LIDAR INVESTIGATIONS OF WIND VELOCITY PROFILES IN THE LOWER ATMOSPHERE DURING THE SATOR–91 INTEGRATED EXPERIMENT

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Systematic investigations of wind velocity profiles in the lower atmosphere were carried out during the summer and fall of 1991. Investigations were performed remotely by means of a lidar based on the correlation technique of the wind velocity sounding at altitudes up to 1.5–2 km. *It is shown that wind speed was moderate (less than* 10 m/s*) and varied only slightly with altitude during the SATOR–91 integrated ozone experiment. The cardinal wind direction was southwestern.*

The information about the motion of air masses seems to be very useful when studying the tropospheric ozone budget. The particular importance of the wind velocity for the interpretation of the ozone measurements is obvious from two principal mechanisms of ozone formation in the troposphere.[1,2] The first is associated with the ozone formation through photochemical processes with participation of pollutants including the anthropogenic ones, while the second is due to the inflow of the stratospheric air richer in ozone during the process of mass exchange between the stratosphere and troposphere. In this case the profiles of the wind velocity characteristics determine the strength and the direction of the inflow of air masses enriched in ozone or pollutants.

In deciding on a system of wind measurement accompanying the ozone observations, one should prefer a measuring system with high spatial resolution and arbitrary (unlike aerological systems) interval between the profile measurements. The lidar wind velocity measurements fit these requirements most completely. During the SATOR–91 integrated experiment the part of the program for studying ozone in the lower troposphere was carried out by means of the LISA lidar for wind velocity sounding.

The results of investigations of the wind velocity profiles by the above–indicated lidar during the SATOR–91 experiment are presented below.

DESCRIPTION OF THE LISA LIDAR

The LISA lidar for wind measurements is based on the correlation technique of the measurement of the velocity of motion of aerosol inhomogeneities entrained by the wind flows with the use of the three–point (three–path) configuration.[3] The lidar was described in detail in Ref 4. Let us give here only the brief description of the sounding technique and data processing. The layout of this lidar is shown in Fig. 1.

A commercial laser with an amplifier used as a light source S transmitted short light pulses at the wavelength λ = 0.53 μm into the atmosphere.

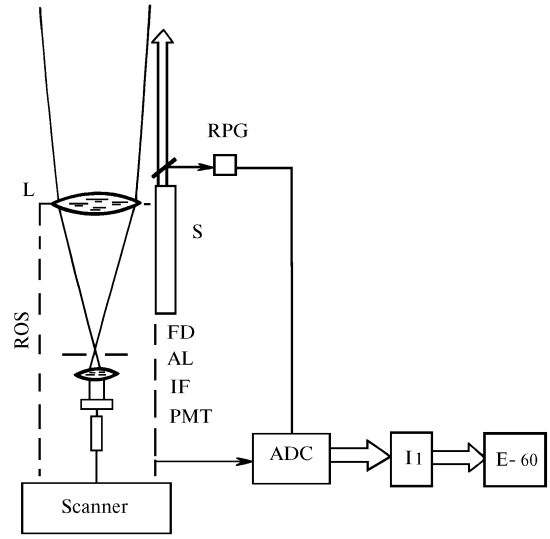

FIG. 1. Configuration of the LISA lidar.

The radiation reflected from the atmosphere enters the receiving optical system (ROS) consisting of the lens L with diameter of 30 cm in diameter, the changeable field diaphragm FD, the accessory lens AL, the interfilter IF, and the unit of the photomultiplier tube PMT, in which the analog signal is converted into the electric one. From the output of the PMT the signal is fed into the input of the 8–bit analog–digital converter with a maximum discretization frequency of 15 MHz synchronized with the laser by means of the reference pulse generator RPG. Numerical data from the analog–digital converter are routed through the parallel interface I1 to an Elektronika–60 microcomputer and then are processed.

Preliminary processing included data packing and storage of obtained data arrays on an electron disk with their subsequent rewriting on the long–term information medium (floppy disk or tape). The total number of readings was 128 which corresponded to the maximum altitudes of

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1280 or 2560 m depending on the sampling rate. Spatial scanning in three specified directions was carried out by means of the unique scanner SC (see Ref. 4) without rotation of the lidar optical parts.

The accumulated data arrays were further used to calculate the wind velocity.

The algorithm for determining the wind velocity is the following :

1. Unpacking the initial data arrays and forming three temporal arrays A_{ijk} where i is the channel number (i = 1...3), j is the number of an altitude range (j = 1...128), k is the shot number in the given channel (k = 1...1024).

