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1.4.3 A LOOK AT PROFILER PERFORMANCE

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INTRODUCTION

Since about 1974, Doppler radars operating in UHF and VHF ranges have been used increasingly to study atmospheric winds. Historically, large systems capable of obtaining data from high altitudes have focused attention on the mesosphere and stratosphere, rather than on the troposphere (MST) wherein abides most of the weather considered by most meteorologists. Excellent histories and exposition of the technology involved have been given by GAGE and BALSLEY (1978) and BALSLEY and GAGE (1982). Perhaps the most recent comprehensive collection of MST studies is the HANDBOOK FOR MAP (Middle Atmosphere Program) Volume 9 (BOWHILL and EDWARDS, 1983).

Refinement of smaller systems with down-to-earth capabilities has stimulated investigation of their application to meteorological problems as evidenced by the existence of the session on forecasting applications at this Workshop. The prospect that vertical profiling radars would provide accurate wind information frequently and automatically is very intriguing to meteorologists at a time when data processing and communicating capabilities are advancing rapidly with commensurate development of numerical meteorological models. One scenario, for example, envisages that a network of wind profiling radars, substantially denser than the present day rawinsonde system but no more expensive, would transmit wind data as often as hourly to a central station, where a grand numerical model would fuse kinematic details with thermodynamic data gathered from weather satellites and perhaps a few ground-based thermodynamic profilers, and produce a weather outlook updated hourly. No weather system 100 km in size or larger would escape detection with this network; incipient storm triggers would be incorporated into the forecasts, and we would only very rarely be much surprised by weather developments.

Since this session includes papers by experts who indicate practical approaches to this meteorological utopia (see especially the outline of mathematical synthesis of diverse data given by Gal-Chen, this volume), we do not dwell on this further here. Rather, we address some questions the meteorologist must logically ask first, viz., what is the actual performance capability of these systems, how accurate is the wind data of interest to meteorologists, and from what altitudes in the troposphere are the data reliably obtained?

LITERATURE ON ACCURACY OF WIND FINDING BY PROFILING RADARS IN THE TROPOSPHERE

CLARK et al. (1985) cite 11 references that present some analysis of the accuracy with which wind profiling radars measure the winds. The findings of these studies are summarized in Table 1 and our list of references includes their sources. From these papers we have drawn the following conclusions:

a. There is a remarkable paucity of solid tests. Most tests involve one or more of the following limitations: check data unfortunately distant in time and/or space; too few cases to be definitive; winds too light to be definitive; test conducted in region where winds are quite variable.

Table 1. Profiler winds compared with winds by rawinsonde and other means.

Radar Location	Frequency	Beam-Width	Author	Date	Rawinsonde site & distance	Radar Method	Results
1. Sunset, Colo.	40 MHz	7.1° E-W 14.2° N-S	Green et al.	1975	Denver, 55 km	2 beams, 30° from vert.	About 65 wind measurements but unclear how many soundings involved. E-W radar wind and rawinsonde winds correlated 0.84. stand. dev. of diff ~5 ms^{-1}.
2. Sunset, Colo.	40 MHz	Presumably as in (1).	Warnock et al.	1978	Tabernash 33 km	2 beam method; compare winds with soundings whose balloons pass within 25 km.	Five cases; correlation 0.96 with winds above 4 km MSL. Some differences up to 5 ms^{-1}. Could be due to spatial separation.
3. Sunset, Colo.	40 MHz	Presumably as in (1).	Green et al.	1980	-	Winds by radar and NCAR aircraft compared.	On a day with Queenair, winds less than 5 m/sec; some differences were about as large, but reasonable agreement in profile shapes. On windy Feb. day with Sabreliner, almost all data (dis)agreed within 5-10 ms^{-1}. Data 4-6 km MSL only.
4. Sunset, Colo. Platteville	40 MHz 50 MHz	4.8° 2.5°	Clark et al.	1985	-	5 beams: one vertical, 2 E-W, 2 N-S	More consistent data on horizontal winds follow correction for vertical winds. Vertical winds more a problem in mountainous areas than on plains.
5. Chatanika, Alaska	1290 MHz	0.6°	Balsley et al.	1977	Fairbanks 5 km	VAD	Agreement to within 1-2 ms^{-1}.
6. Poker Flat, Alaska	50 MHz	2.0° az 4.0° el	Ecklund et al.	1977	2 km	143° component measured at different heights with beam fixed in elevation.	Two weather balloons, one was two hours different in time. Soundings and radar winds agreed to ~2 m/sec. Winds ranged from 1-14 m/sec.

