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Comparisons between Canadian prairie MF radars, FPI (green and OH lines) and UARS HRDI systems

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Abstract. Detailed comparisons have been completed between the MF radars (MFR) in the Canadian prairies and three other systems: two ground-based Fabry-Perot interferometers (FPI) and the UARS high resolution Doppler imager (HRDI) system. The radars were at Sylvan Lake (52°N, 114°W), Robsart (49°N, 109°W) and the main continuing facility is at Saskatoon (52°N, 107°W). Statistical comparisons of hourly mean winds (1988–1992) for the Saskatoon MFR and FPI (557.7 nm green line) using scatter plots, wind speed-ratios, and direction-difference histograms show excellent agreement for Saskatoon. No serious biases in speeds or directions occur at the height of best agreement, 98 km. If anything, the MFR speeds appear bigger. The same applies to the Sylvan Lake MFR and Calgary FPI, where the best height is 88 km. In both cases these are close to the preferred heights for the emission layers. Differences between measurements seen on individual days are likely related to the influence of gravity waves (GW) upon the optical and radar systems, each of which have inherent spatial averaging (350, 50 km respectively), as well as the spatial difference between the nominal measurement locations. For HRDI, similar statistical comparisons are made, using single-overpass satellite winds and hourly means (to improve data quality) from MFR. Heights of best agreement, based upon direction-difference histograms, are shown; there is a tendency, beginning near 87 km, for these MFR heights to be 2 or 3 km greater than the HRDI heights. Speeds at these heights are typically larger for the satellite (MFR/HRDI = 0.7–0.8). Reasons for the differences are investigated. It is shown that the estimated errors and short-term (90 min) differences are larger for HRDI than for the MFR, indicating more noise or GW contamination. This leads to modest but significant differences in median speed-ratio (MFR/HRDI < 1). Also, comparison of the two systems is made under conditions when they agree best and when they show large disagreement. For the latter cases both systems show higher relative errors, and the HRDI vectors are frequently small. It is suggested that spatial or temporal GW wind fluctuations are the likely cause of the larger HRDI-MFR disagreement when wind speeds are small. No satisfactory explanation exists for the overall discrepancy in speeds between the MFR and HRDI.

1 Introduction

Previous comparisons between HRDI and ground-based experiments (radar, optical, rocket) have employed a variety of analysis methods; these include scatter-plots of north-south (meridional) and east-west (zonal) components of individual wind measurements, comparisons of instantaneous height-profiles (EW, NS), and comparisons of tidal and background mean winds for selected intervals (Burrage *et al*., 1993; Burrage *et al*., 1996; Khattatov *et al*., 1996). Briefly, the comparisons have shown slopes of the scatter plots to be generally less than 1, which has been taken to mean that HRDI values are equal or greater than those from other systems. The largest discrepancies are in the meridional component.

Since MF radars have been the dominant ground-based systems, these differences have led to careful and exhaustive examination of possible biases in the winds from such equipment (e.g. Cervera and Reid, 1995; Manson *et al*., 1996). Scatter plots comparing zonal or meridional winds are useful in identifying offsets and magnitude biases between systems which measure the same two independent wind components, such as HRDI and its companion experiment on UARS, WINDII. However, the MF radar analysis produces a vector wind in which the direction is expected to be unbiased, because of the azimuthal symmetry of the measurement, while the speed can be biased by several known effects, e.g. external noise. It is easier to identify such possible

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biases in vector comparisons, viz. speed and direction. The use of direction also allows for the heights of best agreement to be determined between systems.

To provide balance, the same analyses will be applied to comparisons between ground-based radar and FPI optical systems, as well as to radar and HRDI.

The following two sections discuss MFR wind biases and height calibration uncertainties. Sections 4 and 5 describe results for two independent MFR-FPI comparisons, which both show that MFR speeds are a little greater than FPI values. Section 6 compares the Saskatoon MFR and HRDI simultaneous-data sets. HRDI and MF error estimates are examined, to see whether their differences could explain the apparent speed bias. Finally the HRDI and MF values are divided into two sets according to whether they agree or not to see whether any dissimilarities are evident.

In the following study the term "error" is generally used to denote random error in a measurement, not a difference or a bad value.

2 Biases in MFR winds

Sources of potential biases in MFR measurements have been discussed by Meek (1995) among others. The most common one is external noise, which causes depression of antenna-versus-antenna cross-correlation values used by the spaced antenna analysis in wind determination (Meek, 1980). The majority of these could be corrected, but often, possibly due to fitting a Gaussian to a non-Gaussian correlation or to a very narrow auto-correlation function for the noise level determination, correction results in correlation values >1. These latter data would have to be discarded, even though the wind value may not have a significant bias. The effect of noise can also be accentuated by a small receiver array (*triangle size effect*). Correction for noise eliminates this effect (e.g. Meek, 1990). In this work, instead of correcting for noise and accepting the loss of some data, we prefer to select data which are not significantly affected by noise.

Other errors are possible, such as signal statistics not agreeing with the Gaussian correlation model (Meek, 1980) because, for example, there are too few scatterers (Holdsworth and Reid, 1995).

There is also small bias involved by taking a vector hourly mean, viz. if the wind direction is changing, the mean speed could be smaller than any individual speeds. Tests on a large set of MFR data gave median ratios of 0.92 and 0.98 for divided sets of $V < 30$ and $V > 30$ m/s respectively. However, there could be a similar effect acting on HRDI because of its spatial averaging.

The analysis model (full correlation analysis, FCA) assumes statistical stationarity over the record length (5 min). Also, if the fading data are not stationary (or have high noise level), they are more likely to be rejected in the analysis. Thus a selection based on number of values per hour is likely to select data on which the analysis performs best. Since no noise correction is done, these data will have an uncorrected noise bias. A separate statistical study, comparing original (for which the number left after noise correction was >6 of a possible 12), and corrected hourly means showed a residual bias of $<10\%$ above 80 km with a smaller bias ($<5\%$) for $\sim$ 85–94 km in daytime.

It is possible that all these biases could combine, resulting in significantly lower than actual speeds, but as will be seen later, comparisons with FPI systems argue that this is not the case in practice.

3 Errors in MFR heights

The Saskatoon radar has a nominal resolution of 3 km (20 μs pulse). An accurate range calibration was obtained from observations of a research balloon, floating at $\sim$36 km, which carried a global positioning system (GPS) unit. The method was to locate times when the balloon echo-strength was equal at two adjacent height gates $\sim$60–70 km, and work out the real range from the GPS locations of the radar and balloon. The final calibration used here is a rounded version of the measurements. This could result in MFR heights which are up to $\sim$1 km too small.

A more serious source of error is caused by retardation of the radio waves by ionization, the height is then termed *virtual* height. The resulting error is only important near the E-region total reflection echo. Namboothiri *et al.* (1993) have investigated this problem, and found that MFR heights above 94 km begin to depart significantly from real heights at noon in the summer ionosphere at our radio frequency. Away from noon, or in the winter, the departure is less serious because of reduced ionization. We avoid this problem here by selecting appropriate comparison heights depending on season and time of day.

