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DEVELOPMENT OF A VOLUME IMAGING MINISODAR

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INTRODUCTION

Many active remote sensing instruments, such as acoustic sounders and radar profilers, are designed to operate in a triple monostatic mode; that is, they determine the wind components in a vertical plane defined by the horizontal wind direction above the antenna. Thus they provide little or no information about the spatial structure of the wind or turbulence field perpendicular to the mean wind direction. This is also true of in situ tower-mounted instruments. The three-dimensional nature of the wind field can be sampled with arrays of in situ instruments dispersed over a horizontal plane. Scanning remote sensors such as radars and some lidars do sample the three-dimensional wind field; however, they are normally limited to determining only the radial component of the wind field at each point.

In many cases the horizontal structure of the planetary boundary layer (PBL) is not homogeneous; for example, (1) the convective PBL is dominated by thermal plumes, responsible for dispersion and mixing within the mixed layer, that have roots in the surface layer (Asimakopolous et al. 1983) and extend to the top of the mixed layer; (2) flow over and around obstacles or complex terrain can vary rapidly with position; and (3) the nocturnal boundary layer may develop local pockets of isolated turbulence because of the small levels of large-scale turbulent mixing. In each of these cases vertical profiling may obtain a distorted picture of the true nature of the wind and turbulence field because of inadequate or biased sampling in a single vertical plane.

The increasing use of phased arrays for transmitting and receiving antennae presents an opportunity to develop and use instruments that allow sampling of a true three-dimensional volume. By combining a phased array that has independent control of each element, similar to that suggested by Martakos et al. (1990), with multifrequency techniques (Coulter and Martin 1986b) and with the use of multiple transmitter-receivers, we are developing an instrument that can accomplish this task, albeit on a relatively small scale. Because this instrument is an acoustic device, the hardware costs are relatively modest, and the software control devices are relatively modest in cost as well.

CONCEPT

The system, in its initial configuration, will consist of three high-frequency, 36-element phased-array antennae that have individual control over each of the array elements. It is anticipated that the system may eventually have as many as five arrays. Figure 1 illustrates a possible configuration of three antennae. Once a point P(x,y,z) is selected, all of the

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antennae will transmit toward (and receive from) that point. By having the antennae transmit at different frequencies but receive over a relatively broad band, each antenna will detect a signal from each of the other antennae, as well as its own backscattered signal. Thus there will be a total of n^2 ($n = 3$ in this case) separate measurements of components of the wind vector at point P from each sample time: n (3) monostatic and all combinations of bistatic returns among the receivers. Some of the components are repeated (for example, transmit from A_0 through P to A_1 and from A_1 through P to A_0); however, $n!/(2(n-2)!)$ (6 for $n = 3$) of the paths will be different.

