Quality Controls for Profiler Measurements of Winds and RASS Temperatures

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ABSTRACT

A new method for estimating winds and radio acoustic sounding system temperatures from radar Doppler measurements for the new NOAA wind profilers is described. This method emphasizes the quality of 6-min measurements prior to the computation of hourly averages. Compared with the older method currently being used, this new method provides measurements exhibiting better consistency and more complete coverage over height and time. Furthermore, it corrects aliased measurements.

1. Introduction

Profiling radars are capable of measuring wind data (Weber and Wuertz 1990) and radio acoustic sounding system (RASS) virtual temperature data (May et al. 1990) comparable with those provided by rawinsondes but automatically and continuously in time. The accuracy of profiler measurements is limited by meteorological variability and radar measurement errors (Thomson and Williams 1991). Sometimes, however, the algorithms used to process the radar data can also degrade accuracy (Weber et al. 1992).

We present a new method, called the continuity method, for estimating hourly averaged winds and RASS temperatures that exhibit improved consistency over height and over time. This method is based upon an algorithm that eliminates spurious 6-min measurements before they can contaminate hourly averaged estimates (Weber and Wuertz 1991). We demonstrate this method using data from two UHF radars in the NOAA Wind Profiler Demonstration Network. Wind measurements used are from the profiler located at Platteville, Colorado, and RASS temperature measurements used are from the profiler located at Purcell, Oklahoma.

Radial velocities are measured on three different antenna beams (one vertical and two tilted 16.3° from vertical) at 36 fixed heights in two different height modes. In the low mode, measurements are made simultaneously at regular intervals of 250 m from about 0.5 to 9.25 km above ground level (AGL) with a radar range resolution of 375 m. In the high mode, measurements are made simultaneously at regular intervals of 250 m from about 7.5 to 16.25 km AGL with a radar range resolution of 1000 m. However, the measurements are not made simultaneously in both modes and on all three antenna beams. Rather, the radar switches sequentially between height modes and antenna beams in this order: east/high, east/low, north/high, north/low, vertical/high, and vertical/low. Measurements take about 1 min for each antenna beam in each height mode, so that a cycle is completed in 6 min and ten cycles are completed every hour. This provides ten radial velocity measurements every hour at each height on each antenna beam.

The radars have a maximum unambiguous radial velocity on the vertical antenna beam equal to ±12.6 m s^{-1} in the low mode and ±12.5 m s^{-1} in the high mode. On the north and east beams, it is ±15.6 m s^{-1} in the low mode and ±23.2 m s^{-1} in the high mode. These translate to maximum unambiguous horizontal velocities of ±55.6 m s^{-1} in the low mode and ±82.3 m s^{-1} in the high mode. Doppler aliasing of radial velocities, leading to grossly erroneous wind estimates, has been observed frequently in high winds during the first winter of operations.

The Purcell radar was specially configured during the spring of 1991 to measure both the vertical velocity component and the RASS temperature on the vertical antenna beam. Temperatures were measured each half-hour using two out of the ten time samples on the vertical beam in the low mode. The other eight times, vertical velocities were measured. The RASS measurements were made by introducing a frequency offset in the Doppler spectral processing (Strauch et al. 1988). A frequency offset of 884.7 Hz was used before 29 May 1991, giving temperature measurements ranging from −25.8° to +15.4°C. A frequency offset of 952.78 Hz was used after 29 May 1991, giving temperature mea-

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surements ranging from +15.4° to +59.7°C. No temperature averaging was done other than the 1-min observation for each RASS profile.

This special configuration of the radar caused extensive Doppler aliasing of radial velocities, leading to grossly erroneous temperature estimates. However, with new RASS data processing, aliasing is not a problem. Furthermore, with new RASS data processing, vertical velocities and RASS temperatures are measured simultaneously. (Simultaneous measurements were not made during this experiment at Purcell.) This is important sometimes when the vertical wind measurement is used to remove the effects of vertical motion from the temperature estimate (Weber et al. 1992). RASS temperatures are derived from measurements of the vertical component of the acoustic velocity, which is Doppler shifted by the vertical wind. A 1 m s^{-1} vertical wind causes a 1.6°C error in temperature if its effect is not included.

The vertical velocity measurement is also used to remove the effects of vertical motion from the horizontal wind component estimates derived from the radial velocity measurements on the two oblique antenna beams. Strauch et al. (1987) found larger variances for horizontal wind components when they were not corrected for vertical motion in clear air. Wuertz et al. (1988) found dramatically larger variances for horizontal wind components when they were not corrected for vertical motion in precipitation. We also expect larger variances when the wrong vertical velocity is used to correct the horizontal winds for vertical motion (Weber et al. 1992). That can happen when the vertical velocity measured by the vertical antenna beam directly above the profiler is not the same as the vertical velocity affecting the radial velocity measurements on the oblique antenna beams, which are displaced horizontally by several kilometers at the upper heights.

Hourly averaged winds are routinely produced by the profilers using a consensus algorithm (Fischler and Bolles 1981). That algorithm is applied separately each hour to select a consensus subset from the ten 6-min radial velocity measurements on each antenna beam. The consensus subset, which may include all ten points, must meet certain restrictive criteria. First, no two measurements in the consensus subset can differ by more than a certain amount (one-eighth of the maximum measureable velocity). Second, the consensus subset must number at least four out of the possible maximum of ten. If both of these criteria are met, then all 6-min measurements in the consensus subset are averaged and the average is reported as the hourly averaged radial velocity for the particular antenna beam. Points not included in this consensus subset are excluded from the average. If the largest consensus subset has fewer than four points, then no hourly average is computed or reported. At the end of each hour, the hourly averaged radial velocities from all three antenna beams are used to compute the horizontal wind components u, v and the vertical wind w.

Clearly, the hourly averages do not always include all measurements, particularly at higher altitudes where the signal-to-noise ratio is typically lower, yet they are still representative if the winds did not change significantly over an hour. On the other hand, if the winds are highly variable over an hour, only a few of the estimates might be used in computing the averaged winds. Then the averages would not be representative of the actual winds during an hour.

We call the method presently being used to produce hourly averaged winds the consensus method. Most of the time, it gives winds that are consistent both over height and over time (Weber et al. 1990). Sometimes, however, there are obvious errors with the consensus method due to spurious measurements or Doppler velocity aliasing. Other errors due to meteorological variability and radar measurement noise are not so obvious. Errors caused by small-scale spatial variations across the antenna beams are not detectable with a three-beam radar (a five-beam radar is required). However, errors caused by small-scale temporal variations can be detected (Weber et al. 1992).

The new continuity method addresses some of the problems associated with the consensus method. It identifies and removes spurious measurements. It identifies and corrects aliased measurements. It also provides more complete coverage over time and over height, with fewer missing wind reports. Finally, it attempts to provide more representative hourly averaged winds that have better consistency over time and over height.

2. Continuity method

The continuity method relies heavily upon the continuity or consistency of data over time and over height. Consistency is the most powerful check upon the quality of wind profiler measurements presently being used on the wind profiling radars in the NOAA demonstration network (Brewster and Schlatter 1988; Brewster 1989). We believe that this principle also applies to other data such as RASS temperature measurements.

Below, we outline the major features of the continuity method.

a. Winds

1) Aliased data are corrected by unfolding. Large radial velocities (e.g., those exceeding half the maximum unambiguous value) are unfolded and these are included with the original data from a complete hour. Unfolding is accomplished by adding twice the maximum value to negative velocities and subtracting twice the maximum value from the positive velocities. At the end of the process, we find that the aliased data are rejected and the unfolded data are retained when the latter are found to be consistent with the majority of measurements. Bargen and Brown (1980) state that velocity unfolding is better accomplished with larger datasets because larger datasets are less sensitive to cer-

tain kinds of noise that may dominate smaller datasets. Thus, this method uses all data during each hour (ten profiles) for both the low and high modes (72 heights). Bergen and Albers (1988) warn that certain noise must be removed prior to dealiasing because it can adversely affect pattern recognition. The pattern recognition in the new continuity algorithm effectively isolates this noise. We note in passing that this dealiasing step is not unique to the application of the present continuity method.

