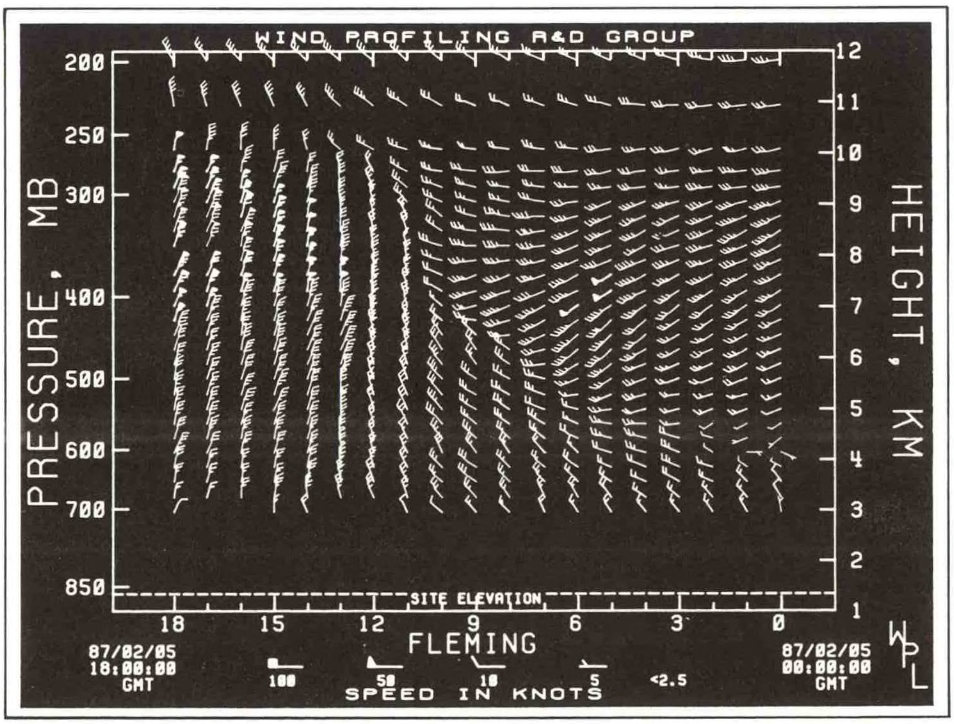
QUALITY CONTROL OF WIND PROFILER DATA

WIND PROFILER

TRAINING MANUAL NUMBER TWO



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BY THE PROGRAM FOR REGIONAL OBSERVING AND FORECASTING SERVICES
ENVIRONMENTAL RESEARCH LABORATORIES
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

PROFILER TRAINING MANUAL #2
Quality Control of Wind Profiler Data

Developed for the National Weather Service
Office of Meteorology

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CONTENTS

1. Why Discuss Quality Control?

For the most part, the wind profilers continuously provide accurate, reliable winds throughout the troposphere. To find the reliability of the system, a one-month data sample (June 1987) from a research profiler in eastern Colorado (Fleming) was edited by hand. Of those data, 96.3 percent were judged to be good measurements. Considering that the summertime data present the greatest challenge for the profiler (with periods of very weak winds and correspondingly weak turbulence, along with frequent thunderstorms) and that the editing was fairly strict, this is a very good success rate. Furthermore, since the network profilers are more sensitive than the research profilers, they are better able to produce good wind measurements where the returned signals are generally weak, namely, in the upper troposphere and in quiescent weather conditions.

Despite the high percentage of good data produced by the profilers, we must keep in mind that the wind profiler demonstration network is a completely automated system: the data pass from the radar site to the central Hub in Boulder and then on to the NWS data distribution circuits without any input or examination by people. A number of phenomena can cause the profiler to produce spurious wind measurements. To screen the data for gross errors (those outside the normal range of meteorological and measurement variability), automated quality control (QC) algorithms have been installed at the profiler network Hub. Additional QC procedures may be implemented in-house while plotting the data or in the data processing for application programs, but none will be provided with AFOS applications. Furthermore, while profilers are designed and operated to allow detection of many small-scale features, some wind measurements that pass the QC checks may actually be artifacts. The purpose of this manual is to explain the QC routines: how they work, where they may have difficulty, and how to add further quality checking to local application programs.

This manual will 1) review the situations which can cause errors in the data, 2) describe techniques for screening the data, and 3) discuss situations when the QC algorithms may have difficulty in deciding which data are bad and which represent a valid extreme or transient meteorological event.

Note that the QC procedures described here and initially used at the Hub have been developed from experience with a research profiler network in northeast Colorado, which consists of one 404-MHz radar, one 915-MHz radar and three 50-MHz radars. (The demonstration network consists entirely of 404-MHz radars.) As experience is gained with the demonstration network profilers, these procedures will be fine-tuned or modified, but the basic techniques will probably remain the same.

The procedures are designed for use with hourly-averaged wind profiles. Preliminary tests show that the techniques used on hourly data can be effective in screening the 6-minute data as well, but further refinement and testing are required. Future software may screen the 6-minute samples before they are combined into an hourly average.

2. Problems with the Data

A prerequisite for any QC effort is the definition of the types of problems to be detected. Data problems fall into three categories: measurement uncertainty, spurious measurements, and unrepresentative observations.

All measurements contain some uncertainty, dependent on the instrument and how it senses the atmospheric condition. If the observations are unbiased, they will be distributed about some central "correct" value. If the variance about this central value is reasonably small, the random error of measurement can be effectively smoothed by means of an objective analysis scheme. In the case of a data plot (for example, a time-height wind barb display) the viewer's eyes do much of the smoothing.

When the basic operating assumptions governing the measuring system are violated, spurious measurements can occur. The remaining sections of this manual will address the assumptions made in making wind measurements with a profiler and under what conditions those assumptions are violated and spurious wind measurements are created. Clearly the spurious data must be screened out before the wind profiler data are used in any application.

A third problem is unrepresentativeness: the measurement is valid but the measured phenomenon is small compared with the spacing between profilers. For example, a surface station samples a small pocket of cold air emanating from a weak thundershower. This temperature measurement is a perfectly valid description of the conditions at the observation site, but it may be significantly different from the ambient flow in the area between the surface stations. We call this an unrepresentative temperature—it does not accurately describe the temperature field on the scale of the station spacing. The same can be true for winds measured by a profiler, particularly in the vicinity of thunderstorms.

Figure 1 shows winds measured near a thunderstorm (shown in the radar summary, Fig. 2) as they appear in a profiler time-height cross section. The thunderstorm winds appear as the strong southerlies between 7 and 10 km (23–33 kft) at 0900 UTC and represent a significant deviation from the ambient wind field before and after the storm. The winds at 0900 UTC are nearly uniform through a substantial depth so they were

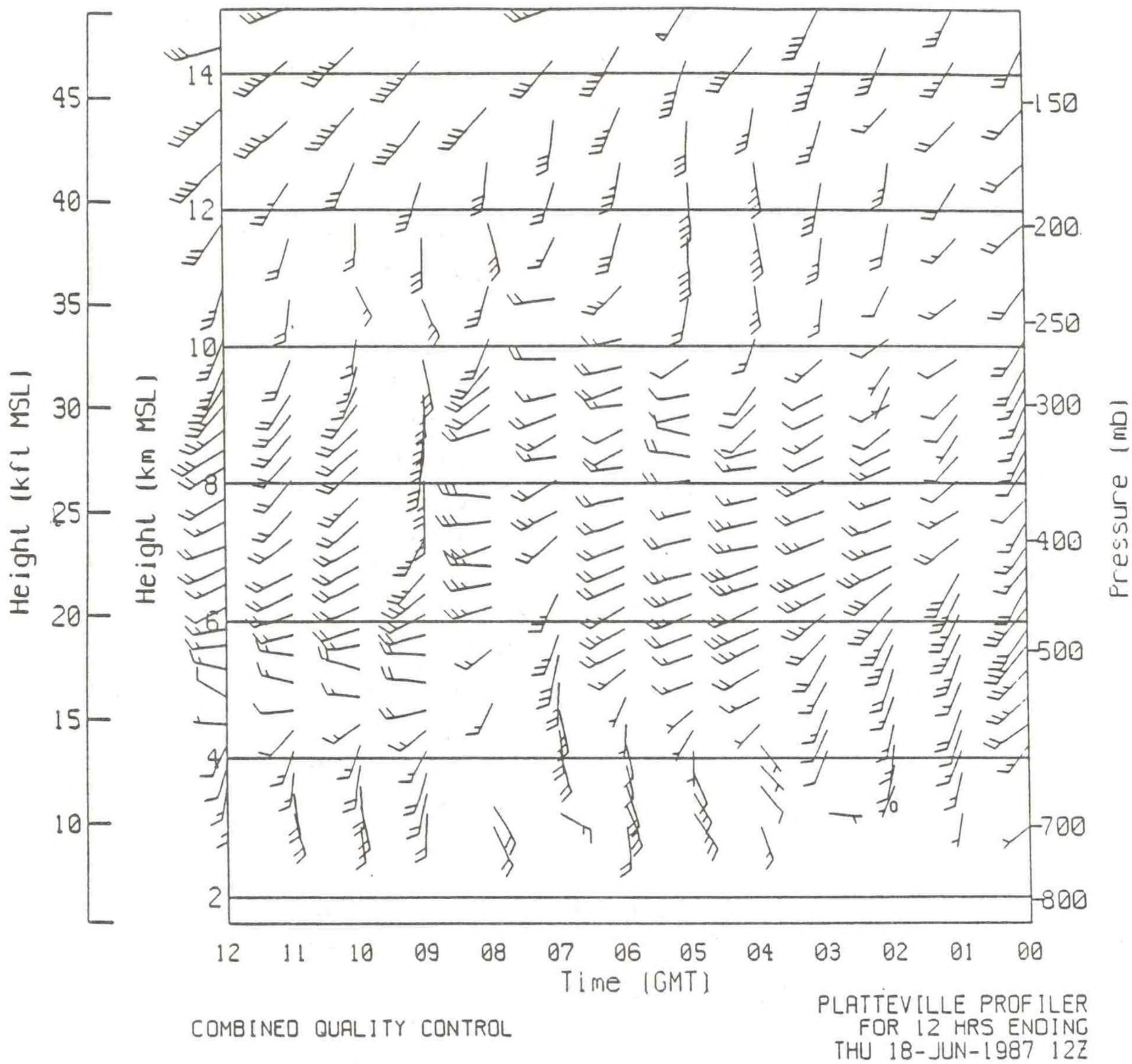

Fig. 1. Time-height cross section of profiler winds at Platteville from 0000 UTC 18 June 1987 to 1200 UTC June 1987 illustrating unrepresentative observations caused by a thunderstorm at 0900 UTC, 8–10 km (26–33 kft). Time (hourly increments) increases from right to left to simulate a west-to-east spatial cross-section. Heights (km above mean sea level [MSL] and thousands of ft [kft] MSL) are on the left vertical scale; corresponding pressure levels are on the right. Surface elevation at Platteville is about 1600 m, the bottom of the cross section plot. Velocities (kt) are coded using standard notation. The plotted data are processed from raw data, with spurious winds removed and remaining observations "thinned" by averaging adjacent (in height) wind observations until no two points are within 250 m of each other.

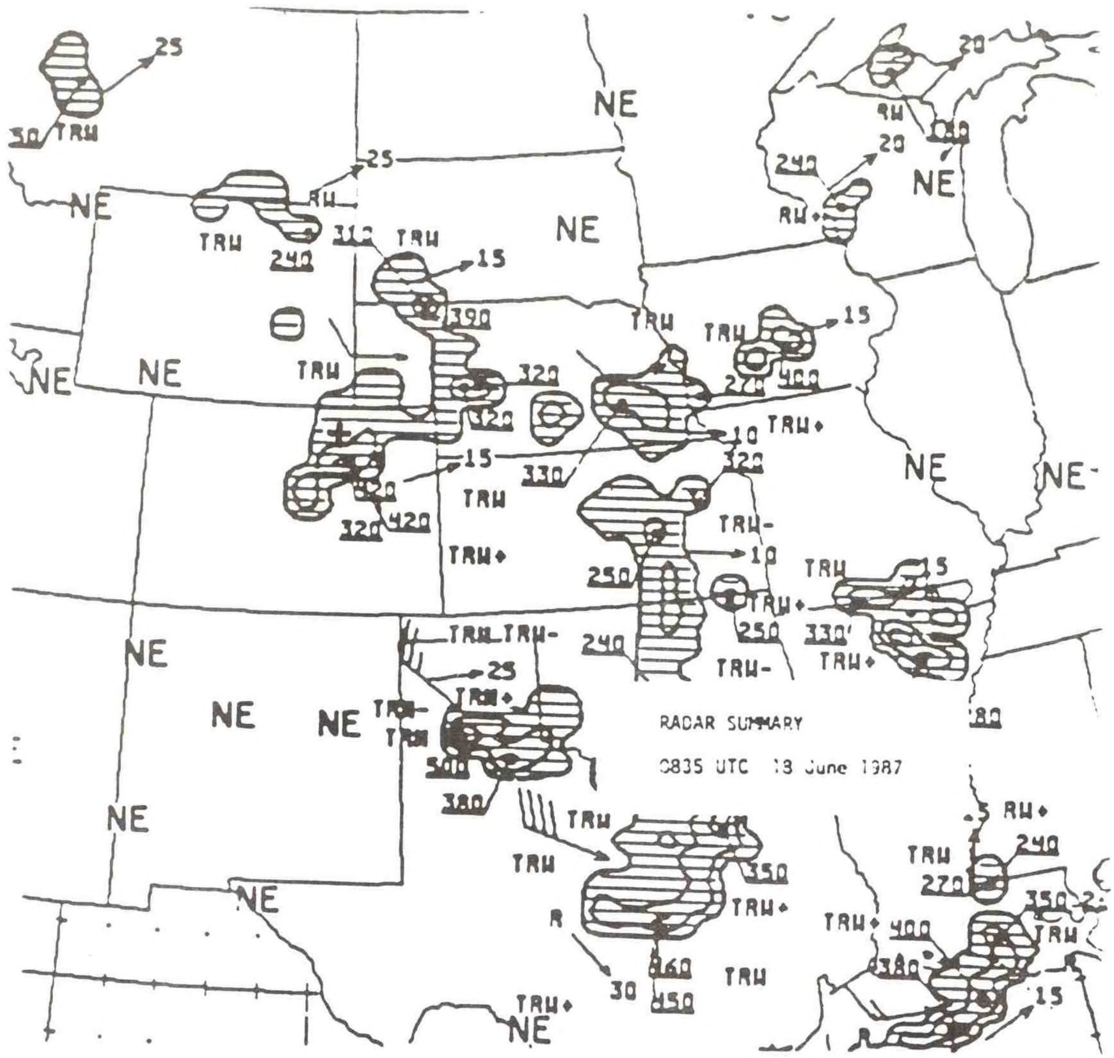

Fig. 2. Radar summary for 0835 UTC 18 June 1987. Note the storm in the vicinity of the Platteville profiler (cross).

retained by the quality control. However, several winds were flagged near 4 km (13 kft) at 0800 UTC by the quality control routines. These winds are not plotted.

