NCAR Workshop on Multiple-Receiver and Multiple-Frequency Techniques for Wind Profiling

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Abstract

An informal workshop was held 7–8 November 1994 at the National Center for Atmospheric Research (NCAR) to discuss developments in clear-air wind profiling techniques. Two areas were emphasized: progress in spaced-antenna methods for wind profiling and frequency domain interferometry for improved range resolution of thin scattering layers. There were approximately 25 participants from 11 organizations. This paper summarizes the research and results reported at this workshop. Because of the technical nature of these results, the authors present them along with background information to provide a context for the strengths and weaknesses of the profiling techniques discussed.

Wind profilers using spaced-antenna methods can determine the three-dimensional wind from scattering by refractive turbulence from within a single pulse volume. They do not alternate through several beam directions to measure the radial wind and so have the potential to provide better temporal and spatial resolution than profilers using a Doppler beam swinging method of wind determination. This improved resolution relaxes the assumption of spatial and temporal uniformity and can lead to more accurate wind measurements in rapidly changing conditions. For example, in the boundary layer, vertical velocities can change quickly as thermal plumes advect over a profiler. A beam-swinging wind measurement could easily produce an incorrect result by combining radial velocities from a beam within such a plume with velocities seen in a different beam outside this plume. Spaced-antenna measurement avoids this error since only a single pulse volume is used; however, it remains to be determined what effects vertical velocity inhomogeneities within the pulse volume have on the spaced-antenna method. Recent theoretical analysis presented at the workshop has suggested new methods for measuring wind speed and direction from the correlation of clear-air signals received at spaced antennas. These methods are more easily implemented than the common approach to spaced-antenna wind profiling—full correlation analysis—and they minimize the uncertainties of decorrelation due to turbulence. The development of a spaced-antenna wind profiler at NCAR was also discussed as well as first results of applying new spaced-antenna techniques to data collected with this instrument.

The technique of frequency domain interferometry makes use of two or more radar carrier frequencies to determine whether localization of scattering in range occurs within the radar pulse volume. If energy is primarily scattered from a single layer that is thinner than the pulse volume, frequency domain interferometry can estimate its range and thickness, but if scattering is uniform throughout the volume, then the multiple-frequency result is identical to that of a single-frequency measurement. When a single, thin scattering layer is present, the increased range resolution made possible with this technique can be used to investigate atmospheric waves and their generating mechanisms. Recent measurements and enhancements to this technique were discussed at the workshop.

Other research reported at the workshop includes the application of spaced-antenna analysis to radio acoustic sounding system signals, new insight into the full correlation analysis technique of spaced-antenna processing, and simultaneous use of spaced-antenna and frequency domain interferometry data collection.

1. Introduction

In recent years, a growing number of "clear air" wind profilers have been used to remotely sense winds in the troposphere and lower stratosphere. These profilers operate at 0.33- to 6.0-m wavelengths and use gradients in atmospheric refractive index to scatter energy back to the receiver. They are distinct from weather radars, which typically operate at shorter wavelengths (0.03 to 0.1 m), scan at low elevation angles, and usually use hydrometeor scatterers. Wind profilers have proven invaluable to both operational meteorology and research programs (e.g., Smith and Benjamin 1993; Parsons et al. 1994). They can operate unattended for long periods and typically provide wind profiles every 30 or 60 min. Their altitude coverage, frequency of measurements, and ability to provide data in remote parts of the globe complement other data sources such as balloon soundings, aircraft, and towers.

The majority of wind profilers measure the line-of-sight component of wind along several beam-pointing directions and combine this information into a vertical profile of the vector wind. This is known as the Doppler beam swinging (DBS) method. Although

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DBS is a useful tool for studying the wind field aloft, it does have some limitations. DBS wind profilers must have a steerable beam and generally collect data in the vertical direction and either two or four oblique directions. With increasing altitude, the distance between the sampling volumes of different beam directions becomes significant. This consideration is important since a uniform horizontal and vertical wind is assumed over the horizontal extent of the measurements. Furthermore, one must assume that the wind does not vary during the time that the wind profiler is cycling between the different beam directions—usually several minutes. Both of these assumptions are often violated in the atmospheric boundary layer.