2) The 6-min radial velocities on each antenna beam are checked for continuity over time and height during each hour using the algorithm developed by Weber and Wuertz (1991). (See the Appendix for a brief description of this continuity algorithm.) Data for the low and high modes are usually considered together, although they can be treated separately. Radial velocity measurements that fail this continuity test are flagged and removed from further consideration in the computation of winds. This is the step that allows the original aliased data to be replaced with the unfolded data when the latter passes the continuity test and when the former fails that test.

3) The 6-min radial velocities on all antenna beams are linearly interpolated to the same times. This is done over 6-min intervals unless data are flagged earlier in step 2. Then the interpolation time interval is extended to 12 min, but never greater. After time interpolation, any missing data are replaced with data at the same time interpolated from adjacent heights above and below. If the height interval between existing data exceeds 500 m, then missing data are not replaced with interpolated data. We note that the interpolation becomes an extrapolation if the point in question is on a boundary, for example, at the end of an hour. Data are never extrapolated beyond 6 min in time or over 250 m in height.

4) The 6-min winds are computed, but only at those heights and times for which all three antenna beams reported a radial velocity. The vertical velocity measurements are used to remove the effects of vertical motion on the other two radial velocity measurements. This vertical correction can also be done after performing the hourly averaging in the next step, and identical results would be obtained.

5) Hourly averaged winds are computed at each height using a simple average of all available 6-min winds, which could be all ten samples or only one. This is to be contrasted with the consensus method which requires at least four of ten samples to be included in the average at each height. The continuity method can use fewer points at each height because it looks for consistency over both height and time. Although there may be only one time sample at a given height, its confidence can be assured by data at adjacent heights. This is an advantage over the consensus method that looks for consistency only over time by using the consensus algorithm at each height separately. If no 6-min winds are computed at a given height during an hour, then no hourly winds are reported there.

b. Temperatures

Temperature data are usually treated similarly to the wind data.

1) Unfolded values are computed for all data that are possibly aliased and are included along with the original data just as with the wind data. However, because of the temporary experimental configuration of the Purcell profiler, uncontaminated RASS temperature data were frequently in the minority. We discovered that aliasing was more common than not during the spring of 1991 because the Purcell profiler was not optimized for RASS temperature measurements. Therefore, we found it necessary to apply meteorological controls as follows. We used a crude model, with temperature decreasing linearly with height, to exclude all measurements that differed by 10°C from this model. The model assumed that temperatures nearest the ground were correct. This assumption was supported by other independent measurements made during the experiment. The slope of the linear model was not critical because the 10° tolerance was so large. The model was only used to unfold aliased data.

2) The temperatures are checked for continuity over time and height during each day using the algorithm developed by Weber and Wuertz (1991). In future real-time applications, the RASS temperatures will be quality controlled separately during each hour when temperatures and vertical velocities will be measured simultaneously, enabling correction of the temperatures for the effects of vertical motion. Temperatures that fail the continuity test are flagged. Again, this is the step that allows the original aliased data to be replaced with unfolded data.

3. Comparisons of hourly winds

We compared hourly averaged winds produced by the consensus method with those produced by the continuity method. The examples given here serve to illustrate four potential problems: (a) aliasing in strong winds, (b) false winds from spurious measurements, (c) missing winds due to signal processing failures, and (d) errors introduced by signal processing.

a. Aliased winds

Figure 1a illustrates aliasing in the hourly averaged winds generated by the consensus method. The aliasing occurred at heights between 8 and 12 km above mean sea level (MSL), where a strong jet produced velocities that exceeded the maximum unambiguous velocity measurable by the radar. Figure 1b shows unfolded hourly averaged winds generated by the continuity method using the same 6-min data that was used to

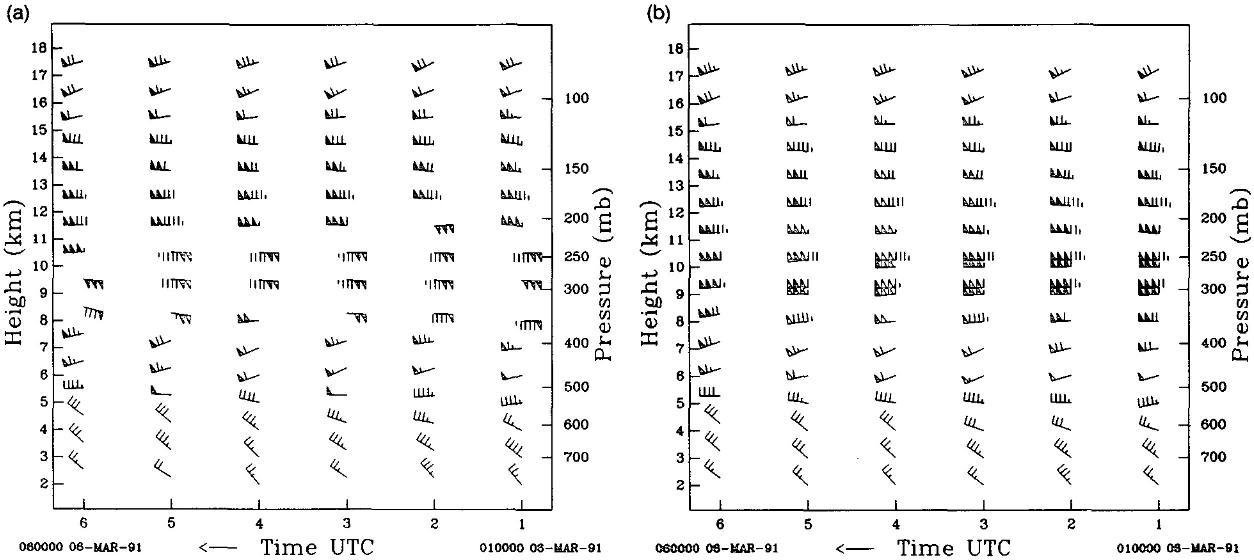


FIG. 1. (a) Hourly averaged winds (consensus method) from the NOAA UHF wind profiler located at Platteville, Colorado, from 0100 to 0600 UTC 6 March 1991. This is an example of strong jet-stream winds between 8 and 12 km MSL causing velocity aliasing. Winds are shown at 1-km intervals, although winds were reported at 250-m intervals. Units are the standard knots (0.5144 m s^{-1}), where a flag equals 50 kt, a full barb equals 10 kt, and a half-barb equals 5 kt. (b) Same as Fig. 1a except that the winds were estimated using the continuity method. Winds are shown closer together where the low and high modes overlap, that is, between 9 and 11 km. [Units are the same as in (a)].

generate the winds in Fig. 1a. Although aliased winds are a nuisance, unfolding them is not particularly challenging for the continuity method.

b. False winds

Figure 2a shows winds generated by the consensus method. There is one obviously false wind just under 17 km MSL at 0500 UTC. This could be an airplane. The radar will occasionally mistake some spurious signal such as an airplane echo for the atmospheric signal, which is generally weaker at the upper heights. There are also many missing winds near and above 17 km MSL and around 14 km MSL during the first 3 h. The consensus method failed to find a minimum of four out of ten measurements on at least one of the east

