

**FIFTH CONFERENCE
ON
LASER RADAR STUDIES
OF THE ATMOSPHERE**

June 4-6, 1973

**Hilton Inn
Williamsburg, Virginia**

CONFERENCE ABSTRACTS

Sponsored by

Group on Laser Atmospheric Probing
American Meteorological Society

in cooperation with the

Optical Society of America

Hosted by

NASA Langley Research Center
Hampton, Virginia



**FIFTH CONFERENCE ON LASER RADAR STUDIES
OF THE ATMOSPHERE
PROGRAM**

PROGRAM CHAIRMAN *S. H. Melfi*

ASSOCIATE PROGRAM CHAIRMAN *M. P. McCormick*

MONDAY, JUNE 4, 1973 8:30 a.m.

WELCOMING ADDRESS *E. M. Cortright*
Director, LRC

Coffee 8:45–9:10 a.m.

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LIDAR SYSTEMS - WHERE WE ARE

by

M. P. McCormick

NASA - Langley Research Center

ABSTRACT

A general review of the past ten years of LIDAR system development will be presented. Equipment problems and many of their solutions are discussed. These include problems with photomultipliers, lasers, interference filters, data acquisition, etc. Calibration and alignment techniques are also presented. Instrumentation for multiwavelength, Raman, doppler, monostatic and bistatic techniques being used by various researchers are described. New developments and a gaze into the future are included.

MOBILE REMOTE SENSING LABORATORY

by

J. J. Grossman, M. Muramoto and J. Kacin
McDonnell Douglas Astronautics Company-West
Huntington Beach, California 92647

ABSTRACT

The McDonnell Douglas Astronautics Company (MDAC), has built a mobile remote sensing laboratory for studying atmospheric optical phenomena and identifying various molecular gases present in the atmosphere.

Major components of this laboratory are (A) the laser system, (B) receiving telescope, (C) spectrometer and detectors, (D) and the data displaying and recording electronics.

The transmitter/receiving telescope (T/R) assembly is mounted on an air-stabilized isolation table which is housed in a temperature-controlled 22-ft trailer truck. This system can be positioned in azimuth and elevation to an accuracy of less than 2×10^{-3} rad. with the aid of voltage readouts. The spectrometer and the laser system are light coupled to a transit-mounted T/R assembly through a mirror-prism system that permits use of the laser and detector systems at fixed position inside the light-tight van enclosure.

One laser is a modified Spacerays Model FD 22 High Powered Q-switched Ruby laser. The ruby is 6.63" long by 3/8" diameter and Q-switched by a KD*P Pockels cell. The output of 6943Å laser line is about 2 joules with a pulse length of about 30 nsec. The system is also equipped with the an ADP crystal frequency doubler producing more than 0.15 joules at 3471Å. The maximum repetition rate is 2 pulses per sec. The cavity, lamps, and ruby rod are temperature controlled by a Dunham-Bush Water Chiller, and the rod is kept at the constant temperature. The output from the laser is collimated by a simple Galilean telescope to give the beam divergence of less than 0.75 mrad.

The back-scattered signal receiving module consists of (1) 12" diam. f/16 Cassegrainian telescope, (a) a multi-mirror beam directing system, and (5) 3/4 m modified Jarrell-Ash Double Spectrometer. This spectrometer is equipped with polychromator housing which holds several photomultiplier (PM)

tubes at preselected Raman spectral lines. Also provision has been made so that the return signals can be PM detected through dichroic filters and various temperature-controlled narrow-band pass filters.

The display and recording consists of (1) the Tektronix Model R 454 and Polaroid camera for recording the output of the photodiode laser energy monitor, (2) a Tektronix model R556 Dual-Beam Oscilloscope with Type 1A4 four-channel amplifier and Type 1A1 dual-trace plug-in unit and a Coleman Oscillatron KD-5 Camera System for recording the output from the photomultiplier tubes. The output of the photo-diode monitor is the trigger start pulse for both oscilloscopes. Additionally, three channels presently are monitored by preamplifier/Biomation 610 B combinations and the data stored on magnetic tape.

A NEW GaAs LASER RADAR FOR ATMOSPHERIC MEASUREMENTS

by

R. T. Brown, Sperry Research Center, Sudbury, Mass.

and

A. P. Stoliar, Sperry Gyroscope, Great Neck, New York

ABSTRACT

A special GaAs lidar using fiber coupled diode lasers was constructed for the purpose of measuring the extinction coefficient distribution within a large atmospheric volume at a rate compatible with atmospheric kinematics. The technique is based on taking backscatter signature ratios over spatial increments after the returns are normalized by pulse integration. Essential aspects of the lidar design are beam pulse power, repetition rate, detection system dynamic range and decay linearity. It was necessary to preclude the possibility of eye hazard under any operating conditions, including directly viewing the emitting aperture at close distance with a night-adapted eye. The electronic signal processing and control circuits were built to allow versatile operations.

Extinction coefficient measurements were made in fog and clouds using a low-power laboratory version of the lidar, demonstrating feasibility. Data are presented showing range squared corrected backscatter profiles converted to extinction coefficient profiles, temporal signal fluctuations, and solar induced background noise. These results aided in the design of the lidar which is described. Functional tests of this lidar and the implications relevant to the design of a prototype model are discussed.

This work was jointly sponsored by Sperry Rand Corporation under its Independent Research and Development program; the Air Force Avionics Laboratory, Wright Field, Dayton, Ohio; and the Naval Ammunition Depot, Crane, Indiana.

DESIGN AND TESTING OF AN ERBIUM LASER RANGEFINDER
FOR USE AS A CEILOMETER

by

Eugene Y. Moroz

Air Force Cambridge Research Laboratories
Bedford, Massachusetts

and

Joseph P. Segre and Norman R. Truscott

American Optical Corporation
Framingham, Massachusetts

ABSTRACT

The use of pulsed laser rangefinders to determine cloud base heights for airfield operations have been investigated in the past. Both ruby and neodymium systems have been shown to be excellent laser ceilometers. However, these systems present a potential eye hazard even at a considerable distance from the source and, therefore, their routine use at airfields is questionable.

This paper discusses an erbium doped glass laser rangefinder that was constructed as an experimental laser ceilometer. The laser operates at 1.54 micrometers (μm) and at this wavelength, the output power density is an order of magnitude below the proposed Z136 ANSI standard. On this basis the system is considered completely eye safe.

The laser uses a clad silicate glass rod (AO 2101-2699), 4 mm core and 6 mm cladding diameter, 150 mm long which is pumped by two 4 x 6 mm flash-lamps. It is Q-switched by means of a sapphire flat, rotating at 24,000 rpm. The laser produces a 35 nanosecond (ns) pulse having a peak power output of one megawatt. It can be fired automatically at a rate of one pulse per minute.

The receiver optics consists of a 12 inch diameter, f:2, reflecting paraboloid. The detector is a germanium avalanche photodiode (TI XL 76). The receiver field of view is 0.4 milliradian, matching the transmitter beam

divergence. The spectral bandpass is from 1.2 to 1.6 μm . The short wavelength cutoff is provided by the receiver window (AO IR glass) and the long wavelength cutoff by the photodiode spectral response. Due to the low level of sky background in this spectral region, a bright cloud background is of the same order as the internal noise of the receiver which has a 40 MHz bandwidth.

The system has been extensively tested on a variety of cloud targets in order to evaluate its capability as a laser ceilometer. Cloud heights have been measured out to 15,000 feet. A signal to noise ratio of five was obtained when ranging out to clouds at a slant distance of 33,000 feet.

Comparative tests were made at AFCRL, Hanscom Field, Bedford, Massachusetts between this system, a ruby laser ceilometer and a rotating beam ceilometer (RBC). The ruby laser ceilometer is manufactured by ASEA of Sweden and has a 30 ns, 2 megawatt output. The RBC is a standard AN/GMQ-13 ceilometer using a 400 foot baseline. Polaroids were made of the three oscilloscope displays. Cloud base heights were determined from the traces using the criterion of Circular N. All three systems were found to be in good agreement. The laser systems showed more detailed information on the cloud structure than the RBC.

ABSTRACT

A REAL-TIME LIDAR SIGNAL PROCESSOR

John Oblanas, William Viezee, and R. Collis

Stanford Research Institute

Menlo Park, California

A real-time, wide band analog signal processor has been developed at SRI for use in lidar studies of the lower atmosphere.

Unlike previous designs, this processor does not employ time-varied gain of the photomultiplier, thus eliminating a potential source of error in the lidar data. The processor generates an analog waveform proportional to the function $2 \ln R$ (where R is slant range). This waveform is summed with the logarithmic output of the lidar receiver to compensate for the inverse range square dependence inherent in lidar returns from volume targets.

When displayed in A-scope form (amplitude vs range), the signature of the range-corrected logarithmic signal provides a direct indication of the degree of homogeneity of the atmosphere and of its extinction coefficient. This follows from the fact that the rate of change of received signal, P_r , with range, R , is a function of the extinction coefficient σ according to the equation.

$$-\frac{1}{2} \frac{d(\ln P_r R^2)}{dR} = \sigma$$

Thus where the atmosphere is homogeneous (a condition that will be indicated by the rectilinearity of the displayed trace) σ can readily be derived from the trace's slope.

Similarly, the output of this processor is well suited for use in intensity-modulated two dimensional presentations of lidar data obtained by scanning (i.e., RHI, PPI, Height/Distance, or Height/Time displays), since the range correction greatly reduces the dynamic range requirements and facilitates the interpretation of the displayed data by inspection. For such displays, a further reduction in dynamic range can be achieved by increasing the

slope of the ramp function $2 \ln R$ to compensate, at least in general terms, for the effects of attenuation.

MONOSTATIC LIDAR DATA RECORDING AND
REDUCATION SYSTEM

J. D. Spinhirne, M. Z. Hansen and J. A. Reagen

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ABSTRACT

A hardware system has been constructed to perform signal compression, analog to digital conversion and digital recording of monostatic lidar returns with 3% single shot accuracy. Emphasis has been placed on simplicity and ease of design and construction.

The system has been built using comparatively inexpensive, commercial units that can be incorporated into lidar data acquisition systems with a minimal amount of design and construction effort. Two techniques are used to compress the photomultiplier signal. An accurate high-speed analog multiplier is used to compensate for the $1/r^2$ decrease of the signal. The signal is also compressed with a gain switching amplifier which utilizes low cost, monolithic, programable gain operational amplifiers to provide gain switching. The amplifier switches and settles in 400 ns. and has a bandwidth of 3.5 mhz on all channels. Analog to digital conversion is accomplished with a Biomation 610 transient recorder which has a versatile input and recording capability and provides a 6-bit, 256 word output.

Data is punched onto paper tape. In addition to the lidar signal; the readout of a digital energy monitor, the slant path angle, instrument settings and time of observation are also recorded. Interfacing between the recorder, punch and auxiliary data source is accomplished with two cards of control logic. During an observation, numerous shots are taken at several slant path angles. The data is fed into a computer for rapid reduction of the data and presentation of atmospheric optical profiles.

A PROPOSED MULTI-CHANNEL PHOTON COUNTER WITH
REAL-TIME DATA ACQUISITION FOR LASER RADAR

by

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ABSTRACT

A high-speed, multi-channel photon counting system has been designed for use with a variety of laser radar experiments. It utilizes two solid state buffer memories to replace the large array of counters normally associated with such a system and a minicomputer to handle data manipulation and display. The speed, versatility, compact size, and low material cost of the system make it a reasonable alternative to systems presently in use. System features include a 250 MHz photon counting rate, 100 nanosecond minimum sample interval, up to 512 channel data accumulation with sub-nanosecond switching times between channels, and a maximum laser transmitter repetition rate of 10 KHz. This system offers several advantages over presently available systems, such as allowing higher laser repetition rates without sacrificing spatial resolution or the total number of data channels, and enabling real-time modification of the system operating parameters as a function of incoming data. This paper describes the parameters influencing such a system and its basic design.

MEASUREMENT OF OVERLOAD EFFECT IN PHOTOMULTIPLIERS
AS APPLICABLE IN LASER RADAR TECHNIQUES

by

D. P. Jones and G. S. Kent

Department of Physics, University of the West Indies

ABSTRACT

Several types of overload effect, or spurious noise pulses, are known to exist in photomultipliers. This paper presents the analysis of experiments to determine the magnitude of the enhancement which occurs up to 1 ms after the tube has received an intense light pulse. The enhancement appears as a decaying elevation in the magnitude of the dark current and is of particular significance in laser radar measurements of atmospheric backscatter.

Intense light pulses were produced from both a pulsed light emitting diode and a ruby laser radar system. Although the intensity from the light emitting diode was barely sufficient to produce a noticeable overload effect, it served as a guide to the intensity of light the photomultiplier tube could withstand before overload occurred. The laser experiments where the overload pulse had a much greater intensity showed that the magnitude of the dark current enhancement was proportional to the intensity of the incident radiation.

This result is of particular importance in relation to the measurement of atmospheric density in the lower atmosphere where, unless special precautions are taken, the receiving photomultiplier tube may be subjected to an initial light pulse whose intensity is much greater than the signal which is measured a short time later.

LASER DOPPLER MEASUREMENT OF ATMOSPHERIC WIND VELOCITY

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ABSTRACT

Our presentation consists of two parts: (1) a summary review of laser Doppler principles and applications, and (2) operational design and preliminary laboratory tests of a CO₂ laser system for NOAA applications.

Laser Doppler velocimeters for short range applications to water tunnels and seeded-flow wind tunnels are widely used and reviewed¹. The non-relativistic expression for the Doppler shift,

$$\nabla v_D = (n/2\pi) \vec{v} \cdot (\vec{k}_s - \vec{k}_o) ,$$

where n is the refractive index of the medium, \vec{v} the scatterer velocity and \vec{k}_s and \vec{k}_o the scattered and incident wave vectors ($2\pi/\lambda$), applies to both local measurement and remote measurement of flows. Remote velocity measurements with a single-ended system at ranges of tens of meters or more severely restrict the usable experimental configurations, however. We will critically review the atmospheric results of infrared heterodyne^{2,3}, two-beam visible differential⁴, and visible incoherent⁵ detection systems, as well as some signal to noise calculations⁶.

For the measurement of wind in severe storm and boundary layer meteorology applications, considerations of background interference, atmospheric refractive index fluctuations, eye safety, laser stability and efficiency, and other practical concerns are properly discussed. Although a heterodyne, CO₂ laser system is attractive for these wind measurement purposes, an analysis of expected return based on the atmospheric aerosol model of McClatchey, et al.⁷, is required to substantiate the adequacy of the technique.

We will present an outline of the NOAA Doppler lidar equipment and exhibit velocity data from a diffuse scattering source at 12 meters. Conference

participants are invited to an interactive discussion of the application of this type of laser radar to problems such as waterspouts, thunderstorms, and helical rolls.

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A COMPARISON OF THE MEASURED SCATTERING MATRIX ELEMENTS OF POLYDISPERSE SYSTEMS OF IRREGULAR PARTICLES WITH THE MATRIX ELEMENTS CALCULATED FOR SPHERES THAT HAVE THE SAME DISTRIBUTION OF PROJECTED AREAS

A. C. Holland⁰, P. J. Hofman⁺ and W. A. Munn⁺

ABSTRACT

The elements of the scattering or Mueller Matrix for three polydisperse systems of irregular, randomly-oriented particles have been measured in absolute terms as a function of scattering angle for several visible wavelengths. The samples consisted of commercially available silicon dioxide particles that fit three distinct lognormal size distributions.

The measured matrix elements were compared with the matrix elements calculated for spheres that had the same refractive index and fitted the same distribution of projected areas. Correlations and discrepancies between the two sets of matrix elements will be discussed.

⁰ NASA/Wallops Station

⁺ Smithsonian Astrophysical Observatory

DETERMINATION OF ATMOSPHERIC AEROSOL CHARACTERISTICS
FROM THE POLARIZATION OF SCATTERED RADIATION

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ABSTRACT

Aerosols affect the polarization of radiation in scattering, hence measured polarization can be used to infer the nature of the particles. Size distribution, particle shape, real and absorption parts of the complex refractive index affect the scattering. From Lorenz-Mie calculations of the 4-Stokes parameters as a function of scattering angle for various wavelengths the following polarization parameters were plotted: total intensity, intensity of polarization in plane of observation, intensity perpendicular to the plane of observation, polarization ratio, polarization (using all 4-Stokes parameters), plane of the polarization ellipse and its ellipticity. A six-component log-Gaussian size distribution model was used to study the effects of the nature of the polarization due to variations in the size distribution and complex refractive index. Though a rigorous inversion from measurements of scattering to detailed specification of aerosol characteristics is not possible, considerable information about the nature of the aerosols can be obtained. Only single scattering from aerosols was used in this paper. Also, the background due to Rayleigh gas scattering, the reduction of effects as a result of multiple scattering and polarization effects of possible ground background (airborne platforms) were not included.

It is convenient to use radiation initially plane-polarized at 45° to the plane of observation. The total, parallel and perpendicular component intensities are meaningful, but fluctuations in the source, number of particles in the scattering volume, and other variables may reduce their experimental usefulness. The polarization parameters of polarization ratio, polarization, inclination angle and ellipticity are ratios and hence not influenced by these changes in the intensities.

The effect of size distribution can be seen by noting the relative contributions to the scattering parameters of the various log-Gaussian components. Large particles, for example, give a strong forward peak, a

rainbow and enhanced 180° backscattering in the intensities. Small particles, though also different in the parallel and perpendicular components, produce a symmetric angular distribution as the sizes get smaller. The variation of parallel and perpendicular components with angle and the variation in phase difference between them give marked polarization effects especially in the backward scattering region up to but not including 180° backscattering. At scattering angles of greater than about 70° there are marked differences produced by the modified gamma and Junge-type power-law size distribution in position and maxima of the polarization ratio, polarization, inclination and ellipticity. Appreciable difference in the exponents of the power law distributions are distinguishable. Obviously, there are differences in the backscattered intensities between Junge and modified gamma size distribution.

An increase in the real part of the refractive index: moves the rainbow to larger scattering angles; enhances the 180° backscattering; decreases the polarization ratio maximum (around 90°); and increases the slope near 0° inclination angle. An increase in absorption on the other hand, flattens and reduces the intensity curves outside the near forward scattering region, including the rainbow, glory, and 180° backscattering effects. Also the polarization ratio maximum increases, and the inclination angle makes a more gradual transition across the 0° inclination axis as it moves to smaller scattering angles. These effects are much more evident for larger particles. The ellipticity, especially at angles of more than 100° scattering, is also sensitive to changes in the particle characteristics.

It is obvious that these analytical calculations are useful for determining aerosol characteristics. However, in dealing with "real-world" aerosols, a multidiscipline approach must be used. This includes: measurement of the physical and optical characteristics of the particles by various sampling techniques; measurement of the 4-Stokes parameters as a function of wavelength and angle; and analytical calculations based on "real" aerosol characteristics .

INVERSION OF ACTUAL ANGULAR SCATTERING DATA
TO OBTAIN PARTICLE SIZE DISTRIBUTION

Philip B. Russell^{1,2} and Gerald W. Grams¹

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ABSTRACT

Measurements of the intensity of laser light scattered by a volume of atmospheric aerosol as a function of scattering angle have been numerically inverted to obtain the size distribution of particles in the scattering volume. The numerical results are compared to simultaneous measurements of particle size distribution made by direct sampling techniques. The data were taken on ambient soil dust aerosols in Big Spring, Texas, as described by Grams et al. (1973). The inversion technique is essentially the "smoothed-least-squares" matrix method described by Twomey (1963, 1965) and Westwater and Strand (1972); however, modifications were made to handle the large measurement errors present in the scattering data. In addition, techniques of singular value decomposition (Golub and Reinsch, 1970) were used to minimize errors caused by ill-conditioning of matrices.

In this method of solution a family of acceptable solutions, rather than a unique result, is obtained; the mean of all such solutions, together with standard deviations at given radius intervals, is then taken to be the best estimate of the particle size distribution. An example of a result obtained in this manner, in a case where the dust particles appeared to be scattering as homogeneous spheres, is shown in Figs. 1 and 2. A synopsis of the solution technique, examples of other cases inverted, and an indication of problems presented by particle asphericity, unknown index of refraction, etc., will be presented.

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† The National Center for Atmospheric Research is sponsored by the National Science Foundation.

