The Accuracy of RASS Temperature Measurements

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ABSTRACT

Temperature measurements obtained using radiosondes and Radio Acoustic Sounding Systems (RASS) are compared to assess the utility of the RASS technique for meteorological studies. The agreement is generally excellent; rms temperature differences are about 1.0°C for comparisons during a variety of meteorological conditions. Observations taken under ideal circumstances indicate that a precision of about 0.2°C is achievable with the RASS technique. A processor being designed for RASS should allow routine temperature measurements approaching this precision.

1. Introduction

The Radio Acoustic Sounding System (RASS) is a technique for remotely measuring temperature by combining radio and acoustic techniques. The radar senses the signal backscattered from a grating created in the refractive index of the air by a high power acoustic source. This allows the speed of sound c_a to be determined (see Peters et al. 1983 and May et al. 1989, for theoretical background on the technique). The virtual temperature T_v is then given to a good approximation by $T_v = (c_a/20.047)^2$ where T_v is in K and c_a is in m s^{-1}. The RASS technique was first developed in the early 1970s (e.g., North et al. 1973) and has been used by a number of groups around the world. The early work was mostly limited to altitudes below about 1 km and low wind conditions (e.g., Bonino and Trivero 1985). An exception was an experiment performed in Japan that used a high-power radar. The radar beam was steered to account for advection of the acoustic pulse by the wind (Matuura et al. 1985). In this experiment temperatures were measured at altitudes as high as 20 km. Recently wind profiler radars (e.g., Strauch et al. 1984) have been used for the RASS technique. Temperatures have been measured up to altitudes of several kilometers without steering the radar beam and in moderately strong wind conditions (May et al. 1988). The extended height coverage is a consequence of such factors as sophisticated signal processing and relatively large radar antennas. Because the radars are sensitive enough to detect inhomogeneities in the refractive index of air, which occur naturally in the troposphere, they can be used to measure vertical and horizontal winds by measuring the Doppler shift of these targets.

Despite the amount of work that has been done on the RASS technique, no statistical study of the accuracy of the temperature measurements has been published. A number of single profiles comparing RASS and radiosonde observations (RAOBs) have been shown (e.g., North et al. 1973; Frankel and Peterson 1976; Bonino and Trivero 1985; May et al. 1988) and the agreement between the measurements has generally been very good, but little quantitative discussion has been possible with these limited comparisons. Bonino et al. (1986) compared several measurements from a meteorological tower and RASS observations, but again the discussion was limited to describing the agreement as excellent. We discuss the accuracy obtained so far with the RASS/wind profilers and the precision that can be attained, on a more quantitative basis. Despite the early stage of the development of the RASS systems the rms difference between radiosonde measurements and the recent RASS observations are already about 1.0°C. Considerable improvement is expected.

2. Signal processing and estimator accuracy

Early RASS systems were generally limited to measuring temperatures in the boundary layer under low wind conditions. However, new sophisticated radars, such as wind profilers, capable of observing backscatter from the clear air continuously, use more advanced signal processing techniques that allow the use of data

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with a much lower signal-to-noise ratio (SNR). Thus, measurements may be performed even under strong wind conditions. The radar samples the complex backscattered power from each range gate over a period of a few seconds and the data are Fourier transformed to give a power density spectrum (the Doppler spectrum). For our RASS, the spectra have 128 points over a Nyquist interval of about ± 50 m s^{-1} centered at about 300 m s^{-1}. Several successive power spectra from each sampled range are summed to improve the statistical reliability of the spectral coefficients. The algorithm used to estimate the Doppler shift of the backscattered signal in the Colorado wind-profiler network radars (Strauch et al. 1984) involves several steps. The noise levels of the spectra are objectively estimated using the technique of Hildebrand and Sekhon (1974). A first guess for the position of the signal peak is obtained by finding the maximum spectral power density when the spectrum has been smoothed with a running mean of three points. Moments are then calculated from the original (unsmoothed) spectrum over the interval surrounding this "guess" out to the first point where the spectral power density falls below the noise level on either side of the guess (Fig. 1). The noise level is subtracted from the spectral values over the signal interval before the moments are calculated. The algorithm is thus a direct calculation of the first moment over a limited spectral range. The objective limit set on the interval over which the moments are calculated effectively filters out much of the noise, and is analogous to coherent averaging of the time series (Farley 1983). As long as the first guess is reliable this method of analysis allows good estimates to very low SNR levels. The procedure also yields an estimate of the velocity even when there is no signal, and thus requires a process for detecting and eliminating outliers (see following discussion). Temperature measurements can be obtained with about 1 min time resolution (May and Strauch 1989). When the SNR is poor the estimates must be averaged.

