7R.7 SIMULTANEOUS WIND VELOCITY ESTIMATION AND DUAL-POLARIZATION MEASUREMENTS OF PRECIPITATION AND CLOUDS BY AN S-BAND PROFILER

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1. INTRODUCTION

The Transportable Atmospheric RAdar (TARA) is an S-band FM-CW profiler that is located at Cabauw, The Netherlands. It is a part of European Union sponsored CESAR Observatory, Russchenberg et al. (2005).

The TARA measurements can be carried out in single polarization mode, alternating polarization mode and/or wind measurement mode, that employs two offset beams. Simultaneous use of alternating polarization and wind measurement modes can provide a unique opportunity for studying both dynamical and microphysical properties of precipitation and clouds. However, the use of these two modes reduces the maximum unambiguous velocity and therefore impairs the wind measurements. Generally four to five measurements are necessary to collect both dual-polarization and two offset beam observations. In this article a method that would mitigate this effect and therefore allows for accurate wind and dual-polarization observations is presented.

A retrieval method of the three dimensional wind velocity is based on processing of Doppler spectra. Because it makes use of three alternating beam observations, the aliasing problem appears as the main drawback of this technique. This limitation is further enhanced by adding dual-polarization measurements. As the maximum unambiguous measurable velocity decreases dramatically (its maximum value was around 4.5 m/s), a very important effort has been dedicated to palliate this limitation. Therefore, a successful dual-polarization technique has been employed for the main beam dealiasing, while a more classical one was used for the other beams with good results, as well.

The results show the good behaviour of this wind velocity retrieval method. Different measurements have demonstrated how this technique behaves in different meteorological conditions, with or without precipitation.

2. WIND MEASUREMENT TECHNIQUE

Doppler radar most often measures the radial speed of hydrometeors and in certain situations, such as vertically directed beams, these velocities can differ significantly from the radial component of wind. Targets such as water drops have small mass and quickly respond to horizontal wind forces to trace faithfully the wind. It has been shown that even for turbulent wind, more than 90% of its fluctuations are acquired by raindrops if their diameter is less than 3 mm, Doviak and Zrnic (1993). For radar beams at low elevation angles, hydrometeors fall velocities give negligible bias error in the radial wind component. At high elevation angles, the meteorological targets fall velocities need to be estimated.

The 3D wind field is necessary information for clouds and boundary layer studies. Furthermore the knowledge of the 3D wind field can be used to remove the wind and turbulence components from the Doppler spectra. Using these corrected polarimetric Doppler spectra, retrievals of the drop size distribution and of the size-shape relationship can be carried out.

In the presented study, the radar TARA (Fig. 1) uses three independent beams (Fig. 2) to acquire weather information. These beams will be referred as Main Beam (MB), Offset Beam 1 (OB1) and Offset Beam 2 (OB2). Only the main beam can be used for polarimetric measurements, using alternating linear polarizations (h,v). In this work we have employed the following acquisition sequence, MB(vv vh hh) OB1 (vv) OB2 (vv). This sequence of 5 different measurements lasts 5 ms and is repeated in time. The cross polar measurement is mainly intended for clutter suppression.

Radar output data is collected and processed in order to obtain three mean Doppler velocities at each height bin. The Doppler spectrum is calculated from the samples at different acquisition time for a fixed beam, polarization and range. The number of samples can vary, but it will have a direct influence on the final accuracy of the wind retrievals. One of the main limitations of this technique is spectrum aliasing, since the sampling time is increased five times, as compared to a single polarization measurement. Thus the maximum unambiguous radial velocity is

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decreased by the same factor. Therefore an important effort is being made to solve this problem. In this work two different dealiasing methods will be discussed. The first one is a based on analysis of polarimetric measurements. And the second one, is based on classical dealiasing techniques.

