NOAA Technical Memorandum ERL WPL-184

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noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

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N. L. Abshire[2], and D. C. Law[2]

ABSTRACT. The National Oceanic and Atmospheric Administration (NOAA) is constructing a wind profiler network in the central United States to evaluate the utility of nearly continuous wind data and, in particular, its effect on short-term weather forecasting. These UHF (404.37 MHz) radars can also measure vertical profiles of virtual temperature in the lower troposphere by the Radio Acoustic Sounding System (RASS) technique. Vertical temperature data are obtained with the same spatial and temporal resolution that are used for wind profiling. A series of tests was conducted in April and May 1990 to obtain a preliminary evaluation of how well RASS would operate with the new wind profilers for the NOAA network. The network prototype radar, located at Platteville, Colorado was used to collect RASS data. RASS data from two other profilers were available for comparison. Height coverage of the RASS data began at 500 m above the surface and extended to 3.5-5.2 km with the NOAA network profiler.

1. INTRODUCTION

NOAA is installing a network of 31 UHF (404.37 MHz) radar wind profiler systems in the central United States starting in 1990. The systems are being built by the UNISYS Corp., Great Neck, New York. The network prototype was installed at Platteville, Colorado and was accepted by NOAA in August 1989 (Weber et al., 1990). The basic radar characteristics are summarized in Table 1 (Chadwick and Hassel, 1987). The purpose of this report is to describe preliminary results of Radio Acoustic Sounding

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System (RASS) experiments with the network prototype. RASS allows the radar wind profilers to measure vertical profiles of virtual temperature in the lower troposphere.

Table 1.--NOAA network radar parameters

Frequency	404.37 MHz	
Wavelength	0.7414 m	
Peak power	16 kW	
Antenna gain	32 dB	
Antenna beamwidth	4°	
Antenna pointing	Zenith, 15° off-zenith to north and east	
System noise temperature	235 K	
Operating Modes	Low	High
Range resolution	0.375 km	0.9 km
Minimum height	0.5 km	7.5 km
Maximum height	9.25 km	16.25 km
Height sampling increment	0.25 km	0.25 km
Average power	0.5 kW	2.2 kW

UHF and VHF wind profilers were used in numerous research programs during the 1980s. The new NOAA network represents a transfer of technology from the research community to operational meteorologists. Wind profilers will be in widespread use during the coming decade. The data they provide would be of far greater value if, in addition to winds, they could also measure temperature profiles. In late 1987, NOAA's Environmental Research Laboratories (ERL) revived RASS research after more than 10 years of little or no activity in the United States. RASS was developed in Europe and Japan during the 1980s primarily for temperature profiling in the lowest kilometer above the Earth's surface (Bonino et al., 1979; Peters et al, 1983). The reason RASS was abandoned in the United States was that there seemed to be no practical way that temperature measurements could be made to altitudes needed for most meteorological applications because of the effects of winds. However, in the mid-1980s, researchers at the Radio Atmospheric Science Center, Kyoto University, Japan, demonstrated that their very powerful and beam-steerable 49 MHz MU radar could measure temperature profiles into the stratosphere (Matuura et al., 1986). These results, coupled with the development of the wind profiler (though less sensitive than the MU radar and with only three fixed beam-pointing positions) and the need to improve remotely sensed temperature profiles obtained by passive microwave and infrared radiometers, prompted ERL to reexamine the RASS technique. Since 1987, a number of experimental results have been reported (Currier et al., 1988; May et al., 1988; May et al., 1990) that show that RASS can be added to wind profilers and will provide the following:

(a) Profiles of virtual temperature with the same time and height resolution as wind profiles in the lowest 2-3 km of the atmosphere (May et al., 1989b; Neiman et al., 1990).

(b) Temperature data that will complement temperature profiles measured by satellite radiometers. Satellite temperature profiles have poor height resolution, and their accuracy is worse near the surface where the meteorologist needs the best information and where RASS can measure with good accuracy and vertical resolution (Schroeder et al., 1990). Indeed, the greatest potential importance of RASS is in improving the quality of temperature profiles derived from satellite instruments such that these data would be useful to operational meteorology. Thus, the combination of RASS and satellite radiometry may provide remotely sensed temperature profiles throughout the troposphere for many meteorological applications.

This report describes RASS results obtained during the first experiments with a 404.37 MHz radar wind profiler that is the prototype of the profiler that will be used in the new NOAA wind profiler network.

2. EXPERIMENTAL METHOD

The RASS experiments were conducted by introducing a frequency offset into the wind profiler receiver so that instead of observing signals from clear-air scattering near zero velocity, the radar observed signals near the speed of sound (about 320 m s^{-1}). This is the method we have used in our previous RASS work (Strauch et al., 1989). The time domain averaging used by wind profiler radars introduces a $\sin(NT\pi f)/N\sin(\pi Tf)$ amplitude filter (Schmidt et al., 1979) on the time signal (where N is the number of time domain averages, T is the pulse repetition period of the radar, and f is frequency) prior to performing digital power spectral analysis. The frequency response of the time domain filter-spectrum analyzer combination is determined by the filter since the digital spectrum analysis is periodic with period $1/NT$. The filter response is determined by N and T, parameters that are fixed with the NOAA network radars. For vertical pointing with best height resolution (the mode used for RASS), $N = 152$ and $T = 96.667$ μs. Figure 1 shows the filter response for these parameters; complex signals allow discrimination of positive and negative velocities (frequencies). The Nyquist interval $\pm 1/2NT$ is shown. Note that RASS signals that occur in the frequency range of 850-930 Hz would be attenuated; signals at 884.75 Hz would be totally attenuated.

