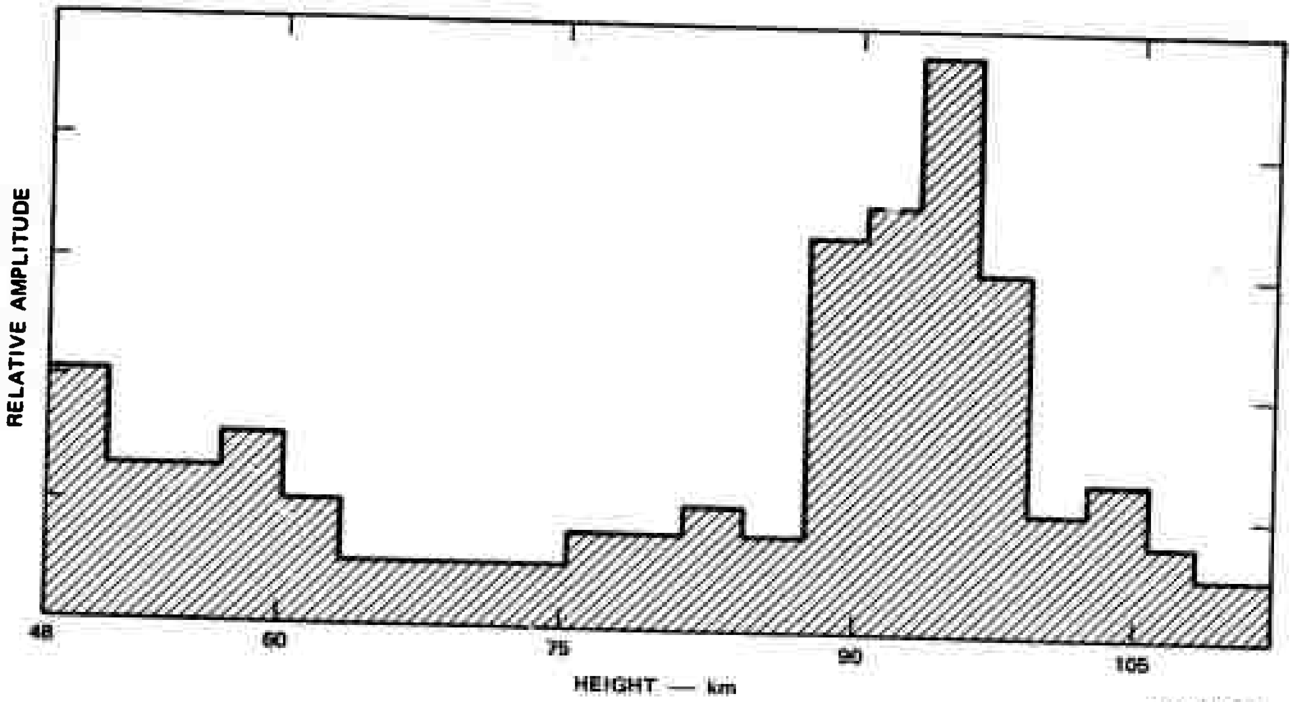

FIGURE 4 SODIUM LAYER OBSERVATION — 26 OCTOBER 1970

IV FIELD OPERATION

The system was operated from before release until well after sunset on the cloud during all twilight tests, except during Event OLIVE, when cloud cover after R +25 minutes terminated data-taking. Laser performance was improved for each test throughout the series, particularly with regard to frequency control and pulse-to-pulse repeatability.

Failure of energy-storage capacitors plagued the program throughout laser development and was a major factor in delaying system testing. Capacitor failures just before NUTMEG and during PLUM decreased performance during those tests. During the series the laser heads were modified, one after NUTMEG, then the other after PLUM, to accept capacitors from a different manufacturer. No failures occurred after the change.

The 12-Å thin-film filter in the optical system was found to be slightly mistuned, but this was nearly corrected by running without the stabilizing heater. Nevertheless, during Event OLIVE the lidar was run with a 40-Å filter that had less insertion loss, but with the passband peaked above the 4554-Å barium-ion line. The system background level from sunlight scattered from the cloud was high enough that the nearby 4607-Å line from neutral strontium must have been accepted by the filter. Consequently, the 9-Å filter was again used for Event SPRUCE.

Problems with the diesel generator absorbed a large number of man-hours during the first half of the series, but this was a major factor affecting operation only during PLUM. Frequency instability of the generator tended to degrade data recorded on the magnetic disc and decrease the effectiveness of the instant-replay capability.