Other lesser errors include moderate angular spread, resulting in a lower effective height (viz. the average height is less than the range). In the extreme case of total reflection from a sporadic-E (Es) layer (these are usually located above 95 km), the measurement will apply to its height even when the apparent height (the range) is greater. Also an extremely height-stable layer could result in an unknown error within the 3 km radar resolution; and an ionospheric tilt would make the measured height larger than real, again because at an oblique angle the range is greater than the height of scatter.

Most of these potential errors lead to MFR winds being appropriate to a lower height than that stated, and since wind speed tends to increase with height, would lead to lower than actual speeds being found.

The technique of sliding the FPI or HRDI, and MFR heights with respect to each other for the lowest direction-difference, which we will employ later, depends on there being a strong tidal signal (circular wind vector rotation with height) with a relatively short vertical wavelength (Manson and Meek, 1986). In this case the wind direction-difference will be very sensitive to height differences, especially at the upper heights where the tides are large.

4 Previous MFR-FPI comparisons

4.1 Saskatoon FPI versus MFR

The Saskatoon FPI was located ~40 km east of the radar. Its field of view had 30° elevation (350 km diameter sampling area at 97 km). A single wind measurement on the 557.7 nm green line lasted 40 min. Objective selection criteria were based on the intensity, background and their variances over the azimuthal scan (G.E. Hall, private communication; Manson *et al.*,1996). MFR hours with more than 6 successful wind determinations (denoted "# > 6" hereafter) at a particular height centred on the FPI record time were selected for the comparison (Manson *et al.*, 1996; Phillips *et al.*, 1994). Partly because of limited MFR data at these heights and partly to approximate the green line layer width, we employ a sliding layer consisting of 2 height gates (~6 km).

Figure 1 shows histograms of speed-ratios and direction-differences (also sometimes called "phase differences" in the figures) for 1988–1992. The number in each histogram is given at its bottom right hand corner, and the labels show the sense of the ratio or difference (directions are measured east of north). It can be seen that the MFR speeds are a little larger than the FPI speeds based on the median ratio, and that the best match is with the MFR 97–100 km layer, both in direction-difference and histogram shape and width (the width is approximately proportional to the bin number at the most probable value). Note that in this and all other histograms presented in this work, off-scale values have been placed in the appropriate end bin. Considering the numbers of comparisons at each height of this layer (not shown), we find that MFR 98 km best matches the FPI data. This height is often considered to be the mean height of the green-line emission layer (Phillips *et al.*, 1994), but as mentioned in that paper, height variations on the order of a scale height (~6 km) have been shown by UARS WINDII measurements. Layer height changes of this order could be responsible for some of the MF-FPI discrepancies evidenced by the histogram widths.

Later in this study we discuss possible biases to median speed ratio due to differing internal errors in the two experiments being compared. For the present case, we have calculated the errors for the MF 97–100 data (see Fig. 1). Both were found to have RMS errors of

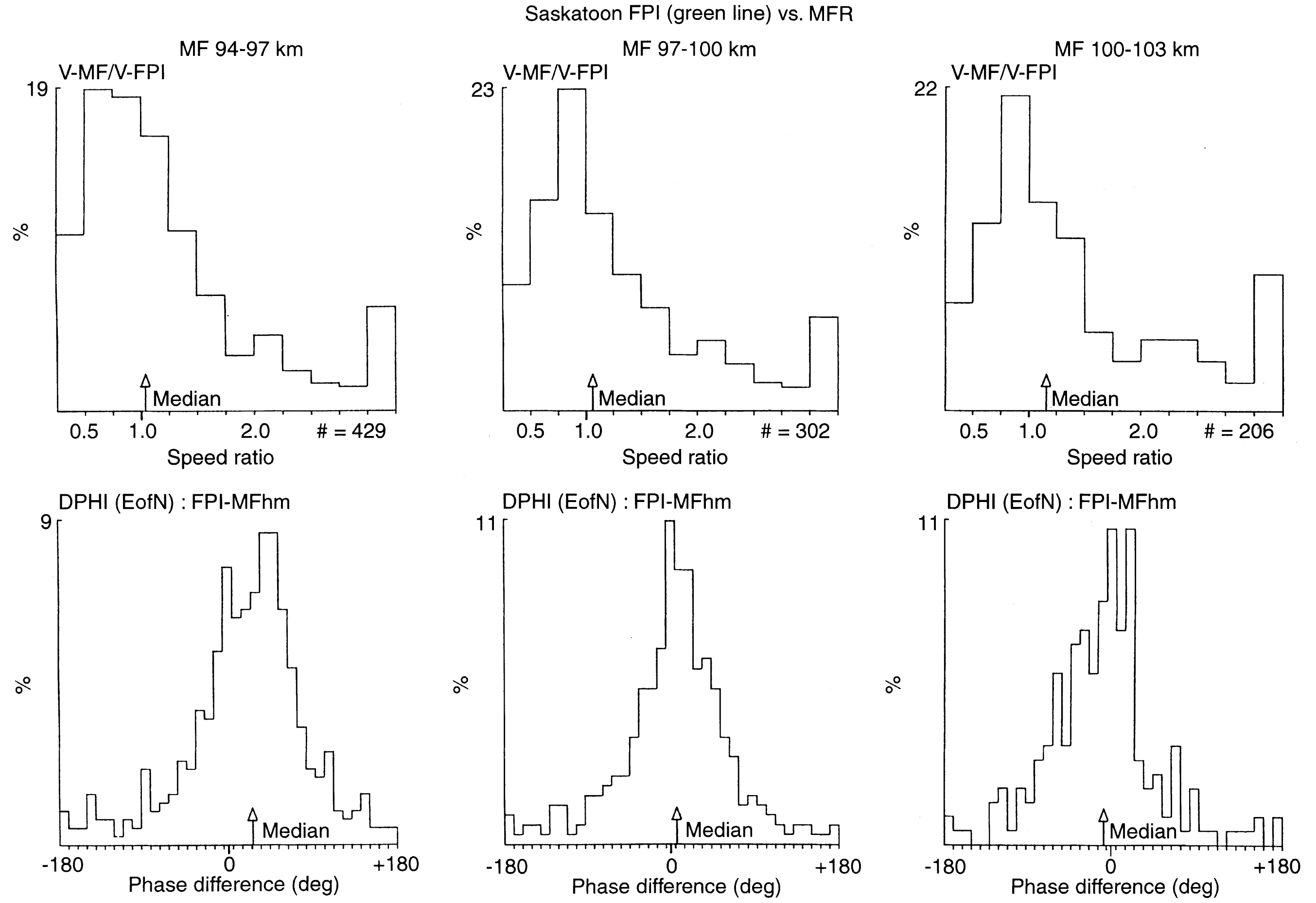

Fig. 1. Saskatoon FPI (green line, nominally at 97 km) compared with three two-height layers of MFR data: 94–97, 97–100, and 100–103 km (hourly means with # >6). Speed-ratio (*top*) and-direction difference (10° bin, *bottom*) histograms

23 m/s, where the error was defined by $\sqrt{\sigma_N^2 + \sigma_E^2}$ (σ_N and σ_E are the standard deviations in the northward and eastward winds for the FPI wind vector fit, or the MF hourly mean). Thus a bias in speed ratio from this effect is not expected.

