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Project Summary

An Evaluation of Wind Measurements by Four Doppler Sodars

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Measurements by four Doppler sodars of wind speed, wind direction, and the vertical component of turbulence were compared to similar measurements made on the 300-m instrumented tower at the National Oceanic and Atmospheric Administration's Boulder Atmospheric Observatory. The sodars were manufactured and were operated during the test by Aerovironment Inc., Radian Inc., Remtech et Cie (formerly Bertin), and Xontech Inc. Sodar measurements were compared to measurements made by fast response sonic anemometers at 100, 200, and 300 m. The comparison ran continuously for 21 d in September, 1982. Results of the experiment indicated that all sodars measured wind speed and direction quite accurately and with reasonably high precision. Comparison of the measurements of the vertical component of turbulence indicated that the sodars tended to overestimate the standard deviation of vertical velocity at night and to underestimate it during strongly convective situations. The precision of measurement for the vertical component of turbulence was considerably poorer than for average wind speed and direction. Comparison also indicated some differences among the various types of sodars. Analysis of the spectra measured by the sodars indicated that measurement inaccuracies may have been due to a combination of sampling volume and aliasing problems.

This Project Summary was developed by EPA's Atmospheric Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

During the first three weeks of September, 1982, an experiment was conducted at the Boulder Atmospheric Observatory (BAO), under the sponsorship of the Environmental Protection Agency (EPA), to assess the ability of in situ and remote sensors to measure the mean and turbulent properties of the lower atmosphere The experiment was conducted in response to the need for comparative data from which scientists could evaluate the accuracy, field precision, and general performance of some of the more commonly used meteorological instruments that measure atmospheric turbulence

Recent advances in the modeling of transport and diffusion of pollutants, achieved largely through theoretical insights gained from field experiments, point to the site-specific nature of turbulence Attention is, therefore, being directed to better on-site characterization of turbulence and to the development of techniques for measuring the mean and turbulent wind variables needed for input into the models This experiment was designed to provide information needed to formulate a monitoring strategy for the development of site-specific dispersion meteorology

The BAO was chosen as the site for the experiment because of the availability of precise profile and turbulence data from sensors on a 300-m tower Facilities for launching rawinsondes and for processing the data received from them were added benefits Four commercially-available Doppler sodars with the capability to measure variances in vertical wind component in addition to the mean three-dimensional wind field were used The question addressed here is whether the sodars can measure the mean and turbulent properties of the flow at heights 100 to 300 m above the ground

Description of Instrumentation

Four Doppler sodar manufacturers who currently market their products in the United States were invited by EPA to participate in the experiment Under arrangements made through EPA's principal contractor, Meteorology Research Inc , the sodars were installed and operated by personnel from the participating firms The four systems differ significantly in their physical configuration and approach to signal processing Two of the systems used three-axis monostatic arrays, one used a bistatic array and the other used a colocated monostatic/bistatic array The following four systems were deployed

AeroVironment Three-Axis Monostatic System (AV)

The system consisted of three acoustic transceivers mounted on a trailer Doppler shifts in the backscattered signals received on each axis were interpreted as wind components in the radial directions Wind components thus measured were transformed into components along the N-S, E-W, and vertical directions Because in this configuration sampling volumes are separated by large distances, the assumption of horizontal homogeneity in the mean wind field is essential to justify the use of wind components measured along the different axes for the coordinate transformation

The AV system transmitted a sound pulse (150-200 W) at a frequency of 1500 Hz (duration 0-18 s) sequentially from each of three adjacent pencil-beam antennas One tilts south 30° from the vertical to be sensitive to the N-S component, one tilts west 30° from vertical to be sensitive to the E-W component, and one points straight up to be sensitive to the vertical component The receiver echo is heterodyned and then passed through an electronic comb filter with 31 teeth to yield the full spectral distribution in the return signal For each 33 3-m altitude range gate, the spectrum is examined according to several criteria to obtain a best estimate of Doppler shift, along with an estimated reliability factor The pulse repetition interval was 8 s

Remtech Three-Axis Monostatic System (REM)

The REM system (developed originally at Bertin et Cie) also uses a trailer-mounted array of three transceivers They are operated in sequence as monostatic systems, the same assumption of horizontal homogeneity is invoked for wind measurements In this system, the horizontal wind sensing antennas are tilted 18° from the vertical in the same directions as are the AV's, the transmitted pulse is a 1600-Hz signal of 0 08-s duration The received signals are digitized after appropriate bandpass filtering, and the Doppler frequency shift is extracted using Fast Fourier Transforms (FFT) techniques The pulse repetition interval was 5 s

Radian Corporation Colocated Monostatic/Bistatic System (RAD)

