Lidar Observations of Sierra-Wave Conditions

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ABSTRACT

Early in 1967 a series of observations using pulsed ruby lidars were made near Independence, Calif.; the objective was to investigate the value of lidar for studying air motion in the Sierra wave, with special reference to indications of turbulence.

Although no intense wave activity occurred, appreciable wave motions were observed, both in what appeared to the eye to be clear air and in air where the particulate matter was sufficiently concentrated as to be visible as clouds. Interruptions in the smooth laminar flow in the clear air were observed, and measurements were made of the length, amplitude and height of waves shown by clouds.

With previously existing techniques, only limited observation of such phenomena have been possible. It is thus concluded that lidar observations are of considerable value in studying wave motion, even in the absence of visible clouds. There is also a possibility that lidar could indicate the presence of turbulence by revealing the breakdown of wave motion or the presence of rotors.

1. Introduction

An experimental program was carried out with two ruby lidars during February and March 1967, to investigate the value of lidar observations for studying air motion in the Sierra wave, with special reference to any indications of turbulent motion.

This period was selected to coincide with a program of research into high-level turbulence and its detection, being carried out with aircraft of the Royal Aircraft Establishment (United Kingdom) and the National Research Council of Canada.

The initial intention was for these aircraft to concentrate on an area near Independence, Calif., the scene of the classic studies on Sierra-wave phenomena made by Holmboe and Klieforth (1957) and Kuettner (1958). The lidar was accordingly located some 11 km due east of Independence. As it happened, no intense wave situations developed in that area during the program, although violent turbulence was experienced there on 14 February 1967 before the lidar observations properly started. One aircraft operated in the vicinity on 1 March 1967 during one period of lidar observations, but experienced no turbulence. Series of lidar observations were made on seven days, but true wave motion was only apparent on 19 and 28 February and 1 March 1967.

2. Methods of observations

Two pulsed ruby lidars, details of which are given in Table 1, were used to observe clouds and discontinuities in scattering in the "clear" atmosphere in the manner described by Collis (1965) and Collis *et al.* (1964). By scanning the lidars through the vertical plane, two-dimensional cross sections of the atmosphere could be constructed analogous to the familiar RHI presentations of weather radar practice.

The observation site was at approximately 1370 m

TABLE 1. Characteristics of SRI lidars (from Northend *et. al.*, 1966).

	Mark I 1967	Mark V 1967
Transmitter		
Laser	$3\times\frac{1}{4}$-inch 90° C-axis ruby crystal; Brewster-angle ends, uncoated	$6\times\frac{3}{8}$-inch ruby crystal, Brewster-angle one end, planar one end, uncoated
Q-switch	Saturable dye (vanadium phthalocyanine)	Rotating prism and saturable dye
Pulse length	24 nsec	15 nsec
Peak power	10 MW	18 MW
Optics	Refractor 4-inch aperture	6-inch Newtonian reflector telescope
Beamwidth	Approximately 0.5 mrad	Approximately 0.3 mrad
PRF	Two per minute	Five per minute
Receiver		
Photomultiplier	14-stage RCA type 7265	14-stage RCA type 7265
Optics	4-inch aperture aerial camera objective with adjustable field stop	6-inch Newtonian reflector telescope with adjustable field stop
Beamwidth	1.2 to 15.0 mrad	0.2 to 0.9 mrad
Bandpass	Approximately 17 Å	Approximately 17 Å