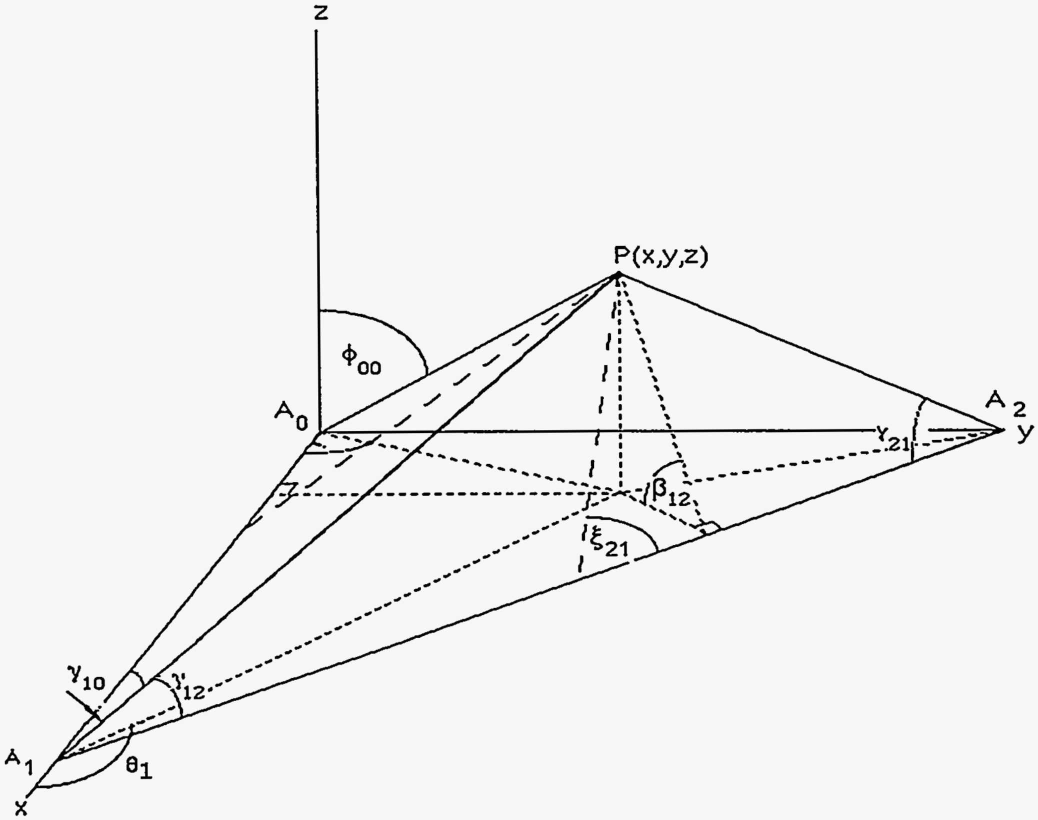

Figure 1. Geometry of Volume Imaging Sodar. Three antennae (A1, A2, A3) transmit toward P and receive signals from all antennae. The three antennae plus P define three planes in which wind velocity vector is sampled.

Evaluation of the geometry outlined in Figure 1 leads to a set of direction cosines, D_{ij}, for each measurement at each position. For monostatic returns,

$$\bar{D}_{aa} = \sin(\phi_a)\cos(\theta_a)\hat{\imath} + \sin(\phi_a)\sin(\theta_a)\hat{\jmath} + \cos(\phi_a)\hat{k} \quad . \tag{1}$$

For bistatic returns,

$$\bar{D}_{ab} = Cos(\beta_{ab})Cos(\xi_{ab})\hat{\imath} + Cos(\beta_{ab})Sin(\xi_{ab})\hat{\jmath} + Sin(\beta_{ab})\hat{k} = \bar{D}_{ba} \quad , \tag{2}$$

where

$$\xi_{ab} = \frac{1}{2}\left(\pi - \left[\gamma_{ab} - \gamma_{ba}\right]\right) .$$

and a,b = 0, 1, 2. A set of samples leads to realizations of the three components of the wind:

$$\begin{pmatrix} R_1 \\ R_2 \\ . \\ . \\ R_m \end{pmatrix} = \begin{pmatrix} a_1, b_1, c_1 \\ a_2, b_2, c_2 \\ . \\ \\ a_m, b_m, c_m . \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} \tag{3}$$

where a_i, b_i, c_i are the components of (1) or (2) (depending upon monostatic or bistatic return) along $\hat{i}$, $\hat{j}$, $\hat{k}$, respectively; $m = n^2$, and u, v, w are the components of the wind. Only 3 (with some exceptions, see subsequent text) of the set of equations in (3) are requiredto determine u, v, and w . There are 84 possible solution groups in (3) if $n = 3$. However having measurements in three different planes is necessary to to uniquely determine the wind components. This requirement reduces the number of solution groups to 48 when $n = 3$. When all possible solutions are averaged, the reliability of the estimate of wind speed will be increased; this significantly reduces the number of pulses required to obtain a good value at each interrogated point. In reality, some of the measurements R_i will not be usable because of poor signal-to-noise ratios, especially for those combinations of transmitter-receivers that require a long path length or when a receiver is exposed to large noise sources while pointing in certain directions.