Fig. 1: Transportable Atmospheric RAdar (TARA)

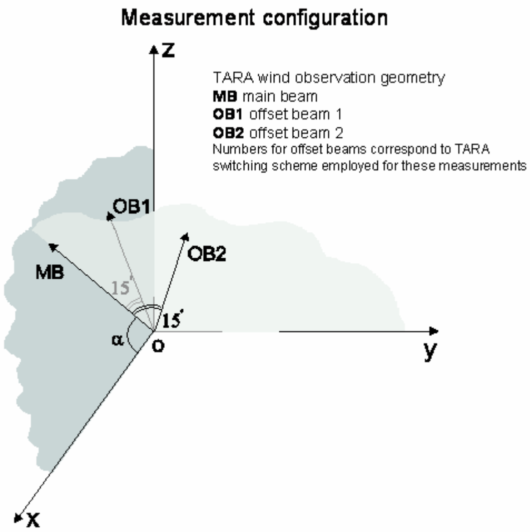

Fig. 2: Measurement configuration: the main beam (MB), in the plane XZ, has an elevation α. The offset beams 1 (OB1) and 2 (OB2), are 15 deg. away from the mean beam, respectively in the plane XZ towards Z and in the Y-direction. The elevation angle of the main beam may be changed but the angle of 15 deg. between the different beams is fixed.

3. POLARIMETRIC DEALIASING (MAIN BEAM)

This technique is discussed in details by Unal and Moisseev (2004). This method allows to carry out consecutive polarimetric measurements with the maximum unambiguous Doppler velocity of a single polarized measurement. Its main principle and implementation are shortly presented here.

The method is based on the phase of the cross-spectrum *hh*,*vv*, which is the phase between *hh* and *vv* measurement per Doppler velocity bin *l*:

$$\psi(l) = Arg\left[\frac{1}{k}\sum_{i=1}^{k}\hat{S}_{vv}(i,l)\hat{S}^{*}_{hh}(i,l)\right] \qquad (1)$$

The number of averages of the cross-spectrum is k and $\hat{S}$ represents the scattering matrix in the Doppler frequency domain. At S-band, with a small maximum range (15 km), for detailed studies of the atmosphere, and measuring vertical or slant profiles, the mean of this phase is 0. But we measure

$$\psi(l) = \frac{4\pi}{\lambda} l v_D \Delta t \quad \text{if} \quad V_D = l v_D \le V_{D,\max} \qquad (2)$$

and

$$\psi(l) = \frac{4\pi}{\lambda}\left(l v_D \pm n_D 2V_{D,\max}\right)\Delta t \quad \text{if} \quad |V_D| > V_{D,\max} \qquad (3)$$

where $V_{D,max}$ is the maximum unambiguous Doppler velocity, V_D is the Doppler velocity of the target, v_D is the Doppler velocity resolution, n_D the number of aliasing and Δt the time difference between the measurements *hh* and *vv*.

Because of the non-simultaneity of the measurements *hh* and *vv*, we measure the phase (2) when the Doppler velocity of the target does not exceed the maximum unambiguous Doppler velocity and the phase (3) in the other case. Therefore a Doppler phase compensation per Doppler velocity bin, $-4\pi l v_D \Delta t/\lambda$, is applied to correct for the non simultaneity of the measurements *hh* and *vv*. This correction is valid for any moving target and improves in accuracy with the Doppler velocity resolution. After correction, the phase of the cross-spectrum becomes

$$\psi^{c}(l) = \pm n_D 2\pi \frac{\Delta t}{nT_s} \; \text{….with } n_D\text{=0,1,2,..} \qquad (4)$$

where T_s is the sweep time or time for a single measurement (T_s=1 ms), n the number of different measurements (n=5 for the sequence *vv vh hh ob1 ob2*) and Δt=2T_s.

It is then clear that the value of the corrected phase of the cross-spectrum (4) indicates the presence of aliasing and in which interval of Doppler velocities, the actual Doppler velocity of the target is (Table 1).

