Title	Precision and Relative Accuracy of a Phased Array Doppler Sodar
Author(s)	TAKEHISA, Masato; ITO, Yoshiki; KATAOKA, Tsuyoshi; MITSUTA, Yasushi
Citation	Bulletin of the Disaster Prevention Research Institute (1992), 42(2): 65-70
Issue Date	1992-06
URL	http://hdl.handle.net/2433/124985
Right	
Type	Departmental Bulletin Paper
Textversion	publisher

Precision and Relative Accuracy of a Phased Array Doppler Sodar

By Masato TAKEHISA, Yoshiki ITO, Tsuyoshi KATAOKA and Yasushi MITSUTA

(Manuscript received on April 23, 1992; revised on May. 14, 1992)

Abstract

We developed a phased array Doppler sodar and participated with the new sodar in the International Sodar Intercomparison Experiment (ISIE) at Boulder Atmospheric Observatory (BAO) in 1988. From the data obtained during this experiment, errors in wind measurement by the sodar were estimated by the method proposed for a microwave wind profiler by Strauch et al. The error in horizontal wind components was 0.35m/s at 75m and 0.60m/s at 300m when the mean wind speed was about 5m/s. The error is separated into random errors in radial velocity measurement of 0.29 and 0.47m/s at 75 and 300m, and errors caused by the assumption of uniform wind in the beam separation of 0.20 and 0.38m/s at 75 and 300m.

1. Introduction

We developed a phased array Doppler sodar with 5x5 horns using a 1400Hz sound signal (Ito et al., 1989)[1], as the next generation of wind profiling sodar (Mitsuta & Uchida, 1985)[2]. We participated with the new sodar in the International Sodar Intercomparison Experiment (ISIE) at the Boulder Atmospheric Observatory (BAO) in 1988 (Gaynor et al., 1990)[3]. In this experiment, comparisons were made against the sonic anemometers on the BAO tower. The rms differences, between the sonic anemometers and the sodar, were 0.89m/s for wind speeds and 11.5° for wind direction in mean wind speed of about 5m/s. However, the horizontal distance between the tower and the sodar was about 650m so instrumental errors and wind variability could not be separated.

As this sodar system is operated with five beams, we can determine observation errors in the data following the same method used with a microwave wind profiler by Strauch et al., (1987)[4]. The precision of horizontal wind component measurement by this sodar was evaluated to be 0.35m/s at 75m and 0.60m/s at 300m during ISIE on average.

2. Specifications of the New Phased Array Sodar (AR–400)

The new phased array sodar (AR–400) has specifications as shown in **Table 1.** The 5×5 horns are switched to form the vertical and oblique beams alternatively. One cycle of the observation, directing vertical, north, east, south, west and then vertical again, is made every 20 sec. Data from these five beams are processed to obtain three dimensional wind components at every 30m in height, assuming uniformity of wind within beam separations of about

Table 1. System parameters of the wind profiling sodar.

Operating frequency	1400Hz
Horn array	5×5
Maximum input power	1500W (electric)
Antenna aperture	$0.64m^2$
Zenith angle of steering beams	23°
Beam width	17°
Pulse length	100, 350ms
Pulse repetition period	4, 8sec
Range resolution	30m
Doppler frequency estimation	FFT/Simple Homodyne Complex Covariance

80m in diameter at the height of 100m.

The details of this system were explained in the previous paper[1]. Processing of the wind components are performed on a micro-processor and the data are recorded in digital form on a floppy disc.