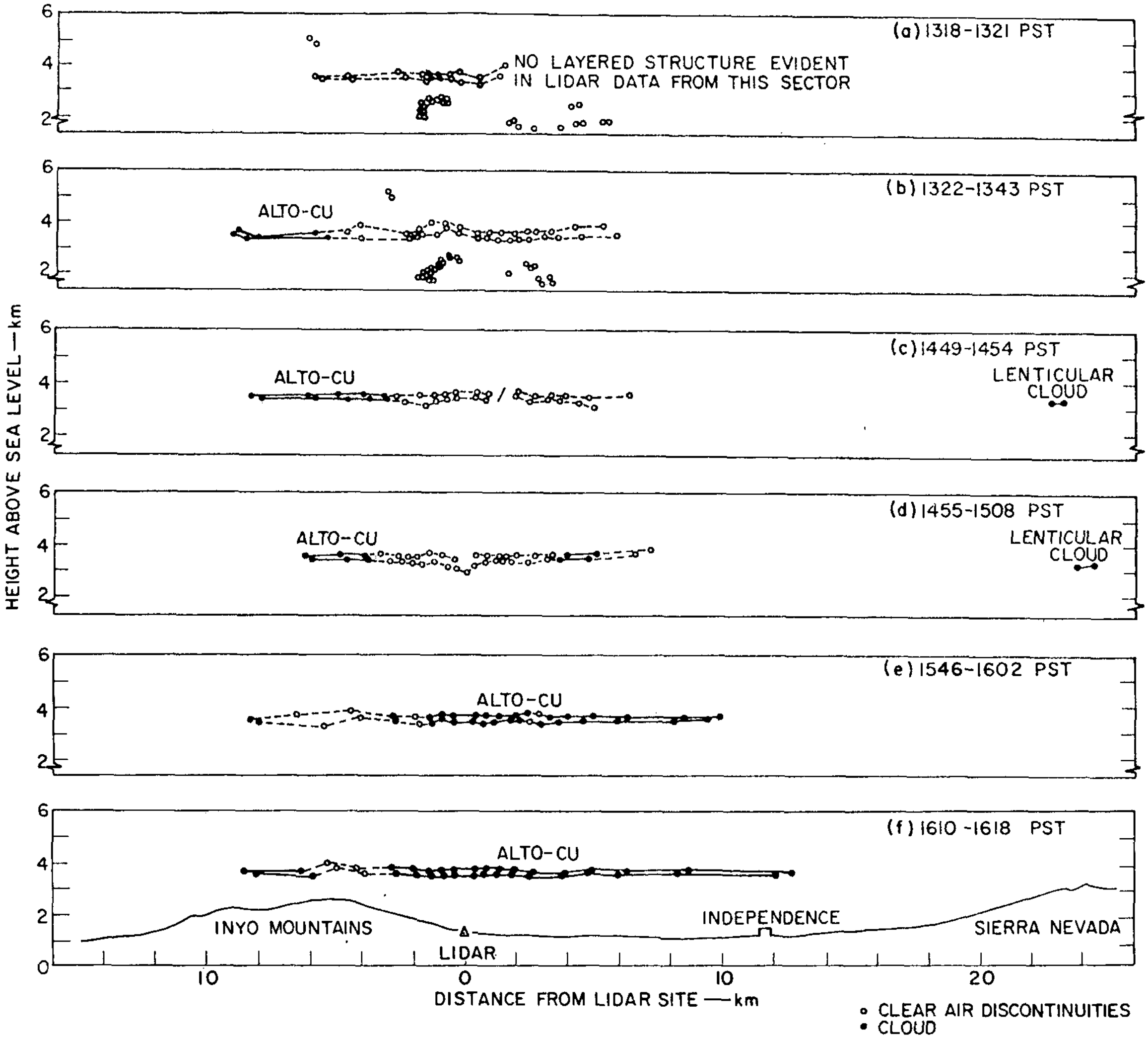

FIG. 1. Lidar observations of wave conditions in the easterly flow over the Inyo Mountains, 19 February 1967. Note that the vertical scale is the same as the horizontal scale.

MSL on the lower slopes of the Inyo Mountains on the eastern side of the Owens Valley due east of the town of Independence (Fig. 1). It was selected to afford a good view of clouds over the center of the valley as well as of the higher wave clouds downwind of the Sierra in westerly winds. It also proved well situated for observations in easterly flow conditions such as those of 19 February 1967. In operation, the lidars were scanned through a E-W vertical plane normal to the mountain ranges.

