INTERCOMPARISON OF LASER RADAR AND RADIOSONDE TECHNIQUES OF MEASURING WIND VELOCITY VECTOR

B.D. Belan, G.G. Matvienko, A.I. Grishin, V.K. Kovalevskii, and V.E. Meleshkin

Institute of Atmospheric Optics,
Siberian Branch of the Academy of Sciences of the USSR, Tomsk
Received July 6, 1991

Results of simultaneous measurements of velocity and direction of wind in the lower atmosphere obtained with a three–path lidar and the "Meteor–RKZ" aerologic system are compared. The lidar employs a temporal spectral correlation technique for measurements of wind velocity by tracking aerosol fields moving across three sensing paths.

The comparison has demonstrated a satisfactory agreement between the results obtained using the two techniques. The values of standard deviations between the data on wind velocity and its direction observed in the experiment were 2.4 m/s *and* 32#*, respectively. Some measures to be undertaken for improving the lidar performance are recommended.*

A progress in solving problems of the weather and climate forecast as well as of the environmental protection strongly depends on the progress in development of noval means for monitoring the atmosphere and underlying surface. Lidars capable of acquiring information about the state of the environment with laser radiation[1,2] have to be mentioned among such means first of all. A possibility of conducting highly operative remote measurements with a high spatial resolution makes these instruments very advantageous compared to contact sensors at a comparable accuracy of measurements. The problem of compatibility of lidar data with those obtained using traditional techniques is studied in this paper. We have already touched upon this problem in Ref. 3. However no experimental data sufficient for making a complete comparison were available, so far. According to Ref. 4 the principal means of instrument intercomparisons include:

1. Direct intercomparisons with the standard measurement means. That technique is the most popular. It is based on simultaneous measurements of one and the same value both by a standard instrument and by the instrument under test. When following this technique one should make sure that both instruments actually measure one and the same value. Therefore, direct intercomparisons are usually undertaken in a specially prepared environment.

2. Comparisons made using a special intermediary instrument (a comparator). Usually the devices employed as comparators, must have a sensitivity sufficient to detect variations in the measured variable that do not exceed the measurement error of a standard instrument. Intercomparisons using such comparator devices may provide a high accuracy. This technique is mainly used to conduct comparisons with the primary standards.

3. Testing against a standard measure. Such a procedure is reduced to measuring the value, reproducible by a standard measure or to comparing with the standard measure itself.

The above techniques are aimed at determining or estimating the principal error of an instrument, which is defined as the maximum deviation of a measured value from the corresponding measure.

The intercomparison quality is described by the ratio of the number n of erroneous comparisons to their overall number, N., i.e., by n/N. The closer is the ratio n/N to zero, the more reliable are the intercomparison results. It has been shown in Ref. 5 that the n/N ratio mainly depends on two arguments

$$\frac{n}{N} = f\left(\frac{\Delta}{\sigma}; \frac{\sigma}{\sigma_{st}}\right),$$

where Δ/σ is the ratio of admissible error Δ to the rms error of the instrument being tested, σ (the admissible range of its values is assumed to be symmetric and equal to 2Δ); σ/σ_{st} is the ratio of rms errors of the tested and standard measuring devices. Note that the value Δ/σ characterizes the quality of instrument manufacture, and the value σ/σ_{st} that of comparisons themselves.

The aim of the present study is to estimate the accuracy of retrieving wind velocity and direction using the laser spectral correlation technique. The physical and methodological grounds, as well as the performance of this technique may be found in Refs. 6 and 7.

Based on the above discussions one can arrive at a conclusion that most suitable for testing the laser spectral correlation technique of wind measurements is the method of direct comparison with a standard technique. However, no generally accepted standard means for estimating the accuracy of aerological measurements of wind velocity and directions are currently available.[8] Therefore, the tests are performed by conducting comparative measurements of one and the same variable by different systems. This assures the compatibility of data under comparison and improves the homogeneity and consistency of the aerological information. In addition, such comparative tests yield certain information about peculiarities of different techniques and about the necessary ground support for them, as well as about the techniques to be applied to processing measurement data. They also allow one to elucidate the ways of updating the existing methods and techniques.

In agreement with reasons given in Ref. 4, specific conditions should either be provided for or controlled during the tests. These conditions are understood as the overall physical environment affecting the metrological parameters of instrumentation being tested. Since comparative tests of aerological systems can only be done in the real atmosphere, which is usually an extremely variable object, the latter factor should be especially accounted for when choosing the standard means for making tests.

0235-6880/91/10 746-04 $02.00

It is generally accepted[9] that any meteorological data obtained should be averaged both spatially and temporally, since no single measurement at any given site may be representative of the state of the atmosphere as a whole. Selecting an adequate averaging technique and its performance in a measuring device is one of the key task of the instrument design, therefore actual scales of both spatial and temporal averaging of the instruments taking part in atmospheric intercomparisons should be properly taken into account.

