DA N85-32475

# 1.5A PERFORMANCE OF THE COLORADO WIND-PROFILING NETWORK

R. G. Strauch, K. B. Earnshaw, D. A. Merritt,
K. P. Moran and D. W. van de Kamp

National Oceanic and Atmospheric Administration
325 Broadway, Boulder, CO 80303

The Wave Propagation Laboratory (WPL) has operated a network of radar wind Profilers in Colorado for about 1 year. The network consists of four VHF (50-MHz) radars and a UHF (915-MHz) radar located as shown in Figure 1. The Platteville VHF radar was developed by the Aeronomy Laboratory (AL) and has been operated jointly by WPL and AL for several years. The other radars were installed between February and May 1983. The radars, their remotely controlled operation, and their data processing are described by STRAUCH et al. (1984). In this paper we summarize our experiences with these radars and discuss some general aspects of tropospheric wind measurements with Doppler radar.

## RANDOM SAMPLE CONSENSUS AVERAGE

In examining the performance of the Colorado Wind-Profiling Network it is important to understand how the data are acquired and averaged. The VHF radars at Fleming, Lay Creek, and Cahone have identical characteristics and operating procedures, as described by STRAUCH et al. (1984). One part of the data processing that is not fully described in that reference is the method used to average data for hourly wind profiles. This averaging is performed as follows for the VHF radars:

Twenty-four observations are made of the (u,v) wind components at each height during a total data acquisition time of about 48 min: twelve measurements are made with a 3-μs pulse duration, and twelve are made with a 9-μs pulse. The u and v components are measured simultaneously. The short pulse or "Low" mode is used to measure winds as close as possible to the surface and extending to about 9 km MSL (the sites are located at about 1.5 km MSL). Data are sampled at range intervals of two-thirds of the pulse width; heights from about 4 to 9 km are observed with both pulses. Figure 2 shows how the time is shared between the two modes of operation. Data acquisition starts on the hour and lasts for about 48 min; 2 min are required to analyze the data and the last 10 min of the hour are used for telephone (dial-up) communications with the network. Figure 3 shows the details of how the time is spent during each mode.

Following the 48-min observation period, the u and v components for each height are averaged using the random sample consensus method (FISCHLER and BOLLES, 1981). The mean radial velocities of the twelve observations at each height are examined to find the largest subset of data points whose mean radial velocities are within two Doppler spectral points of each other. The total number of spectral points in the Doppler velocity spectrum is 64; the window of acceptable data is, therefore, one-sixteenth of the total radial velocity interval. If the largest subset is four or more, the average of this subset is taken as the mean radial velocity during the 48-min observation period. If the largest subset is less than four, the data are discarded and no wind component is computed for that height. If there is more than one subset with the same (largest) number of data points, then the subset containing measurements closest to the end of the data-acquisition period is accepted. Both the u and v components must yield an acceptable subset to calculate wind speed and direction. The width of the velocity window corresponds to a horizontal wind speed of 7.3 m/s for the 3-μs pulse mode and 8.7 m/s for the 9-μs mode. This algorithm has proved effective for rejecting data contaminated by aircraft and for rejecting data when the signal-to-noise ratio is so low that the set of twelve estimates

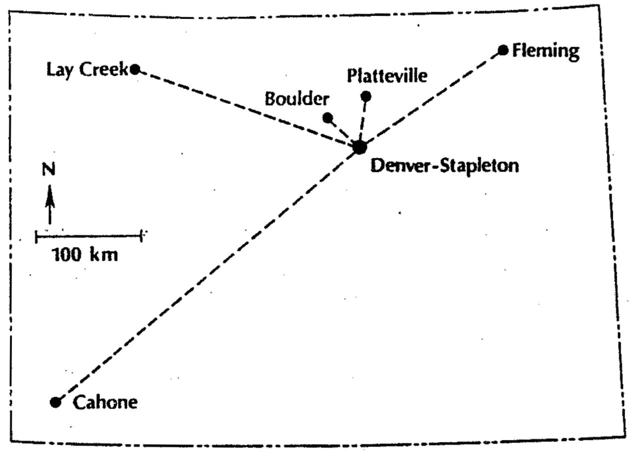


Figure 1. Location of radar wind Profilers. Data are transmitted by telephone to a control computer located at the WSFO at Denver.