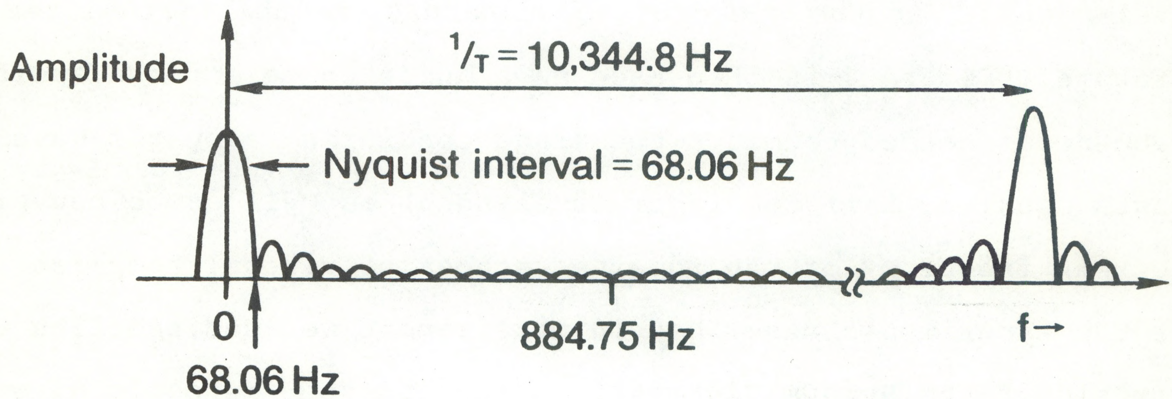

Fig. 1. Time domain filter response, $\sin(N\pi Tf)/N\sin(\pi Tf)$.

We introduced an offset in the receiver, shown in Fig. 2. The 30 MHz reference signal used for mixing the Intermediate Frequency (IF) signals to baseband is offset by the 13th harmonic of the first null frequency of the time domain averager,

$(1/NT)13 = 884.75$ Hz. This can be done in several ways; as shown in Fig. 2, we divided the 30 MHz radar reference frequency by 3 and used this 10 MHz signal to lock an HP 3335A frequency synthesizer. We then simply dialed a new reference frequency (30 MHz - 884.75 Hz) on the synthesizer and used this offset frequency to demodulate the radar echoes. The time domain averager response is then as shown in Fig. 3, where we note that ground clutter is now totally attenuated and clear-air signals near zero velocity are highly attenuated. The power spectra calculated by the radar data processor can then be labeled with frequency, sound speed, or virtual temperature axes (Fig. 4), since $f = 2C_a/\lambda_r$ and $C_a = 20.047\ T_v^{1/2}$ where λ_r is the radar wavelength, C_a is the speed of sound, and T_v is the virtual temperature. Figure 4 is then used as a guide to select the audio frequencies needed to match the Bragg condition (acoustic wavelength equal to half the radar wavelength) as well as to convert the mean frequency of the received echoes to virtual temperature. For the experiments described in this report we used the 13th harmonic of the Nyquist interval as the offset. We could have used an arbitrary offset, but the choice of a harmonic of the Nyquist interval suppresses unwanted clear-air echoes and ground clutter. In warmer conditions we could use an arbitrary offset to shift the band of temperatures seen by the radar or we could allow aliasing of signals greater than 340 m s^{-1}. Although the aliased signals would be attenuated (Fig. 3) by the filter, they would correspond to the warmest temperatures near the surface where the signal-to-noise ratio is usually very high. Aliasing would be easy to recognize and correct (see Section 4 for alternative data processing methods). Note that an offset equal to the 14th harmonic of the Nyquist interval would correspond to a temperature span too warm for general use.

We used three acoustic sources located upwind of the center of the radar antenna by about one radar antenna diameter (~13 m). Each source used a J.B. Lansing 2445J transducer with a flared horn at the focus of a 1.3-m-diameter reflector. Electrical input to each transducer was 50 W, and acoustic power output was 5-10 W. The audio source was frequency swept with a 1 s period from about 860 to 920 Hz. The sweep period was set so that there was no repetition of the acoustic modulation during the dwell time used to measure a single Doppler spectrum and no repetition of the acoustic pattern in space in the radar resolution cell. This avoids generating lines in the Doppler spectrum.

The acoustic excitation for RASS was started about 20 s before the start of the high-resolution vertical beam mode, and it was turned off at the end of this mode (about 80 s later). This sound transmission was repeated every 6 min when continuous RASS observations were made. The sound is audible for a considerable distance, and eliminating this "noise pollution" for nearby residences is the major problem remaining before RASS can be routinely operated near populated areas. For our tests we used no noise-abatement procedures, relying on the remoteness of the site to eliminate annoyance to neighbors.