The consensus algorithm (Fischler and Bolles 1981) is used to detect and eliminate outliers as well as to perform averaging. As incorporated into the analysis of data from wind profilers for RASS, the consensus involves taking a group of six consecutive mean velocity estimates (the number may be varied). Then the largest group that lies within a certain range of values (usually $\frac{1}{16}$ of the Nyquist interval) is found and the mean of that group is calculated. The result becomes the sample estimate. The data are rejected if there are less than three observations in the group. Thus only half of the data need be "good" to satisfy the criterion. If a pure noise signal is analyzed, about 10% of the data will satisfy the "minimum number" criterion; so some bad points may be expected when the SNR is very low. Usually these are easily recognized by their unrealistic values because they are randomly distributed over the Nyquist interval. The percentage of data passing the algorithm depends on the window width for the data, the number of values in the sample, and the minimum number required to pass the test.

The accuracy of this analysis for wind profiler applications has been investigated in some detail by May and Strauch (1989) using numerically simulated data. The technique used to simulate radar data with known statistical properties is similar to that described by Zrnić (1975). RASS signals, however, are at least partly deterministic as the acoustic "screen" moves through the

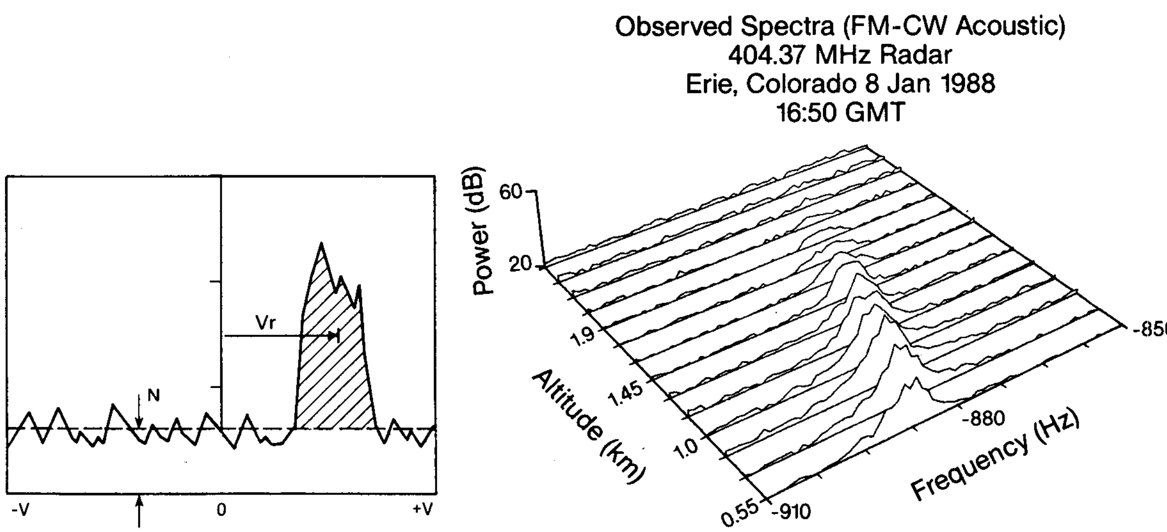

FIG. 1. (a) An illustration of the direct first moment calculation employed by the WPL wind profilers (after May and Strauch 1989). The signal part (over which the moment is calculated) of the spectrum is hatched, the first moment is marked as v_r and N marks the noise level which is objectively estimated. (b) Sample spectra (after May et al. 1990). The axes on the data samplers are drawn at the noise level.