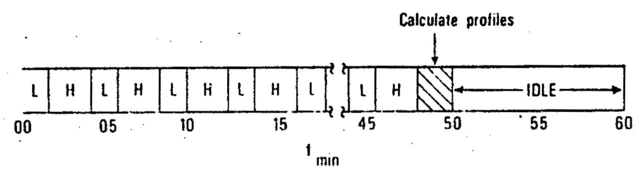


Figure 2. Hourly sequence of wind observations with 3-μs pulses (L) and 9-μs pulses (H). The idle period is for network communications.

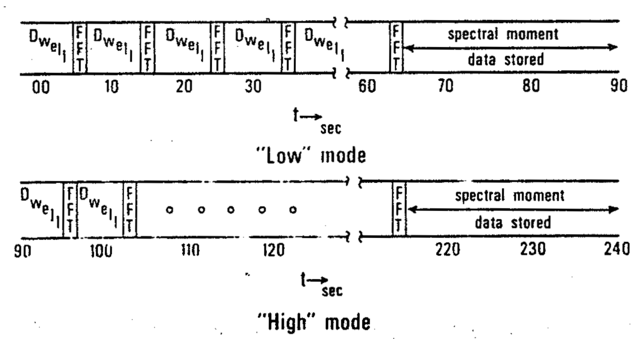


Figure 3. Details of temporal averaging during the 3-μs ("LOW") mode and 9-μs ("HIGH") mode of operation.

of radial velocity are essentially uniformly distributed over the Nyquist velocity interval.

To see how this algorithm functions in the case of no atmospheric signal, and because an analytic solution for the probability of occurrence of the largest subset was not obvious, we simulated the performance. The probability p that exactly k values will be in the data window is the following:

| k | p (largest subset = k) |
|---|---|
| 0 | 0 |
| 1 | 0.007 |
| 2 | 0.413 |
| 3 | 0.463 |
| 4 | 0.104 |
| 5 | 0.013 |
| 6 | 0.001 |
| 7 | 0.001 |

The probability is zero that the largest subset is zero because the algorithm centers the window on each measured data point to count the subset. The probability that the largest subset is greater than seven is too low to measure by simulation. If the input is noise, the probability that the largest subset is four or more is 0.119; if estimates of both u and v are made in noise, the probability of obtaining a "valid" wind estimate is 0.014. When the radar attempts to measure winds at heights where the atmospheric signal is too weak to detect, the largest subset is usually two or three; this indicates that the radial velocity estimates are uniformly distributed, as they must be for this algorithm to function properly.

VHF RADAR PERFORMANCE

The Colorado Network radars have demonstrated that continuous hourly averaged wind profiles could be provided by a national network of radars with automated and unattended operation. Figure 4 shows a sample of the hourly averaged winds measured by the VHF radar at Fleming. (Some of the problems that are apparent with the data from 0600 to 1500 GMT on Feb. 24, 1984, are discussed below.) The details that can be observed during events such as frontal passages give a temporal and spatial picture of the flow fields that is not presently available to the operational meteorologists. Whether this picture can lead to improved weather forecasting is a question that must be answered before an operational network is pursued; however, the interest in such data by commercial aviation is obvious.

An important question in the design of a tropospheric wind Profiler is that of sensitivity: given a desired height resolution, an averaging time for the wind data, the maximum height desired, and the fraction of the time the winds must be measured, how sensitive must the radar be? For VHF radars the answer to this question determines the average transmitted power and effective antenna area required. The VHF radars in the Colorado Network have a power-aperture product of $10^6$ W-m$^2$: 400 W of average transmitted power and a 50 m x 50 m antenna. Figure 5 shows the percentage of time the Lay Creek radar was able to measure hourly winds as a function of height. The squares are the data points for the 3-μs pulse mode, and the circles are the data for the 9-μs mode. Both the u and v wind components passed the random sample consensus test, described in the first section, for the percentage of time shown (as a function of height). The data are from 450 profiles (for each pulse mode) obtained from Nov. 12 to Dec. 12, 1983. We do not have these statistical results from all the data; in general, we expect the same trend as shown in Figure 5, but the rapid decrease in height coverage that starts at about 16 km (9-μs mode)