3. Evaluation of Error Terms

Strauch et al., (1987)[4] have developoped a new method to separate microwave wind profiler errors into those caused by wind field non-uniformity and random errors of observation. Evaluation of the errors in the sodar observations with five beams were made following their method. The radial velocities measured with the five beams pointing north, east, south, west and zenith are as follows (see **Fig. 1**) :

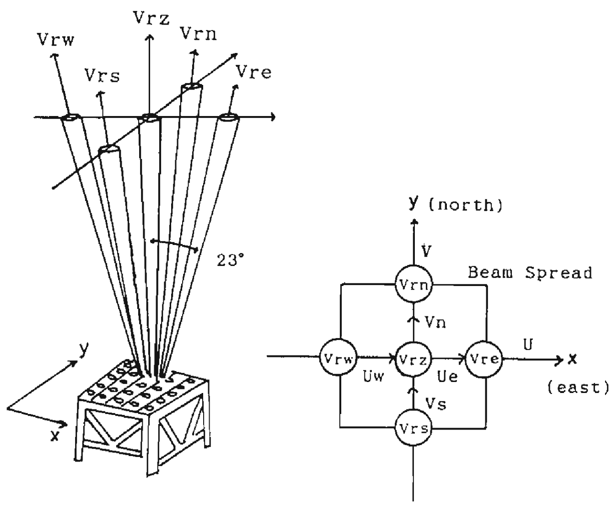

Fig. 1. Directions of the acoustic beams.

$$
\begin{aligned}
Vrn &= v \cos\theta + w \sin\theta + \delta Vrn \\
Vre &= u \cos\theta + w \sin\theta + \delta Vre \\
Vrs &= -v \cos\theta + w \sin\theta + \delta Vrs \\
Vrw &= -u \cos\theta + w \sin\theta + \delta Vrw \\
Vrz &= w + \delta Vrz,
\end{aligned} \tag{1}
$$

where Vrx is the observed radial velocity, u, v and w are the wind velocity components, θ is the elevation angle of the oblique beams and δVrx observational error of radial velocity of the sodar.

3. 1 Errors of wind reduction on the assumption of $w=0$

In a conventional sodar, wind calculations are made on the assumption of zero vertical velocity and horizontal uniformity of wind to simplify the system. In such a case, measured horizontal wind speeds Vx, Ux can be written as follows,

$$
\begin{aligned}
Vn &= v + \delta Vn = Vrn \sec\theta \\
Ue &= u + \delta Ue = Vre \sec\theta \\
Vs &= v + \delta Vs = -Vrs \sec\theta \\
Uw &= u + \delta Uw = -Vrw \sec\theta,
\end{aligned} \tag{2}
$$

when δVx, δUx are the measurement error of the wind component. The error terms, using Eq (1), are

$$
\begin{aligned}
\delta Vn &= w \tan\theta + \delta Vrn \sec\theta \\
\delta Ue &= w \tan\theta + \delta Vre \sec\theta \\
\delta Vs &= -w \tan\theta - \delta Vrs \sec\theta \\
\delta Uw &= -w \tan\theta - \delta Vrw \sec\theta.
\end{aligned} \tag{3}
$$

We define Du and Dv as the difference of the measurement in each direction :

$$
\begin{aligned}
Du &= Ue - Uw \\
Dv &= Vn - Vs,
\end{aligned} \tag{4}
$$

and obtain DC and DS from a coordinate transformation :

$$
\begin{aligned}
DC &= \frac{1}{\sqrt{2}}(Dv + Du) \\
DS &= \frac{1}{\sqrt{2}}(Dv - Du).
\end{aligned} \tag{5}
$$

Then Du, Dv, DC and DS become

$$
\begin{aligned}
Du &= \delta Ue - \delta Uw \\
&= 2w \tan\theta + (\delta Vre + \delta Vrw) \sec\theta
\end{aligned}
$$

$$Dv = \delta Vn - \delta Vs = 2w \tan\theta + (\delta Vrn + \delta Vrs)\sec\theta \quad (6)$$

$$DC = 2\sqrt{2}\cdot w\tan\theta + \frac{1}{\sqrt{2}}(\delta Vrn + \delta Vre + \delta Vrs + \delta Vrw)\sec\theta$$
$$DS = \frac{1}{\sqrt{2}}(\delta Vrn - \delta Vre + \delta Vrs - \delta Vrw)\sec\theta \quad (7)$$