radar pulse volume (May et al. 1989); that is, the scatter is not a random process. Therefore, two cases are investigated. The first is the traditional radar case in which the standard deviation of each spectral coefficient is equal to the mean value of that coefficient. The second case, which may be more applicable to RASS, is when only the noise component of the signal has the described characteristics and the signal is a deterministic function (assumed to have a Gaussian velocity distribution). Thus each spectral coefficient has the same standard deviation. Figure 2 shows a plot of the standard deviation of the velocity measurement for a typical spectral width. The trends are the same for other values of spectral width, although absolute values of the standard deviation may vary by about 50% over the range of widths encountered. Both the spectral width and standard deviation are normalized by twice the Nyquist velocity v_a, and the standard deviation is multiplied by $\sqrt{M}$ where M is the total number of data points (number of spectral points × number of spectra averaged × number of estimates in consensus average if the consensus is used). The curve can be used with or without the consensus averaging with the appropriate value of M. The scale is such that a value of 0.1 corresponds to a standard deviation of about 0.4°C for a typical unaveraged (1 min) RASS measurement. Clearly the precision to which the velocity, and hence virtual temperature, may be measured is high. Simulations for a deterministic spectrum show that the standard deviation rises exponentially for SNR less than about 5 dB and is significantly less than for the random scatter process. The fluctuations in the standard deviation at high SNR for the deterministic case are probably random fluctuations at the very low values observed.

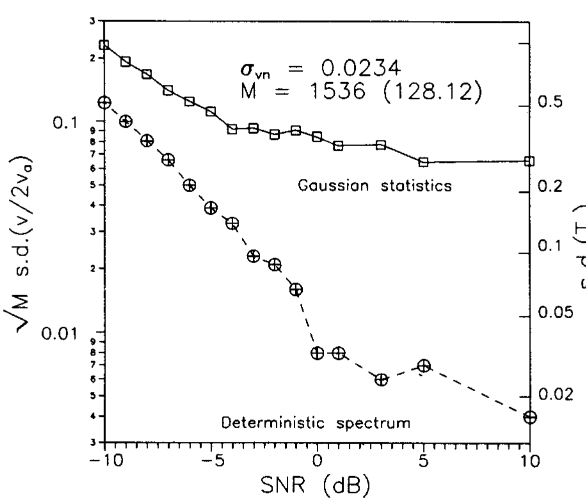

FIG. 2. The normalized standard deviation of the first moment estimates versus SNR. These simulations are for a value of normalized spectral width ($\sigma_{vn} = \sigma_v/2v_a$) equal to 0.025 where v_a is the Nyquist velocity. M is the number of data points analyzed for the moment estimation. The right-hand scale is for a Nyquist velocity of 50 m s^{-1}, temperatures around 270 K and the value of M given. Note that this scale is for no-consensus averaging, i.e., for 1-min samples.

TABLE 1. System parameters for the Denver and Platteville RASS.

	Platteville	Denver
	Radar	
Frequency (MHz)	49.8	915
Wavelength (m)	6.0	0.33
Antenna size (m^2)	10 000	100
Beamwidth (1 way) (deg)	3	2
Range resolution (m)	300	150
Mean power (W)	200	100
Sampling time (1 profile) (min)	1.5	1
	Acoustic	
Frequency (Hz)	~110	~2000
Beamwidth (1 way) (deg)	60	8
Acoustic power (W)	50	40
	RASS Altitude Coverage	
Minimum altitude	2.0 km	200 m
Maximum altitude (km)	5–10	1–2
Observation period	Jun, Oct 1988	Jul–Aug 1988 Nov 1988–Jan 1989

