Lidar Observations in Relation to the Atmospheric Winds Aloft[1]

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(Manuscript received 2 February 1970, in revised form 28 May 1970)

ABSTRACT

Lidar (laser radar) observations of the visually clear troposphere between 4 and 14 km are compared with data from simultaneous rawinsonde ascents for the purpose of exploring possible relationships between lidar echoes and the atmospheric winds aloft. Because of its low intensity, the backscattered laser signal was monitored by means of a pulse-counting technique. The data indicate a relative increase in atmospheric backscatter with height underneath the level of maximum wind speed. The increase in backscatter represents an increase in the concentration of particulate matter. Since its level corresponds to the average altitude for cirrus clouds, it is believed that the increase in particle density detected by the lidar is due to advection and/or formation of ice crystals near the level of maximum wind. It is concluded that lidar-observed backscatter profiles of the upper troposphere may be of value in inferring wind shear or layers of maximum wind speed, particularly in terms of extending information acquired by conventional means to other times.

1. Introduction

The advent of the laser as a high-energy source at optical wavelengths prompts consideration of optical ranging techniques for measuring upper winds. A number of approaches have been suggested, and some have been tried experimentally. In principle, lidars or optical radars could be used to measure upper winds in a variety of ways. The most obvious approach is to track targets such as balloons or parachutes. However, present radars like the FPS-16 have excellent resolution and tracking capabilities and there is little advantage in employing optical radars for tracking solid targets. On the other hand, some possibility exists for tracking tenuous targets such as puffs or trails of smoke introduced into the atmosphere by rockets. Although photogrammetric techniques have traditionally been used for such tracking, the range-determining capability of lidar might be a great advantage in this application. Another possibility is to make use of natural particulates in the atmosphere to study motion aloft. For example, where cirrus clouds or other particulate matter concentrations occur, wind motion could be inferred by observing the displacement of identifiable features. Of course the most powerful approach would be direct application of Doppler radar techniques to lidar systems that would be capable of analyzing the frequency shifts in backscattered energy which are due to motion in the natural aerosol concentrations. A laser Doppler velocimeter has been demonstrated in the laboratory for measurement of highly localized flow velocities in gases and liquids (Foreman *et al.*, 1966). In the real atmosphere, the feasibility of a cw CO_2 laser-Doppler velocimeter has been demonstrated by Huffaker *et al.* (1970).

At present, it appears that a most useful immediate contribution could be made by lidar in using observations of energy backscattered by atmospheric aerosol concentrations to supplement and extend (in space and time) wind data acquired by rawinsonde or FPS-16/balloon (Jimsphere) soundings. On the premise that vertical variations in the lidar-observed backscatter, i.e., vertical variations in particulate content, are associated with the vertical wind profile, a limited sample of nighttime lidar observations of the upper troposphere (4–14 km) obtained in conjunction with GMD-1 rawinsonde ascents has been analyzed. Some preliminary results are presented here. The vertical profiles of received backscatter signal suggest that larger-than-normal concentrations of particulate matter are present underneath the level of maximum wind speed.

2. Observational technique

Observations of the backscattering properties of a visually clear upper troposphere with a ground-based ruby lidar involve the detection of very-low-energy signals. The accepted technique for measuring low-energy signals is to employ a photomultiplier having a small cathode area (small source of thermally emitted electrons) and sufficient electron multiplier gain (10^7 or more), so that anode pulses resulting from individual photon absorption events at the photocathode can be viewed on an oscilloscope connected to the multiplier output (Morton, 1968). Each photon incident on the

[1] This work is based on research supported by the Aero-Astrodynamics Laboratory, NASA-George C. Marshall Space Flight Center, Alabama, under Contract NAS8-21117.

photocathode has a given probability (frequently called *quantum efficiency*) of causing the emission of a photoelectron. Each emitted electron triggers a cascade of $\sim 10^7$ electrons from the multiplier section of the phototube; this cascade appears as an individual anode-current pulse on the oscilloscope display. A count of these discrete anode pulses per unit time interval is related to the arrival rate of photons at the photocathode. The arrival rate of photons, in turn, represents the atmospheric backscatter signal. The pulse-counting technique has been successfully used in many investigations of the upper atmosphere by lidar (Bain and Sandford, 1966; Collis and Ligda, 1966; Nishikori *et al.*, 1965).

