SENSING OF METEOROLOGICAL VARIABLES BY LASER PROBE TECHNIQUES

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Submitted by: Giorgio Fiocco

Massachusetts Institute of Technology
Research Laboratory of Electronics
Cambridge, Massachusetts

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Much of the research in our group is concerned with the properties and use of coherent light in connection with problems of atmospheric physics. Those aspects of the research which deal more directly with meteorological applications are supported by NASA Grant NGR-22-009-(131). Those aspects associated with the influx of dust and related upper atmospheric processes are supported by NASA Grant NGR-22-009-(114). In this report a general outline of the various activities in our group will be given, and in subsequent sections some specific results will be discussed.

1. Outline of Activities

A trailer has been instrumented as a mobile laboratory for research in atmospheric optics containing the optical radar, as well as other instrumentation. We have been analyzing the results of measurements carried out with the optical radar during 1964 and 1965. Observed profiles of the optical backscattering cross section of the atmosphere as a function of altitude have been interpreted to supply information on the dust content of the atmosphere from 10 to 150 km. An analysis of a large sample of the stratospheric data has been completed and will soon be published.[1] These observations of the stratospheric aerosols were made during the two-year study at Lexington, Massachusetts, and also at College, Alaska, during the summer of 1964.

The data have been compared with various meteorological parameters associated with conditions in the lower stratosphere. A significant negative correlation between fluctuations of dust and ozone has been found in the measurements.

At present, we are concerned with the reduction of data in the 35-150 km range. Although difficulties in the reliable operation of a semi-automatic digitizer have unfortunately slowed down the data reduction, we hope to complete the reduction early in 1967.

We expect to be able to study the mesospheric dust content, its possible relation with the electron recombination in the D-region, as well as the possible influx of micrometeoric materials and its relation to E-region ionization.

With regard to the first problem, we are interested in the possibility of performing, simultaneously, dust-density measurements by optical radar and electron-density measurement by rocket, and should like to consider collaborative efforts with other groups.

The production of ionization by micrometeorites has been investigated for a simple model based on the acceleration of upper atmospheric molecules by incoming micrometeorites and the successive neutral-neutral ionizing collisions.[2] We have found that a conservative value of 4×10^3 tons/day for the influx rate of cosmic dust on Earth is sufficient to produce ionization in the amounts found in the E-region at night; since there is still no satisfactory explanation for the formation of the E-region at night, this is probably a significant result.

Another aspect of the role of dust in the upper atmosphere with which we are now concerned is its relation with rainfall; we have correlated fluctuations of stratospheric dust amounts with the occurrence and the amounts of precipitation, but, thus far, we have been unable to find a relationship. We expect to extend the investigation to include mesospheric dust and thus check the validity of Bowen's hypothesis.

Essential to the interpretation of the optical radar data is the availability of theoretical backscattering cross sections for spheres and ensembles of spheres with specified size distributions. We have extended existing computations to cover a wide range of complex values for the refractive index and have considered a variety of size distributions. The computations are almost complete, although we are facing the task of a meaningful yet compact presentation of the data.

We shall also extend the computations to cover scattering angles different from 180°; these tables will be of use to interpret photometric and visual observations of scattering from the zodiacal light and from atmospheric stratifications, as well as an aid in estimating the feasibility of forward-scattering optical communication links.

Some estimate will also be carried out of the effects of various aerosol distributions over the response of the Dobson photometric technique for the measurement of atmospheric ozone.

During the summer of 1966, the optical radar was taken to Norway to continue the investigation of noctilucent clouds that had been initiated in 1964. Several noctilucent displays were observed, and we have collected a very large amount of data that is being analyzed.

An important advantage of the optical radar technique when applied to noctilucent clouds is that, since our observations are performed at night as well as at twilight, we should be able to describe the development of the cloud when no other techniques of observation are available. From the 1964 data we inferred the possibility of substantial vertical motion for the cloud, and hope with present data to be able to substantiate the earlier findings.

The stratospheric aerosol layer was also observed continuously in Norway during the summer of 1966; we intend to make a comparison with activity in the previous years and establish the presence of a latitudinal gradient in the concentration, which was suggested in the earlier work.

An OH airglow meter that utilizes photon counting techniques is being developed and has also been operated in Norway during observation of noctilucent clouds. The importance of studying OH is based on (a) its role in the dissociation of H_2O (H_2O is possibly a major constituent of noctilucent clouds); (b) the fact that the excitation of the rotational-vibrational bands of OH probably reflects the ambient temperature of the mesosphere; and (c) the relation between OH and Na airglow activity. We are designing a multichannel photometer to scan simultaneously several airglow lines.