The implementation of this technique is straightforward. Firstly the cross-spectrum is calculated. Then the Doppler phase compensation per Doppler velocity bin is applied. Finally there is selection of the Doppler velocity interval based on the cross-spectrum phase value (Table 1). This processing is illustrated in Figs. 3-6. They show the Doppler spectra for every height or range bin (spectrograph). Figs 3-6 represent a slant profile of precipitation. The elevation angle is 75 deg. The range resolution is 30 m. The convention for the sign of the Doppler velocities is the following: a target approaching the radar has a negative Doppler velocity. The maximum unambiguous Doppler velocity is too low (4.5 m/s), which corresponds to a sequence of 5 different measurements and a sweep time of 1 ms. The Doppler resolution is 1.8 cm/s. No averaging is performed.

Table 1 Argument of the cross-spectrum after Doppler phase compensation (sequence of 5 measurements) – case of multiple aliasing

Actual Doppler velocity interval	n_D	$\psi^c(lv_D)$
$[-5V_{D,\max}, -3V_{D,\max}[$	2	$\frac{8\pi}{5}$ (–72º)
$[-3V_{D,\max}, -V_{D,\max}[$	1	$\frac{4\pi}{5}$ (144º)
$[-V_{D,\max}, V_{D,\max}[$	0	0
$[V_{D,\max}, 3V_{D,\max}[$	1	$-\frac{4\pi}{5}$ (–144º)
$[3V_{D,\max}, 5V_{D,\max}[$	2	$-\frac{8\pi}{5}$ (72º)

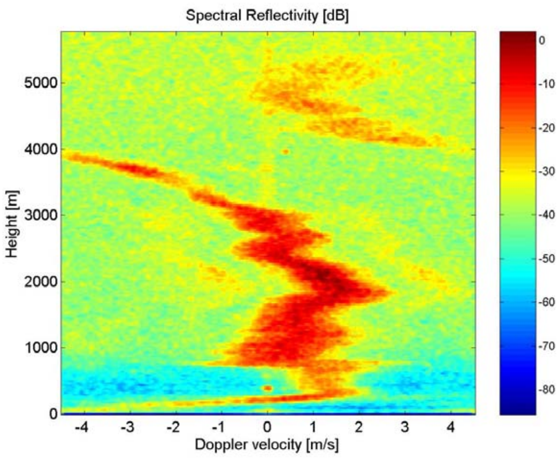

Fig. 3 Slant profile of precipitation: Doppler power spectra.

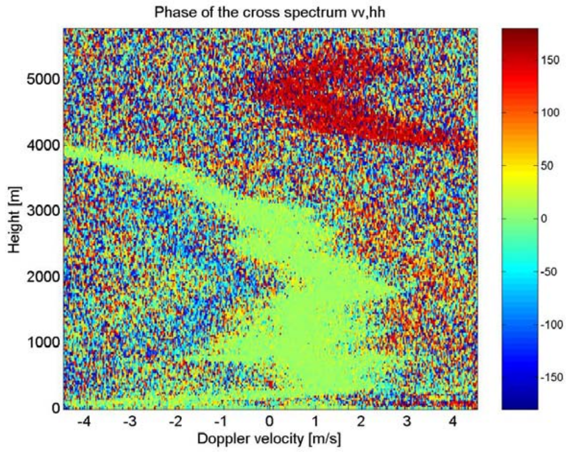

Fig. 4 Slant profile of precipitation: cross-spectrum phase after compensation for the non simultaneity of the measurements *hh* and *vv*. Two main phase values are seen. The green area corresponds to 0 deg. Therefore the related Doppler spectra are not aliased and are well located in [–$V_{D,max}$,$V_{D,max}$[or [–4.5, 4.5[m/s. The red area corresponds to 144 deg., which indicates aliased Doppler spectra, which have to be placed in the interval [–3$V_{D,max}$, –$V_{D,max}$[or [-13.5,–4.5[m/s.