3. Analysis

Detailed data analysis has been limited to 19 and 28 February and 1 March, the only days with true wave activity in the vicinity of the lidar. Unfortunately, the aircraft were not flying on 19 and 28 February 1967. One aircraft, however, was in our vicinity at approximately 1200 PST and again at 1700 PST on 1 March 1967, but did not encounter any turbulence on either occasion. Although special rawinsonde ascents were made at Fresno, Calif., earlier in this program, these were discontinued after 25 February, and it has not been possible to relate the radiosonde data to the lidar observations. In the following analyses, upper wind data have been inferred from the U. S. Weather Bureau charts and radiosonde data relating to the area in general.

19 February 1967. Wave clouds in the easterly flow were first observed on the eastern slopes of the Sierra around 1230 PST. These were lenticular clouds that extended slowly down the valley from the north. There were also clouds to the east, over the Inyo Range, which had the appearance of wispy altocumulus. Dust, stirred up from the valley floor, was moving from the NNW. Winds at 4 km above sea level were generally easterly 12 m sec^{-1}. Observations, each consisting of a scan through the zenith first from SW to NE and then a return scan through the zenith from NE to SW, were

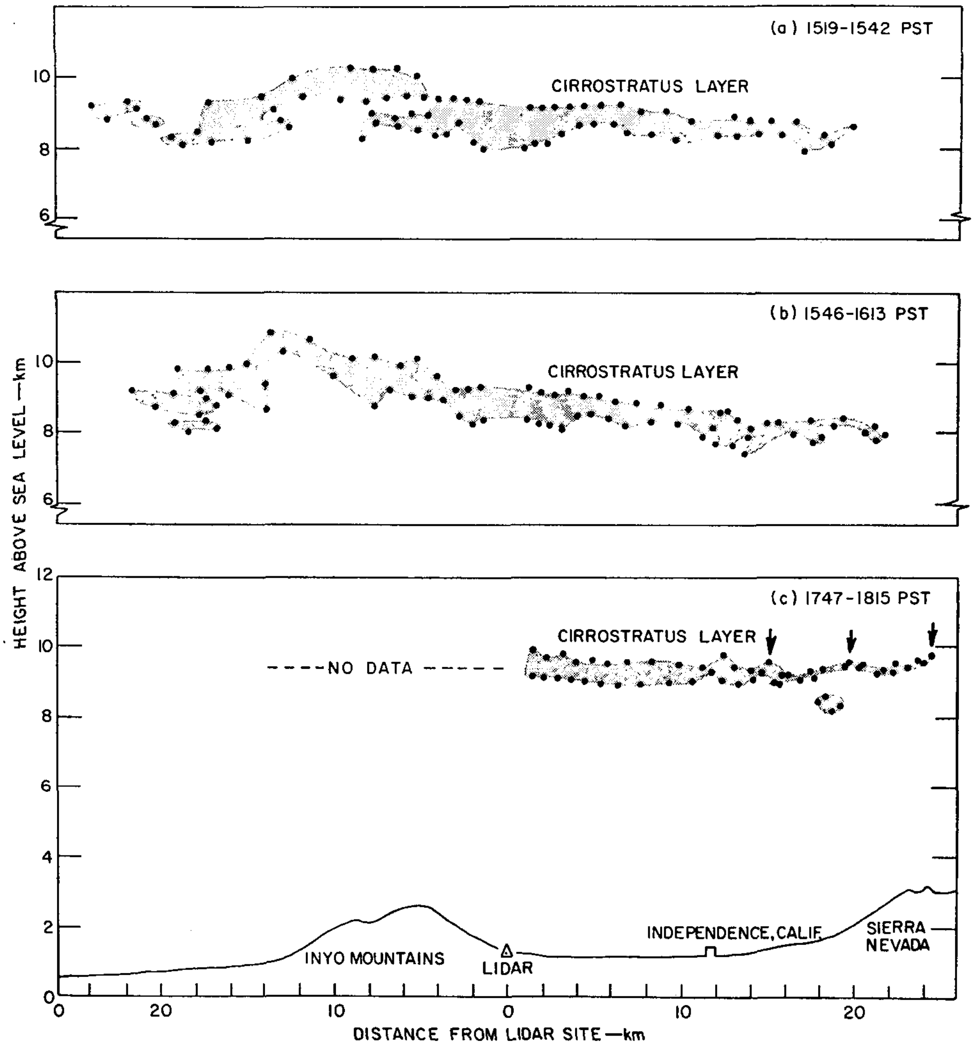

Fig. 2. Lidar observations of wave clouds in lee of the Sierra Nevada, 28 February 1967, with arrows indicating where wave dimensions were measured. Note that the vertical scale is twice the horizontal scale.

made at intervals throughout the afternoon. From each series, cross sections have been constructed (see Fig. 1). Note that because of the limited data acquisition rate, these cross sections are not instantaneous but show the conditions within the periods indicated in the figure. The solid data points show the base and top of the visible cloud. (The determination of cloud *top* by lidar observation is subject to uncertainty when the cloud is dense. In that case, it is sometimes difficult to distinguish between the reduction of signal as the lidar beam penetrates the upper surface of the cloud and a reduction of signal due to attenuation.) The open circles represent data points measured at the bottom and top of the major discontinuity in scattering shown in the lidar trace when there were no