Radar Location	Frequency	Beam-Width	Author	Date	Rawinsonde site & distance	Radar Method	Results
7. Max Planck Inst. for Aeronomy	53.5 MHz	3.5°	Rottger et al.	1978	Hannover 90 km	Measurements at vertical incidence and 12.5° off zenith.	Fair agreement (3 ms^{-1}) between radar and rawinsonde winds in one case. No winds below 1 km from radar. But max. rawinsonde wind only 6 ms^{-1}.
8. Arecibo	430 MHz	0.17°	Farley et al.	1979	San Juan 75 km	VAD scanning 22.5° intervals	Agreement w/San Juan generally to 3 ms^{-1}. Large variations in both ff and dd faithfully mirrored. Measurement above 5 km MSL; strong zero shift returns at low altitudes. Data scaled by hand; reference to need to develop criteria to deal with clutter echoes and complex atmos. echoes with multiple spectral peaks.
9. Arecibo	430 MHz	0.17°	Fukao et al.	1982	San Juan 75 km	Wind components measured along beam directed 15° from zenith, in meridional and azimuthal directions, each for 30 minutes.	Standard deviation of differences between radar and rawinsonde components was under 5 m/sec, ascribed to rawinsonde errors & temporal and spatial variability of winds. Rather faithful match vertical irregularities in Arecibo and San Juan profilers. Winds up to 30 ms^{-1}.
10. Platteville, Colo.	50 MHz	2°	Ecklund et al.	1979	Denver	2 beams, 15° from vertical	2 comparisons. Differences generally ≤ 5 ms^{-1} except one at 8 km >20 ms^{-1}. Only heights above 4 km agl.
11. Kwajalein	410 MHz	1.06°	Crane	1980	-	Compared with Jimsphere tracked with same radar.	Agreement to ~1 ms^{-1}.
12. Jicamarca	50 MHz	0.5°	Fukao et al.	1981	Lima 30 km	2 beams, 3.45° from vertical	Four cases; radar data offset 10-15 ms^{-1} from Lima data 20 km away. Reason for discrepancies unclear. Note that any systematic error must be greatly amplified in calculations because of small zenith angle.

b. In a few cases (5, 8, 9, 11) with radar beams quite narrow (∿1° or less), results are excellent, differences with other reported winds being indisputably within the range of uncertainty attributable to the other wind-finding method.
c. Almost all of the test data concern VHF. There are only three papers treating results in the 400-MHz region, and these apply to unusual and markedly superior equipment, not of the economical type being recommended for development and deployment in a meteorological network.
d. The typical deviation of radar-measured and comparison winds is near 5 m s^{-1}. This is not small enough to give ease but not so large that it cannot be largely explained by spatial and temporal separations in the data acquired.
e. There are not enough data for us to be confident about possible systematic differences between true winds and data gathered with VHF radars of the type proposed for meteorological use. It appears, however, that bias, if it exists, is not greater than about 2 m s^{-1}.
f. Study (4) in Table 1 is persuasive in its indication that vertical velocity contaminates the indications of horizontal winds at the Sunset site and in its suggestions of means to reduce such contamination greatly with multibeam systems. This paper, in a milieu of other meteorological inputs, is also persuasive in its evidence for a substantially smaller magnitude and persistence of vertical velocities in the plains than in the Rocky Mountains.
g. Data collected by the 50-MHz systems deployed for weather studies are in the layer between about 2 km AGL and 17 km.

As we interpret these data to reach our conclusions, we should refer to studies of wind variability and of rawinsonde accuracy; rawinsondes represent usual means for measuring and studying winds. During 1968, during the NSSL spring program of observations, paired soundings were released within five minutes of each other at two sites and tracked with independent tracking systems within a few hundred feet of each other on the ground. Seven pairs at each site produced comparative wind data. The standard deviation of wind speed differences near Fort Sill, Oklahoma, was 1.43 m s^{-1}, and near the television antenna for WKY north of Oklahoma City it was 2.55 m s^{-1}; standard deviations of directional differences were 6.00 and 7.68 degrees, respectively. Since the balloons were launched in fair weather, it is estimated that practically all the differences are attributable to properties of the procedures and equipment used to gather the data. In particular, the larger value given for the WKY site probably reflects some difficulties there that were especially noticeable (BARNES et al., 1971). Also in 1968, at 10-station rawinsonde network near the National Severe Storms Laboratory in Norman, with station spacing ranging from 25 to 132 km and average spacing of 39 km, provided 573 soundings appropriate for study of wind structure, of which 104 soundings were made during periods devoid of local storms (BARNES and LILLY, 1975). The rms vector wind difference measured at the 46 km distance significant for the current study was less than 3 m s^{-1} at each of the altitudes examined -- 1500, 3000, and 5700 m MSL.