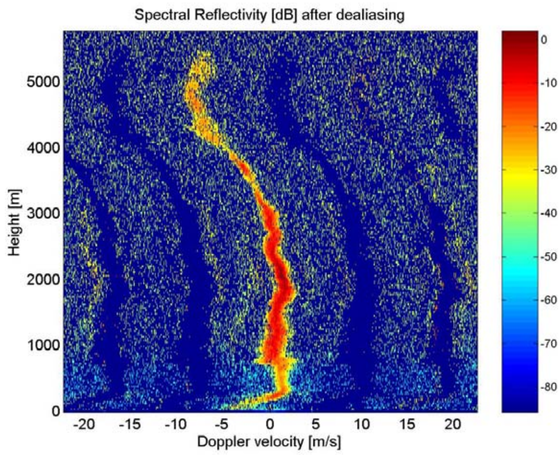

Fig. 5 Slant profile of precipitation: dealiased Doppler spectra. The maximum unambiguous Doppler velocity is increased by a factor 5 (22.5 m/s). The noise is spread in the whole interval [–5$V_{D,max}$,5$V_{D,max}$[due to its random cross-spectrum phase values. The same effect occurs for the clutter, which has generally a mean phase different from 0. By reducing then the Doppler velocity interval of the dealiased spectrograph, noise and clutter reduction is performed.

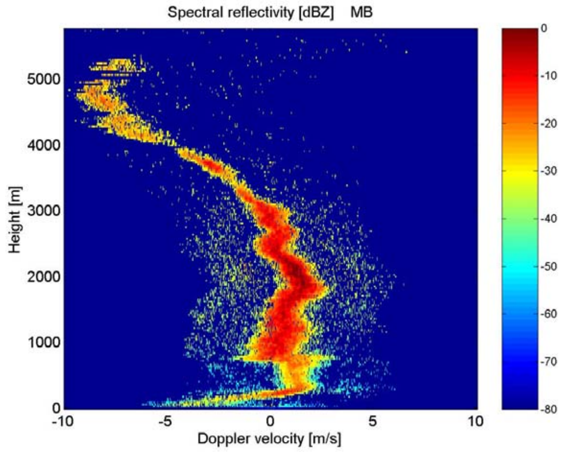

Fig. 6 Slant profile of precipitation: dealiased Doppler spectra with noise reduction and clutter suppression.

Because this measurement is not averaged, the standard deviation of the cross-spectrum phase, σ_ψ which depends on the average number and on the cross correlation coefficient *hh*, *vv*, is rather large. In that case (sequence of 5 different measurements), the standard deviation must not exceed 36 deg., (mean phase $\pm\ \sigma_\psi$). This means that phase ambiguity may occur for targets having a cross correlation smaller than 0.92. Therefore it is better for this case to average two Doppler spectra and cross spectra to decrease the phase ambiguity possibility to targets having a cross correlation smaller than 0.78. We are then sure to keep all the atmospheric information. By suppressing targets with a cross correlation smaller than 0.78, the polarimetric dealiasing technique therefore carries out clutter reduction.

4. DEALIASING OF THE OFFSET BEAMS

The first processing is applied on each Doppler spectrum. The Doppler spectrum is declared folded or not folded searching for significant signal at the edges of the spectrum $\pm\ V_{D,max}$ (the signal is very smoothed and the signal-to-noise ratio considered is larger than 3 dB). An unfolding procedure is then applied on the folded Doppler spectrum using the location of the maximum power of the very smoothed signal.

The second processing is mainly a range continuity procedure of the Doppler spectra and is therefore applied on the spectrograph. The critical part is the search for a reference Doppler spectrum. The standard measurement configuration of TARA will use an elevation angle of 75 deg. and thus OB1 will provide a vertical profiling. We search a cloud Doppler spectrum as reference. From the highest height, the Doppler spectrum, which is expected to be near 0 m/s in that case, not folded, with significant signal and a related Doppler width smaller than 1.8 m/s will be used as a reference. When another elevation angle is selected (generally 45 deg.) for the polarimetric measurements, the mean Doppler velocity profile of the main beam will be used for the reference search. When the Doppler spectrum reference is known, the range continuity procedure can be applied. It uses the cross correlation of the Doppler spectra.

The processing is illustrated in Figs. 7-9. They represent the same precipitation event but now it is a vertical profile. In Fig. 9, the polarimetric clutter suppression to reduce clutter and noise cannot be applied because the offset beam is not polarimetric. Only the Doppler velocity bins with a signal to noise ratio larger than 3 dB (noise reduction) and with a spectral linear depolarization ratio, $Ldr(V_D)$, smaller than -5 dB (polarimetric clutter suppression and noise reduction) are kept, when the measurement is polarimetric.