3. Equipment

The wind profilers used in our RASS experiments have been described by Strauch et al. (1984). In particular the 49.8 MHz radar at Platteville, Colorado and the 915 MHz profiler at Denver Stapleton Airport, Colorado were used. The basic system parameters are given in Table 1. These radars are sensitive enough to detect the weak backscatter from fluctuations in the refractive index of the clear air with receiver input SNR as low as −35 dB. The noise is filtered by coherently summing the signal over N successive pulses, increasing the effective SNR by a factor of N (Farley 1983); Doppler shift measurements can be obtained when the effective SNR is greater than −15 dB (May and Strauch 1989). When the radars are used for RASS their operation is essentially unaltered, except that only a vertically pointed beam is used and the receiver's local oscillator is offset by an equivalent of about 300 m s^{-1}. Thus, the signals from clear air and ground clutter are aliased several times. The offset frequency is chosen such that signals close to zero frequency remain at the apparent zero frequency. A band about the aliased zero frequency is then ignored in the analysis, so the measurements are unaffected by the clear air signal, which can still be large despite the filtering effect of the velocity aliasing. A second requirement is that the radar-pulse repetition frequency be an integer multiple of the frequency offset. This ensures that the fixed ground clutter still appears to have a fixed phase with the frequency offset. This latter requirement was satisfied only in recent RASS operation. Previously there was some bias toward low temperatures when the clutter was severe (see section 4).

The transmitted acoustic power used in these experiments is about 50 W. A single acoustic source placed in the center of the antenna array was used at Platteville. The large radar antenna means that this system is less sensitive to wind since the backscattered radiation is focused onto a diffraction-limited spot about the size of the radar antenna (Clifford et al. 1978). A single source adjacent to the radar dish was used at Denver for many of the comparisons. The Denver radar antenna is considerably smaller (~10 m in diameter) so winds had more effect on the maximum useful height. We are now using four acoustic sources distributed around the radar antenna, producing four spots and it appears that this RASS system's performance in high wind conditions has been substantially improved. Some of the comparisons reported here that were obtained with the Denver wind profiler were made during a wind storm with surface winds in excess of 15 m s^{-1}. There appeared to be little difference in the height coverage before and during the storm (~1.7 km). A compensating factor for the high winds is the accompanying tendency for a high level of turbulence, which acts to broaden the spot and thus compensate somewhat for the spot's displacement (May et al. 1988). As described by May et al. (1989) the acoustic frequency is modulated over a period of about 0.5 (3) s for 150 (300) m radar range resolution for the Denver (Platteville) wind profiler. Use of an FM acoustic signal ensures that there is always a region in which the Bragg condition (the acoustic wavelength is half the radar wavelength) holds within the pulse volume.

The speed of sound relative to the ground is measured by the radar. However, it is the speed of sound in the medium (air) that gives a measure of the virtual temperature. Therefore, in the absence of a measure of the vertical wind motion, there is an error in our estimate of c_a. The clear air profiler can measure the vertical wind motion, but when the receiver offset described above is used this correction is not possible. At present the data are averaged over several minutes to minimize the problem. A more satisfactory alternative requiring more computer power is described in section 6.

4. RASS–RAOB comparisons

About 50 radiosonde observations (RAOB) taken at the Denver site were used to evaluate the accuracy of the RASS measurements. Data were taken during two time periods, summer observations in July and August 1988 and winter observations in November 1988 to January 1989. Modifications to the receiver frequency offset were applied only to the winter dataset. These datasets will be used to validate the RASS technique and show what needs to be done to improve the accuracy of the temperature retrievals. Seven radiosonde profiles obtained near the Platteville 50 MHz profiler were also analyzed.

The RAOBs give a spot measurement in time and height along a slanted trajectory; the RASS observations provide a volume average and thus are potentially more representative. RASS profiles are averaged over about 6 min, using the consensus technique. This period is about the same as the time for the balloon to ascend through the observation range, but since no attempt has been made to remove the effect of vertical winds from the RASS measurements, the RASS profiles before and after each launch are also included in the average. These 18-min averages were compared with the RAOB profiles. The functional precision of the RAOB temperature measurements is about 0.4°C (Hoehne 1980). Although the RAOBs are not ideal measurements they are the de facto standard by historic precedence.