If we assume the average of δVrn, δVre, δVrs and δVrw is zero and the variances of those values are the same $VAR(\delta Vr)$, the variances of Du, Dv, DC and DS become :

$$\begin{aligned} VAR(Du) &= VAR(Dv) \\ &= 4VAR(W)\tan^2\theta + 2VAR(\delta Vr)\sec^2\theta \\ VAR(DC) &= 8VAR(W)\tan^2\theta + 2VAR(\delta Vr)\sec^2\theta \\ VAR(DS) &= 2VAR(\delta Vr)\sec^2\theta \end{aligned} \quad (8)$$

While from Eq(2) and Eq(3),

$$\begin{aligned} VAR(\delta Vn) = VAR(\delta Ue) = VAR(\delta Vs) = VAR(\delta Uw) \\ = VAR(W)\tan^2\theta + VAR(\delta Vr)\sec^2\theta \end{aligned} \quad (9)$$

The variances shown in Eq(8) can be evaluated from the observations of ISIE as shown in **Table 2.** As is clear from Eqs(6 & 7), Du, Dv and DC may deviate from zero because the vertical velocity is not zero and that there are random errors in the observations. However, DS deviates from zero only by random error in the radial velocity observation. The values of DS shown in **Table 2** are much smaller than other values which contain errors caused by the assumption of zero vertical velocity. The observed values of $VAR(Du)$ and $VAR(Dv)$ are almost the same as assumed in Eq(8). This means that the errors, δVrx, are random.

Table 3 shows the square root of the terms of Eq(9) that contribute to the errors in evaluating horizontal wind components. Total errors in evaluating horizontal wind component $(VAR(\delta Vx))^{1/2}$ are 0.49m/s at 75m and 0.98m/s at 300m respectiely. $(VAR(\delta Vr))^{1/2}\sec\theta$ and $(VAR(w))^{1/2}\tan\theta$ are the random errors of radial velocity measurements and the error caused by the assumption that $w=0$. They are 0.29m/s and 0.39m/s at 75m and 0.47m/s and 0.86m/s at 300m. These errors are both smaller at 75m than at 300m because the S/N ratios are

Table 2. The mean and standard deviation (S. D.) of observed values of *DU*, *DV*, *DC* and *DS* with zero vertical velocity assumption.

Height		*DU*	*DV*	*DC*	*DS*
75m	Mean (m/s)	−0.31	−0.24	−0.39	0.05
	S. D. (m/s)	0.93	0.83	1.18	0.41
300m	Mean (m/s)	−0.52	−0.69	−0.85	−0.12
	S. D. (m/s)	1.79	1.88	2.51	0.66

Table 3. Error estimation from Eq (9) using the values shown in Table 2.

Height	Total $\{VAR(\delta Vx)\}^{1/2}$	Random $\{VAR(\delta Vr)\}^{1/2}\sec\theta$	From zero w $\{VAR(W)\}^{1/2}\tan\theta$
75m	0.49m/s	0.29m/s	0.39m/s
300m	0.98m/s	0.47m/s	0.86m/s

larger at lower levels and the assumption of zero vertical velocity is not realistic at higher levels.

3.2 Errors of wind reduction with the assumption of uniform wind

In the previous section, zero vertical velocity was assumed. The new sodar can measure all five components of Eq(1). Therefore, horizontal wind speed can be evaluated without assumed zero vertical velocity. We assume uniformity of horizontal and vertical wind speed within the beam separations and that the vertical velocity is represented by the vertical beam measurement. The Eqs(8) and (9) become:

$$\begin{aligned}
VAR(Du') &= VAR(Dv') \\
&= 4VAR(\delta Vrz)\tan^2\theta + 2VAR(\delta Vrx)\sec^2\theta \\
VAR(DC') &= 8VAR(\delta Vrz)\tan^2\theta + 2VAR(\delta Vrx)\sec^2\theta \\
VAR(DS) &= 2VAR(\delta Vrx)\sec^2\theta \qquad\qquad (10) \\
VAR(\delta Vn) &= VAR(\delta Ue) = VAR(\delta Vs) = VAR(\delta Uw) \\
&= VAR(\delta Vrz)\tan^2\theta + VAR(\delta Vrx)\sec^2\theta
\end{aligned}$$

The mean values and rms of Du', DC' and DS as obtained from the observation of ISIE are shown in **Table 4,** in which DS is the same as that in Eq(8).

