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Accuracy of Wind Measurements from an SPS Doppler Weather Radar

by

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August 1994

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Abstract.

Wind measurements from the Doppler radar at Cobbacombe Cross have been compared with winds from both operational and special collocated radiosonde ascents. The quality of the basic doppler wind output was assessed from a comparison of values of radial winds from the radar with the radiosonde winds measured at the same height. Once appropriate quality control was applied, the RMS errors in the radial wind measurements averaged over a sample area of several km^2 was found to be less than about $2ms^{-1}$ and probably confined to about $1ms^{-1}$. Velocity profiles derived using a VAD (Velocity-Azimuth Display) algorithm, which is available in the radar data processing software, were also compared with the sonde profiles. The VAD wind speeds were found to be too low by approximately a factor of two whereas the RMS error in wind direction was found to be less than 8 deg. It is not suggested that the wind speed bias represents a fundamental flaw in the VAD technique but is probably indicative of a simple error in the processing. If a factor of two error is assumed, then the RMS error in the VAD wind speed was estimated to be about 2 ms^{-1} under ideal conditions. A need for careful quality control of doppler wind data output from the radar was identified.

1. Introduction.

As a precursor to the evaluation of the utility of doppler wind measurements in numerical forecast models, their accuracy must be assessed. This is necessary to give the data appropriate weight in the assimilation and to see whether some initial quality control is required. Accordingly, a series of comparison experiments began in November 1993 in which the wind data from the radar at Cobbacombe Cross were compared with winds from radiosonde ascents. The radar is manufactured by Siemens Plessey Systems (SPS) and incorporates software from Lassen Research. Details of previous tests of the radar and its history up until November 1993 may be found in Lilley (1993).

Previous evaluations of doppler wind data have concentrated on the accuracy of wind profiles derived using VAD or similar algorithms. For example, Andersson and Bandalo (1994) performed comparisons between VAD and sonde winds and found an overall RMS vector difference of 5 ms^{-1}. One of the first comparisons was by Lhermitte (1966) who found differences of $2ms^{-1}$ in speed and 8-10 deg in direction for radar and sonde ascents separated by 32km. Donaldson (1993) reported standard deviations of vector differences as low as 2-$3ms^{-1}$ for collocation distances of 10km. However, the particular VAD algorithm produced significant mean biases of up to $10ms^{-1}$. Unfortunately, in all of these studies there has apparently been no attempt to partition the differences between collocation errors, radar and sonde measurement errors.

It is at present uncertain whether the basic radial wind data or processed VAD profiles will be best for assimilation into the numerical forecast models. We therefore need to assess the quality of both types of data. As the literature does not provide a consistent evidence of doppler wind accuracy, the performance of the SPS/Lassen system cannot be inferred from previously published results. Accordingly, some comparisons were made with operational radiosonde ascents from Camborne and Larkhill both at 150km range from the radar. However, to reduce collocation errors to a minimum, 3 special radiosonde ascents were also made from Dunkeswell airfield which is located about 19 km from the radar site (figure 1).

A fundamental problem associated with doppler winds is that there is an upper limit to the unambiguous wind velocity that can be measured. This limit is a function of the radar pulse repetition frequency (PRF) which in turn determines the maximum range from which data may be retrieved. The SPS doppler radars have a dual PRF algorithm which is used to raise the maximum unambiguous velocity; the theory is given in section 2. Also available as part of the doppler radar processing software is the facility for deriving wind velocity profiles using a VAD algorithm. The particular algorithm believed to be used is described in Section 3 where its relative merits compared to alternative algorithms are briefly discussed.

The results of the wind comparisons are presented in section 4. Comparisons were made both between maximum and average radial wind measured by the radar at a particular height from the radar and the radiosonde wind speed and also between the VAD profiles and the sonde profiles. Finally some conclusions and recommendations are listed in section 5.

2. Velocity folding and the dual PRF technique.

The PRF, used in a single scan, limits the maximum unambiguous radial velocity that can be measured according to the simple relation:

$$Vmax=\pm\frac{(PRF)\,\lambda}{4}$$

If a velocity is encountered that exceeds the maximum unambiguous velocity then a phenomena known as "folding" occurs. On a PPI scan plot of radial winds, the effect is that the scale "folds" where the true radial wind speed equals Vmax; i.e. for a small change in the true radial wind speed, the indicated speed changes from Vmax to -Vmax (e.g. see figure 4.2). The PRF required to give a maximum unambiguous velocity, Vmax, also in turn limits the maximum range from which data can be obtained:

$$Rmax=\frac{c\lambda}{8\,Vmax}$$

where c is the velocity of the speed of light. These relationships are illustrated in figure 2.1. As an example, the maximum PRF attainable on the SPS doppler radars is 1185 Hz for a wavelength equal to 5.3 cm, from the diagram this gives Vmax=15.7ms^{-1} and Rmax=125.7km. Hence, using this single PRF, Vmax will often be exceeded. Although these limits on velocity and range are an inherent feature of doppler radar, by using two different PRF's, the effective value of Vmax may be increased. This is because for each PRF, folding occurs at a different speed. By looking at the difference between the speeds measured at the two PRF's, the correct speed may be identified. Eventually, a point is reached where both PRF's suffer folding at the same speed, and this defines the effective Vmax. If the radar transmits pulse trains at two different PRF's, PRF1 and PRF2 say, then the corresponding values of Vmax, V1 and V2 are related as follows:

$$\frac{V1}{V2}=\frac{K2}{K1}=\frac{PRF1}{PRF2}$$

where the ratio of the velocities is proportional to two integers, K1 and K2 (Collier, 1987).

$$V = 2K1V1 = 2K2V2$$

Again, using as an example, the maximum PRF available on the SPS radar, i.e. PRF1=1185 Hz, and if PRF2 is set at 888Hz, then V1=15.7 ms^{-1} and V2=11.77 ms^{-1} Hence:

$$\frac{V1}{V2} = 1.33$$

and

$$\frac{K2}{K1} = \frac{4}{3}$$

Now

$$V = 6\ V1 = 94.2\ ms^{-1}$$

$$i.e.\ Vmax = 47ms^{-1}$$

The calculation here shows how the Vmax can be extended using this technique from 15.7 ms^{-1} (31 knots) to 47 ms^{-1} (92 knots). The increase in the maximum unambiguous velocity achieved is illustrated in figure 2.1.