Alternative techniques to DBS can overcome some of these limitations. Recent developments in both the theory and equipment for two such alternatives, spaced-antenna (SA) techniques and frequency domain interferometry (FDI), prompted the National Center for Atmospheric Research (NCAR) to hold a workshop in Boulder, Colorado, on 7–8 November 1994. Discussions focused on these two topics, which have the potential of providing accurate winds with higher spatial and temporal resolution than those found by DBS.

2. Spaced-antenna wind profiling

Unlike DBS, SA techniques use a single vertically directed transmitter beam, and backscattered energy from the atmosphere is received using several spatially separated receiving antennas. Information about the vector wind is available through the cross correlation of signals received at the different antennas. A variety of SA analysis techniques have been used in the past for estimating the vector wind from backscatter within a single resolution volume (Larsen and Röttger 1989). Without the need to cycle between three or more beam-pointing directions as in the DBS method, more frequent wind estimates are possible, and a horizontally uniform wind is required over a much smaller volume.

To infer winds, spaced-antenna systems calculate the motion of the diffraction pattern at the surface associated with atmospheric scatterers in the resolution volume. If the scatterers are frozen, the diffraction pattern is advected with a velocity nearly equal to twice the horizontal wind in that volume. By observing the maximum value of the cross correlation of signals at several pairs of receivers, the wind can be estimated using the time lag to that maximum. However, decorrelation of the received signals caused by the relative motion of the scatterers, for example by turbulent eddies, causes an error that can lead to an overestimated wind speed. This is particularly true in regions of light winds and strong turbulence, such as in the atmospheric boundary layer. Therefore, such wind estimates have been given the name "apparent wind." The technique of full correlation analysis (FCA) allows for spatial and temporal variation in the diffraction pattern, and the wind found is called the "true wind." FCA has been widely used in ionospheric measurements and has been used in the troposphere with some success (e.g., Briggs and Vincent 1992). However, it relies on estimates of features of the correlation functions that are sensitive to turbulence and it can underestimate the wind speed. Confidence in the technique has been limited by issues such as the "triangle size effect," whereby the estimated wind speed varies with receiver spacing. However, these issues have recently been addressed by Holdsworth and Reid (1995), whose model appears to explain this effect based on receiver noise.

An alternate method of processing spaced-antenna signals obtained with phase coherent radars is spatial interferometry (SI). Instead of using the time lag between separate antennas, the phase difference is incorporated into the calculations. Sheppard and Larsen (1992) have shown that spatial interferometry is the Fourier transform equivalent of spaced-antenna correlation analysis. A method to correct for turbulent and spatial decorrelation when using SI has been proposed and is called full spectral analysis (FSA). FSA is likewise the Fourier transform equivalent of FCA and, thus, has similar advantages and suffers from the same limitations as FCA.

3. Recent theoretical analysis for spaced antennas

A generalized theoretical analysis of spaced antenna signals was presented at the workshop and is thoroughly described by Doviak et al. (1994). They derive the expected diffraction pattern found at each receiver of a spaced-antenna wind profiler based on statistical properties of a vertically anisotropic refractive index field advected by a mean wind and isotropic turbulence. The diffraction pattern is then related to the cross correlation (or cross-spectrum) of signals at each receiver pair. The formulation leads to new insights into properties of the cross-correlation function, the most important of which is that several features of the auto- and cross-correlation functions are unaffected by the intensity of turbulence. Figure 1 shows the theoretical form of these functions for three levels of turbulence. In this figure turbulent strength is represented by σ_t, the standard deviation of any linear velocity component of the isotropic turbulent field. Note that the autocorrelation function at zero lag has a contribution from noise, that the autocorrelation is normalized by its value at zero lag, and that the cross-correlation amplitude is normalized by the same value. In generating this figure, it was assumed that the wind is directed along a line joining the two receivers. For a case with no turbulence (thick curve, $\sigma_t = 0$ m s^{-1}), the diffraction pattern is "frozen" as it advects. The peak of the cross-correlation function has the same amplitude as the autocorrelation, but this peak is shifted to a time lag τ_p related to advection of this "frozen" pattern. Thus, the two receivers measure identical time series with an offset τ_p in time. As turbulence is added (thin and dashed curves), repositioning of the scatterers by turbulent eddies changes the diffraction pattern and reduces its correlation with time. The autocorrelation function narrows, and the cross-correlation function both narrows and is reduced in amplitude. In addition, the peak of the cross-correlation function moves to smaller lags. From this it is clear why methods that assume a frozen diffraction pattern will overestimate the wind. Turbulence moves the observed peak of the cross correlation to a shorter lag, just as if the wind were more quickly advecting the diffraction pattern over the second receiver.