4.2 Calgary FPI versus Sylvan Lake MFR

Sylvan Lake is ~150 km north of the FPI site at Calgary, and slightly beyond its northernmost field of view. The MFR radar is a less expensive version of the one at Saskatoon (smaller antennas), but the same analysis is used. The FPI data consist of $\frac{1}{2}$ h records. The MFR data are from FPI-centred $\frac{1}{2}$ h; these contain a maximum of 6 raw wind vectors, and we have selected those $\frac{1}{2}$ h with # ≥ 3. The data set runs from Nov 1, 1992 to Mar 1, 1993. The *preferred* height for the OH emission is 88 km. Here we are able to use single heights because the MFR data are more numerous in this lower height region.

Figure 2 shows that the best matching height is slightly less than 88 km (the centre histogram). Here the MFR speeds are significantly larger than the FPI speeds on a median basis (this is opposite to the difference expected from the latitude separation in winter – see Robsart-Saskatoon MFR comparison later in Fig. 3). One possible reason for this, which will be discussed more fully later in relation to the HRDI-MF comparison, is the difference in uncertainty in the two systems' data. Since the FPI measurement errors are presently unavailable, they have been estimated by differencing wind vectors spaced by 30 min, and these are compared with MF data analyzed in the same fashion. The RMS difference magnitudes for FPI and MF (88 km) are found to be 15.0 and 6.5 m/s, respectively for the nights in the study. A simple model combining these with the mean speeds (21.5 and 23 m/s for simultaneous FPI and MF data, respectively) shows that a median speed ratio, MF/FPI, of ~1.16 is expected. Thus this effect can explain most of the median speed-ratio difference from unity.

5 MFR-HRDI comparisons

Before we compare HRDI and the Saskatoon MFR, it is useful to have a *baseline* set of data to show what we expect to see when spatially separated measurements of the same type are compared. This is provided in Fig. 3 by a (winter) comparison between two MFRs (Saskatoon and Robsart) separated by 370 km, ~3° difference in latitude. This distance is approximately equal to the

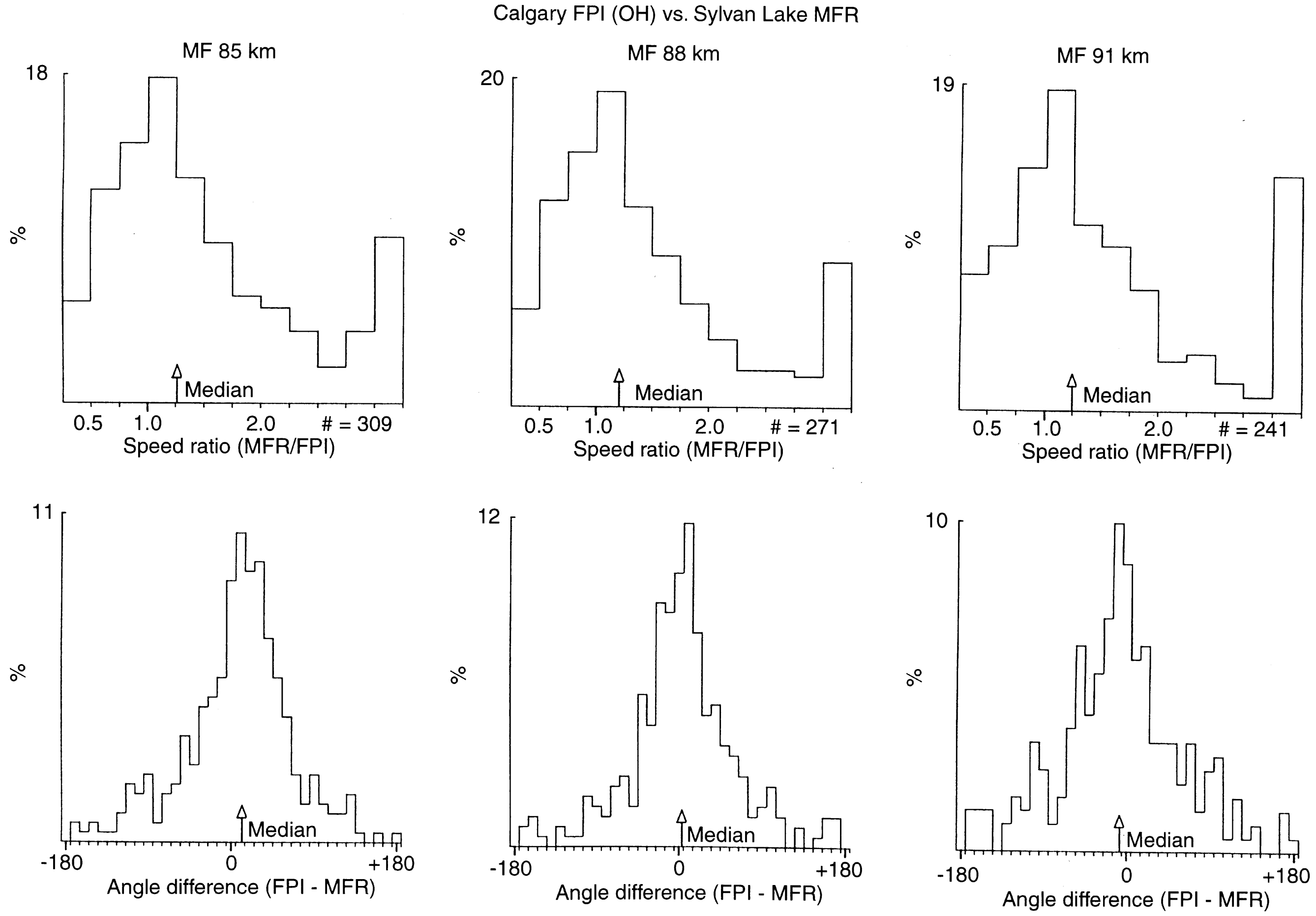

Fig. 2. Calgary FPI (OH line, nominally at 88 km) compared to three heights of Sylvan Lake MFR: 85, 88, and 91 km