The quality control routines attempt to flag the spurious measurements and leave the decision concerning representativeness to the user because each application has its own limit on the scale of motion that can be correctly represented or modelled. For example, a data plot might show **all** the collected data while a numerical model will screen out some data which have variations on a scale smaller than can be supported by the time and space resolution of the model. Because unrepresentative data and spurious data are often similar (they show a large change in winds over a small height or time difference), they can be judged erroneous by the QC routines. At the same time, allowing unrepresentative data to pass may lead to some spurious data passing the checks. This is all the more reason for the forecaster to understand the artifacts that can be introduced into the data and be able to recognize them.

For more information on the accuracy and reliability of profiler data, see the following publications.

Frisch, A.S., B.L. Weber, R.G. Strauch, D.A. Merritt and K.P. Moran, 1986: The altitude coverage of the Colorado wind profilers at 50, 405, 915 MHz. J. Oceanic and Atmos. Tech., 3, 680-692.

Gage, K.S., and B.B. Balsley, 1978: Doppler radar probing of the clear atmosphere. Bull. Amer. Meteor. Soc., 59, 1074-1093.

Strauch, R.G., A.S. Frisch, B.L. Weber, 1986: Wind Measurements in the upper troposphere with UHF and VHF radar., 23rd Conference on Radar Meteorology, September 22-26, Snowmass, Colo., AMS, Boston, Mass., 48-51.

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. Oceanic and Atmos. Tech., 4, 563-571.

3. Sources of Spurious Wind Measurements

For any measurement, assumptions are made which limit the conditions under which valid readings can be obtained. For example, one assumes that rain collects in a rain gage at the same rate as it does on nearby level ground. Under most conditions this is a valid assumption, but if the wind is blowing at 70 kt (36 m/s), a lot of precipitation may strike the side of the gage and never be collected. Steps can be taken to ensure that the assumptions are not violated, for example, installing windscreens around the rain gage. Sometimes, however, even these measures fail.

For a direct measuring instrument like a rain gage, the assumptions are fairly simple and are rarely violated. A remote sensor like a profiler operates under a more restrictive set of assumptions.

The main assumptions are:

- The radar measures the motions of the air or hydrometeors (subject to certain conditions), not birds or planes.

- Air motions (all three components) are uniform over the distance between the beams and do not vary significantly during the 6-minute sampling period.
- Any precipitation that returns significant energy to the profiler is steady over the 6-minute sampling interval and falls at a uniform speed through the three beams.
- The transmission and storage of the data do not change the data. (Bits could be changed or whole sections of the message could be lost during transmission from the profiler site, through the Hub, to NMC. Stored data could be corrupted, or altered during retrieval.)

In the design of the profilers, steps were taken to limit the probability of spurious observations, but the assumptions will still break down on occasion.

3.1 Sidelobes and Ground Clutter

Although the beam of electromagnetic energy directed skyward by the profiler is often depicted as a single cone, the energy of the beam is not so sharply defined. Through the process of focusing and directing the energy with a finite-sized antenna, electromagnetic energy of lesser intensity is also emitted in other directions. The beams of energy outside the primary focused beam (or main lobe) are called side lobes. Figure 3 is a cross section of a network profiler's radar beam. The vertical scale is in decibels, a logarithmic measure. You can see the main lobe at 0° elevation angle and several other emitted-energy peaks which represent the side lobes.

Under normal conditions, the emitted energy in these side lobes is so much smaller than that in the primary beam that the power returned to the radar is equally small and has no effect on the wind measurement. However, the returned power is a function of the reflectivity of the target as well as the transmitted energy. Thus, if energy from a side lobe strikes a strongly reflective object (like a building or a rainshaft or a truck, as in Fig. 4), the amount of energy returned to the radar can be stronger than that received from clear-air returns because the atmospheric reflectivity is weak by comparison.

Because the profiler determines the height of a signal on the basis of the time it takes to return, the side lobe echo will appear to the profiler as if it were at a height equal to the distance between the object and the radar along the side lobe (even though it

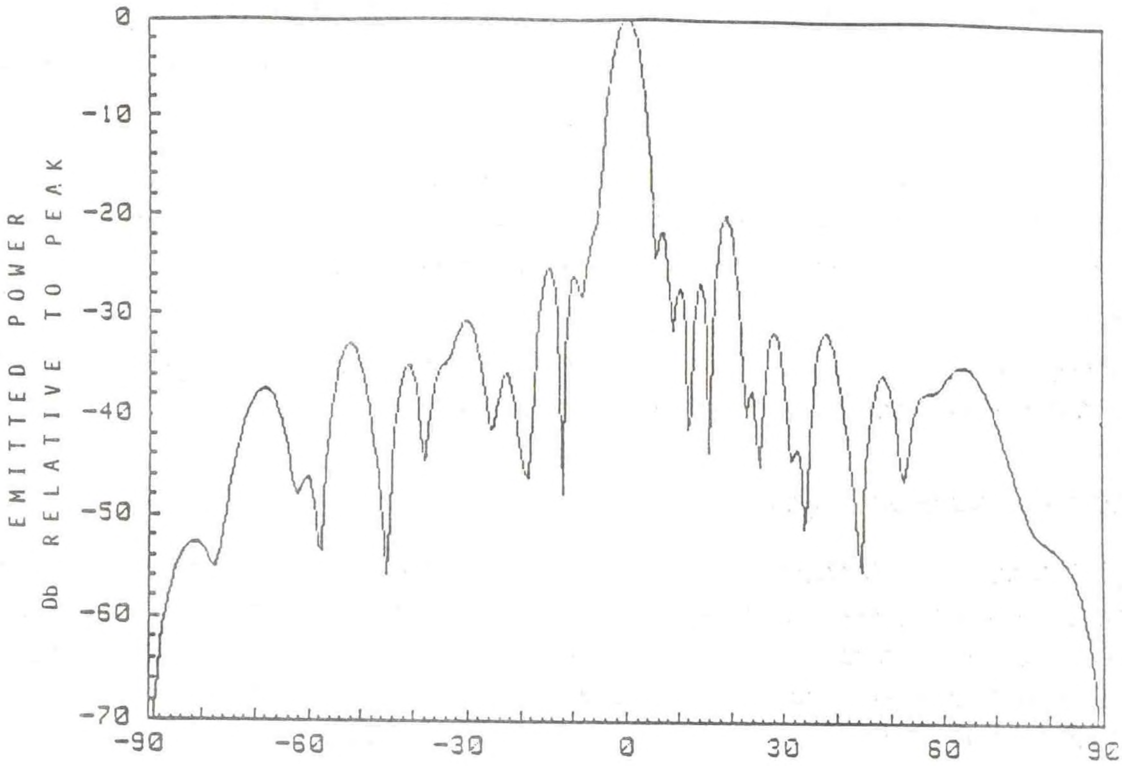

Fig. 3. Measured antenna field strength pattern for the vertical beam. The main beam is the peak at 0°; side lobes appear as peaks elsewhere. Figure courtesy of Unisys Corporation, Great Neck, New York.

might be from an object on the ground). Thus, ground targets can contaminate gates* well above the ground. This problem is magnified when the atmospheric reflectivity is weak (i.e., when there are insufficient fluctuations in temperature and moisture on the scale of half the radar wavelength), as can occur often at high altitudes. The weak signals from atmospheric motions mean that the relative contribution of electronic noise, side lobe returns, and foreign electromagnetic energy can be high enough that spurious velocities are the result. Though provisions exist for removing returns having zero velocities (as would be associated with return from a building), the ground clutter algorithm cannot screen out moving objects.

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* "Gate" is shorthand for "range gate," a distance interval over which the returned power is measured. For the 404-MHz profilers the range gates are spaced 250 m apart. Gate spacing, which is the sampling interval, must be distinguished from the resolution of the measurement. The latter is equivalent to the pulse width (350 m in low mode and 1000 m in high mode).

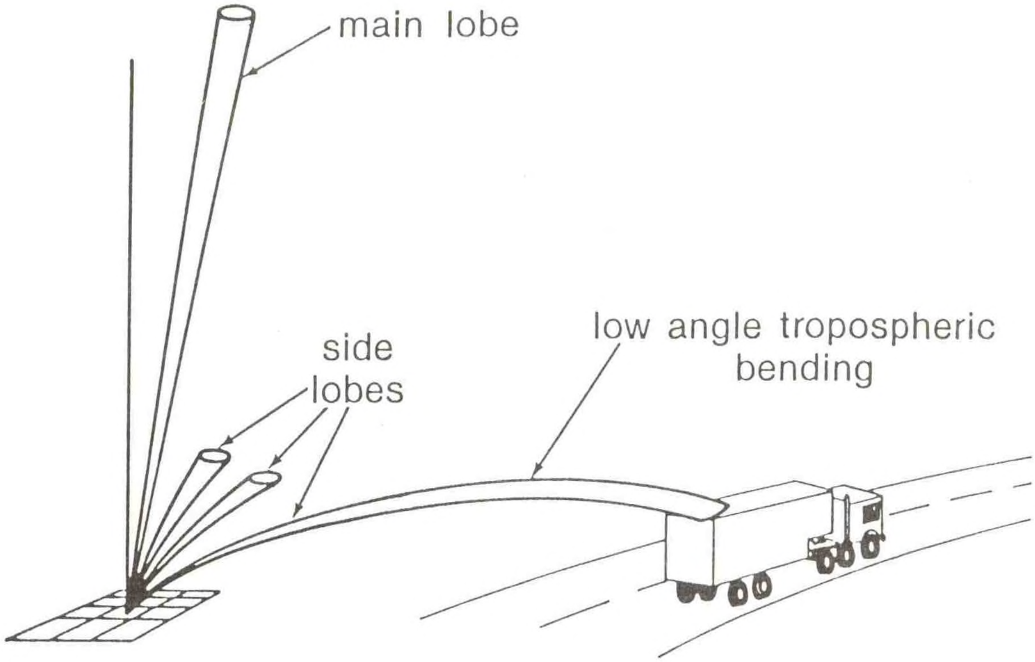


Fig. 4.' Schematic of a side lobe being bent within the lower troposphere to intersect a moving ground target. Tropospheric bending is caused by very stable lapse rates in the boundary layer, the same phenomenon that causes false echoes in PPI radar.

3.2 Spurious Targets

Returns from unwanted targets—anything not travelling at the speed of the wind—can also be received through the main lobe. These targets can include aircraft and birds; obviously, they will affect the measurements adversely. Returns from such targets are typically short-lived, lasting perhaps a few seconds. Though averaged together with the desired atmospheric returns, they can still cause spikes in the one-minute radial velocity data computed by the processor at the profiler site. (It takes six minutes to sample all three beams in both modes, low and high. The sampling time in a given mode for one beam is thus one minute.) A consensus averaging technique, to be described in Section 4.1.1, effectively removes spikes in the radial velocity data. For this reason, the problem of spurious targets in the main lobe is considered to be minor compared with the others presented here.

3.3 Precipitation Contamination

As described in Training Manual No. 1, the wind measurements made by the profiler are derived from the along-beam (radial) velocities measured sequentially in each of three beams. Because the beams point in different directions, at any elevation above the radar each beam is sampling a different volume of the atmosphere. As can be

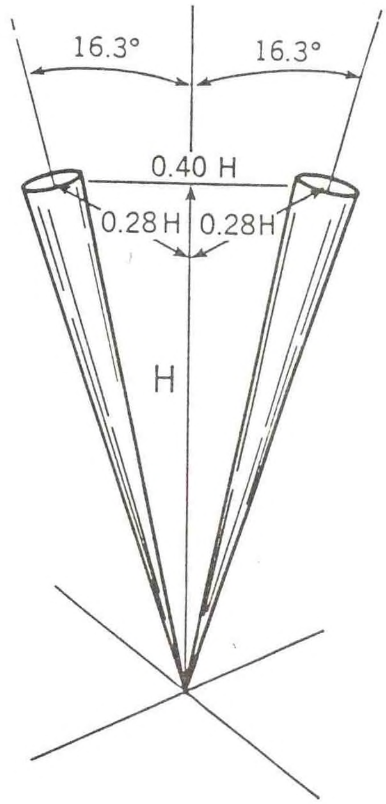


Fig. 5. Beam separation distances for the network radars.

seen from Fig. 5, each off-vertical beam is separated from the vertical beam by a distance of approximately one-fourth (0.28 = cos 73.7°) of the measurement height above the radar. The off-vertical beams are separated from each other by about 0.40 [($\sqrt{2}$) cos 73.7°] times the height above the radar. Since the radar can transmit only one beam at a time, it alternates sampling in each direction for a 2-minute period. Thus, about 6 minutes elapse between the first pulse in the first beam and the last pulse in the last beam. The radial velocities are combined geometrically to produce a single three-dimensional wind measurement. Thus, an important assumption in this measurement is that the wind is uniform over the distances of the beam separation and changes little over the 6-minute sampling period. For the majority of cases these assumptions are valid. There are situations, however, including thunderstorms and strong quasi-stationary wave activity, when these assumptions fail.

The radial velocities measured in the off-vertical beams are made up of horizontal and vertical components. The vertical component is assumed to be the same as that measured directly by the vertical beam. This estimate of the vertical component is accurate when the vertical velocity is horizontally uniform. Errors arise if the vertical component measured by the off-vertical beam differs from that at the vertical beam by much more than the standard error of the radial velocity measurements (approximately 0.2 m/s). The radial velocity standard error is less than the error in the horizontal winds (mentioned in Section 1) primarily because the radial velocity error is magnified by a factor of 1/cos (73.7°) in the computation of horizontal winds. Precipitation is particularly troublesome because the radars can sense the fall speeds of snowflakes, large raindrops, and hail. In stratiform precipitation horizontal velocities can be found because the fall speeds of snowflakes or small droplets are fairly uniform. In convective storms, however, it is sometimes impossible to retrieve the wind components due to the high variability of all three wind components and the variation in fall speeds caused by the wide variety of drop sizes.

Let's examine how the wind measurements are affected by uneven precipitation. First, let's review how the horizontal winds are derived from the radar-measured radial velocities. The radial velocity measured in each beam by the profiler is the wind velocity in the direction of the beam; you may think of it as the velocity projected onto the radar beam. For example, if the wind is parallel to the beam, the magnitude of the radial velocity is the wind velocity; if the wind is perpendicular to the beam, the radial velocity is zero. In mathematical terms, the cosine of the angle between the beam and the velocity vector is used to project the wind. Figure 6 illustrates the projection of a 10-kt (5 m/s) west wind onto the eastward-pointing beam. The sign convention for profilers defines a positive radial velocity for air going away from the profiler and a negative radial velocity for air approaching. This is the same sign convention used for Doppler scanning radars, like NEXRAD.