clouds in the field of view. (Lidar observations in which no discontinuities are apparent are indicated by a line.) Note that the heights of the cloud over the Inyo Mountains, the major discontinuity in the clear air, and the wave cloud over the Sierra are all in close agreement at a level of approximately 3500 m MSL. A wave pattern is evident, but would probably have been even more apparent if the data could have been recovered with finer range resolution (see Section 4).

Initially, at the time of the first series (Fig. 1a), no major discontinuity appeared on the lidar trace when looking over the valley to the SW. By the time of the return scan of this series (Fig. 1b), major discontinuities in the lidar trace show a stable layer over the valley.

On three occasions (Figs. 1b, 1c and 1d), an inflection or interruption of the stratified layer is to be seen. Upstream and downstream of the point at which this occurs, there was either a well-marked cloud layer or a clear-air discontinuity. These indications are absent in the area of the interruption of the layer. The location of this interruption varied between 4.0 and 6.0 km

TABLE 2. Lee-wave measurements and accompanying wind conditions.

Date and approximate time of lidar observations	Date and time of closest upper-wind observations	Estimated winds at radiosonde standard pressure levels (with approximate height of pressure surface)								Mean of estimated winds		Wave measurements based on lidar data	
		700 mb (3.0 km)		500 mb (5.5 km)		300 mb (9.2 km)		200 mb (11.8 km)				Wave-length	Amplitude
		(deg)	(m sec^{-1})	(deg)	(m sec^{-1})	(deg)	(m sec^{-1})	(deg)	(m sec^{-1})	(deg)	(m sec^{-1})	(km)	(km)
28 Feb. 1967 1800 PST	28 Feb. 1967 1600 PST	240	8	270	16	290	19	310	21.5	286	15	6.0	0.3
1 Mar. 1967 1140 PST	1 Mar. 1967 1600 PST	260	11	260	21.5	260	29.5	260	32	260	25	17.5	0.5
1 Mar. 1967 1300 PST	1 Mar. 1967 1600 PST	260	11	260	21.5	260	29.5	260	32	260	24	21.0	0.5

downstream of the main ridge line. Further to the north of the observation site, but in a position corresponding to this presumed interruption, some wispy clouds were apparent. These exhibited cross motion at different levels.

By 1600 PST the cloud cover became more widespread (Fig. 1), extending to the SW of the lidar site over the valley at a height corresponding to the level of the major clear-air discontinuities that appeared at 1330 and 1450 PST.