2. Smoothing the obtained temporal series using the Batterwort frequency filter.[5]

3. Correcting for a trend of a time series by its approximation by the fourth–degree polynomials.

4. Smoothing the ends of a time series by cosine window and obtaining the initial arrays for taking the fast Fourier transform (FFT) $\tilde{A}_{ijk}$.

5. Taking the fast Fourier transform and obtaining the spectral estimates of an initial series

$$S_{ijk} \Rightarrow F(\tilde{A}_{ijk}) .$$

6. Estimating the cross spectral density for the combinations of i = 1 and 2, 1 and 3, and 2 and 3 (the asterisk means the complex conjugation)

$$\hat{S}_{12jk} = S^*_{1jk} S_{2jk} ;$$

$$\hat{S}_{13jk} = S^*_{1jk} S_{3jk} ;$$

$$\hat{S}_{23jk} = S^*_{2jk} S_{3jk} .$$

7. Taking the inverse FFT and obtaining the corresponding correlation functions

$$R_{12jk} \Rightarrow F^{-1}(\hat{S}_{12jk}) ;$$

$$R_{13jk} \Rightarrow F^{-1}(\hat{S}_{13jk}) ;$$

$$R_{23jk} \Rightarrow F^{-1}(\hat{S}_{23jk}) .$$

8. Finding the maxima of the cross–correlation functions and corresponding shifts τ_{12}, τ_{13}, and τ_{23}.

9. Calculating the wind velocity in the examined altitude range.

The potential of the setup makes it possible to obtain the wind velocity at altitudes up to 1–1.5 km at night and up to 1–1.5 km in the daytime.

Total measurement time is the sum of time taken to acquire the experimental data (20–25 min) and of that to process them. Unfortunately, the power of the Elektronika–60 microcomputer makes it impossible to process data very fast; for this reason it takes about 2 min to compute the wind parameters at one altitude. Thus, it takes about 4.5 h to process the data completely.

MEASUREMENTS

Experimental measurements of the wind parameters were carried out as part of the SATOR–91 integrated experiment near Tomsk Akademgorodok during June–July and October–November of 1991. The optical weather during the experiment was typical of the weakly turbid atmosphere for a meteorological visibility range of about 15 km. The measurements were carried out both in the daytime and at night. As a rule, maximum sensing range in the daytime was by 25–30% shorter. The basic results of the experiment are summarized in Table I.

TABLE I. The results of measurements of the wind parameters.

Local time	*H*, m								
	200	400	600	800	1000	1200	1400	1600	1800
1	2	3	4	5	6	7	8	9	10
June, 19									
23:00	6.3	4.8	18	7.0	6.8	5.6	3.7	–	–
	105	154	102	81	69	69	77	–	–
24:00	6.1	5.4	13	6.8	7.2	6.1	4.0	–	–
	102	134	95	81	72	80	82	–	–
June, 25									
21:00	7.9	9.1	10.2	12.6	14.2	15.6	14.8	–	–
	220	226	228	217	232	261	207	–	–
22:30	9.2	9.6	10.3	8.9	11.6	13.2	14.0	17.1	–
	214	220	248	232	223	255	260	266	–
23:10	7.8	8.2	9.4	9.1	6.9	11.7	14.3	15.7	13.1
	210	214	250	233	223	250	260	260	270
00:26	8.0	8.5	9.1	9.6	11.5	13.4	14.8	15.6	15.1
	210	215	256	231	223	256	261	264	258
June, 26									
22:30	10.1	11.1	9.7	12.6	12.8	10.8	14.3	15.6	13.1
	234	244	242	221	198	262	224	244	232
00:30	8.6	8.9	9.6	10.1	11.7	8.9	12.6	13.8	12.1
	240	256	261	221	198	245	288	312	340
June, 29									
13:00	4.8	5.2	4.2	6.8	10.3	14.2	–	–	–
	240	256	298	320	307	289	–	–	–
15:00	4.7	5.3	6.8	7.3	9.1	12.5	–	–	–
	216	255	308	320	336	315	–	–	–
July, 3									
21:00	0.8	0.9	1.6	3.8	3.1	0.9	2.8	2.9	–
	240	256	299	320	240	286	288	296	–
23:10	0.9	1.0	1.5	5.1	0.8	0.7	0.9	1.1	2.7
	255	244	276	312	215	278	296	321	254
01:35	1.0	1.1	1.6	5.2	0.9	0.8	1.0	1.0	2.0
	254	236	256	199	264	239	278	287	300
July, 5									
2:50	4.2	3.1	3.6	3.7	3.5	4.8	–	–	–
	199	202	210	200	220	207	–	–	–
1	2	3	4	5	6	7	8	9	10
July, 6									
22:00	2.3	2.8	2.4	2.7	3.6	2.2	4.1	5.6	8.2
	186	196	208	220	261	299	271	256	264
23:27	2.2	2.7	3.8	3.9	4.7	7.6	5.2	7.0	9.0
	203	209	209	241	266	288	308	300	302
1:00	4.2	2.1	3.6	3.7	3.5	4.8	5.6	6.1	2.7
	199	202	210	200	220	207	224	254	281
3:20	0.8	2.9	3.2	2.7	3.5	4.5	5.1	5.8	6.2
	206	209	231	218	226	258	264	270	241
4:50	1.1	1.9	2.9	2.7	3.8	0.9	5.7	5.1	3.4
	178	204	245	214	209	176	221	245	260
October, 9									
16:00	2.8	3.4	3.2	5.1	7.4	–	–	–	–
	129	101	112	87	117	–	–	–	–
18:00	2.3	4.8	4.2	6.2	7.0	–	–	–	–
	161	138	102	97	63	–	–	–	–