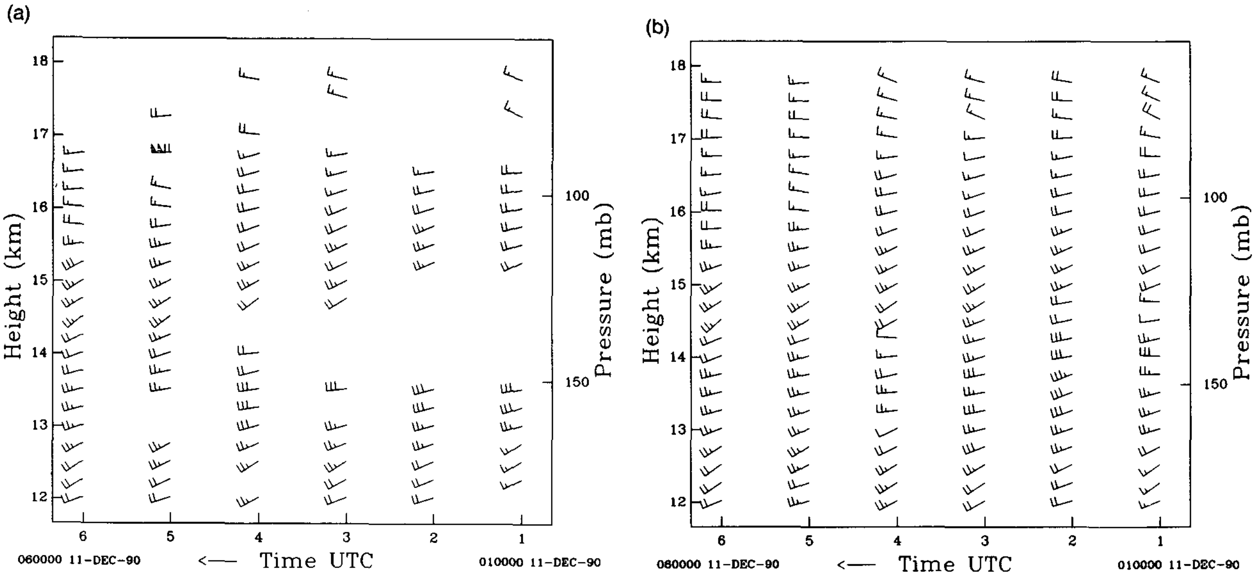
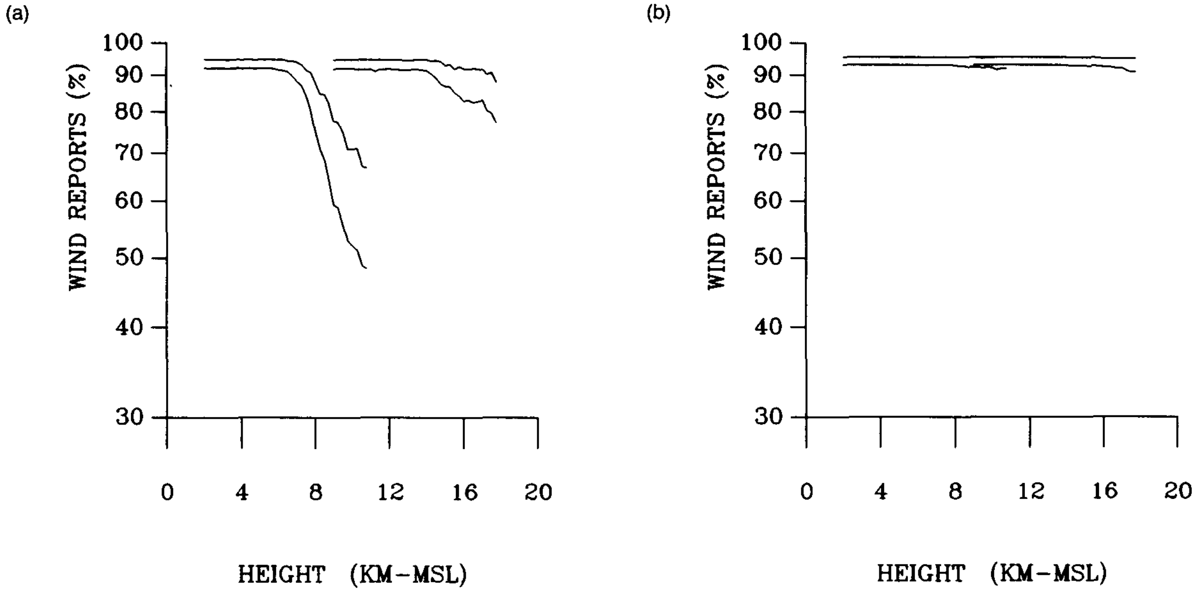


FIG. 2. (a) Hourly averaged winds (consensus method) from the NOAA UHF wind profiler at Platteville, Colorado, from 0100 to 0600 UTC 11 December 1990. This illustrates one spurious wind measurement, perhaps caused by an aircraft, and many failures to report any measurement, probably caused by low signal-to-noise ratio. (Units are the same as in Fig. 1a.) (b) Same as (a) except that the winds were estimated using the continuity method.

and north antenna beams due to weak signals in the radar Doppler spectra. Both antenna beams must pass the consensus test in order to report a wind. Figure 2b shows the hourly averaged winds generated by the continuity method using the same 6-min data. The erroneous 6-min data responsible for the false wind are removed and replaced with values interpolated from the surrounding 6-min data. The many missing winds in Fig. 2a appear in Fig. 2b because the continuity method does not require as many 6-min measurements at a given height. The continuity method looks for consistency over both height and time, not just over time like the consensus method. In addition, interpolation will replace some missing 6-min data due to outliers.

c. Missing winds

Figure 3a gives the percentage of wind reports by the consensus method as a function of height from mid-December 1990 to mid-January 1991. There are four curves, two for the low mode and two for the high mode. The upper curve in each case gives the number of 3-h reports, whereby a report is counted if the profiler reported a wind for at least one of every three consecutive hours. The lower curve in each case gives the simple hourly reports. A consensus of at least four was required in every case. Note the decline in the percentage of reports at the upper gates for both the low and high modes, no doubt due to decreasing signal-to-noise ratio. The percentage does not approach 100%



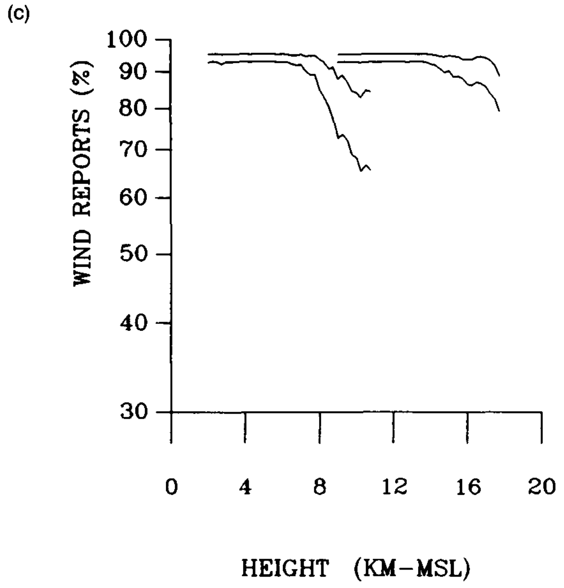


FIG. 3. (a) Percentage of wind reports (consensus method) for the NOAA UHF wind profiler at Platteville, Colorado, from 1200 UTC 11 December 1990 to 1200 UTC 11 January 1991. The two curves to the left are for the low mode and the two curves to the right are for the high mode. The upper curve in each case is for reports during three consecutive hours and the lower curve is for hourly reports. (b) Same as (a) except that the winds were estimated using the continuity method. (c) Same as (a) except that the winds were estimated using the continuity method without time–height interpolation.

at the lowest gates because the profiler was off-line for about 5% of this test period.