A comparison of the virtual temperature measurements from the RASS and from RAOB comparisons performed at Denver is shown in Fig. 3. The agreement is generally excellent. The overall rms difference is about 1.0°C, which is comparable with that obtained

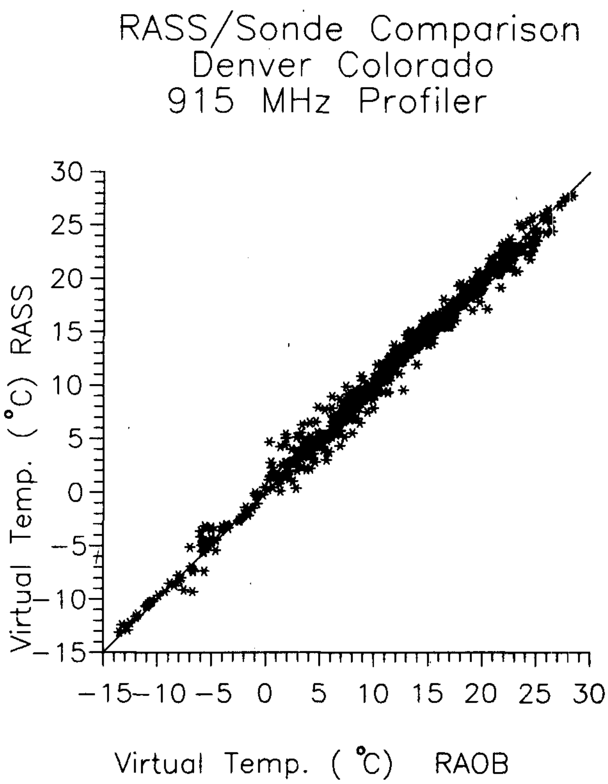

FIG. 3. Virtual temperatures measured by RAOBs and by RASS using the Denver 915 MHz wind profiler. The results of about 50 RAOB soundings are included in this figure with an rms difference of about 1.0°C.

in RAOB–RAOB comparisons (Hoehne 1980). Figure 4 shows the mean and standard deviation of the virtual temperature difference as a function of height. Clearly there is a bias in the RASS measurements in the lowest three or four range gates during the summer and without this bias the overall rms difference would be reduced even futher. However, if we examine the summer and winter data separately a number of trends appear. The summer data show a significant bias in the lowest three range gates; the winter data are not systematically biased. This difference indicates that the modifications to the offset have eliminated the bias present in the summer data that was introduced by the severe radar clutter encountered at the Denver site. The curves of the standard deviation differ significantly. The standard deviation of the temperature measurements was smaller in the summer and generally decreased with height, but in the winter observations the standard deviation increased with height. Examination of the winter data showed that the periods of severe errors (>2.0°C) were periods when strong vertical winds ($\geqslant 1$ m s^{-1}) were observed by the radar before and after the RASS observations. These vertical winds were associated with downslope wind storms (e.g., Klemp and Lilly 1975). Furthermore, the sign of the errors was consistent with the direction of the vertical winds observed, but the large variability of the vertical wind prohibited attempts at a correction. Performing a correction requires simultaneous measurement of the vertical wind component and temperature by RASS. Downslope wind storms are rare in the summer, and the decrease in the standard deviations with altitude is consistent with the errors being due to convection in the boundary layer. If only quiet periods are chosen in the winter observations, the standard deviation of the temperature differences is reduced to about 0.6°C at most heights.

A similar experiment has been performed at the Platteville field site with a 49.8 MHz wind profiler. A smaller sample consisting of three RAOB soundings in June and another four in October 1988 was used. The height coverage obtained is considerably greater with the lower frequency than with the other systems used in our studies. Typically profiles up to 6 km AGL are obtained, but some have been obtained as high as 11 km AGL under light wind conditions. However, the minimum height observable with the 49.8 MHz radar is about 2 km. Since wind appears to be the dominant factor affecting the height coverage with this radar the maximum range is highly variable. Figure 5 shows a scatter plot of the virtual temperatures measured with the RASS and RAOB systems, and again the agreement is clearly excellent. The slight offset is probably due to an error in calibrating the range of the radar system. The rms difference for the entire sample of seven soundings is 0.7°C. The small number of launches precludes a height by height comparison, but if groups of five heights are analyzed together the largest rms difference between the virtual temperatures measured by the RASS and RAOB is 1.0°C.

