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Wind Profiling by a Conical-Scanning Time-Correlation Lidar

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The presernt paper describes a new concept for a wind profiling technique using a conical scanning-lidar (laser radar). Measurement is based on a time correlation method using the pattern of aerosol and cloud distribution as a tracer. The direction of the laser beam is conically rotated about a vertical axis and lidar signals are collected in the preassigned directions. The analytical method is described as well as the results of field experiments.

KEYWORDS: wind, wind measurements, lidar, laser radar, aerosols, time correlation

§1. Introduction

Remote measurements of wind profiles are very important in meteorological and air-pollution studies. Lidar methods for measuring wind profiles based on the Doppler shift of scattered light have been developed by many research groups including NOAA and NASA, and successful results have been achieved.[1-3] Another lidar technique for measuring wind is the correlation method relying on aerosol or cloud distribution patterns. Several research groups have developed a spatial correlation method using a scanning lidar[4] and a time correlation method using lidar data measured in a slant path or in multiple directions.[5-8] The correlation method has an advantage in that the lider hardware is much simpler than those of Doppler lidars.

This paper describes a new concept and data analysis technique of a conical-scanning lidar for wind profile measurements based on the time-correlation method using aerosol distribution pattern.

§2. Principle

We assume a coordinate system shown in Fig. 1, where the coordinate $X-Y$ is fixed in space and the coordinate $x-y$ moves with the wind which conveys aerosols. The aerosol distribution is given as a function of the coordinate $x-y$, $D(x, y)$. Here, we assume that $D(x, y)$ does not change with time. We can choose the direction of the x-axis parallel to the wind direction as shown in Fig. 1 without any loss of generality.

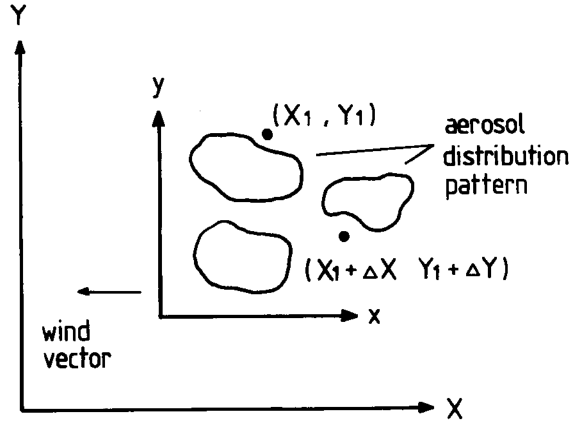

Fig. 1. Coordinates fixed in space $(X-Y)$ and moving with wind $(x-y)$.

Let the coordinates of the two observation points be (X_1, Y_1) and $(X_1+\Delta X, Y_1+\Delta Y)$. They are written in the $x-y$ system as

$$(x_1, y_1)=(X_1+Vt, Y_1)$$
$$(x_2, y_2)=(X_1+\Delta X+Vt, Y_1+\Delta Y).$$

The time correlation of the aerosol density observed at the two points is written as

$$\begin{aligned}S_T(\Delta t)&=c\int D(x_2(t+\Delta t), y_2(t+\Delta t))D(x_1(t), y_1(t))\,\mathrm{d}t\\&=c\int D(X_1+\Delta X+Vt+V\Delta t, Y_1+\Delta Y)\\&\quad\times D(X_1+Vt, Y_1)\,\mathrm{d}t\\&=c'\int D(X'+\Delta X', Y_1+\Delta Y)D(X', Y_1)\,\mathrm{d}X', \quad (1)\end{aligned}$$

where c and c' are constants and

$$X'=X_1+Vt,$$
$$\Delta X'=\Delta X+V\Delta t. \quad (2)$$

This means the time correlation between two points is calculated from a spatial correlation. If we can assume that the aerosol distribution $D(x, y)$ is approximated to be symmetrical with the wind direction, $S_T(\Delta t)$ is independent of Y and takes the maximum value at $\Delta X'=0$. Then the time lag, T_m, obtained from the time correlation is written as

$$T_m=\Delta X/V. \quad (3)$$

Equation (3) is valid as long as the aerosol distribution pattern changes little, compared to characteristic aerosol distribution scales, while travelling between the observation points.