The RAD's antenna configuration permitted both monostatic and bistatic operation Both systems shared the central, vertically pointing, pencil-beam transceiver The two tilted (18° from vertical) monostatic transceivers were not located close to the vertical transceiver as on the AV and REM systems, but were aimed to intersect at a height of 150-m In the bistatic mode, two fan-beam transmitters (located 250 m to the south and to the west) illuminated the vertical beam of the central transceiver The movement of the sound pulse up the vertical beam was followed by time gating of the receiver signal. Doppler frequency shifts in each gated segment were converted to wind velocity components to produce a wind profile

In both configurations, the vertical transceiver was operated in the monostatic mode to measure the vertical wind component Because the three monostatic beams were not divergent, the assumption of homogeneity is not as critical here The RAD system transmitted 120-W pulses at 2 0 kHz (0 1-s duration) and computed Doppler shifts using the Complex Covariance method RAD operated in three modes monostatic, bistatic, and multistatic (alternating one series of monostatic and one series of bistatic pulses) Pulse repetition interval for all systems was 5 s

Xontech Three-Axis Bistatic System (XON)

This bistatic system consisted of a vertical pencil-beam transceiver and two fan-beam receivers aimed at a central vertical common volume Therefore, the geometry in this system was exactly the reverse of the RAD bistatic system The transmitted frequency was 2 0 kHz (0 08- and 0 16-s duration under computer control) Its bistatic baseline was 350-m long The fan-beam antennas received signals scattered from the vertical transceiver beam, so the winds were computed along a vertical column above the transceiver as in the RAD bistatic system A microcomputer determined the Doppler frequency shift with an FFT detection scheme powerful enough to sense small frequency variations in the presence of high ambient noise levels The wind data are, therefore, presented without qualifiers, but if the program could detect a consistent signal for the entire averaging period, no data were printed for the height range The pulse repetition interval was 5 s

BAO Instrumented Tower

The 300-m tower at the BAO is instrumented at 8 levels 10, 22, 50, 100, 150, 200, 250, and 300 m Sonic anemometers installed at each of these levels measured the three-dimensional wind field R M Young propeller-vane anemometers are mounted on the side of the tower opposite from the sonic anemometers to serve as back up wind sensors when the tower is shadowing the sonic anemometers For this experiment, the sonic anemometers were mounted on the booms pointing SSW and the propeller-vane anemometers were mounted on booms pointing NNE. These booms also supported sensors for measuring mean and fluctuating air temperatures and the dewpoint temperature. Data from the sonic anemometers and other fast-response sensors were sampled ten times per second, while the propeller-vane anemometers, like other slow-response sensors, were sampled only once per second

Data from the BAO are recorded in one of two modes In the "regular" mode, only the 10-s averaged data points and 10-s grab samples (last point in a 10-s data block) of the time series are retained In the "raw data" mode, all data points are recorded In both modes, the software computes and lists once every 20 min the means, variances, and fluxes for the preceeding 20-min period These listings become the common reference for comparing the performance of the different sodars. The raw data mode is employed only when the full time series is needed for special analyses or for the details in the structure of the flow Such recordings were made for three relatively brief periods during this experiment for the purpose of comparing the spectral response of the sodars and examining the limitations imposed by sampling volumes and sampling rates

Procedures

The sodar measurements were centered over an area 0 5 x 0 3 km, about 0 65 km southwest of the BAO tower The bistatic arrays were laid out to provide a height range of at least 300 m, hence the requirement for such a large test area The electronic equipment associated with the Doppler systems were housed in trailers located within the visitors area A larger trailer in the same area served as the control center for the experiment

The terrain in the vicinity of the tower, is reasonably flat Except for the trailers and the fence surrounding the visitors area, the site is free of small-scale surface obstructions

Procedures for data collecting and reporting were established to insure against unfair bias for any of the participants. All systems were assumed to be capable of unattended continuous operation All systems provided data in the form of wind speeds, wind directions, vertical wind components, and standard deviations of vertical wind speed averaged over 20-min periods coincident with the BAO averaging periods The three comparison levels were 100, 200, and 300 m The data collected over the previous 24-h period were submitted to EPA personnel directing the experiment every morning at 0800-h MST in exchange for tower data covering the same period

Concurrent operation of some of the sodars was considered at one time, but quickly ruled out because of cross-contamination, even between systems operating at different frequencies The sodars were, therefore, operated in sequence, with the switchover from one system to another controlled by a central timer switch The assigned observing interval was normally one 20-min period each cycle The experiment covered the period from September 1 to 21, 1982

The AV, REM, and RAD computed the standard deviation of w (the vertical wind component) from their time series Missing data points were not filled in by interpolation, but the number of points missed (or accepted) was displayed The REM used 4-point block averages instead of the original time series. The XON computed its standard deviation from the width of its 2-min w spectra, estimated for each level Successive 2-min standard deviations were averaged to obtain the 20-min values Each spectrum was automatically examined for level and shape of background noise and steps were taken to remove their effects