The operating procedure used for obtaining the observations to be presented was as follows: During nighttime, when the sky was visually clear, rawinsonde ascents were made at Pillar Point (an AF/NASA radar missile-tracking facility 17 mi northwest of the Stanford Research Institute location at Menlo Park) by a mobile GMD-1 unit from Vandenberg AFB. Ascents were made coincident in time with the atmospheric backscatter data collected by the SRI Mk V ruby lidar at Menlo Park. The characteristics of this lidar have been described elsewhere (Viezee and Oblanas, 1969). During operation, the lidar was pointed toward the zenith sky and lidar pulses were transmitted at a rate of one 15-nsec pulse per minute. At present, the temperature of the ruby rod cannot be completely controlled during an extended period of operation. Furthermore, the wavelength of the output pulse cannot be measured conveniently. However, the total output energy was monitored and found to remain relatively constant (0.22 J$\pm$2%) from pulse to pulse when firing the lidar at a rate not higher than 1 pulse min^{-1}. The nearly constant output energy has been assumed to indicate no excessive temperature fluctuations and thus no detuning into and out of the water vapor absorption line at 6943.8Å. At each lidar firing, the atmospheric backscatter signal was recorded on the Polaroid photograph of a dual-beam oscilloscope display. An example of this format of data recording is shown in Fig. 1. The trace on the left-hand side presents photomultiplier anode current on a logarithmic scale vs time (0–100 μsec) on a linear scale; this is equivalent to the logarithm of the receiver-output power vs range out to 15 km. The trace on the right-hand side of the oscilloscope display shows (on a linear scale) the individual anode-current pulses recorded over a 5-μsec time interval (750 m height interval) along the left-hand side trace between 8250 and 9000 m. The atmospheric backscatter signal received from the expanded height interval is evaluated by visually counting the number of individual anode-current pulses ($\sim$22 pulses for the 5-μsec interval of Fig. 1). Any 750 m sections of the trace on the left-hand side may be expanded and displayed on the right-hand side by properly time-delaying the oscilloscope sweep. In the present experiment, the first 750 m section was expanded and displayed starting at a height of $\sim$4.5 km (30-μsec time delay). By making a series of observations and increasing successively the time delay of the oscilloscope sweep by 5 μsec, the troposphere between 4.5 and 14 km was sampled or "sounded" in successive 750 m height intervals (one interval per single shot) over a period of $\sim$12 min. All observations were made at night in order to minimize contributions to the signal from the sky background.

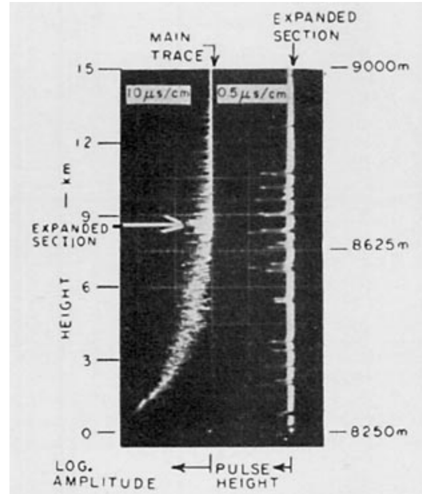

FIG. 1. Photograph of dual beam oscilloscope display used to record lidar observations (4 March 1969, 2238 PST).

Because of the low energy levels involved and the time variations in the response of the lidar receiver system, especially the photomultiplier, meaningful information on atmospheric structure can be derived only from a sequence of observations. Consequently, successive lidar "soundings" were made over time periods of several hours, and data samples were averaged to obtain a vertical profile of received backscatter signal.

3. Comparison between lidar and rawinsonde data

On 20 February 1969, two rawinsonde ascents were made at Pillar Point between 2000 and 2300 PST. The vertical profiles of temperature and scalar wind speed obtained from these ascents are compared to the lidar observations in Fig. 2. The lidar observations (in Fig. 2 and in all subsequent figures) are presented in the form of a vertical profile of pulse count vs height. Each profile is obtained by 1) averaging the pulse counts from six to eight consecutive samples or "soundings" for each 750 m height interval, 2) assigning the average count to the mid-level of the interval, 3) multiplying each average count by the square of the ratio of its mid-level height to 4875 m (the mid-level height of the first interval) to eliminate the inverse range-squared attenuation of the signal, and 4) connecting the average values by straight lines. The $\pm$1 standard deviation of the sample data for each height group is indicated. Thus, the observed profile represents the vertical variation of the