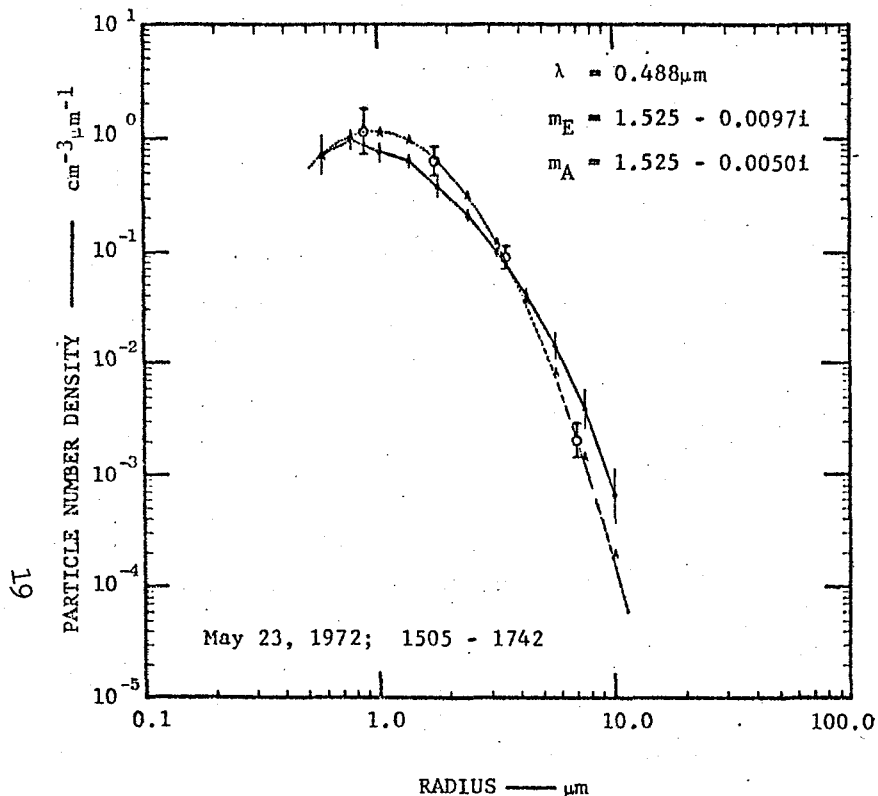


FIGURE 1 COMPARISON OF PARTICLE SIZE DISTRIBUTIONS OBTAINED BY DIRECT SAMPLING AND INVERSION OF LIGHT SCATTERING MEASUREMENTS (\circ direct sampling data point with estimated error; ----- lognormal curve fitted to sampling data points; \dagger inversion solution with standard deviation, computed from measured cross sections in Figure 2)

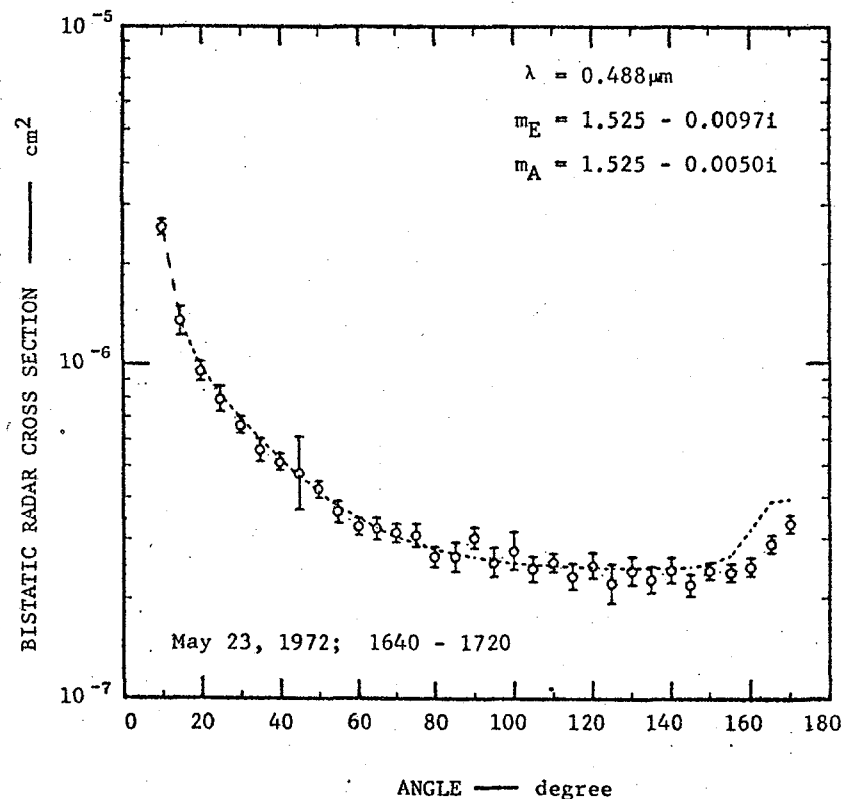


FIGURE 2 TOTAL (GAS PLUS PARTICLE) BISTATIC RADAR CROSS SECTIONS (\circ polar nephelometer measurement with geometric standard deviation; ----- computed value using inversion solution shown in Figure 1)

TECHNIQUE FOR OBTAINING VERTICAL PROFILES OF
BACKSCATTERING AND EXTINCTION CROSS SECTIONS
USING SLANT PATH LIDAR MEASUREMENTS

J. D. Spinhirne, B. M. Herman and J. A. Reagen

ABSTRACT

A method is presented for solving for vertical profiles of atmospheric particulate extinction and backscattering cross-sections utilizing monostatic lidar slant path measurements. The method is an extension of work by Fernald¹. It is shown that the number of assumptions necessary for an iterative solution of extinction and backscattering cross sections can be reduced if lidar slant path measurements are used to solve directly for optical depths.

The technique is useful only if sufficiently accurate lidar measurements are available. With highly accurate measurements it is also possible to solve directly for extinction cross sections without an iterative solution of a transcendental equation if the proper reduction scheme is used. The required accuracy is discussed and results showing the effect of errors are presented.

¹ F. G. Fernald, B. M. Herman and J. A. Reagen, Journal of Applied Meteorology, Vol. 11, No. 3 (1973).

AN APPROXIMATE EQUATION FOR THE
MULTIPLY SCATTERED CONTRIBUTION TO A LIDAR RETURN

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ABSTRACT

An approximate equation is developed which describes the contribution of N^{th} order scattering to a lidar return. This development assumes a homogeneous scattering medium characterized by a scattering function sharply peaked in the forward direction and relatively insensitive to angle near the backscatter direction. The derivation includes the effects of finite divergence of the transmitted laser beam, finite receiver field of view, finite separation between the laser and the receiver and nonparallel system alignment.

The derivation presented uses small angle approximations to reduce the time dependent multiple scattering problem to a time independent form which is then solved with techniques previously developed for multiple small angle nuclear scattering. This derivation results in the following equation for power received due to N^{th} order small angle scattering:

$$P_N = E_0 \frac{C}{2} \beta \frac{A_r}{r} \frac{P(\pi)}{4\pi} e^{-2\beta r} \left(\frac{\beta r}{2}\right)^{N-1} \sum_{m=0}^{N-1} \frac{1}{m!(N-m-1)!} e^{-a\psi} \int_0^{a\delta^2} e^{-u} I_0(2\psi\sqrt{au}) du \quad (1)$$

where:

$$a = \frac{3}{3\langle\delta^2\rangle + \langle\theta_s^2\rangle(3N-2m-3)}$$

$$\psi = \frac{s}{r} + \gamma$$

P_N = Power received due to N^{th} order scattering

E_0 = Transmitter energy

c = Speed of light

β = Scattering cross section per unit volume

r = Range

A_r = Area of receiver

$P(\pi)$ = Backscatter phase function (see Deirmendjian, 1969)

N = Order of scattering

$\langle \delta^2 \rangle$ = Mean square divergence angle of transmitting laser

$\langle \theta_s^2 \rangle$ = Mean square width of the forward scattering peak in the phase function

I_0 = Modified Bessel function of zero order

δ_r = Half-angle receiver field of view

s = Lateral separation between laser and receiving telescope

γ = Angular misalignment of the laser and telescope axis (this misalignment is assumed to be in the plane defined by the telescope mirror and the axis of the laser)

Equation 1 provides a simple means of estimating multiple scattering during operational lidar work. Notice that in the special case of a nearly coaxial system geometry where: $\psi \ll 1$, $I_0(2\psi\sqrt{au}) \approx 1$ for all $u \leq a\delta_r^2$. In this case the integral in equation 1 reduces to a simple exponential and 'slide rule' solutions can be obtained for P_N .

Examples of the multiply scattered lidar return predicted by equation 1 will be presented and compared to preliminary measurements.

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AN OPTICAL MODEL FOR
STRATOSPHERIC AEROSOLS

J. M. Rosen

D. J. Hofmann

T. J. Pepin

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ABSTRACT

Most remote sensing techniques of stratospheric aerosol rely on an optical model to relate the measured quantities with physical parameters such as concentration, size, and composition. By comparing data taken simultaneously using remote sensing and in-situ techniques, it is possible to begin the development of a useful relation between the various results. The heart of this comparison is the size distribution and composition of the particles. This report describes an optical model that is consistent with impactor samples, filter samples (measurement of total mass), photoelectric particle counters, LIDAR results, and solar extinction measurements.

THE EFFECTS OF NON-SPHERICAL PARTICLES ON ESTIMATIONS
OF AEROSOL PROPERTIES

By

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ABSTRACT

A Monte Carlo radiative transfer model has been constructed to investigate the transmission and scattering properties of an inhomogeneous but layered medium. The program has been applied to investigate the multiple scattering properties of the Elterman aerosol model assuming

1. spherical particles with log-normally distributed radii.
2. an aerosol with the same mass distribution as (1) but whose scattering matrix elements have been determined experimentally by Holland, et al. at a wavelength of 0.546μ .

The results are discussed in terms of the detection of non-spherical particles by lidar experiments and the possible influence of these particles on systematic errors in aerosol property estimations.

ABSTRACT

A MODULAR ATMOSPHERIC PROPAGATION PROGRAM (MAPP)

by

M. L. Wright and L. S. Gasiorek

A computer model of the atmosphere has been developed that will solve a wide variety of lidar and atmospheric propagation problems. The lidar system calculations involve the prediction of path loss and lidar signal return for a variety of atmospheric conditions and lidar system configurations. The program contains a very large data base of absorption and attenuation coefficients for all of the naturally occurring gases and several gaseous pollutants such as SO_2 , NO_2 , NO , N_2O , O_3 , HCL , etc. The spectral range of this data base extends from the ultra-violet (1200 Å) through the infra-red. Several aerosol models are included in the program to account for the effects of this important scattering mechanism.

The program incorporates a maximum of flexibility in accepting input data and providing output data in an easily used form. Profiles for the standard atmosphere and for various polluted atmosphere and cloud models are stored in the machine. These stored models can be used singly or in combination, or be supplemented or replaced by additional profiles provided as input data to the program. A variety of output options are available involving either numerical data or graphical data; the output quantities can be attenuation, power returned or power differences, as functions of range or path position.

Path loss is computed by dividing the distance into increments, calculating the absorption for each increment and summing up the loss over the desired path. The absorption for each increment is calculated by multiplying the material concentration times the absorption coefficient for that material. The absorption coefficient for a particular wavelength and material is determined by either table look-up or calculating the coefficient from spectral line data. The line profile is calculated as a function of temperature and pressure. The concentration of the gas as a function of range is either taken from a stored model or an input quantity.

By appropriate selection of a peak absorption and a peak transmission wavelength, the program will calculate a range-resolved return for the differential-absorption lidar (DIAL) measurement technique. Multiple computer runs may be made to determine the optimum pair of wavelengths in using the DIAL technique to monitor the constituent of interest in the presence of other interfering gases.

THE GLOBAL STRATOSPHERIC
AEROSOL BURDEN

J. M. Rosen, D. J. Hofmann, T. J. Pepin
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ABSTRACT

Since mid-1972 the University of Wyoming's Atmospheric Physics Group has been conducting bimonthly global surveys of the stratospheric aerosol using balloon-borne detectors. A total of ten stations are included in the sounding network, of which there are seven in the northern hemisphere and three in the southern hemisphere. From the results of these measurements new information is now becoming available concerning the temporal variations and spatial distribution of aerosols. An effort is being made to assess the characteristics of the natural stratospheric aerosol background. However, since data is available only over a limited time period, it is still somewhat difficult to determine whether or not the present aerosol concentration levels are in a steady state condition.

LIDAR MEASUREMENTS OF STRATOSPHERIC PARTICULATES

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ABSTRACT

Since October 1972, Stanford Research Institute has conducted a program of periodic nighttime observations of stratospheric aerosols using a ground-base lidar. The lidar system consists of a 2 J, Q-switched ruby laser fired at a rate of 0.5 Hz, and a 16-inch cassegrain receiver; with simultaneous analog and pulse-counting modes of data acquisition. The analog data is usable to heights near 30 km, and the pulse-counting data is used above 25 km. Typically 20 minutes of operation is required to obtain one percent accuracy in 1/4-km range bins at 25-km altitude.

The basic data are in the form of vertical profiles of atmospheric backscatter in relative units. Techniques to deduce from these data information pertinent to determining the spatial and temporal distribution of particulate matter in the stratosphere are illustrated.

Observations in the late fall of 1972 and spring of 1973 are analyzed in terms of vertical profiles of the aerosol backscattering coefficient (see Figure 1) that show the presence and height of stratospheric aerosol scattering layers but not their nature. Observed maximum values of total (aerosol plus molecular) backscatter are only 10 to 15% above the molecular backscatter. Multiple-layered structure is evident in the vertical aerosol distribution. Between 20 and 30 km, occasionally large monthly variations in location and thickness of these layers are observed. The data suggest the presence of a quasi-permanent aerosol scattering layer of 5 km thickness centered at 20 km.

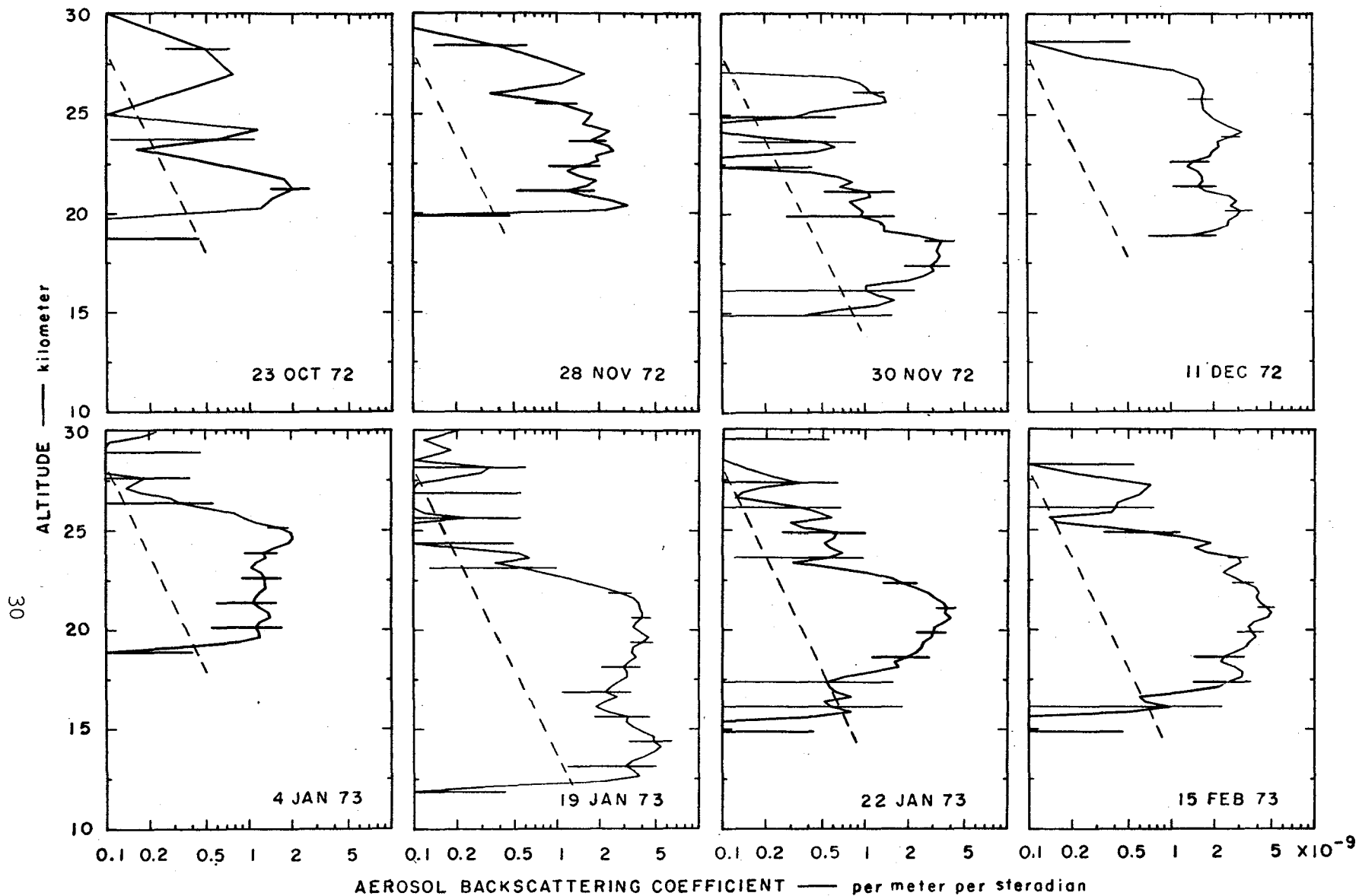


FIGURE 1 TIME SERIES OF AEROSOL BACKSCATTERING COEFFICIENT f_A , VERSUS HEIGHT COMPUTED FROM LIDAR BACKSCATTER OBSERVATIONS MADE AT MENLO PARK, CALIFORNIA

Error bars represent \pm one standard deviation of the data sample. Dashed line represents constant mixing ratio.

(Drawn at 1 percent of the molecular backscattering coefficient)

COMPARISON OF LIDAR AEROSOL MEASUREMENTS

AND DIRECT PARTICULATE SAMPLING

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and Charles L. Frush.

National Center for Atmospheric Research*

Boulder, Colorado

ABSTRACT

Lidar data were collected at Boulder, Colorado, on two evenings; 308 shots between 21:34 and 00:33 (MST) on the night of September 12-13, and 152 shots between 21:43 and 22:51 (MST) on September 15. The averaged lidar returns were normalized with respect to the real molecular atmosphere as determined by Denver, Colorado, radiosondes. Error limits of $\pm 0.67\sigma$ become distinguishable from the normalized returns only above 25 km.

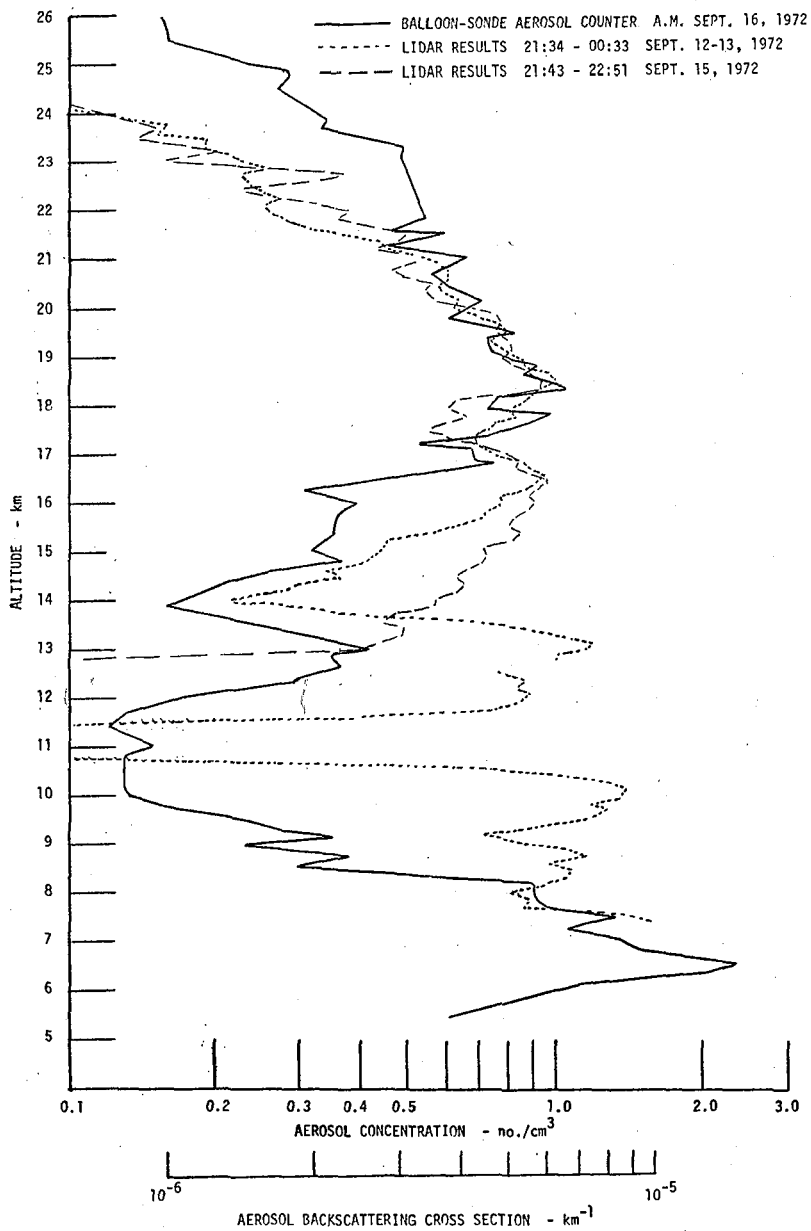
The data for September 12 were normalized to the real atmosphere by determining the level at which the lidar return (average of all 308 shots) was a minimum compared to the molecular atmosphere and setting the ratio to 1.0, that is by assuming that there were no aerosols present in the atmosphere at that level. For the 12th of September this level was 9.5 km. The same procedures, though, could not be successfully applied to the September 15 data for it appears that significant amounts of aerosols were present at all heights (between 7.5 and 22 km) to which this normalization method was applied. The data for the 15th were, therefore, adjusted so that they agreed with the results of the 12th of September in the 16 to 24 km height interval.