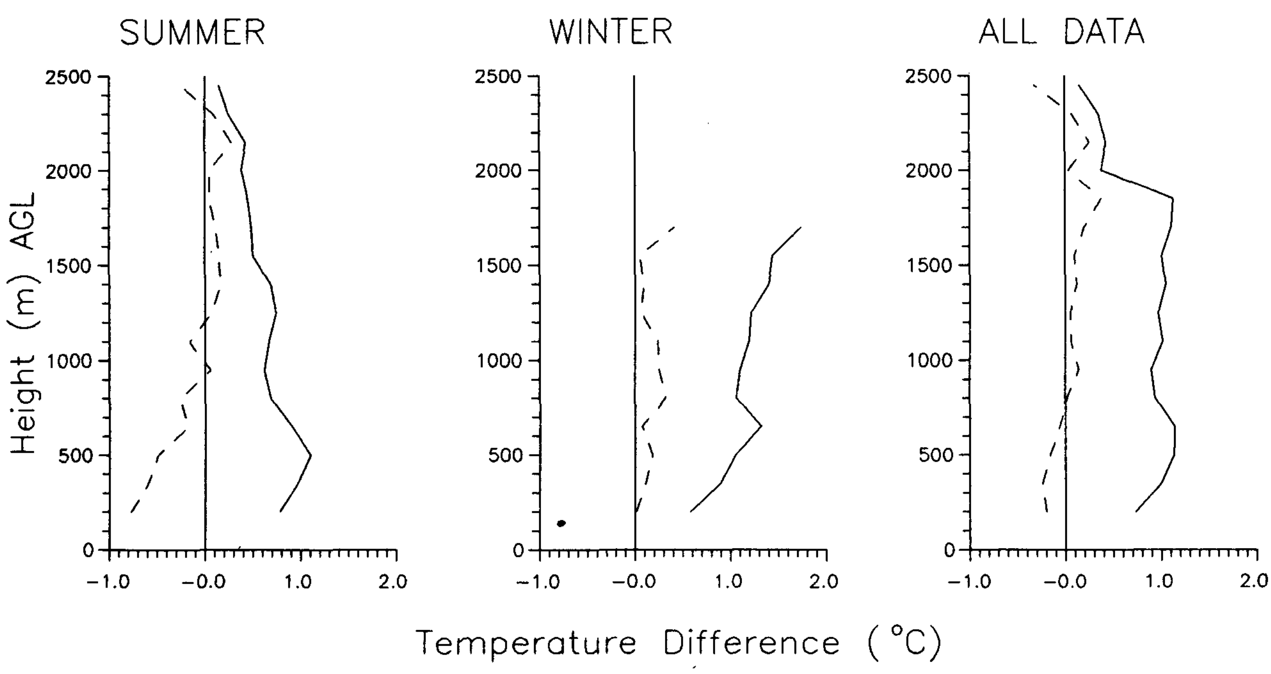

FIG. 4. Panels showing the mean ($T_{RASS} - T_{RAOB}$, dashed) and standard deviations (solid) of differences between the virtual temperature measurements obtained with RAOBs and RASS (using the Denver wind profiler). Summer observations, winter observations, and the combined data set are represented.