One should also keep in mind that adequate averaging is not the only criterion needed for assessing the data quality. Another important fact is economic feasibility of a given technique. A technique, which provides for an equivalent accuracy at a lesser amount of initial data, or which needs for simpler data processing procedures should be preferred (other conditions being equal). The optimal relationship between the accuracy and economic feasibility of a technique is chosen intuitively, and this choice depends on the experience and qualification of an expert making it. The expert should first of all to clearly envisage applicability range of a given technique, and to understand its specific features.

We have accounted for the foregoing when choosing a standard measurement with which to test the laser spectral correlation technique of wind measurements. Our analysis, presented in Ref. 3, has shown that the techniques fitting this purpose best of all were the basis pilot balloon, the tethrone, and the radiosonde techniques. For our present study we employed the radiosonde technique using the "Meteor–RKZ" system. Although its accuracy, as compared to the pilot balloon one is proper, the "Meteor–RKZ" system is currently the basic one. In addition, it is used in some foreign countries too and has been successfully intercompared with the MicroCORA Finnish radiosonde system, the latter is widely used all over the world.[8,10]

The "Meteor–RKZ" system operated in its routine regime during comparative tests.[11] Following Refs. 12 and 13 we assumed the following standard deviations for the lower 1–3 km atmospheric layer: wind velocity $\sigma_v = 2$–3 m/s at $V \le 10$ m/s, $\sigma_v = 1$–2 m/s at $V > 10$ m/s, wind direction $\sigma_\alpha = 20°$ at $V \le 10$ m/s, and $\sigma_\alpha = 5$–$10°$ at $V > 10$ m/s.

As was the wind lidar[6] with the following characteristics was used as the tested measurement means:

Transmitter:	
wavelength, μm	0.53
laser pulse energy, J	0.12
pulsewidth, ns	15
pulse repetition frequency, Hz	12.5
Receiver:	
telescope diameter, m	0.3
telescope field of view, mrad	10
focal length, mm	650
Recording system (ADC):	
number of channels	3
number of digits, bits	8
quantization frequency, MHz	15
buffer capacity, bytes	1024

The principle of operation of this lidar is based on a correlation analysis of temporal behaviors of return signals from a randomly inhomogeneous medium recorded from three scattering volumes located at the tops of a right angle isosceles triangle.[6] The lidar transceiver is mounted on a platform scanning along a cone around its vertical axis; sounding pulses are emitted and laser returns detected at three positions of the platform. The largest angular distance between the paths was 18°; wind transport of aerosol inhomogenieties results in the time series of lidar returns at least for two of the sounding paths were identical although delayed by time which depends on both the distance between the points from which the signals were received, and on the velocity of such aerosol inhomogenieties transportation by wind. Since the distance between these points is known and remains fixed, estimating these temporal lags at each given height one may estimate the profiles of wind velocity and wind direction, using either correlation or spectral analyses.

The generalized information characteristics of the wind lidar are the following: information is obtained from 128 levels with the spatial resolution of 10 m, the number of measurement channels is 3, the number of individual lidar returns stored in each channel is 1024, the time interval for data acquisition is 23 – 24 min, processing time required to obtain corresponding physical values is 5 min, the scanning period is 1.4 s.

Intercomparison experiments have been conducted at the "Yuzhniyi" polygon of the Institute of Atmospheric Optics, Siberian Branch of the Academy of Sciences of the USSR from April to June, 1989. The lidar and the RKZ–2 radiosonde launch pad were at a distance of 30 m from each other. Both day– and nighttime synchronous soundings by both systems were undertaken. Launch times were scheduled at 01, 18, 20, and 24 h, local time. The launch times of 18 and 20 h were referred to a daytime. Since time for lidar data acquisition was more than 20 minutes the lidar was normally put into operation 5 minutes prior to the sonde launch.

The total series of 42 comparative measurement cycles was obtained, 16 of them were at daytime, and 26 were done at nighttime. Measurements were made under different meteorological conditions including clear atmosphere, hazy, and precipitation episodes. Wind velocity varied from 1 to 30 m/s during the experiments. An example of a realization is shown in Fig. 1, presenting the vertical profiles of wind velocity and wind direction. One can see from this figure certain discrepancies between the data obtained by the two techniques.