3. VAD Wind Profiles

A VAD (Velocity-Azimuth Display) velocity profile is constructed by fitting a sinusoidal curve to the radial winds measured within a particular height band (see figures 3.1 and 3.2). The curve then represents the azimuthal variation in Doppler velocities that would be sensed by the radar if a uniform wind were blowing across the entire area scanned by the radar, at that height, and the whole area were filled with precipitation. The vertical fall speed of particles, V_f, is assumed to be negligible, and this assumption imposes the limitation of only using low elevation angles. In widespread precipitation, the accuracy of the curve fitting (and hence the resulting wind profile) is expected to be more accurate.

A VAD algorithm produces an internal estimate of the RMS error, in each height band, which is the RMS residual between the radial wind speeds and the fitted curve. This RMS error is therefore not only a function of the accuracy of the radial velocities but also gives a measure of the validity of the uniform wind field assumption.

Other techniques for deriving velocity profiles are the Volume-Velocity Processing (VVP) method, where data is processed from a range of elevations. The method allows the calculation of V_f from an integration of the continuity equation. The disadvantage of this method is its complexity, but it may provide better results when there is patchy rainfall coverage because the VVP technique largely eliminates possible biases due to an uneven volume distribution of data points. It also provides a better treatment of the errors. In practice, the accuracy of estimates are limited by the inadequacy of the linear vector field approximation rather than random errors in the velocity data. Generally, the results from the VVP profiles are considered to be more representative than VAD's of large scale (i.e. meso-scale) features (Waldeufel and Corbin,1978). Both VVP and VAD profiles can be contaminated by the effects of "folding" (Andersson,1994 and Siggia and Holmes,1991).

The "uniform wind technique", is a more recent variant of the VAD method and relies upon similar assumptions. The method involves estimation of the gradient of the radial wind speed with respect to azimuth within small azimuth sectors. Complex filtering and weighting is required to avoid contamination by clutter and real discontinuities in the wind field (see Doviak et al.,1982, Persson and Andersson,1987).

4. Evaluation of the Doppler Winds

a) Comparison method

For this initial validation exercise six comparisons between doppler winds and radiosonde winds were made during the period Nov 93 to Feb 94. In all but one case data was recorded when there was widespread moderate rainfall; in the exception there was patchy rainfall with only light rain and drizzle, covering about 180 degrees range in azimuth. A brief summary general synoptic conditions is given in table I.

Three comparisons included data from Dunkeswell and in these cases, to minimise temporal collocation errors, doppler winds were derived from PPI scans made within a few minutes of the launch time. The three other cases were analysed using radiosonde data from the operational stations for which the time difference was less critical, but some allowance was made for the spatial separation by choosing a temporal separation such that data were compared in similar positions relative to the frontal rain band. The temporal and spatial differences between scans and sonde ascents, for all cases, are listed in table II.

Winds from operational radiosonde ascents were extracted from coded TEMP and PILOT messages. The operational radiosonde winds were provided by a tracking radar whereas for the special ascents from Dunkeswell, the winds were provided by Loran-C Navaid tracking of the radiosonde. In either case, the RMS error is approximately 1 ms^{-1} (Nash, personal communication).

The RMS difference between doppler radar and radiosonde winds will, in general, contain contributions from three sources, namely; radiosonde measurement error, σ_{sonde}, collocation error, σ_{coll}, and doppler radar measurement error, σ_{dopp}.

$$(rmsdiff)^2 = (\sigma_{sonde})^2 + (\sigma_{coll})^2 + (\sigma_{dopp})^2$$

Data from each case were treated separately, but data from different heights were grouped together to produce a single estimate of the differences in each case.

For the Dunkeswell comparisons, the temporal collocation errors were considered to be negligible and σ_{coll} was estimated from climatological data in Kitchen, 1988. Extrapolation of Fig 3 in Kitchen (1988) suggests that the RMS vector difference between low-level (850hPa) wind measurements, separated by 20km, is about 1.8ms^{-1}. This is an average value and can only be a rough estimate of the order of magnitude of the collocation errors in a particular case. Note also that although sonde launch site and radar were separated by 19km, some of the radar sample volumes, which are close to the maximum radar range, may be separated from the radiosonde by distances up to about 100km.

Collocation errors for comparisons involving operational ascents were estimated by calculating the RMS difference in low-level wind speeds between operational ascents straddling the relevant radar scan in space and time. As the separation between Camborne and Larkhill is approximately twice the separation between either operational station and the radar, the collocation error was taken to be $1/\sqrt{2}$ times the RMS difference. Once again it is recognised that these collocation error estimates are very rough and serve only to place upper bounds upon the estimates of σ_{dopp}.

b) Radial Wind Speed Comparisons

Problems with the archiving of data from the doppler radar meant that all radar data used in the comparisons had to be recorded manually from the display. This placed restrictions on the volume of data that could be processed and permitted only a rather crude evaluation of the radial wind data.

Radial winds were sampled manually at intervals in range along the direction of the wind vector as indicated on the processed VAD profile. At each selected range, several samples were normally taken, all within 5km of each other. Samples were only taken in areas were the presence of precipitation was indicated by the reflectivity data. Comparisons were made using the average value of the radial wind at each range (and height). The radial winds were compared directly with sonde horizontal wind speeds without making corrections for the angle of elevation of the beam, since only low elevation angles were used (e.g. less than 2 degrees). The depth of the sample volume is determined by the radar beam width which is 1 deg (half-power width). At a range of 20km the depth of the beam is 350m and at 60km it is 1050m. The radiosonde winds are averages over approximately 1 minute in time which is equivalent to 300m, in the vertical, at normal ascent rates. Thus the vertical resolution of the measurements were only matched for a limited height range in the profiles. Given the other uncertainties in the analysis, the contribution to σ_{coll}, from this mismatch, was ignored.

Despite the care taken in the sampling, it was apparent that some of the radial wind data were of low quality, either because of contamination by ground clutter or because the signal was too weak. A quality control procedure was therefore adopted to try and limit the impact of these spurious data on the results of the comparison. Data were rejected if the standard deviation of the radial wind samples, within the same height band, was greater than $7ms^{-1}$, or if the average radial wind speeds between adjacent points implied an average wind shear of more than $0.05ms^{-1}$. The second criterion also removed a few data points affected by folding. The results of the comparison should therefore be representative of optimum conditions. If radial wind data are to be assimilated directly into a numerical forecast model, it is clear that some similar quality control will need to be applied to the data. Also, an algorithm for detecting folding, after the application of the dual frequency technique, (see e.g. Ray and Zeigler, 1977) would be useful.