Finally, there is the study of HOEHNE (1980) who found 3.1 m s^{-1} to be the standard deviation of the difference between wind speeds measured with separate tracking systems that tracked pairs of sondes suspended from single balloons. Hoehne's value seems large in view of the results from the NSSL data described above.

Clearly, work remains to define both the wind-profiling performance envelope of the 50-MHz and 405-MHz systems proposed for meteorological use, and the spatial variability of actual winds.

50-MHz PROFILER IN OKLAHOMA

In a project involving cooperation between the Wave Propagation Laboratory in Boulder, Colorado, and the National Severe Storms Laboratory, a 2-beam 50-MHz profiler was installed during Spring 1985 at Great Plains Apiaries, 34°58'N x 97°31'W. This is in Section 21, Township 6 North, Range 3 West, McClain County, Oklahoma, 46 km south of the Oklahoma City Weather Service Forecast Office, where rawinsonde data are obtained twice daily. It is a region of rolling hills with slopes averaging near 2°; and valley bottoms are about 35 meters below hilltops about 2 km apart. The radar is at an elevation of 330 meters MSL and surrounding hilltops are typically 355 meters MSL. In order to minimize displacement of earth during installation and subsequent erosion problems, the 50-m-square dipole arrays were oriented along azimuths 11.3° and 101.3°, referenced to true north, with Earth's surface at the site tilted upward 2.1° toward azimuth 11.3°. The dipoles oriented toward 11.3° project a beam toward azimuth 109.4° and elevation angle 75.4°; and the dipoles oriented toward 101.3° project a beam toward 191.3° and elevation angle 73.4°. The two-way beamwidths are about 5° to half power. The radar was placed "on the air" about May 10th with software applicable to installations on a level surface; software properly accounting for the tilted terrain and beam angles given above was installed on July 15th. Data collected before the revised software was installed can be corrected.

The radar operates automatically, with data transmissions hourly to computers at the Wave Propagation Laboratory in Boulder, Colorado, and at the University of Oklahoma in Norman. The archival data are represented in Table 2. The winds are drived from a composite of up to 12 determinations during the previous hour; the computer selects contributions to the composite on the basis of a sufficiently large signal-to-noise ratio; processing details and other information have been presented by STRAUCH et al. (1985). Details on the Doppler spectra are available but must be requested specifically. A dedicated line will facilitate more comprehensive recording and in-depth study of the Oklahoma data.

SOME COMPARISONS INVOLVING DATA FROM THE OKLAHOMA 50-MHz PROFILER

We have compared rawinsonde data acquired at Oklahoma City on 39 occasions from August 8 to September 8, 1985, and on 11 occasions from October 1 to October 8, 1985, with profiler data acquired at the same times (within one hour of 00 Z and 12 Z). (Obviously erroneous data in both sets, such as the point indicated in Table 2 were excluded.) A majority of the soundings in the first set are characterized by light winds and weak shear throughout the troposphere. The second set is marked by substantially stronger winds and vertical shear.

Vertical interpolation is necessary for comparison of the rawinsonde data with profiler data. Data from one sensor were linearly interpolated to the height of the data from the other sensor. This interpolation is a source of error in the comparison; its magnitude is surely small because of the small vertical separation between data (290 m for the short pulse and 870 m for the long pulse). At the higher heights the long pulse data are sometimes sparse, with larger interpolation errors.

The root-mean-square (rms) average difference for the 39 comparisons of the first set, for both the u (positive to the east) and the v (positive to the north) wind components are listed in Table 3a. The average rms differences of the components are about 2.5 m s^{-1} for the rawinsonde/short pulse comparison, 3.5 m s^{-1} for the rawinsonde/long pulse comparison, and 1.5 m s^{-1} for the long pulse/short pulse comparison. The rms vector differences are the square roots of the sum of squares of the average rms differences.