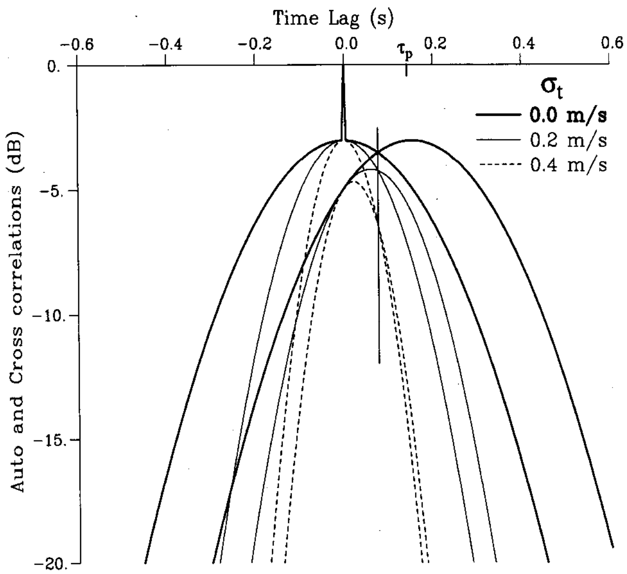

FIG. 1. Theoretical autocorrelation (centered at zero time lag) and cross-correlation functions for the parameters of the NCAR profiler and a wind of 3 m s^{-1} along the receiver pair baseline. The heavy curve is in the absence of turbulence, and the thin and dashed curves show the effects of increasing turbulence. A vertical line indicates the lag of intersection of the two functions, which is independent of turbulent strength (adapted from Doviak et al. 1994).

Closer examination of Fig. 1 shows that some properties are independent of the strength of turbulence. In particular, the lag at which the auto- and cross-correlation functions intersect (marked with a vertical line) is unchanged, as is the slope of the cross correlation at zero time lag. Although these features are independent of turbulent strength, they vary with the mean wind, and using the Doviak et al. development, they can be related to the wind component along a line joining the two receivers. This provides two ways to measure the wind without concern for turbulent decorrelation. In fact, the slope at zero lag is already in use for optical wind profiling (Lataitis et al. 1995). A third time domain method also can be found from the Doviak et al. formulation. It is shown that the logarithm of the ratio of cross correlation to autocorrelation as a function of lag is linearly related to the wind component along the receiver baseline. To use each of these three methods, the antenna characteristics must be well known, and then it is only necessary to estimate features of the correlation functions—effects of the turbulent eddies are irrelevant.

One other result of the Doviak et al. analysis is a frequency domain method that considers the effect of turbulence on the phase of the cross-spectrum. This method requires estimation of the Doppler spectral width (a function of turbulent strength and other effects) using signals from individual receivers. While this spectral domain method is not independent of turbulent strength as are the three time domain methods, if the spectral width can be reliably estimated, it should give a wind estimate comparable to FSA. It should be noted, however, that Doppler measurements of spectral width are relatively poor compared to radial velocity measurements.

Thus, four recently developed methods for spaced-antenna wind profiling were presented at the workshop: three in the time domain and one in spectral space.