Figure 3b shows the wind reports by the continuity method for the same time period. There are also four curves in this figure, but the data are so complete that coverage is nearly constant as a function of height. The continuity method provides fewer missing points, largely due to the time–height interpolation used with the continuity method at the 6-min level. Figure 3c shows that, without interpolation, the continuity method provides only slightly better coverage than the consensus method. This is not surprising since we are not replacing the missing data.

d. Processing errors

Finally, we consider errors introduced by signal processing. Figures 4a and 4b compare the u and v components of winds, respectively, reported at the same times and at the same heights from mid-December 1990 through mid-January 1991 by the consensus and continuity methods. Although a few outliers are evident in these figures, most points cluster around the diagonal going from lower left to upper right, indicating that both methods produced similar wind data.

Table 1 gives the statistics for these first comparisons shown in Figs. 4a and 4b (the first line for each wind component) along with three other related comparisons. The second comparisons (second line) were done with outliers removed from the consensus-method winds since they can bias statistics. There were no such outliers in the continuity-method winds. Outliers were identified by their large inconsistencies with winds at neighboring times and heights. They numbered 474 out of 37 939 points, that is, about 1%, which seems to be far larger than the number of obvious outliers in Figs. 4a and 4b. This apparent inconsistency is resolved once we realize that the differences between the two methods, as represented by the scatter in points about the diagonals in Figs. 4a and 4b, are not insignificant.

The third comparisons (third line in Table 1) were made between consensus-method winds and winds derived by the continuity method without time–height interpolation. The fourth comparisons (fourth line in Table 1) were made between winds derived by the continuity method with and without interpolation. The results of these comparisons show significant disagreements between the consensus and continuity methods. They also show significant, although smallest, differences due to the interpolation (fourth line in Table 1).

The differences between the u and v components produced by the two methods (with outliers removed) have standard deviations of 1.49 and 1.29 m s^{-1}, respectively (second line in Table 1). Those standard deviations are about half of those found in comparisons between this same wind profiler and the NWS rawinsonde at Denver (Weber et al. 1990). Those differences were attributed mainly to meteorological variability over the large distances (at least 60 km) separating the two instruments. Furthermore, these standard deviations are not much smaller than the 2.5 m s^{-1} found in nearly two years of profiler–rawinsonde comparisons (Weber and Wuertz 1990).

These differences between the methods are troubling because the comparisons were done using hourly averaged winds generated by different processing methods that started with the same 6-min measurements made by the same instrument. We attribute these differences to the ways in which the different methods respond to temporal changes over an hour in the 6-min radial ve-

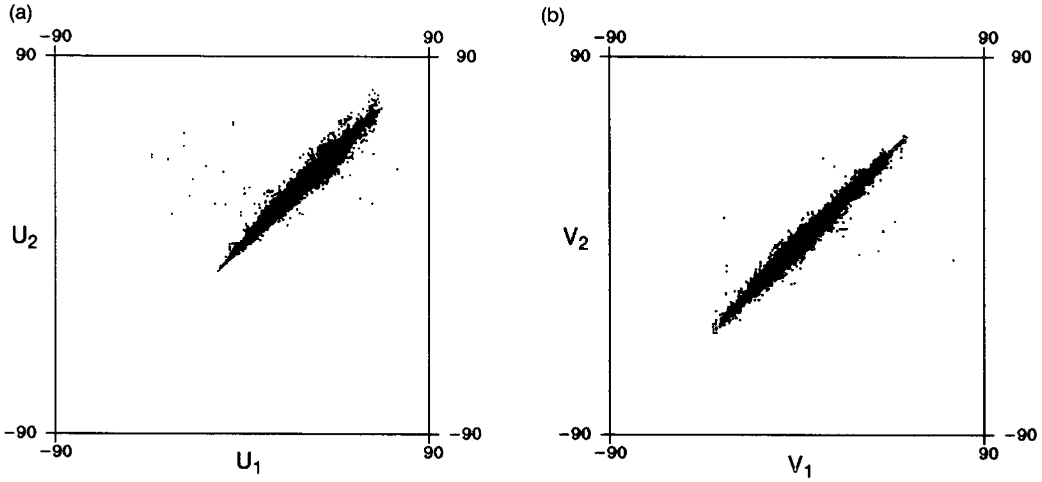


FIG. 4. (a) Comparisons of hourly averaged u component wind measurements for the NOAA UHF wind profiler at Platteville, Colorado, from 1200 UTC 11 December 1990 to 1200 UTC 11 January 1991. The horizontal axis gives the u component estimated with the consensus method, while the vertical axis gives the u component estimated with the continuity method. (b) Comparisons of hourly averaged v component wind measurements for the NOAA UHF wind profiler at Platteville, Colorado, from 1200 UTC 11 December 1990 to 1200 UTC 11 January 1991. The horizontal axis gives the v component estimated with the consensus method, while the vertical axis gives the v component estimated with the continuity method. Units are meters per second.

TABLE 1. Comparison of methods during the period from 1200 UTC 11 December 1990 to 1200 UTC 11 January 1991.

	Pairs	Correlation	Std dev[a]	Std dev[a]	Mean[b]	Std dev[c]
u	37 939	0.99	12.94[d]	12.83[e]	0.04	2.02
	37 465	0.99	12.92[f]	12.86[e]	0.02	1.49
	36 741	0.99	12.80[f]	12.75[g]	0.01	1.49
	58 272	0.99	12.65[e]	12.67[g]	−0.02	1.38
v	37 939	0.99	13.30[d]	13.26[e]	0.16	1.50
	37 465	1.00	13.32[f]	13.29[e]	0.16	1.29
	36 741	1.00	13.29[f]	13.27[g]	0.16	1.32
	58 272	1.00	12.19[e]	12.20[g]	0.00	1.05

[a] Standard deviation (m s^{-1}) of wind components used in comparisons.

[b] Average of differences (m s^{-1}) between wind components produced by different methods.

[c] Standard deviation of differences (m s^{-1}) between wind components produced by different methods.

[d] Wind components estimated with old consensus method.

[e] Wind components estimated with new continuity method using time–height interpolation.

[f] Wind components estimated with old consensus method and with outliers removed.

[g] Wind components estimated with new continuity method *not* using time–height interpolation.

locity measurements. Those temporal changes may be due to meteorological variations and radar measurement errors, which are expected to be larger in the 6-min measurements than in the hourly averaged measurements. Both components of the hourly averaged winds exhibited considerable variability throughout the troposphere over the month of comparisons. Their standard deviations were about 12–13 m s^{-1}. The standard deviations for the 6-min winds were larger than this.

These comparisons (Table 1) alone cannot assess the absolute accuracy of either method. Nor can they be used to argue for or against time–height interpolation in the continuity method. We saw that time–height interpolation dramatically improves coverage, particularly at the upper heights in the low mode (Figs. 3a and 3b). That is the strongest argument for time–height interpolation. Consensus-method winds are reported only if radial velocity measurements are made on both oblique antenna beams (in some cases also on the vertical beam) at each height. Continuity-method winds are reported only if radial velocity measurements are made on all three antenna beams at each height. These restrictions will prevent some 6-min measurements from being included in the hourly averaging unless time–height interpolation is employed.

In general, therefore, there are more 6-min measurements than hourly averaged winds. With fewer missing data at the 6-min level, the time and height intervals used for interpolation are smaller. By not interpolating the 6-min measurements, the present consensus method forces the user of hourly averaged winds to interpolate under less favorable conditions.

However, there is another argument for interpolation even when coverage is complete without it. Figures 5a, 5b, and 5c show hourly averaged winds produced, respectively, by the consensus method, by the continuity method with interpolation, and by the continuity method without interpolation. The consensus method failed to report 19 winds at and around 1900 UTC because it could not find a minimum consensus of at least four out of ten measurements on all antenna beams. The continuity method reported winds at all heights every hour whether interpolation was done or not.