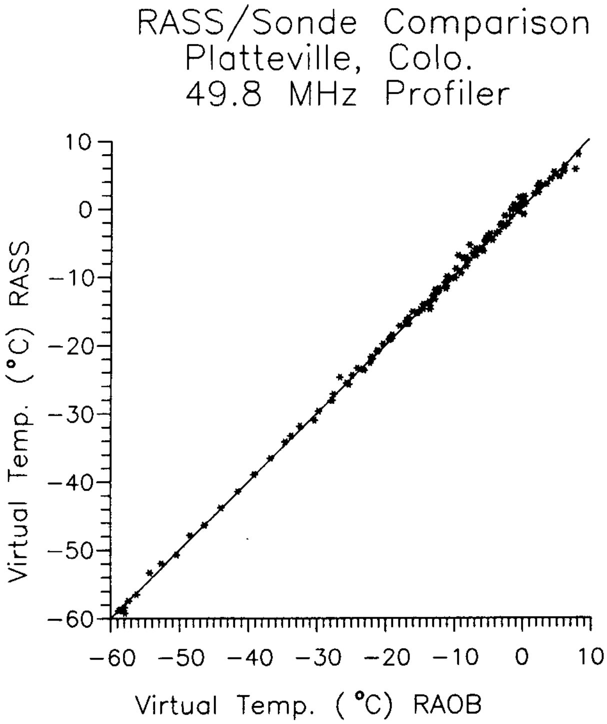

FIG. 5. Virtual temperatures measured by RASS and ROABs. The RASS used the Platteville 49.8 MHz wind profiler. The results of seven RAOB soundings are included. The rms difference is about 0.7°C.

5. Limits of the precision of the RASS measurements

A profile comparing RASS measurements and a RAOB profile obtained on 7 October 1988 is shown in Fig. 6. These data are exceptional for several reasons: (i) The altitude coverage was up to 11 km above ground because of the very light wind conditions and (ii) the fluctuations in the temperature measurements were very small. This indicates that the dominant sources of fluctuations in the temperature measurements, such as vertical wind motions and real temperature variability, were small during these observations. We can use these data to examine the precision that is possible with the RASS technique.

We calculated the standard deviation of the 1-min temperature observations for each height over a 35-min period (i.e., no consensus averaging was performed). Figure 7 shows the standard deviation as a function of height. The dashed curve on the plots represents a theoretical estimate obtained from simulations described in section 2 for a purely deterministic spectrum. At altitudes above 6 km, the observed standard deviations are close to the theoretical expectation, and show that the precision of the temperature measurement technique is better than 0.2°C. Even in the upper heights where the SNR has fallen below 0 dB the standard deviation is less than 0.5°C. Calculations of the autocorrelation function of the temperature time series show that for the measurements below 7.5 km the adjacent temperature measurements are significantly correlated ($\rho > 0.4$), so the observed standard deviation includes fluctuations that are not completely random (as are pure measurement errors). Therefore, a part of the observed standard deviation is due to atmospheric effects such as vertical motions and temperature fluctuations, which is consistent with the discrepancy between the theoretical uncertainty and the measured standard deviations. The fluctuations in the temperature data above 7.5 km are essentially uncorrelated from one observation to the next at most heights, thus they are probably due to measurement error alone.

The mean vertical motion can be measured by the wind profiler during the same time in which the temperature is measured. From Fig. 2 it is apparent that for many cases the error in a vertical velocity estimate will be much greater than the error in determining the speed of sound relative to the ground. Therefore, the former measurement will provide the limit to the accuracy of the temperature measurement. Nevertheless the potential precision of the RASS observations is significantly better than that of present radiosondes.

6. Concluding comments

The current RASS experiments are obtaining temperature measurements that are comparable in accu-