28 February 1967. Fig. 2 indicates three vertical cross sections through a dense layer of cirriform cloud at an altitude of about 9000 m MSL. The first two (Figs. 2a and 2b) were made with the Mark V lidar while the Mark I was used in the third (Fig. 2c). Undulations of the cirrus cloud during this day were irregular and complicated as can be seen in Fig. 2.

1 March 1967. Fig. 3 shows three vertical cross sections made through the standing-wave clouds in the westerly flow across the Sierra on this day. The air at lower levels was very clear, and the lidar returns decreased uniformly with height, with no apparent stratification of the scatterers in the low levels of the atmosphere. There was no wind at the surface, but the wind at cirrus-cloud level (11 km) was approximately westerly at 30 m sec^{-1}.

North of the site, the wave motion was quite strong and persisted through at least three or four cycles downwind of the Sierra. In the flow overhead, however, only the first cycle was well developed. Figs. 3a and 3b show this wave to have an amplitude of approximately 0.5 km and length of 17.5–21 km. At the time of the first run, about 1140 PST, there was tenuous cirrus in the wave trough, downwind of the dense cirrostratus of the leading wave crest. At about 1300 PST (Fig. 3b) the first wave trough was free of cloud.

Late in the afternoon, lenticular clouds formed beneath the cirrus bands. Fig. 3c shows the cross section through a stack of lenticular clouds that formed over the valley directly to the west of the lidar site. The dense lowest lenticular layer prevented a full view of the upper layers. We were able to observe the edges of some of the higher lenticular layers, however, where they extended beyond the tenuous borders of the lower cloud.

4. Discussion

As noted, it had been hoped that concurrent radiosonde data would have been available, together with data measured by the aircraft. In the absence of these data, it has not been possible to explore the relationship of the lidar observations to atmospheric conditions in any depth. However, certain aspects of the lidar observations are obviously highly significant.

Before discussing these, some comments on the range resolution of the lidar observations should be noted. All the data plotted were taken from either Polaroid or 35-mm film records of the lidar trace, with oscilloscope writing speed adjusted to 20 μsec cm^{-1} to give a total displayed range of 30 km. At this setting, features on the trace could be read with a resolution of only 150–300 m. The magnetic disc recorder that was used should have provided better range resolution, i.e., 30–40 m, but, owing to a malfunction, the recorder data in this instance had no better resolution than the film record.

This did not appreciably degrade the data of 28 February (Fig. 2) and 1 March (Fig. 3), as the amplitude of the waves was relatively large with respect to the resolution; but on 19 February (Fig. 1), when the amplitude of the wave was much smaller, reading errors might have distorted the true appearance of the waves.

Apparent interruptions in the laminar flow in easterly waves. The observations made of the easterly flow of 19 February (Fig. 1) are particularly interesting. In the absence of upper-air data (particularly, wind information), it is only possible to speculate on the mechanisms involved. However, a sounding was made at 0430 PST at Fresno, on 20 February 1967, some 140 km due west of the lidar site. With winds in the eastern quadrant in the lower 6 km, and with velocities of 2.5–7 m sec^{-1}, this sounding (not shown) did have some value in indicating possible conditions in the area of the lidar site during the previous afternoon, although the Sierra range was clearly a disruptive influence. The sounding showed a change of air mass and a marked inversion near the 3-km level with a wind shear of the following magnitude: 3.5 m sec^{-1} from 114° at 2.5 km MSL backing to 6.8 m sec^{-1} from 035° at 3.5 km. This change of air mass with height appeared from the synoptic charts covering the period to be associated with a

