Final Report

NAVAL APPLICATIONS OF METEOROLOGICAL LIDAR

Prepared for:

OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.

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ONR PROJECT NR 274-008

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ABSTRACT

This is the final report of a study of naval applications of meteorological lidar. The report describes the characteristics and capabilities of meteorological lidar. As an atmospheric probe and a form of rangefinder, meteorological lidar has many possible applications in naval operations. It can be used for detecting and measuring clouds; determining visibility; observing dust, smoke, haze, and even the invisible (to the eye) particulate matter in "clear air"; measuring wind; and, possibly, determining the properties of the gaseous atmosphere by spectroscopy. The report describes actual accomplishments in certain of these roles, based on the SRI experimental meteorological lidar program. Identification is made of the role of meteorological lidar in the observation of meteorological phenomena, both for the aerologist and for direct application in various naval operations. Further potential and possible operational applications of meteorological lidar are discussed.

It is concluded that meteorological lidar, in its present form, would have only limited applications in naval operations. The limiting factor is in the display and presentation of data; however, relatively little development would be needed to achieve an intermediate model suitable for operational use, using rapid process photography or magnetic recording techniques. However, practical and rugged high-PRF systems must be developed for optimum meteorological lidar performance in naval operations. High PRFs would greatly improve the performance of meteorological lidar and would enable straightforward solution(s) of the display problem.

In the report, identification is made of scientific and technological problems that warrant early attack.

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I INTRODUCTION

The term "lidar" is analogous to radar and derives from "light detection and ranging." The term was first used in 1953 by Middleton and Spilhaus[1*] in connection with pulsed-light cloud detection systems. The term "lidar" has been adopted for use in a similar context by Ligda[2] with the specific provision that it refers to systems using laser power sources. As such, the term has been applied to the instruments and techniques investigated and developed since 1963 at Stanford Research Institute in a pioneer program of atmospheric research using such systems. Thus, lidar refers to a system or technique for probing the atmosphere with laser-generated pulsed light, which presents the intensity of the backscattered energy as a continuous function of range. The term "meteorological lidar" is thus somewhat redundant; it is applied to lidar in this report however, to avoid any possible confusion with laser-powered, rangefinding systems developed to measure distances to discrete targets.

The study of naval applications of meteorological lidar was originally proposed in a paper "Proposed Research Task-Naval Applications of a Meteorological Lidar" by Dr. M. G. H. Ligda, dated 1 October 1963. This paper proposed to investigate the meteorological applications of a system outlined in the appendix of an SRI review of the applicability of laser techniques to naval operations.[3] The scope of this original proposal was extended to consider nonmeteorological uses of a meteorological lidar as a result of discussions initiated by ONR, as noted in a letter dated 8 July 1964, Reference ONR 492, LNM:djl, signed by Captain J. F. Gustaferroe.

The study was conducted from February 1964 through December 1964 and used experimental data from the SRI meteorological lidar development programs. Although no portion of the funds of this project was applied

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*References are listed at the end of this report.

to instrumental developments, a limited program of observations was conducted in accordance with the original proposal. As a result of the discussions noted above, such observational activities were restricted to an absolute minimum. Experimental observations were required in this study because our findings in some areas would otherwise have depended too heavily on speculation. Experience in the use of lidar is so limited, being confined essentially to the pioneer research phase, that the reality of certain applications could not realistically be assessed on the basis of concept or theory alone. The laser, like most new inventions, has been the subject of much extravagant and unrealistic speculation. The assessment of lidar in this application required more data than were available at the initiation of this study. (This factor was strongly implicit in the original proposal.) Due to data which became available from other studies and from the limited experimental program conducted under this project, an improved (though still limited) assessment can now be made of the manner and scope of meteorological lidar utilization in naval operations.

The present study relies almost exclusively on work conducted at Stanford Research Institute. Although others had speculated on, or made proposals for, the employment of lasers in this role, the SRI work was the first brought to the stage of practical demonstration in the area of meteorological applications, and the subsequent SRI program of exploratory studies in this area is unique as far as is known.[2,4-8] Others were known to be working on certain aspects of lidar applications, notably Fiocco's group at MIT, but except for that group's reports,[9,10] no publications were made at that time, and it has proved difficult to obtain comprehensive information on other work in progress. (Even in the case of work sponsored by BuWeps on cloud detection at Barkley and Dexter, Inc., no information was forthcoming until their final report[11] was received in June 1965.)

In these circumstances, a comprehensive and exhaustive study, based on adequate experience and well-established results, was not possible. It also seemed inappropriate, at this early stage, to specify rigidly the requirements of possible areas of naval operations in which lidar could conceivably make a contribution.

At this embryonic stage in the development of a new atmospheric probing technique, only a preliminary assessment can be made of the present and expected advantages and limitations of meteorological lidar for naval applications. This report presents such an assessment and describes the experimental data and other evidence on which the assessment is based (including that obtained specifically for this study).

II FINDINGS

A. Basic Characteristics and Capabilities of Meteorological Lidar

The development of lidar became possible with the advent of the giant-pulsed laser. Energy thus generated is highly monochromatic and is concentrated in very short, high-power pulses, directed by a refracting or reflecting lens system in a beam. Energy backscattered by the atmosphere within the beam is detected by a photomult ier after collection by a suitable receiver optical system and is displayed as a function of range. The laser energy is essentially coherent, enabling the attainment of very narrow transmitter beams (approaching diffraction limits). The monochromaticity of the energy permits the limiting of "noise" (in the form of solar energy) by the use of narrow-band filters. High performance and great spatial resolution may be achieved by lidar systems. The transmitted energy is primarily plane-polarized. The laser's coherence has yet to be exploited in lidar applications, although polarization effects are being investigated.

Appendix A describes the lidar's developed for meteorological purposes at SRI. These lidars illustrate the basic lidar concept although their performance is limited by present technology.

In simple form, lidar can probe the atmosphere along any desired path from a single point and provide information on the variation of backscattered energy with range. In straightforward situations where concentrations of strongly scattering particles occur in otherwise clear atmosphere, no ambiguity exists and clouds or smoke puffs can readily be detected and ranged.

Where variations in the concentration of scatterers are less well-marked, the significance of variations in backscattered signal becomes obscure. Attenuation caused by the scattering and absorption of energy on its passage to and from a given range reduces the signal due to backscattering at that range. In a continuously scattering atmosphere, such as fog or mist, it is difficult to evaluate changes in scattering density. Because absorption may be present (especially in smoke and industrially polluted atmospheres) and because of the inherent instability of the computational process, attenuation cannot be deduced solely from a consideration of signal intensity. A more practical source of information relating to the density of continuously scattering atmospheres is therefore the <u>rate of change</u> of backscattered signal. It is this parameter that offers prospects for the use of lidar in measuring visibility and detecting visibility variations in areas remote from the observing point.

Although lidar transmits the light with which it "sees" and is thus independent of solar or other illumination, atmospheric obscurity limits the range of lidar.

Backscattering by refractive inhomogeneities in the gaseous atmosphere is not observable by any existing or foreseeable application of lidar.[12]

Possibilities exist, however, for exploiting critical wavelength attenuation and wavelength/backscattering relationships. These might make it possible to detect and even measure spatial variations in gas mixtures (e.g., water vapor content) by the use of multiple-frequency lidars.[13-15,16] Such spectroscopic techniques might also be useful in deriving information on drop or particle size distributions, but the operational value of such capabilities is limited.