The error terms for horizontal wind components given in Eq(10) are shown in **Table 5.** $\{VAR(w)\}^{1/2}\tan\theta$ is the error caused by assumption of uniformity of vertical velocity over a beam separation and represented by the vertical beam measurement. This error term is 0.20m/s at 75m and 0.38m/s at 300m, while the random errors of radial velocity are unchanged from the values under the $w=0$ assumption, as is clear from the definition. The total errors of horizontal wind estimate, in case of non-zero but uniform vertical velocity, are 0.35m/s at 75

Table 4. The mean difference and standard deviation (S. D.) of DU', DV', DC' and DS with the assumption of non zero vertical velocity and wind uniformity in beam separation.

Height		DU'	DV'	DC'	DS
75m	Mean (m/s)	−0.05	0.02	−0.02	0.05
	S. D. (m/s)	0.61	0.54	0.70	0.41
300m	Mean (m/s)	0.09	−0.08	−0.01	−0.12
	S. D. (m/s)	1.07	0.99	1.30	0.66

Table 5. The error estimated from Eq (10) using the values shown in Table 4.

Height	Total $\{VAR(\delta Vx)\}^{1/2}$	Random $\{VAR(\delta Vr)\}^{1/2}\sec\theta$	From uniform w $\{VAR(w)\}^{1/2}\tan\theta$
75m	0.35m/s	0.29m/s	0.20m/s
300m	0.60m/s	0.47m/s	0.38m/s

m and 0.60m/s at 300m and are smaller by 0.14m/s and 0.38m/s than the errors in the results assuming $w=0$. The errors of the sodar wind measurements in our five beam system are small enough so that we can use the instantaneous values of wind components in each sounding for turbulence studies.

4. Conclusions

The error terms of Doppler sodar (AR–400) observations were evaluated following the method of Strauch et al., (1987)[4], using data obtained during ISIE[3] at BAO. The results show that the total errors of horizontal wind estimates are 0.35m/s at 75m and 0.60m/s at 300 m for all periods when the mean wind speed was about 5m/s. The errors caused by the assumption of wind uniformity within beam spread is 0.20m/s at 75m and 0.38m/s at 300m, while the random errors in radial velocity measurement is 0.29m/s at 75m and 0.47m/s at 300 m.

We can compute turbulent momentum fluxes using the wind fluctuation data for every 20 sec, one cycle of observation, on all beams. Momentum fluxes were computed during a low level jet during the ISIE; the results are reported in another paper (Kataoka et al., 1990)[5].

References

1) Ito, Y., Y. Kobori, M. Horiguchi, M. Takehisa and Y. Mitsuta: Development of wind profiling sodar, *J. Atmos. Oceanic Technol.*, Vol. 6, No. 5, 1989, pp. 779–784.
2) Mitsuta, Y. and S. Uchida: Convective motions in the cumulus subcloud layer, *J. Climate Appl. Meteor.*, Vol. 24, No. 9, 1985, pp. 993–1000.
3) Gaynor, J. E., C. B. Baker and J. C. Kaimal: The International Sodar Intercomparison Experiment, Ed. S. P. Singal, *Acoustic Remote Sensing*, Tata McGraw–Hill, 1990, pp. 67–74.
4) Strauch, R. G., B. L. Weber, A. S. Frisch, C. G. Little and D. A. Merritt: The precision and relative accuracy of profiler wind measurements, *J. Atmos. Oceanic Technol.*, Vol. 4, No. 4, 1987, pp. 563–571.
5) Kataoka, S. M. Takehisa, Y. Ito, E. Otaki and Y. Mitsuta: Low level jet as observed by doppler sodar during ISIE, *J. Meteor. Soc. Japan*, Vol. 1, No. 2, 1991, pp. 171–177.