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LASER RADAR MEASUREMENTS OF THE AEROSOL CONTENT
OF THE ATMOSPHERE*

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ABSTRACT

This report reviews the experimental program conducted by Professor Giorgio Fiocco and his group at the Research Laboratory of Electronics of the Massachusetts Institute of Technology. A summary of the results of laser radar observations of atmospheric aerosols is presented along with a description of the laser radar system devised during the study and of the data handling techniques utilized for the analysis of the data of the temporal and spatial distribution of atmospheric aerosols. Current research conducted by the group is directed toward the analysis of the frequency spectrum of laser radar echoes to obtain absolute measurements of the dust content of the atmosphere by resolving the molecular and aerosol contributions to the laser radar echoes.

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1. INTRODUCTION

One of the simplest techniques for probing the atmosphere with lasers uses the backscattered radiation from a pulsed laser to detect layers of dust particles in the atmosphere. In the experiments that have been performed, the optical backscattering cross-section of the atmosphere is measured as a function of range, and the presence of aerosol layers is established by locating significant deviations from the laser radar return expected for dry, clean air.

The first experiments to use lasers for ground-based remote measurements of atmospheric parameters were conducted by Fiocco and Smullin (1963). In their preliminary studies, echoes from scattering layers from heights of 60 to 140 km were detected during the summer of 1963. These echoes were tentatively attributed to dust particles of extraterrestrial origin (Fiocco and Colombo, 1964); this interpretation is corroborated by the observed correlation between the laser radar echoes from 110 to 140 km and ionospheric sporadic-E (Fiocco, 1965). Numerical calculations of the ionization resulting from neutral-neutral collisions of the ambient gas induced by incoming extraterrestrial particles (Fiocco, 1967) have verified that the influx of cosmic dust can produce ionization in amounts comparable to that required in the E-region at night and in some types of sporadic-E irregularities. Since subsequent laser radar measurements have not always detected the presence of scattering layers at high altitudes, considerable variability of the influx of extraterrestrial particles is indicated. There is further evidence of increased meteoric activity during the summer of 1963 obtained by techniques other than laser radar observations (see, for example, McIntosh and Millman, 1964; Ellyett and Keay, 1964).

A two-year study to evaluate the average and time-variant characteristics of stratospheric aerosols has been conducted with a laser radar (Fiocco and Grams, 1964; Grams and Fiocco, 1967). Most of the observations were conducted at Lexington, Massachusetts during 1964 and 1965; some data were also obtained during the summer of 1964 at College, Alaska. The vertical distribution of the aerosol particles was obtained by comparing the laser radar return with the return expected from a molecular atmosphere, using the observed echoes from 25 to 30 km altitude to calibrate the instrument. The data consistently showed a maximum in the relative concentration of aerosols between 15 and 20 km altitude. The observations showed that the stratospheric aerosol layer exhibited little temporal variability, with a generally decreasing trend during the two-year observation interval. At the observation site in Lexington, Massachusetts, the observed return from the layer was approximately 1.9 times the expected return from clear, dry air. The daily rms fluctuation of this scattering ratio was approximately 0.3 and hourly fluctuations were smaller. For the observations at College, Alaska, the maximum scattering ratio was ~1.7 with daily fluctuations of about 0.15. The study was conducted during a period following the eruption of the Mount Agung volcano in early 1963; thus, the results may represent anomalous conditions in the lower stratosphere and are likely to be associated with the temporal and spatial distribution of volcanic debris.

The observed scattering ratios have been related to the number of particles per unit volume illuminated by the laser beam by evaluating Mie-scattering functions for backscattered radiation. The calculated concentration of $\sim 1 \text{ cm}^{-3}$ for particles larger than about 0.3μ radius is in agreement with independent studies by other investigators, especially with the particle counts of Rosen (1964). Comparisons with earlier measurements obtained by other investigators using a variety of different techniques indicated that the concentration of stratospheric aerosols was about one order of magnitude higher than before the eruption of Mount Agung; this has also been confirmed by the results of other investigators (see, for example, Volz, 1965).

The observations have been compared with other meteorological parameters in the lower stratosphere. The center of mass of the layer was usually very close to 16 km; day-to-day changes in the tropopause height were accompanied by a tendency for small vertical displacements of the layer. The laser radar observations performed in Alaska agree with the concept that the height of the layer approximately follows latitudinal changes in the tropopause height. A significant negative correlation was found between dust concentrations derived from the results of the laser radar study and ozone concentrations obtained by the Air Force Cambridge Research Laboratories (Hering, 1964; Hering and Borden, 1964, 1965). The anticorrelation was also obtained between the measurements of the dust concentration and measurements of total atmospheric ozone obtained at Bedford, Massachusetts; this result provided additional statistical evidence of a relation between the aerosol layer and stratospheric ozone.

During summer 1964 laser radar experiments were performed in Alaska and Sweden for the purpose of observing the aerosol content of the mesosphere during noctilucent cloud displays (Fiocco and Grams, 1966). In these experiments strong echoes were observed near 70 km and were taken as an indication that measurable processes involving a wide range of mesospheric heights were involved. New experiments to obtain measurements of the aerosol content of the mesosphere at times when noctilucent clouds might be present were conducted in the summer of 1966 near Oslo, Norway (Fiocco and Grams, 1968). The measurements indicate that the altitude region 60-70 km contains an appreciable amount of particulate material in the summertime at high latitudes during periods of noctilucent cloud activity, as suggested by the earlier laser radar results. Observations of the transient features of a noctilucent cloud were also obtained with the apparatus: the height of the cloud varied from 75 to 73 km during the observation interval; the geometric thickness of the cloud was appreciably less than 1 km, and the optical thickness was about 10^{-4} . An estimate of the meridional flux of particulate material at high latitudes was obtained from the measurements by relating the average vertical distribution of aerosols observed by the laser radar during the summer to the general circulation of the upper atmosphere; estimates of the mass flux of extraterrestrial dust based on this data are in agreement with results obtained by other techniques.

