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# Multiple receiver wind profiling techniques for the boundary layer in the presence of hydro-meteors

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**Abstract.** A UHF boundary layer wind profiler has been operated in a multiple receiver mode. The data sets collected are used to estimate the horizontal wind using different multiple receiver analysis techniques performed in the time and frequency domains. Those results are also compared with simultaneous Doppler beam swinging measurements.

The particularity of the data sets used for this inter-comparison is that they were recorded while hydro-meteors were present in the boundary layer. The large mean fall speed and the broad fall velocity distribution of rain drops causes a much more rapid decay of diffraction patterns than in the case of scattering by snow flakes or micro turbulence. Therefore, analysis methods which do not account for the effect of the decay of the diffraction patterns show an over-estimation of the wind velocity, and do so in a different way whether snow or rain is present. To the contrary, algorithms that account for the effect of diffraction pattern decay appear to reasonably estimate the actual horizontal wind and compare well with the Doppler measurements.

## 1. Introduction

Over the last few years, there has been a growing interest to study the dynamics of the planetary boundary layer using UHF wind profilers operated in the frequency band around 1 GHz. These small radars are capable of continuously monitoring the wind profile in the first few kilometers of the atmosphere [Ecklund, 1990]. These systems are very sensitive to the presence of hydro-meteors (snow, rain, drizzle, ...) in their scattering volume. Such hydro-meteors can be the source of large errors when making wind measurements if the problem is not correctly addressed.

Lately, there have been a few experiments to use multiple receiver techniques to derive the wind in the boundary layer with such UHF radar systems [Van Baelen, 1994; Cohn *et al.*, 1997]. The primary motivation for trying out multiple receiver profiling in the boundary layer is to free the measurement process from scanning in different directions, as is necessarily done in Doppler-Beam-Swinging (DBS), and thus reduce estimation errors induced by the highly varying conditions in time and space sometimes encountered in the planetary boundary layer.

In this paper, we address the problem of the effect of hydro-meteors upon multiple receiver techniques. At VHF, Chilson *et al.* [1992] have observed such a phenomenon where both the clear air and a precipitation contribution are clearly visible. Spatial interferometry, as well as further simulations [Chilson *et al.*, 1995], indicate that the velocity estimates obtained from precipitation echoes, for which no turbulent-fading correction has been made, will be strongly affected in a way even more marked than the effect of atmospheric turbulence. At UHF the clear air echo is totally masked by the strength of the precipitation echo. Therefore, the horizontal wind can only be derived from the drift of the hydro-meteors. Thus, the outstanding question remains to evaluate if or how the so-called true velocities, derived with full correlation analysis (FCA), full spectral analysis (FSA), or other methods taking diffraction pattern decay - be it atmospheric turbulence or precipitation induced - into account, are affected by the presence of hydro-meteors in the radar scattering volume. That is the object of the present investigation.

## 2. The System and Algorithms Used

### 2.1. Description of the Radar

The radar used for the measurements described here is located at the Meteorological Observatory of Lindenberg (MOL), near Berlin, Germany. The system is a monostatic pulse radar operating at 1290 MHz. Except for the transmitted frequency, it is identical to the

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MAPR of the National Center of Atmospheric Research described in *Van Baelen* [1994] and *Cohn et al.* [1997] when used in the multiple receiver mode. For multiple receiver measurements four separated panels of the micro-strip phased array antenna can be used as separate receivers in a similar fashion as the MAPR. Likewise, during multiple antenna measurements the system has the capability to simultaneously perform DBS measurements if the transmitted beam is electronically tilted.

## 2.2. Multiple Receiver-Techniques

The time lag of the maxima of the separate receivers time series cross-correlations are inversely proportional to the trace velocity and allow to derive the so-called apparent velocity (*Briggs* [1994] provides a complete description). However, the derivation assumes isotropic and non-changing diffraction patterns. Hence, in order to account for diffraction pattern decay and anisotropy, the full correlation analysis (FCA), which makes use of the mean auto-correlation, was introduced to derive the so-called true velocity [*Briggs, 1984; Meek, 1980*]. Thus, we have here two wind estimation methods: the correlation analysis (CA) - which provides the "apparent velocity" - and the FCA - which provides the "true velocity" -. As argued in *Briggs* [1984], the former should provide over-estimates of the wind speed, in the presence of turbulence which causes a decay of the refraction pattern. However, we will still consider that method in the following as it calls for interesting insights into the scattering mechanisms involved when compared to other method results. For the later method (FCA), we followed the *Meek* [1980] algorithms.

Also making use of time series of the separate receivers, recent theoretical work by *Doviak et al.* [1994; 1996] has shown that the time lag of the intersect of the auto- and cross-correlations was directly proportional to the wind component along the baseline formed by the two antennas, regardless of the turbulence effect on the correlation function shape (here referred to as the intersection method (IM)).