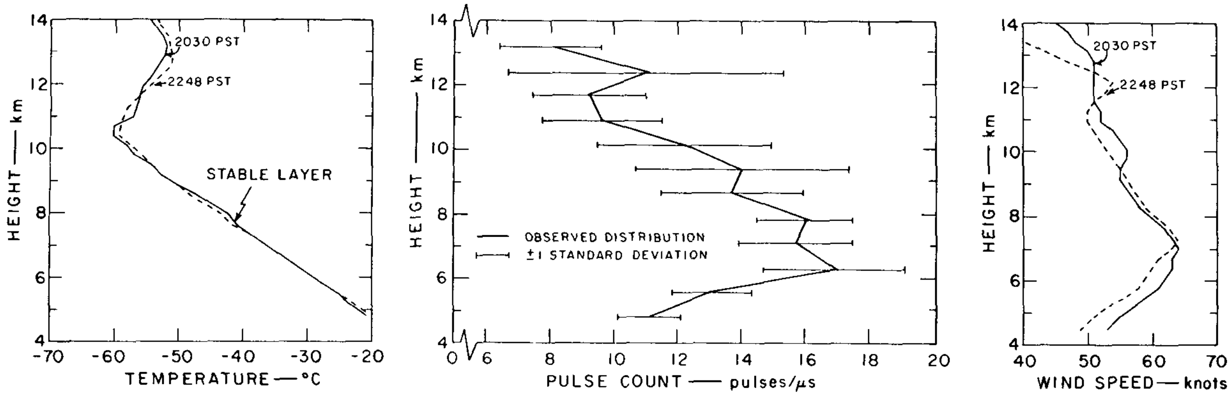

FIG. 2. Comparison between vertical profile of average pulse count (height-normalized to 4875 m) observed by lidar at Menlo Park on 20 February 1969, 2000–2238 PST, and vertical profiles of temperature and wind speed from simultaneous rawinsonde ascents at Pillar Point.

average atmospheric backscatter signal as recorded by the lidar receiver height-normalized to 4875 m. On the basis of statistical significance tests (Wilks, 1961) using the sample means and sample standard deviations of the lidar data shown in Fig. 2, it can be concluded that at the 99% confidence level the count[2] at 6.4 km is larger than the count at 4.9 km. This implies that the aerosol content detected by the lidar increases markedly with height toward the level of maximum wind speed (64 kt at 7.0–7.3 km). From 6.4 km to the height of the stable layer in the temperature profiles, the count is nearly constant with height. From 8–12 km, the received backscatter count shows (within statistically significant limits) a general decrease with height as might be expected in a purely molecular atmosphere or in an atmosphere with average turbidity such as described by Elterman *et al.* (1969). The peak at 12.3 km is not statistically significant due to the large standard deviation of the data sample.

On the night of 4–5 March 1969, lidar observations were made for a period of 5 hr but only one rawinsonde ascent is available for comparison. The data are shown in Fig. 3. Again the vertical profile of backscatter signal based on the lidar data samples does not show the expected decrease with height. On the basis of statistical significance tests using confidence limits, it can be concluded that, at the 99% confidence level, the range-corrected counts received from 7.1 km and from 11.6 km are *larger* than the count from 4.9 km. Between 7.1 km and 11.6 km there are no statistically significant increases or decreases and the received backscatter can be considered constant with height. Thus, the lidar data imply a gradual rise in aerosol content from 4.9 km to the level of the maximum wind speed and the tropopause. Only above this level (12 km) do the lidar data show a normal decrease in receiver backscatter with height.

The most complete observations were made on the night of 7–8 March 1969. Fig. 4 shows the comparative lidar and rawinsonde data for two successive time periods. For each 2-hr period, an increase in the backscatter signal with height is detected under the level of maximum wind speed and under a relatively stable layer in the temperature profile. From the vertical profile of backscatter signal shown in Fig. 4a, it can be concluded, at the 99% confidence level, that the signal