4. First results from new SA wind estimation algorithms

A summary of the recent construction of a spaced-antenna 0.33-m-wavelength wind profiler at NCAR was presented. This profiler is intended to provide boundary-layer flux measurements as part of the Atmospheric Radiation Measurement program of the Department of Energy. It is also a capable vehicle for testing the four new wind measurement methods. The NCAR Multiple Antenna Profiling Radar is a modified version of the commercially available Radian LAP-3000 915 MHz boundary-layer profiler. Modifications allow the radar to be operated using the full antenna (a 2-m by 2-m patch array) to transmit and to receive back-scattered energy independently with each quarter of this antenna. Thus, it has four (1 m by 1 m) receiving antennas and six antenna-pair baselines. The profiler design is described in Van Baelen (1995). The digitized complex time series from each receiver (after coherent integration) is recorded and used in the computation of the correlation functions or spectra. The profiler can also be operated in a 5-beam DBS mode, giving an independent estimate of wind by a more conventional technique. The dual-operating mode and flexibility of this instrument make it a powerful tool for investigating wind profiler signal analysis strategies, including the spaced-antenna methods discussed above.

The results of a first attempt at implementing each of the Doviak et al. methods was presented at the workshop. Calculation of the wind depends on characteristics of the correlation functions or spectra, and also on antenna characteristics; the radiation pattern of the transmitter and each receiving antenna, and the spacing of the antennas, must be accurately known. There are many ways to estimate properties of the computed correlation functions. For preliminary implementation of the techniques, Gaussian functions were fitted to the data, and from these functions the required features were found. Figure 2 shows wind speed and direction measured with the NCAR SA profiler during an experiment in Lamont, Oklahoma. The results using two of the new methods are plotted along with winds from a nearby balloon sounding. Method SA-1 uses the slope at zero lag, and SA-2 uses the lag at the intersection of the autocorrelation and cross correlation to measure horizontal wind. The radar-derived wind profiles are from less than 1 min of data collection and have 100-m vertical resolution. At the time of the radar measurement the balloon sounding was at an altitude of approximately 1.5 km. The figure shows reasonable agreement between the radar- and balloon-estimated winds, with the greatest differences below 1 km and near 2 km likely due to ground clutter. The processing techniques have not been optimized to remove ground clutter, low signal-to-noise measurements, or other outliers. Differences may also be due to the natural variability of the atmosphere. Much testing remains to evaluate each of the methods, but from initial results, it appears the Doviak et al. spaced-antenna techniques can be used to produce accurate winds with good time resolution.

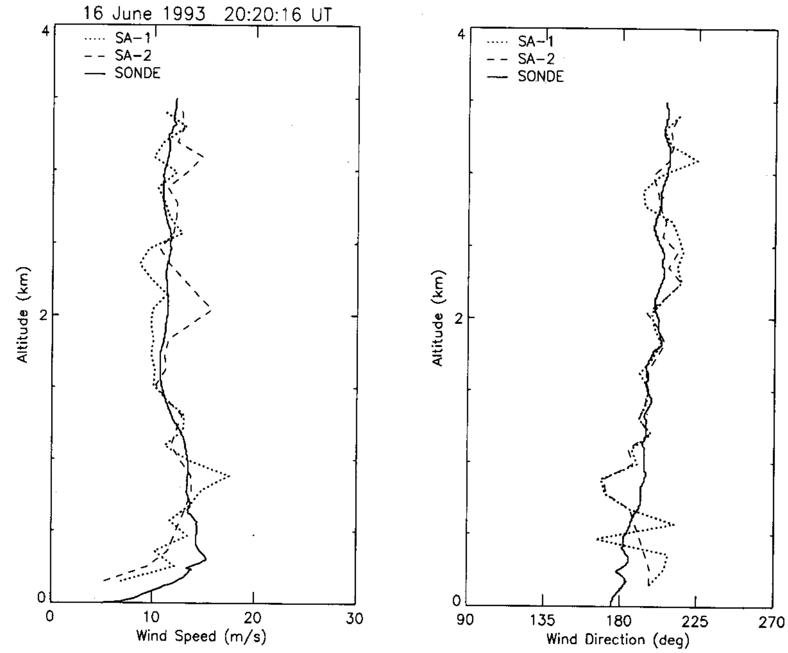

Fig. 2. Sample wind profiles (dotted and dashed) made with two new techniques using the NCAR profiler, compared with a balloon sounding (solid). A small rotational correction was applied to the SA wind directions, compensating for a suspected misalignment of the radar antenna.