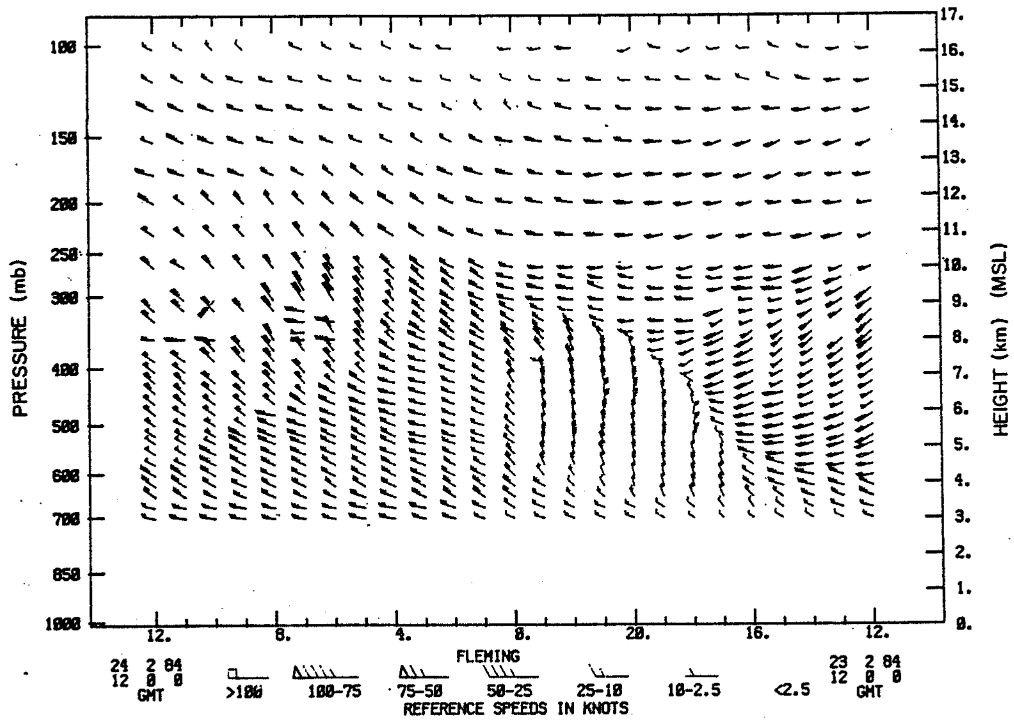


Figure 4. Sample of hourly averaged winds measured by the 6-m wavelength radar at Fleming.

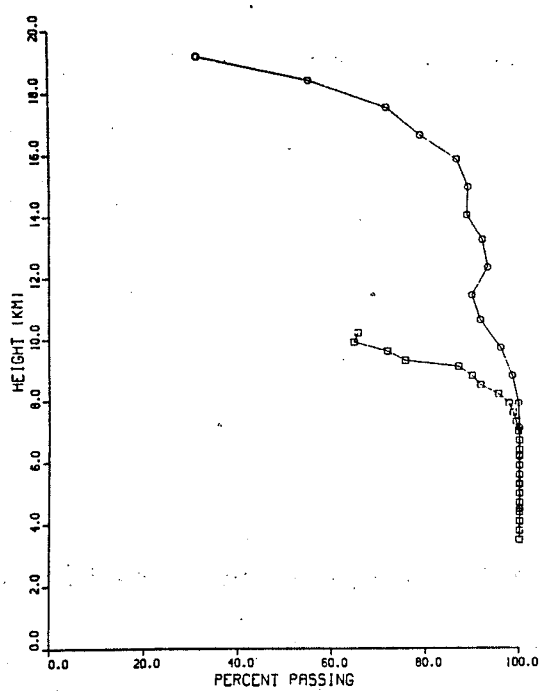


Figure 5. Percentage of time the 6-m radar at Lay Creek was able to measure wind profiles with a 3-μs pulse (squares) and a 9-μs pulse (circles). Power aperture product is the same for both modes. Data shown are from 450 profiles measured from Nov. 12 to Dec. 12, 1983. Twelve profiles are measured during each hour; four or more must pass the consensus test.