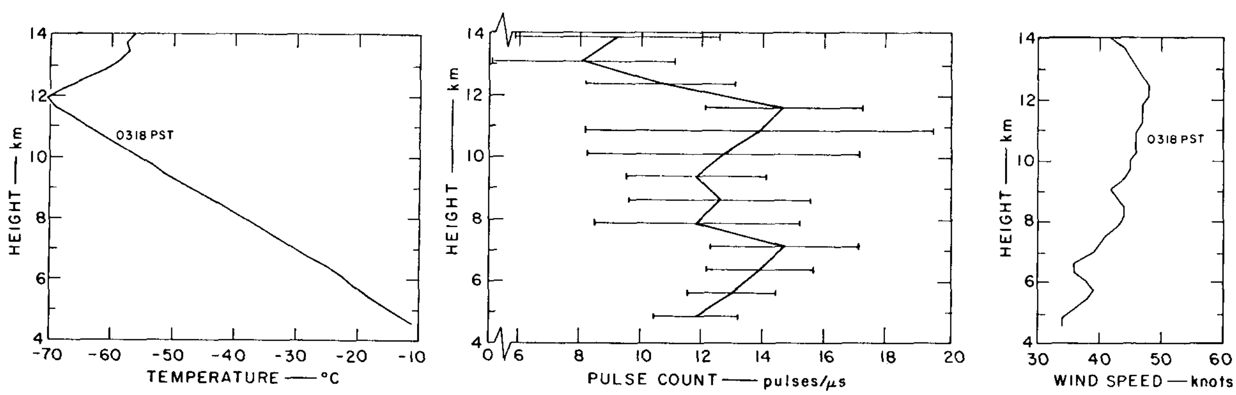

FIG. 3. Comparison between vertical profile of average pulse count observed by lidar at Menlo Park on 4–5 March 1969, 2230–0312 PST, and vertical profiles of temperature and wind speed from rawinsonde ascent at Pillar Point.

[2] All indicated heights are truncated to one decimal place.

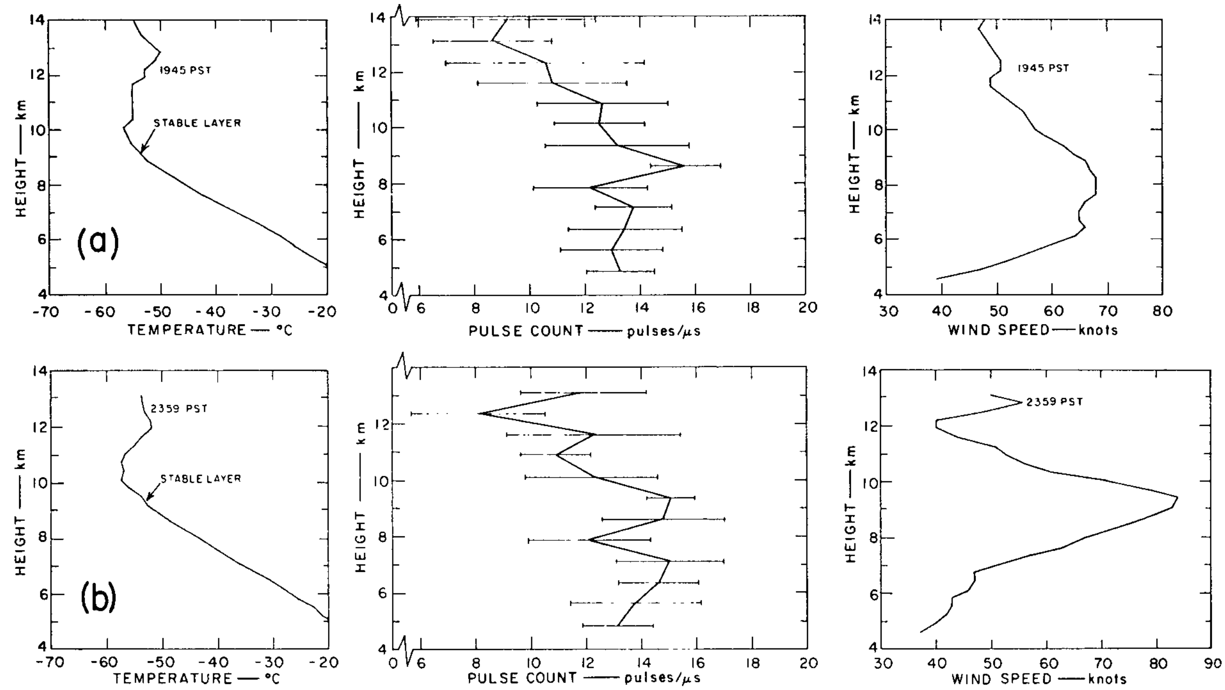

FIG. 4. Comparison between vertical profile of pulse count observed by lidar at Menlo Park and vertical profiles of temperature and wind speed for (a) 7 March 1969, 1903–2132 PST, and (b) 7–8 March 1969, 2201–0030 PST.