The following relationships describe how a wind having easterly, northerly, and vertical components, u, v, and w, respectively, will appear in the vertical (Rv), east (Re), and north (Rn) profiler radial velocities (for simplicity the off-vertical beams are assumed to be pointing toward the north and east):

$$\begin{aligned} Rv &= w \\ Re &= u \cos\theta + w \sin\theta \\ Rn &= v \cos\theta + w \sin\theta \end{aligned} \qquad (1)$$

where θ is the angle from the ground to the east and north beams. For the network profilers $\theta = 73.7°$, $\cos\theta = 0.281$, and $\sin\theta = 0.960$. We will begin with the case of no precipitation, and to make things simple, we will take a case of a 20-kt (10 m/s) westerly wind with zero vertical velocity.

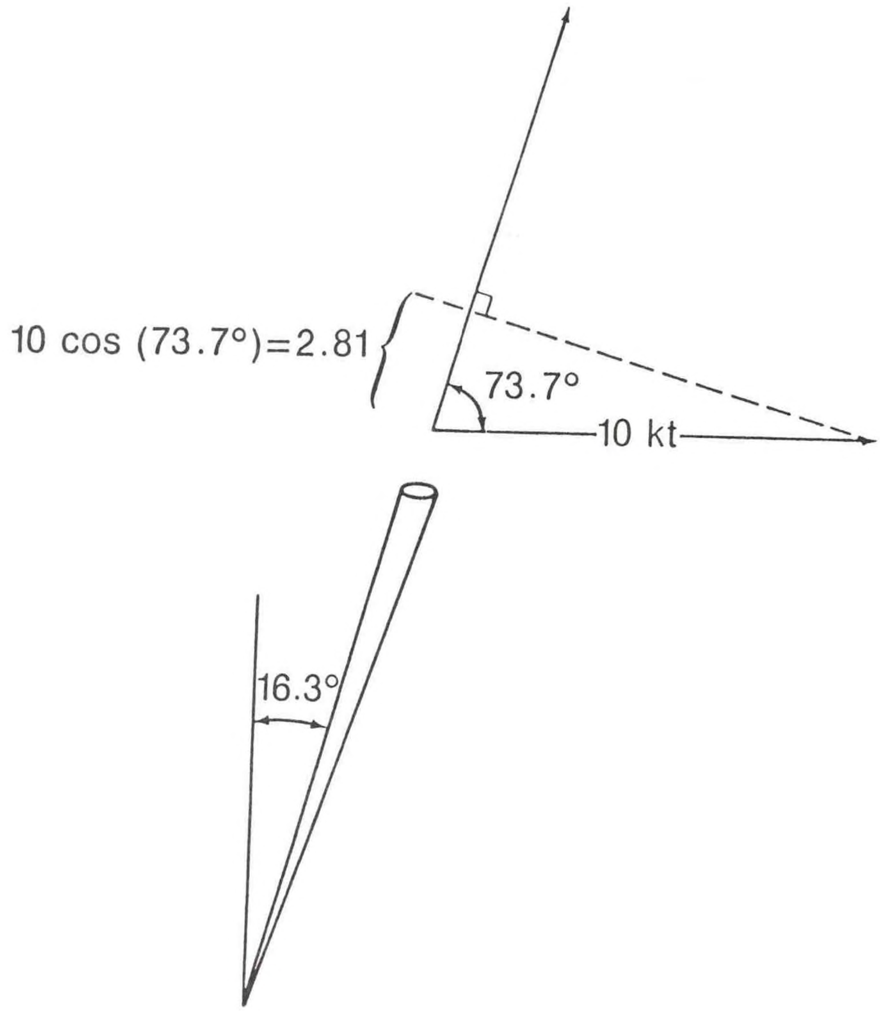


Fig. 6. Projection of a 10-kt west wind onto a radar beam oriented 16.3° from the vertical toward the east.

For this case we find that

$$\begin{aligned} Rv &= 0 \\ Re &= 5.6 \text{ kt } (2.9 \text{ m/s}) \\ Rn &= 0. \end{aligned} \tag{2}$$

Recall from Training Manual No. 1 that the inverse relationships (finding the wind vector from the radar measurements) are found from Equation 1 to be

$$\begin{aligned} w &= Rv \\ u &= (Re - (Rv * \sin \theta)) / \cos \theta \\ v &= (Rn - (Rv * \sin \theta)) / \cos \theta \end{aligned} \tag{3}$$

or

$$w = Rv$$
$$u = Re \sec\theta - Rv \tan\theta \qquad (4)$$
$$v = Rn \sec\theta - Rv \tan\theta.$$

And of course, for our example, we retrieve the 20-kt (10 m/s) u component and 0-kt v and w components.

Now let's introduce a 10-kt (5 m/s) fall speed of large raindrops as depicted in Fig. 7. When there is precipitation, the vertical velocity w, measured in the vertical beam, actually consists of the vertical velocity of the wind less the terminal velocity of the precipitation. Note from Eq. 1 that the vertical velocity (of both the wind and the precipitation) will affect all the radial velocities (presuming that rain is falling in all the beams). The resultant radial velocities are then (from Eq. 1)

$$Rv = -10.0 \text{ kt } (-5.1 \text{ m/s})$$
$$Re = -4.0 \text{ kt } (-2.1 \text{ m/s}) \qquad (5)$$
$$Rn = -9.6 \text{ kt } (-4.9 \text{ m/s}).$$

(Rv is negative because rain is falling toward the radar.)

Note that the impact of the precipitation fall speed on the radial velocities is quite large because the profiler beams are nearly vertical. However, the geometrical relationships (Eq. 3) allow for removal of the vertical contribution, so we can successfully retrieve the proper u, v, and w components.

The correct wind values cannot be retrieved, however, when the precipitation is unevenly distributed among the beams. Let's examine the same 20-kt (10 m/s) westerly wind as before but assume the rain is falling only in the east and north beam, and not in the vertical beam (see Fig. 8). For this case, the east and north radial velocities are the same as in the precipitation case and the measured vertical radial velocity is zero.

$$Rv = 0.0 \text{ kt}$$
$$Re = -4.0 \text{ kt } (-2.1 \text{ m/s}) \qquad (6)$$
$$Rn = -9.6 \text{ kt } (-4.9 \text{ m/s})$$

Now use the inversion equation (Eq. 3 or 4) to solve for the horizontal wind:

$$w = 0$$
$$u = -14.2 \text{ kt } (-7.3 \text{ m/s}) \qquad (6)$$
$$v = -34.2 \text{ kt } (-17.6 \text{ m/s})$$

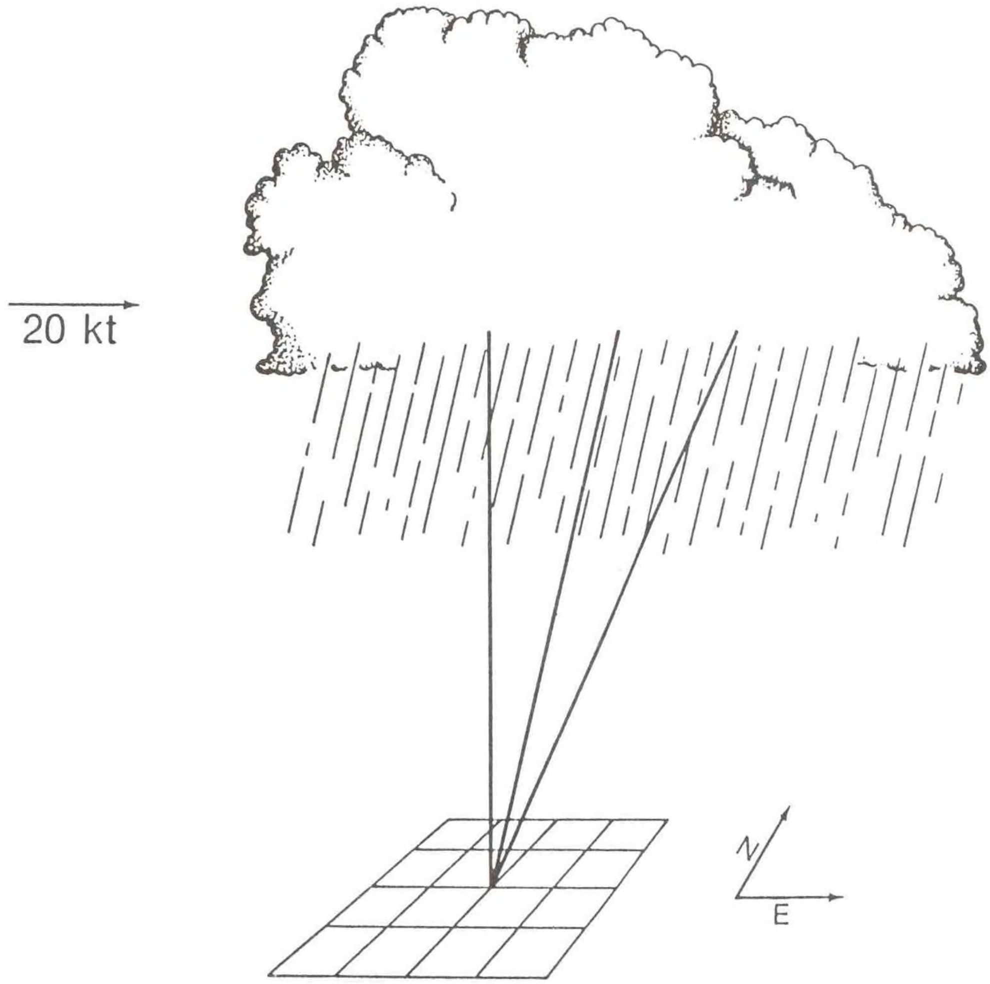


Fig. 7. Rainshower providing near-uniform rainfall in all the profiler beams.

This is a wind from 67° at 37 kt (19 m/s). Rain falling in only the off-vertical beams therefore precludes a valid wind calculation. The effect of falling precipitation is magnified by a factor of almost four when the radial velocities are divided by cos (73.7°) in Eq. (3).

This example illustrates the anomalous precipitation condition which causes a report of unusually strong winds from a direction approximately halfway between the two off-vertical beams. **In fact, this example of precipitation contamination is the one most likely to be reported in the hourly averaged data.** The hourly averaged horizontal wind is computed from the average radial velocity in each beam, but the averaging process requires that a certain number of the 6-minute samples fall within a window about 5 kt (2.6 m/s) wide—more on this in Section 4.1.1. More vertical than off-vertical samples must agree to create an average. When there are too few agreeing vertical velocities, the vertical velocity component is not accounted for when computing the

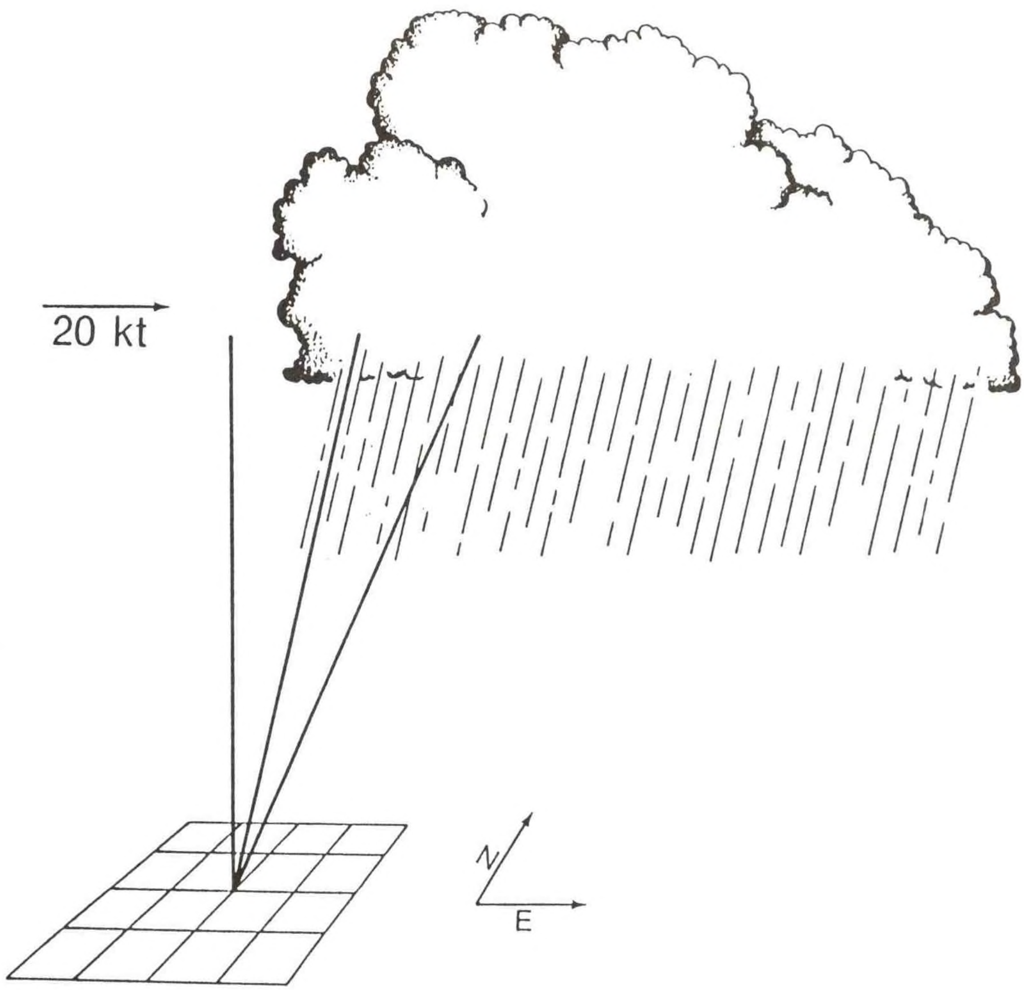


Fig. 8. Rainshower producing rain in the two off-vertical beams of the profiler.

horizontal wind. This is equivalent to using an average vertical velocity of zero, a generally safe procedure when there is no precipitation and the ambient vertical velocities are less than 0.2 m/s. As shown by this example, zeroing the vertical velocity is a hazardous procedure when precipitation is falling.

A real-life example is shown in Fig. 9, data from the profiler at Denver's Stapleton Airport. (The higher operating frequency of this profiler 915 MHz vs. 404 MHz in the demonstration network makes it more sensitive to precipitation.) Stapleton's beams are pointed to the north and east; thus the precipitation-contaminated winds, like those in the previous example, are likely to be from the northeast. Indeed, anomalous northeast winds appear at several reporting times just below 4 km (13 kft). Note the rain shower reports in the SAOs, which correlate well with the bad data.