Characteristics of the lidar as designed and as operated during the SECEDE II series are shown in Table 1. System sensitivity as indicated by the Rayleigh returns is in excess of 20 dB below expectations. With this sensitivity, the signal-to-noise ratio for returns from the barium clouds would be expected to be marginal. These calculations are included in the Appendix.

Table 1

SRI DYE-LIDAR SPECIFICATIONS

	Design, 4554 Å	At SRI Nov. 1970,		In Florida Jan. 1971, 4454 Å
		5896 Å	4554 Å	
Laser Transmitter				
Output energy, J*	0.2	0.1	0.05	0.01 to 0.02
Beamwidth, mrad	0.1	≈0.2		≈0.5
Spectral bandwidth, Å	0.025	< 0.02	0.05	< 0.02
Pulse period, s	1	3	1	1, 2
Pulse width, μs	0.3	0.3		0.3
Receiver				
Aperture, cm^2	1170	1170	1170	1170
Beamwidth, mrad	0.5	0.5	0.5	0.5
Filter bandwidth, Å	10	8	12	12 or 40
Receiver efficiency, %†	6	2 (est)	3 (est)	2

*Includes loss in transmit optics and mirrors.

†Includes telescope, filter, phototube, and counting efficiency (see text).

The chief reasons for the poorer system performance at the barium wavelength (4554 Å) are connected with the dye used. Umbelliferone is expected to have a maximum of 45% of the energy output of the Rhodamine dye used for sodium. Operation during SECEDE II and at SRI in the ensuing period has shown that much more stringent conditions than for Rhodamine are required to obtain even this energy level, however. These conditions include critical adjustments of dye purity, optical components, and flash-lamp synchronization and rise time.

A breakdown of the various factors involved in the 2% receiver efficiency achieved in Florida is as follows: telescope optical transmission, 50%; interference-filter transmission, 45%; photomultiplier-cathode quantum efficiency, 18%; and counting efficiency for photoelectrons, 50%. The figure given for filter transmission may be somewhat high, since the peak of the filter passband was somewhat above 4554 Å, and an attempted compensation by running the filter without a heater ($\sim 50^{\circ}$F ambient) may not have been completely successful. The photoelectron counting efficiency is an estimate based on the performance of the computer in extracting pulses from the digitized data and may also be somewhat high.

The calculation in the Appendix gives a total of 240 counts per km for one pulse, as the signal level expected with the design parameters (Column 1, Table 1) for Rayleigh scattering at 23.7 km altitude and 28.9 km range. Using the output energy of 0.01 J and other parameters demonstrated in Florida (Column 3, Table 1) in the same calculation yields an expected signal level of 4 counts per km. The observed level is 0.57 counts per km. Certainly the atmosphere from the site was seldom as clear at the 50% two-way transmission used in the Appendix. Attributing all of the discrepancy to decreased transmission yields a two-way transmission of 7.3%, or a one-way transmission of 27%. While this is a conceivable level in Florida, it seems too low for the conditions under which SPRUCE was observed. A more likely figure would be 15 to 25% two-way transmission, with a corresponding decrease in receiver efficiency due to the factors mentioned.

The video disc recordings were scanned carefully after each test and again after the return to SRI. Each minute of data can be displayed on a single raster scan to emphasize returns at constant or slowly changing range. No definite ion-cloud returns were located by this method. At SRI, range-versus-time records for all tests were run on a computer from the digital data. Although some possible cloud returns were identified with both methods, no positive identification could be reported at the SECEDE II data-review meeting at Albuquerque.[1*]

Subsequent analysis of the digital data has verified the lack of a strong return signal, but has enhanced the possible returns to a point where the probable return level can be determined. Figure 5 is a plot of recorded signal versus range for a summation of all 164 lidar shots during the first six minutes of Event SPRUCE. The points are the counts recorded in a one-kilometer range bin, with $\sqrt{N}$ error bars indicated at two places. The solid line is an "eyeball" fit to the points, and shows a significant signal increase between 220 and 230 km that we identify with ion-cloud returns. The dashed line at 133 counts/km indicates a constant-level background due to solar flux at 4554 Å resonantly scattered by the ion cloud. The receiver dark count of 50 to 80 counts per second is a negligible part of this background.

Our identification of returns from the ion cloud is supported by a study of the C-6 pictures at R +6 minutes. An overlay of the lidar line of sight shows the ion cloud centered at a range of 210 km.[†]

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[*] References are listed at the end of the report.

[†] N.J.F. Chang, private communication.