We call the region within the array of transmitters where we intend to take a series of measurements the interrogation volume. The length of time required to "scan" the interrogation volume will depend upon the chosen spatial separation between sample locations. Because the beam widths for the antennae are relatively large (about 8° full beam), the volumes queried by different pairs of antennae will vary; the separation between sample points should be large compared with the sample volume, defined by the superposition of all possible pairs of common volumes defined by the intersection of the beams from the antennae. We anticipate that sample locations will be separated by about 25 m horizontally and vertically. This implies that it will require at least 1-2 min to sample a volume 100 m on a side; however, if the volume is limited to a single height, a scan could be done in about 15 s.

Additional information about the three-dimensional spatial structure can be obtained by using the monostatic return signals from each transmitter before and after they reach the common sampling volume. Although the signals in these regions can be combined to form only a coarse estimate of the mean wind speed within the interrogation volume as a whole, the spatial structure of the elements within the volume above the sample volume height can be evaluated with the intensity returns from each antenna.

ANTENNA DESIGN

The antenna consists of 36 piezoceramic tweeters similar to those used in past efforts (Coulter and Martin, 1986a). However, each element is controlled indivdually in both amplitude and phase.

The phase shift necessary for each element is determined by the spacing, D, of the elements and the wavelength, λ. Because each antenna will transmit at a different frequency, the phase shifts necessary will reflect that fact. The necessary phase shift is determined by tilt angles (δ, ε) along the (x,y) axes separately; the phase shift for each element is then equal to the sum of the interelement shifts, $\varphi_{x,y}$, along the x and y axes.

$$\varphi_{x,y} = 2\pi \frac{D}{\lambda} \sin(\delta, \varepsilon) \tag{4}$$

and

$$\tan(\delta) = \frac{x}{z} = \tan(\phi)\cos(\theta); \quad \tan(\varepsilon) = \frac{x}{z} = \tan(\phi)\sin(\theta) \ . \tag{5}$$

The usefulness of each antenna can be maximized by tilting it toward the interrogation region by an angle θ_0 about the z axis and ϕ_0 about the y axis. Then

$$\tan(\delta) = \frac{x\cos(\theta_0)\cos(\phi_0) + y\sin(\theta_0)\cos(\phi_0) - z\sin(\phi_0)}{x\cos(\theta_0)\sin(\phi_0) + y\sin(\theta_0)\sin(\phi_0) + z\cos(\phi_0)} \tag{6}$$

and

$$\tan(\varepsilon) = \frac{y\cos(\theta_0) - x\sin(\theta_0)}{x\cos(\theta_0)\sin(\phi_0) + y\sin(\theta_0)\sin(\phi_0) + z\cos(\phi_0)} \tag{7}$$

Figure 2 shows the calculated phase shifts along the x and y axes of the antenna necessary to interrogate a range of positions within the interrogation volume.