for the winter data will probably start at about 14 km for summer data. The decrease in percentage coverage at about 12 km is due to signal dropout in the core of a jet stream that was over the Network during this period. No systematic data analysis has been performed to sort out the different meteorological regimes.

Figure 6 shows what percentage of the data would have passed the random sample consensus if the algorithm had required that 8 or more of the 12 observations be in the largest subset. The decrease in percentage at about 5 km altitude (3-μs mode) is probably a result of moving clutter, such as automobile traffic, which would tend to cause the data system to select a false velocity, whereas fixed clutter is rejected (to a large extent) by the data processing. Figure 7 shows the percentage of the u (squares), v (circles), and both u and v (triangles) components that pass the consensus. We believe the difference in the u and v data reflects the difference in radar sensitivity (separate transmitters, receivers, and antennas) rather than a difference in radar reflectivity.

The accuracy of the wind measurement is difficult to assess because there is no reference or standard available for comparison. We believe the major limitation on the accuracy of the hourly averaged winds lies in the assumption that the vertical winds averaged over an hour are negligible. If the vertical winds are negligible, then a worst-case accuracy can be found by examining the data-averaging algorithm; if we have but four measured data points in the largest subset, and they are uniformly distributed over the velocity window, then the variance of the consensus-averaged u or v will be $\approx 1.3\ m^2/s^2$. In general, the variances of u and v will be less than 1 $m^2/s^2$ because there

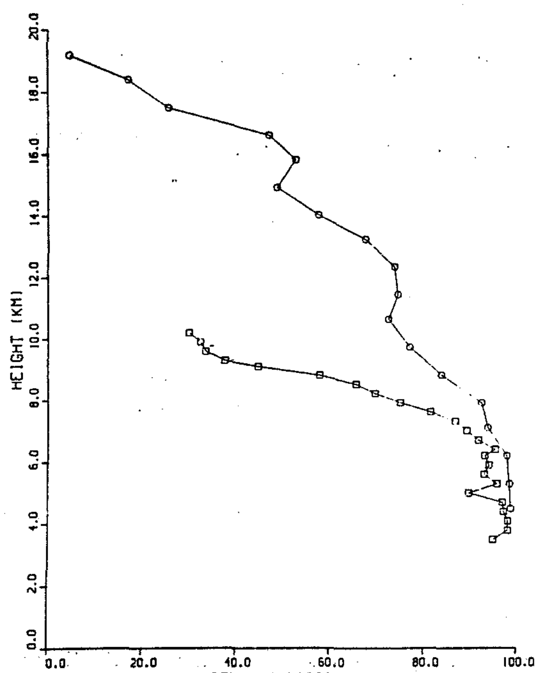


Figure 6. Same as Figure 5 but 8 or more of the 12 profiles must pass the consensus test.

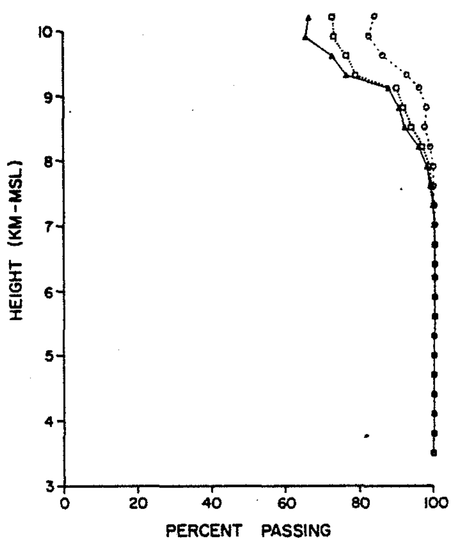


Figure 7. Percentage of time the 6-m radar was able to measure u (squares), v (circles) and both u and v (triangles) with the 3-μs mode. Same data as in Figure 5. Four or more must pass the consensus test.

are usually more than four estimates in the average and they are not uniformly distributed in the window. The spatial and temporal consistency of the wind profiles indicates that the variance of the estimates of hourly averaged winds is much less than 1 $m^2/s^2$.