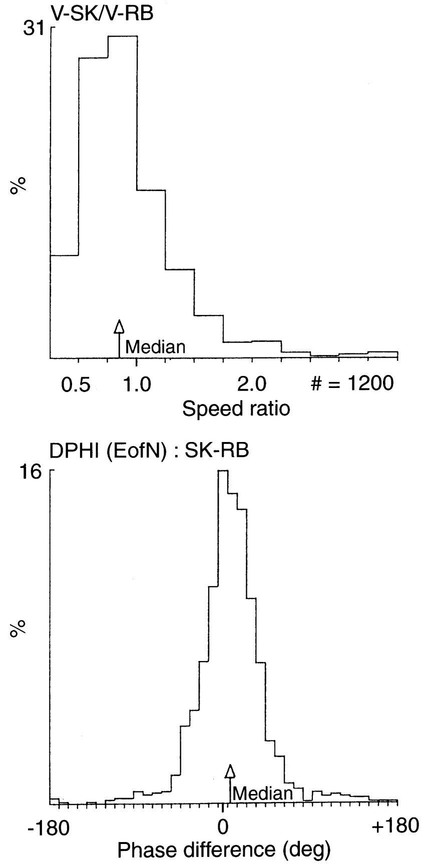

Fig. 3. Speed-ratio and direction-difference histograms comparing Robsart (49°N, 109°W) and Saskatoon (52°N, 107°W) MFR data: data from 82–94 km, Jan 1–Feb 18, 1996, hourly means with # >6

average distance in the HRDI data set (500 km). Note that even here there is a median speed-ratio of ~0.8, with the lower latitude site being larger. We think this is due to a latitude difference in the mean circulation pattern (January zonal winds table, CIRA 86); a similar comparison of Sylvan Lake and Saskatoon data showed negligible speed bias. The negative direction-difference is likely due to Robsart being ~2° west of Saskatoon, and thus at an earlier local time in the clockwise tidal oscillation.

The HRDI passes are distributed more or less randomly around Saskatoon. Spatial and time scales associated with the smoothed HRDI data are 1000 km and 1 h (Khattatov *et al.*, 1996). The HRDI data we use consists of all wind measurements within 1000 km from Saskatoon in the period December 1991 to April 1995, comprising 235 daytime and 218 night-time passes. These data have a lowest height of 70 km, and a sampling step of 2.5 km. The corresponding MFR data selected consists of centred hourly means with # >6 (starting at 70 km, with a step of 3 km). All comparisons are done between MFR and HRDI velocity vectors from individual heights. In the layer comparisons (Fig. 4) speed-ratio and direction-difference values have been combined in single histograms using HRDI heights closest to MFR heights over the layer.

Figure 4 compares HRDI and MFR for two layers: 70–85, 85–94 km. In these the median speed-ratios, MFR/HRDI, are approximately 0.7, while the direction-differences are close to zero. Note the slightly lower spread of the latter in the lower height layer compared with the previous FPI-MFR comparisons (Fig. 1, centre panel), as shown by the number in the most probable bin. That is, in this layer MFR-HRDI agreement in wind direction is a little better than that for the MFR-FPI, even though the distance between the former measurements is usually much greater.

Figure 5 shows a typical single HRDI height (87.5 km) comparison with three consecutive MFR heights. The median speed-ratios are ~0.8, and the best height, based on median direction-difference being zero, is midway between MFR 88 and 91 km, or 89.5 km. The scatter in direction-differences is a little larger than the MFR-MFR case shown in Fig. 3, but very similar to that of both MFR-FPI comparisons (Figs. 1, 2).

Table 1 lists the results of other such single-height comparisons. The MFR speeds are likely biased low by noise at the lowest heights (~6–7% on the average, based on an independent study of the residual noise bias in hourly means with # >6). Table 2 summarizes the best matching heights based on direction-differences. It can be seen that for the best wind direction match, HRDI heights are significantly smaller than MFR heights by several kilometres above ~85 km. In the case of HRDI 100 km versus MFR 100–109 km, the inability to find zero-phase difference, even though MFR virtual heights should be the same as real heights here, could be due to cases of sporadic-E. This would mean that our scatter-height is sometimes limited to the Es height when we assume it to be much greater.

As S. Franke (private communication, 1996) has pointed out, the median speed-ratio can be affected by a difference in relative noise level between the two experiments. This is the subject of the next section.

5.1 *Differential noise level effect on median speed-ratios*

If two experiments are measuring the same value, but their random noise levels are different, the one with the higher noise will seem to have a higher speed value when the median speed ratio is considered.

This can be most easily seen by writing the equation for speed given velocity components u, v with errors Δu, Δv (uncorrelated, zero mean):

$$\text{speed} = \sqrt{u^2 + v^2 + (\Delta u)^2 + (\Delta v)^2 + 2u\Delta u + 2v\Delta v}$$

The squared error terms make the speed greater than that for the original u, v components (by an amount which depends on the size of the error) more often than not. This may lead to a bias in the median speed-ratio between two experiments whose errors are unequal.

Here we try to compare the HRDI and MF errors with a view to examining the obvious bias between HRDI and MFR speeds.

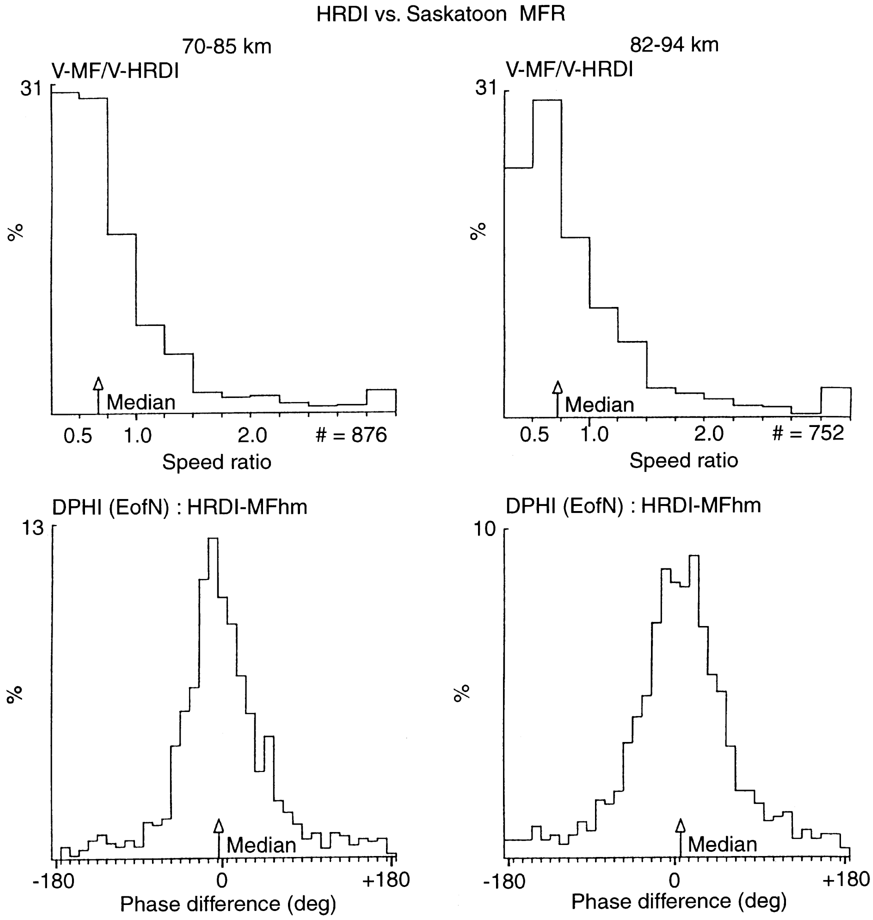

Fig. 4. Speed-ratio and direction-difference histograms comparing HRDI and Saskatoon winds (hourly means with # >6) for two layers: 70–85 and 82–94 km

As mentioned in Sect. 2, the hourly mean process on the MFR data can reduce the speed slightly, and certainly reduces the errors. Consequently a test with single MFR values was made to see how much the ratio may have been underestimated because of the reduction in MFR error. The comparison selected MFR hours with # >6, as usual, but used the 5 min wind value nearest to the HRDI time, rather than the hourly mean. The case of HRDI 87.5 versus MFR 88 km (see Table 1) was reprocessed, resulting in a new median ratio of 0.82 (as opposed to 0.78). Thus, the additional bias caused by taking the MFR hourly mean, is not very significant.