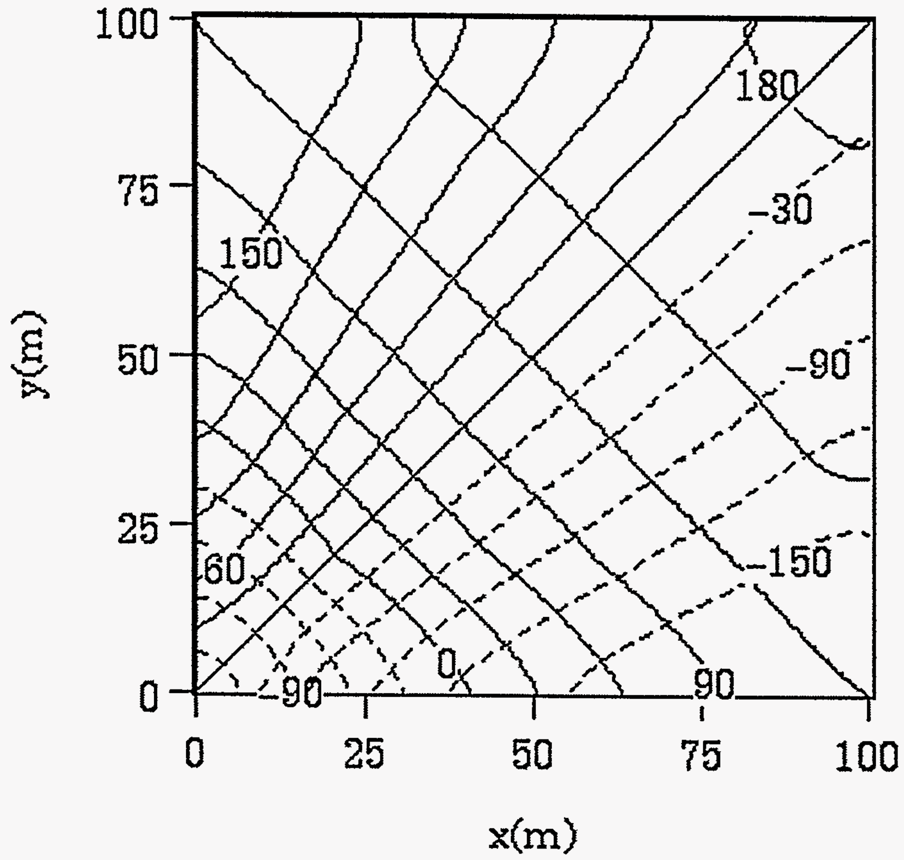

Figure 2. Phase shifts (deg) along the x (absissa) and y (ordinate) axes of the antenna array needed to produce a beam that intersects the z = 50 m horizontal plane at the specified values of x and y, assuming that the antenna is pointed into the interrogation volume at an angle of $30^{o}(\phi_0)$ from vertical and 45^{o} (θ_0) horizontal, as defined in Figure 1.

We are using time delays in the processing of the transducer signals to accomplish beam steering. Digital time delay techniques were examined; however, these methods were judged too costly and cumbersome to achieve the necessary dynamic range and time delay resolution. The time delays are accomplished by using so-called "bucket-brigade" (BB) devices for each element in the antenna array. These inexpensive devices transfer charge on each transition of a clock. Two 128-stage BB devices are used for each element: one each for transmit and receive delay. They are designed to achieve delays from 1.28ms to 2.78 ms which allows tilts of up to 45^{o}.

The primary limitation of the BB approach is a dynamic range of 80 dB. This is partially overcome with the use of log amplification for receive circuitry. The most cumbersome design element in the approach has been the supply of the necessary range of clock frequencies for control of the BB devices.

Overall operation of the system is as follows. A master computer system informs each antenna what azimuth and elevation angle is required for its beam. A microcontroller at each antenna controls an array of digital frequency synthesizer circuits to generate the proper clock frequency for each BB device. The microcontroller computes the necessary time delay required for each transducer and they are converted to clock frequencies that are generated by each frequency synthesizer. Each transducer has its a printed circuit board with receive preamplifier, BB device delay circuitry, filtering, and transmit amplifier circuit. In the receive mode, the signals from each transducer are summed at the antenna and sent to the master computer as a single high-level analog signal. The transmit carrier frequencies are generated at the master computer site for each antenna. The desired signal is sent to the appropriate antenna, where it is delayed by each independent BB device and amplified for driving each tweeter. Heterodyning and filtering are performed for each signal by using existing hardware with Argonne National Laboratory sodars.

PROGNOSIS

As of the writing of this paper, we are constructing a single antenna for proof of concept and design changes. Initial tests of the antenna are anticipated by late spring of 1996. If successful, two more antennae will follow rapidly. We hope to have the three-antennae system in operation before the end of the year. Initial testing of the single antenna should provide estimates of the largest possible size of the interrogation volume for the complete system. The full array of antennae is necessary to develop and test the control and analysis software for the overall system.

Initial deployment of the system outside of Argonne will be at the Argonne Boundary Layer Facility now being constructed near Wichita, Kansas, within the Atmospheric Radiation Measurement Program's Southern Great Plains Cloud and Radiation Testbed site. This facility will be studying the evolution and dynamics of the PBL and its interactions with underlying surfaces, moisture, and larger scale phenomena. The volume imaging sodar will be used to study the three-dimensional character of near-surface layers, thermal plume statistics and to provide validation and input data to large eddy simulation models.

ACKNOWLEDGMENT

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DISCLAIMER

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