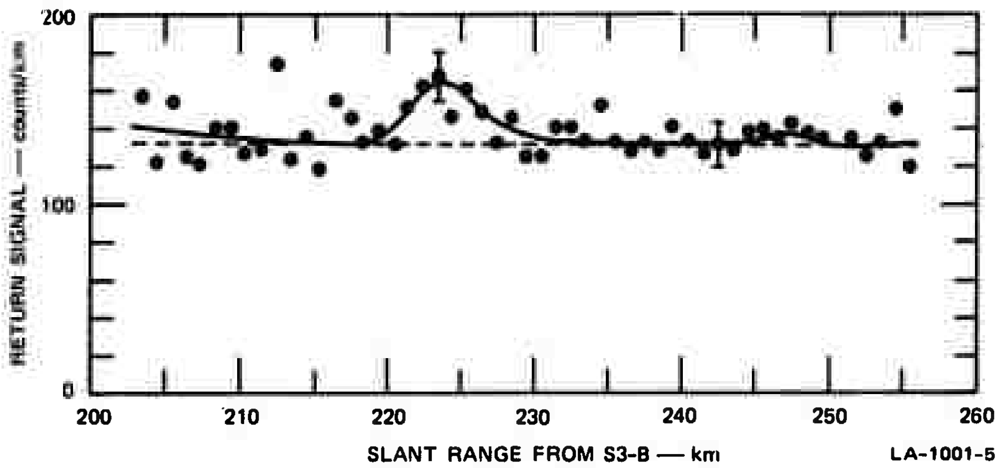

FIGURE 5 INTEGRATED SIGNAL FOR FIRST SIX MINUTES OF EVENT SPRUCE

Triangulation of the release point showed a range of 232 km at release. The observed range of 223 km in Figure 5 is quite reasonable for an integration of the first six minutes of the cloud. The data points in Figure 4 also show a possible return signal at ranges between 210 and 220 km, but not at as significant a level as the farther returns. These possible returns could, however, if included, reduce the discrepancy between expected and recorded signal levels.

The area between the solid and dashed curves may be taken as an estimate of the observed signal return from the cloud. This area corresponds to a total of 178 counts. Since this is a total over 164 laser pulses, the return level is very near 1.1 count per pulse. The calibration of lidar sensitivity using observed Rayleigh returns during this same period leads to a maximum expected return level of 2.5 counts per pulse for an optically dense cloud.

The facet of the scattering process that is not included in the Rayleigh calibration procedure is the wavelength spectrum of the transmitted power. All wavelengths are equally active in producing Rayleigh returns, but only those wavelengths within roughly ± 0.025 Å of the line center at 4553.97 Å are active in producing resonant scattering from the barium ions. It is well known that the ion cloud for as large a release as SPRUCE (48 kg) and at these early times is quite optically thick at all wavelengths within roughly a 0.05-Å band.[*] The maximum return level should therefore apply over this bandwidth. A possible conclusion is that not all of the energy or pulses transmitted during this period were within this 0.05-Å band.

The laser bandwidth was determined in the laboratory holographically to be less than 0.02 Å, but this calibration was not run during the SPRUCE event period. The barium-ion absorption cell did not achieve sufficient ion density to produce usable absorption, and hence was not useful as a fine-tuning aid for the laser, or of value in determining the fraction of laser power that was "on-line"--i.e., within the 0.05-Å bandwidth.

Best operation of the system was achieved on Event SPRUCE. Because of the marginal return level on that event (Figure 4), an exhaustive computer analysis was not made of the other events. Examination of video disc records and of range-time plots showed no signals on other events comparable to the SPRUCE data.

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[*] The value of 0.05 Å is the amount of the spectrum in which the cross section of the 4554-Å line is above 4×10^{-13} cm^{2}, a level that gives an optical depth of unity for an ion cloud of 5 km depth along the line of sight and with a density of 2×10^{7} ions cm^{-3}.

V CONCLUSIONS

During the SECEDE series the lidar sensitivity for resonant barium returns was considerably below expectations, as a result of a combination of low output energy, imperfect spectrum control, poor atmospheric transmission, and somewhat impaired receiver efficiency. The resulting signal-to-noise ratio was not sufficient to produce data of use in characterizing the cloud. Returns from the SPRUCE cloud have been identified, at a level commensurate with observed clear-air Rayleigh scattered signal and the range and cross section of the ion cloud. A calculation of the predicted signal level has shown that it is possible to explain the observed signal levels on the basis of measured and reasonably estimated system parameters. By extension, it will be possible to predict signal levels if these same parameters can be measured in advance of future deployment. The lidar technique is thought to hold great promise for the detailed evaluation of the behavior of barium-ion clouds. It now appears that this lidar system can be improved sufficiently to provide the required data, and that this represents the most efficient approach.

