Improved Radio Acoustic Sounding Techniques

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ABSTRACT

Improved radio acoustic sounding system (RASS) technology for use with radar wind profilers has been developed and applied to 915-MHz and 50-MHz profilers. The most important advance is the simultaneous measurement of the wind velocity to correct the acoustic velocity measurement for air motion. This eliminates the primary source of error in previous RASS measurements, especially on short time scales. Another improvement is the use of an acoustic source that is controlled by the same computer that controls the radar. The source can be programmed to produce either a swept frequency or a random hopped frequency signal. Optimum choices of the acoustic source parameters are explored for particular applications. Simultaneous measurement of acoustic and wind velocity enables the calculation of heat flux by eddy correlation. Preliminary heat flux measurements are presented and discussed. Results of the use of RASS with oblique beams are also reported.

1. Introduction

In the last few years, a number of wind-profiling Doppler radars have been used as radio acoustic sounding systems (RASS) to measure vertical profiles of temperature in addition to standard wind profiles (Matuura et al. 1986; May et al. 1988; May et al. 1990). In RASS, acoustic sources are located near the radar antenna, and the radar measures the speed at which the acoustic disturbance propagates. The virtual temperature T_v can be determined (to a good approximation) in each profiler range gate from the measured speed of sound C_a and the measured vertical wind speed w:

$$T_v\,(^\circ\mathrm{C}) = \frac{(C_a - w)^2}{401.92} - 273.16. \qquad (1)$$

The RASS idea dates back to at least the early 1970s (Marshall et al. 1972; North et al. 1973) but practical application awaited the increased sensitivity of wind profiling radars.

Due to data processing limitations, wind profilers used for RASS in past work have used a receiver frequency offset to shift the response at the speed of sound to near-zero frequency (May et al. 1990). Such systems then compute the speed of sound with a 64- or 128-point fast Fourier transform (FFT), and correct for the receiver offset. We use the larger memory and greater speed of current digital signal processors to carry out a 2048-point FFT over a frequency range that covers both the speed of sound and the wind speed, and, therefore, measure both simultaneously. The accuracy of the temperature measurement is significantly improved.

Various schemes have been used to produce and transmit the acoustic signal. Most of these have limited flexibility. We have devised a system using a digital signal processor to produce the acoustic signal. The signal is controlled by the radar control program. We have also carried out a series of experiments to determine what type of excitation and what parameters are most effective for a given application.

Most previous RASS work has used the vertical beam of the wind profiler. There are advantages to the use of the oblique beams as well, particularly in an operational system. We have explored the advantages and limitations of taking RASS measurements on the oblique beams.

RASS incorporating these improvements (except the use of oblique beams) have been deployed by the Aeronomy Laboratory and Wave Propagation Laboratory (WPL) for field programs since January 1991.

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The programs include the Department of Energy Atmospheric Radiation Measurement Program (ARM), Winter Icing and Storms Project (WISP), the Front Range Air Quality Study, and the San Joaquin Valley Experiment. The profiler control system is also in use on the WPL 50-MHz research profiler at Platteville, Colorado. In addition, several short-term experiments have been carried out, and a 915-MHz system has been operated nearly continuously at Platteville through the summer and fall of 1991.

2. Simultaneous correction for wind

The largest source of error in previous RASS measurements is the neglect of the wind velocity along the beam. If the measurement is made with a vertically pointing radar beam, it may be reasonable to assume that the wind velocity averages to zero over a sufficiently long time. In the planetary boundary layer or in mountain wave conditions, this assumption is not valid. One may also want to make measurements on time scales less than the hour or so required to average out vertical motions even in conditions with little vertical motion, or one may wish to make the measurement on a beam that does not point vertically. In all these cases, a simultaneous measurement of the wind velocity and the acoustic velocity is useful. Other alternatives include making alternating measurements of the acoustic and wind velocities or using wind measurements that bracket the time period during which the acoustic measurement is made. The results below show that simultaneous correction gives better measurements than any of the alternatives.

Currently available digital signal processors (DSP) have sufficient memory and speed to allow us to compute 2048-point FFTs that encompass both the wind speed and the speed of sound. Because of the large number of points in the spectrum, full resolution is retained in the portions of the spectrum containing the signals. The NOAA (National Oceanic and Atmospheric Administration) Aeronomy Laboratory's profilers are controlled by an IBM-compatible personal computer (PC), and the DSP is located on a board that plugs into the computer. The board we currently use has enough memory for 2048-point spectra at up to 14 heights. The computation time is not a limiting factor in taking measurements with normal time resolution. For example, on the 915-MHz profiler, the radar integrates samples for about 0.5 s for each set of spectra. The computation of the spectra for all heights takes about 0.5 s. After a number of spectra have been averaged, the moments are calculated in about 3 s. A full measurement with 14 heights and 50 spectral averages can be taken in less than 1 min. With longer wavelength profilers, the data acquisition time increases while the calculation time remains fixed. Sampling time limitations and optimum choices are discussed further in the section on the acoustic source below.