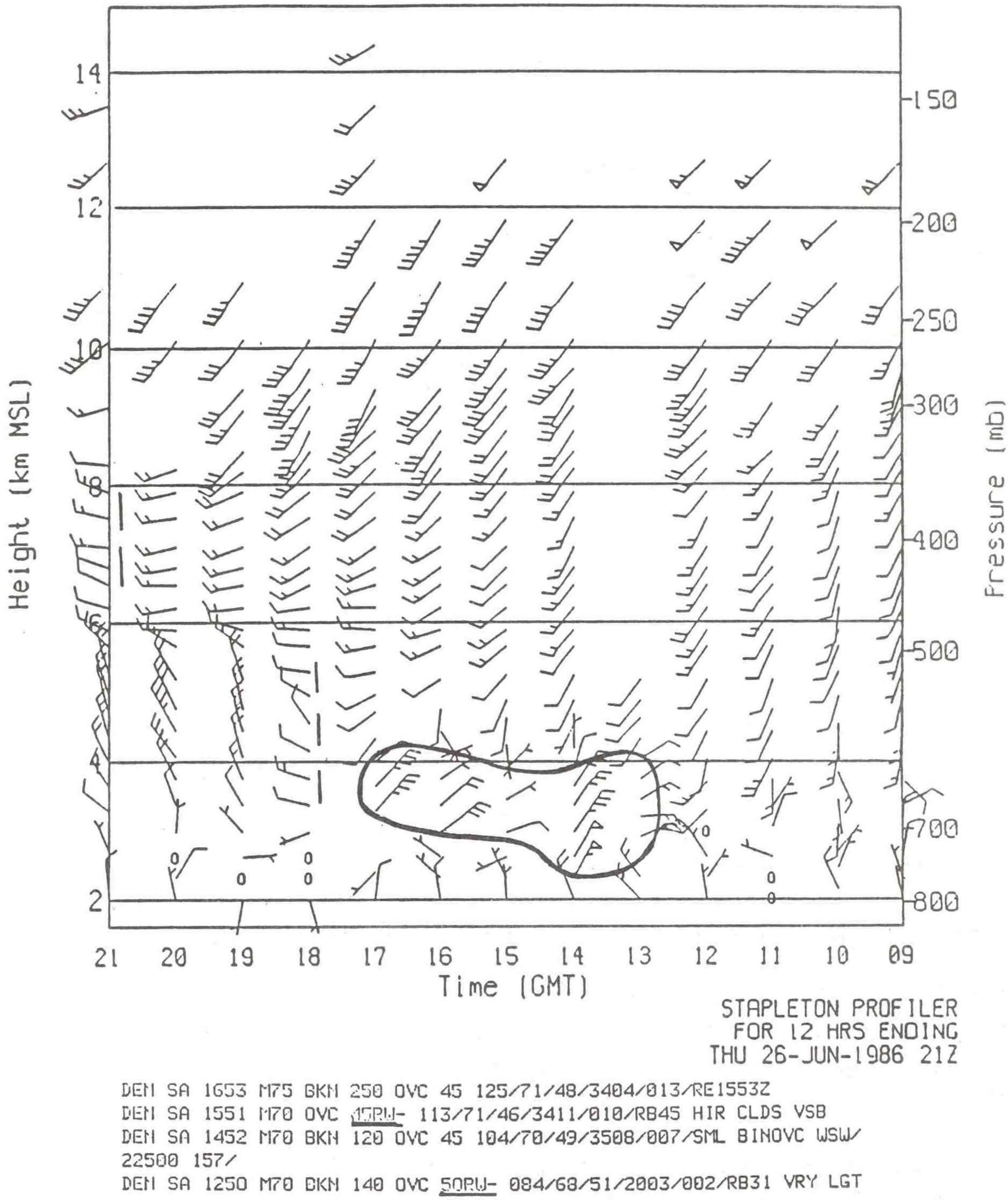


Fig. 9. Annotated time-height cross-section of data from the Stapleton profiler (Denver) from 0900 UTC 26 June 1986 to 2100 UTC 26 June 1986. Dashed line represents a wind shift line or trough axis. Rain-contaminated winds, evident at 1300, 1400 and 1700 UTC as strong northeasterlies below 4 km, are circled. Note the observation of showers at Denver during this time.

What about the case of precipitation falling in the vertical beam but not in the others? Let's try measuring the same 20-kt (10 m/s) westerly wind under these conditions. The vertical radial velocity will be 10 kt, the same as in the sample precipitation case, while the other radial velocities will be the same as the non-precipitating case.

$$Rv = -10.0 \text{ kt } (-5.1 \text{ m/s})$$
$$Rn = 5.6 \text{ kt } (2.9 \text{ m/s}) \qquad (7)$$
$$Re = 0$$

Using Eq. 3 we find the apparent wind to be

$$w = -10.0 \text{ kt } (-5.1 \text{ m/s, the precipitation fall speed})$$
$$u = 54.1 \text{ kt } (27.8 \text{ m/s}) \qquad (8)$$
$$v = 34.2 \text{ kt } (17.6 \text{ m/s}).$$

This is a wind from 212° at 64 kt (33 m/s).

Similarly extreme cases of anomalous winds can be found for the other cases of uneven precipitation falling in each beam. Such an imbalance can also arise from precipitation unevenly distributed in time (with respect to the data-averaging time—1 hour).

Usually, large precipitation errors occur only in the lower troposphere (below 5 km [16 kft]) because that is where the larger (and faster-falling) precipitation particles reside. Hail can, however, be found higher in the atmosphere and will produce similar (if not worse!) anomalies.

3.4 Receiver Recovery Noise.

When the radar switches from transmit to receive mode, there is electronic noise in the system that takes a few microseconds to dissipate. Any signals returned by the atmosphere during this brief period are masked by noise. Because the first signals to return come from the lowest heights in the atmosphere, the lowest sampling gate (500 m) is most susceptible to this problem. This effect is especially noticeable in the data from the 50-MHz research profilers because the first velocity measurement (1.8 km above ground) is made before the noise has completely dissipated. Receiver recovery noise is the limiting factor for the lowest sampling gate in a profiler. Hardware considerations (including the size of the antenna and the speed of the transmit-receive switch) make the recovery time for the 50-MHz radars much greater than for the 404-MHz radars. Hence, the first velocity measurement can be closer to the ground for the demonstration network profilers than for the profilers in the Colorado research network.

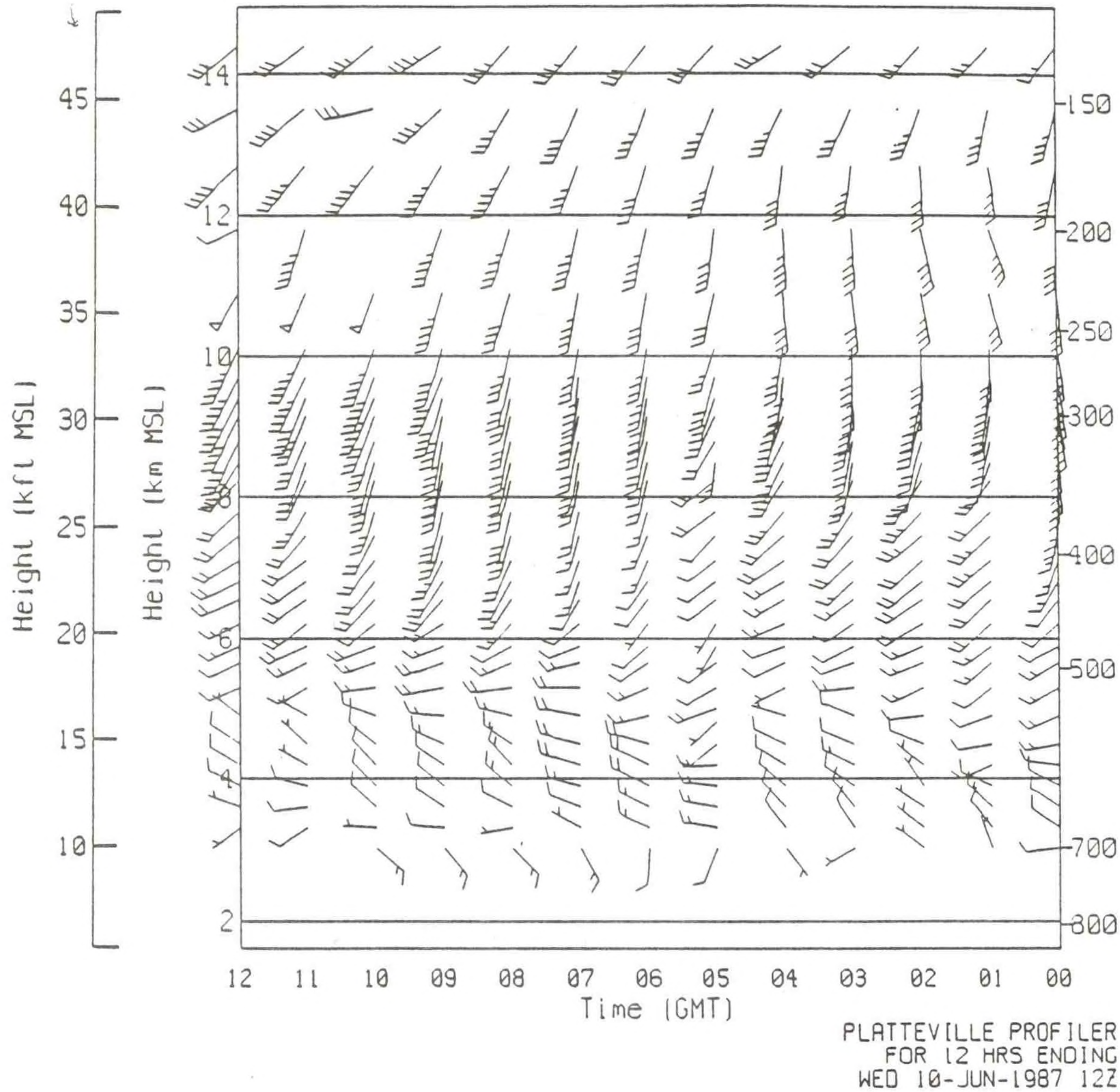


Fig. 10. Annotated time-height cross section of data from the Platteville profiler from 0000 UTC 10 June 1987 to 1200 UTC 10 June 1987.

The lowest reported data in Fig. 10 illustrate this problem. Because these data have no neighboring measurements below them and occur within the boundary layer (or near its top), where there are likely to be naturally occurring large wind variations, error-detecting routines have difficulty in deciding if wind measurements there are erroneous.

Each research profiler exhibits a preferred direction and speed when the wind in the lowest gate is contaminated by receiver recovery noise (southeast at about 10 kt at Platteville). The 404-MHz profilers in the demonstration network are expected to be less susceptible to receiver recovery noise than the research profilers. Nonetheless, with experience, forecasters will be able to recognize this problem when it occurs. The preferred wind direction usually lies along the azimuth of one of the two oblique beams or halfway between the azimuths.

3.5 Contamination by Stationary Turbulent Waves

As described in Section 2, the derivation of horizontal winds from the profiler radial velocities assumes the winds are the same in all three beams at a given height. Because of turbulent eddies, this is not the case at any given instant. Nonetheless, random turbulent eddies move and develop in such a way that for a sufficiently long sampling period, the average velocity at each of the beams is the same. If, however, the turbulence takes the form of a stationary wave like those that can be generated in the lee of a mountain range, the average velocities can be significantly different. Eddies having a wavelength of twice the separation between the beams will have the worst effect, as illustrated in Fig. 11. The vertical velocity in the vertical beam (point "V") is significantly different from that at the east beam (point "E"). If the vertical velocity is on the order of meters per second, then the horizontal wind component errors can be quite large (recall the multiplicative factor applied to vertical velocity noted in Section 3.3).

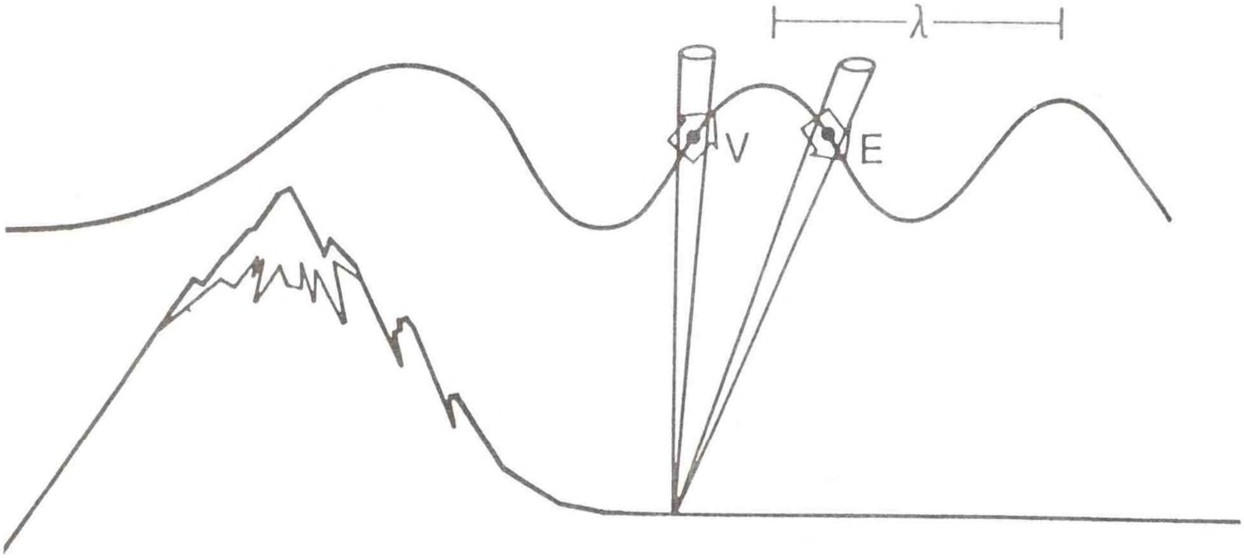


Fig. 11. Stationary wave created in the lee of a mountain. The profiler samples the wave at points V and E, where, in this case, the vertical velocities differ significantly. Lambda is the wavelength.

Because there are many possible turbulent wavelengths and orientations, it is not possible to describe a "typical" result such as we could for precipitation contamination. Because such strong stationary waves are generally limited to the lee of mountain ranges and close to extreme thunderstorms, the number of observations in the demonstration network affected by this problem will probably be very limited.