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A large number of laser radar measurements related to the aerosol content of the mesosphere were obtained in Lexington, Massachusetts, in 1964 and 1965. The data are being analyzed and the results will soon be available.

2. INSTRUMENTATION AND DATA ANALYSIS

The measurements were made with a Q-switched ruby laser used as the transmitter and a 40-cm diameter telescope of the Dahl-Kirkham type as the receiver for a monostatic laser radar system. In the system used for the most recent experiments, the laser emits pulses of approximately 2 joules of less than 100 nsec duration at a maximum pulse repetition frequency of 0.5 sec^{-1} . The radiation is collimated by a transmitting telescope, 10 cm in diameter with 1-meter focal length. The laser is Q-switched through the use of a rotating prism. The instrument includes two synchronized rotating shutters: one is mounted on the transmitter to prevent any fluorescence from the laser after the pulse is radiated; the other synchronized shutter is incorporated into the detector to prevent exposing the photomultiplier to the intense return obtained from scattering at short distances. A temperature-controlled water-cooling system is used to maintain the laser unit and the narrow-band interference filters in the detection system at constant temperature through closed-loop circulation of distilled water. A polarizing filter is included in the receiver to reduce twilight-sky background: the filter is adjusted to match the polarization of the laser radiation; the observations are carried out at the zenith and the apparatus can be rotated around the vertical axis to minimize the polarized sky-background. The EMI 9558A photomultiplier used in the photodetector is refrigerated by circulation of methanol cooled by mixing with dry ice.

To record the data the apparatus utilizes a 35 mm automatic radarscope camera, modified for use with a dual-beam oscilloscope. Two traces, displaying the amplified photomultiplier current, are recorded simultaneously with different sweep rates: one trace displays the signal from 0 to 200 km altitude; the other displays records of either the signal from 0 to 40 km, to provide data on stratospheric aerosols, or the 60 to 90 km signal, to observe detailed features of mesospheric scattering layers. For altitudes above ~30 km, the backscattered signal is so small that a continuous photomultiplier current is no longer recorded. Thus, the high-altitude traces are analyzed by counting the number of individual photoelectrons recorded in specified range intervals, with the range determined by measuring the time difference between the instant the laser was pulsed and the instant the photoelectron was emitted. The data are reduced with the aid of a semi-automatic film reader incorporating an analog-to-digital converter. Coordinates related to the signal intensity for the 0-40 km traces and to the instant of emission of each photoelectron displayed on the high-altitude traces are digitized and punched on data processing cards for subsequent computer analyses.

A considerable reduction in the effort required to digitize the photographic records of the laser radar data is now possible. A computer has been incorporated into a photointerpretive system

for analyzing information recorded on 35-mm film. This system has been used extensively to analyze spark chamber data (Rudloe, Deutsch, and Marill, 1963); it has now been programmed to digitize the coordinates of the photographed oscilloscope traces. Some of the laser radar data have already been digitized with the programmable film reader, and the time and effort required to analyze the measurements have been substantially decreased.

3. CURRENT RESEARCH

Although the studies of the aerosol content of the atmosphere would benefit from the use of lasers of higher average power, the use of more sensitive photodetection systems, or, perhaps, the judicious use of on-line computer systems, it is apparent that the technique used to study atmospheric aerosols suffers from certain limitations in the interpretation of the laser radar returns. In particular, observations of the optical backscattering cross-section of the atmosphere do not provide absolute measurements of the atmospheric aerosol content or of the density of the molecular atmosphere unless the effects of scattering by aerosols and atmospheric molecules can be separated. For this reason, spectral analyses of the light scattered by atmospheric constituents are being conducted.

The main effect on the scattered light is the frequency shift due to the Doppler effect resulting from the motion of the scatterers. As a result of the random thermal motions of atmospheric molecules, the scattered spectrum will be broadened with respect to the radiated spectrum. Measurements of the width of the spectral line are related to the temperature of the gas and could therefore be used as the basis of a system for remote measurements of atmospheric temperature (DeWolf, 1967), while bulk shifts of the scattered spectrum could provide information on wind motion.

Aerosols also contribute to the scattered spectrum. However, the velocities associated with the random Brownian motions of aerosols are much smaller than the thermal velocities of the molecular component of the atmosphere, and the scattered energy from the aerosols is contained in a narrower band of the spectrum than the scattered energy from the atmospheric molecules. Thus, analyses of the frequency spectrum of laser echoes from atmospheric constituents would make it possible to distinguish between the contribution from the aerosols and from atmospheric molecules, if the spectral analysis can be performed with sufficient resolution.

Some preliminary laboratory experiments in which the spectrum of the radiation scattered from a laser beam has been analyzed to provide a measurement of the aerosol component have been reported (Fiocco and DeWolf, 1968). In these experiments the light from a continuous-wave He-Ne laser was scattered from air containing naturally-occurring aerosol particles and from air containing artificially-produced dense fogs. The spectral distribution of the light was measured with a pressure-scanned Fabry-Perot interferometer. Although the apparatus used for these studies requires considerable improvement, a direct measurement of the ratio of aerosol-to-molecular scattering was obtained. This technique provides an

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absolute measurement of the aerosol-to-molecular scattering and therefore provides the information required for the definite interpretation of laser radar echoes.

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