The employment of Doppler techniques has been suggested for measuring motion, as in wind finding or turbulence detection,[13,15,17] but too little is known of the feasibility of this approach to justify detailed consideration in this study.

B. Applicability of Lidar as an Atmospheric Probe

The aforementioned capabilities make the lidar suitable for the following applications:

(1) Ceilometry: Detection and measurement of cloud bases, multiple cloud layers, and tops of distant cumulus (by day or night, in rain, or through gaps in lower cloud cover)

(2) Visibility: Assessment of degree of obscurity, by day or night; assessment of visibility variations distant from the observing point; and detection of fog banks and haze patches or layers

(3) Dust detection: Detection of concentrations of dust or debris, such as produced by nuclear explosions[18]

(4) Observation of discontinuities in particulate matter concentration in "clear air:" Study of aerosol stratification in "clear" atmosphere, detection of significant changes with time in aerosol backscatter from apparently clear atmosphere as an aid to forecasting fog or low cloud formation, delineation of airflows in "clear air" for turbulence detection at all levels

(5) Wind finding: Tracking of specially generated smoke markers, casual smoke targets, or persistent features of upper clouds

(6) Spectroscopy: Observation of gaseous variations (e.g., humidity) by multifrequency techniques.

C. Applicability of Meteorological Lidar in Other Roles

In addition to its use as an atmospheric probe, meteorological lidar could be useful in other roles. As a "radar" operating in the visible or IR spectrum, lidar can act as an optical rangefinder, providing great accuracy and resolution on any target "seen." These targets include nebulous targets (e.g., smoke) which are difficult to range with conventional rangefinders and short-lived targets (e.g., shell splashes and bursts). Even at visible wavelengths, its high directionality and the shortness of its pulses make lidar a relatively secure device, particularly in daylight. Infrared wavelengths, such as are possible with neodymium-doped-glass lidar systems, would be completely invisible. Thus, meteorological lidar could be a valuable source of range information, particularly when electromagnetic silence is imposed.*

As an intense and directable light source, meteorological lidar could be used for signalling if necessary; e.g., in emergencies or where electromagnetic silence is imposed.

The use of meteorological lidar for the precise location of <u>co-operative</u> targets, such as in the case of rescue missions, should be quite straightforward. Inclusion of a kit containing retroreflectors in the equipment of a life raft would enable lidar detection of the raft under otherwise impossible conditions. Some security from hostile search might be realized by use of suitable filters to make the retroreflector responsive only to laser light of a selected wavelength.

D. Meteorological Lidar Applications in Naval Operations

1. General

With the aforementioned characteristics of lidar (analyzed in detail in Sec. III), the potential of meteorological lidar in naval operational applications is considerable and diverse. The meteorological lidar technique is generally most suitable for use at the surface, and could be installed in any convenient ship- or shore-based configuration. However, a possibility exists that special forms of meteorological lidar would be useful in an airborne role. Some investigations in this area are being conducted under ONR contract by the University of Michigan. Additional information is contained in a recent article by Ligda.[19]

The use of meteorological lidar as an atmospheric probe should be distinguished from lidar's use in other roles. Lidar's contribution

*Despite the brilliance of the giant-pulse ruby laser coruscation, personnel participating in this project have been unable to see the spot of light hit clouds at night, even when looking directly along the beam. Thus, a laser ceilometer apparently could be safely employed in nocturnal carrier operations when conventional ceilometers could not be used lest the light scattered from clouds destroy the pilots' night vision.

as an atmospheric probe can be direct or indirect. In a direct role, the data acquired by meteorological lidar are necessary for their own value and are applied in naval operations without further interpretation. Lidar's contribution can be considered indirect where the acquired data are used as input to intermediate functions which, in turn, support naval operations (the acquisition of meteorological data used to generate forecasts is typical).

The applications of meteorological lidar are summarized below, based on the type of contribution and the area of naval operations concerned.

2. Atmospheric Probe: Direct Applications

Lidar's capacity to make direct observations and measurements of cloud ceiling, fog banks, visibility, dust, and haze layers would benefit all operations concerned with visibility. This applies broadly to all forms of naval surface operations, aviation, amphibious operations, and the optical aiming of weapons. Knowledge of the visibility-limiting phenomena is required at all times for the safe navigation and handling of ships and aircraft, but the special conditions of naval warfare impose additional requirements for such knowledge. Apart from tactical considerations, combat operations require that ships and aircraft be operated with narrower margins of safety and in worse weather conditions than in peacetime.

Other direct applications of lidar as an atmospheric probe include the detection and tracking of clouds of radioactive debris, either from aircraft or ships, and possibly the detection of exhaust trails left by ships, submarines, or aircraft. Another direct application would be the detection of turbulent areas in clear air by reference to backscattered energy from the particulate matter indicators therein, as in aircraft carrier operations or high-altitude flight.

Lidar can rapidly and remotely evaluate data such as wind strength and direction; this is important in connection with assault landings and aircraft (including helicopter) operations, and even in the use of smoke screens or CBW.

It should also be feasible to design compact, lightweight, meteorological lidars that could be carried ashore in landing operations for use by beach or combat area weather teams.[11] Such lidars would provide valuable and accurate ceiling and visibility data from a forward area where helicopter, paratrooper, or low-level air support operations are planned under marginal weather conditions.

3. Atmospheric Probe: Indirect Applications

Meteorological lidar is a valuable tool for aerologists, and its capability to provide quantitative information on cloud and visibility would be useful in monitoring and predicting weather conditions, especially those related to navigation of ships and aircraft. Wind measurements, observations of atmospheric stratification, and (possibly) atmospheric constituency would also be important and would provide useful data for gunnery and missile operations.

In wartime, meteorological lidars, aboard submarines on patrol or picket duty, could provide accurate ceiling and visibility information in forward areas or operationally significant regions. It may be possible to make observations through periscopes while submerged, thus maintaining the security of the submarine (a possible objection is that laser radiation of great intensity cannot be brought to a focus without causing breakdown of the air and this may be unavoidable in periscope optics).

Alert operating personnel will probably find numerous "ad hoc" applications of meteorological lidar in tactical situations. As an example, a nocturnal operation dubbed "Artificial Moonlight" enjoyed some temporary success in the Korean War. This operation consisted of aiming powerful searchlights at low clouds over the "no-man's land" between the U.N. and North Korean/Chinese battle lines. At a given signal, shutters covering the lights were suddenly opened, flooding the zone with cloud-scattered light and exposing enemy patrols before they could conceal themselves. Meteorological lidar would have been helpful in the above operation by detecting the presence of low clouds beneath higher cloud decks or in precipitation without comprising the operation.

However, meteorological lidar would make its most important and widest applicable contributions to naval operations in providing the aerologists with a versatile and effective observational facility.