The possibility remains however that HRDI data may have larger errors per value than the MFR, which would lead to a smaller MFR/HRDI median speed-ratio. Since the HRDI analysis produces smoothed (along the path) data, errors cannot be found by differencing sequential HRDI profiles, but their assessment may be possible if we difference wind profiles separated by one satellite pass (~90 min) at the same location (within say 500 km). This implies that the maximum spatial separation between measurements will be 1000 km. If we ignore the spatial differences for now, we can compare the HRDI 90 min difference with the MFR 90 min difference (between 1 h means). Unfortunately, Saskatoon, being at a high latitude, is sparsely sampled by HRDI, and we have no 90 min differences available. Here we use Urbana (40°N, 88°W) passes, which provide a large set comprising 1420 daytime and 5599 night-time passes. Initially we divided the HRDI 90 min differences at each height according to spatial separation, ΔD, of the measurements, but found that often the smallest ΔD (<100 km) exhibited largest RMS wind differences. Since the differences should increase with separation, this suggests that the available spatial separations are within the smoothing area of HRDI, and so we have combined all ΔD. We will term these values *errors* even though they no doubt contain a large gravity wave (GW) contribution, and possibly a contribution from spurious values, such as are sometimes seen at low heights (e.g. Fig. 2 of Khattatov *et al.*, 1996). In addition we have examined the RMS estimated errors (σ_n, σ_e) for HRDI. Because the variance of a difference between two independent measurements is the sum of their variances, we must apply a scale factor before comparing 90 min differences with estimated errors in individual measurements. Here we have chosen to multiply the estimated errors by a scale factor of $\sqrt{2}$ to agree with the 90 min difference scale. Just the north component is considered since the east was found to be virtually the same.

Figure 6 shows HRDI RMS 90 min differences and estimated errors for summer and winter daytime data. The HRDI night-time data have somewhat different errors, and are shown separately. [The separation into seasons was done after it was noted (to be shown later)

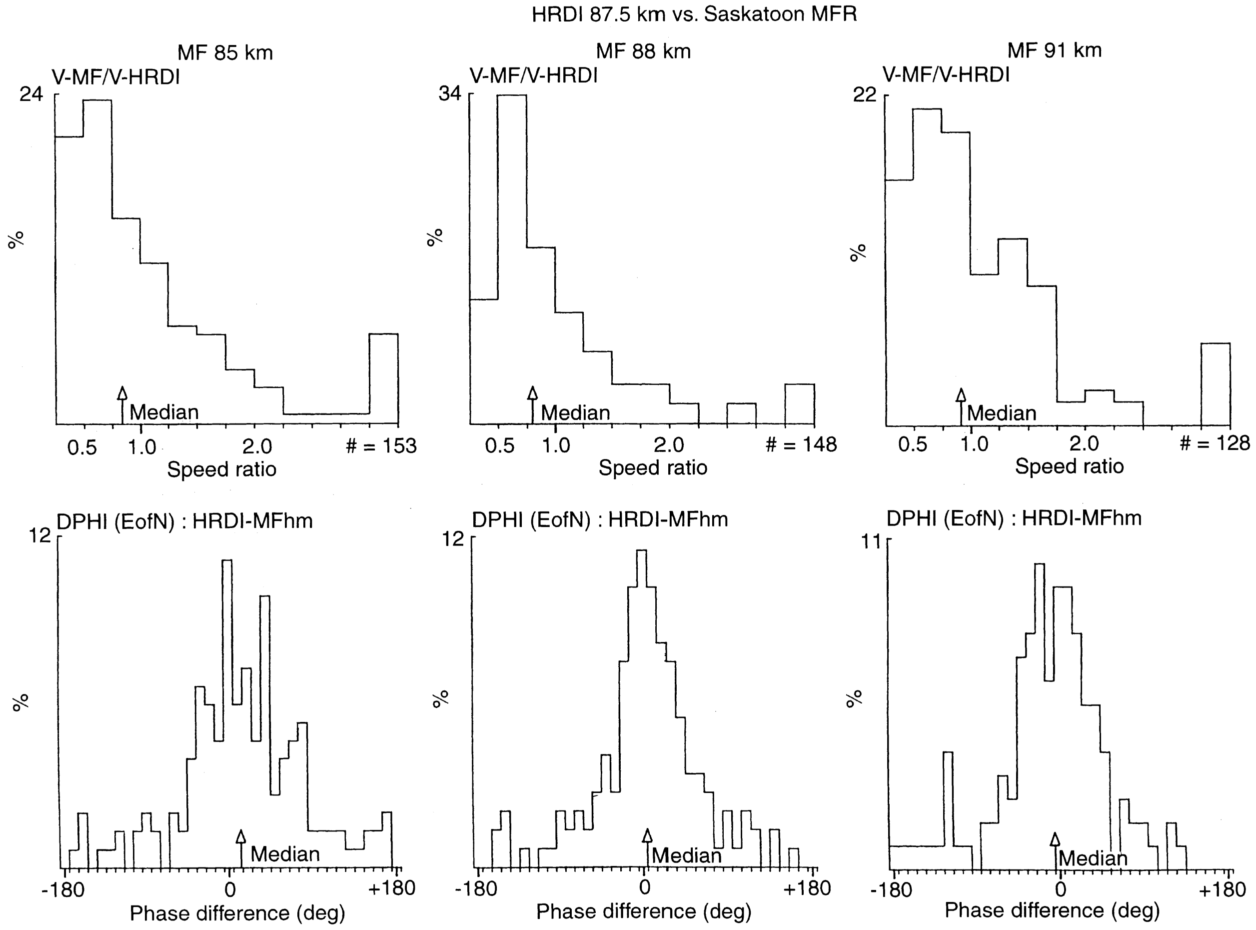

Fig. 5. Speed-ratio and direction-difference histograms comparing single HRDI height data (87.5 km) with those from several adjacent MFR heights (85, 88, 91 km).

that Saskatoon RMS 90 min differences had a seasonal dependence.] It can be seen that up to ~80 km, the estimated and 90 min difference values are of similar size, and decreasing with height. Beyond this height, the estimated error becomes constant while the 90 min difference increases, presumably due to increasing GW perturbations. Although we do not have HRDI 90 min differences for Saskatoon data, the corresponding RMS HRDI estimated errors are virtually the same as those for Urbana, and so we will make the (untestable) assumption that the 90 min differences are also of similar magnitude.