Table III shows the RMS difference and mean difference between doppler radial and radiosonde wind speed for 5 cases. The mean RMS difference over the four best cases (weighted by the number of comparison levels in each case) was $2.0ms^{-1}$. In most cases, the mean differences were significant compared to the scatter. The RMS differences were also compared with the estimated collocation error in Table III. As noted, the collocation error estimates in individual cases are subject to considerable uncertainty, nevertheless it is evident that in most cases, collocation errors and radiosonde measurement errors can account for all or most of the observed RMS difference. Thus the comparison experiment was inadequate for a precise estimate of the radial wind error but the evidence suggests that in most cases the RMS error in radial winds averages over sampling areas of a few km^2 was certainly less than 2ms^{-1} and was probably approximately 1ms^{-1} or less.

The exception was the 24/1/94 case where a large mean difference was observed. In this case, precipitation was drizzle and patchy along the azimuth corresponding to the wind direction (figure 4.1). The strength of the signal was possibly below that required to give reliable doppler wind measurements. This was also the situation in the 18/1/94 case, but here the quality control procedure successfully removed most or all of the spurious data from the comparison.

On 1/2/94 wind speeds in excess of 40 ms^{-1} were recorded below 4 km and radial winds from the PPI scan showed evidence of folding. Without the quality control mentioned previously, the RMS difference was about 5ms^{-1} whereas for the quality controlled doppler winds the RMS difference was reduced to only 1.22 ms^{-1}. An example of the "folding" effect using the SPS doppler radar dual PRF algorithm is shown in figure 4.2.

A scatter plot of quality controlled radial wind speeds against sonde wind speeds, for all the cases, is shown in figure 4.3. A least squares fit to the data, constrained to pass through the origin, produced a gradient equal to 0.97 and a correlation coefficient equal to 0.92.

c) VAD Wind Profile Comparison

The VAD processing was used to generate wind profiles from PPI scans at elevation angles which were in the range 2-5 degrees (depending on the case). The vertical resolution in the VAD profiles was approximately 20m. The radar beam width exceeds 100m at ranges greater than 6km so the effective resolution was much lower.

The depth of precipitation was determined from observations of RHI sections taken through the frontal rain bands. Above the precipitation, VAD winds were output by the system but were obviously very noisy. Thus VAD winds were only considered for comparison up to the height where the measured reflectivity was equivalent to a precipitation rate of about 1.0 mmh^{-1}. This cutoff value was conservative and it is not suggested that all wind data are unreliable below this threshold. Finding the optimum setting for this quality control threshold would require more detailed analysis of the data than was possible here. As for the radial wind data, this subjective quality control would need to be replaced by an objective automatic system before any routine assimilation of VAD profiles could be considered.

A plot of a VAD wind speed profile and the radiosonde profile recorded on 18/1/94 (19:58) is shown in figure 4.4. This and other similar comparisons, between VAD profiles and sonde data, provide strong evidence that the VAD speeds were consistently too low. A scatter plot of radiosonde wind speeds against the VAD wind speeds was compiled using all the data from the three Dunkeswell radiosonde ascents (figure 4.5). The slope of a least squares fit, constrained to pass through the origin, was 1.97 ± 0.09 with a correlation coefficient of 0.89. Given that the radial winds showed no evidence of this systematic bias, the most likely explanation of this result is a fault in the VAD processing software. Since the slope was insignificantly different from 2.0, for the purpose of this analysis, a systematic error of a factor of two was assumed and the data corrected accordingly. The corrected profile has been added to figure 4.4. The wind directions from the VAD profiles were generally in good agreement with the radiosonde wind directions (e.g. see figure 4.6). Unfortunately, the resolution on the VAD graphical screen display only enabled VAD directions to be read with an uncertainty of about 5 deg. Due to an archive problem the text files were unavailable for this analysis.

The RMS differences between the radiosonde winds and the corrected VAD measurements are shown in table IV. RMS differences in speed lay in the range 2.7-3.7 ms^{-1}, with one outlier on the 24/1/94 (6.67ms^{-1}). This latter case also produced poor radial wind comparison results and the patchy rainfall coverage probably exposed limitations of the simple VAD technique, namely the requirement for widespread precipitation distributed over a large range in azimuth. RMS differences in direction were confined to less than 8 deg and the uncertainty introduced in reading from the screen display may have contributed significantly to this difference. Although vector wind differences were not computed in this analysis, a direction error of 5 deg associated with a speed of 20ms^{-1} is equivalent to a vector error of 1.7ms^{-1}. Thus it can be inferred that the observed direction differences made smaller contributions to the vector differences than the wind speed differences in most cases.

Both RMS and mean differences in speed were smaller for the comparisons with Dunkeswell radiosonde ascents than for the operational ascents. This suggests that collocation errors contributed to the observed differences.

In Table V, estimated collocation and sonde measurement errors have been used to estimate, σ_{dopp} (ignoring the contribution from errors in direction). These estimates were all in the range 1.6-2.6ms^{-1} except for the 24/1/94 case. Thus, the evidence suggests that the RMS vector error in VAD winds is about 2ms^{-1} in near ideal circumstances. For most cases, these estimates of the VAD error were smaller than the estimate provided by the SPS VAD algorithm. However, the error computed from the VAD algorithm failed to identify the gross error in the 24/1/94 case. Thus the utility of this estimate remains to be demonstrated.

5. Conclusions

Comparisons between doppler wind data from the radar at Cobbacombe Cross and nearby radiosonde ascents has demonstrated that once appropriate quality control is applied to the data, the RMS error in radial winds averaged over areas of several km^2 is probably approximately 1ms^{-1}. A problem has been identified with the VAD algorithm on the SPS system such that the speeds are too low by a factor of approximately two. Once this systematic bias is corrected, then the RMS vector error in VAD wind profiles is estimated to be about 2ms^{-1} in ideal conditions.