3.6 Velocity Folding

The profiler operating frequency and sampling interval determine the Nyquist velocity, the maximum radial velocity magnitude that can be measured. For the demonstration network profilers the Nyquist velocity is about 30 kt (15.5 m/s) in the low mode and 45 kt (23.3 m/s) in the high mode. Radial velocities greater than the Nyquist velocity are "folded" as if the velocity were being read from a speedometer like that shown in Fig. 12. In the schematic the Nyquist velocity is 30 kt. Figure 12a shows a 25-kt radial velocity being measured correctly; however, in Fig. 12b, a 32 kt (17 m/s) radial velocity is read as -28 kt (-15 m/s). We can think of this as "the wagon wheel effect." In movies a fast-moving wagon wheel is sampled by the movie camera shutter and at certain speeds will appear to be moving very quickly in the opposite direction.

Because vertical velocities are generally small and the off-zenith beams are nearly perpendicular to the ground a large horizontal wind speed is required to create a folded radial velocity. Using Eq. 1, a 108-kt (55 m/s) due north wind is required to fold the radial velocity in the north beam. Although winds of that magnitude can occur in the

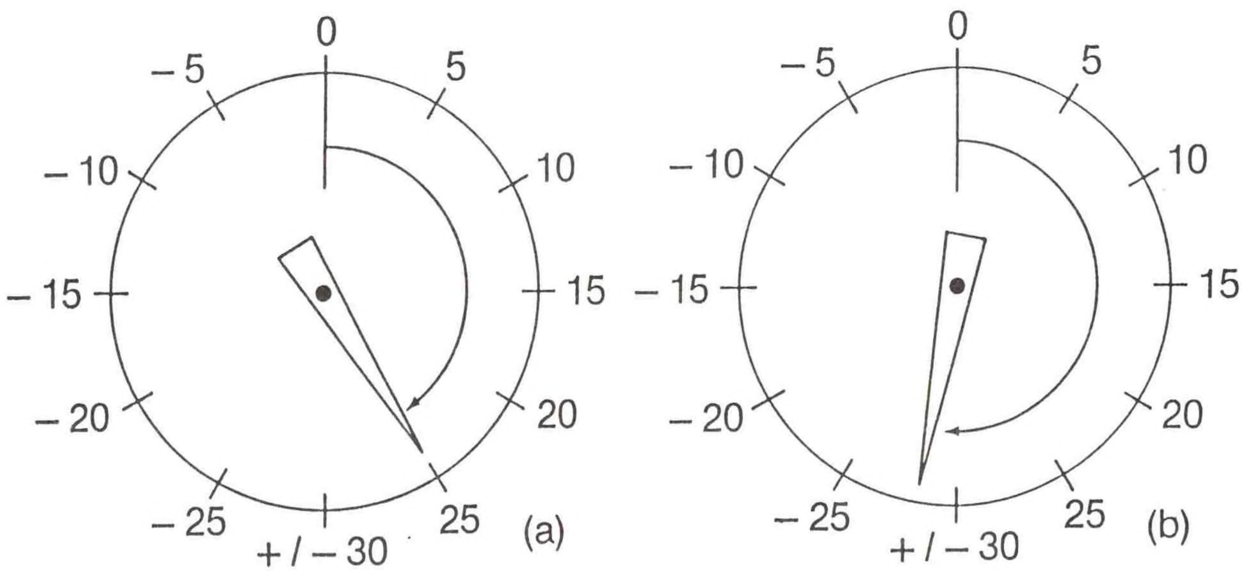


Fig. 12. Nyquist velocity demonstrated by a speedometer having a maximum/minimum speed of +/- 30 kt. a) A speed of 25 kt is correctly measured. b) A speed of 32 kt is reported as -28 kt.

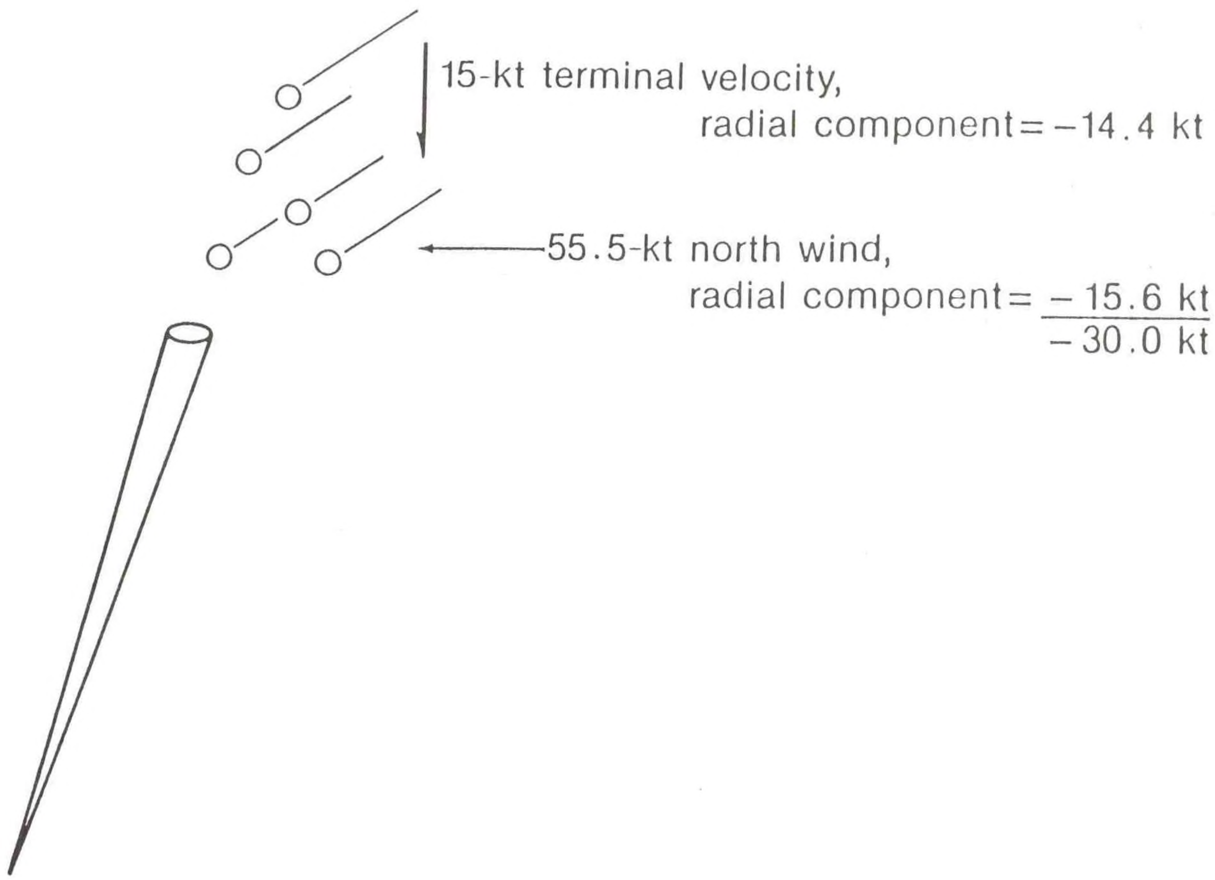


Fig. 13. Large raindrops falling with a terminal velocity of 15 kt and a 55.5–kt north wind combine to produce a radial velocity equalling the Nyquist velocity.

highest extent of the low-mode data (9.25 km AGL [30 kft]), they will be seldom be oriented exactly along one of the beams. If so, folding will occur.

In the case of a thunderstorm or heavy rain, the vertical velocity of the rain (or hail) is not small and needs to be considered. As depicted in Fig. 13, in the presence of a 15–kt (8 m/s) fall speed (typical of a very large raindrop), a north wind of 55.5 kt (29 m/s) will fold the radial velocity in a north-pointing beam. However, it would then take a 160–kt (82 m/s) south wind to cause a fold with the same precipitation fall speed. Such strong winds accompanied by large fall velocities are unlikely except in the vicinity of vigorous thunderstorms or in heavy rainshowers along strong fronts.

Given the cautions expressed earlier in Section 3.3 about thunderstorms, this is one more reason to be wary of winds in the vicinity of storms. On the bright side, the horizontal velocities produced by velocity folds will be so wildly different from correct measurements that they have a high probability of being flagged in the quality control processing. In fact, an algorithm to correct folded radial velocities probably will be developed.

REVIEW TOPICS FOR SECTION 3

The reader should know

- under what conditions accurate wind measurements can be made during precipitation
- why precipitation contamination usually appears below 5 km (17 kft)
- the direction from which the most common type of precipitation-contaminated winds appear to be
- the wavelength for which stationary waves create the greatest error if they are aligned along the direction of a beam
- how radial velocities greater than the Nyquist velocity are reported
- how precipitation fall speed can affect the maximum horizontal wind that can be measured without folding.

For more information on effects of stationary waves on profilers, see the following publication.

Carbone, R.E., R. Strauch, and G.M. Heymsfield, 1986: Simulation of wind profilers in disturbed conditions. 23rd Conference on Radar Meteorology, 22-26 September, Snowmass, Colo., AMS, Boston, Mass., 44-47.

4. Quality Control Schemes

Because we know that spurious data can enter the profiler system much more readily than a direct-measuring system, automated QC procedures have been developed. These procedures take advantage of the consistency of the winds in time and height (on the scale of sample separation, 250 m in height and 6 minutes or 1 hour in time). The QC algorithms for the profiler data calculate an expected value of the datum at its location in time and space and compare the expected value to the measured value. The expected value is typically a function of the measurements surrounding the datum in time and space. It may also depend on some sort of "first guess" provided by a forecast model or expressed as a function of the surrounding data. If the difference between the expected and measured values exceeds a threshold, then the datum is considered suspect. Various procedures may be followed to determine if the datum arises from a plausible but extreme meteorological event or if the large difference is caused by a bad datum among those used to calculate the expected value. In this chapter, several techniques that can be applied to wind profiler data are described—first those developed for use at the profiler Hub, then some others that can be applied in-house by forecasters.

For wind profiler data distributed to the NWS field offices the QC must be done in real time, that is, the data for the current hour must be checked before data from the next hour arrive. Estimating measured values is more difficult because the data are unevenly distributed in time—plentiful data from past times, but none from future times. For some applications, more precise "two-sided" quality control, done after future data have arrived, is not only possible but desirable. Two factors merit consideration: 1) how long after the data collection can one wait before running the QC, and 2) how sensitive is the application to data errors.

4.1 Algorithms Applied to Network Data

4.1.1 Consensus averaging

As described in the first training manual, the 1-hour wind averages produced at the profiler Hub are derived from the 6-minute radial velocity samples by a technique known as consensus averaging. Primarily an averaging process, this technique also has built-in QC. As suggested by the name, not all the data are averaged, but only those that mutually agree within a threshold. (A 1.5-m/s window is used for the vertical velocity. A 2 or 3 m/s window is used for the off-vertical radial velocities, depending upon the mode of operation, low or high.) We review the effect of this technique by considering these ten 6-minute radial velocity samples:

3.3 4.6 20.9 2.8 3.6 4.1 −6.8 3.4 4.0 22.2 (m/s)

The average of all samples is 6.2 m/s. Looking at the individual points you can see that 6.2 does not at all represent the typical sample value during the hour; it has been severely contaminated by three outliers. Now if we collect with each sample all other samples agreeing within +/−1.5 m/s, that is, falling within a 3.0-m/s window, we get these groups:

sample	samples within window							
3.3:	2.8	3.3	3.4	3.6	4.0	4.1	4.6	
4.6:	3.3	3.4	3.6	4.0	4.1	4.6		
20.9:	20.9	22.2						
2.8:	2.8	3.3	3.4	3.6	4.0	4.1		
3.6:	2.8	3.3	3.4	3.6	4.0	4.1	4.6	
4.1:	2.8	3.3	3.4	3.6	4.0	4.1	4.6	
-6.8:	-6.8							
3.4:	2.8	3.3	3.4	3.6	4.0	4.1	4.6	
4.0:	2.8	3.3	3.4	3.6	4.0	4.1	4.6	←
22.2:	20.9	22.2						

The greatest number of samples in a group is seven, a tie among five groups. The group of seven coming latest in the hour (indicated by the arrow) is then selected for the consensus; in this case all five groups of seven are identical so the position within the hour doesn't matter. The consensus average is the average of that group, 3.7 m/s, which almost anyone would agree is representative of the entire sample set.

In practice, mathematical shortcuts speed calculation of the average value that has the most samples lying within the threshold window. If no group has at least four members to form a consensus (as might be found if the data are made up of random values), then the average value is reported as missing. For the vertical beam only, five or more values must form a consensus; if there is no consensus, the vertical velocity is reported as zero.

Consensus averaging handles isolated spikes in the data quite well, as in the example. It also handles cases in which the returned atmospheric signal is too weak to be detected. Then, the data samples are nearly random, and a missing value will be reported.

4.1.2 Combined median filter and shear check

As the name suggests, this routine consists of two checks applied sequentially to hourly averaged data. In the median check (Fig. 14) data are gathered from adjacent hours (the current hour and the last two available hours) and adjacent levels. The median

Data selection for median check:

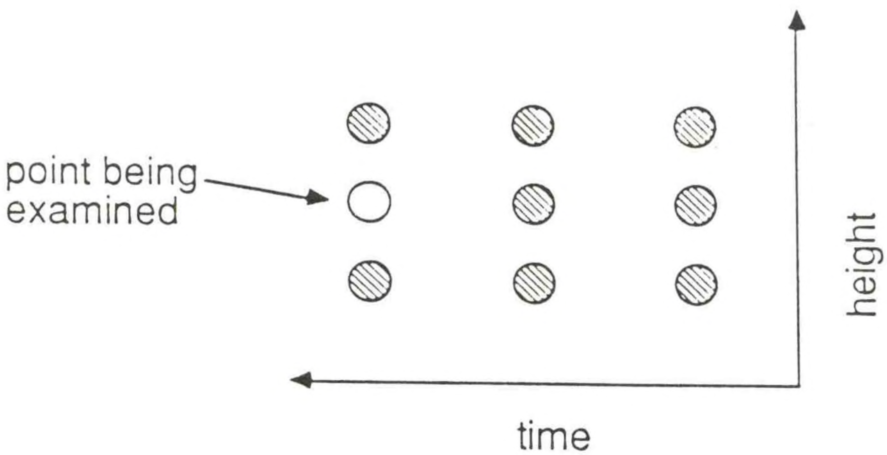


Fig. 14. Data points from which median is calculated in the median check.

(the reported value for which half the samples are greater and half are less) of this collection of data is then computed for the two horizontal wind components. If the difference between the datum and the median is greater than a threshold, the median is recalculated using only those data from the current hour and the last hour. This is done to preserve data in the event of a strong wind shift with time as might be found in a dramatic trough passage. Data are flagged bad if the observed datum and the recalculated median also differ by more than the threshold.