The FFT equivalent of CA and FCA makes use of the slopes of the complex cross-spectral phases to derive the apparent velocity equivalent. This is the radar interferometry (RI) method [*Van Baelen, 1990; Van Baelen and Richmond, 1991*]. Likewise, to account for the effect of turbulence, a full spectral analysis (FSA) scheme has been developed [*Briggs and Vincent, 1992*] to derive the corresponding "true" velocity.

## 3. Observation Parameters and Meteorological Conditions

Two short campaigns were carried-out to test the multiple receiver mode of the Lindenberg-Radar: one on October 23, 1994, and one on March 15, 1995. For both of them the following parameters of that radar

were as follow: pulse width:  $0.7\mu\text{s}$ , inter pulse period:  $40\mu\text{s}$ , first measuring height: 180 m, range gate spacing: 105 m, number of range gates: 40, number of coherent integrations: 120, number of series per records (in a given beam direction): 32. For the spectral averaging a number of 32 spectra were used for all methods. In March a sampling cycle included two tilted beams so that it was possible to simultaneously derive multiple receiver and DBS wind profiles [*Van Baelen, 1994*] for direct comparisons. In October, the multiple receiver mode was operated in the vertical only but the presence of another boundary layer DBS profiler about 400 meters away allows for meaningful comparisons. That radar system is a bistatic FMCW-Radar-RASS wind-profiler operating at 1.2 GHz of the FZ-Karlsruhe. For this experiment a range gate spacing of 100 m, a cycle time for one DBS cycle of 75 sec and a maximum range gate of 2 km was used.

During both experiments, the meteorological conditions were dominated by moderate winds and marked by the presence of drizzle or light rain on the ground.

## 4. Wind Profile Comparisons

Figure 1 and Figure 2 provide comparisons of hourly mean profiles obtained with all the analysis techniques considered for two time periods in March and October, respectively. The wind-speed profiles are shown without dispersion bars for the sake of clarity, although it can be said that the discrepancies between the different methods discussed in the following are significant (i.e. larger than the width of the dispersion of the different techniques' individual profiles). The wind direction profiles are omitted as they show no substantial differences. Finally, the vertical-velocity profiles are presented. They were obtained with the vertical beam in DBS, from the intersect of the cross-spectral slopes with RI [*Van Baelen and Richmond, 1991*], and from the slope of the phase of the mean complex auto-

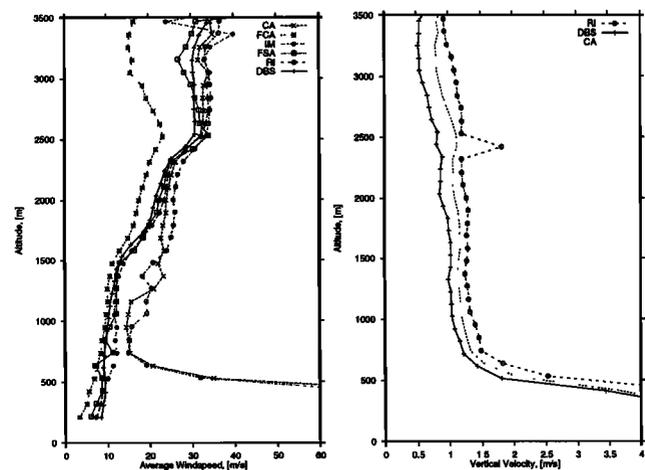
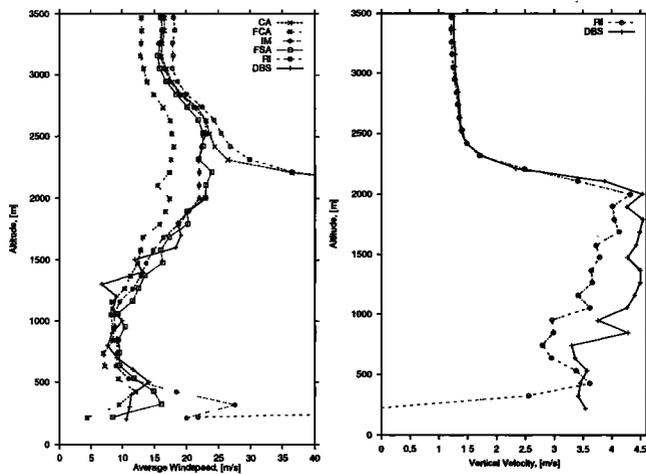


Figure 1. Average profiles of windspeed and vertical velocity measured at 15 March 1994



**Figure 2.** Average profiles of windspeed and vertical velocity measured at 23 October 1994

correlation at zero lag with the CA method. For DBS, the March profile results from a classical consensus window calculation applied to each beam before computing the combined wind profile [Carter *et al.*, 1995], while in October a consensus averaging routine developed especially for the FMCW-Radar was used. For CA, FCA and IM, the straight average of the individual profiles obtained with each record series corresponding to a vertically directed transmitted beam is computed. For CA and FCA, the regular rejection criteria such as those described in Briggs [1984] were used before performing the direct average of the accepted data. Finally, for RI and FSA the calculated wind-values obtained from 32 averaged spectra were averaged using a consensus routine over 60 min for the March data and 30 min for the October data.