The comparisons have raised important issues regarding the quality control of doppler wind data. The data output by the radar software cannot be used as they stand, as both radial wind data and VAD profiles contain data obtained in regions where the radar signal is too low for satisfactory doppler measurements or else from targets other than precipitation. Thus further quality control is essential, which will probably involve several steps. For radial winds, a threshold in reflectivity should be applied. Data should be rejected from areas of clutter and anaprop; and an algorithm for the detection and correction of folding is required to avoid gross errors in cases of high wind speeds. In addition, for VAD profiles, the spatial distribution of precipitation has been found to be an important factor influencing data quality. For example, Donaldson (1993) suggested the criteria that wind estimates be made whenever valid data exists along 30 or more 1 degree radials. It remains to be explored whether similar quality controls would be effective for the SPS system. It is possible that different VAD algorithms may offer improved performance in conditions of incomplete precipitation coverage (see e.g. Andersson, 1992).

Once the fault in the VAD algorithm has been corrected and the facility to archive data has been made to work, it is recommended that further radiosonde comparisons are carried out to verify the improvement. This should also provide the opportunity for refining the experimental method and obtaining more reliable estimates of the errors in the doppler winds. New data should also be useful for testing quality control methods.

In the meantime, it has been decided, partly on the basis of the evidence presented here, to implement the planned trial using radial wind data from the radar, rather than VAD data, in an assimilation into a meso-scale numerical forecast model. Radial winds were chosen in preference to VAD profiles because the more difficult quality control issue, regarding incomplete precipitation coverage, would be avoided. Also the radial wind data may be averaged in the vertical and horizontal as required to match the model resolution and inserted at the correct location in the model domain. This should minimise the spatial representativeness errors associated with the assimilation of the data. Assumptions concerning the wind field should be avoided. Thus the potential impact of the doppler winds will be maximised in cases where there is significant structure on a smaller scale compared to the area of radar coverage.

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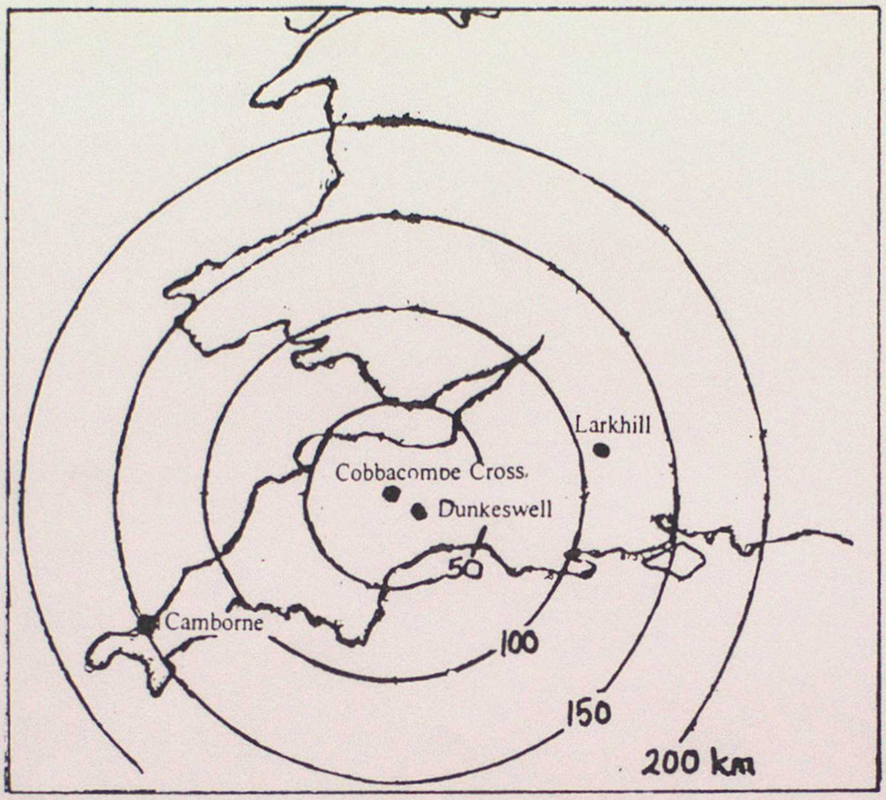


Figure 1 The locations of the radar and sonde sites relevant to the Doppler Project.

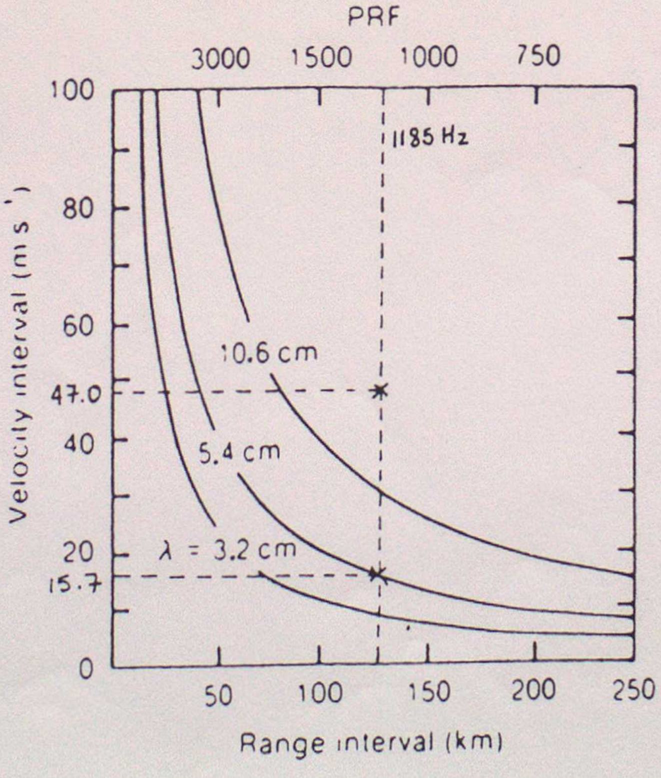


Figure 2.1 The relationship between unambiguous velocity, range, wavelength and PRF for three meteorologically important wavelengths [ref. Collier, 1989].