The threshold value depends on the height of the datum (greater thresholds at greater altitudes), the wind speed (greater thresholds for high speeds), and the time difference between the datum and the data collected for the median computation (greater threshold when there are missing data in previous hours). In the current implementation, the median check is quite loose; it is designed to flag the most widely varying data but may pass along a substantial number of spurious data. The philosophy is to discard the implausible values before the shear check and to leave the more difficult decisions to that second step.

The vertical consistency check uses a gate-to-gate shear threshold, which is a function of height, distance between the observations, wind speed, and the difference in wind direction (greater shear is allowed if the wind direction is unchanging). A typical threshold is about 20 m/s per kilometer or about 13 kt per thousand feet.

If the magnitude of the vector shear between the first and second gates exceeds the threshold, the shear between the second and third gates is checked. If the second shear is nearly the same magnitude as the first and in the opposite direction, the data in the second gate are flagged bad (both horizontal components). This situation is illustrated in Fig. 15a. The magnitude of the shear between the first and second gates, 22.6 kt, is excessive, thus prompting a check on the shear between the second and third gates (27.5 kt). The two shears are comparable in magnitude and nearly opposite in direction (the components have opposite signs). Thus the light northwest wind in the second gate is flagged.

If the wind in the third gate tends to continue the shear between the first and second gates, a straight line is plotted through the u- and v-components of winds in the first and fourth gates. If both components in the second and third gates lie reasonably close to their respective lines, they are accepted as valid measurements. This is the condition shown in Fig. 15b, where the sample winds imply strong shear across a frontal boundary. On the other hand, if either component in the second and third gates lies far from the line, both winds are flagged as bad. Figure 15c illustrates the case of two spurious winds between two valid winds. The line for the u-components lies along the horizontal axis. Although the middle two u-components lie close to the line for u, the middle two v-components lie far from the line for v. Thus the middle two winds are flagged. Note that the scale for u and v in Figs. 15b and 15c has been held constant to facilitate comparisons.

The practical result of these tests is that a layer of winds containing four or five measurements that pass the median check and corroborate each other will be retained even if there is substantial shear at the layer interfaces. Moreover, two adjacent, spurious winds supporting each other are likely to be flagged correctly as bad, as in the above example; three such winds may not be. Conversely, if a layer of anomalous but valid winds is only sampled by two or three gates, those wind observations may be erroneously rejected.

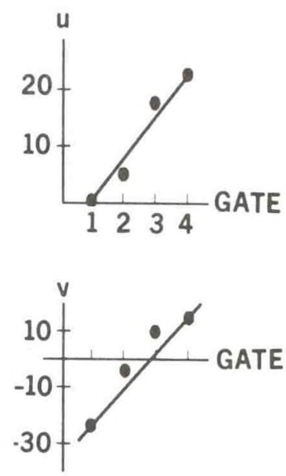
The vertical consistency check is applied once to the low mode data and then to the entire profile, high and low modes meshed together. Checking in each case begins with the lowest gate and proceeds upward. Special processing with linear extrapolation of neighboring data is used at the lowest and highest gates in the profile, should large shear be indicated there.

To re-emphasize, the most powerful check in the system is the vertical consistency check. Substantial changes from one hour to the next are generally allowed to pass through the median check but are rejected later if there is insufficient continuity in the wind shift with height.

ddff	(u,v) (KNOTS)	(SHEAR) (Δu,Δv)	SHEAR MAGNITUDE
3630	(0.0, -30.0)		
		(-5.2,-27.0)	27.5
3006	(5.2, -3.0)		
		(5.2, 22.0)	22.6
3625	(0.0, -25.0)		

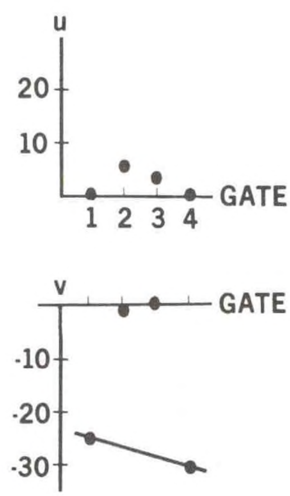
(a)

ddff	(u,v) (KNOTS)	SHEAR (Δu,Δv)
2425	(21.6,12.5)	
		(4.3, 2.5)
2420	(17.3,10.0)	
		(12.1,13.0)
3006	(5.2,-3.0)	
		(5.2, 22.0)
3625	(0.0,-25.0)	



(b)

ddff	(u,v) (KNOTS)	SHEAR (Δu,Δv)
3630	(0.0,-30.0)	
		(-4.0,-30.0)
2704	(4.0, 0.0)	
		(-1.2, 3.0)
3006	(5.2, -3.0)	
		(5.2, 22.0)
3625	(0.0,-25.0)	



(c)

Fig. 15. Three examples of the vertical consistency check. (a) A bad wind between two good winds, (b) good winds with strong shear, (c) bad winds in gates 2 and 3. See text for details.

4.2 Other Methods

This sub-section describes quality control techniques beyond those applied at the profiler Hub. They may be used locally in applications programs which are sensitive to data errors. If you do not plan to develop any programs using profiler data you may skip ahead to the review topics for Section 4.

4.2.1 Optimal Interpolation

Statistical objective analysis, also known as Optimal Interpolation (OI), is widely used for analysis of meteorological variables on quasi-horizontal surfaces. In fact, OI is used today at many national weather centers, including the National Meteorological Center (NMC), for model initial analyses, like the analyses done for the NGM. This method utilizes statistical properties of the observations and the background field (also called a "first guess"). The background is usually a model forecast but climatological averages or persistence can serve the same purpose. The OI analysis takes into account the positions of the observations relative to each other and relative to the analysis point; it has an extrapolative property that aids analyses near data edges.

Optimal Interpolation can be used for quality control. The datum under scrutiny is compared with a value analyzed at the same location by means of OI. Surrounding observations (but not the central one) and the background field contribute to the analyzed value. If the difference between the analyzed and observed value exceeds some threshold, the datum requires further testing. Since the OI method provides an estimate of the analysis error, the threshold can be specified as a function of the analysis error. This allows for more variation when observations are sparse or distant from the datum in question and less variation when the observations are dense or located very close to the datum.

Large discrepancies between the observed and analyzed value may arise either because the subject observation is erroneous or because one of the observations contributing to the analysis is erroneous. To find out which is true, the data are reanalyzed several times, removing one of the surrounding observations each time to see if that produces agreement (Fig. 16). The removed observation is returned for subsequent reanalyses so that only one observation is absent for each reanalysis. If no agreement is found for any reanalysis, the datum being examined is flagged. Should the removal of one of the observations produce agreement, the removed observation is flagged as suspect and is not used in any subsequent QC analysis. Suspect flags are internal to the QC program and are generally not part of the QC output. Typically, a datum is flagged only when it is the subject datum.

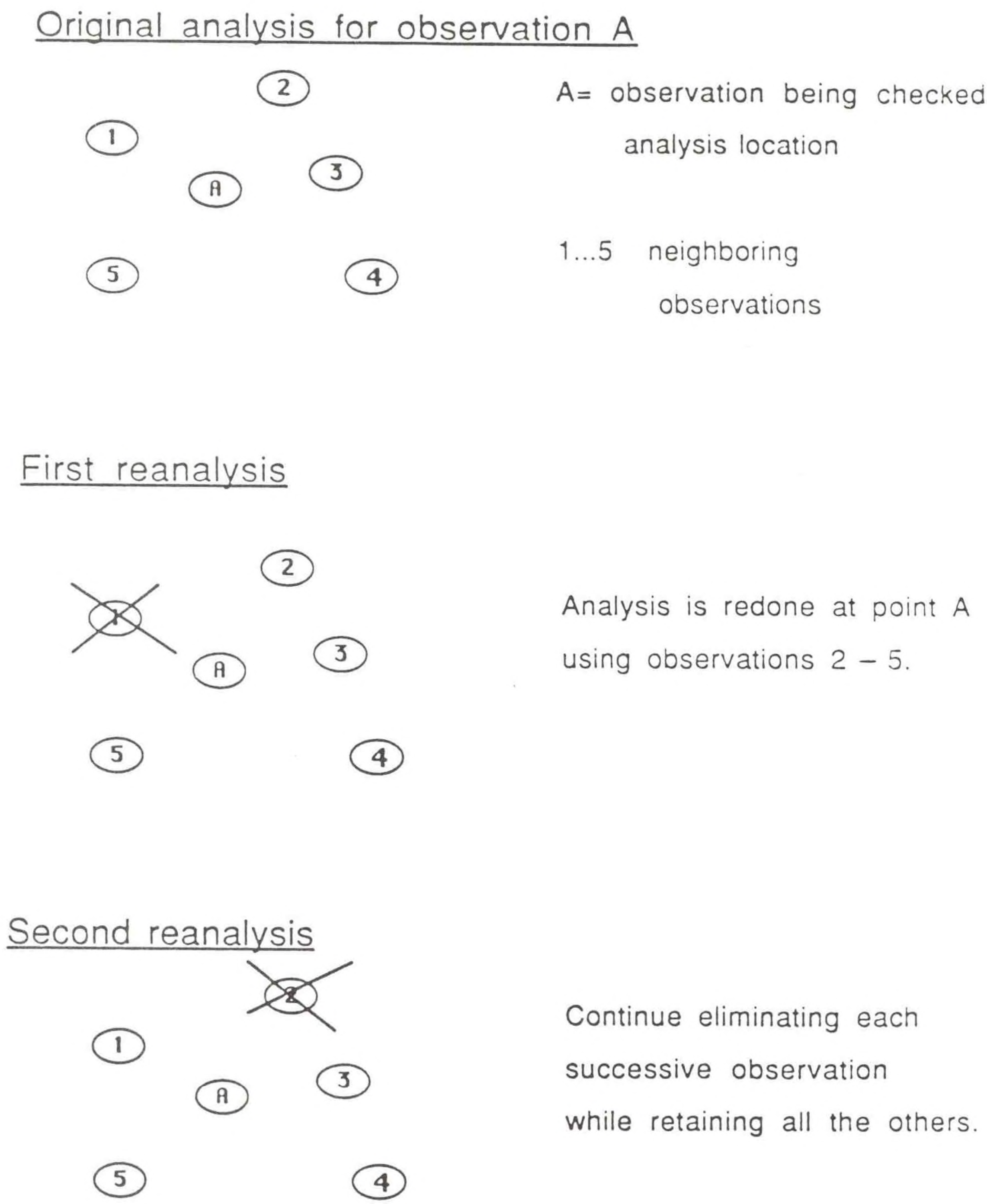


Fig. 16. Schematic of successive elimination process.

The technique just described can be used to check data in a time-height (t, z) cross section as well as on the horizontal surfaces for which it was originally designed. The correlation statistics must then be specified in (t, z) space. OI time-height quality control of profiler data in real time presents a special problem. Because we are always examining the latest hour, our analyses are not centered in time (i.e., we are always analyzing on the edge of the (t, z) domain). A second, often vexing problem is that spurious winds are not always isolated—repeated errors in a given beam, extending over several gates, can cause the reanalysis technique to fail.

The majority of cases can be handled properly if data selection for each analysis is done to minimize the possiblity of multiple bad data points being included. An OI QC alogorithm developed at PROFS makes two passes through the data with the flagging threshold decreasing on the second pass. In the first pass, data are checked in sequence from the lowest gate to the highest. The two nearest data points are collected from each of the numbered sectors shown in Fig. 17, except those which have not yet been checked (those in the shaded area—Sector 1 and part of the sector containing the subject point P). The eight data points which correlate best with the point being examined (as determined from historical data) are used in the analysis. The flagging system is the same as described in the paragraph above. The second pass proceeds as the first, but data are accepted from all the sectors. In this pass it is presumed that if there are any spurious data above the point being examined (i.e., not yet checked on this pass), they have been flagged bad in the first pass or flagged suspect when they were used as a contributing observation on the second pass.

4.2.2 *Recursive filter*

Quality control can be built into the analysis itself by adjusting the observation weights based on the observation difference from a first guess or, more commonly, from the previous analysis in a multiple pass (successive correction) analysis method. In this approach, data points are not discarded but are given a very small weight. Hayden and Purser (1988) used this approach in the design of a simple and fast analysis technique they call the recursive filter.

The recursive filter analysis uses bilinear interpolation to place the observed data (actually the difference from a first guess field) onto a regularly spaced grid. To smooth the analysis, a numerical filter (similar to a weighted running average) is applied to the grid-point values. Then the process is repeated using the last analysis as a first guess. With each pass, the filter is modified so that less smoothing is done. Quality control is introduced by weighting each observation according to its difference from the previous analysis. One can discard an observation if its "quality weight" becomes very small, or,

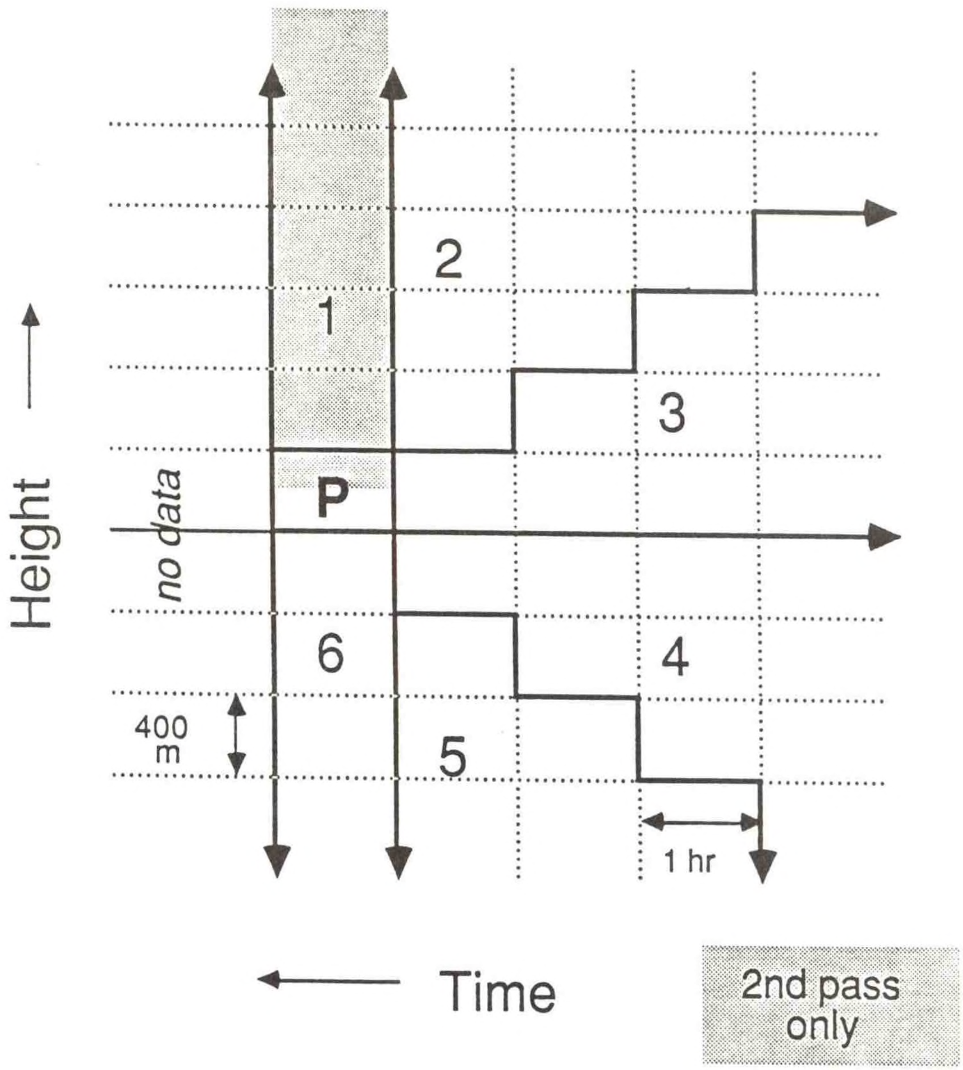


Fig. 17. Data search strategy for optimal interpolation analysis (OI) QC. Sector searching assures an even distribution of data around the datum being checked. Data within shaded area are excluded in the first pass; all sectors are searched in the second pass.

if the data density is high enough, one can presume that observations with very small weight will be overwhelmed by those with large weight (good quality observations). Because the recursive filter requires far less computation than optimal interpolation and no data searching it is much faster than OI. The speed depends upon the number of reanalysis passes necessary and the number of filter passes performed for each analysis pass. A good first guess can make the number of analysis passes very small (e.g., five) and can greatly increase the accuracy of the quality control decisions.