Since ΔX is represented as

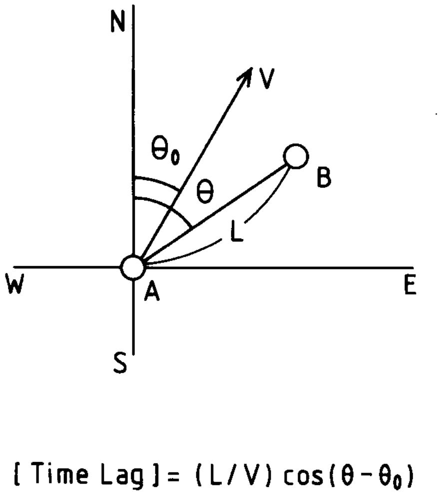

Fig. 2. Time correlation method. A and B: observation points, V: wind vector.

$$\Delta X = L\cos(\theta-\theta_0), \qquad (4)$$

where L is the distance between the two points, V is the wind speed, θ_0 is the wind direction, and θ is the direction from one observation point to the other as illustrated in Fig. 2, the time lag, T_m, can be written as

$$T_m = L/V\cos(\theta-\theta_0). \qquad (5)$$

Equation (5) predicts that the experimentally obtained time lags divided by L, T_m/L, makes a circle in the polar coordinate as a function of θ under the assumption that the horizontal wind is uniform over the area covered by the observation points. Thus, wind speed and direction can be determined from the diameter ($1/V$) and the direction of the diameter of the circle. The present method can be validated by plotting a graph of T_m/L as a function of θ. The deviation of the data points from a circle gives a good index of the accuracy of the method.

§3. Field Experiments

3.1 *Lidar system*

Wind profiles are estimated from the lider data which is obtained from the measurements in multiple directions. In this experiment, the measurement was made in six directions. A block diagram and system parameters of the lidar are shown in Fig. 3 and Table I. The laser beam from a Nd:YAG laser (532 nm) is conically scanned by a motorized rotating mirror, and the laser pulses are transmitted in the six prefixed directions. The lidar return signal is collected by a 20-cm spherical mirror and optical fiber light guides arranged for the six directions. The collected signals are detected by a single photomultiplier tube. The direction of the measurement is scanned every single shot with 10-pps pulse repetition. The zenith angle of scanning is adjusted by the angle of the rotating mirror and the position of the light guides. The received lidar signals are stored on a magnetic tape for every single shot and the recorded data are processed in an offline moder after the measurements.

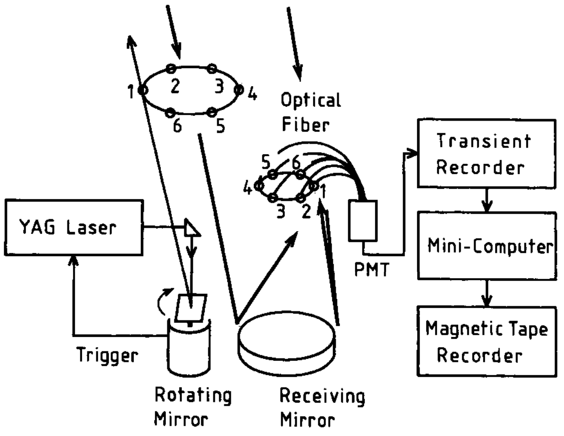

Fig. 3. Block diagram of the conical-scanning time-correlation lidar.

Table I. System parameters of the conical-scanning time-correlation lidar.

Laser	Nd:YAG (SH)
wavelength	532 nm
output Energy	130 mJ/pulse
repetition	10 Hz
Receiving mirror	
diameter	20 cm
focal Length	1 m
Optical fiber light guide	
diameter	5 mm
Filter	
spectral bandwidth	3 nm
Photomultiplier	RCA 8852
Transient recorder	Autnics S121
sampling rate	20 MHz
accuracy	10 bits
Microcomputer	SORD M343

The time correlations of the signal intensities are calculated for all fifteen combinations out of the six observation points for each altitude.

3.2 *Results and discussion*

The field experiment was carried out on July 28–29, 1987. The lidar measurements were made every one hour with simultaneous pibal measurements. The lidar data in the six directions were recorded for 15 minutes (1500 shots for each direction) for a single measurement. The scanning angle was set at 11.3 deg. (full angle) considering that the maximum wind speed was a few tens of meters per second and that the characteristic scale of the aerosol distribution pattern may cover from several tens of meters to a few hundred meters. The angle separates the nearest observation points by 10 m at a 100-m height.

Figure 4 shows an example of the time-height indication in the six directions. The normalized deviation of the received signal from the average, $(P(R)-\overline{P(R)})/\overline{P(R)}$ is shown to enhance the pattern of the aerosol distribution. Figure 5 shows the temporal change of the received signal at a height of 200 m. The structure reflecting the aerosol distribution pattern can be seen in this figure. Similar structures are found for each of the six directions and a small time lag can be seen between them. The time correlation between all fifteen pairs of the lidar signals in the six directions was calculated to derive a time lag for each pair, which gives the maximum value of the correlation. Figure 6 shows an example of the correlation between direction 6 and direction 3, which gives a time lag of 15 seconds. The correlation was calculated using data segments 15 minutes in length.