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Table 2.

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SITE: OKLAHOMA
DATE: 85  5 23
TIME: 23  0  0
NPRO:  12  NTDA:  350  NOSP:  13  PULW:  3.67  PRPR:  238.00
MAX HOR VEL:       62.87
FIRST HT (AGL):    1.64
NUMBER OF HEIGHTS:   24
DELTA HEIGHT (KM):  .29
POWER ANTENNA:       EW

GATE  SPEED DIRECT HEIGHT  #E  #N  POWER
  1 -999.00 -999.0   1.97   2  12 -999.0
  2    5.37  301.5   2.26   9  12   48.3
  3    7.57  297.5   2.54  12  12   58.9
  4    7.88  303.6   2.83  12  12   69.4
  5    7.42  307.2   3.12  12  12   72.0
  6    7.84  322.9   3.41  12  12   65.6
  7    6.17  338.4   3.70  12  12   57.2
  8    5.45  343.3   3.99  12  12   52.3
  9    4.88  323.7   4.28  12  12   49.1
 10    6.80  304.3   4.57  12  12   46.5
 11    8.12  299.9   4.86  12  12   45.5
 12    5.65  300.4   5.14  12  11   48.5
 13    4.60  294.8   5.43  12  11   48.2
 14    3.89  294.3   5.72  12  11   42.7
 15    3.27  293.4   6.01  11  10   36.1
 16    5.46  302.1   6.30  11   9   35.2
 17    9.74  302.0   6.59  11  10   38.0
 18   10.34  299.2   6.88  12  11   38.0
 19   10.84  294.2   7.17  12  10   35.7
 20   11.43  293.2   7.46  10   9   31.3
 21   11.22  292.2   7.74   9   7   29.2
 22   13.54  287.7   8.03   8   6   25.0
 23   13.61  288.7   8.32   8   5   23.6
 24    2.25  314.5   8.61   5   5   34.8
```

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SITE: OKLAHOMA
DATE: 85  5 23
TIME: 23  0  0
NPRO:  12  NTDA:  124  NOSP:  22  PULW:  9.67  PRPR:  672.00
MAX HOR VEL:       62.85
FIRST HT (AGL):    2.65
NUMBER OF HEIGHTS:   18
DELTA HEIGHT (KM):  .87
POWER ANTENNA:       EW

GATE  SPEED DIRECT HEIGHT  #E  #N  POWER
  1    7.22  310.7   2.98  12  12   65.8
  2    7.35  317.8   3.84  12  12   66.9
  3    6.70  314.4   4.71  12  11   61.8
  4    5.85  305.8   5.58  11  10   54.1
  5    6.20  309.1   6.44  11  12   46.2
  6    7.59  301.9   7.31  11  12   42.3
  7    7.83  294.1   8.18  10  12   37.8
  8    8.82  287.3   9.05   9   9   32.0
  9    6.36  291.2   9.91   9   8   28.6
 10   11.75  294.6  10.78   8  10   25.9
 11   20.44  289.1  11.65   8  10   24.6
 12   19.53  292.0  12.51   8  10   24.8
 13   19.65  287.5  13.38   7   7   23.4
 14   18.03  285.5  14.25   5   7   20.6
 15   10.49  291.9  15.11   6   8   23.2
 16   11.79  303.7  15.98   7   4   21.7
 17   10.82  279.2  16.85   5   5   19.9
 18 -999.00 -999.0  17.71   5   3   27.4
```

Table 3a. Average RMS difference of the u and v wind components for 39 comparisons during August 8 - September 8, 1985.

Comparison	Average RMS difference		RMS vector wind difference ms^{-1}
	u	v	
Rawinsonde/short pulse	2.55	2.44	3.5
Rawinsonde/long pulse	4.15	2.93	5.1
Long pulse/short pulse	1.73	1.17	2.1

Table 3b. Average RMS difference of the u and v wind components for 11 cases during October 1-8, 1985.