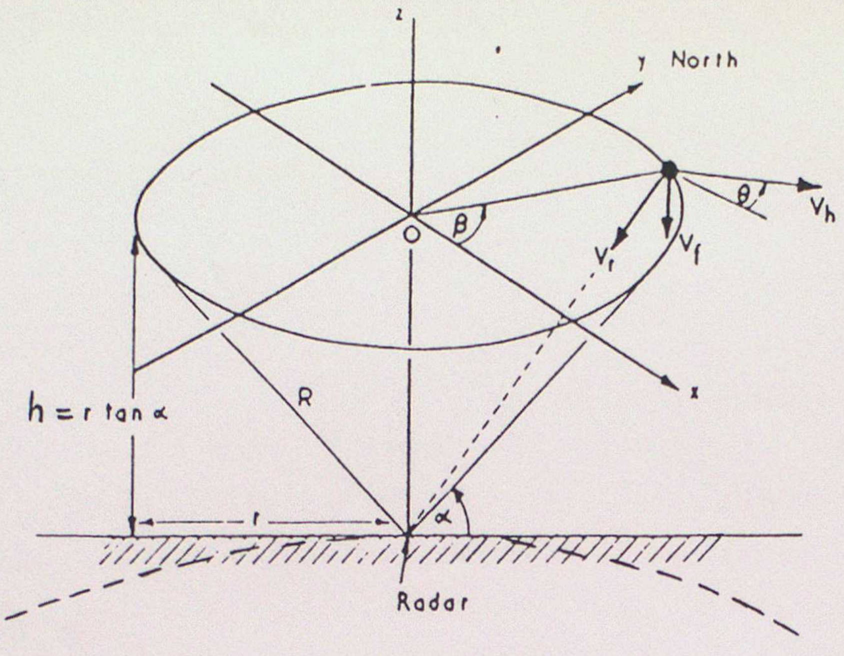


Figure 3.1 Geometry of a radar scan [ref. Browning and Wexler, 1968].

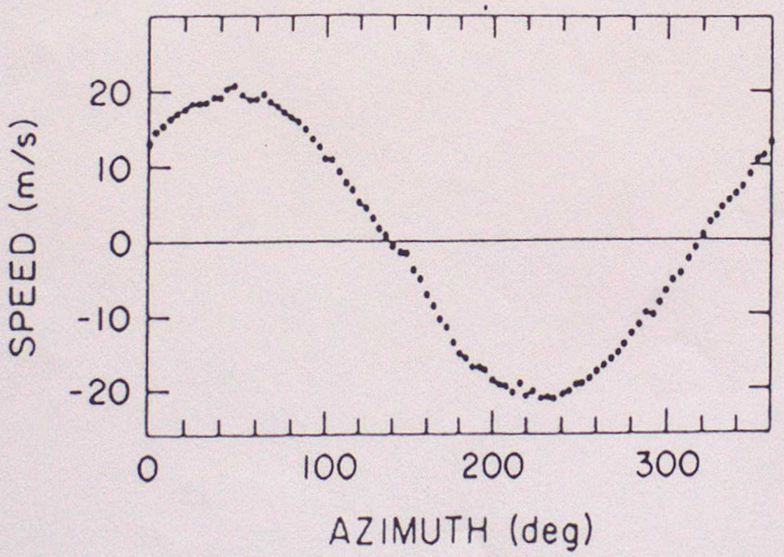


Figure 3.2 Velocity-Azimuth Display (VAD) [ref. Wilson, 1980].

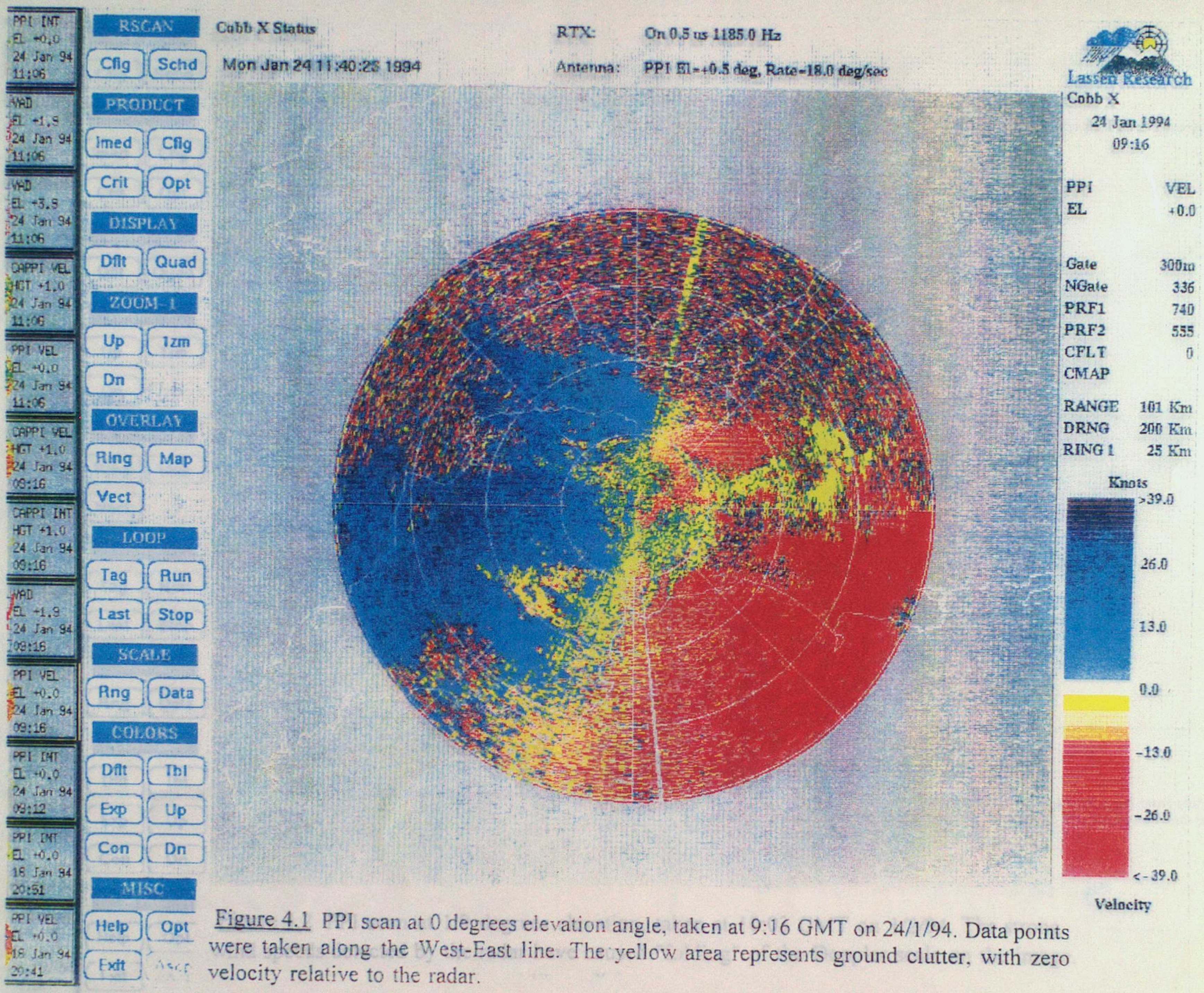


Figure 4.1 PPI scan at 0 degrees elevation angle, taken at 9:16 GMT on 24/1/94. Data points were taken along the West-East line. The yellow area represents ground clutter, with zero velocity relative to the radar.