Figure 1 shows three plots of a spectrum obtained for a single run using this technique with a 915-MHz profiler. The plots are taken from the profiler on-line display. The top panel shows the entire 2048-point spectrum at six heights spaced 100 m apart. Each displayed spectrum is an average of 20 spectra obtained over a period of about 20 s. The peaks at the left side of the spectra correspond to Doppler shifts at the speed of sound due to radar returns from the acoustic disturbance, and the peaks near zero correspond to the clear-air return that gives the vertical wind speed. The lower left panel is an expanded view centered roughly on the mean acoustic velocity. The expanded spectra show the range of Doppler velocity from −350 to −338 m s^{-1}. The lower right panel is centered on zero velocity and also shows a 12 m s^{-1} range. In all three views, the small crosses indicate the computed means of the signal distributions. The two expanded views can be directly compared. Note also that the plots show radial velocity ($-C_a$ and $-w$).

In the lower left panel, the spectral peaks show a decreasing speed with height, which indicates that the temperature also decreases with height [Eq. (1)]. However, the vertical wind speed also becomes more downward with height. We can see qualitatively that part, but not all, of the decrease in apparent sound speed with height is due to the vertical wind.

a. 915-MHz profiler

The simultaneous correction technique has primarily been used on NOAA boundary-layer profilers. Details of the profiler are presented by Ecklund et al. (1988), so we give only a brief description here. Table 1 shows key system parameters.

A set of data from a boundary-layer profiler at the Boulder Atmospheric Observatory tower illustrates the advantages of the simultaneous correction technique. The site is near Erie, Colorado, on a rounded ridge in rolling cropland, 1580 m above sea level and roughly 30 km east of the Rocky Mountains. The dataset covers 30 min around noon on 7 September 1990.

Figure 2 shows the arrangement of the vertically directed profiler antenna and the four acoustic horns used in these tests. The profiler antenna is enclosed in a shield to reduce the effects of ground clutter. The acoustic drivers are offset feedhorns with apertures of about 0.7 m and are placed about 2 m from the center of the antenna. All four horns are continuously driven. Details of the acoustic excitation are given below.

Figure 3 is a time series of observations at three heights. The data were taken at 26-s resolution. The time series were individually smoothed with a three-point moving average in order to improve the visual presentation. There are several interesting features in this plot. The air is sinking slowly most of the time, with occasional periods of rising air (e.g., around 1152, 1201, and 1207 MDT). There is a classic thermal