More troubling than the missing winds are the differences in the winds reported by the two methods. For example, the wind reported by the consensus method above 7 km MSL at 1900 UTC is about 15 kt larger than the winds reported by the continuity method with time–height interpolation (Fig. 5b) and about 10 kt larger than the winds reported by the continuity method without time–height interpolation (Fig. 5c). Since both the consensus method and the continuity method began with the same 6-min radial velocity data, each method must have used a different subset of those data.

When comparing all winds at the same times and at the same heights, we find that the consensus-method winds in Fig. 5a differ most from the continuity-method winds in Figs. 5b and 5c (Table 2). The continuity-method winds in Figs. 5b and 5c show the closest agreement. The differences in their wind components have standard deviations that are less than half the standard deviations of the differences between those wind components and the consensus-method wind components. That is not surprising since the two continuity methods use the same subsets of 6-min radial velocities. These comparisons (Table 2) are consistent with the earlier comparisons (Table 1), even though the standard deviations of the wind components in the present case are less than half those in the earlier case.

Although we could not assess the absolute accuracy of either method using these comparisons, we can determine the self-consistency of each method by comparing all wind pairs reported by each method that fell within 1 h and within 250 m of one another (Table 3). The continuity method with interpolation gave the most uniform winds. The continuity method without interpolation gave the next most uniform winds and the consensus method gave the least uniform winds. Remember that interpolation was not required in this case in order to replace missing hourly data. There were only a few outliers in the 6-min data, but the main effect of interpolation was to correct for the sample time differences on the various antenna beams. That correction was necessary because the winds, in this case, were affected by large vertical velocities due to strong wave motion that caused large variations in the radial velocity measurements over an hour (Weber et al. 1992).

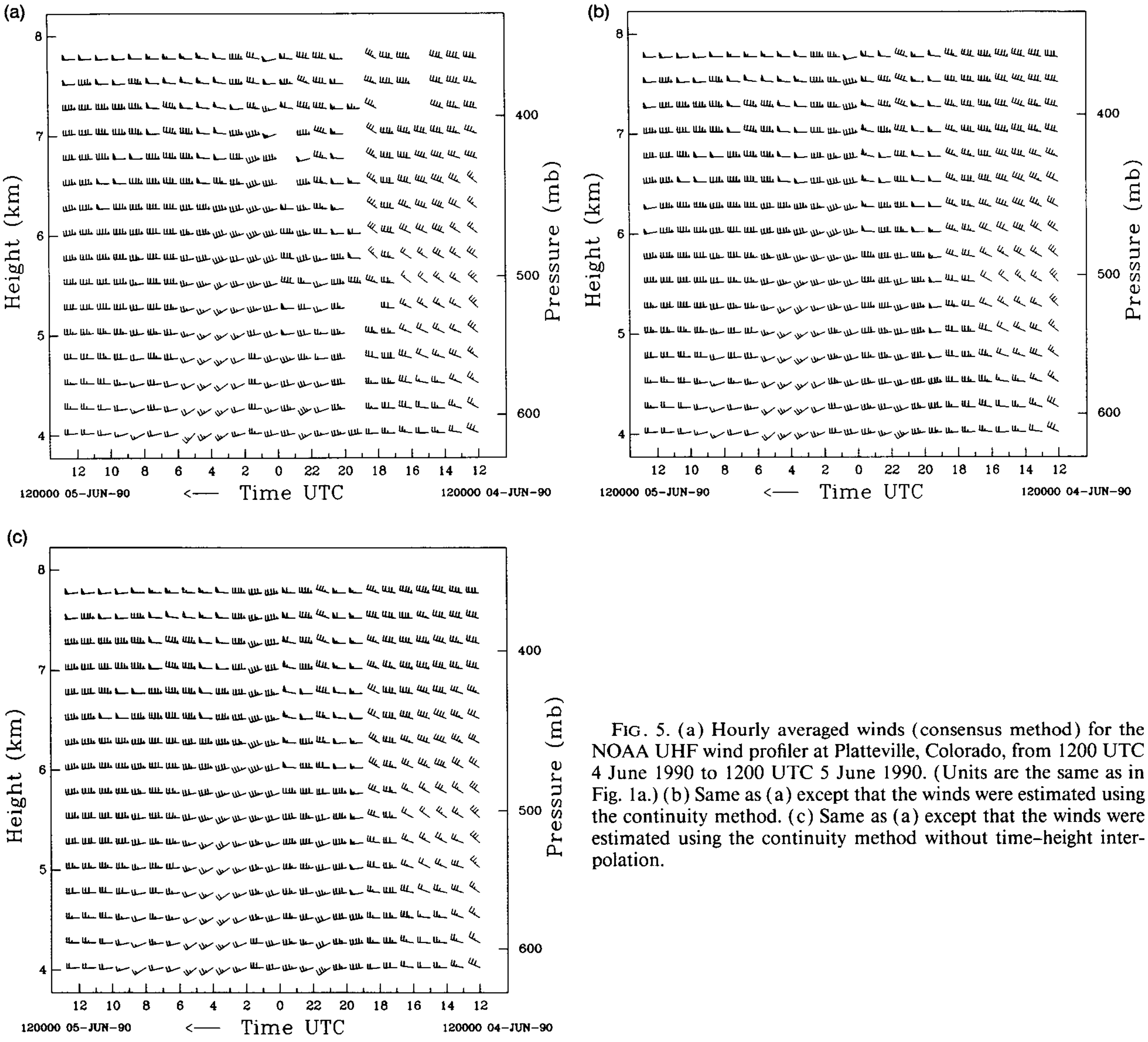


FIG. 5. (a) Hourly averaged winds (consensus method) for the NOAA UHF wind profiler at Platteville, Colorado, from 1200 UTC 4 June 1990 to 1200 UTC 5 June 1990. (Units are the same as in Fig. 1a.) (b) Same as (a) except that the winds were estimated using the continuity method. (c) Same as (a) except that the winds were estimated using the continuity method without time–height interpolation.

4. RASS temperatures

Figure 6a shows RASS temperature measurements, with extensive aliasing, during one 24-h period. (With new RASS data processors aliasing is not a problem.) Figure 6b shows those measurements after application of the continuity method without using the crude linear temperature model. It had no trouble unfolding the aliased data even though the correct temperatures were greatly limited in the original data and there was extensive noise above 3 km due to low signal power.

Figures 7a and 7b illustrate a case in which the crude temperature model was necessary. The correct data were in the minority, even after dealiasing. They are obvious in Fig. 7b, but they are not so obvious in Fig. 7a. The temperatures are clearly aliased at the lower heights (Fig. 7a). Yet, note the temperatures of about −10°C that are widely distributed during the first half of the day and that blend with temperatures in the upper gates during the second half of the day. Based purely upon their continuity and large numbers alone, it is not obvious that any of those temperatures are bad. We eliminated them only by using the crude temperature model. Did we do the right thing? This example illustrates the importance of meteorological models and independent checks on the quality of profiler measurements of winds and temperature.

5. Sampling errors

Radar sampling errors can limit the accuracy of profiler measurements of winds and temperatures. Under ideal conditions, when the winds are uniform across the antenna beams and when the winds and temperatures are constant over an hour, consensus averaging will produce accurate measurements. However, when

TABLE 2. Comparison of methods during the 24-h period starting at 1200 UTC 4 June 1990 for heights between 4 and 8 km MSL.