Comparison	Average RMS difference		RMS vector wind difference ms^{-1}
	u	v	
Rawinsonde/short pulse	2.8	2.3	3.6
Rawinsonde/long pulse	4.3	3.3	5.4
Long pulse/short pulse	3.1	1.5	3.4

In order to learn if the average rms differences include a systematic bias, we also computed the mean wind speed at all the points for which comparative data existed (approximately 400 from each sensor). These mean winds for the first set of data are listed in Table 4a. Note that the average profiler winds, both with long pulse and short pulse, are smaller than the mean winds estimated by rawinsonde. In the rawinsonde/short pulse comparison the difference between the mean wind estimates is 1.9 m s^{-1}; the speed of the short pulse winds averages 74.3% of the rawinsonde winds. Similarly, the long pulse winds average 71.9% of the rawinsonde winds or 2.5 m s^{-1} less than corresponding rawinsonde winds.

The findings from the August 8 - September 8 period are reinforced in the October data, represented in Tables 3a and 4a. The October period was one of substantially stronger winds, as shown by the u component listed in Table 4a.

All in all, these comparisons of rawinsonde and profiler data indicate a bias toward zero in the profiler winds. More comparisons with other sensors as well as in-depth analysis of Doppler spectral data with collocated profiler and rawinsonde should be informative. It will be particularly important to determine whether the rawinsonde/profiler differences represent a constant offset or a percentage bias.

It should be noted that the average differences discussed here are compounded of rather widely different situations. Thus, Figure 1a shows a case with marked systematic differences between wind speeds at the rawinsonde and

Table 4a. Mean wind speeds for the three comparisons in Table 3a.

Sensor	Mean Wind	Sensor	Mean Wind	Difference
Rawinsonde	7.24 m s^{-1}	short pulse	5.38 m s^{-1}	1.86 m s^{-1}
Rawinsonde	8.94	long pulse	6.43	2.51
Long pulse	5.22	short pulse	5.11	0.11

Table 4b. Mean wind speeds for the three comparisons in Table 3b.

Sensor	Mean Wind (u comp.)	Sensor	Mean Wind (u comp.)	Difference of means
Rawinsonde	14.2	short pulse	12.8	1.4
Rawinsonde	18.1	long pulse	15.2	2.9
Long pulse	15.5	short pulse	13.4	2.1

profiler sites, but 1b shows that wind directions reported on the same occasion agree quite well. On another date, shown in Figure 2a and 2b, rawinsonde and profiler wind speeds are in remarkable agreement except in the layer from 7.5 to 11 km, where differences are up to about 15 m s^{-1}, while directions are in close agreement except differences up to about 60° in the layer from 3 to 6 km! We certainly must identify the reason(s) for such features since they represent very large deviations in implied kinetic energy and are correspondingly significant for forecasting; such interesting characteristics are present in practically every sounding pair.

POSSIBLE EXPLANATIONS FOR DISCREPANCIES IN OKLAHOMA DATA

The following possible sources of differences noted above are: ground clutter contamination; interference from stray electromagnetic transmissions during oil field operations, rawinsonde errors, spatial and temporal variability of the wind, hardware and software discrepancies in the profiler radar; backscatter from edges of the main beam and from sidelobes, and contamination by vertical velocities associated with standing and/or migratory waves. At this writing we are just beginning to investigate these possibilities and to look for others.

The authors believe that the differences presented are significantly larger than can be explained by spatial variability of the wind. We plan to evaluate this definitively during Spring 1986 with aid of a rawinsonde unit at the radar site.

The sometime differences between profiler indications on long and short pulse illustrated in Figure 3 may be relatable to nonlinear vertical distributions of wind shear interactive with the different pulse lengths.