Another area of interest in our group is the measurement of atmospheric temperatures by the broadening of laser radiation backscattered by air molecules. We have theoretically analyzed and partially implemented schemes for heterodyne and homodyne detection, as well as more conventional schemes with optical filtering used, and we are now assembling a system consisting of a high-power Ar^+ laser of high spectral purity, and a pressure-scanned Fabry-Perot interferometer.

We are now becoming interested in the generation of high power at the wavelength of optical transitions of atmospheric gases; there is the possibility that, because of resonant scattering, cross sections would be greatly enhanced, thereby allowing us to observe the presence of even minor constituents in the upper atmosphere and in the laboratory. We are carrying out experiments to explore the practicality of carrying out observations at the following wavelengths: 6560.1 Å (He^+), 3582 Å (N_2^+), 6707.9 (Li), 5973 (O_2), 5889.9 (Na), 7698.9 and 7664.9 (K), as well as other transitions.

It would appear that it is possible to generate high outputs at these wavelengths by the combination of Raman effects, second-harmonic effects, and thermal tuning of laser light. The possibility of measuring the line-width of resonant transitions, by tuning the laser to a specific wavelength suggests a method for the measurement of the concentration, as well as the temperature of ionic species. Since the power levels would be much higher than those available heretofore, it should be possible to study the profiles of spectral lines at great distance from resonance and at very low pressures, and gather information on the collisional effects, as well as the Doppler effects.

Further work on the laser scattering diagnostic technique for plasmas, first developed in this laboratory, is now being carried out. We are carrying out observations of incoherent scattering of pulsed ruby laser light in a reflex discharge, and are modifying the system to study the possibility of observing scattering from a cw Ar^+ laser light; the use of a relatively low-power, continuous source would constitute a great advance in the practicality of this diagnostic tool.

2. Correlation of Stratospheric Dust with Rainfall

Since the nucleating properties of dust provide a mechanism for starting the condensation of water vapour, the vagaries of weather might be somewhat related to fluctuations of the dust content of the atmosphere. Bowen[3,4] has given evidence that peaks in average daily rainfall amounts follow, with a time lag of approximately one month, the dates of regular meteor showers, thereby suggesting that meteor showers have some influence on world rainfall.

These results have been the object of controversy (see among others

Martyn,[5] Kline and Brier,[6] Rosinski and Pierrard[7]). A possible criticism is that, because of the great variety of expected sizes in the dust influx and of the resultant difference in settling velocities, it would seem to be difficult to preserve the necessary coherence in the vertical transport process to determine detectable effects.

We have made observations of the dust content of the atmosphere at Lexington, Massachusetts, for a period of approximately two years, in 1964 and 1965, and data related to the stratospheric dust content are now available. The data are obtained by observing with an optical radar the echoes back-scattered by atmospheric constituents and comparing their intensity with the returns that one would obtain from a dust-free atmosphere (see Fiocco and Grams,[8] and Grams and Fiocco[1]).

The optical radar technique is particularly sensitive to particles in the size range from ~0.1-μ to 1-μ radii, since a transmitted wavelength $\lambda = 0.694\ \mu$ is utilized. This is the typical spectrum of particle sizes obtained in the stratosphere by balloon and aircraft collections.

The dust content of the stratosphere during the period of study was approximately an order of magnitude larger than usual, because of the injection of volcanic material following the eruption of Mt. Agung, in 1963. It is therefore doubtful whether any of the features of the stratospheric aerosol layer at the time of observation could be attributed to the influx of extraterrestrial dust.

Since our study has provided us with a record of the stratospheric dust content and its fluctuations, we have correlated the relative dust amounts at heights of 12 km and 16 km with the daily amount of precipitation averaged among 103 stations in New England, in an attempt to establish that a relation with rainfall might exist.[9] Although the stratospheric dust amounts are probably not related to meteoric activity, one might expect that the incursion of stratospheric dust into the upper troposphere would affect rainfall amounts, regardless of the source. The time scale for stratospheric-tropospheric exchange is difficult to specify, however, since such processes, at best, are only poorly understood. The times involved in the vertical diffusion from the lower stratosphere to the upper tropopause may be several weeks (see Junge, Chagnon, and Hanson[10]).