	Pairs	Correlation	Std dev[a]	Std dev[a]	Mean[b]	Std dev[c]
u	381	0.95	5.74[d]	5.35[e]	0.26	1.83
	381	0.96	5.74[d]	5.39[f]	0.13	1.67
	400	0.99	5.40[e]	5.50[f]	−0.09	0.80
v	381	0.94	4.35[d]	4.05[e]	0.12	1.48
	381	0.94	4.35[d]	4.12[f]	0.12	1.54
	400	0.98	4.05[e]	4.12[f]	0.02	0.74

[a] Standard deviation (m s^{-1}) of wind components used in comparisons.

[b] Average of differences (m s^{-1}) between wind components produced by different methods.

[c] Standard deviation of differences (m s^{-1}) between wind components produced by different methods.

[d] Wind components estimated with old consensus method.

[e] Wind components estimated with new continuity method using time–height interpolation.

[f] Wind components estimated with new continuity method *not* using time–height interpolation.

small-scale motion is present, this method of computing hourly averaged winds can be inaccurate (Weber et al. 1992).

Three-beam profiling radars are incapable by themselves of detecting or compensating for spatial nonuniformities in the winds. The presence of large vertical velocities may indicate the existence of nonuniform winds, although three-beam radars are unable to determine the errors caused by those nonuniformities. Yet, even if the winds are spatially uniform across the antenna beams, temporal variations during an hour can cause errors in hourly averaged winds. These errors are caused by time offsets in the measurements made on the different antenna beams. Some time offsets are caused by the fact that the measurements are generally not made simultaneously on all antenna beams. But these time offsets are typically only about a minute or so for hourly averages. A more important source of time offsets is subsampling due to data editing that removes spurious measurements. The consensus method presently being used makes no attempt to compensate for these time offsets, whereas the continuity method does by interpolating the measurements on the different antenna beams to the same time.

The radial velocity (positive directed away from the radar) observed on any given antenna beam is represented by

$$v_r(t) = u_0(t)\sin\phi\sin\theta + v_0(t)\cos\phi\sin\theta + w_0(t)\cos\theta + v_r', \tag{1}$$

where the antenna beam has a zenith angle θ from vertical and an azimuth angle ϕ clockwise from north. The subscript r is replaced with e, n, and z to denote the east, north, and zenith antenna beams, respectively.

The east, north, and vertical wind components are represented by u_0, v_0, and w_0, respectively. In the case of RASS, w_0 represents the acoustic velocity Doppler shifted by the vertical wind component. These are assumed to be functions only of the time t and therefore are the same at all three antenna beam locations for a given height. The term v_r' includes both radar measurement errors and meteorological noise.

The wind profiler measures a reflectivity-weighted average of radial velocity in each resolution cell, where reflectivity is weighted by the spatial distribution of refractivity fluctuations with spatial scale of half the radar wavelength. It is the strength of these refractivity fluctuations, along with the size of the radar antenna and the transmitted power that limit the profiler sensitivity or its ability to detect weak atmospheric signals in noise. Sometimes the atmospheric signal is so weak (or missing altogether) that the profiler spectral processing mistakes ground clutter, an airplane echo, or some noise spike for the atmospheric signal. Then, the radar measurement has no relation to reality. Fortunately, the consensus method or the continuity algorithm eliminates those measurements from further consideration when they exhibit no consistency with neighboring measurements.

When a real atmospheric signal is detected though, accuracy is usually limited by meteorological noise. Meteorological noise is caused by turbulent fluctuations within the scattering volume of both the radial velocity and the refractivity. The meteorological noise is revealed as a broadening of the atmospheric signal, which usually extends over several Doppler bins in the radar Doppler spectrum. It is this broadening that limits the accuracy of the spectral moment estimates and, thus, the radial velocity estimates. The Doppler bin size is determined by the radar pulse repetition frequency,

TABLE 3. Consistency of methods during the 24-h period starting at 1200 UTC 4 June 1990 for heights between 4 and 8 km MSL.[a]

	Pairs	Correlation	Std dev[b]	Std dev[c]
u	3077	0.73	5.66[d]	4.13
	3358	0.82	5.31[e]	3.19
	3358	0.77	5.41[f]	3.64
v	3077	0.83	4.32[d]	2.54
	3358	0.85	4.01[e]	2.19
	3358	0.84	4.09[f]	2.31

[a] Comparisons were made for each method using wind components reported within 1 h and 250 m of one another.

[b] Standard deviation (m s^{-1}) of wind components used in comparisons.

[c] Standard deviation of differences (m s^{-1}) between wind components.

[d] Wind components estimated with old consensus method.

[e] Wind components estimated with new continuity method using time–height interpolation.

[f] Wind components estimated with new continuity method *not* using time–height interpolation.

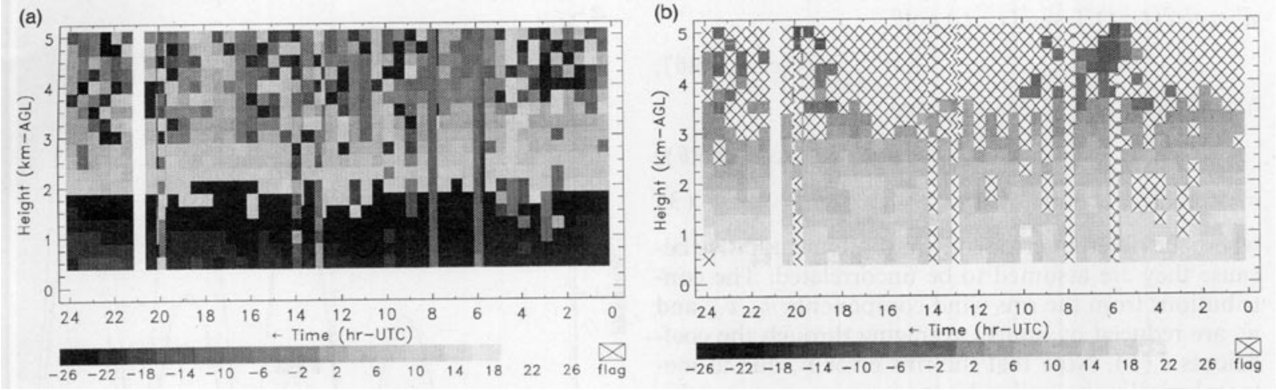


FIG. 6. (a) Original RASS virtual temperatures (°C) from 0000 to 2400 UTC 26 April 1991 for the NOAA wind profiler at Purcell, Oklahoma. (b) Same as (a) after continuity method.

the number of coherent time averages, and the size of the fast Fourier transform (FFT), which were selected to give the best overall compromise within the constraints of operation (Hassel and Hudson 1989).

A three-beam profiler is designed based upon the assumption that the winds are uniform across the spatially separated antenna beams. Therefore, any nonuniformity in the winds must be included in the noise term v'_r. For the purposes of the present analysis, we shall assume meteorological noise and radar measurement errors are statistically the same on all antenna beams. We also assume that the noise components v'_r are random with zero mean value and with no correlation between antenna beams. Such noise produces unbiased, random errors in the wind estimates. It should be recognized that in some cases actual noise may violate certain of these conditions.

Time sampling differences on the different antenna beams can, however, cause biased errors when the winds change with time. This is indicated by the errors

$$u' = u_0(t_e) - u_0(t) + [w_0(t_e) - w_0(t_z)]\cot\theta + v'_e \csc\theta - v'_z \cot\theta,$$

$$v' = v_0(t_n) - v_0(t) + [w_0(t_n) - w_0(t_z)]\cot\theta + v'_n \csc\theta - v'_z \cot\theta,$$

$$w' = w_0(t_z) - w_0(t) + v'_z. \qquad (2)$$

These errors were computed by taking the differences between the 6-min winds (1) and the true winds. The time t is some arbitrary time during an hour at which the winds are reported. The actual times at which samples are taken on the east, north, and zenith antenna beams are t_e, t_n, and t_z, respectively. Kristensen and Gaynor (1986) give a thorough examination of the errors in second moment estimates caused by temporal and spatial variations across separated beams. Here we are interested only in errors caused by temporal variations.