In the following the DBS profiles are considered as the reference profiles in order to compare the different method results. The first noticeable feature is that, as expected, the apparent velocities (CA in the time domain and RI in the frequency counter-part) are over-estimates of the wind amplitude with respect to the DBS profiles. In particular, in both cases (March and October), there is an altitude level under which the over-estimation becomes extremely large. Considering the radiosonde temperature profiles obtained from launches at the radar site at approximately the same times those altitude levels do correspond to the melting layer. Clues of this were also present in the vertical velocity profiles. Obviously, those techniques exhibit a different behavior when the scattering volume is filled with snow flakes or rain drops. We believe that this is due to the fact that the hydro-meteors present under the melting layer exhibit a larger mean fall speed and a much broader velocity spectrum than those above. Thus, the broader spectrum induces a significantly faster decay of the diffraction patterns which in turn provoke a reduction of the cross-correlation maximum lag or a shal-

lowing of the cross-spectral slopes responsible for the over-estimation of the derived horizontal wind.

The so-called true velocities appear to be better estimates of the horizontal wind amplitude and compare well with the DBS profiles in the lower range gates. However, the FCA analysis tends to under-estimate the wind speed, especially at higher altitudes. The FCA under-estimation is definitely marked above 2 km. That behavior seems to be caused by a higher noise level in the upper range gates leading to a large noise peak in the correlation functions and a loss of the Gaussian functional form which is assumed in the Meek [1980] algorithm. Although this comment would also hold for the IM, the later appears to be less affected as it is argued below.

A similar underestimation of the FCA-derived true velocity caused by an increased noise level was also mentioned in Meek [1990] and was reproduced by a radar backscatter model described in Holdsworth and Reid [1995]. It was also shown in the later work that the implementation of the FCA proposed by Briggs [1984] with an adequate compensation for noise could remove such an underestimation, although other problems concerning the implementation may arise there.

On the other hand, the FSA true velocity seems to compare very well with DBS over the entire altitude range covered by the radar during this experiment. Nonetheless, the experience showed to us that this excellent result was achievable only when a careful implementation of the FSA regarding noise and clutter removal was performed. The significant difference between the two true velocities of FCA and FSA seems to be caused by the different compensation of noise in the implementation of the two techniques.

Finally, the IM appears to provide very good results and compares very well with DBS. That comment is especially relevant considering that the mean profile plotted in both cases is the result of a straight average (no rejection or consensus algorithm applied) of all the individual profiles derived over the analyzed time period. Thus, the IM approach appears to be a fairly robust technique to estimate the horizontal wind amplitude.

The differences in the estimation of the vertical velocity by the three techniques are considered to be caused by the above mentioned differences in the implementation and by the fact that all these techniques try to estimate one representative vertical velocity from a broad velocity spectrum of the falling hydro-meteors.

## 5. Concluding Remarks and Discussion

In this note, we have presented hourly wind profiles obtained with a multiple receiver UHF boundary layer radar and using several wind estimation methods. We have shown that not only did the presence of hydro-meteors cause large over-estimations with the so-called apparent velocities, as expected following the work of

Chilson *et al.* [1995]. But also that the over-estimation could vary by a large amount depending upon the type of hydro-meteors being present in the atmospheric volume sampled due to the varying refraction pattern decay induced by the different mean fall speed and velocity spectrum of i.e. snow or rain. To the contrary, the so-called true velocities are not affected by the various degrees of refraction pattern decay induced by the different types of hydro-meteors. Accordingly, the FSA "true" velocity provides a good estimate of the wind amplitude profile when compared to DBS. On the other hand, the FCA technique shows a tendency to underestimate the wind speed. This is especially marked at higher altitudes where the signal to noise ratio is greatly reduced. Finally, the IM technique appears quite robust and provides an accurate estimate of the wind amplitude.

Therefore we can conclude that multiple receiver techniques have similar capabilities to provide measurements of the horizontal wind as the Doppler technique in the presence of stratiform rain.

The underestimation of the FCA derived true velocity and the experiences with the implementation of the FSA stress the fact that a careful handling of noise and clutter effects is the key to a successful estimation of the wind velocity.

In situations with a horizontally inhomogeneous velocity field (orographic structure or convective rain) all multiple receiver techniques promise to have advantages estimating the horizontal wind in comparison with the Doppler technique as all multiple receiver techniques use only one measuring volume.

Rain measurements as they are presented here, are difficult conditions for multiple receiver techniques as can be seen from the large differences between true and apparent velocities. The good results of the techniques that provide the true velocities stress the reliability of multiple receiver techniques in all situation, especially in the less difficult clear-air situations.

Therefore the FSA and the IM, and to a certain extent the FCA offers good promises for simultaneous measurements of the 3 wind components in the same measuring volume with a much higher time resolution than with DBS: in the order of 10 seconds. Such a capability would allow an adequate estimation of momentum flux profiles in the atmospheric boundary layer.

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