VHF RADAR PROBLEMS

Some of the problems encountered with the VHF radars in the Colorado Network are associated with the particular hardware implementation we used and some are the result of VHF operation.

Problems associated with VHF operation:

(1) Frequency allocations are difficult to obtain at VHF. The frequency allocation for the Colorado Network is on a noninterference basis with another user.

(2) Even when frequency allocations are obtained, the authorized bandwidth limits the height resolution of the radar. The bandwidth authorized for the Colorado Network is 400 kHz, so the best height resolution is about 400 m.

(3) The weakest signal that can be detected by the VHF radars is about -145 dBm. It is difficult to avoid interference from the many communications systems that operate at nearby frequencies. We have had occasional interference problems with all our VHF systems.

(4) A remote site with an acre or more of level ground is required. We selected our VHF radar sites in rural Colorado to be at least 10 miles from small towns or airports; sites were relatively easy to find, and all the sites are relatively free from moving clutter. However, the remote locations can lead to problems with primary power and telephone service. The radar site at Lay Creek has had very unreliable power; power outage occurred several times per week during the thunderstorm season. The computer at that site had to be modified so it could be reset by telephone. (All systems self-start after power failure unless the power remains off for more than 30 min; if this happens the computer must be reset.) The site near Craig has also had telephone problems; when telephone service is interrupted, rural locations are the last to be restored. Note in Figure 4, for example, data for the 3-μs mode was lost during telephone transmission at 1500 GMT on Feb. 24, 1984.

Problems related to our particular hardware:

(1) The minimum height that can be measured in the 3-μs pulse mode is about 1.7 km AGL. It should be possible to measure winds below 1 km AGL, but the combination of recovery time of the transmit/receive switch and switching transients limits the minimum height.

(2) The power-aperture product of $10^6$ W-$m^2$ does not always permit hourly wind measurements at all heights of interest. In particular, the core of the jet stream is a region of poor signal-to-noise ratio where signal dropout occurs. Note the data dropout at about 300 mb from 0600 to 1600 GMT on Feb. 24, 1984, in Figure 4. Whether this is a serious problem that needs to be corrected by increased average transmitted power or increased antenna aperture must be determined by the users.

(3) Colinear-coaxial dipole arrays provide a low-cost, large-aperture

antenna. Their radiation patterns are not of high quality, and antenna sidelobes have caused some problems. The enhanced echo observed with VHF zenith-pointing radars can sometimes be strong enough to be observed through an antenna sidelobe. This spurious signal from the zenith, if it is strong enough, can cause the velocity estimate for that height to be near zero. We believe this is the explanation for the group of wind vectors that show only west winds near 300 mb from 0600 to 1400 GMT on Feb. 24, 1984 (Figure 4). The north-pointing antenna measured almost zero radial velocity. The signal-to-noise ratio of the turbulence echo is low in this region (note the dropouts discussed above), so it could be smaller than the specular signal observed through an antenna sidelobe. The main lobe of the antenna points 15 degrees off-zenith; a pointing angle change to direct an antenna pattern null toward zenith could reduce the number of times this occurs. Other spurious echoes occur occasionally, but their origin cannot always be identified. A higher-quality illumination pattern would no doubt eliminate some of them.

(4) We have operated the radars at remote stations (one site is an 8-h drive from the laboratory) in an unmanned and automated mode. The remote locations cause maintenance problems, particularly with hardware that has not been through development and tests for long mean times between failures. Most of our problems are associated with high-voltage/vacuum-tube transmitters; the problems are easy to correct and the radar is usually returned to operation a short time after someone reaches the site. We have relatively unskilled local people available to correct problems that can be diagnosed by telephone, and they have been very valuable in saving time and travel. However, successful operation of a network of Profilers that operate unmanned requires that skilled personnel make routine visits for preventative maintenance; in our year of operation we have responded to problems rather than trying to prevent them.