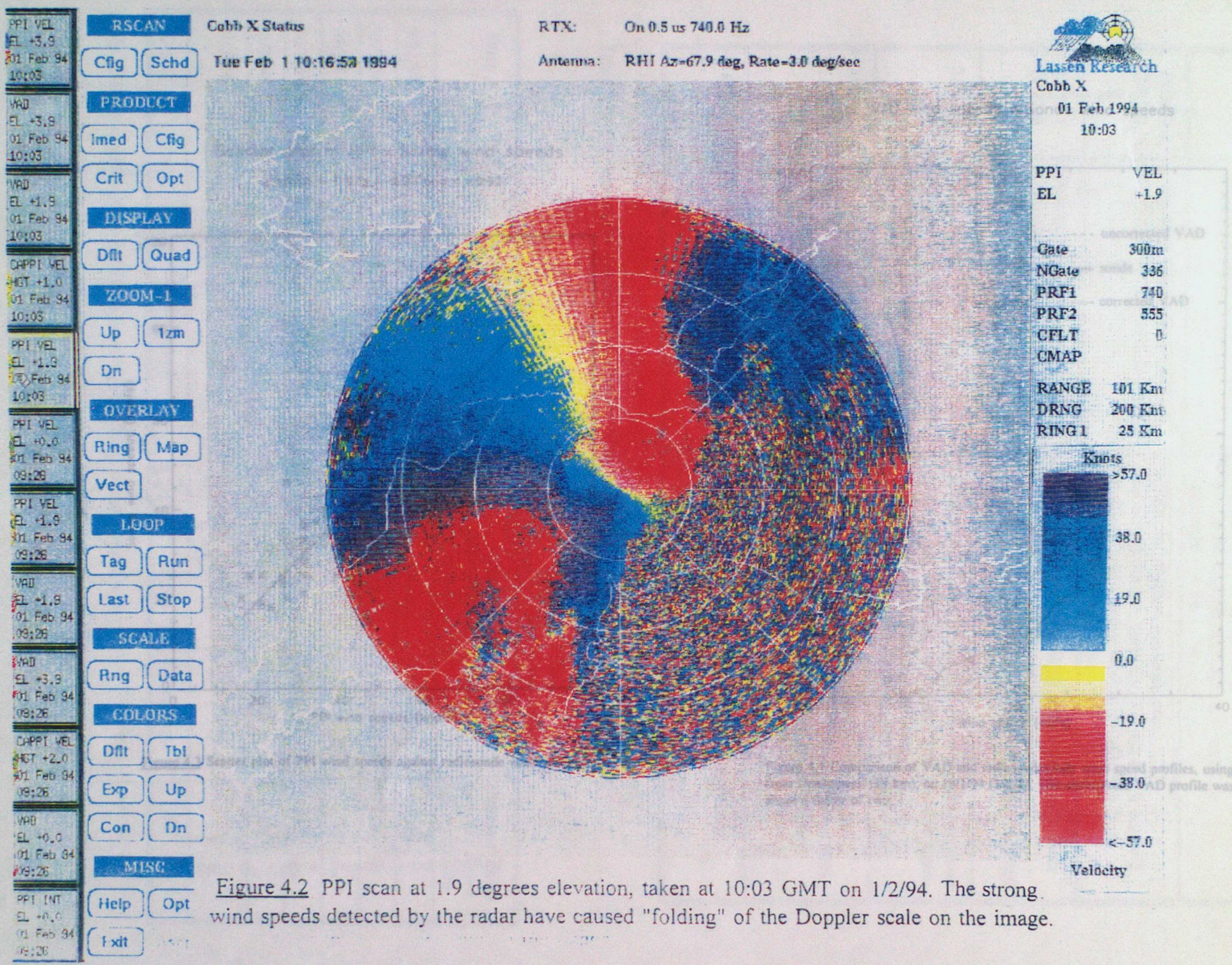


Figure 4.2 PPI scan at 1.9 degrees elevation, taken at 10:03 GMT on 1/2/94. The strong wind speeds detected by the radar have caused "folding" of the Doppler scale on the image.

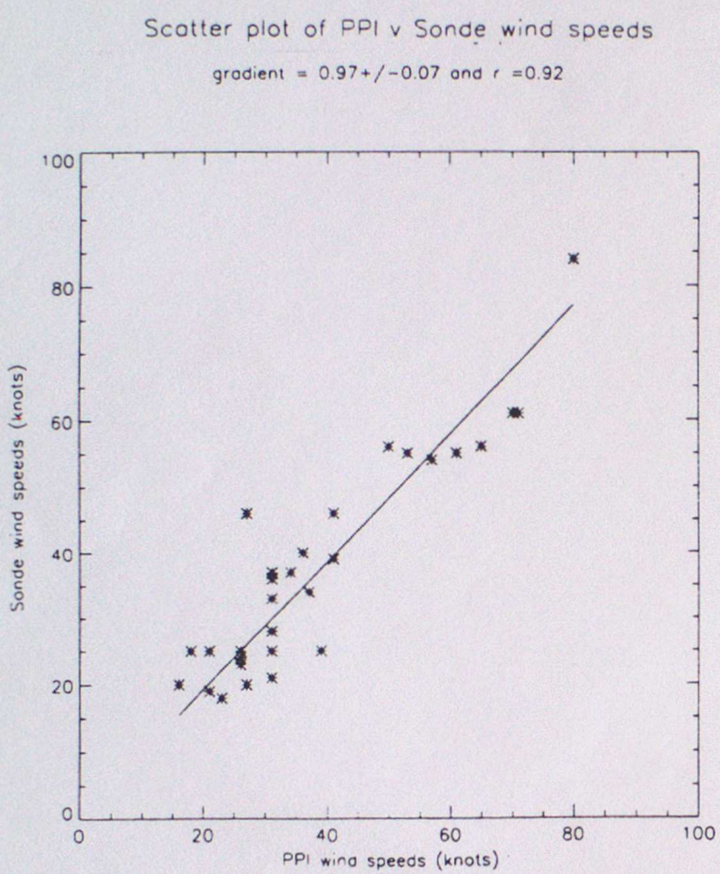


Figure 4.3 Scatter plot of PPI wind speeds against radiosonde wind speeds.