The length of time necessary to introduce stratospheric dust into the troposphere makes it almost naive to assume that a correlation between the two local parameters might be found. Our study of the stratospheric dust layer (Grams and Fiocco[1]) indicated, however, a degree of persistence of stratospheric dust amounts involving time periods of almost a week. Assuming a wind velocity of 20 m/sec, one may estimate the length scale of a stratospheric dust "cloud" to be of continental dimensions. This lends considerably more justification to comparing the rainfall figure for the New England states with the stratospheric dust measurements carried out at Lexington, Massachusetts.

Using approximately 60 pairs of data, we calculated the correlation coefficients as a function of the time lag between the measurements for the dust content at different heights and the averaged measurements of rainfall amounts. Although small positive correlations were apparent for time lags of 15-25 days, these might be ascribed to the limited size of our statistical sample. No trend was evident to indicate a correlation between the two physical quantities.

Such correlations are only indirectly a test of Bowen's hypothesis. In order to establish a meteoric effect on rainfall, we should perhaps try to correlate mesospheric dust amounts with rainfall. In fact, the mesospheric dust amounts should be related to meteoric influx and a local measurement of it should exhibit more global features than a local measurement of stratospheric dust. Data related to the mesosphere have also been collected, and will be available for such analyses at a future date.

3. Observations of Noctilucent Clouds in Norway by Optical Radar during Summer 1966

Observations of noctilucent clouds were carried out in Oslo, Norway, during the summer of 1966, to obtain information on the temporal variability of the height, structure, and other physical characteristics of noctilucent clouds. The apparatus is basically the same as the optical radar unit used in Sweden in the summer of 1964 (Fiocco and Grams[11]), but many improvements were incorporated to improve the reliability and general performance of the system. In the laser unit the ruby, flashlamp, and cavity were cooled by closed-loop circulation of distilled water through a water-cooling unit. This and other improvements in the laser itself provided approximately 2-J pulses of 100-μsec duration, at a maximum p.r.f. of 0.5 sec^{-1}. To record the data at these higher rates, the apparatus utilized an automatically advanced 556-BH1 radarscope camera, modified for use on a Tektronix 555 dual-beam oscilloscope. Two traces displaying the amplified photomultiplier current were recorded simultaneously with different sweep rates: one trace recorded the echoes from 0-200 km altitude for the noctilucent cloud data, the other displayed the echoes from 0-40 km for a simultaneous study of the 20-km aerosol layer to establish latitude and time variations of the dust content of the stratosphere.

In addition to the optical radar instrumentation, a developmental airglow photometer was also mounted in our instrumentation trailer to derive simultaneous measurements of the intensity and rotational temperature of the OH emission from the mesosphere. The changes in temperature and water-vapor content near the mesopause inferred from these airglow measurements might provide an insight into the meteorological processes associated with the formation of noctilucent clouds.

Viewing conditions were excellent throughout the summer: more than half of the nights were sufficiently clear to obtain data. Noctilucent clouds of varying degrees of intensity were observed visually on approximately one-third of the nights, when data could be obtained. Therefore, we have accumulated a considerable amount of data on the dust content of the mesosphere for various noctilucent cloud displays, as well as background information of the scattering properties of the mesosphere in the absence of the clouds. A preliminary analysis of the photographic records is under way: earlier problems associated with the reliable operation of our Benson-Lehner Oscar F semiautomatic record analyzer have recently been eliminated, and an appreciable proportion of data records has now been digitized and is available for analysis. Furthermore, previous efforts to program a Digital Equipment Company PDP-1 computer to automatically digitize our records for subsequent analyses on the IBM 7094 computer at the Computation Center, M.I.T., are now being realized, and a considerable reduction in the time required for analyzing our data may soon result.

The present results of our data analysis, at an admittedly preliminary stage, corroborate the results of the summer of 1964, with definite echoes observed from altitudes between 65 km and 70 km, the strongest echoes being observed when noctilucent cloud displays were visible overhead during twilight hours. The rapid rate at which data could be gathered has reduced the observation time for obtaining statistical evidence of the presence of noctilucent clouds; this increases the probability of studying transient features of the clouds that would ordinarily be lost by averaging over long observation periods. We are, at present, considering a simplified model for atmospheric motions of a tidal nature induced by the thermal effects of a layer of dust near the mesopause. We hope that resulting estimates of the vertical motions induced by the dust will be consistent with the temporal variability observed in our experiments.