4. Use in Other Roles

For specific rangefinding requirements, and particularly for tracking ships, aircraft, and missiles, special forms of laser radar are indicated, and instruments of this type are already under development. The availability of a meteorological lidar for occasional use other than as an atmospheric probe would make many ranging operations possible. Thus, the accurate determination of distance for station-keeping, the accurate location of position by reference to a single visible mark, coastal navigation, hydrographic surveying, and many similar applications may be discerned in connection with the navigation and handling of surface craft. Similar considerations apply in the case of aircraft and submarines. In all cases, apart from the routine use of lidar ranging techniques, the special advantages of such techniques for rangefinding in weaponry must be considered. The ability of meteorological lidar to range on diffuse targets (e.g., smoke, dust clouds, or shell splashes) is important in spotting, both at sea and in coastal bombardments. Lidar techniques have considerable security in such roles. When electromagnetic silence is imposed, lidar can be a useful standby for certain radar functions; in ECM and ECCM environments, meteorological lidar might supplement radar.

Operating at visible frequencies (or at other frequencies with suitable detection equipment), a meteorological lidar transmitter could be used as a discrete signaling device. As an example, meteorological lidar (with its very narrow beam) could be directed at a particular point ashore, or at a specific craft, and used to flash signals, which could not be intercepted (even at visible frequencies) by receivers more than a few feet from the aiming point. (CW gas laser transmitters are indicated for routine use in this application.)

Meteorological lidar could also be employed for wave height and profile measurement from an airborne platform. A high-PRF lidar would be aimed downward toward the surface and a record obtained of the distance to within a few feet of small areas of the surface. FM/CW microwave radar has been considered for this application,[20] but lidar might be superior from such considerations as precision, resolution, and lightness and compactness of equipment.

5. Summary of Applications

Meteorological lidar could make many valuable contributions to naval operations. These contributions could be numerous and varied, due to the versatility of lidar; however, its main contribution will come initially from straightforward observations of meteorological phenomena. These observations will be used directly (by executive personnel) and indirectly (by support personnel). The most obvious and immediate application is in the observation of clouds, particularly in the measurement of cloud base. Another obvious application is in the qualitative observation of varying visibility conditions, especially the detection and tracking of fog banks at night. The quantitative observation of visibility and the techniques for observing such other phenomena as turbulence and atmospheric stratification are promising but need further development. Full realization of lidar's potential also depends upon certain technological advances, described in Sec. II-E.

E. Technological Conclusions

1. General

An objective of the present study was to provide guidelines for the form and specifications of suitable equipment. Laser technology is in its infancy, with important developments occurring frequently. Although in its present form the immediate application of lidar in routine naval operations is feasible it does not appear practicable. However, only relatively small steps need be taken to achieve a useful operational system. These developments, which are under active study at this time, can be expected in the near future. The form and specifications of an optimum first-generation operational meteorological lidar for naval applications, described below, are thus realistic in terms of attainment within, say, one or two years. Assuming straightforward development and trials, such a system could be in fleet use within five years.

2. Optimum Form of First-Generation Meteorological Lidar

A system that would provide general utility in a variety of roles would be based on a configuration primarily designed for atmospheric probing. Such an instrument would take a form similar to those developed at SRI and used in our experiments (refer Appendix A). The major difference would be that an optimum system would generate series of pulses at high repetition rates. This would make it possible to display data more conveniently and more meaningfully.

The salient features of such a system are described in the following paragraphs.

a. Laser Transmitters

Transmitters would be giant-pulse, solid-state lasers, capable of continuous transmission of high-peak-power pulses at high repetition rates (minimum ten per second). Pulse lengths would be of the order of 20-30 ns. Peak power would be as high as possible (minimum, 5 MW). Frequency would depend upon attainment of other parameters, but would be in the visible, or near infrared, band. (The ability to vary frequency or employ two or more frequencies simultaneously would be attractive but not essential in a first-generation instrument.) Solid-state or liquid Q-switching is indicated for simplicity and reliability, and any heat dissipation arrangements would need to be similarly simple and reliable.

b. Receiver

The receiver would be comprised of narrow-band filter/photomultiplier combinations, with high efficiency, followed by preamplitication stages, if necessary. The receiver must have sufficient dynamic range to handle signals of widely varying intensity automatically. An inverse range-squared correction would be desirable, and logarithmic amplification could be used.

c. Optical Systems

Optical systems would be used on both transmitter and receiver to provide narrow pencil beams. Ideally, a common optical system could serve both transmitter and receiver; however, if separate systems are employed, ease and permanence of alignment must be considered, and the ability to converge the beams at short ranges must be incorporated. Beam widths of 0.03 degree are suggested and could be attained compactly with 4-inch-aperture reflecting optical systems.

d. Mounting

The mounting would be fully directional so that the instrument could be freely pointed, with accurate, easily read indications of angular data. Suitable open and telescopic sights for manual training should be provided. It should be possible to lock the system so that the instrument points in a fixed direction, particularly at a 90-degree elevation for vertical soundings. The instrument should also be capable of continuously scanning in azimuth and elevation at controlled rates, with provision for sector scan. (For shipborne use, stabilization would be necessary for scanning or fixed pointing.) As with radar, scanning rates will be determined by beam width and pulse repetition rate values.

e. Calibration and Performance Checks

Provision must be made for monitoring overall system performance and readily checking alignment of the system and its sights. Provision should be made for controlling and monitoring the laser temperature since this controls the wavelength of emissions.[14]

f. Data Presentation and Display

Data should be presented in an immediately readable form. Amplitude-modulated A- and R-scope CRT displays are suggested, with strobes for readily evaluating range. (If range normalization is not applied at the receiver stage, it should be incorporated in the display.) Choice of scales should be possible both for range and amplitude.

A suitable display would present the logarithm of amplitude, corrected for the range-squared effect, vs. the range (i.e., the abscissa would represent range in lineal units, while the ordinate would represent log amplitude plus 2 log R).* This device facilitates the recognition of homogeneity in atmospheric echoes, and makes possible the immediate evaluation of the coefficient of extinction in such cases by measurement of the slope of the echo trace.

A valuable feature would be provision for making photographic or other forms of hard copy records of the observations, as required. In addition to the amplitude-modulated displays, provision should be made for displaying information acquired by two-dimensional scanning. This could most readily be accomplished by intensity-modulated CRT displays in the PPI, Z-t, or RHI form familiar in microwave radar practice. Again, photographic or other forms of recording would be a useful adjunct.

g. <u>General Principles</u>

Reliability and simplicity of operation and maintenance, as well as ruggedness and compactness are needed, and readily portable units should be considered. To ensure maximum utility of meteorological lidar systems in operational applications, a possible approach would be to develop a flexible modular system in which each main functioning unit would be a separate entity. Thus, optimum configurations for major classes of use could be achieved with minimum redundancy or complication. Scanning mode drive units and two-dimensional display units need not be used where only ranging functions are required.

For certain applications, an airborne version of the lidar system might be required.

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*This type of display is a proprietary concept of Stanford Research Institute and is the subject of a U.S. patent application.

3. Possible Intermediate Configuration

Although high PRFs are considered to be the answer to many of the problems of implementing an operational meteorological lidar system, intermediate use might possibly be made of a system in which single-shot observations are made at intervals of several seconds. This form would closely resemble the experimental system already developed at SRI. The limitation of this approach is the display system. Polaroid photography as now used is clearly inappropriate for an operational application, and the feasibility of an intermediate single-shot system depends upon the development of an adequate continuously viewable display. Various possibilities exist and these are described in Sec. II-F.