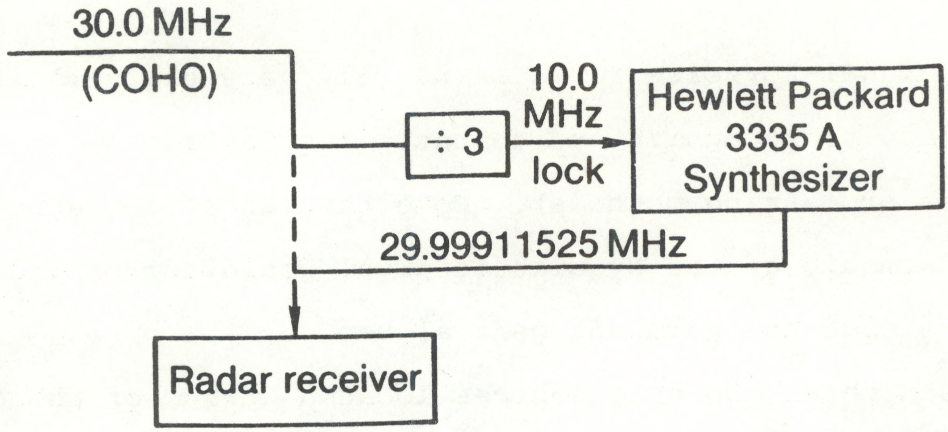

Fig. 2. Offset frequency demodulation technique for these experiments.

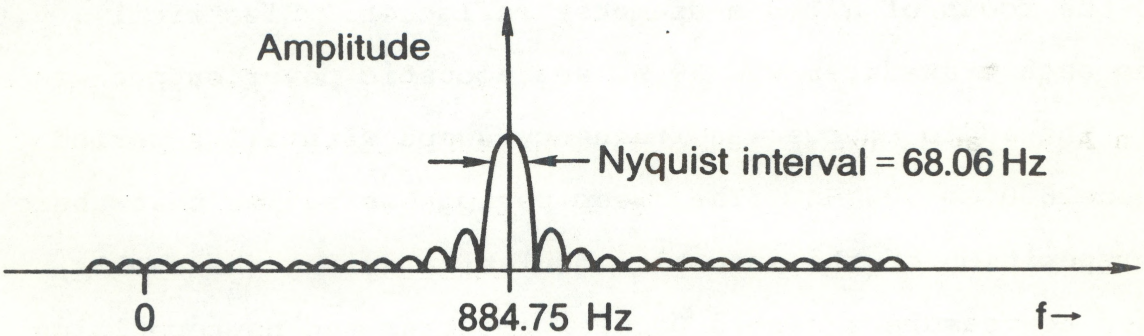

Fig. 3. Time domain filter response with offset receiver.

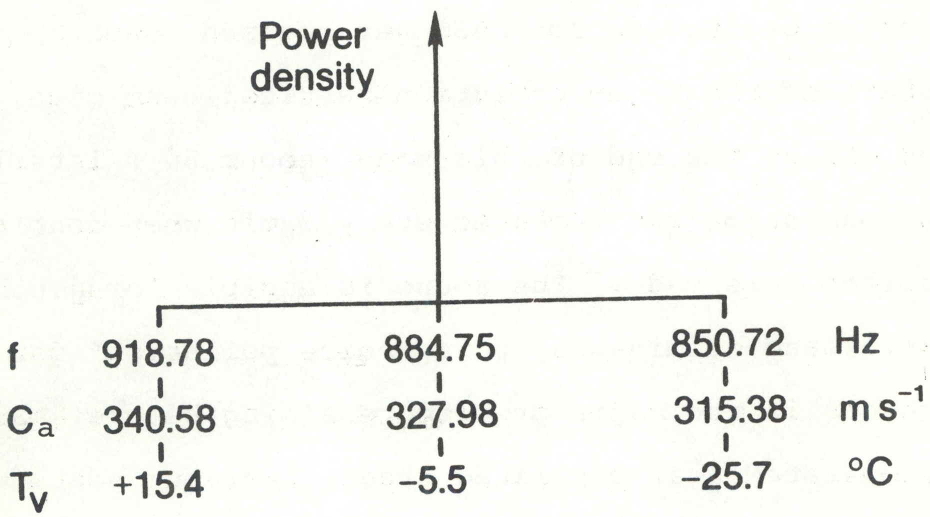

Fig. 4. Doppler spectrum for RASS; f is frequency, C_a is sound speed, and T_v is virtual temperature.

We used the data processing algorithms normally used for clear-air echoes to process the RASS data (Strauch et al., 1984). This includes the data processing used to find the first moment (mean velocity or virtual temperature) from each Doppler spectrum and the consensus average technique used to average 10 RASS profiles acquired each hour (for those tests where RASS was used every 6 min).