Two month samples of winter/summer 90 min differences for the MFR are plotted in Fig. 7. These exhibit the expectations for purely GW perturbation noise, viz. a consistent increase with height. At ~60–80 km, the HRDI 90 min differences are a factor of ~2.5 greater than those of the MFR, above 90 km, they are ~1.5 greater.

In order to generate a model from which biases in speed-ratio may be assessed, we also need to know the "real" wind to which the errors are added, and also what kind of error. If the errors are independent of the wind value, i.e. *absolute* errors, there will be a larger effect when the wind is small. Unfortunately we do not know the "real" wind value to which errors are applied.

However we can estimate experimental values of, and generate a model with, relative errors. In the model the standard deviation of the random error is a constant fraction of the "real" value being measured.

The 90 min relative difference (for MFR and HRDI) is defined as

$$|\vec{V}_1 - \vec{V}_2|/|\vec{V}_1 + \vec{V}_2|$$

where $\vec{V}_1$ and $\vec{V}_2$ are wind vectors with a 90 min separation, and the HRDI estimated relative error will be defined as

$$\sqrt{\frac{\sigma_n^2 + \sigma_e^2}{(V_n^2 + V_e^2)}}.$$

In order to equalize the error scales, we divide the estimated relative error, defined above, by $\sqrt{2}$ before plotting.

Figure 8 shows these parameters for HRDI and Fig. 9 for the Saskatoon MFR for the same winter and summer data sets as were used in Figs. 6 and 7. The relative 90 min differences for HRDI and MFR are seen

Table 1. Median speed-ratio (MFR/HRDI), direction difference, and number of values for single height comparisons: MFR heights across, HRDI heights down

HRDI height	MFR height			
	MFR76	*MFR79*		
77.5	0.70	0.70		
	-2°	+2°		
	148	138		
	MFR79	*MFR82*	*MFR85*	
82.5	0.85	0.75	0.70	
	+3°	-6°	0°	
	148	144	153	
	MFR85	*MFR88*	*MFR91*	
87.5	0.80	0.78	0.85	
	+12°	+5°	-5°	
	153	148	128	
	MFR91	*MFR94*	*MFR97*	
92.5	0.61	0.70	0.72	
	+15°	+5°	-1°	
	128	97	86	
	MFR91	*MFR94*	*MFR97*	
92.5[a]	0.69	0.85	0.82	
	+47°	+20°	-10°	
	16	14	16	
	MFR94	*MFR97*	*MFR100*	*MFR103*
95[b]	0.62	0.82	0.80	0.78
	+20°	-2°	-2°	-25°
	84	63	42	26
	MFR100	*MFR103*	*MFR106*	*MFR109*
100[b]	0.59	0.62	0.70	0.75
	+67°	+25°	+15°	+5°
	14	15	10	15

[a] Dec, Jan, Feb only
[b] Night-time only

to be similar above ~85 km, but the HRDI values are much larger below this height. This suggests that the largest effects of differential system errors on median speed-ratio should occur at the lowest heights. This effect can be seen in Table 1, but it is quite weak.

We can easily generate a model for each of these kinds of errors, with a random Gaussian variable as the "real value", and two other values representing HRDI and MF created from this by adding either values from two random number populations whose standard deviations are fixed, representing the (different) absolute errors in the two systems; or whose standard deviations are proportional (by different fixed amounts) to each particular "real" value, representing relative errors. In the absolute error case, it is possible to get quite large modifications in the median speed-ratio. For example if the "real" value of (signed) speed has a standard deviation of 100 m/s and the two errors have absolute standard deviations of 20 and 50 m/s, a 15% change in the median speed-ratio is found. On the other hand, in the relative-error model, even with relative error differences up to 60%, only small changes in median speed-ratio are found. In other words, the magnitude of the speed-ratio bias is very strongly dependent on the type of error.

Table 2. Approximate best matching height based on direction-difference medians

HRDI (km)	MRF(km)
77.5	77.5
82.5	80.5 or 85 (ambiguous)
87.5	89.5
92.5	96
95.0	97 and 100
100.0	> 109

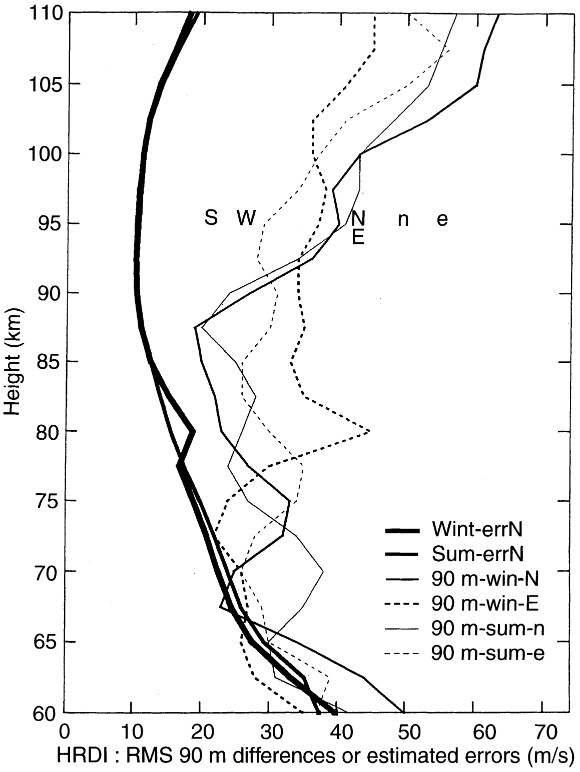

Fig. 6. HRDI RMS 90 min differences ($\Delta D < 1000$ km) for north and east components, winter (Nov.–Feb.) (labelled *90 m-win-N* and *90 m-win-E*), and summer (May–Aug.) (labelled *90 m-sum-N* and *90 m-sum-E*), and RMS estimated errors, scaled up by $\sqrt{2}$), for winter and summer north component: *wint-errN* and *sum-errN*. Night-times (95 km) are shown by characters as follows: *N*, *E* represent winter, and *n*, *e* summer, 90 min differences, while *S* and *W* are summer and winter estimated errors, All HRDI data shown in this figure are from Urbana overpasses

It should be noted that these biases in speed-ratio do not apply to a comparison between mean winds (e.g. seasonal) from the two systems, because here the random errors should cancel in the mean.

Since the mean MFR and HRDI wind components do exhibit a bias, with HRDI values larger (e.g. Khattatov *et al.*, 1995), it seems that while differential errors may be partially responsible for the speed bias found in this work, they are not a complete explanation. We are left with the conclusion that there is a real wind-magnitude bias between the MFR and HRDI systems.