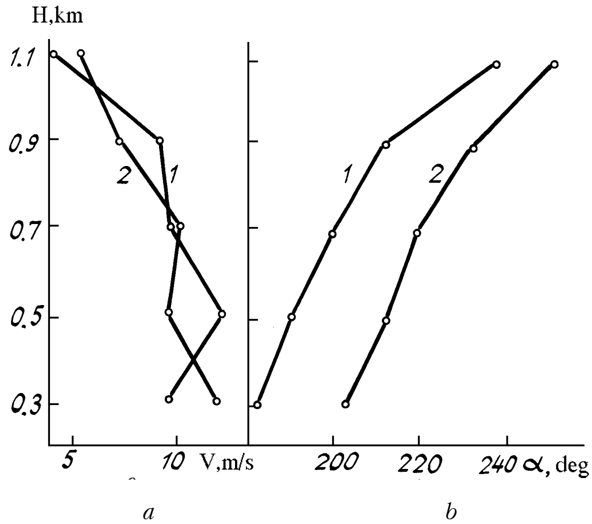

FIG. 1. Vertical profiles of wind velocity (a) and wind direction (b). 1) Lidar measurements and 2) radiosonde data. May 31, 1989, 20:00 hLT.

Since spatial resolutions of the lidar and sonde are different (the latter was in its standard version, see Ref. 11) the data were averaged over the vertical layers 200 m thick, starting from the altitude of 200 m. Layers were centered at the heights 0.3, 0.5, 0.7, 0.9, and 1.1 km. The initial height of 0.1 km was excluded from analysis to avoid the effect of local orography and buildings at the site.

The procedure of estimating the accuracy of lidar wind measurements involved calculations of a systematic, standard, and weighted average deviations of wind velocity and wind direction, obtained with the help of the lidar and the "Meteor–RKZ" systems, respectively. The procedure also accounts for the instrumental error of the RKZ sondes. These deviations for a parameter x are calculated using the following expressions:

$$m_{xj} = \frac{1}{n_j}\sum_{i=1}^{n_j}\Delta x_{ij} ,$$

$$\sigma_{xj} = \left[\frac{1}{n_j - 1}\sum_{i=1}^{n_j}(\Delta x_{ij} - m_{xj})^2\right]^{1/2} ,$$

where Δx_{ij} are the partial differences between the data obtained with the tested and the standard measurement means at the "jth" level, i is the number of a particular measurement at the "jth" level, and n_j is the total number of measurements at the "jth" level.

Weighted average deviations were estimated using the total bulk of data:

$$m_{0x} = \sum_{i=1}^{N}n_j\, m_{xj} \Big/ \sum_{i=1}^{N}n_j ,$$

$$\sigma_{0x} = \left(\frac{1}{\sum_{i=1}^{N}n_j}\sum_{i=1}^{N}n_j\, s_{xj}^2\right)^{1/2} ,$$

where N is the number of altitude levels.

In addition, the values m_0 and σ_0 were grouped according to wind velocity values from the following intervals: 1–10, 10–15, 15–20, 20–25, and 25–30 m/s.

In addition to the accuracy characteristics, the maximum height of lidar sounding was estimated. It was assumed to be the height, at which the standard deviation of wind velocity reached 1.0 m/s. Based on the whole series of measurement data the average maximum height of lidar sounding $\overline{H}_{\max}$ was estimated to be

$$\overline{H}_{max} = (0.85 \pm 0.23) \text{ km}.$$

Other characteristics of these measurements are presented in Tables I and II. Note that Table I gives the values of n_j showing the overall amount of data used to estimate the discrepancies between the data of two measurement systems.

It can be seen from the data presented in Tables I and II that the data obtained using both techniques agree quite satisfactorily. However, systematic deviations are observed between the lidar and radiosonde data. As to the wind direction the deviations m_α are negative and their absolute values remain within 20–23°. Systematic deviations in wind velocity are also negative (with the only exception for the level at 0.3 km, where the values of m_V are positive and very small, remaining within 0.15 m/s) and increasing with height too. Note that the value of m_V at the 1.1. km height drops against that at 0.9 km, which presumably may be explained by insufficient number of measurement points at that height (n_j = 26). The latter value contrasts with those for heights were n_j = 42.

TABLE I. Statistical characteristics of measured discrepancies between the lidar and radiosonde data.

Height, km	m_V, m/s	m_a, deg	σ_V, m/s	σ_d, deg	n_j
0.3	0.15	–21.5	2.54	33.4	42
0.5	–0.40	–22.8	2.22	30.1	42
0.7	–1.35	–12.4	2.00	39.3	42
0.9	–1.50	–19.8	2.95	33.7	30
1.1	–0.71	–22.8	2.63	24.7	26

TABLE II. Weighted average values of the wind velocity deviations calculated for different wind velocity values.

Wind velocity, m/s	m_0, m/s	σ_0, m/s
1–10	–0.54	2.40
10–15	–0.76	2.50
15–20	–0.81	2.34
20–25	–0.12	2.38

The systematic error in wind direction resulted from poorly done orientation measurements both for the lidar and the "Meteor" system. Poor accuracy of orientation of sounding paths also contributed into the systematic error of comparative measurements of wind velocity. The latter is confirmed by increasing the value m_V with height.