All of the problems associated with our particular hardware implementation can be solved, so we conclude that a network of VHF wind Profilers is feasible provided that the fundamental constraints of frequency allocations, bandwidth, and interference, imposed by VHF operation, do not unduly compromise the measurement objectives.

UHF RADAR OPERATION

The 915-MHz (33-cm wavelength) radar was installed near the Weather Service Forecast Office at Denver's Stapleton International Airport in January of 1983. Unlike the remote VHF radars, which have been operated in the same mode since they were built, the UHF radar has operated in many different modes for special experiments and comparisons with other instruments. When it is used for wind profiling, the data processing and signal averaging are the same as for the VHF radars. The UHF radar uses pulse widths of 1-, 3-, and 9-μs with corresponding average power-aperture products of $1.1 \times 10^4$, $2.6 \times 10^4$, and $4.5 \times 10^4$ W-m$^2$. Observation of u, v, and w wind components is sequential, not simultaneous. Hourly averages of 12 observations are made in each antenna position and with each pulse width.

Figures 8-10 illustrate the height coverage of the UHF radar. These figures show the results of 415 profiles (for each pulse width) acquired from Nov. 5 to Nov. 23, 1983. Circles show the north antenna data, squares show the east data, and triangles show the percent of the profiles where both the north and east data passed the consensus. Figure 8 shows data for the 1-μs pulse mode with a largest subset required of 5 or more of the 12 observations. The

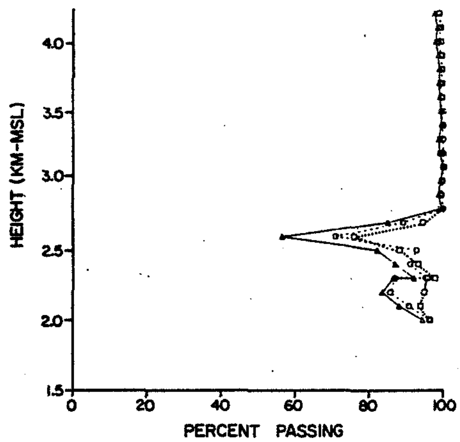


Figure 8. Percentage of time the UHF radar was able to measure hourly averaged winds in the 1-μs pulse mode. East component (squares), north component (circles), and both components (triangles) passed the consensus test with 5 or more of 12 profiles in the largest subset. Data are from 415 profiles obtained Nov. 5 to Nov. 23, 1983.

radar is located at 1.6 km MSL; the first range gate is about 350 m AGL. Data are sampled every two-thirds of a microsecond or about every 100 m in height to about 4.3 km MSL. The consensus algorithm shows the problems caused by clutter in the lowest eight range locations (1.9-2.7 km MSL). The abrupt decrease in percentage passing at 2.6 km is caused by traffic on a nearby interstate highway; moving clutter cannot be eliminated in the Doppler spectrum as readily as fixed clutter. The signal-to-noise ratio of the atmospheric scatter is higher at these lower altitudes than it is at the upper heights where the winds are measured nearly all the time. The clutter is strong enough to impair the ability of the radar to measure winds in the lowest 1.1 km AGL. Figure 9 shows the 3-μs pulse data when the largest subset required is eight or more. Figure 10 shows the corresponding data for the 9-μs pulse mode. The increased height coverage with 9-μs pulses as compared with the height coverage with 3-μs pulses is much less pronounced for the UHF radar than for the VHF radar

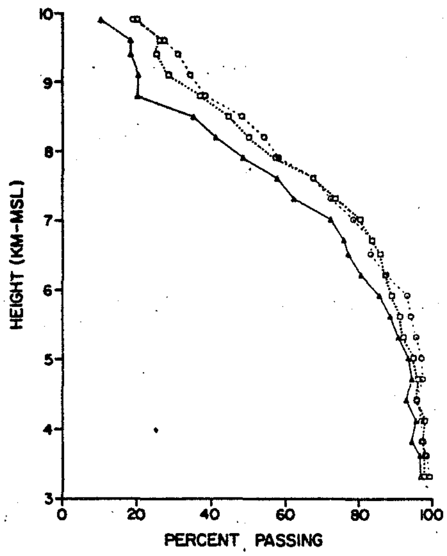


Figure 9. Same as Figure 8 except the data are obtained with a 3-μs pulse and a largest consensus requirement of 8 of 12 profiles.