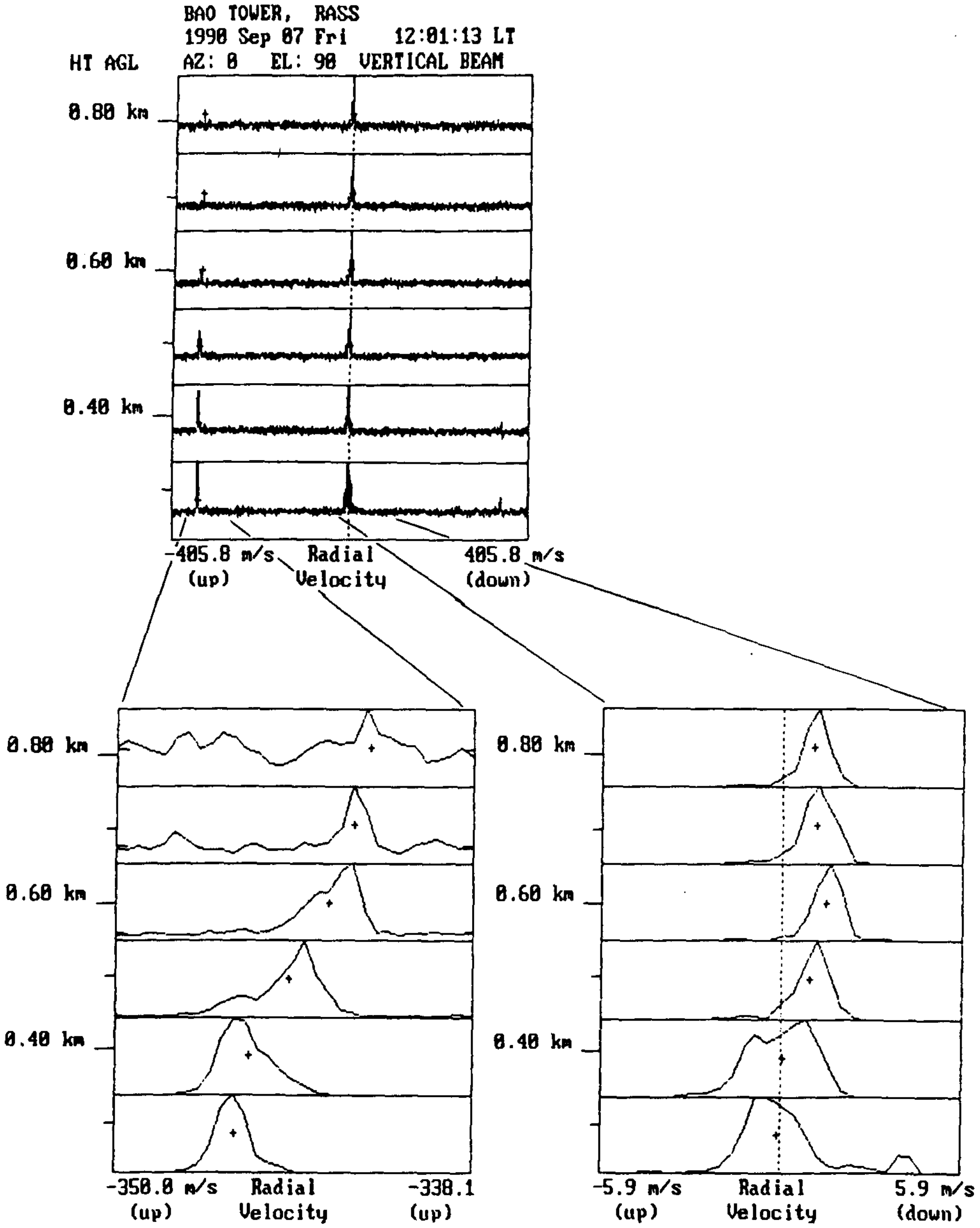

FIG. 1. Spectra from RASS measurement. Top: Full spectrum of 2048 points, ±406 m s^{-1}. Bottom left: Expanded view of acoustic echo. Bottom right: Expanded view of clear-air vertical wind echo.

plume signature at 1159–1202 where the temperature rise and rising air show up slightly earlier at each higher range gate (Priestley 1959, p. 70).

The rising air is associated with higher temperatures. Note that the acoustic velocity and the vertical wind track closely, and temperature changes are associated with small differences in their difference. This illustrates the importance of the simultaneous vertical wind measurement and correction. Without the correction, the apparent temperature fluctuations would be much larger. This can be seen especially clearly in the latter part of the plot, where there are large fluctuations in the vertical wind and the acoustic velocity that are not associated with actual temperature changes. If the vertical wind correction had been done not on the basis of simultaneous measurements but with measurements spaced in time even as much as 30 s, much of the detail of the thermal plumes would be lost. In fact, the results might be significantly in error if the vertical wind and acoustic velocity measurements were taken during dif-

TABLE 1. Boundary-layer profiler–RASS parameters.

Frequency	915 MHz
Peak power	500 W
Antenna	Microstrip array
Beamwidth	9°
Acoustic frequency	2000 Hz (nominal)
Acoustic power	30 W

ferent conditions—for example, during and after a thermal episode. Simultaneous vertical wind and acoustic velocity measurements are clearly necessary if we wish to resolve thermal features in the convective boundary layer or make other measurements requiring time resolution of the order of minutes or less.

Given these arguments, we can quantify the differences between various methods of computing the temperature.

Four different methods of calculating the temperature were examined using this data. The first method was to neglect the wind velocity entirely [assume $w = 0$ in (1)]. The second method divided the 30 min of data into 10-min segments. The temperature was computed using the average wind velocity from the first and third segments to correct the acoustic velocity measured during the middle segment. The third method used alternating measurements. Two temperatures were computed from this method, one using even-numbered acoustic and odd-numbered wind measurements, the other using odd-numbered acoustic and even-numbered wind measurements. Finally, the fourth method used simultaneous correction. The value of the vertical wind velocity was subtracted from the value of the acoustic velocity to give a corrected value at each time point. The corrected values were then averaged. No quality control was applied to the data in any method.