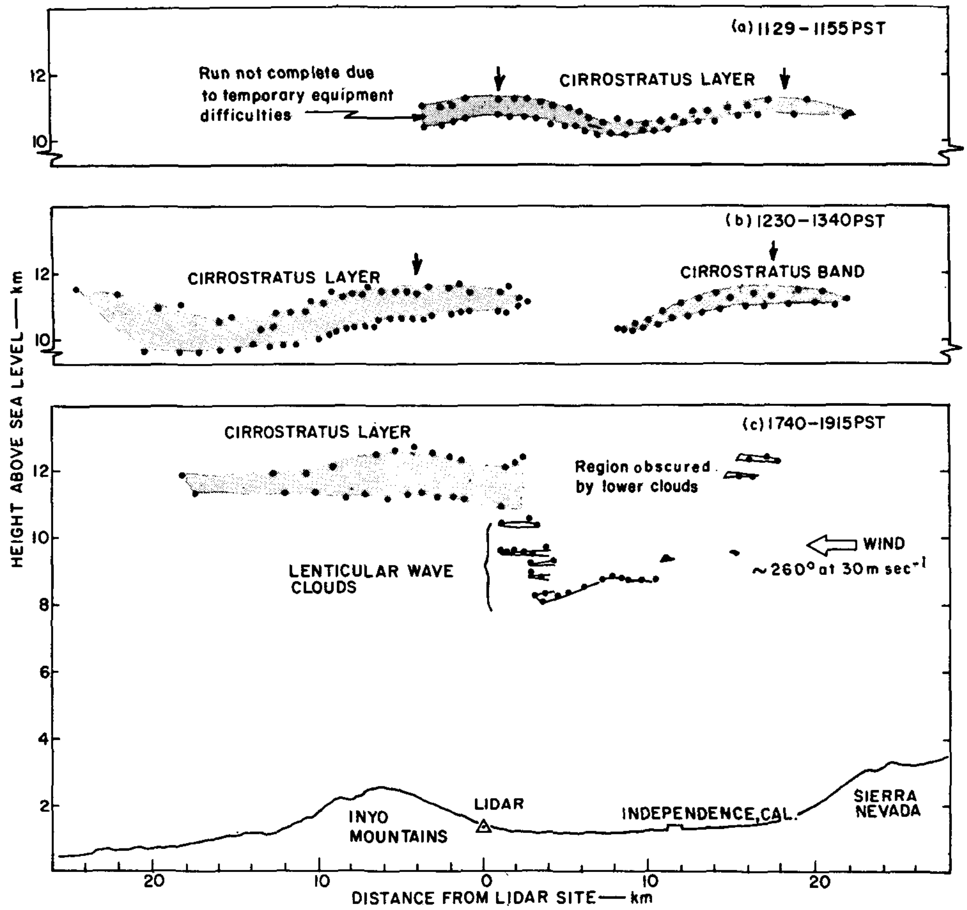

FIG. 3. Same as Fig. 2 except for 1 March 1967.

stagnant frontal system located south of the area. It seems reasonable to associate the lidar-observed discontinuity in the scattering profile of the clear air and the visually-observed altocumulus cloud layers with this air-mass transition. The lidar-observed variations in the stratification of the aerosol in this air flow are thus indicative of variations in the air flow in the vertical plane. In these circumstances, it is tempting to seek an explanation to the apparent interruptions of laminar flow seen in the early afternoon observations in terms of rotor development or hydraulic pressure jumps. The observational supporting data are too sparse to warrant this, however. In any case, in the relatively light wind conditions prevailing, one would not expect well-developed rotor or turbulence phenomena to develop, and the waves are quite weak.

The importance of this series of observations would seem to lie in the demonstration they provide of how the lidar can reveal, at least under certain conditions, the structure of air flow. Given the presence of adequate particulate matter indicators, even if too sparse to be seen by eye, the lidar can provide quantitative data on the variations of concentrations of such indicators in space and time, from which motion can be inferred. The potential of this approach for revealing interruptions of smooth air flow, and thus indicating areas in which turbulence may be expected, has been noted by Collis (1964).