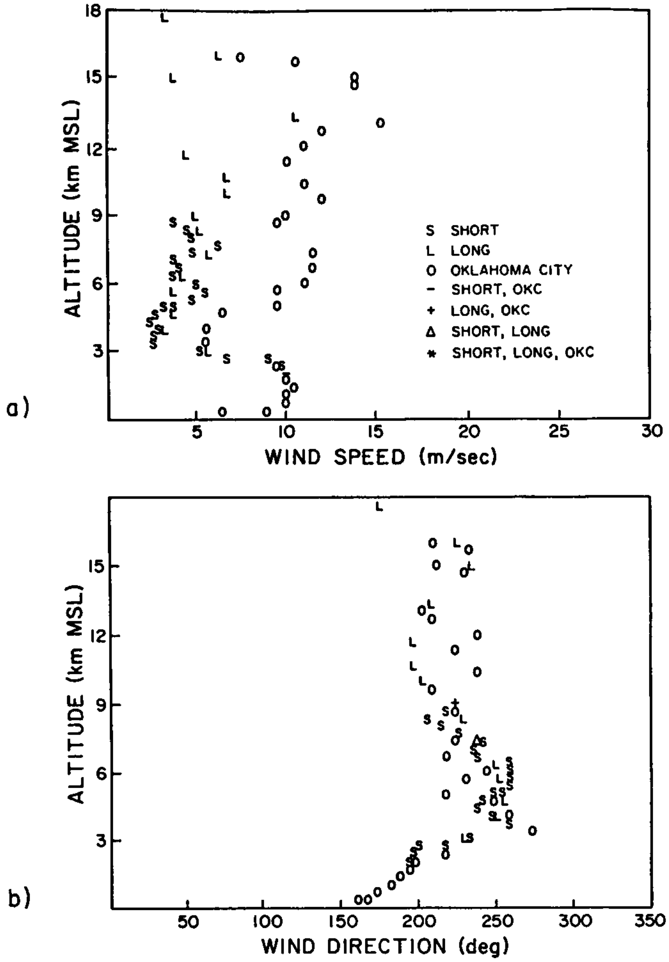

Figure 1. Wind speed (top) and direction (bottom) measured by rawinsonde (O) and Oklahoma profiler (other symbols) on 13 August 1985, 00 GMT. Abscissae show wind speed in increments of 5 m s^{-1} and direction in increments of 50°, respectively. Ordinates show heights MSL in km.

Concerning variations of reflectivity with elevation angle, it has been noted that since VHF reflectivity declines with increasing zenith angle, the measured velocities are biased low by the more reflective patches that have smaller radial velocities in the more elevated portions of the beam. Although formulations by DOVIAK and ZRNIC' (1984) show this effect to be negligible at zenith angles larger than about 8° (Figure 4), consideration of sidelobes may alter first impressions. A useful experiment in this regard would involve addition of switchable phase shifters to the profiler antenna system and study of backscattered power from a beam scanned in elevation.

GENERAL CONCLUSIONS

Highly accurate wind finding is confirmed for radars with narrow beams, especially when VAD scanning is employed. Systematic differences up to 2 m

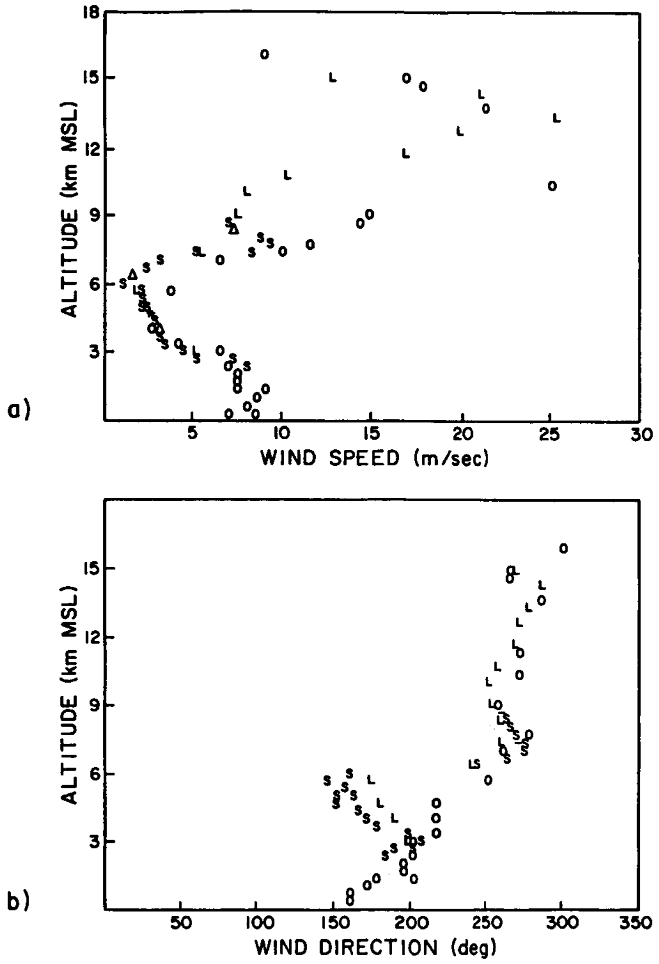

Figure 2. Same as Figure 1, except 19 August 1985, 00 GMT.

s^{-1} between wind data from rawinsondes and profilers of the inexpensive type recommended for widespread use, average random variations up to 5 m s^{-1} between wind data from these sensors, and occasional differences up to 15 m s^{-1}, are not well explained in much of the data reported so far. This is not reason to be discouraged, however, because confidence in the basic profiler method is well founded (KOSCIELNY et al., 1984), and the studies that leave us with concerns, including this one, are insufficiently definitive. We are stimulated to concentrate our efforts toward quantifying the differences in observations by profilers and other sensors, and then seeking their causes, so that large variances can be understood and data of known and acceptable accuracy can be produced routinely. We can be confident that a much better situation will develop as we direct our resources strongly to this problem.