5. More encouraging SA results

Also reported at the workshop were SA results (using the FCA technique) from an FMCW–radar–RASS system at the University of Hamburg (Hirsch 1994). While most wind profilers use naturally occurring variations of the atmosphere's refractive index as a scattering mechanism, the Hamburg profiler uses refractive index disturbances generated artificially with sound waves (radio acoustic sounding system, RASS). These disturbances are tracked using an FMCW (frequency modulated continuous wave) radar operating at a mean frequency of 1.235 GHz. Using acoustic refractive index perturbations as tracers overcomes the problem of ground clutter since the Doppler velocity of the RASS signals are nearly 300 m s^{-1}. The radar frequency is modulated using a ramp generator, and range and velocity information can be obtained by comparing the phase shifts between the transmitted and received signals (Strauch 1976). FMCW radars offer range resolution as fine as a few meters and time resolution of just a few seconds (Eaton et al. 1995).

During August 1993, the University of Hamburg wind profiler was operated in northern Germany in an SA mode. A SODAR (an acoustic radar) also made wind estimates during the experiment for comparison. The wind profiler has only two spatially separated antennas, and the baseline of the antennas must be aligned parallel to the direction of the horizontal wind in order to estimate the wind magnitude and not just a component. In addition to comparison with the SODAR, the FMCW radar was sometimes operated in a DBS mode for further comparison with SA-estimated winds. Good agreement was found between all three methods. During the comparison measurements, SA estimates of the winds were averaged over 2 min, which was the minimum sampling time for the SODAR measurements. Figure 3 shows an example of wind estimates obtained while the wind profiler operated at its highest sampling rate. Some points have been removed by data rejection techniques. Note that the temporal resolution of the data is about 1 s and that the range resolution is 50 m. If shown to be accurate, velocity measurements with such resolution provide an excellent research opportunity for turbulence studies.

6. Frequency domain interferometry

Frequency domain interferometry employs two or more radar carrier signals to enhance the range resolution of wind profilers. This technique provides a means of increasing the range resolution of clear-air measurements whenever a scattering layer is localized rather than distributed throughout the radar pulse volume. The vertical extent of the scattering layer can be several meters to hundreds of meters, while the range resolution of typical wind profilers is 100 to 300 m. The increased range resolution made possible with FDI is necessary when investigating finescale structures or small-amplitude wave motions of the atmosphere. Examples of such processes include internal gravity waves, Brunt–Väisälä oscillations, shear instabilities, and mountain-generated lee waves.

Using FDI, the wind profiler alternates between closely spaced carrier frequencies while sampling a given volume of space. A cross-correlation or cross-spectral analysis is conducted on the resulting time series data recorded at each pair of frequencies. The location z_l and width $2\sigma_l$ of a localized scattering region can be estimated through the phase and magnitude of the complex correlation coefficient (correlation analysis) or coherence spectrum (spectral analysis). Typically, it is assumed that the layer is horizontal and consists of scatterers having a vertical distribution given by a Gaussian function. If no scattering layer is present within the scattering volume or a layer is present but its vertical extent is large, there will be little coherence between the two frequencies. But if most scatter comes from a single layer thinner than the sampling volume, then the coherence and phase values provide the location and width of the scattering layer (Franke 1990). For a frequency separation properly chosen to match the range resolution of the radar, the phase obtained from the cross-correlation (cross spectral) analysis will map into a location within the sampling volume, allowing the height of the scattering layer to be determined with a resolution greater than would have been possible using only one frequency. So far the technique of FDI has been implemented at only a few wind profiling sites around the world. During the workshop it was reported that FDI measurements have been made at the SOUSY (Sounding System) very high frequency radar in Germany, and first results were presented.