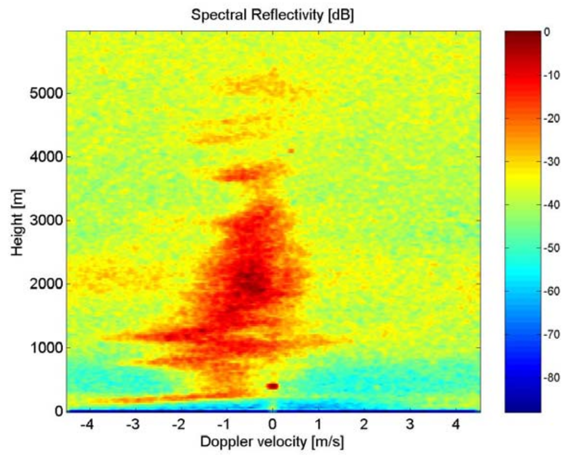

Fig. 7 Vertical profile of precipitation: Doppler power spectra. The melting layer (strongest echo) is around 2000 m. Under the melting layer, there is rain and above the melting layer, a precipitating cloud.

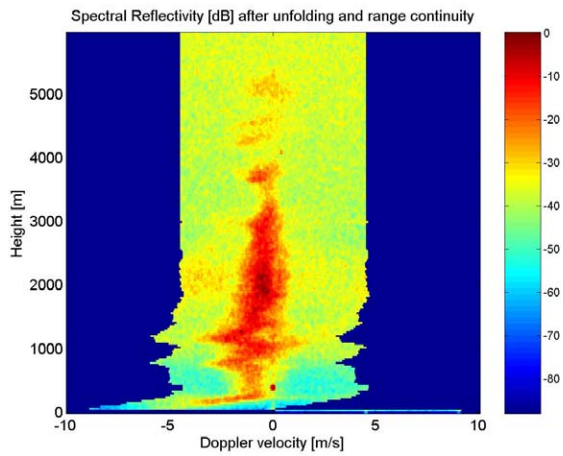

Fig. 8 Vertical profile of precipitation: dealiased Doppler spectra. The range continuity did not operate on the first Doppler spectrum (near field of the radar and clutter) because of its too large Doppler width. From the highest height until 2500 m, the Doppler spectra have been declared not folded.

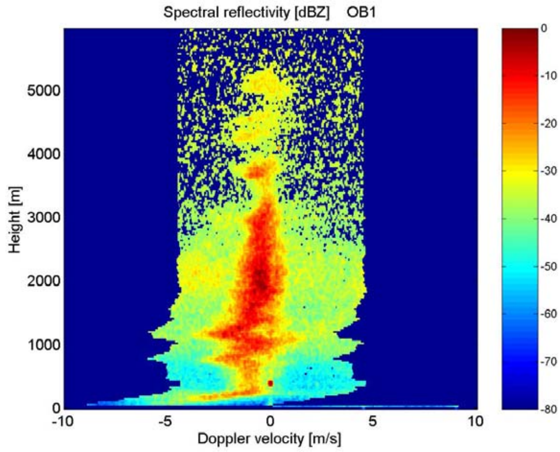

Fig. 9 Vertical profile of precipitation: dealiased Doppler spectra with noise reduction.

5. PROFILING RESULTS

Profiles of the atmosphere are calculated with a high resolution in space (30 m) and time (2.56 s). The time resolution will be decreased to 5.12 s to average two Doppler spectra and cross spectra. The reflectivity (5), the mean Doppler velocity (6), and the Doppler width are obtained for the three beams.

$$Z = a_Z \sum_l \hat{S}_{vv}(l)\hat{S}^*_{vv}(l) \tag{5}$$

$$\overline{V} = \frac{a_Z}{Z} \sum_l \hat{S}_{vv}(l)\hat{S}^*_{vv}(l) V_D(l) \tag{6}$$

The summation is carried out on the Doppler velocity bins with a signal larger than the noisefloor + 3 dB and with a related spectral linear depolarization ratio smaller than -5 dB when the measurement is polarimetric. The constant a_Z is a unit conversion factor from m^2 to mm^6m^{-3}. The vertical polarization is used for the calculation of the reflectivity (5) and mean Doppler velocity (6) because the offset beams are only vertically polarized.