October, 16–17									
21:35	4.9	6.8	7.3	5.1	9.8	11.6	10.4	12.6	–
	91	118	132	112	97	121	142	133	–
23:55	3.2	4.7	6.9	5.0	9.0	12.7	9.9	12.7	–
	111	132	123	116	132	156	137	132	–
November, 6									
10:15	3.9	4.8	7.8	8.8	7.6	9.9	–	–	–
	176	158	161	172	180	196	–	–	–
12:30	3.6	4.6	7.7	8.3	7.3	9.4	–	–	–
	170	182	163	158	143	144	–	–	–
15:40	3.8	4.4	7,5	8.1	7.2	9.0	–	–	–
	165	174	160	155	140	138	–	–	–
18:20	3.0	4.0	6.8	3.1	6.5	8.8	10.1	9.5	–
	196	199	224	211	246	218	197	190	–

Note: Here the wind speed V (m/s) is given in the upper row and the wind direction W (deg) (from where it blows) – in the lower row.

From the analysis of the obtained data it follows that the wind speed was moderate and varied only slightly with altitude during the experiment. The cardinal wind direction was southwestern, i.e., from the center of the town to the Akademgorodok. Possibly, this substantially affects the optical situation in the measurement region.

The measurements of the wind parameters were carried out by the radiosounding technique using a METEOR aerological station in conjunction with the lidar. This enables us to compare the data obtained by two radically different techniques and to estimate the reliability of the data. The Student criterion, which is well suited for a small number of experimental points and is robust for the systematic shifts, served as a reliability criterion. The analysis of the results with the use of this criterion showed that all vertical profiles satisfy the reliability criterion with a significance level being not more than 0.05.

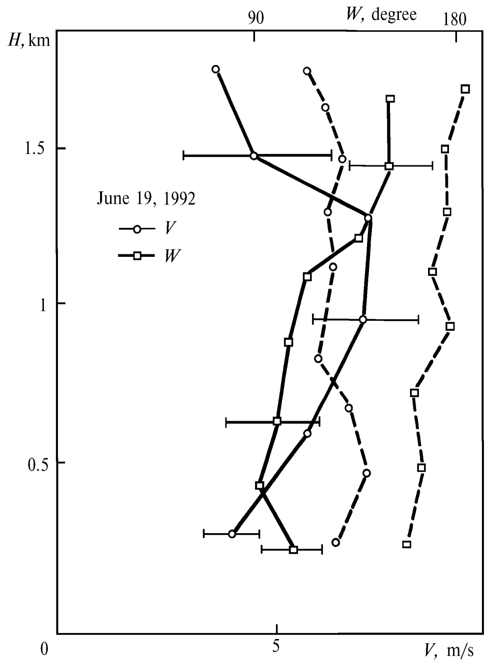

FIG. 2. Profiles of the wind speed V and direction W measured by the lidar and METEOR station on June 19, 1991. Horizontal bars indicate the 0.9 *confidence level.*

The profiles of the wind speed obtained by the lidar (solid lines) and by METEOR (dashed lines) are shown in Figs. 2–4. It can be seen from the figures that the data obtained by different techniques agree fairly well, especially at the altitudes up to 1 km.

The behaviour of the spatiotemporal characteristics of the aerosol inhomogeneities is of interest. Study of the spatiotemporal structure of the aerosol inhomogeneities showed that both the shape and the contrast of the aerosol inhomogeneities depend strongly on the altitude of sounding, measurement time, and the wind direction. Thus, the decrease of the size of inhomogeneities measured from the width of the principal maximum of autocorrelation functions was observed. So, the typical size of aerosol formations at an altitude of 300 m was 100–200 m, while at an altitude of 2000 m it decreases down to 70–90 m. This result is in agreement with the data of airborne sounding of the atmosphere.[6]

The comparison of experimental shapes and size of aerosol inhomogeneities with the wind regime showed that the inhomogeneities have the distinctive properties for the south–southwestern wind direction. Since Tomsk is situated in the same direction we can conclude that there is an essential difference between aerosol formations of anthropogenic and natural origins.