3. EXPERIMENTAL RESULTS

Nine RASS tests were conducted with the NOAA wind profiler radar in April and May, 1990. Since we had previously conducted a number of tests (May et al., 1989a) to determine the accuracy of RASS data, using radiosondes as the measurement standard, our main interest for these tests was to determine how RASS could be added to the NOAA radars and what altitude coverage would be obtained. The altitude coverage of RASS depends primarily on acoustic attenuation, horizontal winds, turbulence, and temperature gradients. With 400 MHz wind profiler radars, acoustic attenuation and horizontal winds limit height coverage. The acoustic attenuation depends on temperature and humidity. Figure 5 shows the attenuation of 900 Hz acoustic waves at 850 mb pressure. Although the attenuation can be quite large, for our experiments it was about 3-5 dB km^{-1}. Horizontal wind reduces the height coverage of RASS because the wind advects acoustic waves, and then the location on the ground of maximum observed electromagnetic scattering is moved. If the radar antenna and acoustic source are collocated, the maximum scattered signal is found downwind from the radar antenna. We used several acoustic sources upwind of the radar antenna to mitigate wind effects. Surface wind speeds were less than 10 m s^{-1} for our experiments, and winds 2 km above the surface were less than 15 m s^{-1}. Table 2 summarizes the general atmospheric conditions and the maximum height of RASS measurements for our experiments. Height coverage was typically 4.25 km above ground, with a minimum height of 3.5 km and a maximum height of 5.25 km. Surface meteorological data were obtained from the surface station that is part of the network prototype profiler. Wind speed at 2 km above the surface was obtained from a nearby VHF wind profiler. The acoustic attenuation was computed from the surface data.

Table 2.--Summary of RASS experiment

Exper. no.	Date 1990	Time UTC	# of Profiles	Avg. max. RASS height km-AGL	T_s °C	RH %	$\alpha(s)$ dB km^{-1}	WS(s) m s^{-1}	WS(2) m s^{-1}
1	4-6	2036 2100	5	3.5	6.4	55	3.3	3.3	7.7
2	4-10	1742 1854	13	3.9	0.3- 1.1	82	2.9	4.2	12.6
3	4-11	1642 1700	4	3.75	1.0- 2.4	85	2.7	1.5	9.5
4	4-12	1818 1842	5	4.25	13.2- 16.0	55-35	3.5- 3.9	2.2	13.1
5	4-13	1606 1648	7	4.0	8.5- 9.9	59-39	3.2- 3.8	7	7.2
6	4-16	1706 2336	64	4.7	13.0- 5.0	61-75	3.3- 2.9	7	3.1
7	4-25	1754 1900	8	4.6	9.4	80	3.1	8.5	3.3
8	5-1	0306 0536	5	4.4	8.3- 2.8	30-86	5.1- 2.8	3.5	3.3
9	5-2	1418 1748	6	5.25	2.0- 10.0	90-57	2.7- 3.3	3.2	4.7

T_s - surface temperaure (start-finish)
RH - surface relative humidity (start-finish)
$\alpha(s)$ - surface acoustic attenuation (start-finish)
WS(s) - average surface wind speed
WS(2) - average wind speed - 2 km AGL

Figure 6 shows profiles of virtual temperature measured by three different-wavelength RASS systems on April 11, 1990. The Wave Propagation Laboratory (WPL) Stapleton profiler is a 915 MHz (33-cm-wavelength) system located at Denver's Stapleton Airport, about 50 km south of the 404.37 MHz network profiler at Platteville. The WPL Platteville profiler is a 49.8 MHz (6.02 m-wavelength) system located about 200 m from the network profiler. The 915 MHz system uses acoustic frequencies near 2 kHz, where atmospheric attenuation limits RASS height coverage to 1.5-2 km above the surface. It has 150 m height resolution, and as shown in Fig. 6, resolved the temperature inversion better than did the NOAA system whose height resolution is about 375 m. The lowest measured height of the 915 MHz system is about 200 m above the surface (AGL), whereas the first height for the network profiler is 500 m AGL. The 50 MHz system cannot measure RASS signals in the lowest 2 km and has a range resolution of about 450 m. It uses acoustic frequencies near 100 Hz, where acoustic attenuation is negligible, so horizontal wind limits the height of RASS coverage to typically 6-8 km above the surface. The profiles measured by the three RASS systems are in very good agreement, especially considering the differences in resolution and location. The data also illustrate the relative height coverage of RASS data that we expect to obtain under a wide variety of meteorological conditions for those radar frequencies. The height coverage for the 404 MHz systems will be higher than for 915 MHz systems but not as high as for 50 MHz systems.

The data shown in Fig. 6 demonstrate that the NOAA network profilers are not boundary layer profilers. Some temperature inversions will be smoothed by the vertical resolution and therefore will not be measured at full strength or with the vertical structure that a point sensor would measure. Also, the lowest measurement height (500 m AGL) is too high for boundary layer applications. However, the basic 404.37 MHz radar used in the NOAA network could be made to operate with much better resolution. It is restricted in transmitted bandwidth by its frequency allocation and therefore cannot be operated with better resolution.

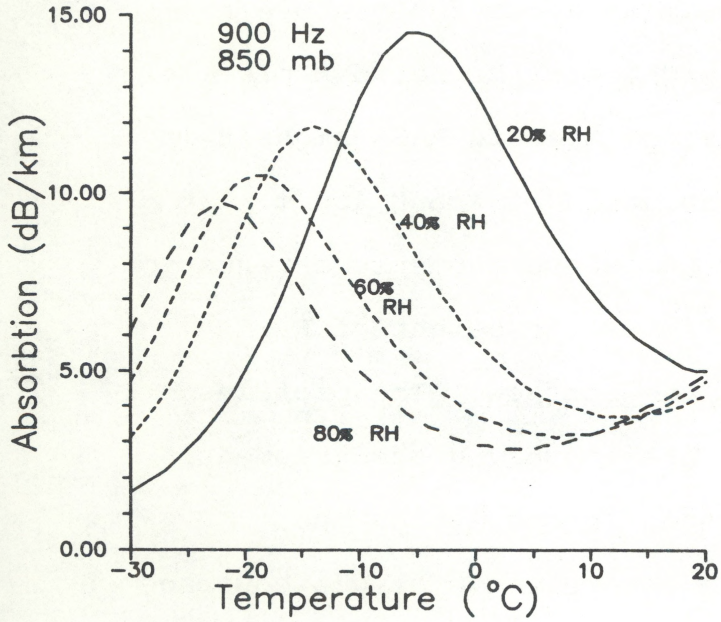

Fig. 5. Acoustic attenuation for RASS with a 404 MHz radar.