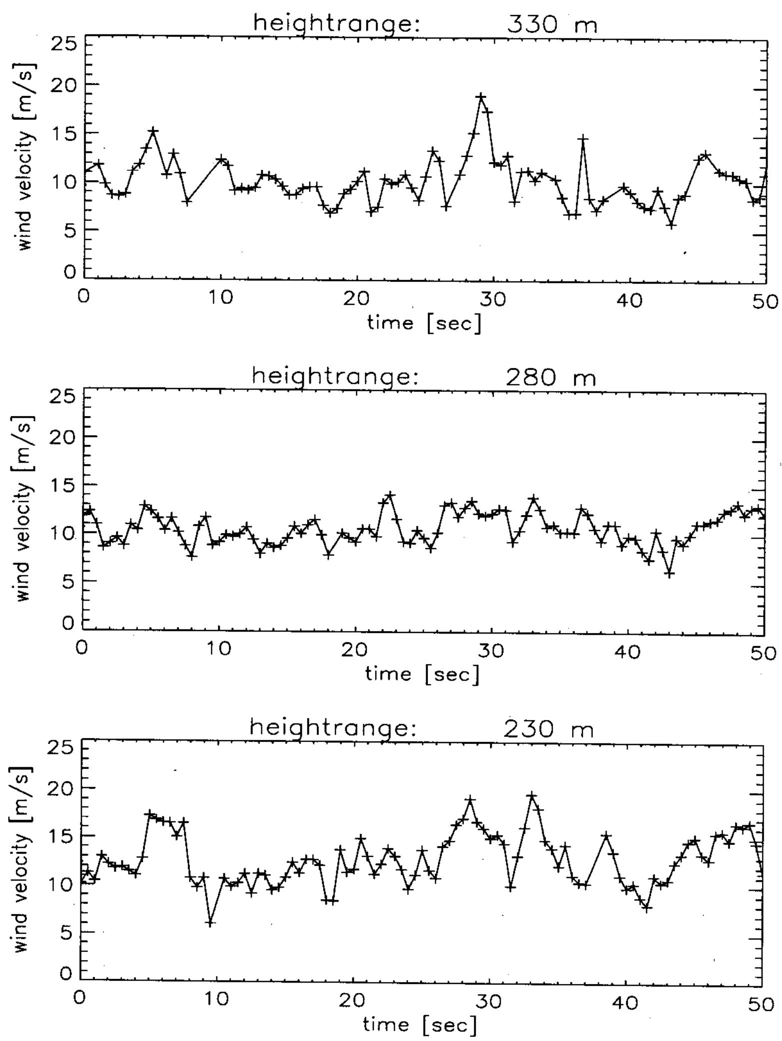

Fig. 3. Time series of winds measured with the University of Hamburg FMCW–radar–RASS. The three plots show 1-s time resolution and 50-m altitude resolution (courtesy of L. Hirsch and G. Peters.)

Figure 4 shows plots of the echo intensity made with the SOUSY radar while the beam was oriented vertically. The intensity of the signal returned from the atmosphere is given as signal-to-noise ratio (SNR) expressed in decibels. In the upper panel, SNR values are shown using a standard height–time-intensity plot, with the calculated SNR value for each height used to color code its corresponding height interval for a given time. Well-defined descending layers are evident below 8 km, possibly indicating subsidence resulting from the passage of a high pressure system over the radar site. Though not as distinct, a layer of enhanced reflectivity can also be seen between 13 and 14 km throughout the observation period. Sounding data taken 90 km northwest of the radar show that this layer approximately matches the altitude of the tropopause, seen at 12.5 km at 1100 LT and 13.5 km at 2300 LT.

The lower panel shows the same data, but the plot has been adapted to include information obtained from FDI. For each range increment, only the region between $z_I \pm \sigma_I$ has been color coded with the SNR value. If no distinct layer is detected, that is, if σ_I is greater than the range resolution of 300 m, then the entire range interval is shaded (this is the same as the standard plot). Note that the lower panel shows the same features as the conventional plot, but the layer structures (location and thickness) can now be easily identified. It is interesting to note that small amplitude oscillations in the layer structures can be identified in the lower panel (around 4 km) that are not apparent in the conventional height–time-intensity plot.

7. Combined SA and dual-frequency analysis

Research currently being conducted at the University of Nebraska was also reported at the workshop. This work is focusing attention on the possible combined use of multireceiver and multifrequency techniques. Such measurements would provide wind profiles with increased angular and range resolution. In the summer of 1994, an experiment was conducted at the middle and upper atmosphere radar in Shigaraki, Japan, using multiple receivers, frequencies, and beams. Analysis of these data is presently underway in an attempt to simultaneously implement FDI, DBS, and a technique called imaging Doppler interferometry. At present, it seems promising that wind profiles with spatial resolution better than that of the pulse volume will be possible.