The corresponding aerosol backscattering cross sections have been plotted superimposed upon the University of Wyoming balloonsonde aerosol counter data. The agreement among these three sets of data in the stratosphere (above 14 km)

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

is very good considering their spatial and temporal differences. A cirrus cloud layer appearing between 10 and 12 km on the 15th of September has not been plotted, since the relatively large backscattering cross sections of these sub-visible cirrus particles greatly exceeded the scale of the graph.

Perhaps most important of all, it appears that an integration from the tropopause to 24 km would produce results within a few percent for the three sets of data.



GLOBAL RECONNAISSANCE OF STRATOSPHERIC AEROSOL
BY AIRBORNE LIDAR

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ABSTRACT

As part of the Climatic Impact Assessment Program (CIAP), a series of airborne lidar measurements have been performed to eventually determine, on a global scale, the extent and degree of particulates in the stratosphere. Thus far, two missions have been flown. The first, starting 25 February 1973, went from Albuquerque, New Mexico - Goose Bay, Labrador - Fairbanks, Alaska - 85°N latitude - Hawaii - equator. The second mission, starting 1 April 1973, went from Albuquerque, New Mexico - Goose Bay, Labrador - Iceland - Madrid, Spain - Albuquerque. Several local Iceland missions were flown to determine if the Helgafell volcanic activity had penetrated into the stratosphere.

The items to be discussed will include a general discussion of the overall global mission, the experimental interface of the lidar and the Air Force NC-135 aircraft, and a discussion of the preliminary results to date. These latter include nacreous clouds and associated low temperatures in mountainous northern latitudes; and layers up to 30 km in the equatorial regions.

*The National Center for Atmospheric Research is sponsored by the National Science Foundation.

COMPARISON OF LIDAR AND IN-SITU

MEASUREMENTS OF STRATOSPHERIC AEROSOLS

by

S. H. Melfi, G. B. Northam, M. P. McCormick (NASA Langley Research Center)

and

J. M. Rosen, T. J. Pepin, D. H. Hofmann (University of Wyoming)

ABSTRACT

This paper will present the results of a comparative study conducted in Laramie, Wyoming, during the summer and fall of 1972, as part of the Department of Transportation's Climatic Impact Assessment Program (CIAP). The study included independent, and nearly simultaneous, measurements of stratospheric aerosols using a LIDAR system and a balloon-borne in-situ particle counter.

The LIDAR provides a remote measurement of volume backscatter (aerosols and molecules) in a narrow wavelength region centered at the ruby wavelength (6943\AA); whereas the balloon-borne in-situ counter measures aerosol concentration by counting aerosols greater than $\approx 0.30 \mu\text{m}$ in a diameter as they are pumped through a chamber and scatter white light forward into photo-detectors.

The comparison of measurements that will be discussed using the two techniques involves formulating the LIDAR data so that it is compatible with the counter data. The formulation includes separation of the scattering due to aerosols from the total and displaying this in terms of aerosol scattering function. Aerosol scattering function is proportional to aerosol concentration if the aerosol parameters, such as size distribution and composition, are constant with altitude.

In separating the aerosol scattering from the total, the need for real atmospheric number density over the Standard Atmosphere is also discussed.

STRATOSPHERIC AEROSOL LIDAR MEASUREMENTS

OVER JERUSALEM

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Department of Atmospheric Sciences

The Hebrew University of Jerusalem, Israel

ABSTRACT

The laser radar system, consisting of a ruby laser as the emitter, has been used to map the aerosol layer centered at 20 km. Scattering measurements were made in two polarizations and changes as a function of time in the number density as well as in the size distribution were detected.

The size distribution variations were observed by the analysis of the depolarization of the backscattered light.

The results were compared to those obtained in different sites over the whole globe and the height of the maximum concentrations vs. latitude and season were plotted.

Regular measurements of the stratospheric aerosol profile are being carried out in order to detect future concentration variations due to volcanic eruptions or other possible dust sources. The profile describes the altitude dependence of the aerosol concentrations between 10 - 30 km, by use of a multichannel analyzer.

LASER RADAR OBSERVATIONS ON THE MESOSPHERE AND LOWER THERMOSPHERE
OVER KINGSTON, JAMAICA

by

G. S. Kent and W. Keenlside

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ABSTRACT

The Mark II laser radar system has been in use on a routine basis for nearly three years. Typically three continuous operational periods of 8-10 hours are made each month, and the variations of the signal scattered at heights from 60-100 kilometres studies. The normal integration period used is approximately 30 minutes and the relative accuracy of measurement of the received signal, under good atmospheric conditions, varies from about 1% at 70 km to 15% at 100 km. The following properties of the atmosphere in this height range have been established.

- 1.(a) The solar diurnal tidal oscillation has a dominant wavelength of 15 km, which is within the range of wavelengths predicted but which cannot be assigned to any specific mode. The wave is strongly attenuated with increasing altitude. Seasonal variations are observed in wavelength and phase; spring and autumn showing the most regular behaviour.
 - (b) The solar semi-diurnal tide is found to agree well with theoretical predictions. It does not appear to be greatly attenuated with altitude and is stronger than the diurnal tide above about 90 km. Below this height the diurnal tide is dominant. Seasonal changes in phase are observed.
2. A seasonal variation in atmospheric density is observed. Maximum density is observed in winter and minimum in summer; the annual range is approximately 10% at a height of 90 km.

3. There is no regular mesospheric dust or aerosol layer present over Jamaica.
4. Considerable day-to-day variability in behaviour is observed, both in the background density and the tidal oscillations.
5. Good agreement has been obtained between the characteristics of the atmospheric tides as observed by the laser radar system and by meteor radar and short-wave radio sounding at the same location.

MEASUREMENT OF RESONANCE SCATTERING CROSS SECTION OF SODIUM D LINES
AND LASER RADAR DETECTION OF SODIUM LAYER IN THE UPPER ATMOSPHERE
BY A TUNABLE DYE LASER

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ABSTRACT

The recent development of tunable dye laser technology is promoting a new approaches to high resolution spectroscopy, atmospheric research and air pollution analysis. This paper describes some output characteristics of a tunable dye laser and its application to the measurement of resonance scattering cross section. Furthermore, the measurement of the sodium layer in the upper atmosphere with a resonance scattering laser-radar system performed by our laboratory is reported.

A flashlamp-pumped dye laser was designed and constructed for the resonance scattering study. A combination of a linear flashlamp and an elliptical cylindrical reflector was employed to pump uniformly the Rhodamine 6G solution for obtaining high frequency stability. The flashlamp is driven by a $0.5 \mu\text{F}$ low inductance capacitor, which produced a pumping light with a fast rise time shorter than $0.3 \mu\text{s}$. Spectral narrowing of the oscillation width and tuning of the wavelength are accomplished with a tilted Fabry-Perot filter mounted between a diffraction grating and a mirror. The laser output is typically about 5 mJ and the spectral width varies from $0.01 \overset{\circ}{\text{A}}$ to $0.04 \overset{\circ}{\text{A}}$ as the flashlamp input increases.

The resonance scattering cross section of sodium D lines were measured carefully by irradiating the dye laser beam in a 3-cm diam spherical sodium vapor cell. Table 1 shows the theoretical and experimental values of the

Table 1.

Na I line		D ₁		D ₂	
Measured direction		0,π	π/2	0,π	π/2
(dσ/dΩ) (10 ⁻¹³ cm ² /sr)	Experimental	-	3.3	-	6.4
	Theoretical	3.1	3.1	6.5* 7.7** 6.9***	5.9* 5.4** 5.7***

*Calculated on the basis of the two-photon process including the hyper-fine structure.

**Calculated on the basis of the two-photon process including the fine structure.

***Calculated from the absorption crosssection.

and D₂ lines, respectively. These values indicate a good agreement with theoretical values.

The laser radar system using this dye laser as a transmitter was installed at the Zao Upper Atmospheric Observatory, Tohoku University (140.5°E, 38.3°N) in order to detect the upper atmospheric sodium layer. A 50-cm diam Cassegrain telescope and a 10-channel photon counter were used for receiving the resonance backscatter. Seasonal variation of the structure of the sodium layer has been observed during 1972. Figure 1 shows one of the typical observed results performed on June 14-15, 1972, indicating the location of the sodium layer. As an interesting result of these measurements,

differential cross section for the resonance scattering of the sodium D₁ and D₂ lines. The theoretical values were calculated on the basis of two different interaction schemes; 1) absorption, and 2) two-photon process.

The cross sections measured at a right angle to the laser beam were 3.3X10⁻¹³ and 6.4x10⁻¹³ cm²/sr for D₁

Table 2.

Date	Time	Number density (10 ³ cm ⁻³)			Column density (10 ⁹ /cm ²)
		Altitude (km)			
		Peak 1	Peak 2	Peak 3	
Jun. 14	2220-0010	1.0 (90-95)	0.2 (120-125)		1.1
Oct. 7	0030-0435	1.0 (90-95)	1.2 (100-105)	0.9 (120-125)	3.1
Oct. 8	2050-2200	1.8 (75-80)	2.3 (90-95)	1.2 (120-125)	3.7
Oct. 10	0240-0440	2.9 (90-95)	1.6 (110-115)	1.7 (120-125)	7.2
Oct. 13	0340-0430	0.4 (90-95)	0.5 (115-120)		1.4

for instance, an increase in the N_a abundance was evidently observed just after the Jacobini meteoric shower on Oct. 8, 1972.

Table 2 illustrates the change of sodium density distribution before and after this meteoric shower. This result may give one of possible explanations concerning the origin of the atmospheric sodium.

Other experimental results will be reported in detail.

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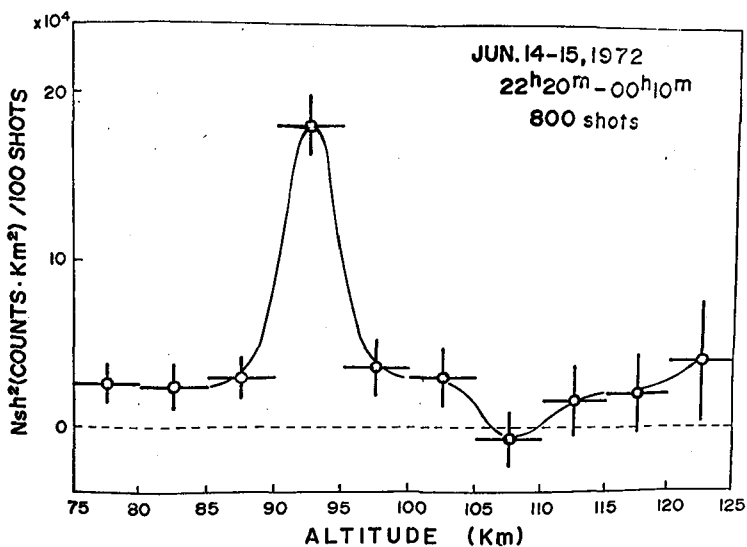


Fig. 1

FLUORESCENCE OF AMBIENT ATMOSPHERIC
AEROSOLS AND ITS IMPLICATIONS FOR REMOTE
DETECTION OF GASEOUS ATMOSPHERIC POLLUTANTS

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ABSTRACT

The visible fluorescence of aerosols in the ambient atmosphere has been monitored in situ using cw argon ion laser excitation.¹ Fluorescence was observed at 90° in bands of 500 and 1000 Å over the spectral range of 0.56 to 0.81 μm. Aerosol and nitrogen dioxide (NO₂) fluorescence and Mie scattering were monitored in the ambient air in practically real time. The buildup and decline of the aerosol levels and NO₂ concentrations were similar (Fig. 1).

The observed aerosol fluorescence can constitute a limitation upon the ability of a LIDAR to measure pollutant concentrations. The aerosol data in conjunction with measured Raman scattering from nitrogen permits estimates as to the extent of aerosol interference to remote Raman measurements.² For example, under severe aerosol loading in the Los Angeles basin, the fluorescence of aerosols generates a signal equivalent to 600 ppm of SO₂ when detecting the Stokes wavelength (bandwidth of 35 Å) excited at 4880 Å.

This limitation can be largely overcome by utilizing a two wavelength excitation method where the aerosol fluorescence is approximately constant while the molecular signals differ. For many LIDAR applications the background radiation exceed the molecular signals. Under this condition it is shown that the degradation in signal to noise ratio with aerosol fluorescence compared to the identical situation without aerosol fluorescence is directly proportional to (1-β); where β is the ratio of the molecular signals at the two wavelengths, β less than unity.

We have demonstrated the effectiveness of the two wavelength method by in situ measurements of atmospheric NO₂ levels in the presence of ambient aerosol fluorescence. Excitation was provided at 4965 Å and 5017 Å. The fluorescence signals from NO₂ monitored at 0.65 to 0.75 μm were twice as

large when excited 4965 Å as compared to 5017 Å excitation while the signals from the aerosol remained constant. The two wavelength scheme accurately measured the ambient NO₂ levels of several parts per hundred million (pphm). Therefore, by application of appropriate techniques, low pollutant concentrations may still be determined by LIDAR in the presence of aerosol fluorescence.

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FIGURE CAPTION

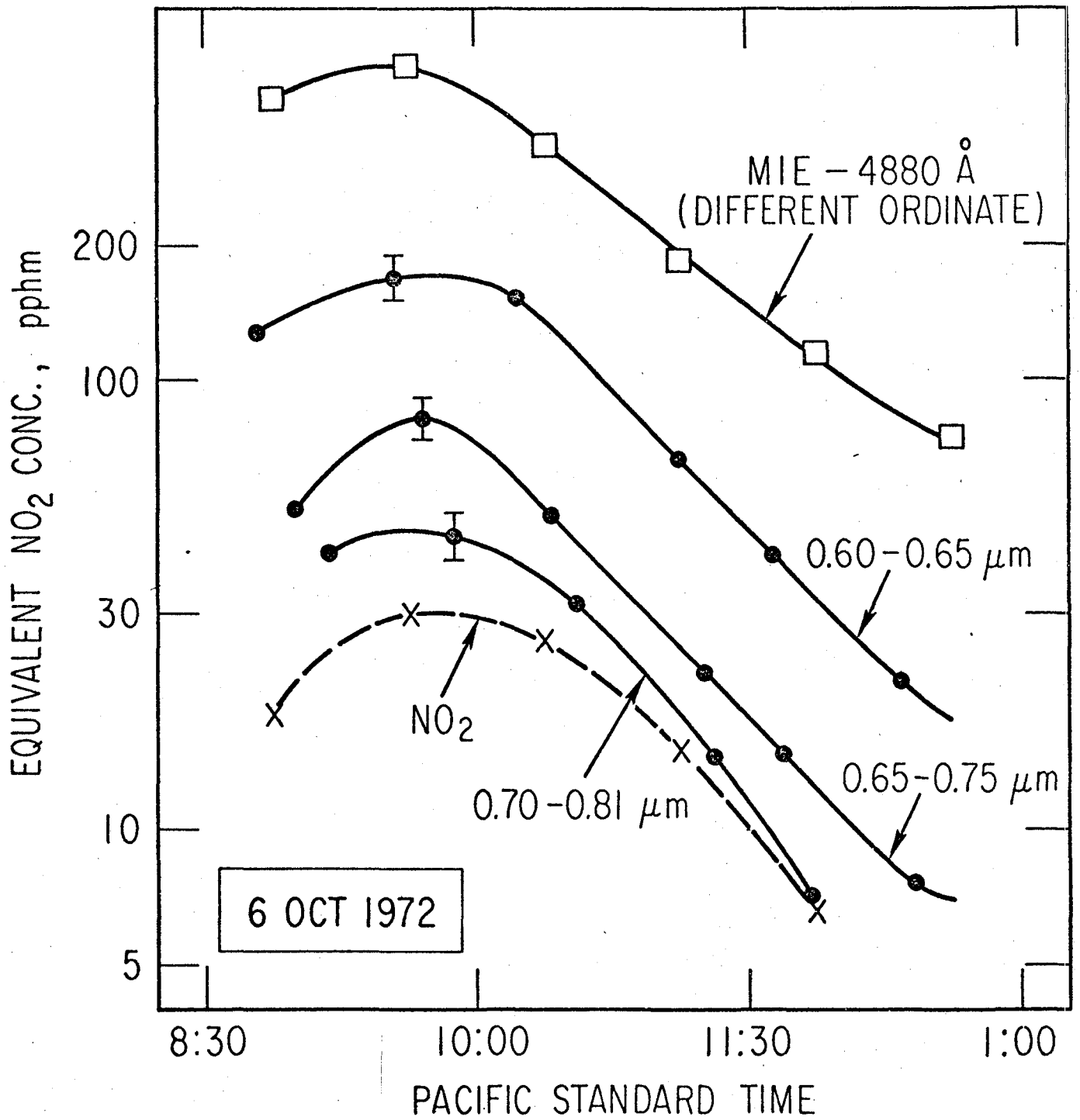


Fig. 1. Temporal variations of aerosols and NO₂ monitored by fluorescence in three spectral bands.

SO₂ SPECTROSCOPY WITH A TUNABLE UV LASER

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ABSTRACT

A portion of the fluorescence spectrum of SO₂ has been studied using a narrow wavelength doubled dye laser as the exciting source. One purpose of this study is to evaluate the use of SO₂ resonance re-emission as a probe of SO₂ in the atmosphere.

When the SO₂ is excited by light at 300.2 nm, for example, a strong re-emission peak is observed which is Stokes-shifted from the incident light wavelength by the usual Raman shift (the ν_1 symmetric vibration frequency 1150.5 cm⁻¹).

The intensity of this peak is sensitive to small changes (.01 nm) in the incident wavelength. Measurements of the N₂ quenching and self quenching of this re-emission have been obtained. Preliminary analysis of this data indicates that the quenching is weak but not negligible.

The dye laser in our system is pumped by a pulsed N₂ laser. Tuning and spectral narrowing are accomplished using a telescope-echelle grating combination. In a high power configuration the resulting pulses have a spectral width of about 5×10^{-3} nm and a time duration of about 6 nsec. The echelle grating is rotated by a digital stepping motor, such that each step shifts the wavelength by 6×10^{-4} nm.

In addition to the tunable, narrow wavelength uv source and spectral analysis of the consequent re-emission, the system also provides time resolution of the re-emitted light to 6 nsec resolution. This capability is being used to study the lifetime of low pressure SO₂ fluorescence at different wavelengths and pressures.

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INELASTIC LIGHT SCATTERING PROCESSES

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ABSTRACT

Five different inelastic light scattering processes will be denoted by ordinary Raman scattering (ORS), resonance Raman scattering (RRS), off-resonance fluorescence (ORF), resonance fluorescence (RF), and broad fluorescence (BF). A distinction between fluorescence (including ORF and RF) and Raman scattering (including ORS and RRS) will be made in terms of the number of intermediate molecular states which contribute significantly to the scattered amplitude, and not in terms of excited state lifetimes or virtual versus real processes.

The theory of these processes will be reviewed, including the effects of pressure, laser wavelength, and laser spectral distribution on the scattered intensity.

The application of these processes to the remote sensing of atmospheric pollutants will be discussed briefly. It will be pointed out that the poor sensitivity of the ORS technique cannot be increased by going toward resonance without also compromising the advantages it has over the RF technique.