In its single-shot form, a meteorological lidar system would have many attributes of a high-PRF system used in a range-amplitude role. However, such a system would have a lower data rate, with a finite delay, and could not provide continuous two-dimensional data.

F. Technical Problems and Areas Requiring Further Development

1. General

There are two major areas in which current technology is inadequate for the successful implementation of operational meteorological lidar systems. Firstly, higher PRFs must be achieved with no substantial sacrifice of peak power levels. Secondly, techniques must be advanced so that lidar-acquired intelligence can be readily interpreted by the operator, with minimum complexity and at reasonable cost. Some of the laser-radar rangefinders noted in Sec. I have direct numerical readout, but this form of readout is unsuitable for most of the observational techniques discussed in this report. The achievement of high-PRF systems will largely solve the display problem because, to a considerable extent, the two problems are interrelated.

2. The Pulse Repetition Rate Problem

High pulse repetition rates are necessary to: (a) increase the data rate of a probing or scanning system, thus extending coverage in terms of space or time; (b) provide data on time variability of phenomena; and (c) enable the recovery of data at low signal-to-noise ratios by signal integration techniques.

The achievement of high PRFs is largely a problem in thermodynamic engineering, involving the efficient conversion of energy from one form to another form, and the dispersal of the heat generated as the result of nonideal performance in the conversion.

Even with ruby crystals, fairly high PRFs (five to ten per second) are already attainable with high peak powers. The thermal dissipation arrangements are troublesome, however, and attention is shifting to more efficient laser materials which coruscate at lower pumping thresholds. As an example, neodymium-doped glass emits at a first harmonic wavelength of 1.06 microns and some 20 percent of its energy can readily be converted to its second harmonic frequency (wavelength: 5328Å).

Intensive research is being conducted to develop other laser materials.

There is little doubt that practical techniques will soon be available for producing high-power, high-PRF lasers at reasonable cost.

3. Display Problems

Meteorological lidar, like radar, operates on a time scale determined by the speed of light. A lidar (or radar) range of 20 km is achieved in 133 μs. To make a presentation of signals from a single shot available for evaluation, the signals must therefore be recorded.

With pulse lengths of the order of 30 ns, the raw data bandwidth approximates 100 Mc/s. Recording data of even considerably less resolution than this can only be done with difficulty, and the only reasonably practical method yet developed of making such recordings, in such a way that they can be viewed very soon after they were made, is photography of an oscilloscope. Other techniques that can be considered (e.g., magnetic recording or electronic storage tube devices, involve increased cost and complexity. The data must be recorded and also presented in a suitable form with minimum delay.

Given a sufficiently high PRF, however, a straightforward CRT display could readily present lidar data in an apparently continuous form. This approach is identical to that employed in conventional radar displays and lends itself readily to the presentation of two-dimensional data by intensity-modulation techniques. Since the prospects of achieving high PRFs are excellent, even in this early stage of laser development, and since high PRFs offer other important advantages, it seems pointless to seek a solution to the display problem in other directions (the development of storage techniques is at a mature stage and major breakthroughs appear unlikely at this time). Therefore, it seems preferable to attack the problem of designing an operational meteorological lidar system in the area of increased PRFs, rather than the area of single-shots with storage displays.

While the best approach to an optimum operational meteorological lidar system is considered to be that of high-PRF lasers, the employment of single-shot systems in an interim operational system merits serious attention.

Three possible approaches to the problem are described in the following paragraphs.

a. Rapid Process Photography

Although somewhat cumbersome, a number of systems are available for making photographs of oscilloscope displays on continuous strips of standard film that can be viewed with a delay of about ten seconds. Series of these photographs (made automatically) would provide continuity in time; e.g., in showing variations in cloud bases as detected by a vertically pointing meteorological lidar firing automatically at intervals of, say, one minute.

The adaptation of such systems to the meteorological lidar display problem appears fairly straightforward; however, some development is necessary to provide suitable oscilloscope displays to handle the full range of resolution available in the original signal and to photograph the trace at the writing speeds required.

b. Magnetic Storage

Recent developments in recording video signals on magnetic discs offer promise for recording meteorological lidar signals. Designed to handle TV signals, commercially available systems of this type appear adaptable to provide at least a limited solution to the problem of recording the meteorological lidar signal and providing a continuous readout for display on a standard oscilloscope. Difficulties lie in extending the present bandwidth (approximately 4 Mc/s) to 16 Mc/s, or so, which would represent a reasonable capability for meteorological lidar applications.

This approach, apart from its basic simplicity, lends itself readily to various methods of further processing the signal, in either analog or digital form, and providing a hard-copy record by various moderate-cost techniques.

c. Storage Tubes

Although an oscilloscope employing a direct-view storage tube would be suitable in principle for displaying meteorological lidar signals, available equipment appears to lack adequate bandwidth. However, development under way in this area may produce faster-writing tubes. Experiments at SRI with a commercially available oscilloscope of this type demonstrated that it severely restricted lidar performance, and permitted only gross evaluation of meteorological signals. This approach would not of itself provide a continuous record.

Electronic storage tubes could also be used in this application, particularly in scan-conversion configurations that would enable the use of signal processing and hard-copy-readout techniques. However, such an approach is costly and complex.

G. Areas Requiring Further Research for Applications

Further research is necessary to realize the optimal value of meteorological lidar in operational applications in the following four areas:

1. Visibility Measurement

The possibility of using meteorological lidar to quantitatively determine visibility away from its immediate vicinity (particularly, slant visibility for aircraft landing operations) is most challenging, and warrants the earliest attention.

2. Cloud and Fog Formation Prediction

Further experimentation and study are necessary to learn whether and how meteorological lidar can be used to anticipate the formation of low stratus or fog, based on the change of atmospheric scattering properties.

3. Aerosol Motion and State

The ability of meteorological lidar to detect discontinuities in backscattered returns from the atmospheric aerosol offers hope that it may be possible to study the motion and structure of "clear air." This possibility is already receiving attention in connection with the problems of clear air turbulence (CAT) detection for aviation and missile operation.[8] The use of meteorological lidar to study and detect turbulence at low levels also merits attention in connection with aircraft operation from carriers. Further work is also needed on the interpretation of aerosol density profiles as observed by meteorological lidar in terms of the thermal profile or atmospheric stratification. Possible applications exist in CBR warfare.

4. Spectroscopic Observations

An attractive and important concept is that of remotely probing the particulate matter and gaseous constituency of the atmosphere by meteorological lidars operating at two or more frequencies. This concept warrants early investigation because of the possible uses in ballistics, weather prediction, and detection of chemical warfare agents.

III CAPABILITIES OF LIDAR AS AN ATMOSPHERIC PROBE

A. General

The various capabilities of meteorological lidar as an atmospheric probe are described below. These assessments are based on actual experience with the lidars developed at Stanford Research Institute. The applications are listed in the order representing the readiness with which meteorological lidar can make useful contributions to operational problems. These applications are attainable to a large degree with the standard of performance (in power and sensitivity) already achieved. Further advances necessary for full realization of an application are noted.