5.2 Separation into agree/disagree *data sets*

Figure 10 splits the 82–94 km HRDI-Saskatoon data pairs into two equal-size data sets: those data in which

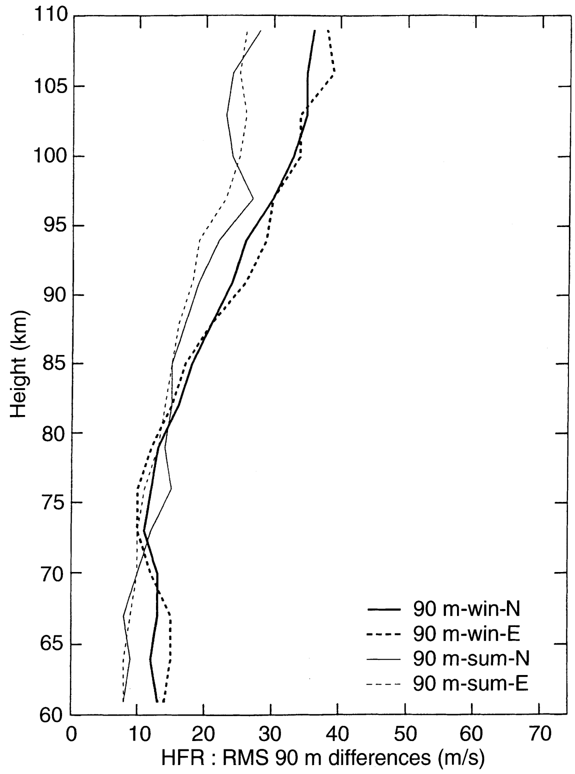

Fig. 7. Saskatoon MFR RMS 90 min differences for north and east components (from an arbitrary year): summer (labelled *90 m-sum-N*, *90m-sum-E*), and winter (labelled *90 m-win-N* and *90 m-win-E*)

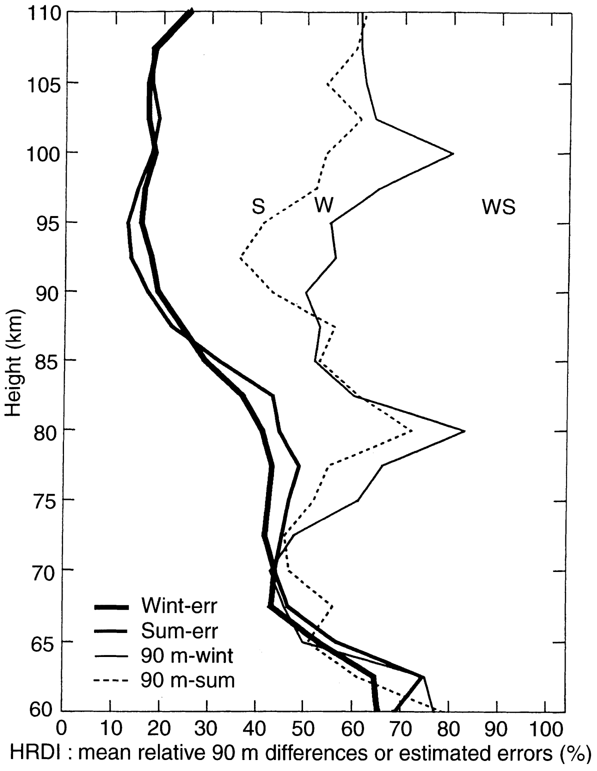

Fig. 8. HRDI mean relative 90 min differences and estimated errors (the latter scaled down by $\sqrt{2}$) for winter and summer Urbana passes, expressed in percent

HRDI and Saskatoon best *agree* and the remainder, in which they *disagree* (by definition). This data division can be done either by requiring agreement/disagreement with speed-ratios or with direction-differences. Here we do it both ways. Because HRDI data is obviously biased in speed with respect to Saskatoon MFR, it has been multiplied by 0.7 (which is a best guess at the bias over this height layer, see Fig. 4). The *agree* data sets consist of 50% of the data, 25% on either side of 1.0, for the velocity ratio; and 25% on either side of 0° direction-difference, for the phase. The remaining data form the *disagree* sets.

Now that the data are divided, we can examine the two for different characteristics. One such is the internal error in each measurement, these are shown on the right hand side of the figure as histograms of *coefficient of variation*, which is just

$$\sqrt{\frac{\sigma_n^2+\sigma_e^2}{V_n^2+V_e^2}}.$$

(in the case of the MFR, the σs are just the standard deviations over the hour; for HRDI the σs are the error estimates accompanying the data that we have.)

It can be seen in the top half of the figure (division by speed-ratio) that <u>both</u> HRDI and the MFR separately have bigger relative errors when they disagree, this seems to point to some condition affecting both: e.g. local GW or other sudden wind variations.

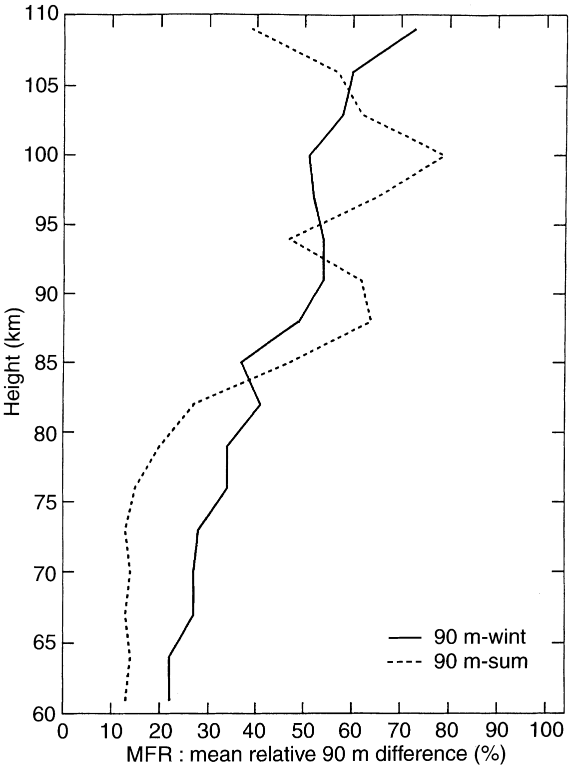

Fig. 9. Saskatoon MFR mean relative 90 min differences (same data as used in Fig. 7) expressed in percent