No attempt is made in this report to present the results of our standard deviation of wind direction comparisons The azimuth direction standard deviations showed very large scatter The data are withheld pending a better understanding of the reasons for the scatter Meanwhile, *we can only suggest caution in using* standard deviation of wind direction for diffusion predictions

The AV, REM, and XON maintained a consistent operating pattern throughout the experiment However, RAD changed its operating mode every 24 h, switching from multistatic to bistatic and monostatic, then back to multistatic, and so on

Results

Measurement of the Standard Deviation of Vertical Wind Velocity

Because the sonic calculations of the standard deviation of vertical wind speed provide reference values, the accuracy and precision of each sodar system can be determined from the collection of 20-min average differences The two input variables for these computations are the standard deviation of vertical wind velocity calculated from sodar measurements and the standard deviation of the sonic vertical wind velocity The comparative statistics used to estimate accuracy and precision then become the average difference (sample bias) and the standard deviation of the differences In addition, the root mean square difference, or comparability, is computed, this statistic characterizes the repeatability of a system Finally, the precision is also represented as a percentage of the average value, a coefficient of variation

Values for these statistics are presented in Table 1 for the combined sodar *observations at each of three heights*, as well as for the individual vendor data subsets The sample bias showed a large range of values around nearly constant composite values of 0 08 At 100 m the spread was greatest, with the REM having the only negative sample bias value (i e , sodar < sonic) and the XON having a sizable 0 23 m/s sample bias The AV was well below the composite sample bias value, the RAD was above it At 200 m the REM value was slightly negative, the AV remained small, the XON was the same as the composite value, but the RAD was in excess of 0 2 m/s At 300 m the RAD sample bias continued to be relatively large, but the other vendors were grouped between 0 03 and 0 07 m/s

From Table 1 it is clear that there is much scatter in the comparability and percentage of the average value about the true value in all systems There was no statistical difference between the standard deviation of the differences and

Table 1. *Standard Deviation of Sodar Vertical Wind Speed Compared to the Standard Deviation of Sonic Vertical Wind Speed*

Height (m)	*Vendor*	*b*[1] *(m/s)*	*c*[2] *(m/s)*	*s*[3] *(m/s)*	*s*[4] *(%)*	*N*[5]
100	Composite	0 08	0 24	0 22	50	678
	AV	0 01	0 16	0 16	35	190
	RAD	0 12	0 25	0 21	47	178
	REM	-0 05	0 18	0 17	38	139
	XON	0 23	0 34	0 24	53	171
200	Composite	0 08	0 27	0 26	54	576
	AV	0 03	0 20	0 20	43	167
	RAD	0 22	0 39	0 32	65	144
	REM	-0 00	0 19	0 19	39	119
	XON	0 08	0 25	0 24	51	146
300	Composite	0 09	0 27	0 26	54	665
	AV	0 04	0 25	0 25	53	214
	RAD	0 23	0 38	0 30	62	158
	REM	0 07	0 23	0 22	47	136
	XON	0 04	0 19	0 18	38	157

[1]*b = sample bias (sodar measurement-sonic measurement) Estimates accuracy*
[2]*c = comparability*
[3]*s = standard deviation of differences Estimates precision*
[4]*s' = s expressed as a percentage of the average value of the sonic standard deviation*
[5]*N = number of observations*

the percentage of the average value for the AV and the REM at any of the levels

Measurement of Wind Speed

To examine the accuracy and precision of the sodars, simultaneous observations of wind speed were recorded from sonic anemometers at the same three heights on a tower about 600 m from the sodar systems The sonic systems had a sampling rate of 10 Hz, and they were regarded as the reference instruments in the evaluation However, due to a wind shadow zone created by the tower, extending ±40° from north for the sonic instruments, reference data in this sector were obtained by the propeller vane at the BAO tower A comparison of sonic and propeller wind speed measurements on the tower showed that the instruments were approximately equivalent

Values of sample bias, comparability, standard deviation for the differences between sodar and reference values are presented in Table 2 for combined sodar observations at each height as well as for the sodar record of each vendor Propeller wind speeds were excluded when the wind speed was less than 1 m/s

The estimates of sample bias in Table 2 show mostly negative values at 100 m, with a composite value near -0 4 m/s Because the difference was sodar minus reference, this means that the sodar systems tended to register too low An exception was the RAD, which did not have a significant sample bias at 100 m

At 200 m, the vendors all recorded too high At 300 m the RAD and XON again recorded too high, whereas, the AV and REM were unbiased Sample biases were also computed for day (0600-1800 h) and night (1800-0600 h) values Most differences between day and night were insignificant