B. Cloud Detection and Measurement[6]

Meteorological lidar can readily detect ice and water clouds and measure their range. The distance at which clouds can be detected depends upon the system in use, the density of the clouds, the transmissivity of the atmosphere, and the amount of solar illumination. By day, a lidar comparable in performance to the equipment described in Appendix A can generally detect all clouds visible to the eye within, say, 45 degrees of the zenith, and even penetrate through thin cloud layers. In clear conditions, lidar can even detect ice particle or water droplet concentrations too sparse to be visible. In clear conditions clouds can be detected at much lower angles, and, at night, where solar energy noise is absent, all forms of detection are enhanced.

Cloud detection can take a variety of forms. Cloud base height can be evaluated for both layered and isolated clouds. Observations can be made obliquely, and upper cloud data can be obtained by observations made through gaps in lower cloud cover, even when the gap is not overhead. Vertical development of distant clouds may be assessed from slant range and elevation angle of the cloud tops. The density gradient of cloud droplets may be inferred by the nature of the lidar "echo," particularly in the case of cloud bases. A rapid transition from clear air to dense cloud is marked by a clean-cut echo profile, with rapid attenuation of the meteorological lidar signal. Diffuse cloud bases show a prolonged trace. In such cases, however, the cloud boundary can be easily recognized and height measurements can be precisely made in conditions where (to the eye) the cloud base is completely indeterminate.

This capability is especially noteworthy in cases where rain or drizzle is falling from nimbostratus. Even when the main base is at medium levels, it can readily be determined by lidar.

C. Visibility Determination

Where fog banks or low clouds reduce visibility in surface or aircraft operations, lidar can detect and range on such phenomena in much the same way as in cloud observation. Thus, fog banks at sea or drifting fog banks ashore can be detected and tracked, and warning provided on areas of limited visibility or local visibility deterioration. Where more general atmospheric opacity occurs (as in fog, haze, or mist), lidar can delineate spatial variations in the density of the atmospheric turbidity. This extends the usefulness of any opacity measurement at a given point; e.g., the touchdown point of an airfield.

The capability of studying the detailed spatial variation of transmissivity could have considerable operational value. Because the act of "seeing" involves light transmission over a path, the human eye has become accustomed to consider spatial variations in turbidity in terms of the line integral of the extinction coefficient. Meteorological lidar has demonstrated that, in reduced visibility, atmospheric turbidity normally has considerable local variation. Thus, any instrument that attempts to measure visibility by reference to a small atmospheric sample has serious limitations. (This applies to transmissometers, but especially to instruments that measure the scattering coefficient of the atmosphere in their immediate vicinity.)

While the use of lidar for revealing the patchiness or local variations in density of turbidity is important and readily feasible at this time, a possibly more important question is whether meteorological lidar can <u>measure</u> visibility conditions. Meteorological lidar can make indirect observations of two of the factors determining visibility conditions. Firstly, lidar observes <u>backscatter</u> from the atmosphere, and thus provides data on its <u>scattering</u> properties in general. This is important in assessing the scattering of natural light by day (and the contrast to be expected from a given object). Secondly, and more importantly, it provides a signal, the magnitude of which is affected by the <u>transmissivity</u> over the two-way path from the lidar.

However, two variables are involved in a single equation:

$$I_R = I_o \, K \, \beta'_{180} \, e^{2\int_o^R \sigma \cdot dR} \, R^{-2} \quad , \tag{1}$$

where

I_R is the intensity of the received signal from range, R

I_o is the transmitted power

K is a factor relating the parameters of the lidar optics to the backscattering volume, R

β'_{180} is the coefficient of volume backscattering of the atmosphere at that range

σ is the coefficient of extinction varying with range.

Since both β'_{180} and σ vary with range, even if they were uniquely related, the evaluation of $\int_o^R \sigma \cdot dR$ would present great difficulty in nonhomogeneous conditions because an inherently unstable technique is involved. (In homogeneous conditions, a local reading of transmissivity would be representative of an area.) While β'_{180} and σ are closely related in fogs and mists composed of clean water droplets, this is not true in haze, smoke, or industrially contaminated atmospheres. In these cases, light energy is also absorbed, in addition to being scattered by the particulate matter causing the obscurity. Thus, the coefficient of extinction may be expressed as, $\sigma = a + b$ ... 2, where *a* is a coefficient of total scattering and *b* is a coefficient of absorption. In industrial hazes and smoggy conditions, *b* frequently exceeds *a*, however, over the open ocean, *b* is normally negligible.

In practice, then, considerable difficulties exist in determining transmissivity by reference to meteorological lidar returns from a turbid atmosphere. The most significant parameter in such observations is considered to be the rate of change of signal intensity with range, dI_R/dR. Because of the inverse range-squared effect and the exponential nature of extinction [Eq. (1)], it is convenient to present the return signals from a turbid atmosphere in a form* with the logarithm of the range-corrected signal intensity as abscissa and the lineal range as ordinate. In this arrangement, signal intensity changes with ranges, $d\ell n I_R R^2/dR$, are represented as straight lines having a negative slope proportional to σ. However, where the trace is not straight, one of two possibilities exists: (a) the volume scattering function is changing or (b) the absorption factor is changing. In these circumstances, nothing can be inferred from the trace other than the presence of one of these two phenomena. In other words, the parameter, $d\ell n I_R R^2/dR$, is only meaningful and capable of quantitative interpretation when

$$\frac{d^2 \ell n I_R R^2}{dR^2} = 0 \quad .$$

An operational system of measuring visibility (or, more specifically, evaluating the extinction coefficient) based on backscatter signals from the atmosphere itself does not appear to be readily achievable. (Given reflectors of known efficiency and knowing the absolute lidar system performance, attenuation over the path could readily be determined by reference to the reduction in returns from the fixed targets. This method is a form of transmissometry and suffers most of that technique's lack of flexibility.

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*This type of display is a proprietary concept of Stanford Research Institute and is the subject of a U.S. patent application.

Hopefully, techniques may be developed for measuring mean extinction over extended paths by reference to changes in backscattering from along the path. One such method is to identify portions of the trace (nearby and distant) where the extinction rate is comparable. On the assumption that backscattering from such parts of the atmosphere would also be similar, the attenuation over the intervening path can be calculated from the relative amplitudes of the signals from the atmosphere at the ranges in question. Other approaches for determining slant visibility from the surface have been proposed but not investigated.

Where a log IR^2 vs. R display trace shows one or more homogeneous air masses, it would be relatively straightforward to calculate the mean coefficient of extinction over any path. Difficulty would be experienced in atmospheres where there is a gradient of aerosol density, however, and this is a common condition, particularly in the vertical.

In any discussion of visibility (as understood in naval operations), atmospheric transmissivity is only one factor. A practical "visibility"-measuring system must also consider the other variables involved: (1) contrast (which depends upon target size, shape, and color; the nature of the background or the intervening atmosphere; and illumination of the target, its background, and the intervening atmosphere); or (2) intensity of the source, in the case of a light; and (3) visual acuity of the observer. Although determination of the transmissivity of the atmosphere and its scattering properties is probably the prime task of any useful visibility-measuring instrument,[21] the difficulty of incorporating the other aforementioned factors makes an early solution to this problem doubtful. Another possible difficulty, rather thoroughly examined by Twomey and Howell,[22] is the possible differences in scattering and absorption of white as compared with highly monochromatic light. Since Mie scattering is involved (particles large in comparison to wavelength), large variations from the mean or white light scattering function may occur for laser light if the fog particles are, for any reason, predominantly of a uniform size.