Experimental results on inelastic light scattering from I_2 vapor will be presented. As a single longitudinal mode 5145 Å argon-ion laser line was tuned away from an I_2 absorption line, the scattering was observed to change from RF to ORF. The basis of the distinction is the different pressure dependence of the scattered intensity. Nearly three orders of magnitude enhancement of the scattered intensity was measured in going from ORF to RF. Forty-seven overtones were observed and their relative intensities measured. The ORF cross section of I_2 compared to the ORS cross section of N_2 was found to be 3×10^6 , with I_2 at its room temperature vapor pressure.

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ATMOSPHERIC TEMPERATURE FROM RAMAN SCATTERING

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ABSTRACT

Raman scattering signatures are functions of the scattering-gas temperature, and are therefore of potential use for practical atmospheric temperature probes. The method described uses either ratios of pure rotational Raman scattering intensities for air utilizing various spectral bandpasses, or, alternatively, ratios of air-rotational to nitrogen-vibrational scattering intensities. Three aspects of work relating to the development of such probes are discussed in this presentation: (1) fundamental absolute Raman data,¹ (2) construction of air spectra from these data,² and (3) temperature-sensitivity of the signature.²

The fundamental data described are the absolute rotational and vibrational scattering cross sections. Recent measurements in this laboratory of rotational cross sections for N_2 , O_2 , and CO_2 are emphasized, as are their use in predicting absolute magnitudes of Raman scattering signals. Next is described the computation of air rotational Raman spectra as a function of temperature calculated through use of the experimentally-measured cross sections. The spectra are based additively upon nitrogen and oxygen contributions, since pure rotational Raman scattering from water vapor is very weak.

Finally, the sensitivity of the scattering intensity ratios to temperature is explored as a function of choice of spectral bandpass for the monitored rotational Raman scattering. Various compromises will be discussed which must be made in choosing bandpasses appropriate for specific purposes and experimental conditions.

1. This work was supported in part by NASA Lewis Research Center on Contract NAS3-15825. A more complete description of this material can be found in "Absolute Intensity and Polarization of Rotational Raman Scattering from N_2 , O_2 and CO_2 " by C. M. Penney, R. L. St. Peters, and M. Lapp, NASA Report No. OR-121091,² January 1973.
2. This work was supported in part by Aerospace Research Laboratories, Wright-Patterson Air Force Base on Contract F33615-71-C-1867. A more complete description of this material can be found in "Application of Light-Scattering Techniques for Measurements of Density, Temperature, and Velocity in Gas-dynamics," by M. Lapp, C. M. Penney, and J. A. Asher, Aerospace Research Laboratories, WPAFB, Report No. ARL 73-0045 (in press).

REMOTE MEASUREMENT OF ATMOSPHERIC
TEMPERATURES BY RAMAN LIDAR

by

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ABSTRACT

The Raman shifted return of a lidar, or optical radar, system has been utilized to make atmospheric temperature measurements. These measurements were made along a horizontal path at temperatures between -20°C and $+30^{\circ}\text{C}$ and at ranges of about 100 meters. The temperature data were acquired by recording the intensity ratio of two portions of the Raman spectrum which were simultaneously sampled from a preset range.

The lidar unit employed in this testing consisted of a 4 joule-10ppm laser operating at 694.3 nm, a 10-inch Schmidt-Cassegrain telescope, and a system of time-gated detection and signal processing electronics. The detection system processed three return signal wavelength intervals - two intervals along the rotational Raman scattered spectrum and one interval centered at the Rayleigh-Mie scattered wavelength. The wavelength intervals were resolved by using a pellicle beam splitter and three optical interference filters. Raman return samples were taken from one discrete range segment during each test shot and the signal intensities were displayed in digital format. The Rayleigh-Mie return was monitored continuously through standard oscilloscope display techniques.

The test site utilized to evaluate this measurement technique encompassed a total path length of 200 meters. Major components of the test site included a trailer-van housing the lidar unit, a controlled environment test zone, and a beam terminator. The control zone which was located about 100 meters from the trailer was 12 meters in length, 2.4 meters in diameter, and was equipped with hinged doors at each end. The temperature of the air inside the zone could be either raised or lowered with respect to ambient air through the use of

infrared heaters or a liquid-nitrogen cooling system. Conditions inside the zone were continuously monitored with a thermocouple rake assembly. The test path length was terminated by a 1.2 meter square array of energy absorbing cones and a flat black screen.

Tests were initially conducted at strictly ambient conditions utilizing the normal outside air temperatures as a test parameter. These tests provided a calibration of the Raman intensity ratio as a function of temperature for the particular optical-filter arrangement used in this system while also providing a test of the theoretical prediction formulated in the design of the system. Later tests utilized zone temperatures above and below ambient to provide temperature gradient data. These tests indicate that ten shots, or one minute of data acquisition, from a 100 meter range can provide absolute temperature measurements with an accuracy of $\pm 3^{\circ}\text{C}$ and a range resolution of about 5 meters. Because this measurement accuracy compares well with that predicted for this particular unit, it is suggested that a field-application system could be built with significant improvements in both absolute accuracy and range.

THE USE OF TUNABLE LASERS IN INFRARED
ATMOSPHERIC SPECTROSCOPY*

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ABSTRACT

A review will be given of tunable sources of coherent infrared radiation with particular emphasis on lead salt diode lasers. Characteristics such as linewidth, power output and mode tuning will be discussed.

High resolution tunable laser studies have been carried out for molecules of interest in atmospheric studies, such as H_2O , SO_2 , NO , CO and C_2H_4 . Measurements have been made on widths, strengths, shapes and relative positions of absorption lines. Dicke narrowing, hyperfine structure, Λ -doubling, and Stark and Zeeman tuning have been studied.

Air pollution measurements can be made with tunable infrared lasers; these include point sampling, long path atmospheric transmission, and heterodyne spectroscopy of remote emission sources. Online automobile exhaust measurements of ethylene, in situ smokestack measurements of SO_2 , and long path atmospheric measurements of ethylene will be described.

*This work was sponsored by the Department of the Air Force.

COMPARISON OF LIDAR METHODS FOR REMOTE MEASUREMENT
OF AIR POLLUTANTS

by
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ABSTRACT

This paper presents quantitative comparisons of several single-ended lidar techniques for the remote measurement of gaseous pollutants. These techniques are divided into two groups. The first group is based on the measurement of energy scattered directly by the gas of interest. The gaseous scattering processes considered are ordinary fluorescence, resonance fluorescence (also called resonance scattering), Raman scattering, and resonant (or nearly resonant) Raman scattering. The second group is based on the measurement of a characteristic differential absorption produced by the gas of interest at two discrete wavelengths, using energy scattered back toward the receiver by a remote reflector other than the gas of interest. The remote reflector may be intermixed with the gas of interest, as is the case with aerosols and atmospheric gases (principally nitrogen), or they may be fixed reflectors such as terrestrial objects or retroreflectors.

The detectability of a given material will depend on the magnitude and characteristics of the optical interaction with that material. The main characteristics of interest are the cross section, the response time, and the spectral response of the material relative to both the transmit and receive functions of the lidar. These characteristics and their implications for remote sensing will be reviewed for the four direct scatter processes and for the differential absorption technique.

The characteristic behavior of the direct backscatter technique is different from the differential absorption technique with respect to sensitivity, concentration of material, and the effect of range. For these reasons, the direct backscatter processes cannot be compared directly to the differential absorption technique. The two techniques can be compared for specific material and system configurations, however. This paper describes specific lidar system

configurations and gives the calculated performance level for these systems in both the direct backscatter and differential absorption modes for a wide variety of pollutant monitoring situations.

The results of this comparison of techniques indicate that the differential-absorption lidar technique can provide adequate range and sensitivity for a wide variety of pollution monitoring applications involving a number of interesting pollutant materials. No other single technique appears to provide these capabilities for such a wide range of materials.

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AN ERROR ANALYSIS OF THE DIFFERENTIAL ABSORPTION TECHNIQUE

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ABSTRACT

The measurement of the spatial distribution of atmospheric gases by means of a lidar operating in the absorption mode is presently being investigated by a number of groups. In this technique a pulsed laser is tuned to the center of an isolated absorption line of the gas under consideration and a measurement is made of the backscattered radiation as a function of distance. A similar measurement is then taken with the laser tuned to an adjacent window region so that the absorption and scattering processes of the atmosphere can be separated from those of the gas. The spatial distribution of the gas is obtained by differencing the logarithm of the ratio of the two measurements of back scattered power in such a manner as to obtain the differential absorption of the laser radiation by the gas with respect to the lidar range. This technique has been referred to by the mnemonic DASE (Differential Absorption of Scattered Energy). The purpose of this paper is to present an error analysis of the DASE technique with particular reference to the measurement of atmospheric water vapour.

The power captured by a lidar receiver is given by the expression:

$$P_{r\nu} = \frac{cJ_{\nu}A}{2R^2} \beta_{\nu} \exp - 2 \int_0^R (\gamma_{\nu} + 2\rho K_{\nu}) dr \quad (1)$$

An expression for $\bar{\rho}$ averaged over a distance ΔR can be obtained if equation (1) is evaluated at ranges R and $R + \Delta R$ for back scatter measurements made at frequencies corresponding to line center ($\nu=L$) and to the window ($\nu=w$).

$$\bar{\rho} (R) = \frac{1}{2K_L \Delta R} \left[\ln \frac{P_{rL}(R)}{P_{rL}(R+\Delta R)} - \ln \frac{P'_{rW}(R)}{P'_{rW}(R+\Delta R)} + T^* + B^* \right] \quad (2)$$

where

$$T^* = -2 \left[\gamma_L - \gamma'_W \right] \Delta R$$

$$B^* = \ln \frac{\beta_L(R+\Delta R)}{\beta'_W(R+\Delta R)} - \ln \frac{\beta_L(R)}{\beta'_W(R)}$$

The prime notation indicates that the window measurement is made at a time different than that of the line measurement.

$\bar{\rho}(R)$ can be determined from (2) if T^* and B^* are known. It can be shown that $\gamma_L \sim \gamma_W$ and $\beta_L \sim \beta_W$ for frequency shifts of $L - W$. Further, it can be demonstrated that if the measurement pairs are made within 10^{-3} seconds then $\gamma_L \sim \gamma'_W$ and $\beta_L \sim \beta'_W$. Consequently B^* and T^* can be taken to be zero for a suitably designed lidar system.

The variance in the deduced quantity $\bar{\rho}$ due to the nature of the measurement process can be shown to be approximately equal to the expression:

$$\frac{\sigma_{\bar{\rho}}^2}{\bar{\rho}^2} = \frac{\sigma_K^2}{K_V^2} + \frac{1}{\bar{\rho}^2 K_V^2 \Delta R^2} \cdot \frac{\sigma_{Pr}^2}{P_r^2} \quad (3)$$

The first bracketed term represents that portion of the fractional variance of $\bar{\rho}$ which is accounted for by uncertainties in the knowledge of K_V . The uncertainty in K_V arise from unknown variations of temperature and pressure along the path of the lidar path as well as in the knowledge of v .

$$\frac{\sigma_K^2}{K_V^2} = a \frac{\sigma_T^2}{T^2} + b \frac{\sigma_P^2}{P^2} + \left[\frac{\Delta M^2}{(2 nt \alpha_L)^2 + \Delta M^2} \right]^2 \quad (4)$$

Here a and b are of the order of unity. ΔM gives the uncertainty in the axial mode number for a laser whose cavity length is nt , tuned to a Lorentz line whose half width is α_L .

Substitution of typical parameters into equation (4) leads to an estimate of the fractional standard deviation of K_V to be approximately 5%.

The second bracketed term of equation (3) involves $\frac{\sigma_{pr}}{P_r}$ which is the noise to signal ratio of the measured back scattered power. The information content of the measurement is equal to the absorption of the laser radiation over the path ΔR . Therefore the uncertainty in the deduced value of ρ will depend upon the noise to signal value of the measurement divided by the power loss in ΔR . ΔR is normally taken so that the product $\rho K \Delta R$ is approximately 0.1. Therefore the fractional standard deviation of ρ is of the order of 10 times the noise to signal ratio of the power measurement.

An application of the analysis presented will be made to the measurement of tropospheric water vapor by the DASE technique.

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LASER RADAR STUDY USING RESONANCE ABSORPTION
FOR REMOTE DETECTION OF AIR POLLUTANTS

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ABSTRACT

A laser radar using resonance absorption has an advantage of increased detection range and sensitivity compared with that achieved by Raman or resonance back scattering .

In this paper, new laser radar system using resonance absorption is proposed and results obtained from this laser radar system are discussed.

NO_2 , SO_2 gas has an absorption spectrum at 4500 \AA and 3000 \AA respectively as shown in Fig. 1. A laser light including at least a set of an absorption peak λ_1 and a valley λ_2 is emitted into a pollutant atmosphere. The light reflected with a topographical reflector or an atmospheric Mie scattering as distributed reflectors is received and divided into two wavelength components λ_1 , λ_2 . From the ratio of these two components $Y(x)$, the distribution of the pollutant gas $n(x)$ can be calculated by

$$n(x) = \frac{1}{2(\sigma_1 - \sigma_2)} \frac{dY(x)}{dx}$$

, where σ_1 , σ_2 correspond to the absorption cross sections of the pollutant gas at λ_1 and λ_2 respectively.

The laser radar system used in the investigation is shown in Fig. 2 and consists of a dye laser transmitter, an optical receiver with a special monochromator and a digital processor. Table 1 shows the molecular constants of NO_2 , and SO_2 and the dye laser used in this experiment.

		NO ₂	SO ₂
λ_1	(\AA)	4482	3001
λ_2		4469	3014
$\sigma_1 - \sigma_2$ (cm ²)		2.0×10^{-19}	2.5×10^{-18}
$\lambda_1 - \lambda_2$ (\AA)		13	13
Dye Material		calcein blue	SHGed Rhodamine B
Spectrum width (\AA)		30	30
Pumping Source		Sum of SHGed and fundamental Nd: YAG	SHGed Nd: YAG

Table 1 Molecular constants of NO₂ and SO₂ and dye laser used

In this system, the absolute concentration of the pollutant gas can be measured in comparison with a standard gas cell. The concentration of NO₂, SO₂ as low as 0.1 ppm have been measured at 100 m depth resolution. For a 1 mJ laser output, the observable range of this system achieved up to 300 m using the distributed Mie reflector.

The capability and technical limitation of the system will be discussed in detail.

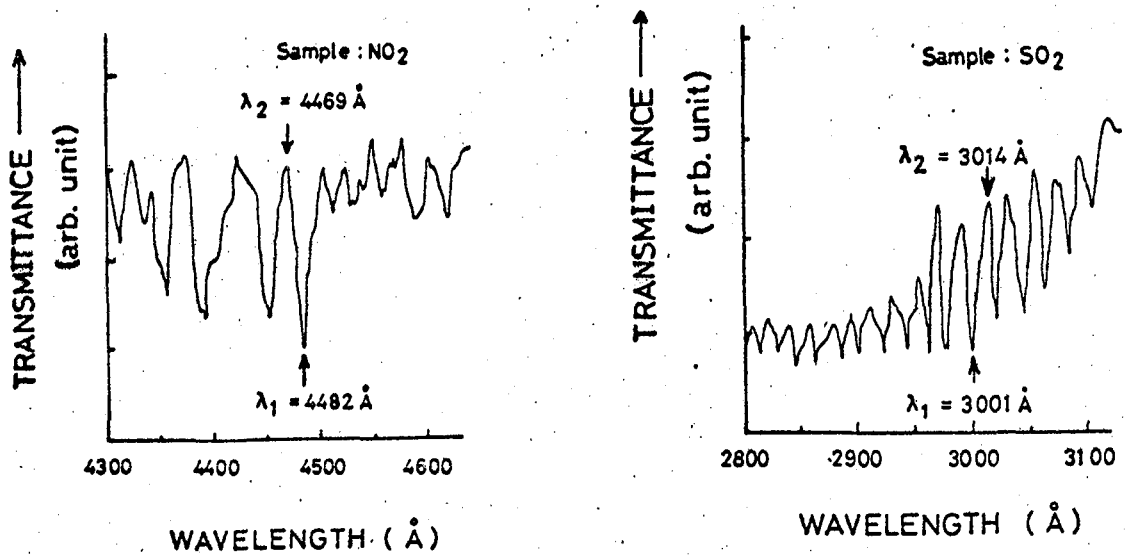


Fig.1 Absorption spectrum of NO₂ and SO₂

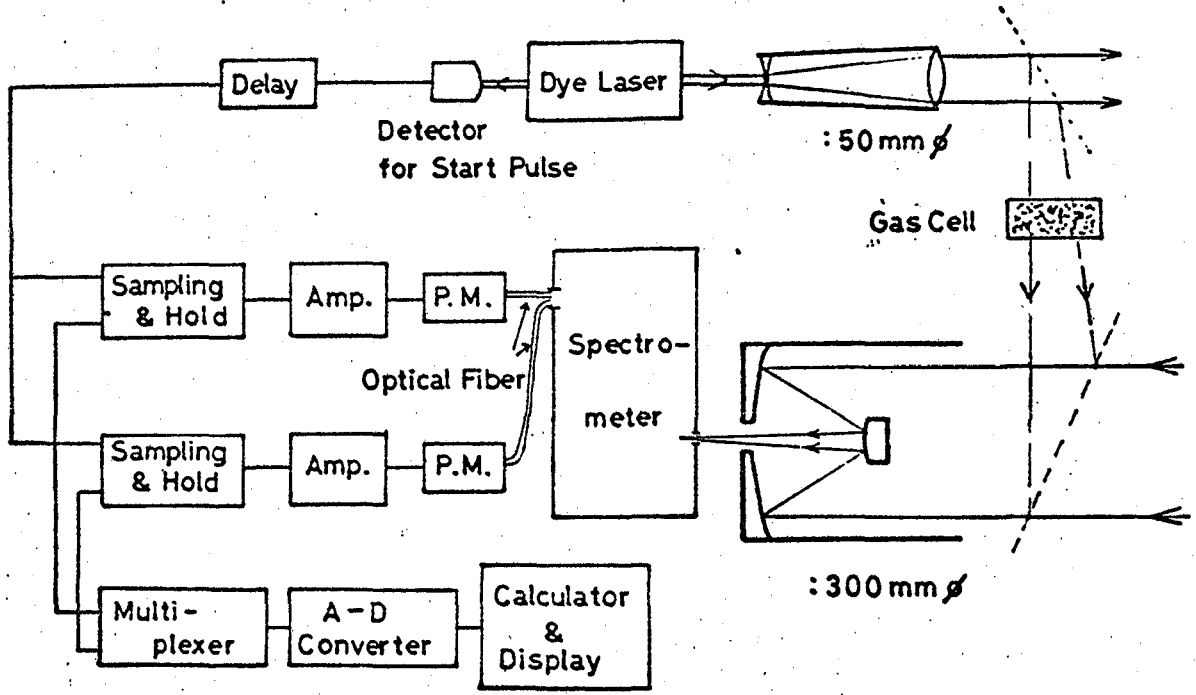


Fig.2 Schematic diagram of laser radar system using resonance absorption for detection of air pollutants.

DETERMINATION OF SPATIAL DISTRIBUTION
OF AIR POLLUTION BY DYE LASER MEASUREMENT OF
DIFFERENTIAL ABSORPTION OF ELASTIC BACKSCATTER

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ABSTRACT

This paper presents the results of an analytical study of a lidar system which uses tunable organic dye lasers to accurately determine spatial distribution of molecular air pollutants. Also described will be experimental work to date on simultaneous multiwavelength output dye laser sources for this system.

Basically the scheme determines the concentration of air pollutants by measuring the differential absorption of an (at least) two wavelength lidar signal elastically backscattered by the atmosphere. Only relative measurements of the backscattered intensity at each of the two wavelengths, one on and one off the resonance absorption of the pollutant in question, are required.

The various parameters of the scheme are examined and the component elements required for a system of this type discussed, with emphasis on the dye laser source. Potential advantages of simultaneous multiwavelength outputs are described. The use of correlation spectroscopy in this context is examined. Comparisons are also made for the use of infrared probing wavelengths and sources instead of dye lasers.

Estimates of the sensitivity and accuracy of a practical dye laser system of this type, made for specific pollutants, show it to have inherent advantages over other schemes for determining pollutant spatial distribution.