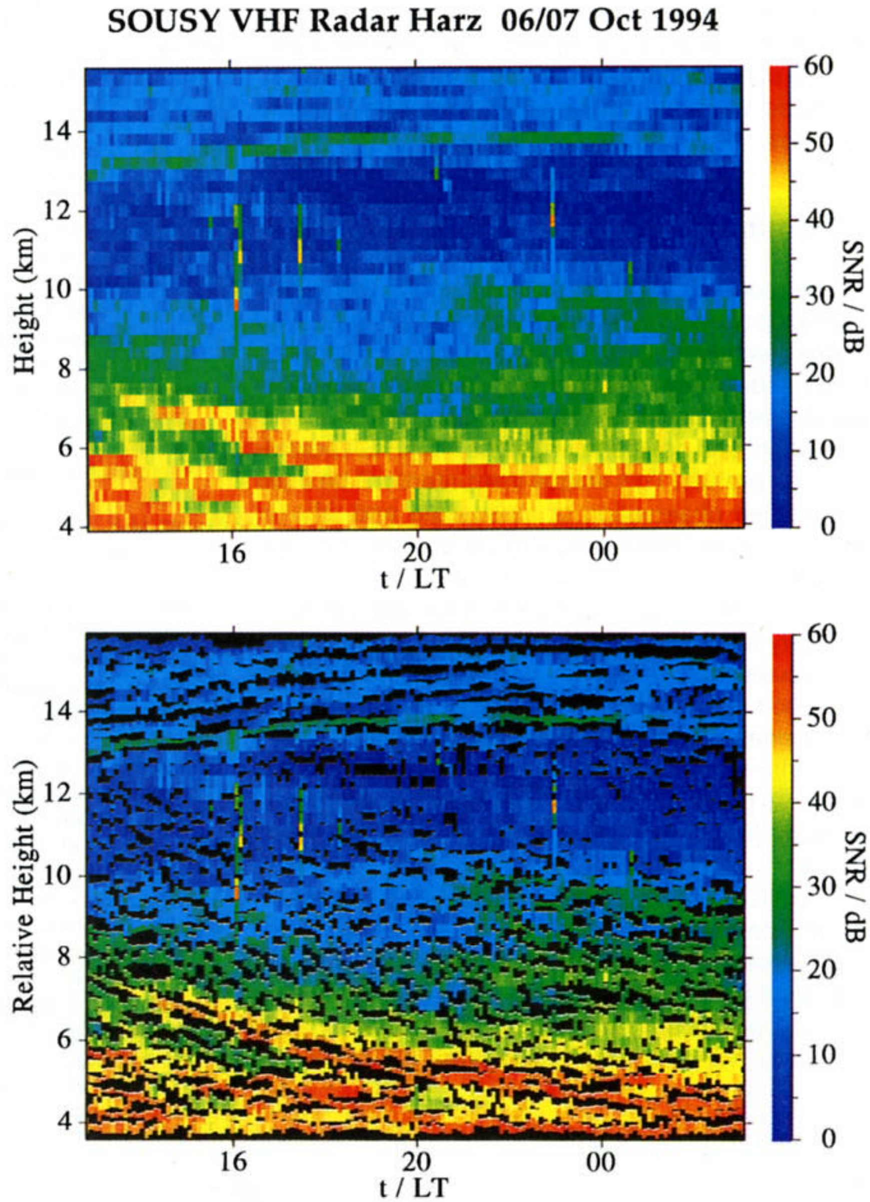

FIG. 4. Height–time-intensity plot for the vertical beam of the SOUSY radar, using the standard display (upper) and a display taking advantage of FDI to improve resolution of thin scattering layers.