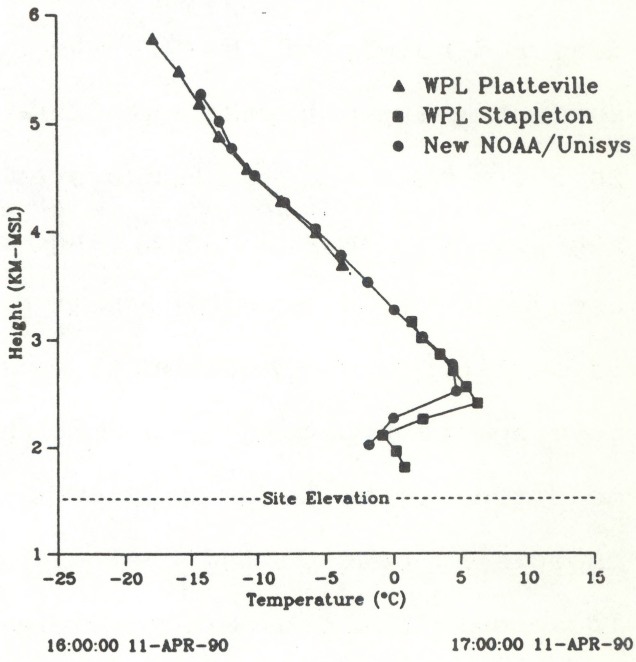

Fig. 6. Temperature profiles from three separate RASS systems.

On April 16, 1990, we conducted a RASS test from 1706 to 2336 UTC, measuring RASS profiles every 6 min. The network profilers measure radial velocities at three antenna-pointing positions with high and low height resolution every 6 min, and we measured a RASS profile every time the profiler cycled to the vertical antenna position with high resolution. If RASS is added to the network profilers such that vertical wind and the speed of sound can be measured simultaneously (see Section 4), RASS profiles and wind profiles would be measured every 6 min. Figure 7 shows virtual temperature contours measured during this 6½-h test. During this time a cold front was moving into the Platteville area and the surface temperature decreased about 1°C h^{-1} from 13°C at the start of the experiment to 5°C at the end. RASS data extended from the lowest measurement height (500 m) to 4.5 or 5.0 km above the surface for the 66 profiles used for Fig. 7. Acoustic velocity was measured in 16-18 height increments (250 m per increment). Below 5.8 km only one measurement point had to be edited (deleted) from the 66 profiles, and two profiles were lost during this test because the radar is automatically shut off to prevent radio interference with satellites. Hourly-averaged temperature profiles were calculated for this experiment (Fig. 8) using the consensus algorithm (Strauch et al., 1984) that edits and averages the 10 profiles measured each hour. The algorithm rejects outliers such as those caused by radar transmitter turn off or very low signal-to-noise ratio. The last profile was an average of the 6 profiles measured from 2306 to 2336. There are