Even when visible clouds are present, the quantitative nature of lidar observations should enable the significance of the cloud structure to be more readily evaluated. This is illustrated in the following discussion of the conditions of 28 February–1 March 1967.

Lee-wave dimensions and their relationship to synoptic conditions. On the successive days of 28 February and 1 March, we obtained several good sequences of lidar observations of cloudiness at the cirrus level where wave-form motion was occurring (see Figs. 2 and 3). These data permitted us to make estimates of wave characteristics (Table 2) and also enabled us to study the effects of a changing weather pattern on these characteristics.

In addition to wave measurements, Table 2 also shows wind values at a number of levels over the lidar site, estimated by interpolation on the closest (in time) U. S. Weather Bureau constant-pressure charts. Interpolation on these charts was required because the closest rawinsonde sounding (both in time and space) was made at Tonopah, Nev., about 120 n mi (220 km) to the NNE. These wind values enabled us to compare our wavelength measurements with results that Corby (1957) derived from radiosonde data in his study of lee waves in the British Isles. His data showed a highly significant empirical relationship between wavelength and mean tropospheric wind speed. Our data did not fit Corby's relationship very well, although the general sense is in agreement. It is not clear whether the poor correlation is due to errors in assessing the wind over the area, or whether it is due to the nature of the waves.

Although undulations are apparent during all three series of lidar observations on 28 February (Fig. 2), the waves were quite irregular and complicated most of the time. At about 1800 PST, however, a simple wave cycle may be distinguished just east of the Sierra. It is the wavelength measured during this period that is given in Table 2. The increase of wave amplitude as the cloud level rises downwind of the Sierra is noteworthy, as are the irregular undulations in the flow suggested by the cloud patterns over the Inyo range. It is unfortunate that no aircraft reports were available to provide information on the presence or absence of turbulence in these conditions. The relative absence of simple regular waves on 28 February was probably due to the fact that there was a marked directional shear in the wind with height (see Table 2). On the other hand, on 1 March, simple regular wave motion was quite apparent at the cirriform-cloud level during most of the lidar observation period (Fig. 3). Note the constancy of wind direction and increase of wind speed with height at the time (Table 2), both conditions being highly favorable for lee-wave development.

Table 2 also shows our estimates of wave amplitude on these two days. Such estimates are readily made in the relatively well-defined, small-amplitude waves where the cloud is fairly continuous. However, some difficulty might arise in assessing amplitude in those cases where cloud occurs only at the crest of each wave, and where the wave shape cannot be inferred from the slope of the cloud.

Another aspect of interest concerns the change in wavelength observed during these two successive days and its relationship to the synoptic weather conditions, which were also changing. At the time of the lidar observations on 28 February 1967, a cold front north of the lidar site was moving southeastward, accompanied by an increase in westerly flow aloft in advance of the front. As Table 2 shows, winds aloft at the lidar site at observation time on 28 February were relatively light with considerable directional shear in the vertical. Table 2 also shows that the wavelength was relatively short at the time. By observation time on the next day (1 March), the cold front had moved closer to the lidar site, and the increased westerly flow associated with the upper trough had moved over the area. Evidence of this is indicated in Table 2, which shows west winds with no vertical directional shear and higher speeds at all levels on 1 March than the day before. Note also that the wavelength at that time was considerably longer than on the previous day. This change is in agreement with Corby's results, which show that an increase in tropospheric wind speed should be accompanied by an increase in wavelength of the lee waves.

From these observations on successive days, there appears to be some promise for using lidar to detect changes in the wavelength of lee waves, which are indicative of changes in mean tropospheric wind speeds and, possibly, wind speeds at particular levels. Such a capability could aid the meteorologist in detecting changing wind flow and associated weather patterns on an immediate basis.