D. Dust, Smoke, and Haze Detection and "Clear Air Echoes"[4,5]

Patches or layers of dust, smoke, or haze can be readily detected at distances up to several miles. The range of detection and penetration depends on the concentration of the particulate matter and its scattering properties and absorption along the path. Even heavily absorbent smokes, which are perceptible to the eye because of their contrast with a lighter or colored background, give strong meteorological lidar returns. Even where the eye would seem to be at an advantage because of the contrast effect, the ability of the meteorological lidar to discriminate in <u>range</u> more than compensates for this, and echoes from particulate matter are commonly observed even in very "clear" conditions. Thus, haze layers can readily be detected even on bright, clear days with blue skies.

Echoes from haze layers (or discontinuities in the backscatter signals from a continuously scattering atmosphere) can be related to the thermal profile.[4] Where an inversion can be inferred on other grounds, for example, lidar offers a means of confirming the reality of the inversion, assessing its intensity, and (especially important) measuring its precise height. Similarly, lidar-observed discontinuities in the clear air at heights of up to 7 km or so can be related with frontal surfaces located by reference to radiosonde and other meteorological data. Thus, in certain cases, meteorological lidar observations can be used to extrapolate (in space and time) data on the upper atmosphere obtained by infrequent and distant radiosonde ascents.

Lidar's ability to evaluate the scattering and attenuating characteristics of parts of the atmosphere, at least in homogeneous layers, offers a new parameter for observation. These additional data could be very valuable in identifying particular types of air mass or atmospheric conditions, especially in connection with problems of fog or cloud forecasting.

Meteorological lidar observations can also detect discontinuities in clear, moving air,[5] such as occur in turbulent air near the ground or where air coming from different directions intermingles (e.g., at a sea breeze front). The capability of meteorological lidar to distinguish such variations in backscattering from "clear air" has important implications. The possibility of mapping the effects of air motion, and in particular that associated with "clear air turbulence" is considered promising. This approach should be distinguished from any concept of obtaining lidar echoes from the turbulent gaseous atmosphere itself. Although the dielectric gradients resulting from the turbulence-induced local variations of temperature or pressure could theoretically result in backscattering of lidar energy, the magnitude of the effect is completely inadequate in practice.[12] Similarly, any variation in the intensity of the return signal due to backscattering from the atmospheric gases resulting from such local differences in density is far too small to be useful. The presence (or possible presence) of particulate matter would in any case mask any effects due to gaseous inhomogeneities.

Meteorological lidar's ability to delineate airflow patterns on this basis might have applications in the study or detection of turbulence patterns in the wake of aircraft landing or taking off, or in the landing approach path of an aircraft carrier. In either case, the particulate matter already present as a result of fuel combustion, etc., might provide adequate indication. For carrier trials or operations, additional "tracer" material could be generated. At higher levels, clear air turbulence (CAT) is becoming an increasingly serious hazard in certain types of aircraft operation[23] and is closely related to the disturbed airflow which can be significant in missile operations.

Although aerosol density averages substantially less at higher levels than near the surface, attenuation is also less at higher levels. Calculations based on the known broadscale variation of aerosol density with height encourage the belief that discontinuities of the order observed at low levels can be perceived at high levels, even at the existing stage of technological development. It is not inconceivable that the larger eddies causing clear air turbulence, or the larger scale features, such as jet streams and tropopause wind shear areas with which clear air turbulence is known to be associated, can be detected by meteorological lidar. The approach would be to use lidar to detect variations and discontinuities in the clear air by reference to the particulate matter or water droplet tracers or indicators. Thus, even if turbulent eddies could not be detected directly, significant mesoscale features of the atmosphere might be recognized in the same way that weather radar delineates convective storms. From these data, pilots can infer the motion to be expected in any given storm area, largely on an empirical basis, and avoid areas of turbulence. Although active study is proceeding on this approach, it requires considerable technological development and research, and an early application of lidar in this role is not anticipated.[8]

Possibly, CAT can be detected, or wind velocity can be measured, by reference to the Doppler shift in the energy returned by atmospheric targets. The most realistic concept involves the energy backscattered from the particulate matter present in the atmosphere. Various techniques of accomplishing this have been proposed,[13,15] and the concept is under active study by North American Aviation, Inc. [Contract AF 19 (628)-5135] under Air Force sponsorship. However, considerable advances are needed in basic technology before the Doppler principle can be thus applied. This technique offers little of operational significance in the foreseeable future in the area of CAT detection or the measurement of wind velocity in clear air. The technique might be applied to the detection of the motion of hydrometeors, particularly cloud droplets or ice particles, but this application is limited in scope.

E. Wind Measurement

The capability of meteorological lidar to obtain range and direction information concerning distant targets makes it possible to track puffs of smoke or recognizable cloud features. The displacement of such targets over successive time intervals yields wind data. Apart from a few casual, and rather unsuccessful attempts, the use of natural targets for this purpose was not investigated. A few experiments were conducted, however, using smoke puffs and trails generated by pyrotechnics. These proved extremely effective and this technique of windfinding is considered suitable for many naval operational applications. Smoke puffs could be generated at almost any required height, using rockets, pyrotechnics, or shells. Experiments were limited to the use of red and white smoke, but the smoke reflectivity to the meteorological lidar is less critical than the characteristics which make for easy visual tracking of the smoke puff. Such puffs should be compact and persistent, in addition to being readily visible in the conditions of light and background obtaining.

In addition to the straightforward determination of wind data for ballistic and aviation purposes, and such operations as the laying of smoke cover, this technique also suggests applications in research, particularly related to airflow around structures (refer to Sec. III-D).

The delineation in three dimensions of trails of rocket exhausts is another possibility which would enable the deformation of the trail by windshears to be studied much more readily than is possible with stereophotography and photogrammetry.

Meteorological lidar could also be used to track balloons for windfinding in conditions of good visibility. Although radar is commonly used for this purpose, it is sometimes unavailable; e.g., in conditions of electromagnetic silence or when radar is in use for more urgent operational roles. Also, the use of a radar-reflective balloon could be undesirable as it might disclose the launching vessel position to an enemy radar, even when the vessel is below the radar horizon. Thus, although visually tracked pilot balloons are frequently used for windfinding, the addition of accurate range information that meteorological lidar could provide would make this method of windfinding more satisfactory than is currently possible with pilot balloon theodolites, ashore or afloat, because an assumed rate of balloon ascent must presently be used to resolve plan displacement. Such assumptions are notoriously uncertain and, because of the geometry of the solution, errors in height cause increasingly serious errors in plan range as elevation decreases below 70 degrees or so. No experiments in balloon tracking were conducted, although an unsuccessful attempt was made on one occasion to obtain echoes from a meteorological balloon that drifted overhead at an estimated altitude of several thousand feet. The difficulty in tracking was undoubtedly due to the unsuitability of the aiming sight and possibly the display of the experimental lidar in question.

F. Spectroscopy

The dependence upon wavelength of scattering and absorption of optical- and near-optical-frequency energy by the atmosphere offers possibilities of remotely probing its particulate matter or gaseous condition. This concept is included in the present discussion because of its importance, but no detailed consideration or experimental investigations have been made.