Table 2 summarizes the results for the range gate at 335 m. Here, Tw0 is the result from the first method, neglecting the wind velocity; Tbrac was computed by the second method, using the wind velocity from the first and last 10 min of the dataset to correct the acoustic velocity measured during the middle 10 min. The results from the third method, Teo and Toe, were computed using even-numbered wind and odd-numbered acoustic measurements (Teo) or odd-numbered wind and even-numbered acoustic measurements (Toe); Tsc is the simultaneous correction result.

During the time covered by these data, the mean wind velocity was significantly downward (-0.76 m s^{-1} at 335 m). Neglecting the wind velocity makes Tw0 substantially lower than Tsc. Method two, using bracketing measurements, also differs substantially because the wind velocity was more downward during the first and third segments than during the middle segment.

Method three, using alternating measurements, gives results that are much closer to the individual correction result. This is as we would expect, since only the smallest measurable scales are neglected in this method. However, it is interesting to note that computing the temperature using even-numbered or odd-numbered measurements of both the wind and acoustic velocity (not shown) gives much smaller differences (0.02° and −0.01°C, respectively) from Tsc.

b. 50-MHz profiler

A profiler control system incorporating the improvements described in this paper is also in use with the 50-MHz profiler radar operated by WPL at their Platteville, Colorado, site. In June 1991, this system was operated as a RASS continuously for several hours. Figure 4 shows the time series of measurements at two heights over about 30 min. Note that the time scale is reversed. This figure is similar to Fig. 3 except that the activity at 4823 m appears to be in the form of waves rather than thermals. As in Fig. 3, the vertical wind fluctuations are clearly significant and highly correlated to the acoustic velocity fluctuations.

c. Limitations

The simultaneous correction technique has one drawback. It will only work when both the vertical wind and acoustic velocity measurements are available and uncontaminated. The height coverage of the acoustic velocity measurement is greatly reduced in wind (May et al. 1988). On the other hand, the clear-air wind measurement can be difficult in cold, dry, calm conditions due to low radar reflectivity. Furthermore, in rain or snow the 915-MHz radar detects the fall speed

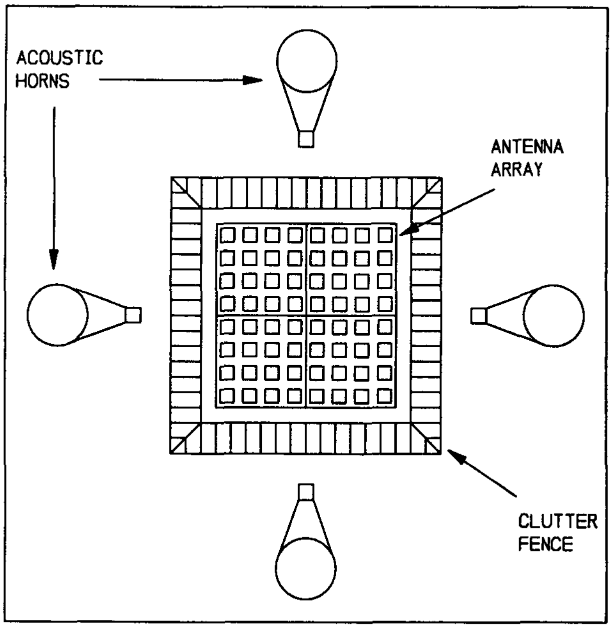

FIG. 2. The 915-MHz profiler–RASS in plan view.