Appendix

SYSTEM SENSITIVITY AS DETERMINED FROM RAYLEIGH BACKSCATTER

Appendix

SYSTEM SENSITIVITY AS DETERMINED FROM RAYLEIGH BACKSCATTER

It has been found by persons working in the laser radar field[2,3] that the most accurate way to evaluate the performance of a long-range laser radar system is to calibrate the return signal level against the Rayleigh-scattered returns from a region of the neutral atmosphere. This region must be high enough that it is above the highly variable attenuating regions of the lower atmosphere, yet low enough that the return level is statistically accurate. It also should be at an altitude free of particulates. Thirty km is the altitude usually chosen.

For the SRI lidar in SECEDE II, a slant range of 30 km was the farthest that the Rayleigh signal could be useably distinguished, which corresponds to an altitude near 25 km at the viewing angles for the barium clouds. As determined at SRI and elsewhere,[4] particulate scattering at this altitude contributes approximately 25% of the return signal. Examination of the video disc records for Event SPRUCE shows an average total return of 0.76 counts/km of range for a single pulse at 28.9 km range (23.7 km altitude), or 0.57 counts/km for the atmosphere without particulates. The Rayleigh backscatter cross section for an atmospheric molecule at 4554 Å is 1.1×10^{-27} cm^2 ster^{-1}, and the neutral density at 23.7 km altitude is (USSA, 30°N, January) 1.1×10^{18} molecules cm^{-3}.

The lidar equation that applies when the receiver beamwidth entirely encompasses the transmit beamwidth and the transmit pulse is short compared to the receiver integration time is

$$C = \frac{A}{4\pi R^2}\, \epsilon\ P\ T\ (4\pi\sigma)\ N\ell \qquad \text{(A-1)}$$

where

C = Signal counts per range bin per pulse

A = Clear area of the receiver (1.17×10^3 cm^2)

R = Range to the observing point (28.9 km)

ϵ = Receiver efficiency including PMT quantum efficiency, transmission of the telescope optics, and interference-filter transmission (0.06)

P = Photons transmitted per pulse (0.2 J = 4.6×10^{17} photons at 4554 Å)

T = Two-way atmospheric transmission (0.5 at 4554 Å)

σ = Backscatter cross section (1.1×10^{-27} cm^2 ster^{-1} for Rayleigh backscatter of atmospheric gases at 4554 Å)

N = Species density (1.1×10^{18} molecules cm^{-3} at 23.7 km altitude)

ℓ = Range-bin length (1 km).

The values in parentheses following the parameter definition are appropriate to the design goals of the system expressed in Table 1, and give an expected signal level of 240 counts per km for a single pulse. The observed level of 0.57 counts per km is 26.2 dB below the expected level. An explanation of individual factors contributing to this 26.2 dB is presented in the main body of the report.

For a barium-ion cloud at 220 km range with an optical depth of 0.5 [$4\pi\sigma\ N\ell = 0.5$ in Eq. (A-1)], a signal-return level of 1320 counts per pulse is predicted. This represents returns distributed over the range of the entire cloud, and is an upper limit for power transmitted at any optically thick wavelength within the 4554-Å-line profile. Application of the 26.2-dB loss of sensitivity achieved in the field gives an expected signal level of 3.2 counts per pulse distributed over the range cells encompassed by the cloud.

The calculation thus far has assumed a two-level ionic system where one 4554-Å photon is emitted for each 4554-Å absorption event. In actuality only 74% of the 4554-Å absorptions lead to 4554-Å emission, with the balance of the ions branching to the metastable ion levels by emission of a 6142-Å or 5854-Å photon. The expected return level is thus reduced from 1320 to 980 counts per pulse for the design specifications. For the system sensitivity determined by the Rayleigh calibration procedure, the expected return would then be 2.5 counts per pulse.

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The level of performance obtained in the field was due to the extremely hard work and resourcefulness of the project leader, David Jackson, and the other field personnel--David Arnold, William Evans, Billy Ficklin, Charles Code, and Lloyd Alterton.

2. M.R. Bowman, A.J. Gibson, and M.C.W. Sandford, "Application of Dye Lasers to Probe the Upper Atmosphere by Resonance Scattering," The Radio & Electronic Engineer, Vol. 39, No. 1, p. 29 (1970).

3. M.C.W. Sandford, private communication.

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