The main difference is associated with the fact that the anthropogenic aerosol formations have high contrast which is described by the ratio of the standard deviation to the mean value. Thus, the most typical range of variation of contrast of natural aerosols is 4–7%, while the inhomogeneity contrast of industrial aerosol can reach 15–20%. The anthropogenic aerosol formation shape, more elongated in the wind direction than that of the natural inhomogeneities, is also specific. Evidently, it is due to the fact that the sources of anthropogenic aerosol are most often local. It can be confirmed by the fact that the dissimilarity of the aerosol inhomogeneity structure is less pronounced at night than in the daytime. It is associated with a sharp decrease of the industrial activity of Tomsk.

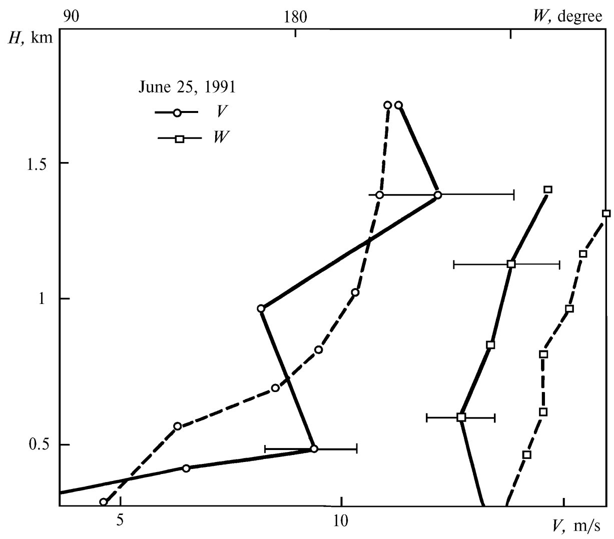

FIG. 3. The same as in Fig. 2 but for June 25, 1991.

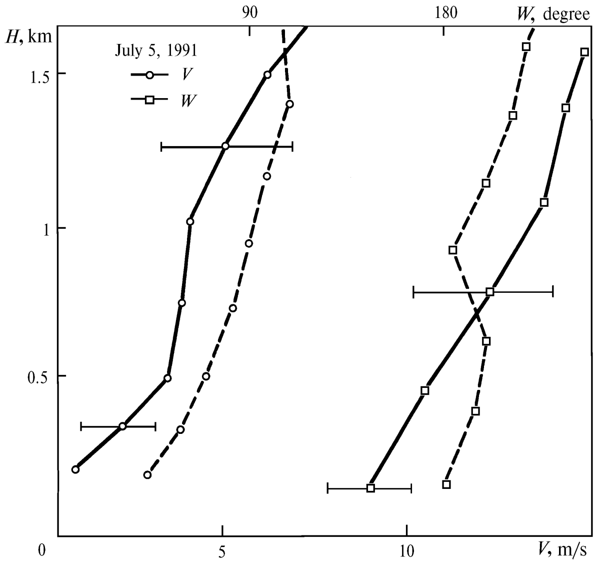

FIG. 4. The same as in Fig. 2 but for July 5, 1991.

The analysis of the errors in correlation measurements of the wind velocity made in Ref. 3 showed that one can represent the total error in measuring the wind speed in the form

$$\sigma_R^{(V)} = \left(\sigma_m^{(V)2} + \sigma_l^{(V)2} + \sigma_t^{(V)2} + \sigma_n^{(V)2}\right)^{1/2} , \quad (1)$$

where σ_m is the systematic error of correlation measurements caused by the statistical nature of aerosol formations, σ_l is the error caused by fluctuations of the laser energy, σ_t is the error due to the fluctuations of the atmospheric transparency, and σ_n is the error determined by the quantum noise of the optical signal. One can write down the analogous expression for the error in determining the wind direction $\sigma_R^{(z)}$.

The wind velocity measurements showed that the components σ_m and σ_n, whose total contribution can reach 20–25% under unfavourable conditions (low wind speed, intense background illumination, etc.) are of prime importance in Eq. (1). The contribution of the other terms does not exceed 5% for the given experimental conditions.

Thus, the total error in measuring the wind parameters did not exceed 30% for all altitude ranges and sounding conditions.

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