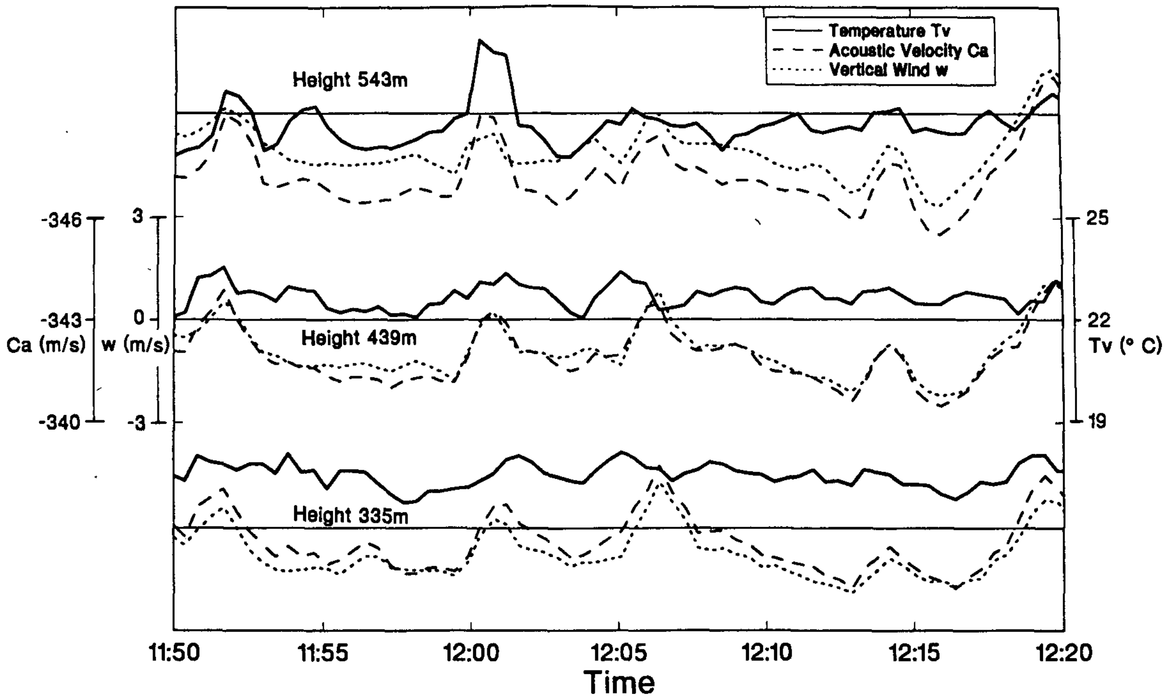

FIG. 3. Temperature, acoustic velocity, and vertical wind velocity during 7 September 1990 at BAO. Data are plotted for three heights. Plotted temperature is calculated from acoustic velocity and vertical wind as in Eq. (1). Scales are the same for all three heights. Note particularly the thermal plume at around 1200 MDT, and the fluctuations in the vertical wind without comparable fluctuations in temperature after 1210 MDT.

of the hydrometeors, not the wind speed, and the correction is not possible. Ground clutter and airborne targets such as birds, insects, and aircraft can also contaminate the vertical wind measurement. Data processing techniques need to be developed to handle these problems, possibly by deciding when to use and when not to use the correction.

3. Acoustic source

a. Implementation

The acoustic excitation is a vital element of a RASS. To have more flexibility, we now use a second digital signal processor board similar to the one that processes the radar signals. This board is programmed to produce the acoustic signal through an on-board digital to analog converter and coder–decoder (CODEC) circuit. The signal is a series of single-frequency segments of a specified duration or "dwell time." At the end of each dwell time, a new frequency is selected.

TABLE 2. Temperature results computed by four methods for height 335 m.

Tw0	22.28
Tbrac	24.65
Teo	23.84
Toe	23.34
Tsc	23.59
Tsc − Tw0	1.30
Tsc − Tbrac	1.06
Tsc − Teo	−0.25
Tsc − Tbe	0.25
Teo − Toe	0.50

The frequency series can be either a series of steps of specified size, or a random choice. In either case, the user chooses a frequency range or window. The series of steps is usually done with a step size small enough to make the series approximate a linear sweep, and this is called the "sweep mode." In the current implementation, the step size can be selected in 1-Hz increments. The frequency is stepped across the window from the lowest to highest frequencies and then the sweep is repeated.

Pseudorandom frequencies are chosen in the "random hop" mode. The only constraint on the spacing of the frequencies is the resolution of a floating-point number in the DSP. The choices are uniformly distributed across the selected frequency window.

Each frequency segment is a synthesized sine wave directly computed by the DSP. When the frequency is changed between segments, phase continuity is maintained.

A very practical advantage of this acoustic source is that it can be controlled by the same program that operates the radar, making it an integral part of the radar–RASS. We have programmed the computer to turn on the acoustic source for a selected period of time during each hour, for example, and to reconfigure the radar to operate in RASS mode during that time. This can be helpful at sites where continuous RASS operation might disturb nearby residents. It will also be possible to adapt the acoustic frequency window to changing temperatures, allowing the use of a smaller frequency window and therefore making better use of the available acoustic power.

b. Relationships with radar parameters

The acoustic excitation must be carefully chosen for optimum RASS performance. If the acoustic bandwidth is too narrow, the signal returned will be biased toward the transmitted acoustic frequency rather than that corresponding to the speed of sound (May et al. 1990). On the other hand, if the bandwidth is too broad, there will be too little power at the Bragg frequency at any given height, the return signal will be weak, and height coverage will suffer.