The resulting time lags divided by the distance between the corresponding two points, T_m/L, are plotted in Fig. 7 as a function of the direction of the two points in the polar coordinate. As predicted from the theory, the data points take a circular shape. The numbers attached to the data points in Fig. 7 represent the maximum correlation coefficients from which the time lags were determined. The circle shown in Fig. 7 was fitted by the least squares method. The speed and the direction of wind can be deter-

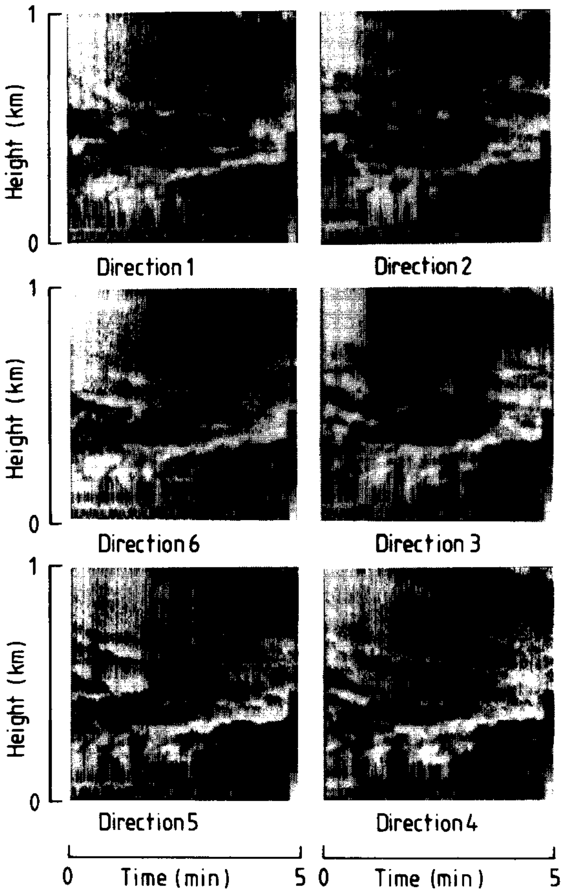

Fig. 4. Time-height indication of the lidar data measured in the six directions.

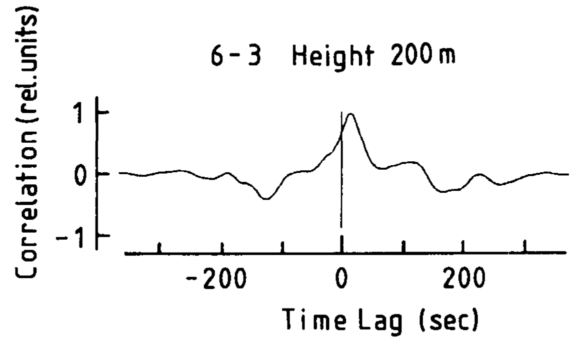

Fig. 6. Time correlation of the received signals in the two directions.

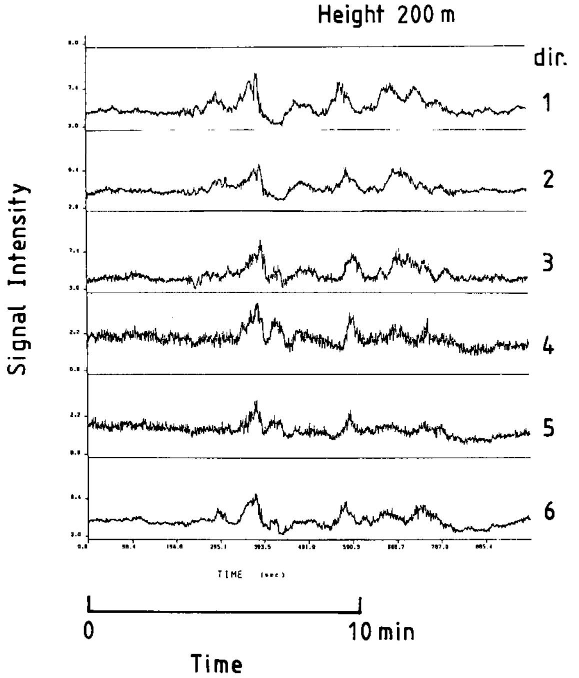

Fig. 5. Temporal change of the received signal intensity.