REMOTE SENSING OF METHANE USING AN ERBIUM/YAG LASER:
A FEASIBILITY STUDY

by

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ABSTRACT

A program is underway to determine the feasibility of a remote sensing scheme for the detection of methane based on a coincidence between the emission of the Erbium/YAG laser and a methane absorption line. This recently discovered coincidence occurs with the R(6) line in the $2\nu_3$ overtone band of methane. The methane line is centered at 1645.1nm and is about 0.1nm wide; the Erbium/YAG laser emission is centered at 1644.9nm and is about 0.6nm wide. Theory indicates that the absorption line is composed of four or more components, and initial measurements indicated that there was structure in the line.

Two remote sensing techniques are being considered: the differential absorption transmission method and the differential absorption backscatter technique. In order to obtain results, the line parameters for the methane absorption line are needed. However, very little information is available on this absorption line. The research program consists of an experimental part, to determine the spectral line parameters, and a theoretical part, to determine performance. The experimental program consists of two parts: a measurement of the absorption coefficient for the line, and measurements to determine the structure of the line and the positions, halfwidths, and strengths of the

components. The theoretical program was also divided into two sections. The first was a study using the best available data. The second part uses more accurate experimental data as it becomes available. The results of the study using the best available data indicate for the differential absorption transmission method that if the receiver system can detect a 1% change in transmission, then a 5% change in the methane concentration can be detected with a range of 100m to 8km, depending on the value of the absorption coefficient. Results of this study have been plotted as change in transmission versus range for various changes in the methane concentration for several values of the absorption coefficient. The bounds on the parameters were: minimum detectable change in transmission, 0.01 to 100%; range, 1m to 10km; change in methane concentration, 1 to 5000%, and absorption coefficient, 0.025 to 1.65 ppm⁻¹km⁻¹.

For the differential absorption backscatter technique, preliminary work consisted of comparing the available methane line parameters with those of the O₂ and H₂O lines in the region of the ruby laser emission. A detection scheme based on the ruby laser is feasible for the detection of O₂ and H₂O. The data indicates that the absorption coefficient for the absorption lines of methane are up to an order of magnitude larger. However, the wavelength dependence of the scattering and the detector parameters available at 1.6 micrometers combine to decrease the available signal by 2 to 3 orders of magnitude.

The above results indicate that the measurement of methane using an Erbium/YAG laser and the differential absorption transmission technique is feasible. However, the use of the differential absorption backscatter method appears marginal unless sophisticated detection methods, such as photon counting, are used. Results of the experimental program and the second part of the theoretical program will also be presented.

ON ATMOSPHERIC TEMPERATURE MEASUREMENT
BY LIDAR DIFFERENTIAL ABSORPTION

by

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ABSTRACT

The differential absorption of laser energy in the atmosphere by different lines within a molecular rotational band can be measured to obtain the relative strength of the lines. Since line strengths are directly related to local temperature via the partition function, a method for measuring temperature is suggested.

By considering the propagation of lidar energy at both absorbed and non-absorbed wavelengths, a simple relationship has been derived via the lidar equation which expresses the temperature of the absorbing gas in terms of the backscattered signals only. It is found that the temperature is related to the ratios of the scattered powers and the spatial derivatives of these ratios.

A computer program incorporating resonance absorption has been used to calculate the lidar returns from model atmospheres and to compute temperatures using the appropriate partition functions. It is found that the computer values closely follow the temperature profile of the chosen model. It is further found that the required measurable factors, namely the power ratios and their spatial derivatives, exhibit an appreciable sensitivity to temperature variations, even over relatively short path increments and for relatively weak absorptions.

These calculations were based on the absorption lines in the 1-0 band, $3\Sigma^- - 1\Sigma^+$ transition, of the O_2 molecule. Some of these lines lie in the tuning range of the ruby laser. Line parameters were estimated from data obtained from R. K. Long (Ohio State University).

Laser emissions were assumed monochromatic and simultaneously occurring

at three wavelengths, two of which were centered on absorption lines on opposite sides of one branch of the band and the other lying between lines. The choice of lines is based on the fact the lines on one side of a branch increase in strength while those on the opposite side decrease as temperature is varied. In this way the sensitivity of the measurement is optimized. The simultaneity and superposition of the pulses allow the assumption of identical atmosphere paths in treating their propagation characteristics, and thus eliminate pulse-to-pulse variability in the returns and allows real-time analog processing methods to be considered.

Another feature of the method is that the measurement of temperature is an absolute rather than a relative one and does not require any tie-on-measurement at some reference point along the path.

RAMAN SCATTERING FROM ATMOSPHERIC NITROGEN IN THE STRATOSPHERE

by

M. J. Garvey & G. S. Kent

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ABSTRACT

The Mark II laser radar system at Kingston, Jamaica, has been used to make observations on the Raman shifted line from atmospheric nitrogen at 828.5 nm. The size of the system makes it possible to detect signals from heights of up to 40 kilometres. The effects of aerosol scattering observed using a single wavelength are almost eliminated, and a profile of nitrogen density may be obtained. Assuming a constant mixing ratio, this may be interpreted as a profile of atmospheric density whose accuracy is comparable to that obtained from routine meteorological soundings.

In order to obtain an accurate profile several interfering effects have had to be examined and, where necessary, eliminated. These include:

- 1) Fluorescence in optical components
- 2) Leakage of signal at 694.3 nm.
- 3) Overload effects and non-linearities in the receiving and counting electronics.

Most of these effects have been carefully examined and comparisons are being made between the observed atmospheric density profiles and local meteorological radio-sonde measurements. Good agreement has been obtained over the region of overlap (15 - 30 Km), discrepancies being of the same order as the experimental accuracy (1-10%), depending on height and length of period of observation.

LASER RADAR MEASUREMENTS OF ATMOSPHERIC POTASSIUM

by

F. Felix,† W. Keenlside,† G. S. Kent† and M. C. W. Sandford*

ABSTRACT

A dye laser capable of transmitting in the near infra red region of the spectrum has been constructed to be used in conjunction with the large Mark II laser system at present in existence at Kingston, Jamaica.

Preliminary measurements have been obtained of concentration of atomic potassium in the 70-100 km region of the atmosphere. The data indicates the likelihood of a double peak in the height distribution. The lower peak, which is the larger, is at a height of about 82 km, the upper peak is at a height of 94 km. Although an exact value for the scattering cross-section has not been obtained, a reasonable approximation of this parameter yields a value of about $1-15 \times 10^{11} \text{ m}^{-2}$ for the column density of atomic potassium, which is in agreement with other data.

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FEASIBILITY OF REMOTE MEASUREMENT OF SO₂ AND NO
IN SMOKE STACK PLUMES

by

E. K. Proctor*, M. L. Wright†, Graham Black**

ABSTRACT

Enforcement of pollution abatement regulations can, in many instances, be abetted by use of portable remote monitoring instruments that do not require cooperation by emitters or access to their facilities. Two of the most important pollutant emissions from fixed sources are SO₂ and NO, especially from coal-fired power plants. Both of these gases have absorption and fluorescence spectra in the eye-safe near-ultraviolet region of the spectrum that offer potential mechanisms for remote measurement with lidar equipment. Prospective ways of realizing these potentials are analyzed in this paper. The effectiveness of the ozone layer in reducing the daytime background noise level is also examined. The problem of achieving adequate penetration of plumes by probing signals at the concentration levels of interest is addressed, and a promising way of overcoming this difficult penetration problem is described.

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**Molecular Physics Group

DETECTION OF SO₂ AND NO₂ IN STACK PLUME BY RAMAN SCATTERING

AND FLUORESCENCE

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ABSTRACT

We have been studying laser-Raman radar which can be used as the remote detector of SO₂ concentration in the stack plume of boiler exhaust gas, and some results have been published¹⁾.

In this paper, we report the interference of NO₂ fluorescence against SO₂ Raman scattering and the measuring method of SO₂ and NO₂ concentration.

In a stack plume, high density dust and high concentration CO₂ are included, therefore very strong Mie back-scattering and CO₂ Raman scattering are observed. The separation of these scattering signals from SO₂ Raman signal was the first problem for the laser-Raman radar. But, this problem was solved by using the filter which have high resolving power.

It is well known that NO₂ can be excited to emit fluorescence of broad spectrum by blue-green light. The light source of the laser-Raman radar is SH of Nd:YAG laser, and boiler exhaust gas includes several tens ppm of NO₂, then the interference of NO₂ fluorescence brings the error to SO₂ measurement.

The rejection of the interference can be achieved by the subtraction of the NO₂ fluorescence contribution from detected signal at SO₂ Raman scattering wavelength. The NO₂ fluorescence contribution can be measured by two methods. The first is to convert the NO₂ fluorescence intensity which is measured at a different wavelength from SO₂ Raman line into the one at SO₂ Raman line. The second is to convert the detected signal intensity, which is obtained when the range gate is set just behind the plume, into the one obtained at the range of the plume using the difference of the time dependence between SO₂ Raman scattering and NO₂ fluorescence. NO₂ fluorescence has lifetime of about 300nS, while Raman scattering has none.

By either of the two methods, the contribution of NO₂ fluorescence is determined. Then, we can measure the NO₂ and SO₂ concentration.

The minimum detectable concentration and the experimental results of the remote sensing of SO_2 and NO_2 in stack plume will be discussed in detail.

Reference

- 1) S. Nakahara et al. Opto-Electronics 4(1972) 169-177.

LIDAR OBSERVATIONS OF RAMAN SCATTERING FROM SO₂

IN A POWER PLANT STACK PLUME

By M. L. Brumfield, S. H. Melfi, and R. W. Storey, Jr.

ABSTRACT

LIDAR techniques have been successfully applied to the detection of the Raman backscatter from SO₂ in the plume of a 200 megawatt coal-burning electrical-generating plant from a distance of 210 meters. The LIDAR system used consists of a 61 cm diameter, f/4 Newtonian telescope and 1.0 - 1.5 joules-per-pulse, 1 pulse-per-second ruby laser. Narrow band interference filters are used to select the 7546 Å ν_1 vibrational line of SO₂. The signal from a photomultiplier tube was sequentially applied to each 254 nsec wide channel of a 15-channel photon counting system, resulting in a direct correlation between channel number and range increment. Photon counts were accumulated from the backscatter of a number of laser pulses (typically 50 or 100), and the accumulated counts per channel printed on paper tape.

One sequence of measurements was made during a two-hour period while the plant electrical output was being reduced by approximately 50%. Although the Raman system had not been quantitatively calibrated, the LIDAR data correlated well with the varying plant electrical output. N₂ scattering observations were also made and an approximate quantitative SO₂ concentration obtained by ratioing the SO₂ data to N₂ data. This ratio compared well to the in-situ measurements made during the same period by Environmental Protection Agency sampling instruments.

RAMAN LIDAR MEASUREMENT OF AIRCRAFT
TURBINE ENGINE EXHAUST EMISSIONS

by

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ABSTRACT

A program is currently underway to demonstrate the use of laser Raman backscattering as a means to measure the composition and temperature of aircraft engine exhaust emissions.

The physical property of turbine exhausts that most significantly influences Raman spectroscopic analysis is the relatively low pollutant concentrations in combination with elevated temperatures such that significant upper level excitations can occur with subsequent broadening and overlapping of the Raman spectra. These effects must be correctly taken into account if Raman scattering is to be used for quantitative gas analysis at elevated temperatures.

An experimental lidar unit was constructed using a 0.5 watt average power 3371 Å pulsed nitrogen laser, a 24-inch diameter Dall-Kirkham Cassegrainian-type receiver telescope and a 1 meter, double, scanning spectrometer for spectral analysis. The entire system operation is controlled by computer, including calibration, data collection and data analysis.

Preliminary experimental results will be presented.

A METHOD OF MONITORING NON-RESONANT RAMAN LIDAR
RETURNS DURING DAYLIGHT HOURS

by

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ABSTRACT

A method for using non-resonant Raman lidar during daytime hours is presented.

A dual (or quadruple) arrangement of electro-optical channels is set up in the lidar receiver. Each channel contains its own optical spectral response as determined by an appropriate set of interference filters. The incoming signal is split and fed into two channels, filtered (simultaneously) and then inserted into the input terminals of an operational amplifier. The difference signal is selected and amplified whereas the common portion of the signal is highly attenuated (Common Mode Rejection Ratio = 75-80db). For the present hardware, daylight intensities 10^2 - 10^3 times Raman signals are received simultaneously. Mean values of intensities of daylight signals which give rise to a constant differences merely shift the value of the measured variable at the ground. These mean value signals have their common part highly attenuated.

The differences of the fluctuation portions of the daylight signal represents a noise signal. Identical (space-time) optical paths for each component of the daylight signal produce the same fluctuational spectra in each channel. Hence noise levels, much less than signal levels, are anticipated.

First a N_2 - H_2) signal pair is differenced. Then an N_2 - O_2 pair is differenced and used for instrumental normalization purposes.

Signal levels to be encountered are quite well known as a result of prior field work.

Improved optical design of laser system can reduce mean value of daylight intensities by 10^2 . Thus the mean daylight intensity can be set equal to the expected signal levels by more advanced optical design.

Performance characteristics of photomultiplier pairs are discussed in this connection.

LIDAR DEVELOPMENT AT SRI - THE FIRST DECADE

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ABSTRACT

On 22 July 1963 the first lidar observations of the lower atmosphere were made at SRI with a pulsed ruby system developed by a team led by the late Myron G. H. Ligda. Since that time SRI has carried out a continuous program of exploration and development of the technique, primarily related to applications in atmospheric research in the troposphere.

In this frankly personal retrospective, some of the highlights of this ten years are reviewed, both in terms of progress made and difficulties experienced. Topics discussed will include the technological aspects of the lidar systems used, the range of applications identified and explored and the various forms of information recovery and display that have been developed.

LIDAR SCATTERING IN THE TROPOSPHERE

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ABSTRACT

This paper describes measurements of the properties of the backscattered signals from a ruby laser radar obtained under a variety of atmospheric conditions. The lidar system constructed for these measurements employs the fundamental (694.3nm) and second harmonic (347.2nm) ruby wavelengths. A Pockel's cell and polarizer in the cavity are used to provide a linearly polarized Q-switched output with energies up to 3 Joules at the fundamental. A KDP doubler external to the cavity provides the second harmonic. The pulse duration is approximately 15 ns and the pulse repetition rate is about 10 pp min. The transmitter collimator provides an output beam 5 cm in diameter with a divergence less than one milliradian.

Four optical receivers are equipped with rotatable polarizers and retardation plates, interchangeable narrow band filters and photomultipliers to detect the backscatter signal. The main receiver channel is a 20 cm diameter Newtonian telescope and the other three are refractive telescopes with 7.5 cm apertures. With this system it is possible to measure the complete polarization properties of the backscattered signal at either wavelength with a single transmitted pulse. This feature permits the study of rapidly changing atmospheric properties whose polarization properties could not be obtained by sequential firings.

A parameter of particular interest is the depolarization, δ , which is determined from the relation $\delta = P_r/P_\ell$ where P_r and P_ℓ denote the backscattered power polarized perpendicular and parallel to the transmitter polarization. This parameter is very easily measured and is found to vary greatly with atmospheric conditions. Measurements with this system have been in progress for

about two years and provide considerable information on the variation of the backscattered signal polarization for a variety of meteorological conditions at altitudes up to about 10km. For "clear" (urban) air δ is typically of the order of 0.2 but it can vary between 0.05 and 0.9 while well developed hazes have δ generally smaller than 0.1. For fog, δ values at both wavelengths are around 0.1 and higher. Snow gives values of δ of the order of unity. Clouds exhibit depolarizations covering the whole range from about zero to unity and in many cases the presence of multiple scattering is clearly seen in the increase of depolarization with penetration depth. Cloud measurements show considerable variation of δ with altitude and the results indicate that polarization signatures could be useful for cloud characterization and classification.

LIDAR MEASUREMENTS OF THE THERMIC STRUCTURE IN THE TROPOSPHERE

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ABSTRACT

Lidar measurements by UTHE (1972) and similar measurements with acoustic radar by HALL (1972) have shown, that short time variations in the troposphere can be determined.

Aerosol backscatter measurements give the vertical structure. A series of such results shows the time variation of the tropospheric structure. The Figure is an example for a measuring period during half an hour in summer 1972 (1 pulse per minute). These variations were produced by humidity variations. For example, at humidity variations from 75% to 77% aerosol particles with 1 micron radius change their radii during 50 to 100 milliseconds. By lidar technique it is possible to determine this effect qualitatively. With a pulse repetition rate of 1 per second we plan to investigate the thermic structure at different weather conditions.

By simultaneous measurements of the nitrogen Raman component it would be possible to compare the short time variations by temperature and humidity. The influence of wind can be determined by scanning a defined region (region or space).

The meteorologist is interested in results of short time variations in the troposphere (microscale). By this remote sensing method he can get these values continuously.

UTHE, E. E. 1972: 4th laser radar conference, Tucson

HALL, F. F. 1972: Short Course in Remote Sensing, Boulder

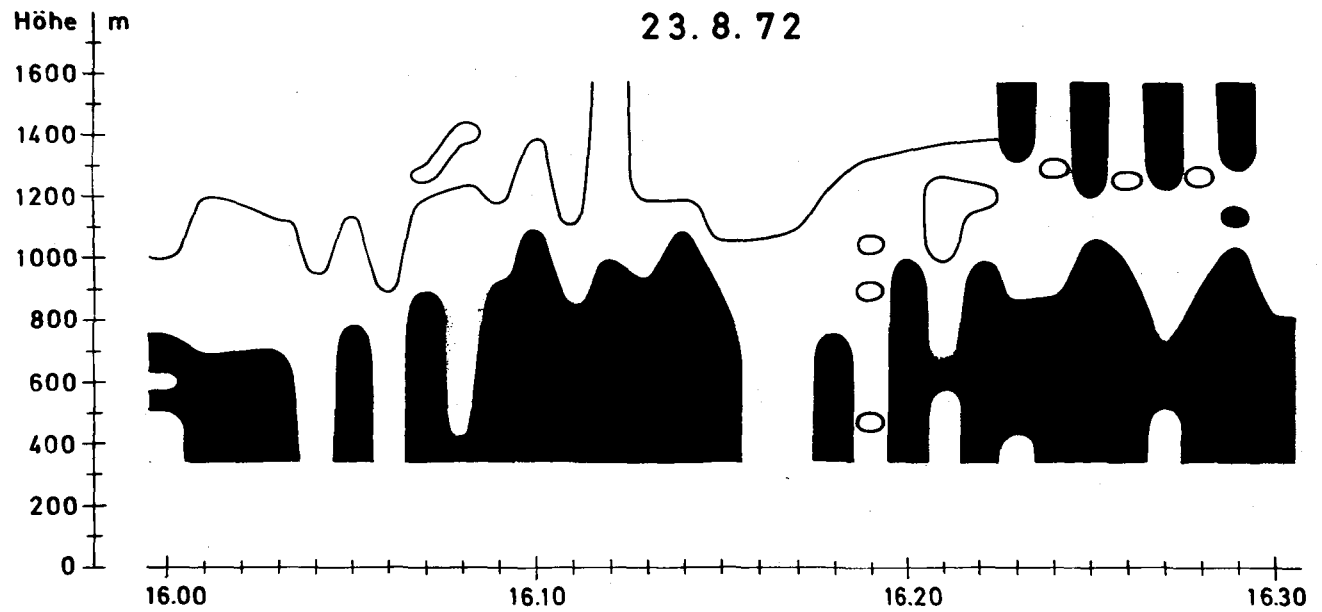


Figure : Time variation of the tropospheric structure

LIDAR MEASUREMENTS OF ON-SHORE WIND DIFFUSION

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ABSTRACT

The concept to place electric power generating stations on the oceans off the coast of the United States has instilled new efforts in research for improved understanding of the diffusion properties of the atmosphere in the ocean-air interface.

The Atomic Energy Commission has instigated a program by the Meteorology Group at Brookhaven National Laboratory to investigate the low level, on-shore wind systems that dominate many of the coastal regions. Analytical techniques and specialized instrumentation from previous studies at Brookhaven are being used in this new program. The Brookhaven Lidar system is used to measure some of the physical properties of the oil-fog plume originating from a portable smoke generator on a boat off the coast. The oil-fog plume is used as a tracer which can be observed, photographed and measured to determine the diffusive power of the atmosphere associated with the ocean-air interface and the discontinuities found in the ocean-land boundary.

This paper will describe the program rather briefly and the oil-fog scattering measurements that have been made with the Lidar system.

This abstract submitted for presentation at the Fifth Conference on Laser Radar Studies of the Atmosphere, June 4-6, 1973, Williamsburg, Va.