The pulsed Doppler radar does not sample uniformly. Between the acquisition of each coherently integrated time series, it pauses to compute the FFTs. If a deterministic acoustic signal (such as a sweep) is accidentally synchronized with the radar sampling period, the acoustic energy satisfying the Bragg condition at some heights (temperatures) will be present only during the calculation time, and an artificial gap in the height coverage will result.

We have found the random hop and linear sweep types of acoustic excitation described above to be the best solutions to these constraints. The random hop appears to give slightly better results when the radar sample time is relatively long, and the sweep works better for short sample times. These observations come from experiments in the atmosphere itself and from direct measurements of the spectrum of the acoustic excitation by the radar.

We ran an experiment with a 915-MHz profiler at the BAO site on 7 December 1990 to compare the performance of the two acoustic excitation types. Frequency window widths of 30, 50, 100, and 150 Hz were used, and the dwell time was varied from 1 to 100 ms. The number of spectra averaged by the radar was varied from 3 to 50. Due to the variability of the atmosphere, it is difficult to draw rigorous quantitative conclusions; however, the qualitative results may be summarized as follows:

1) The signal-to-noise ratio of the acoustic return is correlated most strongly to the width of the frequency window. This is as expected, since a larger window spreads acoustic energy over a larger range, most of which does not meet the Bragg condition.

2) Random hop gives stronger return signal than sweep for windows of 50 Hz or wider, but weaker for the 30-Hz window. The difference can be up to several decibels. Again, we expect this result, since the random hop gives a more even distribution of energy over the wider windows during the sampling interval.

3) In the sweep mode, frequency step size as large as 5 Hz has no visible effect on the spectrum of the return signal. This is probably because the bin size of the FFT is 3 Hz and atmospheric turbulence and wind spread the signal peak.

4) When small numbers of spectra are averaged, as for example when high time resolution is required, the sweep mode works better, since it ensures that there is acoustic energy at all frequencies over a short time. With 10 spectra averaged, the sweep mode with very short dwell time (5 ms) and 1-Hz steps works well.

A second experiment used the radar as a spectrum analyzer to examine the spectrum of the transmitted acoustic signal. The output of the acoustic source was fed directly into the input of the radar analog to digital converters. The resulting output is the spectrum of the acoustic excitation as seen by the radar, including the effects of nonuniform sampling. The desired spectrum is flat over the range of frequencies corresponding to the temperature range of the atmosphere during our measurement, and contains no components outside that range.

Figure 5a shows a power spectrum determined by this method for a random hop excitation with 100-Hz window and 25-ms dwell time. The radar averaged 25 spectra. Figure 5b shows the spectrum for the same 100-Hz window and 25-ms dwell time for sweep mode with a 1-Hz step size. The two spectra are similar, but the sweep mode spectrum has slightly sharper edges. The implication is that the frequency window should be set slightly larger for the random hop mode, which would negate much of the advantage it appeared to have in the real-atmosphere experiment described above.

It is important to note that the nonuniform spectra of Fig. 5 are fundamentally different in character. The random hop spectrum tends to uniformity for sufficiently long averaging times. The sweep mode, on the other hand, has a deterministic ripple, which does not average out. Any nonuniformity in the transmitted acoustic spectrum will be reflected in the radar return, and may bias the measurement. The effect is not clearly shown in the figure because the averaging times are relatively short.

We have settled on parameters close to those of Fig. 5 for our long-term experiments. They are a good compromise between high time resolution and good return power. A fairly wide frequency window (up to 150 Hz for the 915-MHz radar) is required for long-term operation over wide temperature ranges.

Some observers find the random hop mode less annoying to the ear than the sweep mode, which has been compared to a siren. Others find either mode equally annoying.