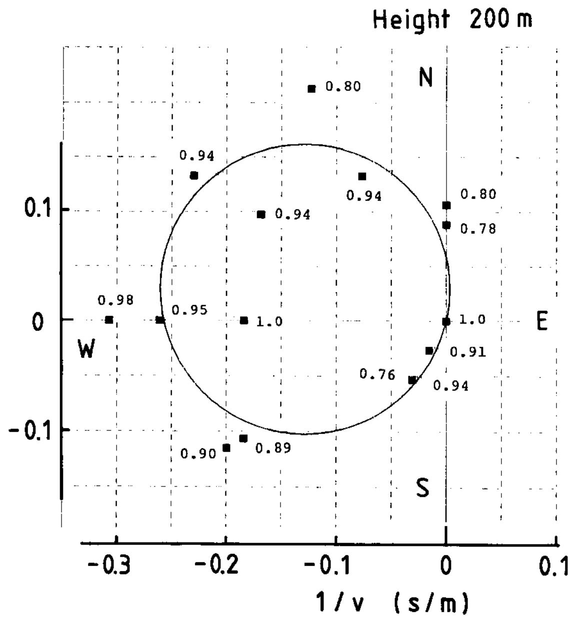

Fig. 7. T_m/L as a function of θ.

mined from the diameter and the direction of the diameter of the circle. In this manner, the wind direction and the wind speed at each height were obtained.

Figures 8 and 9 show the wind profiles (solid curves) obtained by the lidar. The dashed lines in Figs. 8 and 9 show the simultaneous pibal measurements. The wind around 3000 m high in Fig. 8 was obtained from the correlation of the pattern associated with a cloud ceiling. In Fig. 8, the wind in the height range 600–900 m was not determined, because there was no characteristic aerosol distribution pattern detectable with a high signal-to-noise ratio as seen in Fig. 4.

We investigated dependence of the wind profiles on the data length used to calculate the correlation. The error will be caused by taking a correlation using too short or too long data in the case so that few data points are processed or that wind direction changes with time on a larger scale. The present experiment showed no significant difference in the results for the periods from 15 min, 10 min and 5 min. Increasing the time segments from 5-min to 15-min length should generally improve the results such that wind profiles look smoother (simply due to the averaging effect). However, a bias of 1 hour or so can be introduced if the length becomes too long.

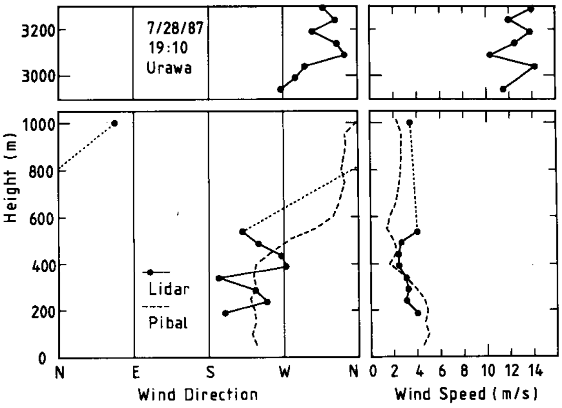

Fig. 8. Wind profile obtained by the conical-scanning time-correlation lidar.

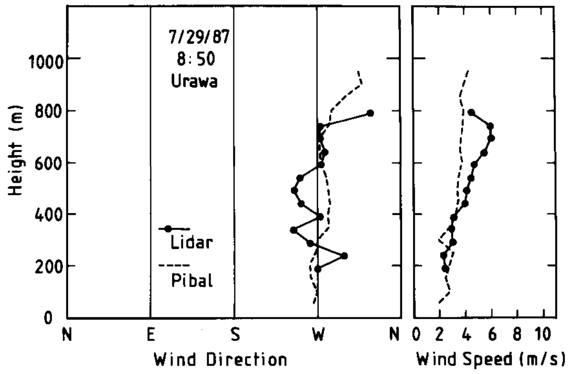

Fig. 9. Wind profile obtained by the conical-scanning time-correlation lidar.

Considering the difference in that the pibal measures a Lagrangian-average wind within a certain height interval at each height, while the lidar measures temporally averaged wind over the lidar site, the agreement between the lidar and pibal measurements shown in Figs. 8 and 9 is good.

§4. Conclusions

In this paper we described the methodological concept of wind profiling by a conical-scanning time-correlation lidar and some examples of measurement and analysis. Refinement in the pre-processing of raw data would improve the signal-to-noise ratio and give better results. The present technique was revealed as a promising one for lower atmospheric wind profiling.

We are improving the system using a 30-cm telescope and a 30-cm rotating wedge window instead of a mirror for scanning the laser beam, and plan to conduct further experiments.

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