The comparability of sodar wind speeds with reference values is also given in Table 2 Precision is represented by standard deviation and percentage deviations The percentage deviation values ranged from about 15% to 35% around composite values near 25%

Measurement of Wind Direction

An investigation of the propeller-vane data indicated that they could not be substituted as reference values There were unexplained disparities between the propeller and sonic data that are still under investigation Because sonic data showed more consistent behavior and we believe them to be more reliable, only the sonic wind direction measurements are used as reference data

Values of sample bias, comparability, and standard deviation for the differences between sodar and sonic reference values are presented in Table 3 for combined sodar observations at each height as well as for the sodar record for each vendor

The values of bias in Table 3 show negative values at 100 m and 200 m for all vendors, but positive values at 300 m for all vendors except for RAD However, most of these values were not significantly different from zero, considering the variability of the wind direction and the number of cases included

The comparability of sodar wind direction with sonic reference values is also given in Table 3 Considering the scatter in data, it can be assumed that the vendors' measurements of wind directions were equivalent to each other

The Project Report also gives information on the sodar performance above 300 m It also compares vertical velocity spectra determined from the sodar measurements and from the sonic anemometer measurements

Conclusions and Recommendations

The wind measurements analyzed in this report represent the state-of-the-art in Doppler sodar wind sensing Considering the requirements that the sodar operation be unattended, except for maintenance and repair, and that the data be subjected to no editing by the vendors, the results obtained were reassuringly good The scatter in the wind speed and direction data compared very well with scatter in past experiments when some of the same sodar systems were compared under more controlled conditions In these data, some vendors showed more scatter than others, but much of that could be attributed to factors such as rain, high winds, cable damage, and transducer failures If data from these suspected periods are eliminated, the scatter for the different systems would appear more similar

The measurement of standard deviation of vertical wind velocity with sodars seems to show promise, at least for daytime conditions Here too, vendor performance showed variations that could be attributed in some cases to weather and equipment failure, but individual differences in processing the data might also have been a factor here The predictable behavior of sodar vertical velocity spectra in the convective boundary layer leads one to believe that vertical velocity variance measurements can be made to within 10% of heights above 100 m However, the nighttime results are not so encouraging More work is needed to ascertain the reasons for the large discrepancies in the vertical velocity measurements at night

Table 2 *Sodar Wind Speed Compared With Reference Wind Speed*

Height (m)	Vendor	b[1] (m/s)	c[2] (m/s)	s[3] (m/s)	s'[4] (%)	N[5]
100	Composite	-0 42	1 28	1 21	28	1179
	AV	-0 50	1 03	0 90	21	327
	RAD	0 02	1 18	1 18	28	315
	REM	-0 12	0 62	0 60	14	236
	XON	-1 04	1 88	1 56	37	301
200	Composite	0 14	0 98	0 96	23	1019
	AV	0 05	0 72	0 72	17	298
	RAD	0 31	1 00	1 47	35	258
	REM	0 12	0 73	0 72	17	194
	XON	0 09	0 71	0 70	17	269
300	Composite	0 16	1 24	1 23	27	1005
	AV	-0 10	1 15	1 15	25	328
	RAD	0 29	1 17	1 69	37	198
	REM	0 02	0 74	0 74	17	183
	XON	0 44	1 20	1 12	25	296

[1] *b = sample bias (sodar measurement-sonic measurement) Estimates accuracy*
[2] *c = comparability*
[3] *s = standard deviation of differences Estimates precision*
[4] *s' = s expressed as a percentage of the average value of the sonic standard deviation*
[5] *N = number of observations*

Table 3. *Sodar Wind Direction Compared With Sonic Wind Direction*

Height (m)	Vendor	b[1] (deg)	c[2] (deg)	s[3] (deg)	N[4]
100	Composite	-4 41	28 59	28 25	667
	AV	-3 87	26 70	26 41	187
	RAD	-6 76	27 06	26 20	177
	REM	-2 03	18 51	18 40	137
	XON	-4 49	37 85	37 58	166
200	Composite	-3 43	23 22	22 97	523
	AV	-0 79	19 47	19 45	155
	RAD	-7 86	25 67	24 43	128
	REM	-3 89	24 67	24 36	110
	XON	-1 85	23 80	23 73	130
300	Composite	0 75	29 59	29 58	697
	AV	0 26	28 56	28 56	227
	RAD	-3 25	29 98	29 80	131
	REM	0 62	19 70	19 69	142
	XON	4 05	35 96	35 73	197

[1]b = Sample bias (sodar measurement-sonic measurement) Estimates accuracy
[2]c = comparability
[3]s = standard deviation of differences Estimates precision
[4]N = number of observations

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The complete report, entitled "An Evaluation of Wind Measurements by Four Doppler Sodars," (Order No PB 85-115 301, Cost $13 00, subject to change) will be available only from:
National Technical Information Service
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