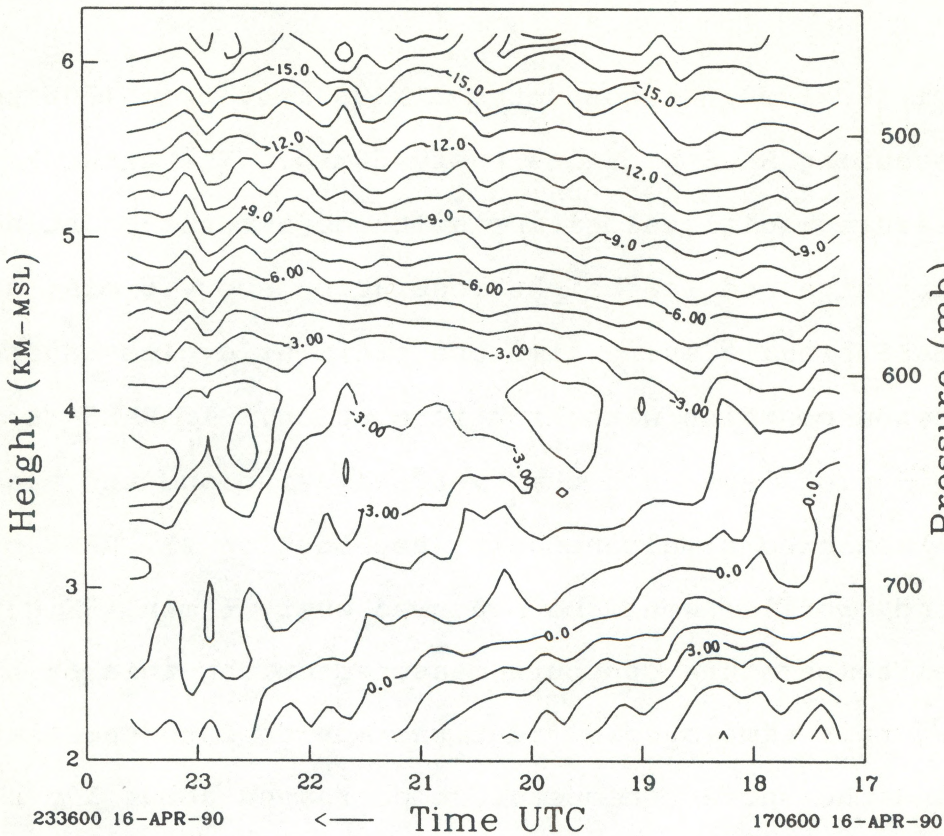

Fig. 7. Contours of virtual temperature profiles for a **6½-h** RASS test.

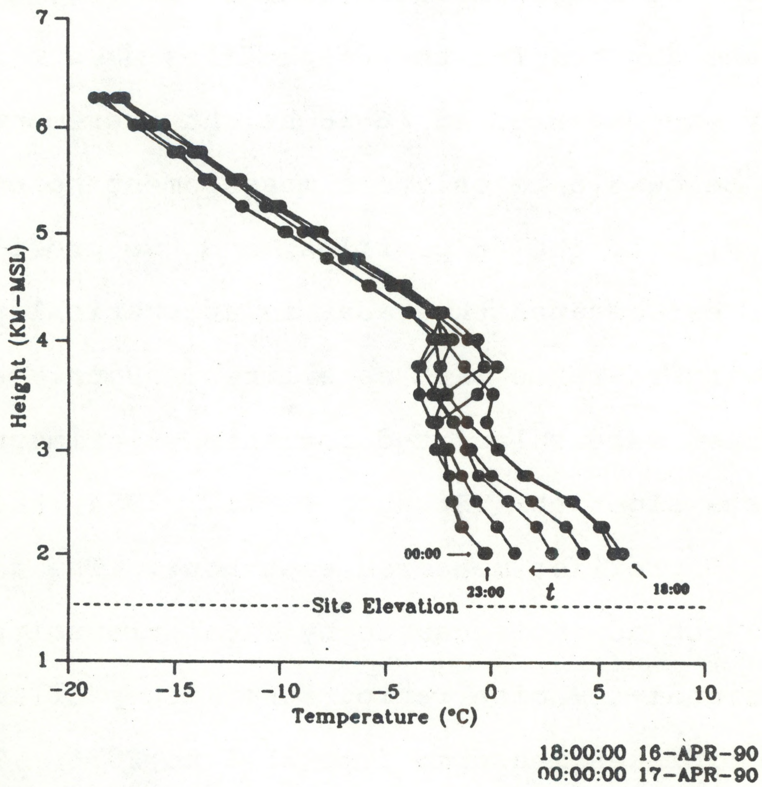

Fig. 8. Hourly-averaged temperature for a 6½-h RASS test (10 profiles/h).

seven hourly-averaged profiles in Fig. 8; the profiles at 2300 and 0000 are nearly identical in the lower levels. Wind profiles measured by the Stapleton Airport 915 MHz profiler during this experiment are shown in Fig. 9. The Stapleton profiler shows the frontal interface that accompanied the surface cooling. Above about 4 km MSL there was relatively little cooling as the front passed.

On April 10 we measured 13 RASS profiles during a 1½-h period when the temperature changed very little with time. Figure 10 shows the average profile. The root-mean-square (rms) difference between the 13 measured values and a straight line fit to these values is shown at each height. The average rms temperature difference is 0.31 °C, an approximate measure of the precision (not accuracy) of the RASS measurements. Note that the rms differences include atmospheric temperature fluctuations as well as measurement error. Measurement errors increase with height as signal-to-noise ratio decreases, and this increase is observed in these measurements.

The purpose of the tests conducted on May 1 and May 2 were to demonstrate that if RASS measurements are made twice per hour, then wind measurements would have only a slight degradation. The radar would still measure 10 clear-air radial velocity profiles every hour on the north and east antenna beams and 8 per hour on the zenith beam. Since the low-resolution (high-altitude) mode of the profiler does not require vertical velocity to compute a horizontal wind profile, the height coverage for horizontal winds