The height values and the height resolution of the main beam are taken as reference. For the two other beams, the reflectivity, mean Doppler velocity and Doppler width are interpolated. Using geometrical transformations, the wind field is calculated. For the moment the vertical Doppler velocity consists of the vertical wind and the fall velocity of the atmospheric targets. There is not yet dissociation. The validity of the 3D wind field in terms of the reflectivity correlation of the three beams has still to be investigated. The polarimetric measurements of the main beam leads to profiles of the differential reflectivity, the linear depolarization ratio and the cross correlation coefficient.

An example of profiles is given below in Figs. 10-17. It is a cloud layer measurement (4.2 mn). One profile is obtained each 2.56 s. There is no average yet on the Doppler spectra.

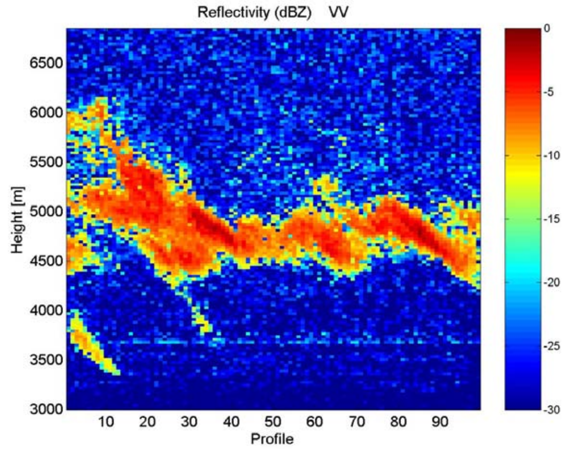

Fig. 10 Slant profile of cloud: Reflectivity (dBZ).

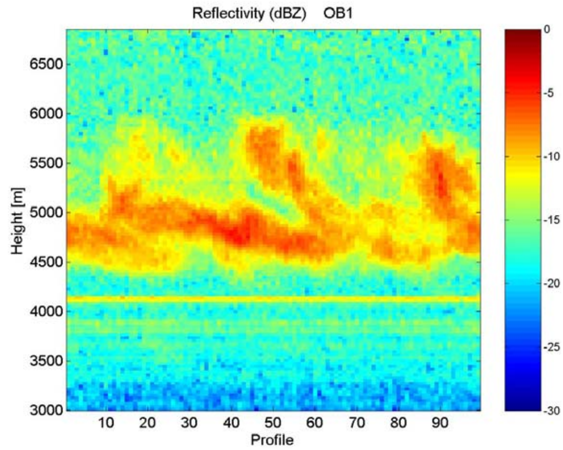

Fig. 11 Vertical profile of cloud: Reflectivity (dBZ). Because the polarimetric clutter reduction cannot be applied for the offset beams, there is more clutter. The noise level is also higher for the offset beams and less reduced.

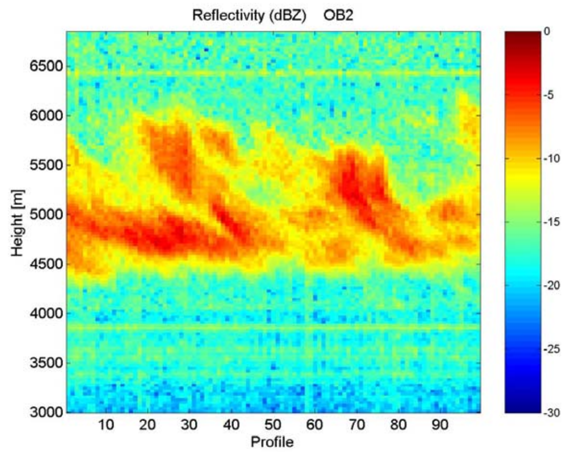

Fig. 12 Slant profile of cloud: Reflectivity (dBZ).