Turbulence and lidar observations. Apart from the possibility of providing direct indications of turbulence, as when cloud structure shows a breakdown of regular wave motion, or when interruptions are apparent in the smooth flow of "clear" air, the capability of lidar for observing the wavelengths and amplitudes of lee waves may have important implications in detecting the presence or imminence of turbulent conditions. One possibility is that such observations may reveal rotor motions that may give rise to turbulence (Scorer, 1963). Also, the information on wave dimensions, such as those measured on 28 February and 1 March, could be valuable inputs to turbulence prediction techniques, which are based on dynamic considerations such as those described by Reiter and Foltz (1967).

5. Summary and conclusions

Although no major wave activity, of the type that has made this area famous, occurred during the period of observations, lidar observations revealed moderate wave motion and indicated the nature of the air flow in two very different situations. In the first situation, in an easterly flow over the Inyo mountains, lidar observations detected subvisible particulate matter and revealed structure in what appeared to the eye to be quite clear air. This made possible detection and monitoring of changes in position of apparent interruptions of smooth laminar flow. Subsequently, on two successive days, the wave structure was apparent in visible cloud formed in a westerly flow over the Sierra; lidar observations made it possible to measure wavelength, amplitude and height with precision from a ground site as well as to monitor the changes therein.

Hitherto it has only been possible to make observations of mountain waves and turbulent air motions aloft from aircraft and gliders (Holmboe and Klieforth, 1957), or by tracking balloons (Lamberth *et al.*, 1965). Photogrammetric measurements of visible clouds have also been made (Reiter and Nania, 1964).

From the facility demonstrated in the course of this investigation, it is concluded that lidar has potential for studying air motion in mountain waves, even when visible cloud is not present. There is some encouragement for believing that lidar observations could indicate the presence of turbulent or potentially turbulent areas. Marked disruptions of regular wave motion or laminar flow, or the presence of rotor motion would offer *prima facie* evidence of turbulent conditions. Alternatively, lidar observations of lee-wave dimensions might prove valuable in the application of prediction techniques based on dynamic considerations.

It would seem highly desirable to make further lidar observations of this type with concurrent radiosonde and constant-pressure balloon measurements. This would provide a unique opportunity to review current theoretical concepts of mountain waves and turbulence. In addition, particularly if aircraft reports of flying conditions could be obtained, turbulence phenomena could be investigated on an empirical basis.

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REFERENCES

Collis, R. T. H., 1964: Lidar detection of CAT. *Astronautics and Aeronautics*, December, 52–55.

——, 1965: Lidar observations of clouds. *Science*, **149**, 978–981.

——, F. G. Fernald and M. G. H. Ligda, 1964: Laser radar echoes from a stratified clear atmosphere. *Nature*, **203**, 1274–1275.

Corby, G. A., 1957: A preliminary study of atmospheric waves using radiosonde data. *Quart. J. Roy. Meteor. Soc.*, **83**, 49–60.

Holmboe, J., and H. Klieforth, 1957: The mountain wave. Final Rept., Contract AF19(604)-728, Univ. of California at Los Angeles, 290 pp. (DDC No. AD 133606).

Kuettner, J. P., 1958: The rotor flow in the lee of mountains. G. R. D. Res. Notes, No. 6, Air Force Cambridge Laboratories, Bedford, Mass., 15 pp.

Lamberth, R. L., R. D. Reynolds and M. G. Wurtele, 1965: Mountain lee waves at White Sands Missile Range. *Bull. Amer. Meteor. Soc.*, **46**, 635–636.

Northend, C. A., R. C. Honey and W. E. Evans, 1966: Laser radar (lidar) for meteorological observations. *Rev. Sci. Instr.*, **37**, 393–400.

Reiter, E. R., and H. P Foltz, 1967: The prediction of clear air turbulence over mountainous terrain. *J. Appl. Meteor.*, **6**, 549–556.

——, and A. Nania, 1964: Jet-stream structure and clear-air turbulence. *J. Appl. Meteor.*, **3**, 247–260.

Scorer, R. S., 1963: *Atmospheric Turbulence and Its Relation to Aircraft*. London, H. M. S. O., 147–172.