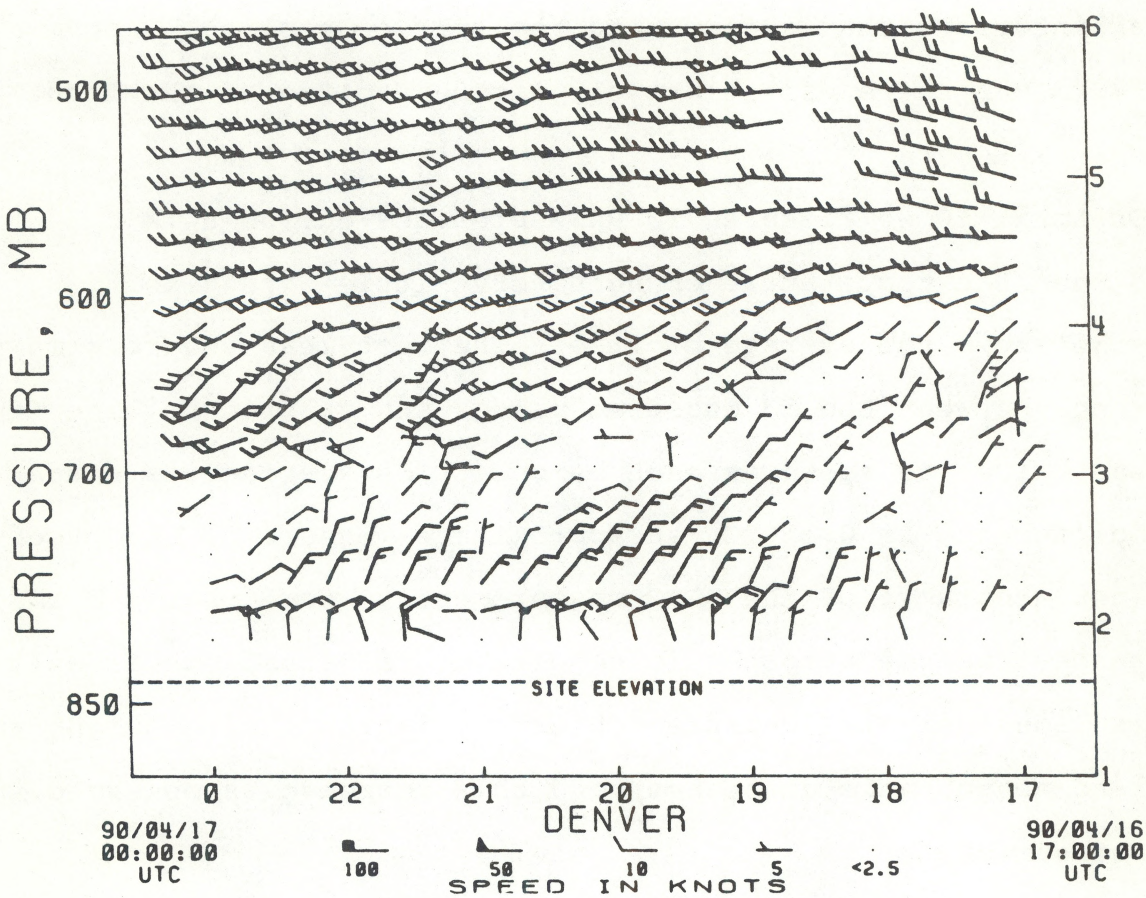

Fig. 9. Horizontal winds from the 915 MHz wind profiler at Stapleton Airport during a 7-h RASS test.

would not change in this mode. However, in the high-resolution mode the loss of two profiles per hour would result in decreased height coverage because in this mode a consensus-averaged vertical wind is required for computing horizontal winds. The reason for requiring a vertical velocity measurement in the high-resolution mode is that large errors in horizontal wind measurements will occur if there is precipitation and vertical velocity is ignored. Horizontal wind measured during these tests had the same height coverage as when RASS was not used. A statistical test would be needed to find the reduction in height coverage caused by one or two RASS profiles per hour.

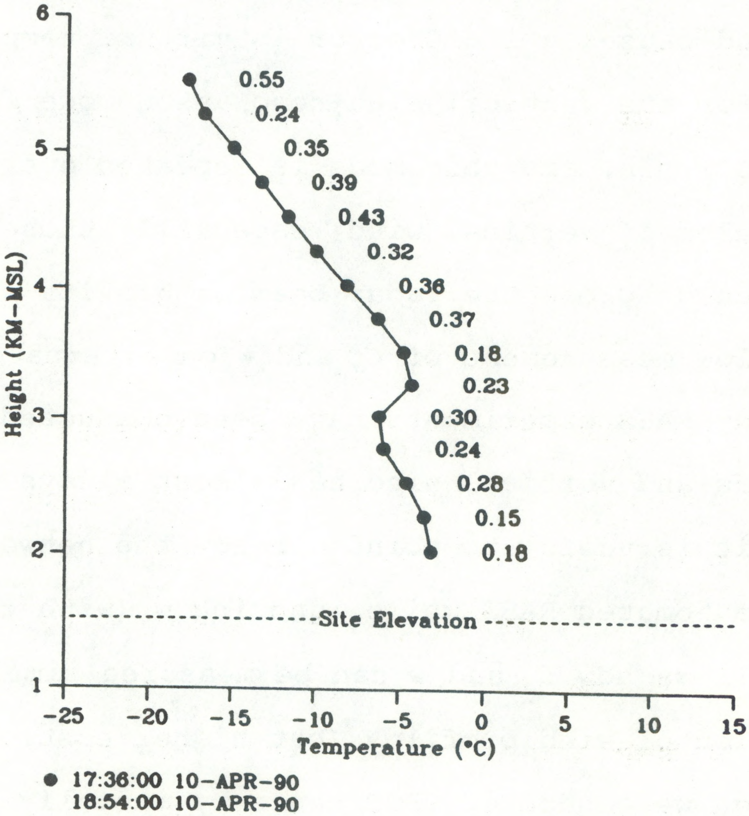

Fig. 10. Average virtual temperature profile and rms differences (listed) between 13 measured temperatures and a straight line fit to these values.