Sponsored by

1. Group on Laser Atmospheric Probing
2. American Meteorology Society
3. Optical Society of America

ESTIMATING VERTICAL DIFFUSION COEFFICIENTS BY LIDAR

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ABSTRACT

The Atmospheric Turbulence and Diffusion Laboratory at Oak Ridge, Tennessee has been conducting routine probing of the lower troposphere and comparing the results with those obtained with turbidity photometers and a distant suspended particulate station. The change in scale height, K_z/v_s , with time permits the vertical turbulence coefficient K_z to be estimated if V_s is known or assumed. Extremely high monthly correlations of turbidity vs. the log of backscatter at 100 meters have been obtained. In addition, high correlations of suspended particulate matter at Chattanooga and Oak Ridge suggest that the bulk of particulate matter is of natural, rather than industrial, origin.

ATMOSPHERIC AEROSOL AND THERMAL STRUCTURE
IN THE BOUNDARY LAYER OVER THE LOS ANGELES BASIN*

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ABSTRACT

A field study using a mobile lidar was recently conducted in the L. A. Basin, California, to (1) examine the relationship between the vertical aerosol and the thermal structure, and (2) map the vertical aerosol structure in the atmospheric boundary layer over the basin. These data are needed for use in the development of a mixing-depth submodel required for photochemical air quality simulation models. Toward these ends, a series of lidar aerosol measurements in conjunction with balloon and aircraft temperature soundings were taken at a site in El Monte, and in a mobile mode along a 90-mile freeway loop between El Monte, Santa Monica, and Long Beach. The lidar data are presented in the form of time-height and distance-height cross sections. The results indicate that, although aerosol concentrations are frequently present above the base of the marine inversion, these are generally in stratified layers in contrast to the more uniform nature of the lower convective layer, permitting the mixing depth to be distinguished on this basis. The lidar-derived mixing depths are well correlated (within 100 m) with daytime temperature inversions. Other significant features shown by the lidar data include large Basin-wide mixing-depth variations, waves with amplitudes of 200-300 m and wavelengths of 1000-1500 m on the lower aerosol layer, and apparent aerosol "chimneys" with overrunning in the vicinity of convergence zones.

* This work was performed while the author was affiliated with the Meteorology Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, N.C.

LASER SOUNDING OF INDUSTRIAL MIST

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ABSTRACT

A ruby lidar has been installed at about 2 km from the pollution sources.

The profiles of the backscattering factor σ_{π} and attenuation factor α are obtained by the probing in different directions. The absolute laser calibration has been realized that permits to solve a laser radar equation using layered restitution of profiles σ_{π} and α . The value of a phase function γ_{π} in 180° direction is estimated in the surface boundary layer assuming the atmosphere being homogeneous in a horizontal plane. In this case a logarithm of the signal value multiplied by distance square is a straight line according to the slope of which α can be found and the laser radar equation can be solved.

Thus estimated values of γ_{π} oscillate about average value of 0.033 with the root-mean-square deviation ± 0.0105 . An average value of a phase function is used for solving the laser radar equation when it is impossible to estimate γ_{π} .

The solutions obtained allow to derive the field of σ_{π} values and compare these data with dustiness estimated by direct sampling. A comparison proves to be possible with an error up to 70 per cent. Feasible reasons for obtaining poor agreement of the optical measurements with the results of sampling are discussed.

Some attempts have been taken up to restore the profile at σ_{π} along vertical and inclined routes. An essential inhomogeneity of the atmosphere is observed in the horizontal direction up to 1800 m height. This makes determination of vertical transparency by probing along different zenith directions to be of little use under the industrial city conditions. Estimate

of the concentration gradient of contaminating impurity proves to be possible at different altitudes.

The layers of increased turbidity are observed at 1200-1700 m height. The statistical relation between the existence of such layers and the dustiness of the surface boundary layer is found. The coefficient of correlation between the value of σ_{π} at 1500 m level and the value of dustiness in the boundary layer is estimated to be 0.72.

TROPOSPHERIC TRANSMISSIVITY MEASUREMENTS USING THE
RAMAN NITROGEN LIDAR TECHNIQUE

by

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NASA - Langley Research Center

ABSTRACT

LIDAR measurements in Azusa, California, during October 1972, were made in which the backscattered Raman-shifted nitrogen return was ratioed at different altitudes in order to obtain transmissivity. Rawinsonde data from nearby El Monte were used to determine the temperature and nitrogen number density altitude profiles.

These data and other meteorological data are compared to the vertical aerosol and transmissivity structure determined by LIDAR. Also data analysis techniques are shown for obtaining q^2 (transmissivity) and β (attenuation coefficient) as a function of altitude.

A COMPARISON OF ATMOSPHERIC STRUCTURE AS
OBSERVED WITH LIDAR AND ACOUSTIC SOUNDER TECHNIQUES

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ABSTRACT

During the METROMEX* 1972 field program, Stanford Research Institute (SRI) and Argonne National Laboratories (ANL) conducted a joint lidar and acoustic sounder data collection program in a manner that readily allows comparison of atmospheric structure observed with these instruments. A preliminary analysis of the data has been completed and it is the purpose of this paper to present these results.

The SRI Mark IX lidar uses a Pockels cell Q-switched ruby laser capable at firing at 60 pulses/min with an energy output of approximately 1.0 joules/pulse. A 2-inch transmitter lens is coaxial with a 6-inch Newtonian receiver. Lidar backscatter signatures were electronically corrected for the inverse range-squared dependence, logarithmically amplified, and stored on a magnetic video-disc recorder. Each of the 1000 tracks of the disc can contain up to 160 lidar signatures and these signals can be fed through electronics that produce intensity-modulated cross-sections of aerosol structure.

The ANL acoustic sounder emits sound pulses of approximately 100 ms in duration, 100 watts (RMS) in power, and near 1000 Hz in frequency. The transmitter and receiver uses a five-foot diameter parabolic dish with the transmitter/receiver transducer mounted at the focus. During the field

*METROpolitan Meteorological EXperiment--an investigation of weather modification by urban effects. The SRI program was supported by NSF Grant GI-34770 (Environmental Systems and Resources, Weather Modification Program).

program, a sound pulse was emitted every 12 s and the detected backscattered energy from each pulse was filtered, logarithmically amplified, corrected for the inverse range-squared dependence, and displayed on a facsimile-type recorder. Hence, the lidar and sounder returns were similarly processed and displayed and, therefore, can be readily compared.

The displayed returns (S) can be related to the single-scattering equation:

$$S = \log \left(\frac{PR^2}{K_1 E} \right) = \log (K_2 \beta T^2)$$

Where P = power returned

R = range

K_1, K_2 = instrumentation constants

E = transmitted energy

β = volume backscatter coefficient

T^2 = round-trip transmission.

For the lidar, β and T^2 are principally determined by the optical properties of the scattering particles and the particle concentrations. For the sounder, β is determined by temperature irregularities (fluctuations) and T^2 is determined by scattering from temperature and wind fluctuations and absorption by water vapor. Hence, the backscatter returns are related to entirely different atmospheric parameters; however, they may be spatially and temporally correlated because of similar dependence on various atmospheric dynamic and physical processes.

Figure 1 presents an example of the data collected with the lidar and the sounder separated by approximately 100-yards and both pointing vertically upward with a lidar beamwidth of one milliradian and a sounder beamwidth of 120. The lidar firing rate was 3 pulses/min. Increased signal return in these presentations is represented as increased brightness for the lidar data and decreased brightness for the sounder data. (Note that there is a factor of two difference in the vertical scales of the two records.) The dark streaks in the sounder record are a result of background noise sources, primarily jet aircraft.

The early morning mixing depth and its gradual increase by convection as determined from both data types are well correlated. However, the sounder record does not give this information after 1230 CDT. This is a result of low signal-to-noise ratios at heights greater than 3000-feet and because vertical

air motions associated with active convection tend to give returns containing little vertical structure. The turbulent cells are easily identified on the lidar presentation (1330-1500 CDT). During this time period, near-surface wind sensors recorded light and variable winds. The wind speed increased and shifted in direction at 1530-1620 CDT. These events are recorded on the lidar data as sudden decreases in the near surface aerosol concentrations and on the sounder data as sharp vertical discontinuities.

A cellular-structured air parcel passed over the area between 1800 and 1900 CDT that lifted the atmospheric layers. This perturbation introduced short-period atmospheric waves that were detected by both indirect sensors. The sounder record during this time period indicates that a new low-level mixing layer was being established. The sounder normally detects the reestablishment of the mixing layer before the lidar, since particulate gradients normally result from a trapping of particles by thermally stable stratifications.

Other data to be presented illustrates complex day-to-day variations of atmospheric structure and provides information on how lidar and sounders may effectively be used in atmospheric research and operational programs.

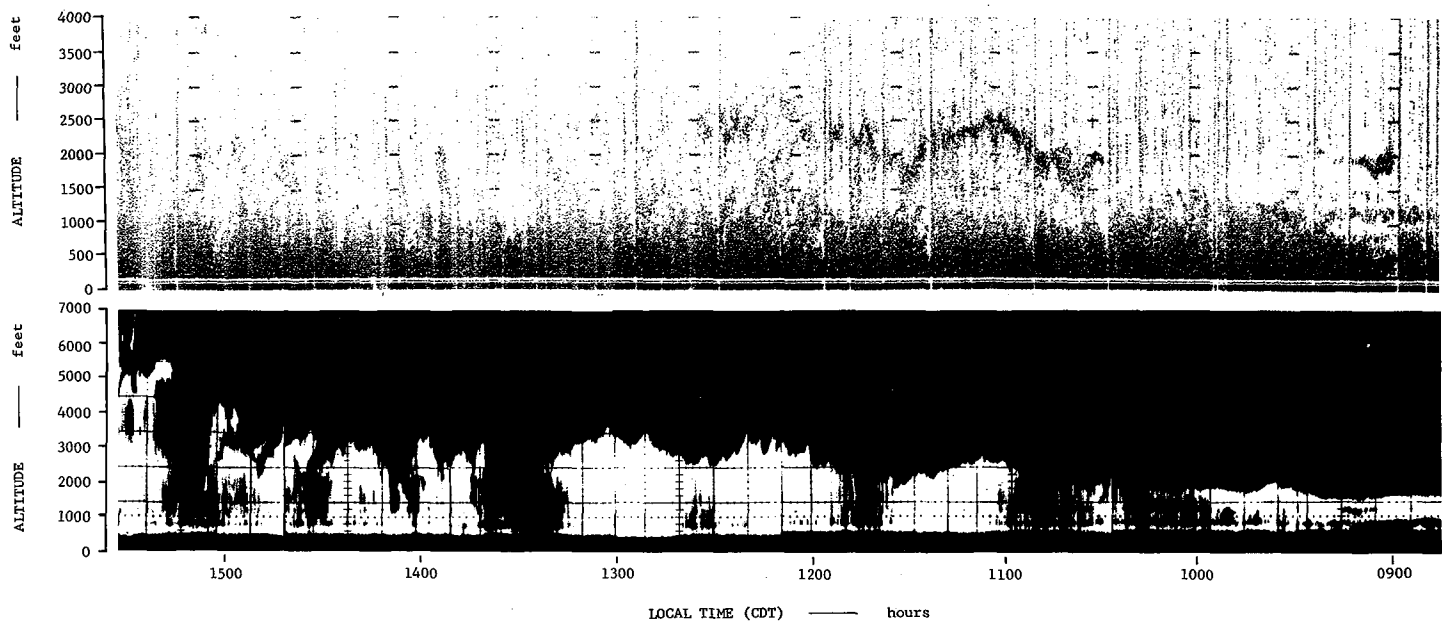
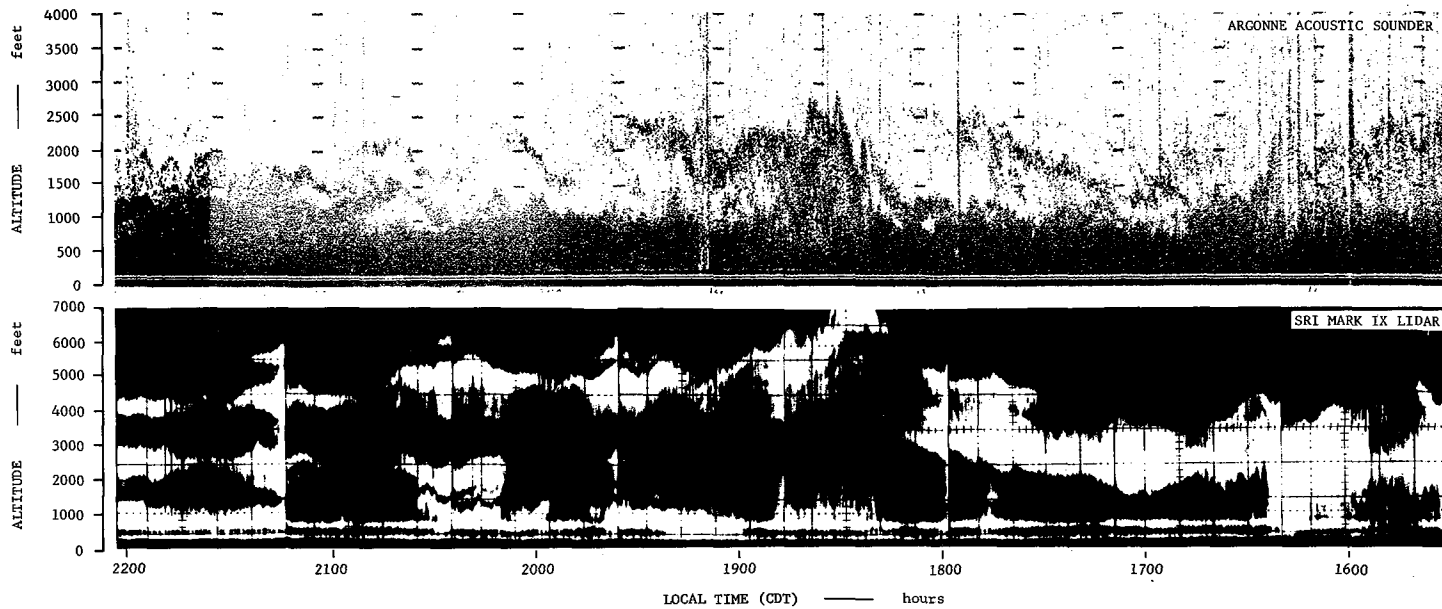


FIG. 1 ATMOSPHERIC TIME SECTIONS OBTAINED BY LIDAR AND ACOUSTIC SOUNDER, AUG. 20, 1972, ST. LOUIS

OBSERVATIONS OF INVISIBLE PLUME BY SHGed YAG LASER RADAR

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ABSTRACT

The enormous efforts to reduce exhausted materials contained in a plume which cause air pollution has been taken into plant operations. As a result, exhausted plume became invisible to naked eyes and new observation facilities are needed to monitor the diffusion of plume. The following is the report on the experimental observation to confirm the suitability of SHGed YAG Laser Radar for invisible plume monitoring.

A certain Kombinat area near Tokyo was chosen as a test range. The exhausted plume from ultra high stacks which we chose as a target were invisible to naked eyes even in clear daytime. Eight observations, three in daytime and five in nighttime, were performed at two locations within the Kombinat yard using mobile SHGed YAG Laser Radar ¹⁾ which has 1 MW output power at 0.53 micron, 50 pps repetition frequency and facilities of RHI, PPI and A scope display. The RHI and PPI display were recorded on 35 mm photographic films for further analysis.

The photographic data of three observations, one in daytime and two in nighttime, were chosen and analysed.

Fig. 1 and fig. 2 show the analysed result of observation performed on 1972, 9, 25 at 2100 - 2120 JST. Fig. 1 is plan position indication which is the projection of diffused volume to the ground and fig. 2 is range height indica-

1) H. Tanizaki et al; Conference abstracts of the fourth conference on laser radar studies of the atmosphere (Jan. 26 - Jan. 28, 1972, Tucson, Arizona U.S.A.) pp. 82

tion which is the projection of diffused volume to the vertical plane parallel to the wind direction. The wind direction, wind speed and temperature at the observation were NNE, 1 m/sec and 21 degree Centigrade respectively.

It is obvious from fig. 1 and fig. 2 that the diffusing space expanded to the wind direction and the effective height of three ultra high stacks reached respectively 1.7, 1.8 and 1.5 times of their physical heights at that time presumably due to slow wind speed.

Thus, the suitability of SHGed YAG Laser Radar for invisible plume diffusion monitoring is confirmed by this observation as we have been technically anticipated. But, real time Laser Radar echo processing system must be developed before practical use of Laser Radar as a monitoring system.

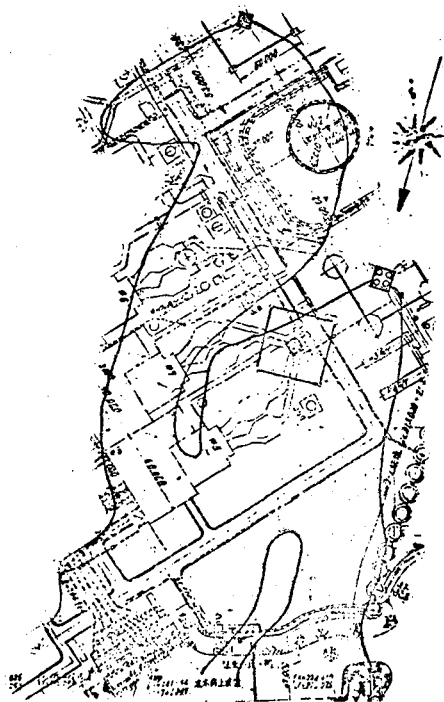


Fig. 1 Plan position (1972,9,25 2100-2120 JST)

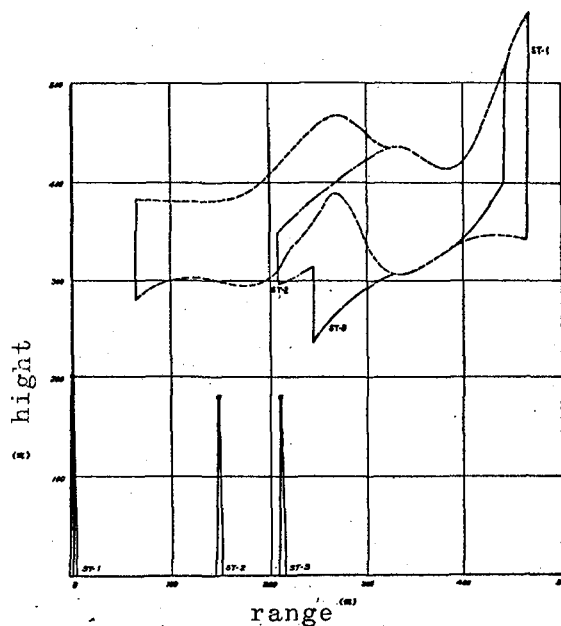


Fig. 2 Range height (1972,9,25 2100-2120 JST)

DETECTION AND ESTIMATION OF ATMOSPHERIC

TURBIDITY FROM THE POLARIZATION OF SCATTERED RADIATION

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ABSTRACT

Estimates of the 'effective' turbidity of the atmosphere due to particulate pollution have been made from an interpretation of the results of ground-based and high altitude balloon measurements of the polarization of scattered radiation, obtained over the past five years, in the light of numerical computations of the polarization of emergent radiation in models of turbid atmospheres. Ground-based measurements were made at Los Angeles where the occurrence of low level pollution is frequent and well defined. The balloon measurements were made from altitudes of 28-30 km over southwestern New Mexico. Programmed, servo-governed photoelectric polarimeters were used in these measurements which were confined to the near ultraviolet and visible regions of the spectrum.

The polarization of emergent radiation was computed in two simple, singular but possible models of a turbid atmosphere based on the solution of the radiative transfer problem. The variable model parameters are the amount and type of aerosols and the reflective properties of the ground. Computations have been made for two different types of polydisperse aerosols with sizes governed by the modified gamma and power law distributions and with different refractive indices. The ground has been assumed to be a Lambertian reflector.

The optimal values of the aerosol optical thickness which yield good correspondence between theory and experiment are found to depend upon the phase function asymmetry factor associated with the type of aerosols used in the

model computations. The turbidity factor, defined as the ratio of the total optical thickness of the atmosphere to the molecular optical thickness, varies from 2 to 5.5 over the spectral region of interest on normal turbid days. The similar effects that the aerosols and the Lambertian ground have on the emergent radiation introduces a certain amount of ambiguity in the interpretation of the experimental results. This ambiguity will be discussed in terms of a model parameter sensitivity analysis.