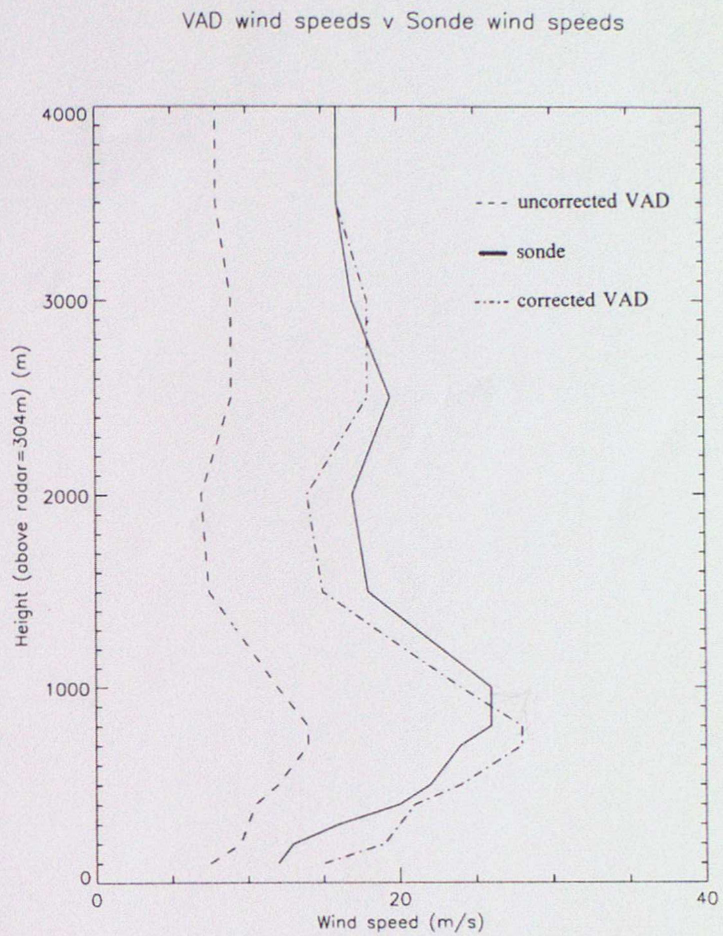
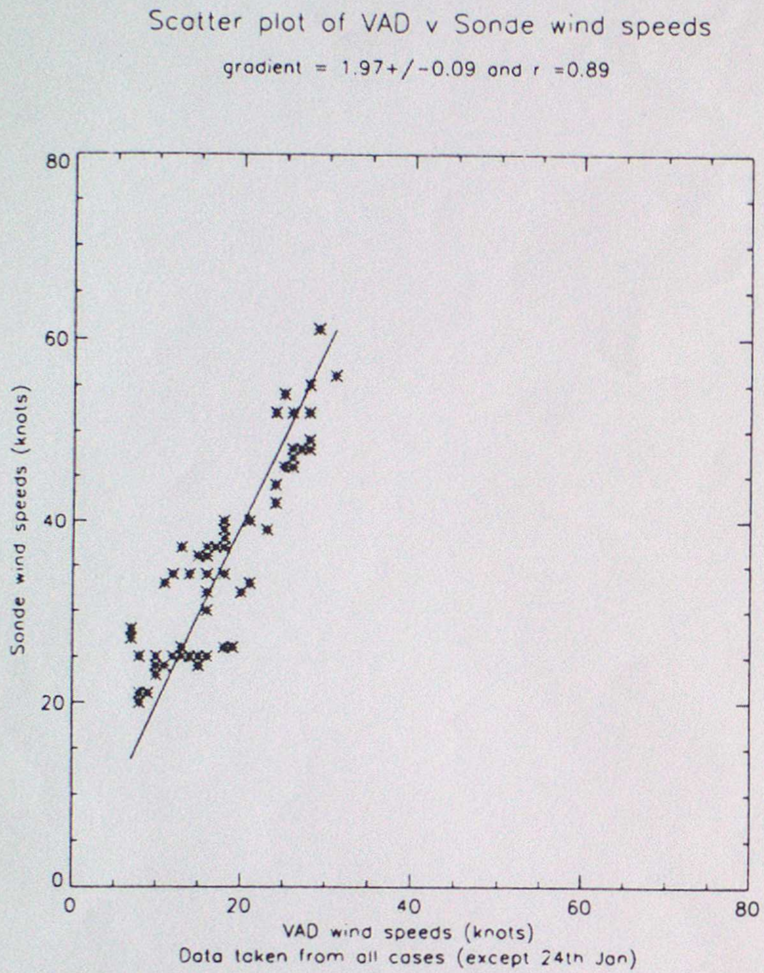
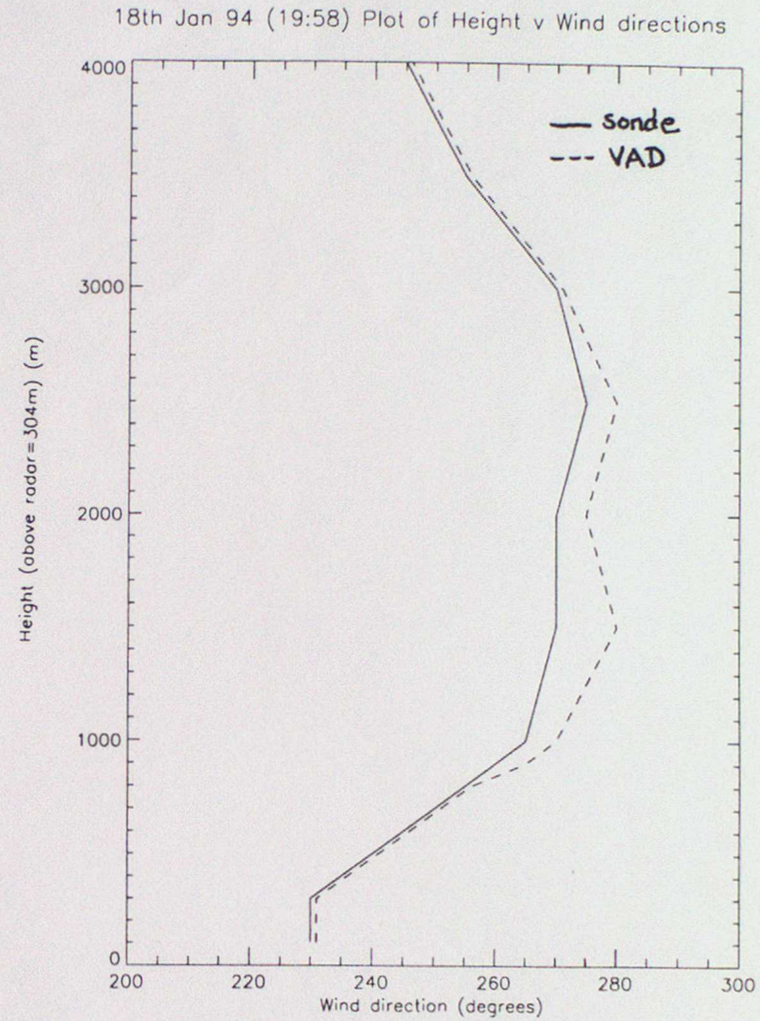