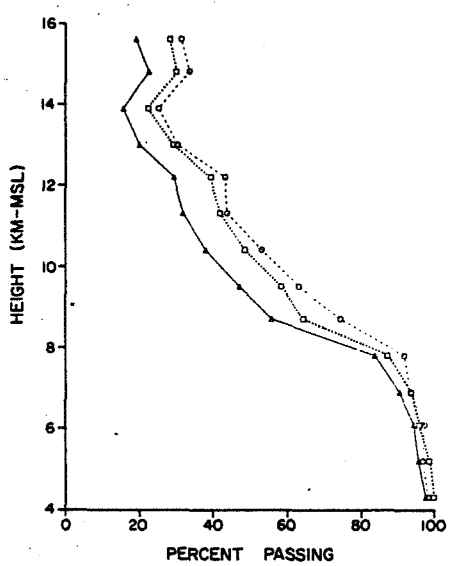


Figure 10. Same as Figure 8 except the data are obtained with a 9-μs pulse and a largest consensus requirement of 8 of 12 profiles.

(Figures 5 and 6). At the 60% passing level, the 9-μs pulse mode only increased the height coverage by about 1 km for the UHF radar. For the UHF radar the power-aperture product of the 9-μs mode is 6 dB greater than the 3-μs mode, but for the VHF radars it is the same so the height coverage difference is all the more dramatic. We believe the failure of the increased sensitivity of the 9-μs mode to increase the height coverage of the UHF radar is an indication that the inner scale of turbulence is less than half the radar wavelength at 10 km MSL or below in at least some meteorological conditions. The 33-cm radar can measure winds to 14 km MSL in some cases, but its wavelength may be too short for routine tropospheric coverage. We are comparing the reflectivity profiles of the 33-cm radar with those measured by a colocated 10-cm radar to attempt to identify how the inner scale of the inertial subrange limits the measurement height at these two wavelengths.

## UHF RADAR PROBLEMS

Problems associated with using UHF radar for wind profiling:

(1) The height coverage of the UHF radar may be limited more by the scattering mechanism than by sensitivity (power-aperture/noise temperature) considerations.

(2) Clouds and precipitation detected from antenna sidelobes can be stronger than the refractive turbulence signal from the main lobe. Although this has no doubt occurred with our 33-cm radar, we do not have a procedure to identify when it happens.

Problems encountered that are related to our particular UHF hardware implementation:

(1) A major airport is an extremely poor choice for a site for a sensitive clear-air radar. The ground clutter in the lowest 1.1 m height impairs our ability to measure winds close to the surface. The clutter power does not saturate the receiver or data system, so it would be much more tolerable if it was not caused partly by moving targets (automobiles, aircraft taxiing and flying).

(2) The only component failures in a year of operation are the mechanical rf switches that select the antenna pointing direction. They are being replaced with another type of switch with a longer rated life time.

(3) The maximum power-aperture product available is $8 \times 10^4$ W-m$^2$; the height coverage expected with this radar is less than expected with the VHF radars.

(4) The UHF radar uses the same data processing as used with the VHF radars. However, the VHF radars require 5 or 6 s to acquire the time series of radar returns needed to calculate a 64-point Doppler velocity spectrum whereas the UHF radar acquires the same data in about two-thirds of a second. (The dwell time is proportional to the radar wavelength.) Therefore, software power spectral analysis does not represent a serious overhead time (about 1 s) for the VHF radars, but it seriously reduces the incoherent integration time available for the UHF radar.

(5) A zenith-pointing antenna position is included in the UHF radar, because the scattering from hydrometers can exceed that from refractive turbulence, and therefore a correction for particle fallspeeds must be made during precipitation. The correction has not been implemented.