ON THE INVERSION OF LIGHT SCATTERING DATA
INTO INFORMATION ON AEROSOL PROPERTIES

by

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ABSTRACT

The Backus-Gilbert inversion technique was applied to scattering data and calculated examples were given to ascertain its ability to recover the aerosol properties with no a-priori assumptions.¹

In order to cheque this inversion procedure as well as other techniques (such as Daves' and Herman's et al.), a controlled experiment was performed.

The experiment dealt with spherical particles the Mie scattering curves of which was measured by use of a dye-laser. These curves were used to accurately determine the refractive index of the particles.²

Mixtures of three different known sizes were then prepared and the scattering intensity vs. wavelength was measured at 90° scattering angle. The mixtures contained also various known relative concentrations of the three sizes.

The analysis of the measured results will be shown and discussed.

1. E. Westwater and A. Cohen.....Appl. Opt. June 1973.
2. A. Cohen, V. E. Derr, R. E. Cupp and T. McNice.....Appl. Opt. May 1973.

+ Now with the Dept. of Atmos. Sciences, the Hebrew University of Jerusalem, Israel.

THE AEROSPACE CORPORATION AEROSOL SCATTERING STUDIES

Richard T. Hall, R. Douglas Rawcliffe,
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ABSTRACT

An experimental apparatus for measuring the differential scattering cross section of micron-sized aerosol particles has been designed and constructed at the Aerospace Corporation. The apparatus uses the 10.6 μm laser transition of CO_2 for illumination of the aerosol particles. Two mercury-doped germanium, liquid helium cooled detectors are used to measure the scattered 10.6 μm radiation. One detector is mounted at right angles to the laser beam while the other is moveable between the forward scattering and backwards scattering positions.

The apparatus has been used to measure the differential scattering cross sections of 9 to 20 μ diameter carbon particles and 2 to 15 μ diameter aluminum particles. Calculations of the differential scattering cross section as predicted from Mie theory have been carried out to provide a comparison between theory and experiment.

SIMULTANEOUS RED - BLUE LIDAR
AND AIRBORNE IMPACTOR MEASUREMENTS

by
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W. H. Fuller^{*}, and G. W. Grams^o

ABSTRACT

Simultaneous two-color (0.6943 micro meters and 0.3472 micro meters) LIDAR measurements were made in the troposphere and lower stratosphere over Boulder, Colorado during March 1973. In addition, on the evening of March 26, airborne single-stage impactor measurements were made at four altitudes-- 10,500, 25,000, 33,000 and 43,000 feet MSL. These data were integrated at constant altitude for 15, 45, 45, and 60 minutes respectively.

The LIDAR data were taken with Langley's 48" LIDAR using a dichroic beamsplitter to separate the return at 0.6943 micro meters and 0.3472 micro meters. The analog waveforms for both colors were digitized simultaneously; one on an NCAR data acquisition system and the other on the 48" Langley data acquisition system. A discussion of the preliminary results from these measurements will be presented.

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^oNational Center for Atmospheric Research

MULTIPLE SCATTERING MEASUREMENTS AS A
FUNCTION OF WAVELENGTH BY USE OF A DYE-LASER

by

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ABSTRACT

Dow latex monosized spheres were used as scatterers in a laboratory system containing a dye-laser as the light source (the system has been described elsewhere¹). Eight samples of different particle concentrations (1:2:4:8:16:32:64:128) were prepared and the optical depth of each was measured. The two lowest concentrations gave the same relative Mie Scattering intensity curve as a function of wavelength as is expected when merely single scattering occurs (the absolute intensity was doubled at all wavelengths). The shape of the curve started to change with the further increase in the number density of the particles. The main characteristics of the changes was the gradually disappearance of the minima and for higher concentrations - also the maxima.

Special measurements were made to ensure that the beam path and the sample volume were big enough to include most possible multiple scattering effects influencing the scattering intensity. Thus, this experiment provides (within a specified degree of accuracy) the multiple scattering Mie curves vs. optical depth for a range of $\sim 1000 \text{ \AA}$.

1. A. Cohen, V. E. Derr, T. McNice and R. E. Cupp, Mie Scattering.....
Appl. Opt. May, 1973.

+ Now with the Dept. of Atmospheric Sciences, The Hebrew University of
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AIRBORNE LASER POLAR NEPHELOMETER

by

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ABSTRACT

A polar nephelometer has been developed at NCAR to measure the angular variation of the intensity of light scattered by air molecules and particles. The system has been designed for airborne measurements using outside air ducted through a 5-cm diameter airflow tube; the sample volume is that which is common to the intersection of a collimated source beam and the detector field of view within the airflow tube. The source is a linearly polarized helium-neon laser beam. The optical system defines a collimated field-of-view (0.5° half-angle) through a series of diaphragms located behind a 172-mm focal length objective lens. A photomultiplier tube is located immediately behind an aperture in the focal plane of the objective lens. The laser beam is mechanically chopped (on-off) at a rate of 5 Hz; a two-channel pulse counter, synchronized to the laser output, measures the photomultiplier pulse rate with the light beam both on and off. The difference in these measured pulse rates is directly proportional to the intensity of the scattered light from the volume common to the intersection of the laser beam and the detector field-of-view.

Measurements can be made at scattering angles from 15° to 165° with reference to the direction of propagation of the light beam. Intermediate angles are obtained by selecting the angular increments desired between these extreme angles (any multiple of 0.1° can be selected for the angular increment; 5° is used in normal operation). Pulses provided by digital circuits control a stepping motor which sequentially rotates the detector by pre-selected angular increments. The synchronous photon-counting system automatically begins measurement of the scattered-light intensity immediately after the rotation to a new angle has been completed.

The instrument has been flown on the NASA Convair 990 airborne laboratory to obtain data on the complex index of refraction of atmospheric aerosols. A particle impaction device is operated simultaneously to collect particles from the same airflow tube used to make the scattered-light measurements. A size distribution function is obtained by analysis of the particles collected by the impaction device. Calculated values of the angular variation of the scattered-light intensity are obtained by applying Mie scattering theory to the observed size distribution function and assuming different values of the complex index of refraction of the particles. The calculated values are then compared with data on the actual variation of the scattered-light intensity obtained with the polar nephelometer. The most probable value of the complex refractive index is that which provides the best fit between the experimental light scattering data and the parameters calculated from the observed size distribution function.

1 The National Center for Atmospheric Research is sponsored by the National Science Foundation.

OPTICAL MEASUREMENT OF ATMOSPHERIC AEROSOL

by

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and

R. J. Charlson

ABSTRACT

Nephelometric measurements of extinction due to aerosol scatter are found to be consistent with solar and stellar extinction measurements by Voltz photometer and astronomical telescope respectively [all measurements at or corrected to 500 nm]. Sites without obvious contamination by man or regional vegetation such as Mauna Loa and Mauna Kea, Hawaii have optical aerosol scatter and extinction coefficients that average 0.2 or less of Rayleigh scatter and extinction. Average stellar aerosol extinction values of less than 0.31 Rayleigh extinction have been measured at Cerro Tololo, Chile; Cape of Good Hope, South Africa; Kitt Peak, Arizona. Solar extinction measurements at some 40 stations at rural and urban locations in the U.S. show that at every location there are clean periods when the measured aerosol extinction is less than 0.5 Rayleigh, and the average aerosol extinction is only 1.2 times Rayleigh over the central western states during continental polar synoptic conditions.

This collected data, from measurements by our group and others, is not consistent with either extinction calculated from searchlight measurements or the model atmospheres of Elterman.

Both authors are on the staff of the University of Washington.

NUMERICAL EXPERIMENT ON MULTIFREQUENCY LASER SOUNDING OF CLOUDS AND ESTI-
MATION OF PARTICLE SIZE DISTRIBUTION

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Determination of particle size distribution parameters of polydisperse medium on the basis of optical measurements is connected with solution of inverse problems of scattering theory. Solution of these problems in general form encounters definite mathematical difficulties. However, in the case of cloudy media a priori information on the refractive index and the particle size distribution form allows practically realizable procedures of the optical measurements inversion to be obtained.

An effective numerical algorithm based on the method of optimal parametrization is suggested for this purpose in the present paper. As a priori model of distribution function the modified gamma distribution is used [1], the parameters of which are determined from the optical measurements or equivalent numerical estimates, performed for a number of wavelengths. Necessary information on characteristics of scattered radiation is derived from solution of a known laser radar equation valid for the single scattering approximation. It is supposed that small viewing field of optical detectors gives sufficient guarantee of applicability of single scattering equations to calculate the lidar systems. However, as the estimates show, at sounding of optically dense atmospheric aerosols (clouds, fogs, ground mist) this question requires careful research.

Accordingly, numerous calculations of space-time characteristics of back scattering at cloudy layer sounding were carried out. The numerical solution of the nonstationary transfer equation was produced by the Monte-Carlo technique for boundary conditions corresponding to the real schemes of sounding at $\lambda = 0.6943; 1.06; 2.36; 3.51; 5.3$ and 10.6μ . The results obtained give a

possibility to analyze the influence of multiple scattering depending on the choice of a cloud optical model, viewing field of a detector, cloud altitude, etc. In particular, substitution of the value of signal being detected into the laser radar equation (at preliminary calibration of "numerical lidar") allows the high-altitude profile of volume backscattering coefficient $\beta_{\pi}(H)$ "to be measured" taking into account a distorting correction of multiple scattering.

Fig. 1 shows an example of such profile for a cloud model, having drop concentration invariable in the altitude H , $N = 100 \text{ cm}^{-3}$. The results are given for a scheme of monostatic sounding at $\lambda = 2.36 \mu\text{m}$; the height of the cloud lower edge is 1000 m. Curve 0 corresponds to the single scattering component, curves 1-4 are obtained by treatment of total signal arriving to the detector, the angular aperture being equal to $3'$, $20'$, 1° and 5° , respectively.

The values of $\beta_{\pi}(\lambda, H)$ obtained as a result of numerical experiment are inversed to the particle size spectrum by the method of optimal parametrization. An algorithm of optimal parametrization is based on the approximation of particle size distribution, found by a certain model distribution, the parameters of which are determined in scanning process of function minimum, characterizing a degree of proximity of calculated optical characteristics and measured in some points of spectral interval. The parameters evaluated are: modal radius and distribution density.

Special attention in this paper is given to the questions of optimal choice of wavelengths of optical sounding. Possibilities of numerical simulation of the experiment according to the known initial data ensure practically absolute control of efficiency of treatment procedure.

Curve 0 in Fig. 2 illustrates coincidence of reducible density of particle size distribution with initial function of gamma distribution for a cloud model $Ci[1]$ with an accuracy being not less than 1 per cent. In this case the absolute values of $\beta_{\pi}(\lambda)$ for the points $\lambda = 2.36$; 3.51 ; and $5.3 \mu\text{m}$, being not distorted by multiple scattering, are used for the treatment. The distributions 1 - 5 are obtained according to the values of a total signal of back scattering, arriving in the aperture $\phi = 1^{\circ}$ from the altitudes 30, 60, 90, 120 and 150 m, respectively, measured from the cloud lower edge. Their deviation from the real one characterizes increased influence of multiple

scattering in the course of the light beam penetration into the cloud.

The points of spectral interval $\lambda = 0.6943, 1.06$ and $10.6 \mu\text{m}$ appear to be less informative for the reasons of remote determination of size distribution of cloud drops.

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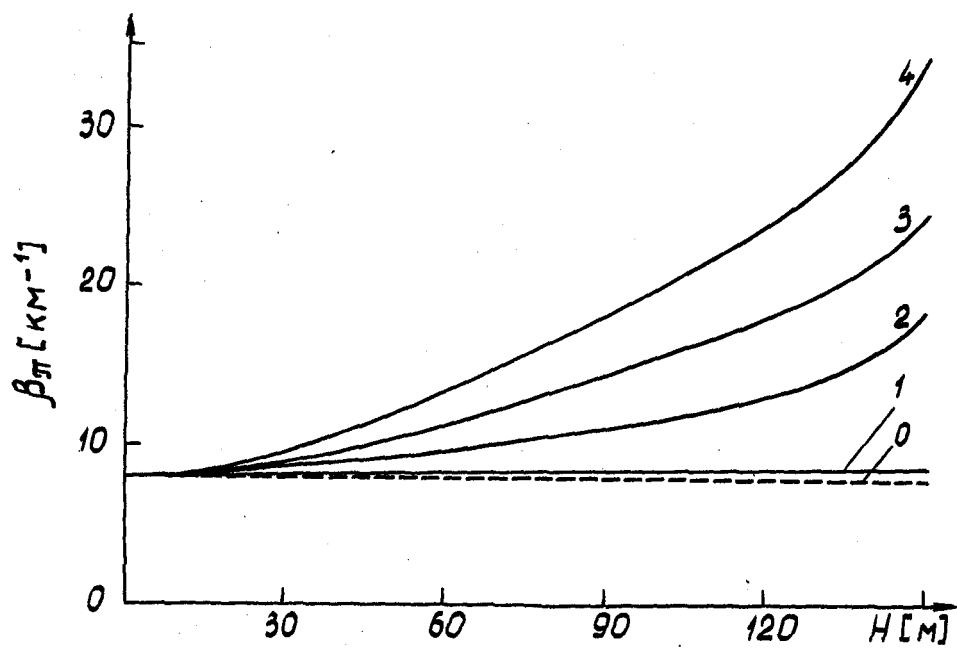


Fig. 1

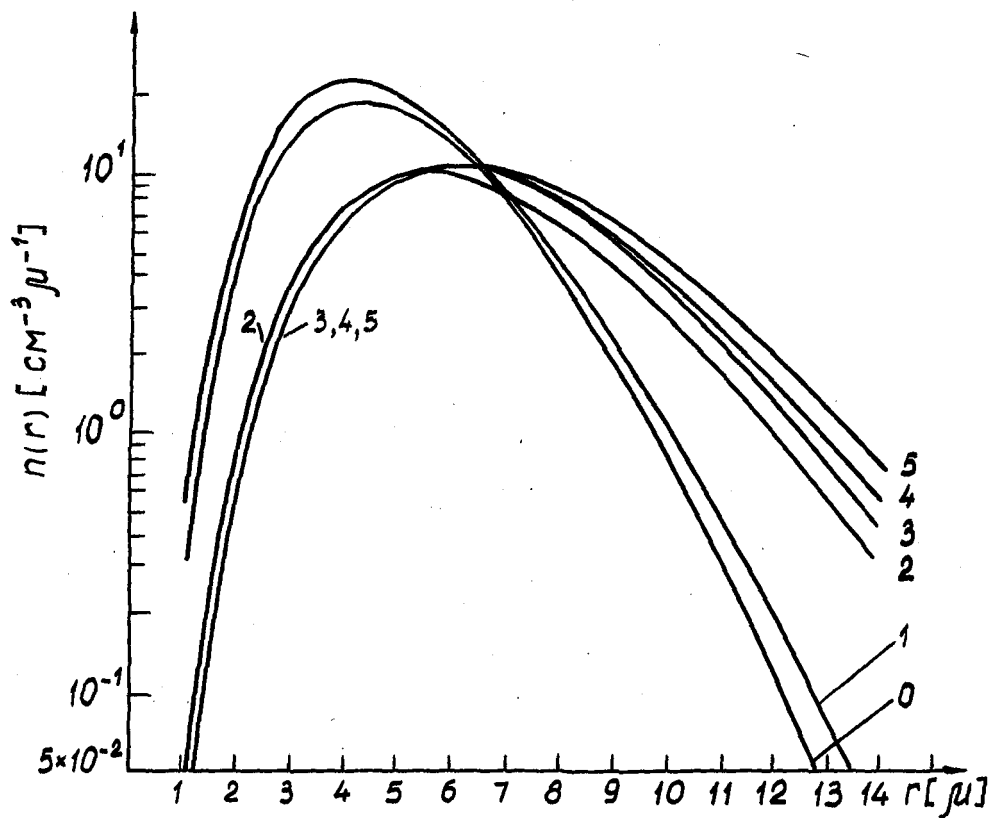


Fig. 2

ON LIDAR SOUNDING OF THE ATMOSPHERE TO ESTIMATE
STATIC AND DYNAMIC CHARACTERISTICS OF AEROSOL INHOMOGENEITIES

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ABSTRACT

1. A possible application of intensity fluctuations of a pulse light signal reflected by atmospheric aerosols is analyzed by the correlation method to evaluate static (medium sizes, shape) and dynamic (speed and direction of movement, lifetime) characteristics of aerosol inhomogeneities. The aerosol inhomogeneities are assumed to be expanded, pressed, disintegrated and originated constantly in accordance with random laws, the set of inhomogeneities as a whole traveling together with air masses and having predominant movement in wind direction. It is shown that the characteristics of aerosol inhomogeneities considered can be expressed by the coefficients of the correlation function expansion of the reflected signal fluctuation intensity in Taylor series.

2/ Correlation systems for evaluating static and dynamic characteristics of driving objects can be divided into two types according to the kind and quantity of used information: the systems with coordinates of the information removal "points" to be fixed in space, and the systems with a parallel simultaneous information removal at discrete moments of time.

The systems for determination of wind direction considered in [1,2] are the examples of the first type system. However, the operating information removal for two points is insufficient to estimate completely static and dynamic characteristics of inhomogeneities, their quantity ought to be increased up to three of them for two-dimensional problem and up to four of them for three-dimensional problem as it is usually done in the ionospheric studies.

The second type systems are used for the investigation of a medium shape and speed of the clouds according to photographs made from satellites. These

systems are also used for solution of navigation problems [3].

The use of optical quantum generators with a scanning beam is seen to increase greatly the working information removal in comparison with the first type systems. Nevertheless, scanning rate is not sufficient sometimes in order to consider a general picture of aerosol inhomogeneities to be stationary. In this connection the use of the systems of second type treatment becomes a matter of essential difficulty.

3. Aerosol inhomogeneities simulation has been carried out on the basis of the digital computer experiments with the aim of estimating static and dynamic characteristics of inhomogeneities by an optical beam in the atmosphere at different scanning procedures.

The dependence of determination accuracy of these characteristics on the type of chosen laws of aerosol particle distributions in the atmosphere, the parameters of inhomogeneities geometry, their speed and the law of scanning have been obtained.

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A COMPARISON OF NEAR SIMULTANEOUS LIDAR RETURNS
AND PARTICULATE COLLECTIONS ON FILTERS
FLOWN AT SIX STRATOSPHERIC ALTITUDES

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ABSTRACT

Collections of particulates on both Los Alamos Scientific Laboratory (LASL) and National Center for Atmospheric Research (NCAR) filter systems were made from an RB 57F aircraft flown at one tropospheric and six stratospheric altitudes over the Boulder, Colorado, area. This daytime flight was spanned by lidar returns on evenings before and after the flight.

Scanning electron microscope examination of the LASL filters showed no evidence of solid particulates greater than $.2 \mu\text{m}$ (the instrumental resolving power). Quantitative analysis of the NCAR filters yielded chemical composition and mass. The mass values were normalized to the total air flow through the filters to yield mass mixing ratios at the various altitudes. The lidar returns, normalized to molecular densities obtained from sonde data, were put in the form of particulate scattering divided by molecular scattering, i.e., an optical mixing ratio. A plot of the optical mixing ratio versus mass mixing ratio, in the stratosphere, yielded linear relationship, for five of the six data points, going through the origin.

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**The Los Alamos Scientific Laboratory is operated under AEC contract by the University of California.

USE OF POLARIZATION LIDAR FOR INVESTIGATION
OF METEOROLOGICAL FORMATIONS

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ABSTRACT

This paper presents the results of theoretical and experimental investigations of depolarization characteristics of different meteorological formations. Experimental investigations are carried out with a monostatic lidar. The ruby laser radiation is polarized in a vertical plane. The radiation reflected is accepted by a lens system of 150 mm in diameter and a viewing angle of 12' and further it is divided by Wollaston prism into the components polarized orthogonally. In this case the principal plane of the prism is exposed parallel with the laser polarization plane.

Investigations show the degree of radiation polarization, reflected from water clouds, to be changed within 1 ± 0.7 (seldom up to 0.6) depending on their density. In most cases a signal reflected from the cloud leading edge is polarized completely. The time shift is observed between polarized and crosspolarized components of a signal, reflected from a cloud, depending on the density of a meteorological object. While penetrating into the cloud depth a degree of polarization decreases up to 0.8-0.7, and the character of this decrease is different for various types of clouds.

For crystal clouds the shift between the components of the reflected signal is not observed and the magnitude of polarization degree amounts to 0.1 ± 0.3 in comparison with water clouds. The polarization degree of radiation reflected by fog is not less than 0.6, and that in the rains of average intensity (about 5mm/h) is always about 1.