This technique has been tested on 6-minute profiler data at PROFS. The analysis is done on a 100-m by 6-minute grid and the first guess consists of the median of 11 observations around each grid point. A time-to-space conversion which equates 6 minutes to 100 meters is used, and data are discarded (QC flag set to "bad") if their weight is less than 10^{-3}.

4.2.3 Horizontal "buddy" check

All checks performed at the profiler Hub examine the internal consistency of data from a single profiler. Time constraints at the Hub computer do not allow more powerful checks for horizontal consistency, wherein data from adjacent profilers corroborate each other. Such checks are nonetheless advisable for applications involving spatial derivatives or model predictions. NMC performs these checks before using profiler data in its operational models. The earlier discussions of optimal interpolation and recursive filtering in the time and height dimensions apply equally well to the horizontal dimensions. In fact, OI and the recursive filter are commonly applied in horizontal "buddy" checking of a great variety of data.

REVIEW TOPICS FOR SECTION 4

The reader should know

- what group of observations is used to compute the median for the median check
- whether two bad data points adjacent in height probably will be detected by the Hub quality control
- whether six bad data points adjacent in height probably will be detected by the Hub quality control
- what methods are available for additional quality control after profiler data leave the Hub.

For more information on listed topics, see the following references.

Quality Control Techniques

Brewster, K.A., and T.W. Schlatter, 1986: Automated quality control of profiler data. 11th Conf. on Weather Forecasting and Analysis, Kansas City, Mo, June 17–20, AMS, Boston, Mass., 171–176.

Brewster, K.A., and T.W. Schlatter, 1988: Recent progress in automated quality control of wind profiler data. 8th Conf. on Numerical Weather Prediction, Baltimore, Md., Feb. 22-26, AMS, Boston, Mass., 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. for Comput. Mach., 24, 381–395.

Hayden, C.M., and R.J. Purser, 1988: Three-dimensional recursive filter objective analysis of meteorological fields. 8th Conf. on Numerical Weather Prediction, Baltimore, Md, Feb. 20–26, AMS, Boston, Mass., 185–190.

Stankov, B., and M.A. Shapiro, 1986: An objective routine for editing and temporal filtering of wind profiler data. Profiler Forum, July 1986 (available from Profiler Program, NOAA/ERL/FSL, 325 Broadway, Boulder, Colo, 80303), 2–4.

Objective Analyses

Thiebeaux, H.J., and Pedder, M.A., 1987: Spatial Objective Analysis With Applications in Atmospheric Science. Academic Press, Orlando, Fla., 299 pp.

5. Typical Difficulties

Quality control procedures at the profiler Hub are performed in real time, not centered in time; they do not use outside data or model forecasts. These constraints reduce the probability of a correct decision when distinguishing between a gross error and a legitimate wind shift. Although the QC can fail in a number of situations, only the two most significant will be described here.

One of the most difficult situations to handle is the presence of persistent, correlated error in the data, as in the case shown in Fig. 18. In this summertime case, the air between 10 and 13 km was so stable and lacking in turbulence that a zone of anomalous light northwest winds was reported. Apparently electronic noise or ground clutter of some kind was producing a signal of non-zero Doppler shift, and mutually consistent wind observations. Theoretically, a non-turbulent layer results in random signals which, by nature, cannot survive the consensus averaging. Indeed, there are many data holes in the same region as the suspect data where a consensus could not be found.

Could this be a real atmospheric signal? The vertical wind shears are not strong, but the occasional appearance of a 35-kt (17 m/s) WNW wind at 11 km (36 kft) is a strong clue that the true wind is that velocity (35 kt also agrees with the surrounding data). Further evidence is in the upper level charts from that day which show (Fig. 19) an 80-kt (42 m/s) jet passing to the north of Colorado at 200 mb. The isotachs suggest that the wind should have been about 40 kt (21 m/s) at Platteville at 200 mb.

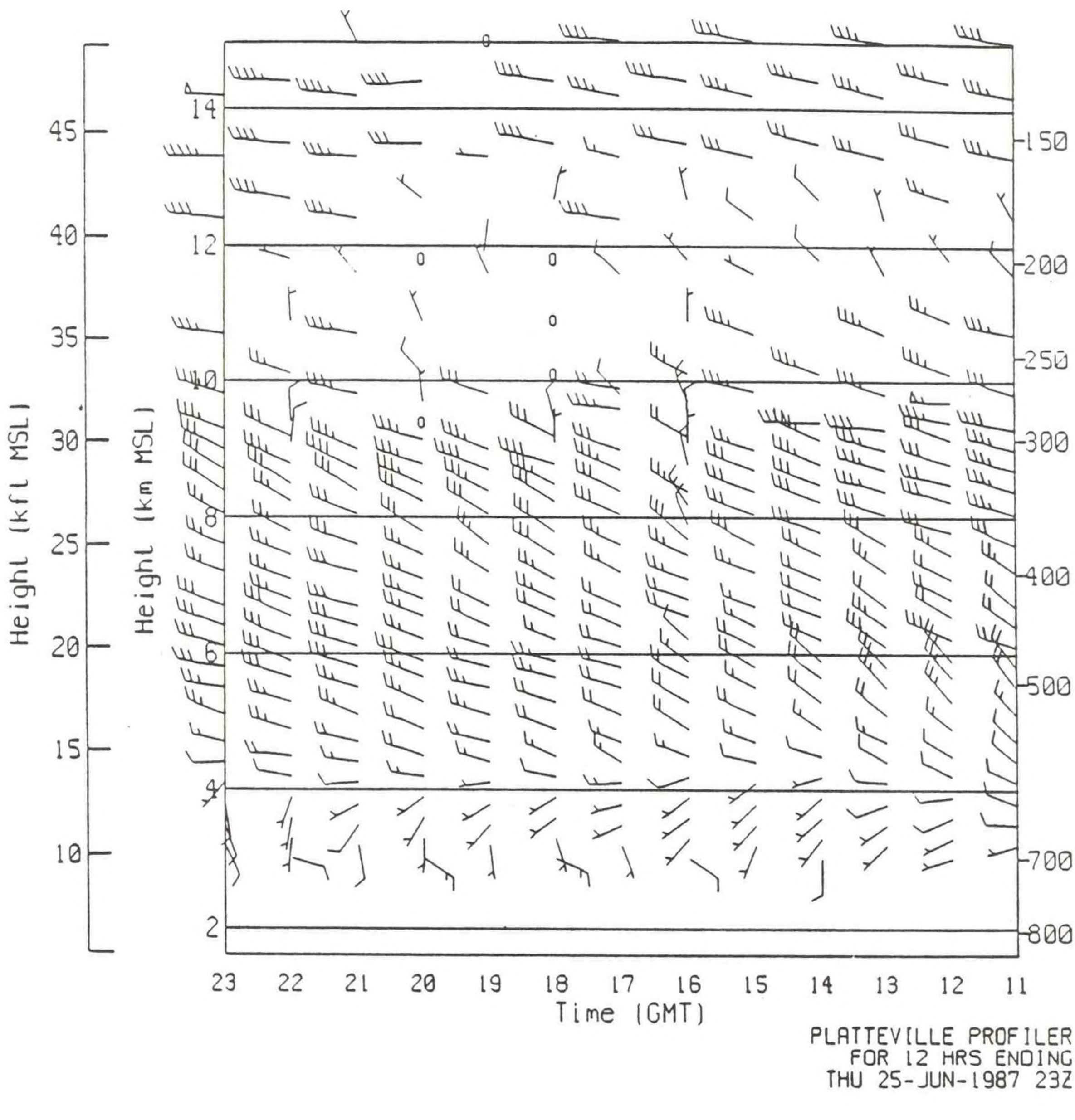
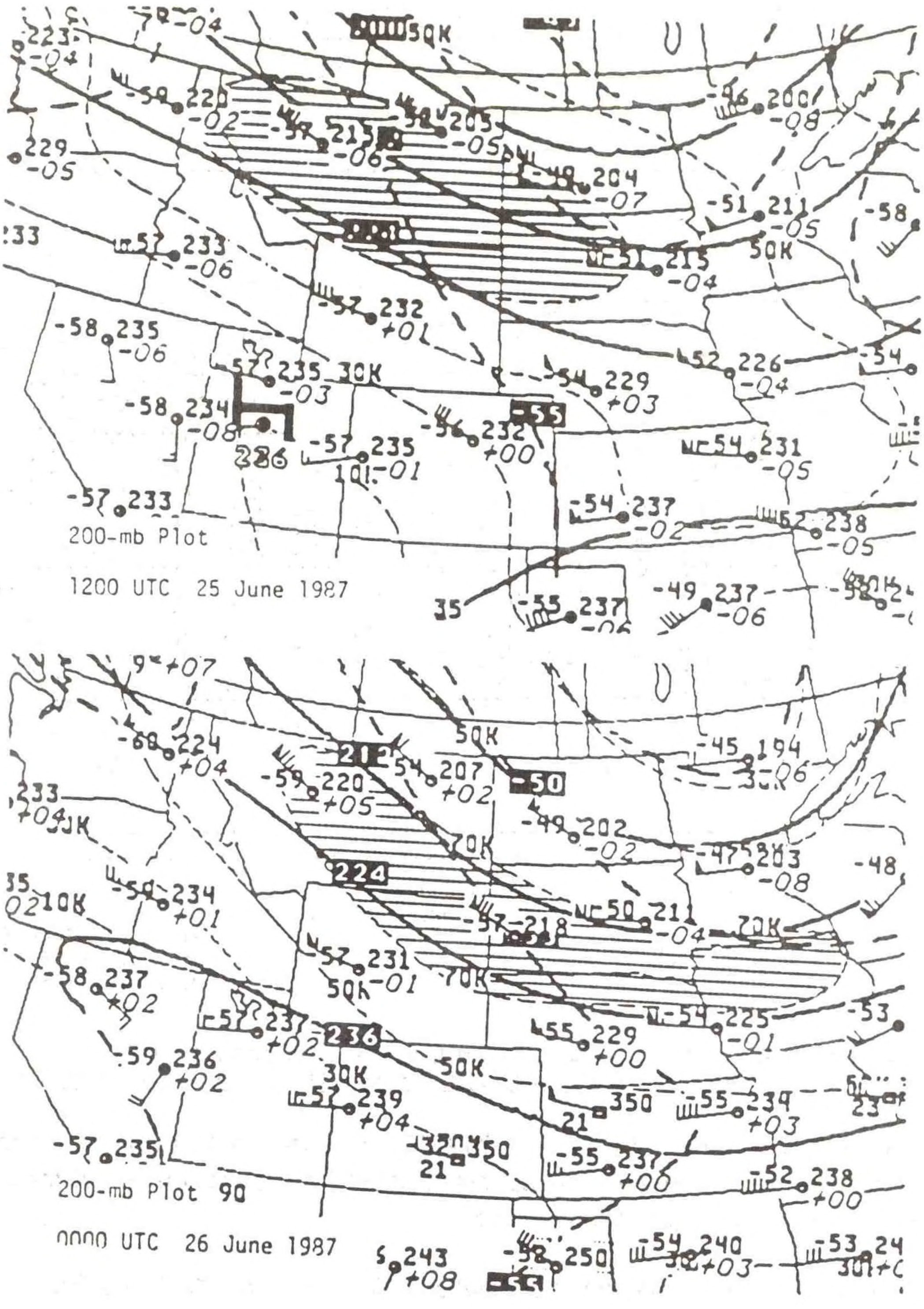


Fig. 18. Time-height cross section of data from the Platteville profiler from 1100 UTC 25 June 1987 to 2300 UTC 25 June 1987. Original data (consensus averaging only).



a

b

Fig. 19. NMC 200-mb data plot and analyses of height, temperature, and isotachs for a) 1200 UTC 25 June 1987, and b) 0000 UTC 26 June 1987.