4. ROUTINE RASS OBSERVATIONS WITH THE NOAA WIND PROFILER

The motivation for performing these RASS tests was to demonstrate how effective the new wind profilers will be for providing virtual temperature profiles in the lowest several kilometers above the surface. The method we used for these tests is not the method that will be used when routine RASS observations are made, because our method does not allow measurement of C_a and vertical wind w simultaneously. Since the profiler measures the vertical component of the local speed of sound (the sum of C_a and w), both must be measured. Otherwise, a 1 m s^{-1} vertical wind causes a 1.6°C error in virtual temperature. The dwell time for the vertical high-resolution mode for the new profilers is 1 min, and this mode is repeated every 6 min. Temporal scales of vertical wind, especially those of thermal plumes advected across the radar beam or gravity waves, are too short to allow measurement of C_a and w on alternate dwell times. However, many RASS experiments have been conducted during the past 20 years and vertical wind has almost always been ignored. Therefore, it is useful to point out how the network profilers could have automated RASS while ignoring w (with relatively low cost) as well as how C_a and w can be measured simultaneously with no degradation of wind profiles (but higher cost).

Although we conducted RASS tests by manually turning on the audio source and dialing an offset demodulation frequency with a synthesizer, it would be a simple matter to automate our RASS method. An alternate method of generating the offset frequency is to mix the 30 MHz reference with the audio offset in a single-sideband mixer, a technique we are using for automated RASS on our research profilers. Figure 11 illustrates the automated control we would use for the network profilers. The RASS mode would be selected 1, 2, 5 or 10 times per hour, since the vertical mode is used every 6 min. If only one or two RASS profiles are measured each hour, there would be little degradation of the measurement of hourly-averaged vertical winds. Since the profiler selects a coarse-range-resolution mode before it uses the high-resolution mode, the high-power audio that creates the radar scatter would not be turned on until about 30 s prior to starting the high-resolution vertical mode. Vertical winds would not be measured when RASS is selected.

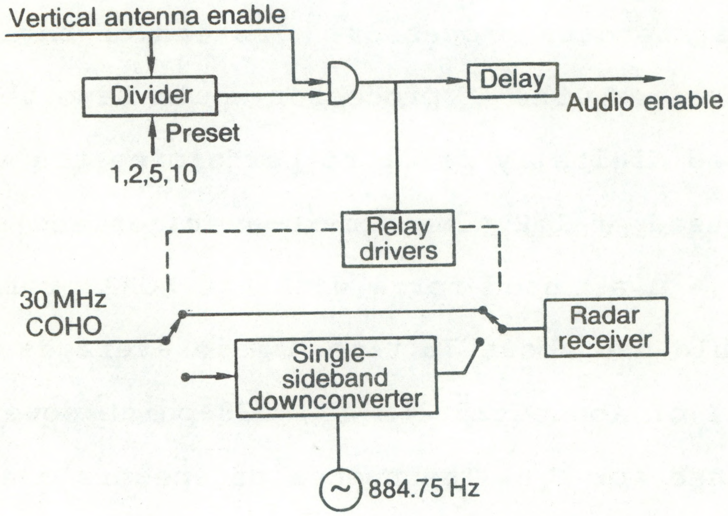

Fig. 11. Automated RASS method for the NOAA network wind profiler.

Measurement of C_a and w simultaneously with the network profilers requires changes or additions to the radar. There are several ways to consider. The most direct method would be to modify the data processor so that Doppler spectra of long time series (~2048 complex points) would be measured with a Nyquist interval of about ±350 m s^{-1}. In this way both the clear-air signal near zero velocity and the RASS signal near 320 m s^{-1} are measured with about the same resolution and sensitivity as that used with the offset frequency method and the 128-point Doppler spectrum analysis that we used in our tests. Estimates of the signal spectra would be made on the appropriate subintervals of the Doppler spectrum.

A second method for measuring C_a and w simultaneously would require a dual signal processor. Vertical wind would be found normally, and the same video voltage samples would be processed for C_a in a separate data processor. Instead of having an offset in the radar receiver, the C_a processor would have the same offset introduced digitally prior to performing the time domain averaging. Instead of 152 time-domain averages and a Nyquist interval of ±12.6 m s^{-1} used for w with the NOAA profilers, the C_a processor would use about 76 time domain averages with a Nyquist interval of about ±25.2 m s^{-1}; 128-point power spectra would also be used for C_a. The number of spectra averaged during the 1-min dwell time would be 30 for w and 60 for C_a. A digital offset frequency of 884.75 Hz would suppress clutter and clear-air signals. A method similar to this is being developed by the radar manufacturer (private communication).

5. CONCLUSION

RASS capability was demonstrated on the 404.37 MHz radars in the new NOAA wind profiler network that is being installed in the central United States. Although the tests were too brief to include operation in a variety of meteorological conditions, the results verified expectations that were based on RASS experiments with other wind profilers, namely, that the new radars could measure virtual temperature profiles starting at their lowest height (500 m AGL) and extending to 3.5-5 km AGL with a measurement every 250 m. A low-cost RASS capability could be added to these profilers to measure virtual temperature profiles (while ignoring vertical wind) once or twice per hour with only minor degradation of routine wind measurements. However, simultaneous measurement of vertical wind and the speed of sound is needed for operational RASS, and this requires some modifications to the radar data processor. Finally, if RASS is to be used on wind profilers that are located near populated areas, 900 Hz acoustic sources with very low sidelobes need to be developed.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1990 - 773-002/21004