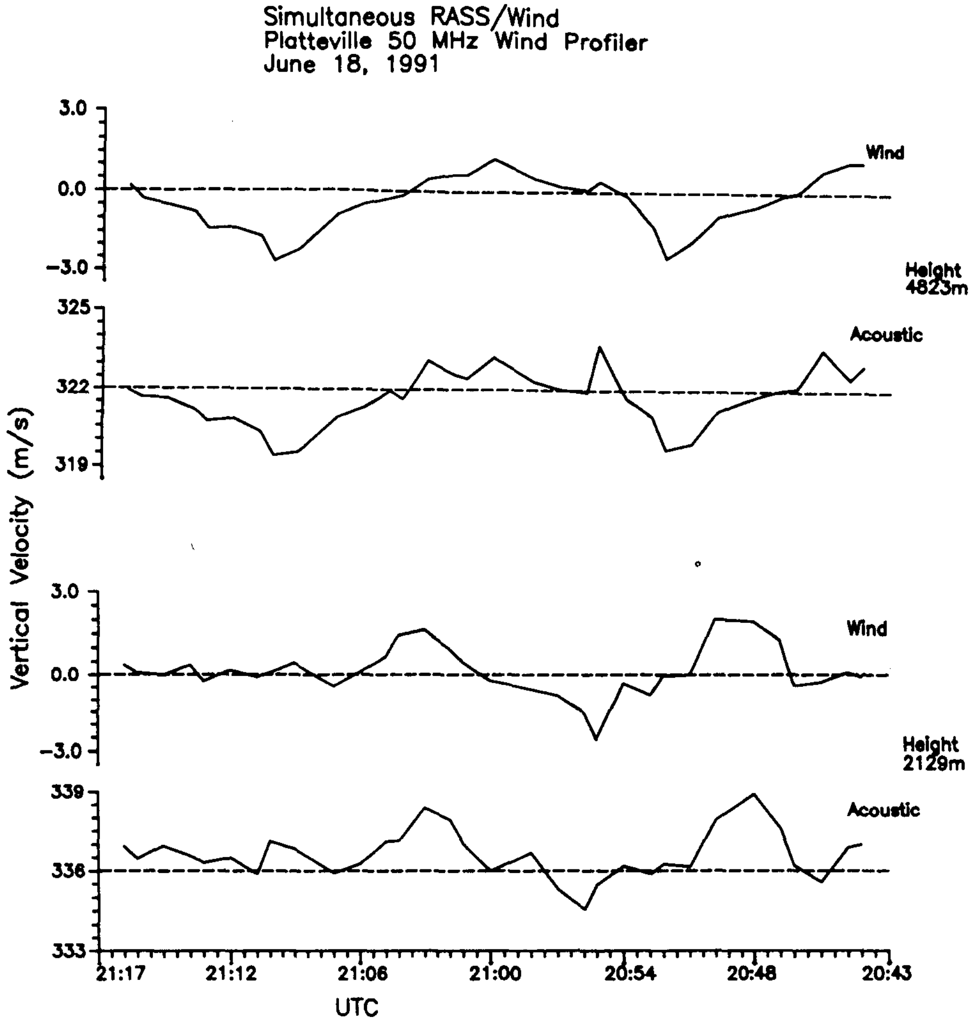

FIG. 4. Vertical wind and acoustic velocity from the 50-MHz Platteville profiler. Data are plotted for two heights. Note the wavelike activity.

4. Heat flux

The simultaneous measurement of temperature and vertical wind velocity makes possible the calculation of the virtual heat flux by eddy correlation. In particular, we can calculate the vertical flux of virtual heat due to turbulence $\overline{w'T'_v}$. This technique and results are discussed by Angevine et al. (1993).

5. RASS on oblique beams

Most RASS work to date has used only a vertical radar beam, the exception being work done at the MU radar in Japan involving real-time beam steering (Matuura et al. 1986). There are situations in which using the off-vertical (oblique) beam directions of the profiler for RASS is desirable, even for radars that do not have real-time steering capability. In a system designed to profile winds in three dimensions as well as temperature, the radar usually cycles through two or four oblique beam directions between each measurement on the vertical beam. As a result, the vertical beam is sampled infrequently. The available sampling rate using only the vertical beam may limit the time resolution that can be achieved, especially in convective or otherwise turbulent conditions. For flux measurements, good sampling density is even more vital.

There is no theoretical barrier to the measurement of the acoustic velocity along the oblique beams, although there are some practical engineering considerations. Primarily, it is essential that a correction for the radial velocity of the wind be applied. The technique discussed above applies equally well to the correction of the acoustic velocity for the radial wind in any beam direction. Also, the beamwidth of the acoustic sources must be large enough to give relatively constant acoustic power throughout the region covered by the oblique beams, or the acoustic beam must be steered along with the radar beam.