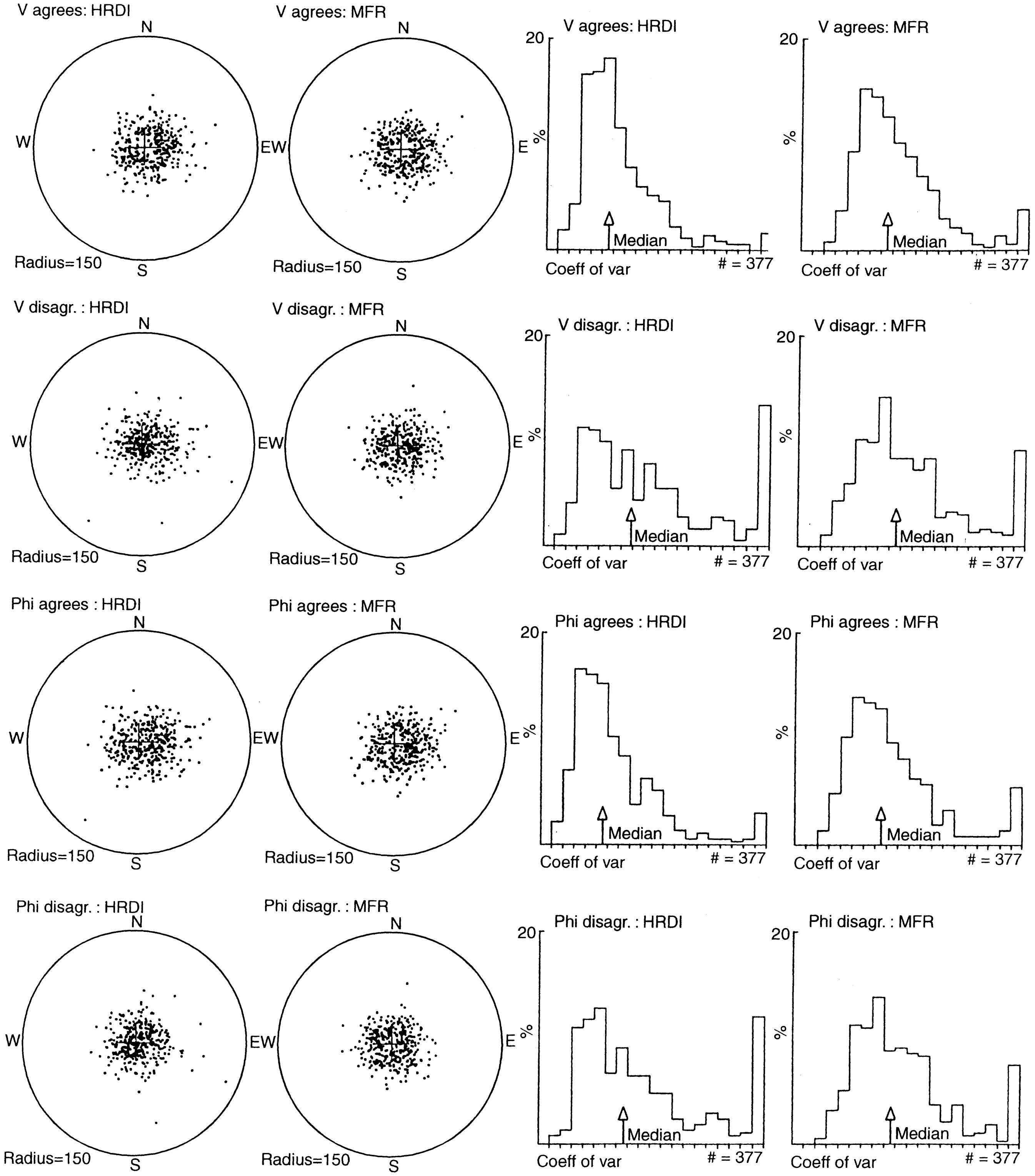

Fig. 10. Division of Saskatoon MFR and HRDI data (where HRDI wind vectors have been multiplied by 0.7) into two equal parts, *agree* and *disagree*, according to speed (top half of figure) and direction (bottom half). *Left hand polar plots* show wind vectors. *Right hand histograms* show relative internal errors. All data from 82–94 km are used

Meek *et al.* (1995), showed similar results in a comparison between the Saskatoon FPI and MF radar.

It is worthwhile examining the actual wind vectors in each data set for differing characteristics, in the hope that some reasons for the MF-HRDI differences can be proposed. These are shown on the left hand side of Fig. 10 as polar plots. It is very interesting, comparing the vectors between the agree and disagree sets, that when HRDI and MFR disagree, clearly smaller HRDI speeds occur, and although less obvious, the MFR vectors also seem smaller. When they agree, particularly in speed, fewer small values are seen, witness the *hole* in the centre of the vector plots. This could mean that there is a small *zero-offset* error remaining in the HRDI data, whose effect would be more strongly seen in measurements of weak winds.

We have ruled this out by taking the mean of the vector: MFR – 0.7*HRDI (selected pairs with both speeds small) to see if the errors are uniformly distributed in azimuth or not. The distribution (not shown) appears uniform and the mean insignificantly different from zero, which seems to rule out the *HRDI uncorrected zero-offset* theory, and leaves the reasonable argument that smaller background winds are more strongly perturbed by gravity waves. Here the spatial variations would affect HRDI and the temporal differences the MFR, since we use an hourly mean. (Manson *et al.*, 1996 have discussed the effects of GW induced spatial variations on FPI measurements.) The results from the direction-difference division (bottom half of Fig. 10) are similar to those of the speed-ratio division.

A obvious question at this point is whether the median speed-ratio, MFR/HRDI (as in Fig. 5), is closer to 1 for the half of the data in which the directions agree compared to that when they disagree. To answer this question, the histogram analysis was applied to the data displayed in the bottom half of Fig. 10. Contrary to what was hoped, the resulting MFR/HRDI speed-ratio histograms (not shown) actually have a smaller median ratio (0.70) for the *directions-agree* set than for the *directions-disagree* (0.76). We have not been able to find a suitable explanation for this.

6 Conclusions

This study has compared MF radar wind data with those of two FPI systems and the UARS/HRDI experiment. The agreements in wind directions were quite similar between the co-located (40 km) Saskatoon MFR and FPI, the Calgary FPI and Sylvan Lake MFR (150 km north of the FPI), and the Saskatoon MFR and HRDI (0–1000 km in all directions); viz. the widths of the direction-difference histograms as estimated by their heights, are all similar.

However, the speeds did show some biases. There was negligible bias between the Saskatoon MFR and FPI (97 km layer), but the Sylvan Lake MFR found values larger than the FPI (88 km layer) by a factor of 1.2, while Saskatoon MFR speeds were less than HRDI values by factors 0.7–0.85.

An accompanying comparision between two MFRs (Saskatoon and Robsart, separated by 366 km) showed much better agreement in direction, but a speed bias of ~0.8 (Fig. 3).

Although there are certainly uncorrected biases left in the MFR data, such as a slight residual noise bias and the bias incurred by an hourly average, they will only amount to a few percent, not enough to explain the HRDI-MFR speed difference. Also, the fact that MFR speeds are equal or greater than FPI values at 88 and 97 km argues that these residual biases are not very important, and because FPIs have a "footprint" similar to HRDI, it is difficult to argue that the different spatial averaging causes the MFR-HRDI speed bias.

Considering that HRDI noise appears greater than MFR noise, at least at the lower heights (Figs. 6, 7), some speed-ratio bias in the sense MFR < HRDI is expected on statistical grounds. This could conceivably be enough to explain most of the MFR-HRDI speed bias, but since average winds (which should not be affected by random errors) show differences in the same sense (e.g. Khattatov *et al.*, 1996), a more reasonable conclusion is that there is a real difference in speed measurement.

Finally MFR and HRDI data were divided into equal-size data sets, one in which the wind vectors agreed relatively well and the remainder in which they did not. It was found that the set that disagreed had generally smaller vectors, suggesting that the MFR and HRDI wind vectors were being affected significantly and differently by some background level of wind perturbations, presumably gravity waves. This finding was supported by examination of the internal errors in each measurement, which showed that on the average when the MFR and HRDI winds disagreed, their error estimates were greater. It is encouraging to find that the MFR and HRDI are affected similarly when they disagree.

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