(6) We have observed occasional interference from other transmitters. A request has been made to shift transmitted frequency to between 910 and 915 MHz to solve this problem.

WIND MEASUREMENTS WITH FIXED-BEAM DOPPLER RADAR

The radar wind Profilers in the Colorado Network are fixed-pointing systems with two or three pointing directions. The two-beam systems have orthogonal viewing directions at 15 degrees off-zenith; the three-beam systems also have a zenith-pointing position. The choice of elevation angle and the method of wind measurement is discussed by STRAUCH et al. (1984).

The meteorological assumptions needed to measure hourly averaged horizontal wind profiles with a two-beam system are (a) the errors cause by vertical velocity will be negligible; and (b) the horizontal wind components, measured at separated volumes in space, are representative of the mean wind at the radar location. Vertical velocity at the measurement volume causes an error in the measured horizontal wind component of w tan $\Theta_e$ (m/s) where w is the vertical wind and $\Theta_e$ is the elevation pointing angle. For the Colorado radars we must assume $w < 0.25$ m/s for an hourly average if the error in the horizontal component is to be less than about 1 m/s. The representativeness assumption applies when the horizontal components are combined and said to be the vector wind at the radar location. The difference in the wind at the measurement volume and at the radar is (grad $u_i$) (h) cotan $\Theta_e$ where h is the measurement height and grad $u_i$ is the mean gradient of the wind component in the direction that the component is translated. Gradients normal to the translation direction do not enter into the wind calculations; nevertheless, a tacit assumption of a locally uniform wind field underlies the two-beam measurement technique. It is important to note that vertical wind causes errors in the measured horizontal wind components. Horizontal gradients do not introduce an error in the horizontal wind component at the measurement location. In some applications the wind components would be assigned to their actual locations so there would be no error from horizontal gradients.

The meteorological assumptions needed to measure hourly averaged winds with a three-beam system are that horizontal gradients of w will cause negligible errors and that the wind components measured at separated volumes can be combined to form a vector wind. Horizontal wind accuracy of about 1 m/s requires that (grad w) (h) cotan $\Theta_e$ be less than 0.25 m/s. The assumption of a locally uniform wind field is unchanged with the addition of a third beam. The third beam adds relatively little to the ability of the radar to measure hourly averaged horizontal winds. The zenith beam provides a direct measurement of w, and it measures the temporal scale of vertical fluctuations so it can indicate the temporal averaging period needed to reduce vertical motion contamination of horizontal measurements. The two-beam system will have significant errors in the measured horizontal components if the period of vertical velocity perturbations is long compared with the averaging time; the three-beam system allows a correction for this long-term vertical motion but only if the spatial wavelengths of w are large compared with the separation of the measurement volumes. Correction of the horizontal winds for vertical motion on a short-term basis (wind components are measured every 2 min in the VHF systems) does not seem possible because the measured vertical motion cannot be related to the vertical motion where the horizontal winds are measured without some knowledge of the spatial wavelengths of w. Perhaps the greatest value of the zenith beam is that at VHF the vertical beam can measure the height of the tropopause (GAGE and GREEN, 1982), while at shorter wavelengths the vertical beam can allow a correction for fallspeed of particles in widespread precipitation.

## CONCLUSIONS

The Colorado Wind-Profiling Network operates continuously and unattended; it automatically measures hourly average vertical profiles of the horizontal wind and sends these data to a central control computer. Experience with the radars has shown that an operational network of wind Profilers is feasible. We believe that this network could use radar wavelengths in the range of 0.7 to 7 m (40 to 400 MHz). The wavelength choice would depend on available frequency allocations and the data requirements.

## ACKNOWLEDGEMENTS

The cooperation and assistance of the Atmospheric Dynamics Group of the Aeronomy Laboratory are gratefully acknowledged. The VHF radar techniques we have exploited were developed in that group by Ben Balsley, Warner Ecklund, and Dave Carter. Tony Riddle has assisted us in processing Platteville data, and Judy Schroeder obtained the statistics on radar coverage.

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