The authors have suggested an algorithm of numerical solution of nonstationary transfer equation in the vector form to forecast the influence of multiple scattering effects on polarization characteristics of

the lidar light signal. The method of statistical simulation (Monte-Carlo technique) forms the basis of the algorithm.

Numerical estimates obtained for a model of stratocumulus at $\lambda = 0.6943\mu$ under boundary conditions close to the conditions of natural experiment being discussed proved to be in a good agreement with the results of observation.

Specifically, Fig. 1 shows the profiles of polarization (P) versus depth (L) of the following drop formations: fog (curve 1) with horizontal meteorological visibility of 4 km two stratocumulus at a height of 1100 m with the attenuation factors $\delta = 0.01\text{m}^{-1}$ (curve 2) and $\delta = 0.05\text{m}^{-1}$ (curve 3). Curve 3 shows the results of numerical estimates and the value of their statistical error.

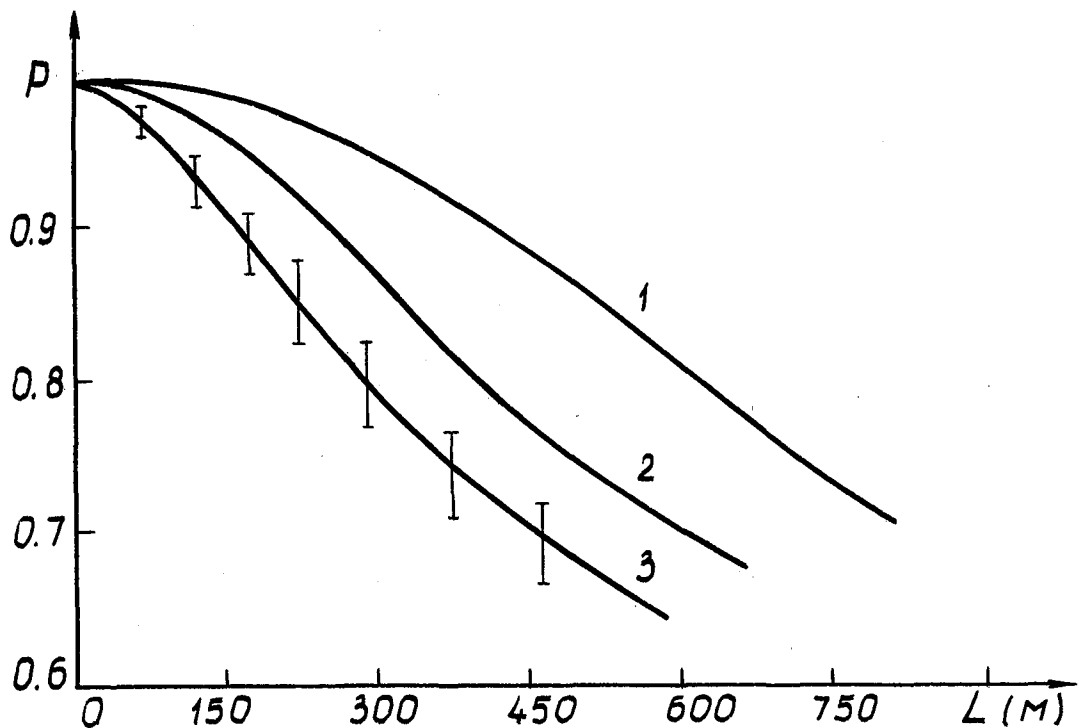


Fig. 1

STATISTICAL PROPERTIES OF BISTATIC LIDAR SIGNALS

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ABSTRACT

Bistatic lidar systems which employ short pulse Q-switched lasers for transmitters yield "instantaneous" received signals that are quite analogous to those collected by monostatic lidar^[1]. In particular, the bistatic lidar equation for the instantaneous received power for scattering through an angle θ_s is proportional to an instantaneous scattering depth, ℓ' , (depth along either the transmitter or receiver axes) given by

$$\ell' = \frac{\ell}{2 \sin^2 \left(\frac{\theta_s}{2} \right)},$$

where ℓ is the laser pulse length. Bistatic signals are only received during the time the transmitted laser pulse is within the bistatic common volume, and the common volume depth, L_t , along the transmitter axis is given by

$$L_t = \frac{2 r_2 \theta_R}{\sin \theta_s},$$

where r_2 is the distance from the center of the common volume to the receiver and θ_R is the half-angle of the conical receiver field-of-view. As the received bistatic signals will be independent from one another for scattering from instantaneous scattering volumes separated by approximately ℓ' , the effective number of independent signal samples, N , collected during the passage of the laser pulse through the common volume is given by

$$N \sim \frac{L_t}{\ell'} = \frac{4 r_2 \theta_R \sin^2 \left(\frac{\theta_s}{2} \right)}{\ell \sin \theta_s}.$$

If the rms signal to noise ratio of the instantaneous bistatic signal is n ,

time integration of the bistatic signal would therefore be expected to yield an improved signal to noise ratio of $n\sqrt{N}$. Assuming temporal stability, the signal to noise ratio may be further improved by averaging the integrated signals collected for a number of laser shots.

For the University of Arizona bistatic lidar system^[2], the observed instantaneous rms signal to noise ratio is less than 5 for typical measurement conditions (θ_s from 100-150° and scattering heights 1-2 km), and theoretical calculations using representative aerosol distributions yield similar results. In order to improve the signal to noise ratio to a level which will permit meaningful aerosol size distribution information to be extracted from bistatic measurements, signal integration and averaging techniques of the type described above are required. Sample observations and supporting statistical calculation are presented to demonstrate the degree of accuracy one can practically attain with such signal improvement methods.

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AEROSOL SIZE DISTRIBUTIONS DETERMINED FROM
BISTATIC LIDAR OBSERVATIONS

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ABSTRACT

Bistatic lidar observations at several scattering angles have been collected with the University of Arizona bistatic lidar (1). These measurements are estimated to have errors not exceeding $\pm 3\%$, thus representing a considerable improvement over earlier results reported with this system (2). These improved measurements have permitted mathematical inversions to be performed for determination of the aerosol size distribution (3). Results of such inversions will be presented.

The technique for the mathematical inversions used in this work is departure from that employed in the earlier studies in that a modified form of the technique reported by Chahine (4) is used. This technique has the advantage of guaranteeing a nonnegative solution (i.e., the particulate number density is always positive within any size interval, as it must be) even in the presence of large observation errors. Of course the quality of the solution deteriorates as the errors increase, but nevertheless, an optimal solution results. A more complete description of this technique will be presented.

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BOUNDS ON THE IMAGINARY PART OF THE AVERAGE
INDEX OF REFRACTION OF TROPOSPHERIC AEROSOLS
FROM BISTATIC LASER SCATTERING

by

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ABSTRACT

Measurements of the degree of polarization and the intensity as a function of scattering angle, compared with a theoretical model combining a regularized Junge distribution with Mie and Rayleigh scattering cross sections, has allowed us to determine the complex average index of refraction of the atmospheric aerosol. The values of the real part of the index of refraction cluster around 1.50, and lie within ± 0.05 . The values of the imaginary part of the index of refraction average -0.005 , within a factor of two. Three parameters of the particle size distribution were also determined. Data taken during March through June 1972 will be presented along with best fits from an atlas of theoretical curves. Inaccuracies arise due to an oversimplified particle size distribution, and from the nonspherical particle problem.

MEASUREMENT OF RAINFALL INTENSITY BY LIDAR

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ABSTRACT

The University of Wisconsin monostatic lidar has been fired horizontally in rainfall, providing digital information on returned power in 15 meter increments to about 5 km. Simultaneous operation of rain gages under the beam path indicates that derived optical extinction and gage rainfall rates are correlated. Results from a stratus shower of 20 October, 1972 are given in figure I; the experimental relationship between the extinction coefficient β (km^{-1}) and rainfall rate R (mm/hr) is

$$\beta \approx 0.13 R^{.94}$$

A relaxation algorithm giving the extinction coefficient from lidar returns as a function of range has been developed. Examples of lidar returns and the derived extinction coefficients from spatially inhomogenous showers are presented. Experimental correlations of the extinction coefficient to rainfall rate are also given for spatially inhomogenous rainfall.

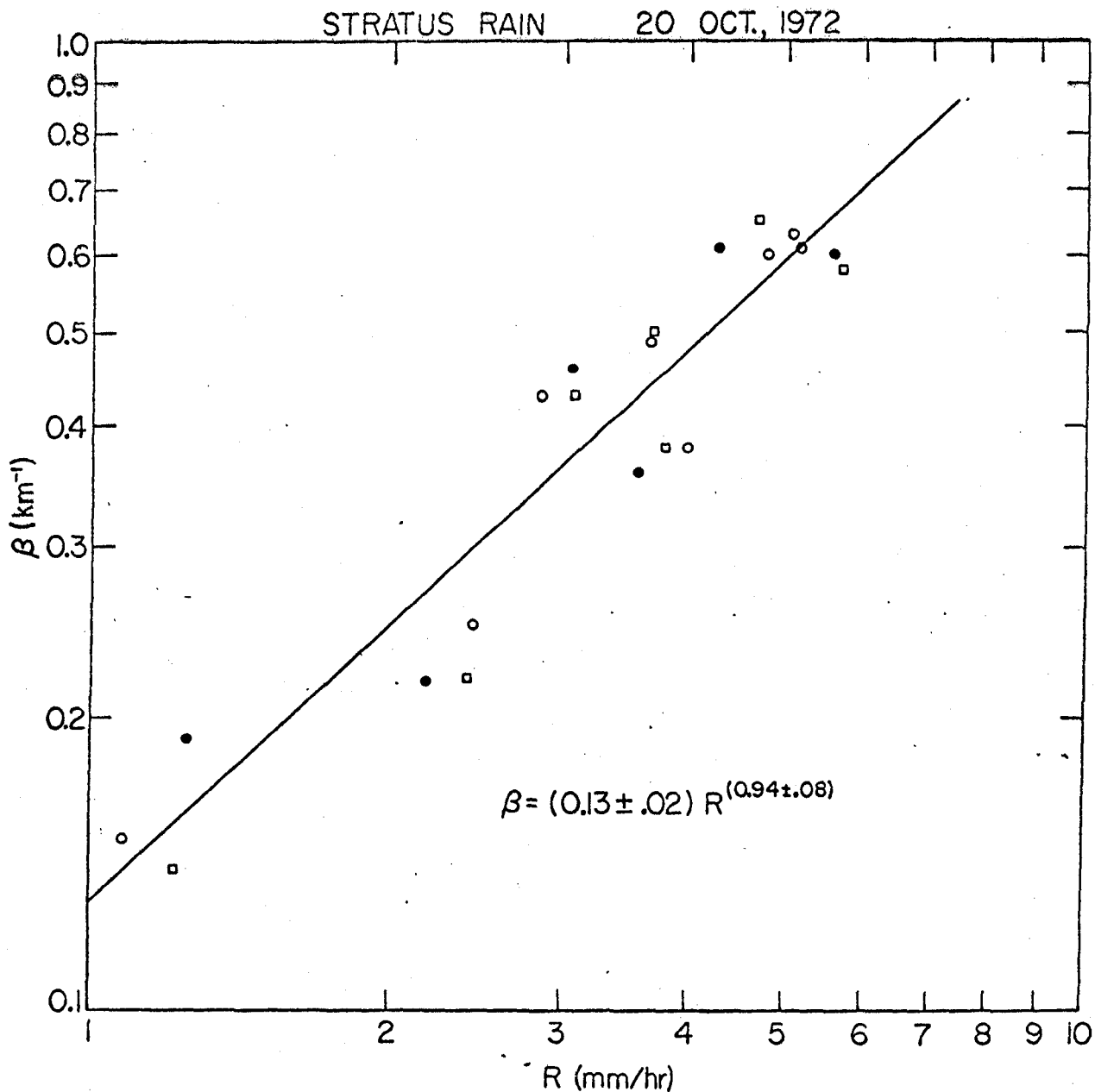


Figure I. Average extinction as measured by lidar plotted with average rainfall rates given by three tipping bucket rain gages. The variance of the regression coefficients is due to the scatter of the data points about the line of regression. The correlation coefficient is 0.94.

MEASUREMENTS OF TRANSMISSIVITY OF LASER LIGHT THROUGH CLOUDS

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ABSTRACT

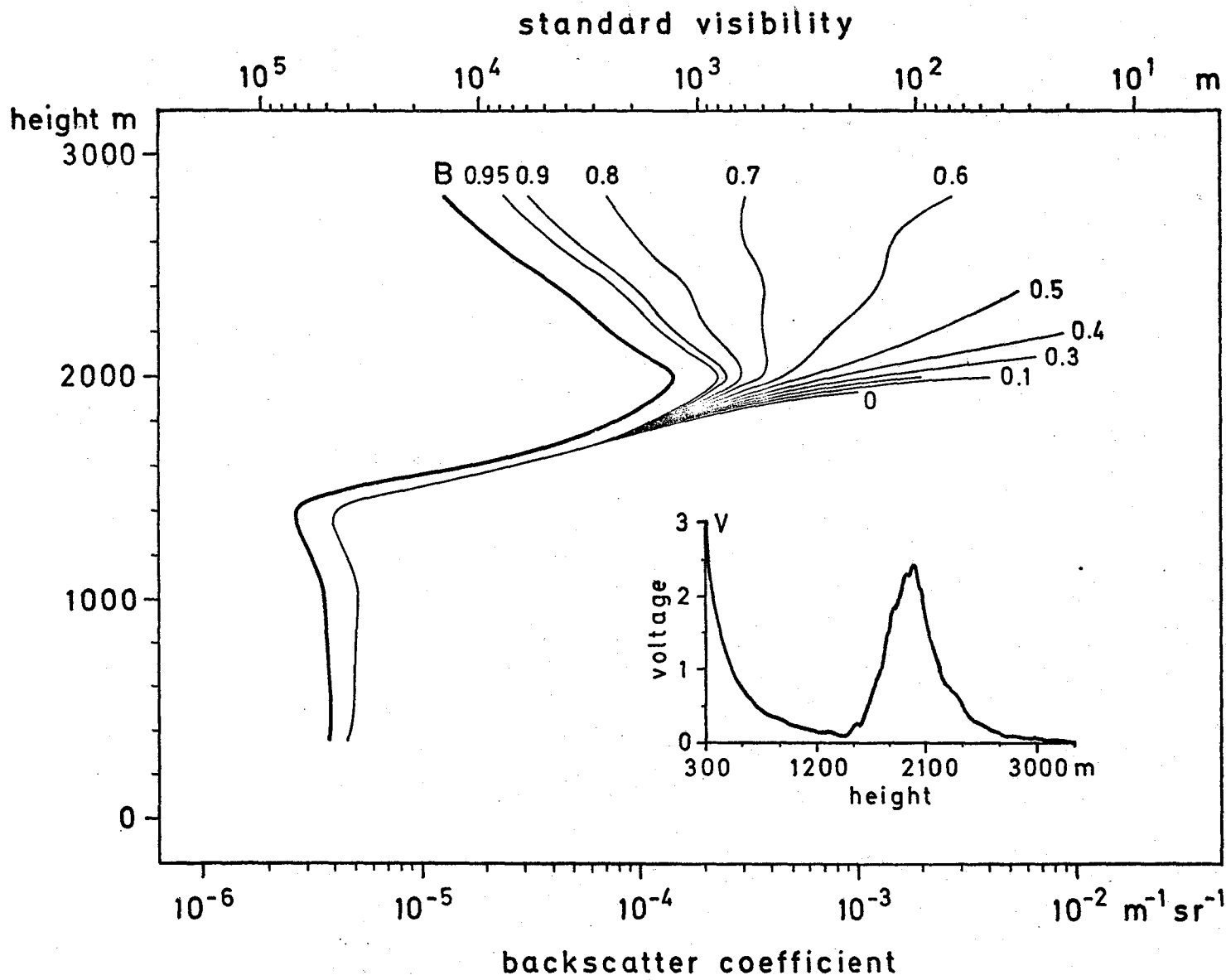
By lidar measurements of clouds we determined that the transmissivity is better than it could be expected theoretically for the direct laser beam. For example, we could measure a cirrus cloud through a thick altostratus layer. If the lower cloud was absent, the signal from the higher cloud was only two times greater.

The scattering in clouds almost is a forward scattering. A portion of the scattered light has the same direction as the direct beam. This portion will be estimated for an empirical solution. The forward scattered portion of the extincted radiation in a layer d will be named α . The sum of directed (τ) and diffuse transmissivity $\alpha(1 - \tau)$ then is

$$\tau' = \tau + \alpha(1 - \tau), \quad \tau = \exp \left\{ - \int_0^d \sigma dx \right\}.$$

The Figure shows the result. The oscillograph photo of a lidar measurement is on the right side. By calculations with the lidar equation at first we get the value $B = \beta \tau'^2$ (β = backscatter coefficient). For different portions α ($\alpha = 0, \dots, 0.5, \dots, 0.95$) then we get the backscatter coefficient $\beta = B/\tau'^2$. Figure 1 shows that an agreement with the measurement for the value α greater 0.7 can be accepted. The standard visibility ($V_N \approx \frac{3.91}{\sigma} \approx \frac{3.91 \cdot 0.6}{\beta \cdot 4\pi}$) is a value for the accuracy (upper scale). Visibilities of some hundred meters within the clouds may be correct.

With other examples and model calculations the possibilities of utilization the forward scattering for range finding in fog and the limits for the other remote sensing methods are discussed.



AN ANALYSIS OF THE RISE TIMES
OF LIDAR RETURNS FROM CLOUDS

by

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ABSTRACT

Analysis of lidar returns from clouds shows that the rise time of the lidar return varies as the cosecant of the lidar's elevation angle. Plass and Kattawar have calculated the returned pulse shape for cloud models having both constant particle densities and monotonically increasing particle densities. Comparisons of the experimental values with the theoretical values shows the experimental values lying between the theoretical values. Calculations show that the increase in rise time attributable to the lidar's beamwidth and changes in elevation angle are small in comparison with the observed changes in rise time. The observed changes in rise time could result from the presence of a boundary or developmental layer at the cloud base.

RAMAN-LASER STUDIES OF THE LOWER ATMOSPHERE

by

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ABSTRACT

The development of an air-pollution measuring system considering Raman- and Resonant Raman Scattering is under progress at different groups in Germany since 1971. The preliminary experiments are undertaken with a high-power high repetition rate ruby-laser system either at the uv or the red ruby line. The receiver consists of a conventional Cassegrain optical system, followed either by vary narrow line filters (2-6 Å) or double monochromators. Optimization of emitter and receiver optics, including photon-enhancement by TIR (total internal reflection light guides), showed same surprising results for the received Photon flux and SNR. An overall efficiency calculation is given for Ruby, N₂ and Dye Laser Systems, taking into account normal and Resonant-Raman Scattering.

The commercially available long life time Ruby Laser was developed for other purposes at Impulsphysik GmbH, Hamburg, (150 MW, 20 ns, 2 cps), the N₂ Laser at the University of Darmstadt and the Dye Laser at the ISL Laboratories of Weil/Rhein. Power ranges for both the N₂ and Dye Laser are 0.1 - 10 MW at repetition rates of 10 - 100 cps.

Using high gain low noise multipliers emission values in the range of 50 - 100 ppm are to be measured by an A-scope technique and imission values of 0.2 - 5 ppm with photon counting methods. The insertion of a multi-channel-plate imate intensifier - vidicon data processing system is taken into consideration as a future step.

Quantitative measurements are carried out in an "artificial atmosphere" produced in defined ppm quantities in a large vacuum-vessel located some distance away from the experimental set up.

Laser heads are constructed to be easily exchanged for different wave lengths. These measurements are running at Impulsphysik GmbH in Hamburg until

August 1973 in cooperation with the MBB laboratories and the University of Munich. In parallel exact scattering cross-section measurements are carried out at the Spectroscopic Institute of the University of Munich under the leadership of Prof. Dr. Brandmüller.

DETERMINATION OF TRANSPORT PARAMETERS IN THE ATMOSPHERIC
BOUNDARY LAYER BY DOPPLER OPTICAL RADAR

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ABSTRACT

With the Doppler Optical Radar it is possible to measure, simultaneously, and at different heights in the lower troposphere, the vertical component of wind velocity, w , and the aerosol concentration n .

Thus it is possible to separate the data into average and fluctuating components

$$w = \bar{w} + w'$$

$$n = \bar{n} + n'$$

and therefore obtain the eddy flux

$$\phi = \overline{n'w'}$$

Also, since the gradient $\frac{\partial n}{\partial z}$ is also measurable, it is possible to obtain the diffusion coefficient of aerosols K .

The variable character of ϕ can be studied as well as its spectrum.

Results of recent experiment will be described.