4. Laser Radar for Measuring Atmospheric Temperature

We propose to measure the temperature of the atmosphere as a function of altitude, using a ground-based optical radar. Progress toward this goal is summarized in this section.

The optical radar now in use by this group provides information on the intensity of the scattered return from a given altitude. But the returning optical signal carries spectral, as well as amplitude, information, and the former can be related to the velocity distribution of the scattering particles in a low-density gas through the theory of the Doppler effect. By measuring the spectral broadening occurring when the emission from a high-powered, single-frequency laser is scattered from a gas, one can determine the kinetic temperature.

This work is going forward in three stages. Our purpose in the first stage, which has been completed, was to determine the feasibility of the experiment and select the best technique for spectral analysis. It is now clear that conventional interferometric spectroscopy is better suited to our purpose than the newer optical mixing technique, since the scattered radiation is very weak, spatially incoherent, and spectrally rather broad. Calculations show that the use of a photoelectrically scanned Fabry-Perot interferometer should permit reasonably accurate (of the order of $\pm 1\,0\,^{\circ}C$) temperature determinations in the troposphere and lower stratosphere in a few minutes of integration time.

The second stage, which is now in progress, involves the use of an He-Ne laser and a Fabry-Perot interferometer to make a measurement of the temperature of air at one atmosphere pressure in the laboratory. This is desirable in order to calibrate and test the interferometer. Scattering from gases at STP is of interest for its own sake, at the present time, because of its connection with high-frequency sound propagation (Greytak and Benedek[12]).

With this end in view, we have constructed a photoelectric Fabry-Perot interferometer that can be pressure-scanned (Jacquinot[13]). The Fabry-Perot plates are 3.7 cm in diameter, of high quality, and flat to a hundredth of a wavelength. They are mounted in an airtight chamber that can be filled with nitrogen gas to a pressure of 3 atm. Behind the interferometer is a small aperture and an EMI 9558 phototube that has a 6% quantum efficiency at 6328 Å. The electron-cascade pulses are then counted and recorded.

We have also purchased a Spectra-Physics Model 130B He-Ne laser that provides 0.75 mW of output power in a single transverse mode at 6328 Å.

At the present time, we are constructing several Invar spacers for the interferometer to allow high-resolution spectra to be recorded with good fineness; a fineness in excess of 20 is expected.

The third stage will involve the adaption of the temperature-measuring technique for use as an optical radar; this is tentatively scheduled to be under way in the summer of 1967. As a source for this radar, we are considering a high-powered Argon ion laser adapted to operate at a single frequency (see section 5). Zory[14] has reported an output power of 130 mW at the 4880 Å line for single-frequency operation.

We conclude that temperature measurements with the use of this technique are feasible. Such a system might satisfy the need for a reasonably fast, ground-based, temperature-sensing device for the lower atmosphere. Moreover, in view of the rapidity of development in laser technology, it is likely that this technique might, in the future, be applicable to measurement of temperature in the upper atmosphere, also.

5. Laboratory Laser-Scattering Experiments

Some laboratory experiments to detect and analyze the spectrum of the light scattered by gases at low pressures and by low-density plasmas is now being assembled. The apparatus consists of a stainless-steel vacuum chamber attached to a 6-inch diffusion-pump system. The ultimate pressure of the system is 10^{-6} Torr. A plasma can be generated by a reflex discharge in an axial magnetic field ranging up to 1500 Gauss. A plasma column, 1-cm in diameter and 10-cm long, with a peak density of 5×10^{12} electrons/cm^{-3} can be attained.

The light source is a 1-watt continuous Argon laser operating at the 4880 Å line. Both the 1-watt output beam and the higher power field within the mirror cavity can be used in the scattering experiments. The detector consists of an EMI phototube preceded by a narrow-band interference filter (full width at half maximum = 1.58 Å), a polaroid filter, and a lens system. Scattering may be detected at a variety of angles. Both synchronous detection and counting techniques can be applied to the phototube output.

The electron density and temperature of the plasma will be determined by scanning the narrow-band filter across the spectrum of the light scattered at 8°. Experiments will also be conducted at smaller angles to measure the ion temperature. We hope that scattering from collective phenomena such as Bernstein waves in a magnetized plasma will also be detected.

This apparatus will also be used to measure the optical cross sections of atomic, ionic, and molecular species present in the upper atmosphere.

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