We compute hourly averages of the errors (2) while including some number of the samples $n \leq 10$. Then, we compute the rms values for those hourly averaged errors using a statistical ensemble in which the wind components are random and uncorrelated. As a result, the rms errors are found to be

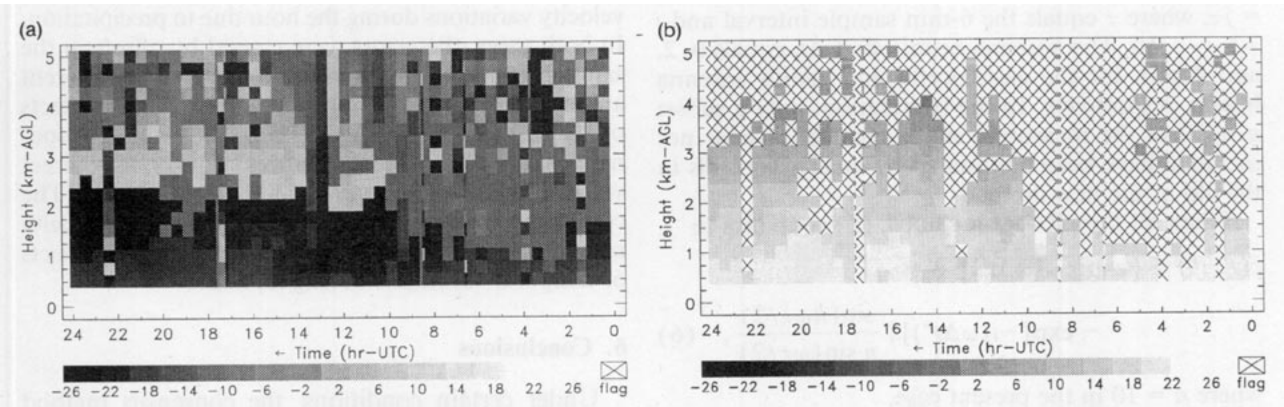


FIG. 7. (a) Original RASS virtual temperatures (°C) from 0000 to 2400 UTC 12 May 1991 for the NOAA wind profiler at Purcell, Oklahoma. (b) Same as (a) after continuity method.

$$\begin{aligned}\bar{u}' &= \bar{u}_0\bar{c}(t_e, t) + \bar{w}_0\bar{c}(t_e, t_z)\cot\theta \\ &\qquad + n^{-1/2}\bar{v}'_r(\csc\theta + \cot\theta), \\ \bar{v}' &= \bar{v}_0\bar{c}(t_n, t) + \bar{w}_0\bar{c}(t_n, t_z)\cot\theta \\ &\qquad + n^{-1/2}\bar{v}'_r(\csc\theta + \cot\theta), \\ \bar{w}' &= \bar{w}_0\bar{c}(t_z, t) + n^{-1/2}\bar{v}'_r, \end{aligned} \tag{3}$$

where the different error contributions are additive because they are assumed to be uncorrelated. The contributions from the rms wind components $\bar{u}_0$, $\bar{v}_o$, and $\bar{w}_o$ are reduced by hourly averaging through the coefficients $\bar{c}$ (5). Note that the rms error $\bar{v}'_r$ due to meteorological noise and radar measurement errors (this is the same on all antenna beams) is reduced by the factor $n^{-1/2}$, which is 0.32 if all ten samples over an hour are included in the average (it is larger if fewer than ten samples are included). Hence, averaging over an hour does not significantly reduce this source of errors.

We assume that the wind components vary periodically with time according to

$$\exp[-i(\omega t)], \tag{4}$$

where ω is the wave frequency. The amplitudes and the phases of the wind components are taken to be randomly varying in the ensemble average. We use complex notation here, but of course the measurements are real. Therefore, we take the real part of our results to represent physical quantities.

Then the coefficients for hourly averaging are defined by

$$\begin{aligned}\bar{c}(t', t'') &= \overline{\exp[-i(\omega t')] - \exp[-i(\omega t'')]} \\ &= \{\exp[-i(\omega\Delta t')] - \exp[-i(\omega\Delta t'')]\} \\ &\qquad \times \frac{1}{n}\sum_j \exp[-i(\omega t_j)]. \end{aligned} \tag{5}$$

The times t' and t'' are the times t, t_e, t_n, and t_z in (2). The time at which measurements are made on a given antenna beam is $t_r = t_j + \Delta t_r$. The sample times $t_j = j\tau$, where τ equals the 6-min sample interval and $j = 1 \cdots 10$. The antenna beam offset Δt_r equals 0, 2, and 4 min for the east, north, and zenith antenna beams, respectively. In the summation, only a subset $n \leqslant 10$ of the measurements is included. Those not included have been eliminated by quality controls in the old or the new method.

When all samples are included, (5) simplifies to

$$\begin{aligned}\bar{c}(t', t'') &= \{\exp[-i(\omega\Delta t')] \\ &\qquad - \exp[-i(\omega\Delta t'')]\}\,\frac{\sin(n\omega\tau/2)}{n\sin(\omega\tau/2)}, \end{aligned} \tag{6}$$

where $n = 10$ in the present case.

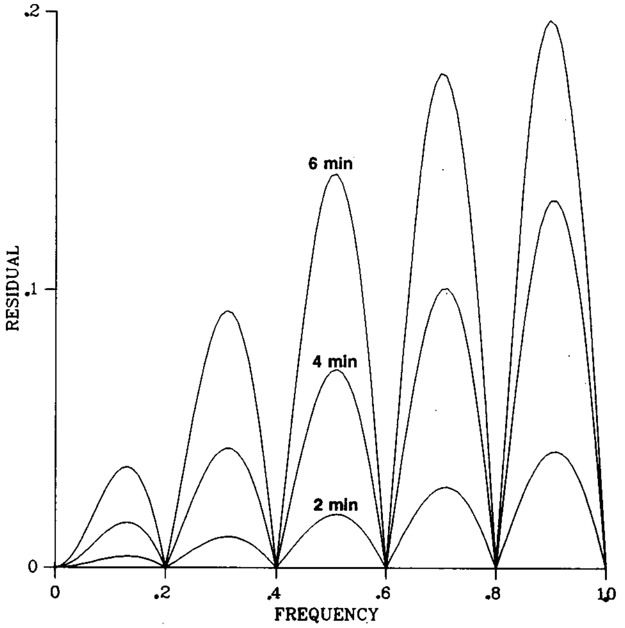


FIG. 8. The residual, given by the time-averaging coefficient [Eq. (6)], as a function of frequency (fraction of Nyquist), for time offsets of 2, 4, and 6 min.

Figure 8 shows that the time coefficient (6) increases dramatically when the time offset increases from 2 to 4 to 6 min. This coefficient has the highest values for frequencies approaching the Nyquist frequency $(2\tau)^{-1}$ (τ = 12 min). This result in Fig. 8 shows that there can be biases up to 20% of the magnitude of the wind components, and this is the best case. When fewer than all ten samples are included in the average, the residuals are larger. If there is no time offset, then this coefficient vanishes at all frequencies. It also vanishes when the frequency ω is zero, that is, for stationary winds. In those cases, errors are entirely due to meteorological noise and radar measurement errors $\bar{v}'_r$.

Weber et al. (1992) showed that large errors can occur in both wind and temperature measurements due to wind variations during the hour. Wuertz et al. (1988) showed that large errors can result from vertical velocity variations during the hour due to precipitation. In both cases, the errors were caused by offsets in the sample times for the measurements on the different antenna beams. It is important to remove the effects of vertical motion from the horizontal wind components and the RASS temperatures by using the correct vertical velocities measured at the same times. The continuity method interpolates 6-min radial velocity measurements in order to minimize the negative effects of temporal variations during an hour.