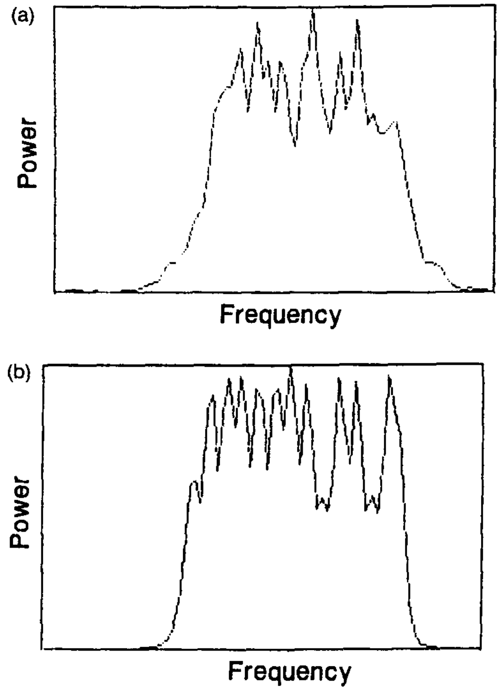

FIG. 5. Spectra of the acoustic source as measured directly by the radar. Horizontal axis is frequency, vertical axis is amplitude (linear scales). Source parameters: Window 1950–2050 Hz, dwell time 25 ms. Radar averaging 25 spectra. (a) Random hop mode. (b) Sweep mode with 1-Hz step.

Experiments with RASS using all five beams of a boundary-layer profiler system have shown that the technique works. The profiler used beams at vertical and 10° off zenith in each of four directions, with a beamwidth of about 9°. The acoustic horns used have a beamwidth of about 10°, which is too narrow for the application. As a result, the RASS height coverage in the oblique beams is poor compared to that in the vertical beam. The loss of height coverage was 30%–50%. As might be expected, there was a difference in height coverage in the upwind and downwind directions, the downwind direction generally having better coverage.

6. Conclusions

The set of techniques we have presented can significantly improve the performance and versatility of RASS based on wind profilers. Correcting the acoustic velocity by simultaneous measurement of the vertical or radial wind is practical, inexpensive, and has significant benefits. For high time resolution studies, simultaneous wind and acoustic velocity measurements are clearly essential.

The integrated acoustic source allows greater control and flexibility of the acoustic excitation. The measurement of virtual heat flux by profilers with RASS may add an important capability for boundary layer experiments. The use of RASS with all beams of the profiler, not just the vertical beam, allows for measurements of higher quality on short time scales, and may not require changing the profiler operating mode when temperature profiles are taken.

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REFERENCES

Angevine, W. M., S. K. Avery, W. L. Ecklund, and D. A. Carter, 1993: Fluxes of heat and momentum measured with a boundary-layer wind profiler radar–RASS. *J. Appl. Meteor.*, **32,** 73–80.

Ecklund, W. L., D. A. Carter, and B. B. Balsley, 1988: A UHF wind profiler for the boundary layer: Brief description and initial results. *J. Atmos. Oceanic Technol.*, **5,** 432–441.

Marshall, J. M., A. M. Peterson, and A. A. Barnes, Jr., 1972: Combined radar-acoustic sounding system. *Appl. Opt.*, **11,** 108–112.

Matuura, N., Y. Masuda, H. Inuki, S. Kato, S. Fukao, T. Sato, and T. Tsuda, 1986: Radio acoustic measurement of temperature profile in the troposphere and stratosphere. *Nature*, **333,** 426–428.

May, P. T., and R. G. Strauch, 1989: An examination of wind profiler signal processing algorithms. *J. Atmos. Oceanic Technol.*, **6,** 731–735.

——, ——, and K. P. Moran, 1988: The altitude coverage of temperature measurements using RASS with wind profiler radars. *Geophys. Res. Lett.*, **15,** 1381–1384.

——, ——, ——, and W. L. Ecklund, 1990: Temperature sounding by RASS with wind profiler radars: A preliminary study. *IEEE Trans. Geosci. Remote Sens.*, **28,** 19–28.

North, E. M., and A. M. Peterson, 1973: RASS, a remote sensing system for measuring low-level temperature profiles. *Bull. Amer. Meteor. Soc.*, **54,** 912–919.

Peters, G., H. Hinzpeter, and G. Baumann, 1985: Measurements of heat flux in the atmospheric boundary layer by sodar and RASS: A first attempt. *Radio Sci.*, **6,** 1555–1564.

Priestley, C. H. B., 1959: *Turbulent Transfer in the Lower Atmosphere.* University of Chicago Press, 130 pp.

Strauch, R. G., D. A. Merritt, K. P. Moran, K. B. Earnshaw, and D. van de Kamp, 1984: The Colorado wind-profiling network. *J. Atmos. Oceanic Technol.*, **1,** 37–49.