SUMMARY

The Workshop provided a valuable exchange of information among meteorologists and engineers. Clearly, advances in communicating, data processing, and

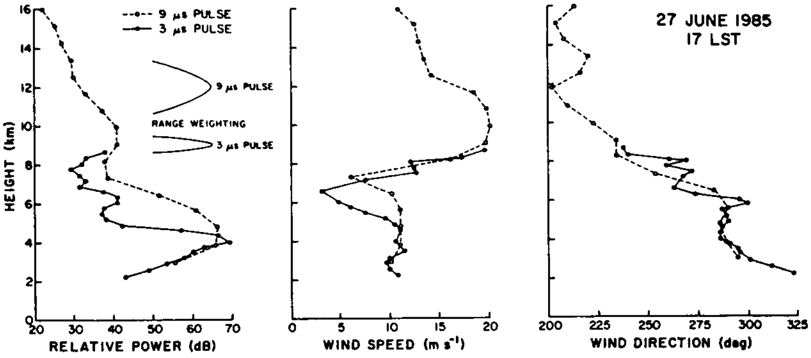

Figure 3. Vertical variations of reflectivity in a layer with vertical wind shear produce differences between the winds measured with short pulse and long pulse. Ordinates show heights in kilometers. Abscissae left to right are relative power, wind speed, and wind direction measured by the 50-kHz profiler in Oklahoma.

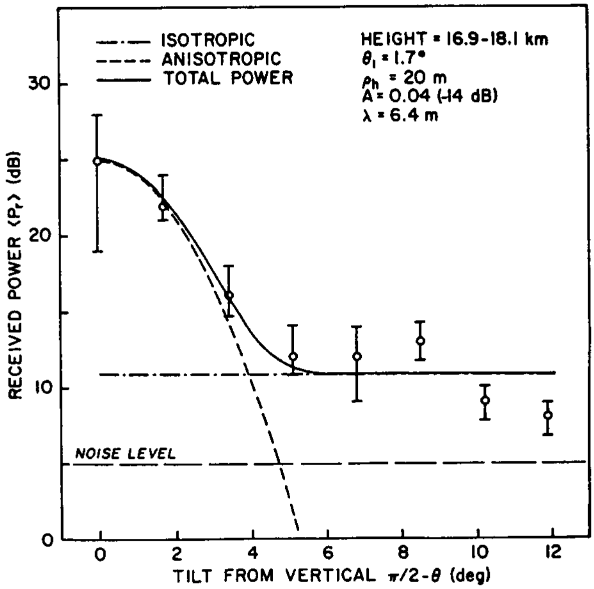

Figure 4. Reflectivity vs zenith angle based on data gathered by Rottger and a model by DOVIAK and ZRNIC' (1984).

mathematical modeling of meteorological phenomena have brought the meteorological community to the threshold of effective use of kinematic and thermodynamic data gathered more frequently and on a finer grid than heretofore. Such additional data provided routinely should lead to improved models and to improved forecasts of precipitation and other weather variables.

Conference papers demonstrate a wide range of interesting studies ongoing with profilers, but the performance envelope of wind profiling radars needs better definition. In particular, further address is needed toward questions concerning possible bias in profiler wind data, measurement of winds in the planetary boundary layer, and the accuracy of wind estimates in relation to the time period over which averages are calculated.

In view of great interest in boundary layer parameters and their importance to interpretation of individual profiler data, as well as to forecasting with network data, it is urged that profiler programs identify and implement means for providing boundary layer data, especially on wind and precipitation, at profiler radar sites.

The meteorological community is interested in prospects for studying lightning and precipitation processes with VHF and UHF profiler radars because Doppler signatures of meteors and of the air motion itself may be apparent simultaneously.

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