count at 8.6 km is larger than that at 4.9 km which implies an increase in the aerosol content with height to a level which is just above that of the maximum wind speed (68 kt from 7.6–8.3 km) and which coincides with the base of the stable layer indicated in the temperature profile. During the second observation period (Fig. 4b), the signal count increases, at only the 95% confidence level, from 4.9 to 7.1 km and decreases at the 95% confidence level from 7.1 to 7.8 km. However, the backscatter signal from 9.4 km is significantly larger (at the 99% confidence level) than that from 4.9 km, so that there is again evidence of an increase in aerosol content with height underneath the level of maximum wind speed (84 kt at 9.4 km) and under the stable layer in the temperature profile. For both time periods, there is generally a decrease of backscatter signal with height above the level of maximum wind, although the lidar data of Fig. 4b show a complicated profile above 11 km which may be associated with the development of the secondary wind speed maximum observed at 2359 PST. Fig. 5 shows how the vertical profiles of time change in temperature and wind speed obtained from the data of the two rawinsonde ascents relate to the atmospheric layer which contains the levels where the backscatter signal detected by the lidar was significantly larger than at the other levels that were sampled. During the observed period of 4–5 hr, a significant temperature increase (1–2C) and wind speed increase (10–20 kt) is observed near the layer of the relative maxima in backscatter signal (8.6–9.4 km). It is noteworthy that the complicated structure observed above 11 km in the lidar backscatter profile of Fig. 4b is near a region of large temporal change in temperature.

4. Discussion

The four periods of lidar-rawinsonde observations presented in Figs. 2–4 suggest that in the upper troposphere between 4 and 14 km the variation of the atmospheric backscatter signal with height can be significantly different from the normal decrease which is characteristic of an atmosphere with average turbidity.

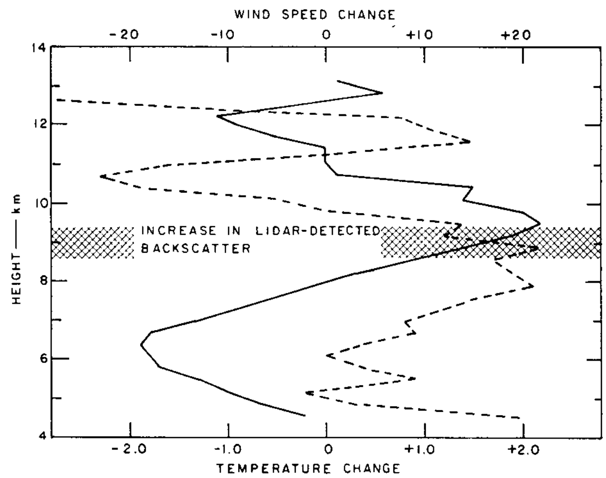

FIG. 5. Temperature change (dashed profile) and wind speed change (solid line) observed by successive rawinsonde ascents during lidar observations on 7–8 March 1969.

In the four cases examined the data indicate increased aerosol content near the level of maximum wind speed. In one case, the increase in particulate matter detected by the lidar appeared related to the tropopause. In the remaining cases the increase was observed below the tropopause under a stable layer in the temperature profile.

Since the backscatter from the tropospheric levels in question is very small, samples of lidar observations are required in order to eliminate fluctuations inherent in photon counting, in system response and in atmospheric variations. The relatively large standard deviations of the lidar-signal samples from particular levels deserve notice. Since the effects on the signal from system noise and sky background noise are negligible, it is suspected that atmospheric variations are responsible. The large standard deviations between 10 and 11 km in the data for 4–5 March 1969 (Fig. 3) are an example. Although during this time period of observation, the sky appeared visually clear to the lidar personnel, the official record of surface observations from Moffett Naval Air Station (10 mi southeast of Menlo Park) showed that thin cirrus clouds were reported after midnight. It is, therefore, likely that the increase in aerosol content detected by the lidar under the level of maximum wind was associated with tenuous cirrus and that the large standard deviations involved in the measurements were associated with temporal and/or spatial variations in ice crystal concentrations. No middle or high clouds were reported during the periods of observation on 20 February and 7–8 March. However, on 7–8 March, the layer of large backscatter signal was closely related to a layer of large warm-air advection which suggests again that the lidar may have detected sub-visible cirrus (James, 1957).

The limited observational program suggests that lidar can possibly provide *indirect* information on the atmospheric winds aloft in apparently clear skies by monitoring variations in the particulate content of the atmosphere with height. This capability could potentially be utilized in extrapolating or interpolating wind data from other sources—for instance, monitoring the height change of a maximum wind or large wind shear level identified in earlier conventional soundings. The statistical evidence that lidar-detected anomalies in the vertical profile of atmospheric particulate content may be related to the level of maximum wind speed or possibly to layers of wind shear has important implications in connection with the identification of turbulence.

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