Figure 4.4 Comparison of VAD and radiosondesonde wind speed profiles, using sonde data from Dunkeswell (19 km), on 18/1/94 (19:58). The uncorrected VAD profile was too low by about a factor of two.



<u>Figure 4.5</u> Scatter plot of all (uncorrected) VAD wind speeds versus sonde wind speeds.



<u>Figure 4.6</u> Comparison of VAD and sonde wind direction profiles, using sonde data from Dunkeswell (19 km), on 18/1/94 (19:58). The directions show good agreement.

Date	Weather summary	Rainfall coverage
9/11/93	Moderate rain as front moved NE. Wind SW, 13 ms^{-1} average	Widespread coverage (~80%), fewer returns from the edges of the radar area (range=150 km). Max height = 4 km
18/1/94 (18:56)	Cold front swept across the SW. Wind SW, 24 ms^{-1} max at 1 km	Widespread uniform moderate rain. Max height = 3 km. Intensity, 7.0-4.0 mm/h below 2 km. There was a bright band at 1 km, and a much weaker signal above 2 km.
18/1/94 (19:58)	Cold front passed through Cobbacombe Cross (CX) Fairly strong winds SW, 26 ms^{-1} max at 1 km	Widespread coverage (~70%), patchy areas and fewer returns from the edges (range=100 km). Max height = 4 km. Intensity, 7 mm/h below the bright band at 1 km.
24/1/94	A warm front pushed slowly NE and passed through Dunkeswell between 6 - 12 z Wind SW, 20-25 ms^{-1} average	Uneven distribution of rainfall, centred mostly south of the radar site. Total coverage about 50%. Mainly light rain and drizzle. (no RHI pictures available to show the max height)
1/2/94	Strong winds and frontal rain over CX, passed through Camborne and Larkhill between 6-12 z. Wind SW, 27 ms^{-1} average below 3 km, max = 42 ms^{-1} at 3.4 km.	Uniform moderate rain coverage over whole area, 100% for VAD! Complete coverage for PPI over 60% of image W & NW of radar site. (Range=100km) Intensity ~7 mm/h at surface and ~1 mm/h between 2-4 km. Bright band observed at 1 km.
8/2/94	Intermittent slight-moderate rain as warm front passed through CX. Wind SW, 12 ms^{-1} average	Even distribution close to the radar, up to 50 km. Max height = 2 km. Intensity=7.0-4.0 mm/h below 2 km.

Table I A summary of the synoptic conditions for each of the case studies.

Date	VAD scan time (GMT)	elevation angle	PPI scan time (GMT)	elevation angle	Sonde launch time (GMT)	Sonde location	Distance (km) between sonde and radar site
9/11/93	15:02	5	14:42	0	18:00	Larkhill	150
18/1/94	18:56	4	---	---	18:57	Dunkeswell	19
18/1/94	20:01	4	20:21	0	19:58	Dunkeswell	19
24/1/94	09:16	2	09:16	1	06:00	Camborne	150
1/2/94	10:31	4	09:26	2	11:00	Larkhill	150
1/2/94	10:31	4	10:03	hgt=1km (CAPPI)	11:00	Larkhill	150
8/2/94	15:21	2	15:57	2	15:50	Dunkeswell	19

Table II Tmes of radar scans and radiosonde launches used in the comparisons.

Date	No. of samples	Radiosonde - radial wind speed		Collocation error, σ_{coll} (ms^{-1})
		RMS difference ms^{-1}	mean difference (sonde-PPI) ms^{-1}	
9/11/93	8	2.90	+ 1.83	3.2
18/1/94 (19:58)	3	2.60	- 2.37	1.8
24/1/94	5	4.72	+ 3.56	1.4
1/2/94	9	1.22	- 1.92	2.4
8/2/94	14	1.91	- 1.09	1.8

Table III Comparison of PPI average radial wind speeds with radiosonde measurements.

Date	No. of samples	radiosonde - VAD wind speed (ms^{-1})			radiosonde - VAD direction (degrees)	
		Uuncorrected	Corrected		RMS difference	mean difference (sonde-VAD)
		RMS difference	RMS difference	mean difference (sonde-VAD)		
9/11/93	11	9.71	3.71	+ 2.82	4.5	+ 2.5
18/1/94 (18:57)	16	9.54	2.76	- 1.46	6.6	- 3.8
18/1/94 (19:58)	24	9.37	2.86	- 0.68	3.5	- 1.9
24/1/94	6	13.50	6.67	+ 5.84	7.9	+ 0.5
1/2/94	6	13.51	3.69	+ 1.87	7.5	- 4.0
8/2/94	18	6.88	3.14	+ 1.02	5.8	+ 0.4

Table IV Comparison of VAD and radiosonde wind speeds and directions .

Date	RMS difference (ms^{-1})	σ_{coll} (ms^{-1})	σ_{dopp} (ms^{-1})	RMS error from VAD algorithm (ms^{-1})
9/11/93	3.71	3.2	1.59	2 - 8
18/1/94 (18:57)	2.76	1.8	1.84	4
18/1/94 (19:58)	2.86	1.8	1.98	5
24/1/94	6.67	1.4	6.44	4
1/2/94	3.69	2.4	2.62	4.5
8/2/94	3.14	1.8	2.37	3.5

Table V Estimation of the errors associated with VAD wind speed measurements.