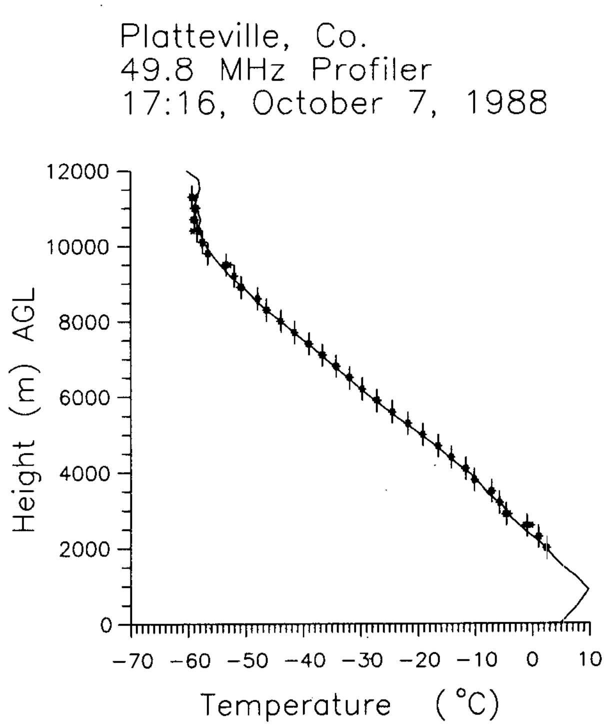

FIG. 6. A comparison of temperature profiles measured by RASS (using the Platteville 49.8 MHz profiler) and a RAOB. The stars represent the four RASS soundings during the RAOB ascent through the troposphere and the vertical bar marks the mean RASS measurement for each height. The solid line is the RAOB profile.

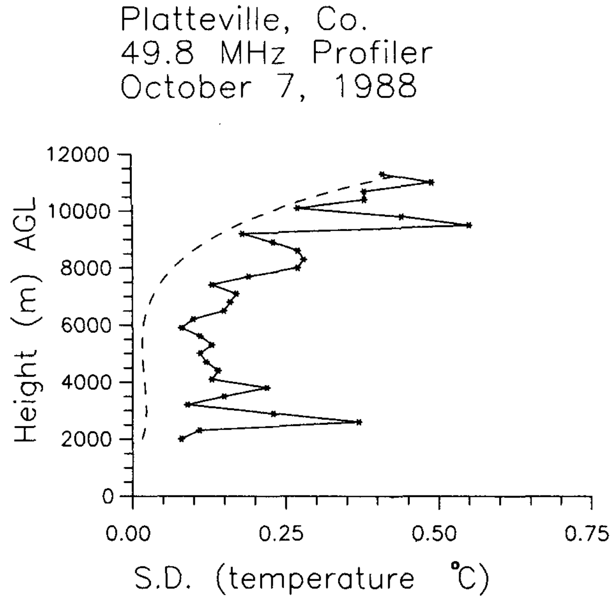

FIG. 7. Standard deviation of the 1-min interval temperature measurements, obtained with the Platteville 49.8 MHz profiler, over a 35-min period for each height (stars connected by the solid line) against height. The dashed curve is an approximate estimate of the standard deviation based on model simulations assuming a deterministic spectrum.

racy with radiosonde observations, although some averaging of the measurements is necessary to minimize the effects of vertical wind motions. Some recent observations have suggested that still greater accuracy is obtainable if corrections are made for the vertical wind motions. Again we note that such measurements can be made simultaneously with the temperature measurements.

A new RASS signal processor, which will operate in parallel with the routine wind profiler, is being designed. This processor will "piggyback" on the wind profiler, by sampling the raw output from the profiler's receiver and using the profiler's timing signals and local oscillator. However the new processing system will not use the long coherent integration periods that limit the Nyquist interval to about ± 50 m s^{-1}. Thus the system will measure a spectrum over an interval of about ± 400 m s^{-1}, or in an interval of ± 200 m s^{-1} with an offset of about 150 m s^{-1}. Because the acquisition time remains the same the frequency resolution will be maintained, so there will be many more points in the Doppler spectrum that are obtained (e.g., 2048 instead of 128). Now the processor will apply the standard analysis described earlier on two separate portions of the spectrum, one near zero velocity (vertical wind) and another near 330 m s^{-1} corresponding to the speed of sound. The sensitivity is unaffected because most of the noise part of the spectrum is ignored (equivalent to filtering it out with the time domain integration); but now we have simultaneous estimates of both the vertical wind speed and the speed of sound relative to the ground, so the effect of the mean vertical motions can be subtracted. Another benefit is that these two measurements may allow the measurement of the vertical heat flux (Peters et al. 1985). The only extra requirement is in computing costs.

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