The application of this technique to the determination of the atmosphere's water vapor content[16] demonstrates the principles involved. Water vapor has an absorption band at a wavelength of 6937.7Å. A ruby laser crystal emits energy at this frequency at a temperature of 175°K. Reducing the crystal temperature to, say 150°K causes the crystal to emit energy at about 6936.6Å, well away from the water vapor absorption band.[14] The difference in wavelength involved is very small in terms of backscattering, even where Mie scattering applies and resonances cause large changes in scattering coefficient for small changes in the particle size to wavelength ratio. Therefore, at these two wavelengths, any backscattering from particulate matter would be substantially identical; however, attenuation would be strongly dependent upon the atmosphere's water vapor content over the path. Because of lidar's capability for distinguishing range, the distribution and possibly the amount of water vapor along the path might be determined by considering the relative signal intensity at these two wavelengths and at various ranges.

Other applications of this concept have been suggested.[13,16] Remote observations of the atmosphere by techniques of this type would be valuable in numerous naval applications. The approach, while of considerable promise, has yet to be explored and no practical exploitation can be anticipated for a number of years.

G. Atmospheric Density

Research into the feasibility of measuring atmospheric densities by lidar has been initiated under Air Force sponsorship at the University of the West Indies.[24] Initial results were claimed as promising and follow the experience of Friedland, *et al.*,[25] who used a pulsed searchlight employing a krypton flash lamp, and Elterman,[26] who used a continuous-beam searchlight technique.

However, this approach has limitations due to the uncertainty introduced into the observations by the possible presence of particulate matter. This possibility decreases above 30 km (although meteoritic dust showers can be encountered,[9] but below this level, dust layers appear to be relatively common. Observations of such high-level dust layers have been made by Elterman's[27] and Fiocco's[10] groups, at the University of the West Indies,[24] and by SRI.[7]

IV CONCLUDING REMARKS

For a new and novel instrument, meteorological lidar has a surprisingly broad possible range of applications in naval operations. Some of the applications suggested in this report are clearly more useful or practical than others. Many of these apparent applications must be more thoroughly examined before specifications can be prepared for production-line meteorological lidar systems. Probably, no one meteorological lidar system will be suitable to accomplish a wide variety of functions just as no single type of meteorological radar is suitable for all possible uses of radar.

Future effort should be in thorough exploration of single or related groups of applications of meteorological lidar in areas urgently requiring solutions to problems or improvement of existing capabilities or procedures. The objectives of such investigations should be to determine the following:

(a) Ultimate capabilities and limitations of meteorological lidar under a realistic range of operating conditions

(b) Optimum meteorological lidar parameters with respect to such factors as PRF, beam width, power, and wavelength

(c) Optimum data processing and display systems for the particular application

(d) Utilization of meteorological lidar in conjunction with systems or instrumentation currently used in the same operation or application.

While meteorological lidar in its present stage of development exhibits a clear-cut superiority over other currently available instruments for some types of weather observations, considerable research must be accomplished in order to realize lidar's potentialities. There are perhaps three areas where sufficient experience has been accumulated to make it logical to launch research programs at this time:

(a) Stratus and fog observation and prediction: Observations described in Sec. III-A-2 suggest good possibilities for the development of observational and analytical techniques for predicting the formation of fog and low stratus clouds. At some naval installations, this is an important operational problem and one that could be brought under early attack.

(b) Horizontal and slant visibility determination: Considerable ground work, some of it predating the advent of lasers, has been accomplished on pulsed-light determination of visibility. Work done under the present contract, described in Sec. III-B, outlines the fundamental considerations. The development of this application of meteorological lidar for carrier operations is especially desirable because of the impracticality of other methods of making measurements along the approach glide path, and as with ceilometers and transmissometers at airfields.

(c) Low-level turbulence observation: The use of meteorological lidar for high-level, clear air turbulence observation is already under study by such organizations as NASA, the Weather Bureau and Air Force Cambridge Research Laboratories, and their contractors. Dr. P. Franken of the University of Michigan has made a preliminary study of the applicability of meteorological lidar for low-level turbulence detection. This problem is important in naval carrier operations, where high-performance aircraft must sometimes make approaches at near stalling speeds in turbulent air created by the carrier island or the vortices caused by other planes in the pattern. The detection of low-level turbulent eddies with meteorological lidar might well be simpler than the detection of high-level turbulence because of the lesser distances involved and the more turbid air in the atmosphere's lower layers. Scatterers, such as low concentrations of smoke, could even be deliberately injected into the carrier's atmospheric wake at suitable positions for lidar observation.

Other probably fruitful areas of study could be suggested but the results of this investigation indicate that the above areas presently offer the best opportunities for early and substantial returns. Advances in laser and photodetector technology to be reasonably expected in the near future will remove, or greatly reduce, the obstacles which currently discourage development of many potential operational applications of meteorological lidar. Accordingly, the field of laser technology should be continuously reviewed so that technological advances can be exploited as rapidly as possible.

APPENDIX A

EXPERIMENTAL METEOROLOGICAL LIDAR SYSTEMS DEVELOPED AT SRI

APPENDIX A

EXPERIMENTAL METEOROLOGICAL LIDAR SYSTEMS DEVELOPED AT SRI

The experimental lidars developed at Stanford Research Institute since 1963 for atmospheric probing applications have employed a Q-switched giant pulsed laser, employing either ruby or neodymium-doped glass crystals, and operating, respectively, at wavelengths of 0.6943μ or 0.53μ in the second harmonic mode. Various Q-switching techniques have been used. Optical systems used for the transmitter and receiver have included 4-inch refracting lens systems in a simple Galilean arrangement, 8-inch Cassegrainian reflector telescopes, and 12.5-inch Newtonian reflector systems. (Mode of operation and details of construction are described in Refs. 28, 29.) All models generated single pulses at intervals of at least 30-40 seconds, and displayed return signals as amplitude-modulated traces in A- or R-scope form recorded by Polaroid photography. All versions could be pointed at will. Sufficient system performance can readily be achieved to obtain echoes from water and ice particle clouds, from the water droplets and other particulate matter in fog, mist, and haze, and even from the particulate matter of what commonly passes for "clear air." In the simple experimental systems used, angular resolution was of the order of one degree and range resolution was of the order of a few meters, depending upon the display scales used.

Table I lists specifications of typical systems. Figure 1 shows a typical configuration for mobile use (Mark I, 1964).