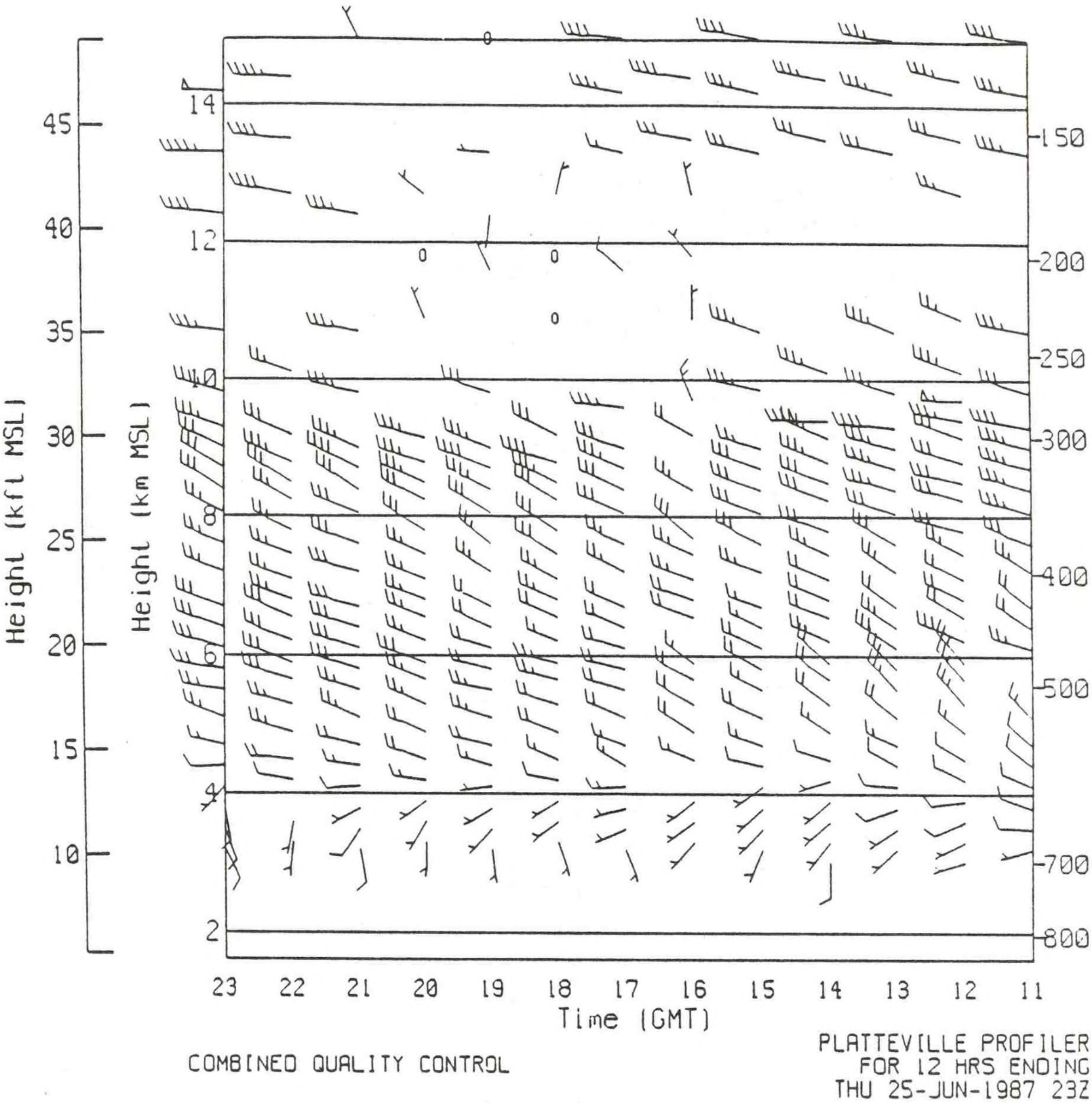


Fig. 20. Time-height cross section of data from the Platteville profiler from 1100 UTC 25 June 1987 to 2300 UTC 25 June 1987. Quality controlled data.

Hodographs from the Denver raobs at 1200 UTC 25 June and 12 hours later (not shown) are smooth in the upper troposphere, reinforcing the argument that there was no daytime lull in upper tropospheric winds.

How did the quality control handle this situation? Not well. Fig. 20 shows the data after quality control. Some of the bad winds were discarded (1100–1400 UTC), but between 1600 and 2100 UTC many of the bad winds were retained and some good winds were discarded. Faced with mutually consistent data in the high troposphere and constrained to look only at past data from a single profiler, the QC routine failed to detect many apparently bad observations.

The lesson to learn is this: **be suspicious of data near an area having high dropout frequency,** particularly when the reported velocities are very low. Also, of course, refer to wind information available from other sources (observations and forecasts).

Another example of potential QC failure is in a region of extremely high, but valid wind shear. Provisions are made for such shear, but if the shear is discontinuous in height and does not behave as anticipated by the QC algorithm, valid winds can be discarded in the area of strong shear. In most cases this effect persists for only an hour or two, but it is worth watching for because of the effect such a shear zone might have on the weather.

Fig. 21 shows unedited data from the Denver Stapleton profiler. Because that profiler (a 915-MHz system) samples with very fine height resolution (100 m [303 ft]), measured shears can be higher than those encountered with other systems. In this case there was strong shear at 700 mb related to a sharp frontal discontinuity. The quality control discarded several winds along the frontal boundary (Fig. 22) which should have been retained. Similar situations could occur with the 404-MHz network profilers.

This case points out the need to monitor carefully the performance of the QC algorithms when the surrounding data suggest a sharp discontinuity might exist. Again, supporting data in the form of surface and conventional upper-air observations will help identify the correct QC choices.

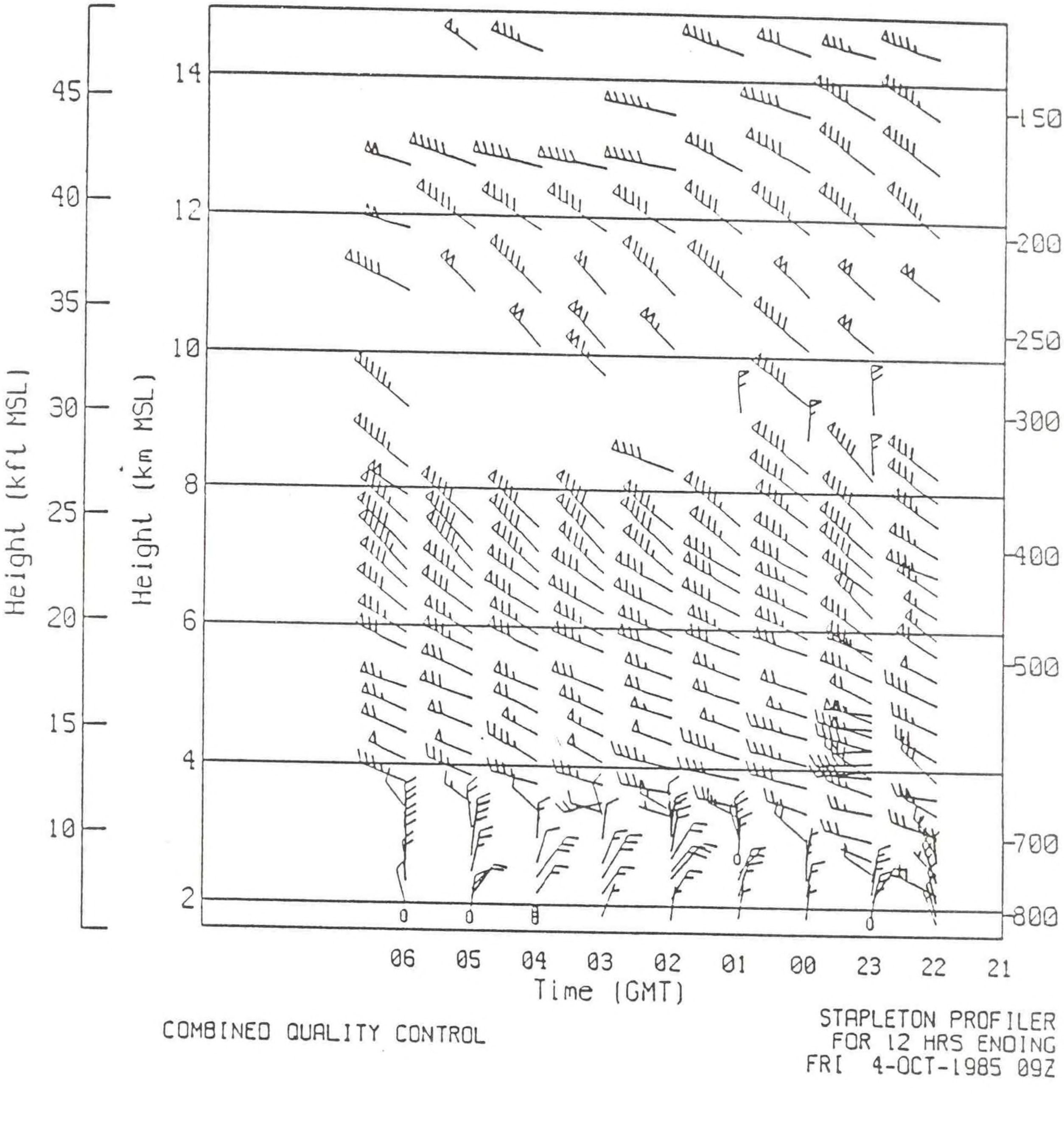


Fig. 21. Time-height cross section of data from the Stapleton (Denver) profiler from 2200 UTC 03 October 1987 to 0600 UTC 04 October 1987. Original data (consensus averaging only).

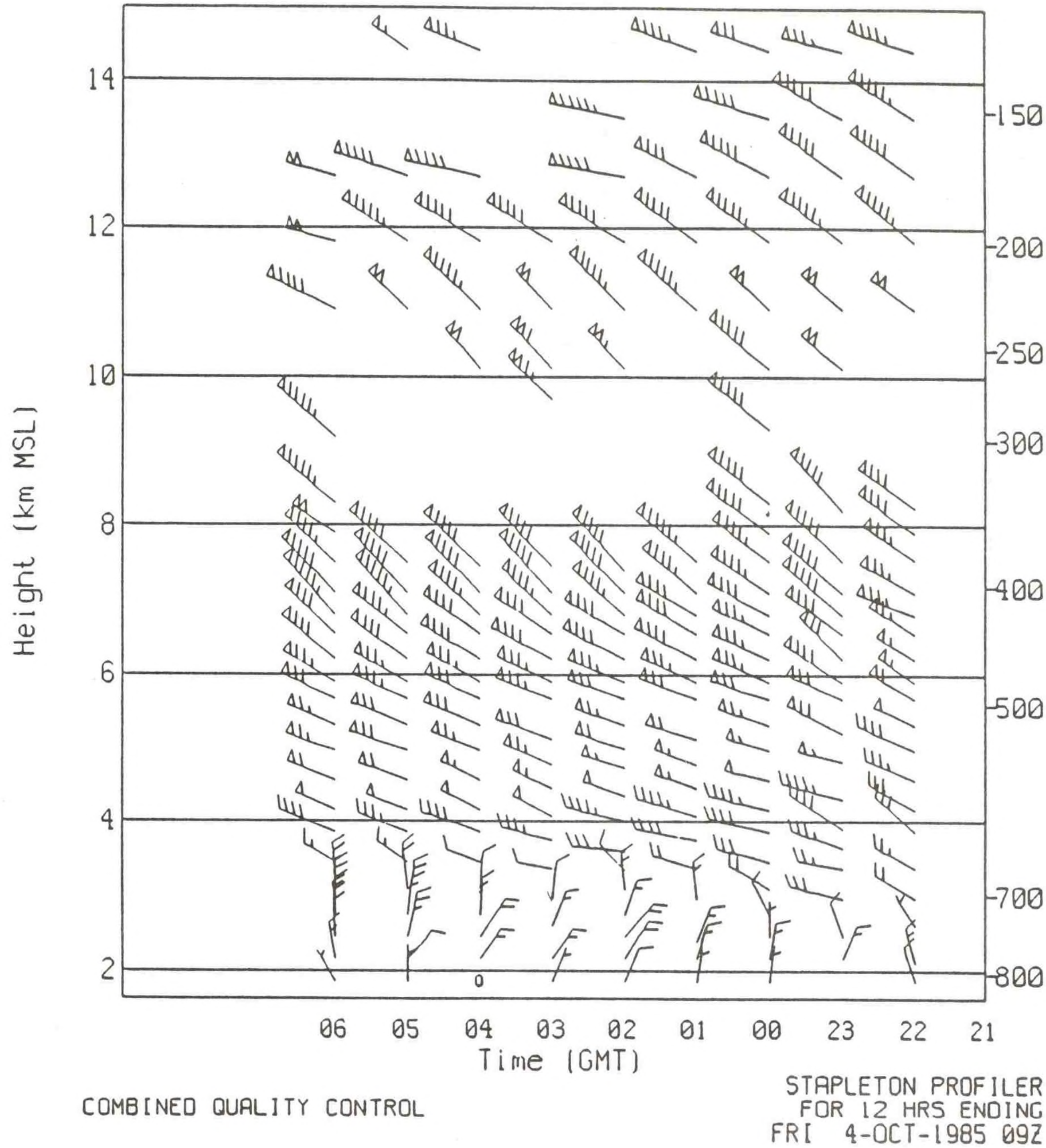


Fig. 22. Time-height cross-section of data from the Stapleton (Denver) profiler from 2200 UTC 03 October 1987 to 0600 UTC 04 October 1987. Quality controlled data.

REVIEW TOPICS FOR SECTION 5

The reader should know what data other than wind profiler data can be used subjectively by the forecaster to judge data quality.

6. Summary

This manual has covered the many aspects of profiler data quality of concern to the daily user. The possible errors of the profiler and how the quality control identifies gross errors have been discussed. Note, however, that the expected performance of the network profiler described herein has been extrapolated from experience with the research profilers. Therefore many details of the profiler's behavior and the effectiveness of the quality control system at the profiler Hub are unknown at this writing. The forecaster should be alert for updates from the Profiler Program and the NWS regarding the latest improvements or findings in this area.

It is hoped that the information presented here will enable you to use the profiler data with the proper critical eye. Although the focus has been on the "warts" of the profiler, the information in the two manuals on summertime and wintertime forecasting applications should convince you of the great utility of the profiler network, warts and all.

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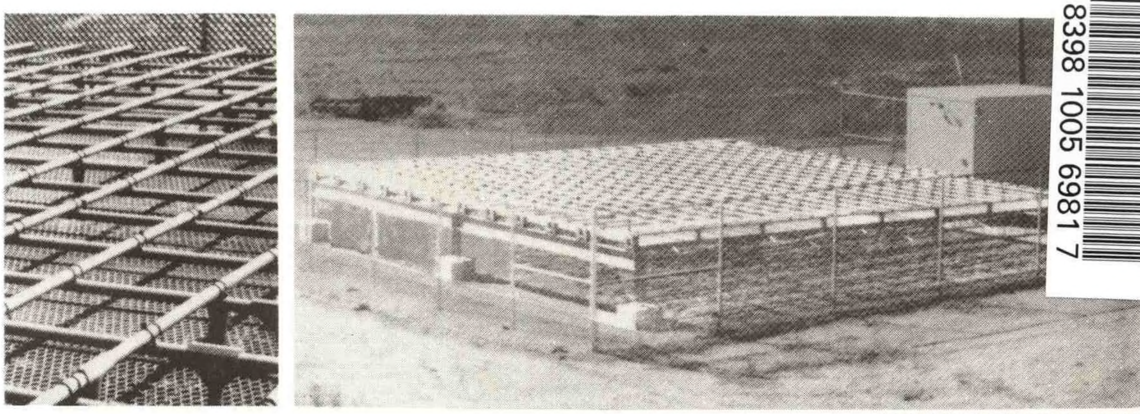

PROFILER PROTOTYPE ANTENNA