Other multireceiver research being conducted at the University of Nebraska in collaboration with Clemson University and Cornell University is the implementation of a spectral domain technique called spatial interferometry at the Arecibo Observatory in Puerto Rico. The radar system at Arecibo is one of the largest in the world, having an effective aperture of 200–300 m. Although the radar is very powerful, its sheer size produces mechanical difficulties when steering the beam. A complete azimuthal scan requires up to 30 min. In the near future, three sets of spaced receivers will be installed in close proximity to the radar dish and used in conjunction with the existing UHF radar system. Since steering of the beam is not required for these wind measurements, temporal resolution should be greatly improved. Another useful feature of the system is that wind measurements can be made whenever other UHF experiments are in progress.

8. Summary

The research in progress presented at the NCAR workshop shows that spaced-antenna and frequency domain techniques are rapidly developing. Interest in SA measurements has been generated by theoretical developments, improved understanding of FCA implementation, and development of the NCAR SA boundary layer profiler. This unique instrument will be used for detailed observation of mesoscale and smaller events and for measuring vertical profiles of turbulence and fluxes. Spaced-antenna wind profilers have the potential to significantly enhance our ability to remotely observe the atmosphere.

Discussion of frequency domain methods at the workshop showed a growing interest in the value of these measurements for the study of stratified layers and other refractive index discontinuities. This technique will provide detailed observation of inversions, airmass (frontal) boundaries, and turbulent shear layers.

The NCAR workshop was first planned as a meeting of interested researchers in the Boulder, Colorado, area. Its spontaneous expansion to include scientists from distant facilities in the United States and Europe is a sign of the current level of interest in new radar wind-profiling techniques. We hope that this summary has conveyed the rapid development of and optimistic expectations for these clear-air profiling techniques.

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References

Briggs, B. H., and R. A. Vincent, 1992: Spaced-antenna analysis in the frequency domain. *Radio Sci.,* **27,** 117–129.

Doviak, R. J., R. J. Lataitis, C. L. Holloway, and J. Van Baelen, 1994: A generalized theoretical analysis of cross-correlation and cross-spectra for spaced-antenna wind profilers. NCAR Tech. Note NCAR/TN-407+STR, 105 pp.

Eaton, F. D., S. A. McLaughlin, and J. R. Hines, 1995: A new FW–CW radar for studying planetary layer morphology. *Radio Sci.,* **30,** 75–88.

Franke, S. J., 1990: Pulse compression and frequency domain interferometry with a frequency-hopped MST radar. *Radio Sci.,* **25,** 565–574.

Hirsch, L., 1994: Estimations of the horizontal wind velocity by spaced-antenna-drift measurements in the time domain using a FMCW-radar-rass. *Proc. Third Int. Symp. on Tropospheric Profiling: Needs and Technologies,* Hamburg, Germany, Max-Planck-Gesellschaft zur Förderung der Wissenschaften, 303–305.

Holdsworth, D. A., and I. M. Reid, 1995: Spaced antenna analysis of atmospheric backscatter model data. *Radio Sci.,* **30,** 1417–1433.

Larsen, M. F., and J. Röttger, 1989: The spaced antenna technique for radar wind profiling. *J. Atmos. Oceanic Technol.,* **6,** 920–938.

Lataitis, R. J., S. F. Clifford, and C. L. Holloway, 1995: An alternative method for inferring winds from spaced-antenna radar measurements. *Radio Sci.,* **30,** 463–474.

Parsons, D., and Coauthors, 1994: The integrated sounding system: Description and preliminary observations from TOGA COARE. *Bull. Amer. Meteor. Soc.,* **75,** 553–567.

Sheppard, E. L., and M. F. Larsen, 1992: Analysis of model simulations of spaced antenna/radar interferometry measurements. *Radio Sci.,* **27,** 759–768.

Smith, T. L., and S. G. Benjamin, 1993: Impact of network wind profiler data on a 3-h data assimilation system. *Bull. Amer. Meteor. Soc.,* **74,** 801–807.

Strauch, R. G., 1976: Theory and application of the FM–CW Doppler radar. Ph.D. dissertation, University of Colorado, Boulder, 97 pp.

Van Baelen, J. S., 1995: A UHF boundary layer Doppler/interferometric profiler: Comparison of hourly wind measurements in the Doppler beam swinging and the multiple receiver modes. *Radio Sci.,* in press.