6. Conclusions

Under certain conditions, the consensus method (currently being used on the profiling radars in the NOAA demonstration network) may report inaccurate or nonrepresentative hourly averaged winds and RASS temperatures. We have identified four types of conditions that degrade profiler performance. 1) Measurements are aliased when radar Doppler velocities are too large. 2) No measurements are reported (usually at the upper range gates of the low and high modes) when a consensus is not found. 3) Spurious measurements are reported when the Doppler spectral processing mistakes ground clutter or other false targets for the atmospheric signal. And 4) erroneous measurements are reported when winds are nonstationary over an hour. The new continuity method described here attempts to solve these problems. We have demonstrated that it more reliably produces hourly averaged measurements with better consistency over time and over height than does the consensus method.

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APPENDIX

The Continuity Algorithm

The continuity algorithm (Weber and Wuertz 1991) checks the consistency of profiler measurements of winds and RASS temperatures over height and over time. The algorithm does this by looking for large changes in the measurements over the radar sample intervals (250 m in height and 6 min in time). For example, consider a case for Colorado just east of the Rocky Mountains. Profiler measurements over a 24-h period reveal strong winds out of the west with a jet near the 10-km altitude and a peak velocity around 55 m s^{-1}. There is one measurement in the middle of the jet giving a velocity of about 55 m s^{-1} out of the east. This solitary measurement is aliased because the wind velocity exceeded the maximum unambiguous velocity measureable by the radar. It is clearly inconsistent or discontinuous with the rest of the wind field.

The continuity or discontinuity of an individual data point like the one in the preceding example is established by comparing its data value with the value interpolated from neighboring data points. If the difference between the data value and the interpolated value exceeds some control, then we say that the point is discontinuous with its neighbors. We typically use a control value equal to one-sixteenth of the maximum measureable Doppler radial velocity (about 24 m s^{-1}), but this is not critical. We also typically use two neighboring heights above and below and two neighboring times before and after to do a linear least-squares interpolation.

This linear interpolation scheme does not discriminate against large slopes in the data. Therefore, large shears and large accelerations in the wind field are tolerated by the continuity algorithm so long as they are supported by the data themselves. However, points of inflection with excessively large curvature are identified as points of discontinuity. The algorithm has adjustable control parameters that define what is excessive curvature based upon realistic meteorological models. We note in passing that the consensus method currently being used on the NOAA network profilers assumes a meteorological model in which the winds are assumed to be constant during any given hour. The method also has a window or tolerance parameter that is adjusted to allow some variation with time.

The identification of discontinuities using this interpolation scheme is straightforward and general. The identification of *good* data and *bad* data is, however, not always so obvious. The problem would be simpler if we could assume that all bad points are isolated like the one in the preceding example. Frequently that is the case, but sometimes bad points come in clusters, for example, due to Doppler velocity aliasing (Fig. 1) or due to ground clutter. Therefore, the continuity algorithm uses pattern recognition when deciding which points are good and which points are bad.

Neighboring points with nearly the same data values are placed in the same branch of some pattern. Neighboring points with large differences in their data values are placed in different branches that may be part of the same pattern or that may belong to completely different patterns. In the foregoing example with one outlier, the background wind field is composed of a single continuous pattern with possibly several branches all interconnected. The outlier is alone in its own pattern, disconnected from the much larger background pattern. The continuity algorithm assigns greater confidence to the larger number of points in the background wind field based upon overall pattern size. Therefore, the smaller pattern (of one in this case) involved in any discontinuity is assigned the lesser confidence.

This algorithm has been successfully tested on many months of wind data, including some containing frontal discontinuities. The algorithm will tolerate a discontinuity as long as the winds on either side of that discontinuity are adequately supported by significant patterns of winds because confidence is assigned based upon the number of points in a pattern.

REFERENCES

Bargen, D. W., and R. C. Brown, 1980: Interactive radar velocity unfolding. Preprints, *19th Conf. on Radar Meteorology,* Miami, Amer. Meteor. Soc., 278–283.

Bergen, W. R., and S. C. Albers, 1988: Two- and three-dimensional de-aliasing of Doppler radar velocities. *J. Atmos. Oceanic Technol.,* **5,** 305–319.

Brewster, K. A., 1989: Quality control of wind profiler data. Profiler training manual No. 2 developed for the National Weather Service Office of Meteorology, 39 pp. [Available from Nat. Tech. Info. Service, 5285 Port Royal Rd., Springfield, VA 22161.]

——, and T. W. Schlatter, 1988: Recent progress in automated quality control of wind profiler data. Preprints, *8th Conf. on Numerical Weather Prediction,* Baltimore, Amer. Meteor. Soc., 331–338.

Fischler, M. A., and R. C. Bolles, 1981: Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography. *Commun. Assoc. Comput. Mach.*, **24**, 381–395.

Hassle, N., and E. Hudson, 1989: The wind profiler for the NOAA Demonstration Network. Instruments and observing methods Rep. No. 35. *Papers presented at the Fourth WMO Tech. Conf. on Instruments and Methods of Observations (TE-CIMO-IV)*, Brussels, WMO/TD, 261–266.

Kristensen, L., and J. E. Gaynor, 1986: Errors in second moments estimated from monostatic Doppler sodar winds. Part I: Theoretical description. *J. Atmos. Oceanic Technol.*, **3**, 523–528.

May, P. T., R. G. Strauch, K. P. Moran, and W. L. Ecklund, 1990: Temperature sounding by RASS with wind profiler radars: A preliminary study. *IEEE Trans. Geosci. Remote Sens.*, **28**, 19–28.

Strauch, R. G., B. L. Weber, A. S. Frisch, C. G. Little, D. A. Merritt, K. P. Moran, and D. C. Welsh, 1987: The precision and relative accuracy of profiler wind measurements. *J. Atmos. Oceanic Technol.*, **4**, 563–571.

——, K. P. Moran, P. T. May, A. J. Bedard, and W. L. Ecklund, 1988: RASS temperature sounding techniques. NOAA Tech. Memo., ERL WPL-158, 12 pp. [Available from Nat. Tech. Info. Service, 5285 Port Royal Rd., Springfield, VA 22161.]

Thomson, D. W., and S. R. Williams, 1991: Analysis of comparative wind profiler and radiosonde measurements. Preprints, *Seventh Symp. on Meteoreorological Observations and Instrumentation*, New Orleans, Amer. Meteor. Soc., 281–284.

Weber, B. L., and D. B. Wuertz, 1990: Comparison of rawinsonde and wind profiler radar measurements. *J. Atmos. Oceanic Technol.*, **7**, 157–174.

——, and ——, 1991: Quality control algorithm for profiler measurements of winds and RASS temperatures. NOAA Tech. Memo., ERL WPL-212, 32 pp. [Available from Nat. Tech. Info. Service, 5285 Port Royal Rd., Springfield, VA 22161.]

——, ——, R. G. Strauch, D. A. Merritt, and K. P. Moran, 1990: Preliminary evaluation of the first NOAA demonstration network wind profiler. *J. Atmos. Oceanic Technol.*, **7**, 909–918.

——, ——, D. C. Law, A. S. Frisch, and J. M. Brown, 1992: Effects of small-scale vertical motion on radar measurements of wind and temperature. *J. Atmos. Oceanic Technol.*, **9**, 193–209.

Wuertz, D. B., B. L. Weber, R. G. Strauch, A. S. Frisch, C. G. Little, D. A. Merritt, K. P. Moran, and D. C. Welsh, 1988: Effects of precipitation on UHF wind profiler measurements. *J. Atmos. Oceanic Technol.*, **5**, 450–465.