Table I

LIDARS DEVELOPED AT STANFORD RESEARCH INSTITUTE

Component	Mark I, 1963	Mark II, 1963	Mark I, 1964	Mark II, 1965
Transmitter				
Laser	3 × 0.25-inch, 90° C-axis ruby crystal, transparent and semi-reflecting coatings on flat ends	3 × 0.25-inch, 90° C-axis ruby crystal, transparent and semi-reflecting coatings on flat ends	3 × 0.25-inch, 90° C-axis ruby crystal, Brewster angle ends, uncoated	(Two)* 3 × 0.5-inch, 60° orientation ruby crystal, rooftop and Brewster angle ends, uncoated
Q switch	Rotating prism	Rotating prism	Uranyl glass (UO_2^{++})	Rotating prism
Pulse length	30 ns	30 ns	24 ns	30 ns
Peak power	5 MW	5 MW	10 MW	10 MW
Optics	None	Refractor: 4-inch aperture	Refractor: 4-inch aperture	12.5-inch Newtonian reflector, telescope
Beam width	0.5°	Approx. 0.03°	Approx. 0.03°	Approx. 0.01°
PRF	1/min	1/min	2/min	2/min (each laser)
Receiver				
Photomultiplier	10-stage RCA Type 7326	10-stage RCA Type 7326	14-stage RCA Type 7265	(Two)* 16-stage ITT Type FW130G S-20 cathode
Optics	4-inch-aperture aerial camera objective with adjustable field stop	4-inch-aperture aerial camera objective with adjustable field stop	4-inch-aperture aerial camera objective with adjustable field stop	12.5-inch Newtonian reflector telescope
Beam width	0.07° min. to 0.8° max.	0.07° min. to 0.8° max.	0.07° min. to 0.8° max.	0.01° min. to 0.7° max.
Bandpass	Approx. 20Å	Approx. 20Å	Approx. 17Å	Approx. 4Å
Display	Tektronix 555 dual-beam oscilloscope	Tektronix 555 dual-beam oscilloscope	Tektronix 555 dual-beam oscilloscope	Tektronix 555 dual-beam oscilloscope and range-gated threshold discriminator and digital counter

*Mark II, 1965: This equipment comprises two separate transmitter and receiver systems capable of operating successively through the same optical system at intervals as short as 0.75 ms. Provision is made for varying the polarization of the transmitted energy and analyzing the received energy.

FIG. 1 Mark I 1964 mobile pulsed ruby lidar shown on trailer with gasoline electric generator. Not shown are the lidar power supply and oscilloscope. The barrel assembly, which can be pointed in any direction, demounts from the support and is stowed in a fitted case for transit. The support lifts off the trailer. The separate lidar power unit and oscilloscope are readily lifted by two men.

REFERENCES

1. W. E. K. Middleton, A. F. Spilhaus, "Meteorological Instruments," University of Toronto Press, p. 208 (1953).

2. M. G. H. Ligda, "Meteorological Observations with Lidar," Proceedings of the 11th Weather Radar Conference, NBS, Boulder, Colorado, pp. 482-489 (September 1964).

3. R. B. Battelle, P. R. Gillette, R. C. Honey, "An Analysis of the Feasibility of Laser Systems for Naval Applications (U)," Final Report, Office of Naval Research Contract Nonr-2332(00), SRI Project 2167-80/83, Stanford Research Institute, Menlo Park, California (November 1963), CONFIDENTIAL.

4. R. T. H. Collis, F. G. Fernald, M. G. H. Ligda, "Laser Radar Echoes from a Stratified Clear Atmosphere," Nature, 203, pp. 1274-1275 (19 September 1964).

5. R. T. H. Collis, M. G. H. Ligda, "Laser Radar Echoes from the Clear Atmosphere," Nature, 203, p. 508 (1 August 1964).

6. R. T. H. Collis, "Lidar Observations of Clouds," Science, Vol. 149, pp. 978-981 (27 August 1965).

7. R. T. H. Collis, M. G. H. Ligda, "Note on Lidar Observations of Particulate Matter in the Stratosphere," submitted 1965 to Journal of the Atmospheric Sciences.

8. R. T. H. Collis, "Lidar Detection of CAT," Astronautics and Aeronautics, Vol. 2, No. 2, pp. 52-54 (December 1964).

9. G. Fiocco, L. Smullin, "Detection of Scattering Layers in the Upper Atmosphere (60-140 km) by Optical Radar," Nature, 199, p. 1275 (1963).

10. G. Fiocco, G. Grams, "Observations of the Aerosol Layer at 20 km by Optical Radar," Journal of the Atmospheric Sciences, 21, p. 323 (1964).

11. R. E. Lundberg, R. B. Wilson, "The Feasibility of Utilizing a Laser System as a Menas for Determining Cloud Base Heights," Final Report, Contract N600(19)62325, Barkley & Dexter Laboratories, Inc. (22 March 1965).

12. R. J. Munick, "Optical Backscatter from Turbulent Air," New York Meeting Report, Optical Society of America (1964).

13. G. G. Goyer, R. Watson, "The Laser and its Application to Meteorology," Bulletin of the American Meteorological Society, Vol. 44, No. 9, pp. 564-570 (September 1963).

14. R. K. Long, "Atmospheric Attenuation of Ruby Lasers," Proceedings of IEEE, 51, p. 859 (1963).

15. G. R. White, L. J. Nugent, L. W. Carrier, "Laser Atmospheric Probes," paper presented at 20th Annual IAS Conference, Los Angeles, California (1965).

16. M. Hirono, "On the Observation of the Upper Atmospheric Constituents by Laser Beams," Journal of the Radio Research Laboratories, Tokyo, Japan, Vol. 11, No. 56, pp. 251-270 (July 1964).

17. E. D. Harris, L. J. Nugent, G. A. Cato, "Laser Meteorological Radar Study," Final Report, Contract AF 19(628)-4309, Project 0000-39, Electro-Optical Systems, Inc., Pasadena, California (January 1965).

18. A. Vassiliadis, R. B. Battelle, "A Study of the Applicability of Laser Radars to Probe Nuclear Weapons Effects and Natural Upper-Atmosphere Phenomena (U)," Final Report, Defense Atomic Support Agency Contract DA-49-146-XZ-324, SRI Project 5080, Stanford Research Institute, Menlo Park, California (January 1965), SECRET-RESTRICTED DATA.

19. M. G. H. Ligda, "Lidar - a CAT Hunter?" Shell Aviation News, No. 328, pp. 2-8 (1965).

20. C. M. Morrow, "Ocean Wave Profiling Radar System," Report 6052, U.S. Naval Research Laboratory (21 April 1964).

21. W. E. K. Middleton, "Vision through the Atmosphere," University of Toronto Press, p. 228 (1963).

22. S. Twomey, H. B. Howell, "The Relative Merit of White and Monochromatic Light for the Determination of Visibility by Backscattering Measurements," Journal of Applied Optics, Vol. 4, No. 4, pp. 501-506 (April 1965).

23. J. A. Fusca, "Clear Air Turbulence," Space/Aeronautics, pp. 60-69 (August 1964).

24. B. R. Clemesha, G. S. Kent, R. W. H. Wright, "A Study of the Feasibility of Measuring Atmospheric Densities by using a Laser-Searchlight Technique," Annual Scientific Report, Contract AF-AFOSR-616-64, University of the West Indies (1 April 1964-31 March 1965).

25. S. S. Friedman, J. Katzenstein, M. R. Zatzick, "Pulsed Searchlighting the Atmosphere," Journal of Geophysical Research, Vol. 61, No. 3, p. 415 (September 1956).

26. L. Elterman, "Seasonal Trends of Temperature Density and Pressure in the Stratosphere Obtained with the Searchlight-Probing Technique," Air Force Cambridge Research Laboratories Technical Report 54-19 (July 1954).

27. L. Elterman, A. B. Campbell, "Atmospheric Aerosol Observations with Searchlight Probing," Journal of the Atmospheric Sciences, 21, p. 457 (1964).

28. M. G. H. Ligda, "The Laser in Meteorology," Discovery, London, England (July 1965).

29. C. A. Northend, R. C. Honey, W. E. Evans, "A Laser Radar (Lidar) for Meteorological Observations," submitted 1965 to the Review of Scientific Instruments.