Standard deviations between the values of wind velocity reached 2.0–2.9 m/s, and those of wind direction were within 24–39°, and is practically independent of height. With an account for the intrinsic errors of the "Meteor–RKZ" system,[12,13] and keeping in mind that measuring systems are completely independent, one can state that the rms error of the lidar wind measurements is comparable to that of the aerologic system, varying from 0.5 to 1.5 m/s for wind velocity modulus, and from 15 to 25° for the wind direction. Since the errors are apparently independent of height, one may assume that both the perturbing effect accumulated along the sounding path preceding a particular level being sounded, and that of the noise (up to heights where the signal–to–noise ratio is at least 2) are insignificant. Note that the processing algorithm calculates the SNR which is understood as the ratio of variance of fluctuations of the return signals to the variance of the noise itself; the ceiling of sounding was taken at the level where that ratio equaled 2.

Differences seem to be not growing at higher wind velocities either (Table II), what means that the lidar technique works quite reliably within a wide range of wind velocities.

Note also that the discrepancies observed in the experiment could also result from the variability of the wind field itself; it must have affected the lidar data more strongly because of essentially longer measurement time (~ 20 min) than that of radiosonde sensing (~ 30–40 s). The altitude averaging introduced into the lidar data processing made it possible to equalize spatial resolutions of both techniques.

In conclusion we should like to note some peculiarities in the wind lidar operation.

It follows from the analysis of lidar capabilities that its daytime sensing ceiling lowers on the average by 25–30%, compared to the nighttime, due to background noises. The sky background increases with the appearance of clouds, particularly, cumulus clouds. Precipitation may noticeably incapacitate the lidar, because the droplets have poor entrainment characteristics, have large vertical velocity component and rain washes out the aerosol from the atmosphere.[14] However, weak precipitation (below 2 mm/h) may even simplify sensing, as compared to clear sky conditions, because the signal increases against the background noise.

Results of comparison allowed us to reveal certain ways for improving the lidar performance. A more powerful computer would reduce retrieval time per single profile by a factor of 4 – 5. An increase in the rate of scanning to 10 rev/s, the use of higher buffer interference filters, an increase of the repetition frequency of sensing pulses and their energy would result in lower measurement error and higher sensing ceiling. High–precision elements and units for geodesic aligning of the lidar and for measuring angles between the sensing paths could eliminate the systematic error component from data.

REFERENCES

1. V.E. Zuev, *Laser–meteorologist* (Gidrometeoizdat, Leningrad, 1974), 178 pp.
2. V.E. Zuev, *Advances in Hydrometeorology and Monitoring of the Environment* (Gidrometeoizdat, Leningrad, 1987), 98 pp.
3. I. Kolev, K. Nenkov, G.G. Matvienko, and B.D. Belan, in: *Zb. Dokladov of Bulgarian–Soviet Seminar "Laser Means and Techniques for Monitoring of the Environment.* Sofia, Institute for Electronics, Bulgarian Ac. Sci. (1985), p. 144.
4. N.P. Fateev, *Testing Meteorological Instruments* (Gidrometeoizdat, Leningrad, 1975), 312 pp.
5. E.F. Dolinskii, *Processing Measurement Data* (Standart, Moscow, 1973), 191 p.
6. G.G. Matvienko, G.O. Zadde, E.S. Ferdinandov, et al., *Correlation Techniques in Laser Sounding Techniques of Wind Velocity Measurement* (Nauka, Novosibirsk, 1985), 224 pp.
7. B.D. Belan, A.T. Grishin, G.G. Matvienko, and I.V. Samokhvalov, *Spatial Variability of Characteristics of Atmospheric Aerosol* (Nauka, Novosibirsk, 1989), 152 pp.
8. P. Karkhunen, G.P. Trifonov, and V.A. Yurmanov, Meteor. Gidrol., No. 11, 111 (1987).
9. R.L. Kagan, *Averaging Meteorological Fields* (Gidrometeoizdat, Leningrad, 1979), 214 pp.
10. N.A. Zaitseva, R.Kh. Akhmet'yanov, and P. Karkhunen, Meteor. Gidrol., No. 1, 105 (1989).
11. *Manual for Hydrometeorologic Stations and Posts,* (Gidrometeoizdat, Leningrad, 1979), No. 4, Pt. 3a, 256 pp.
12. B.S. Derbenev and B.P. Istomin, Meteor. Gidrol., No. 6, 46 (1964).
13. N.A. Zaitseva, in: *TROPEX–74* (Gidrometeoizdat, Leningrad, 1976), Vol. 1, p. 712.
14. G.L.Grozdovskii, Uch. Zap. Tsentr. Aerogidrodin. Gos. Inst. **5**, No. 2, 80 (1974).