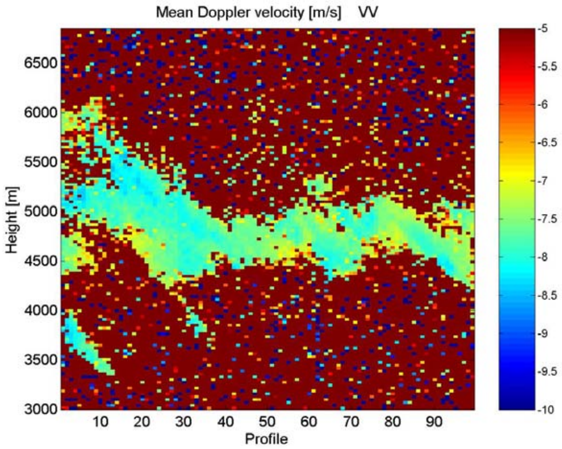

Fig. 13 Slant profile of cloud: Mean Doppler velocity (m/s).

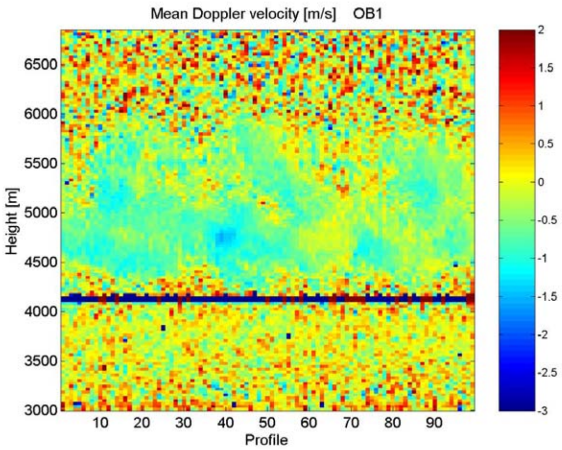

Fig. 14 Vertical profile of cloud: Mean Doppler velocity (m/s). The mean Doppler velocity consists of the fall velocity of the hydrometeors and the vertical wind.

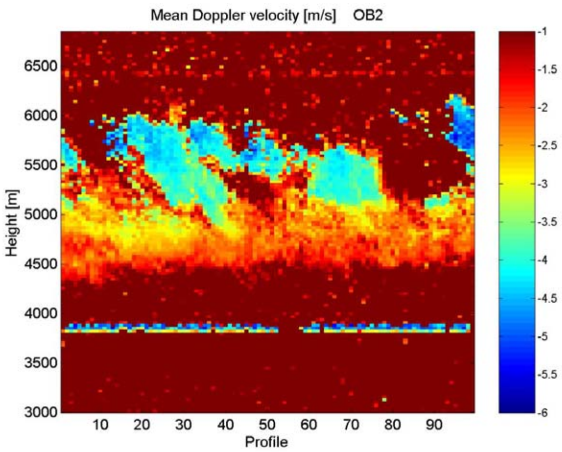

Fig. 15 Slant profile of cloud: Mean Doppler velocity (m/s).

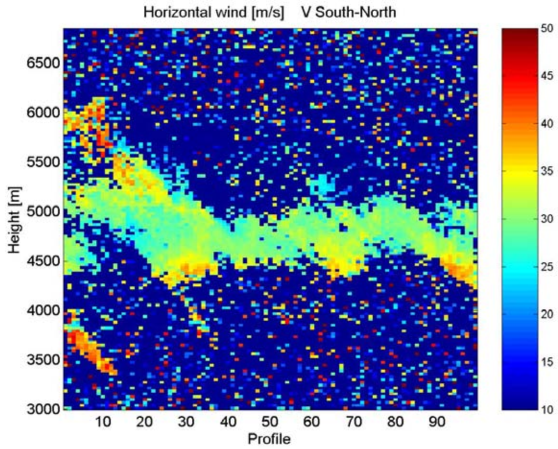

Fig. 16 Horizontal wind South-North (m/s)

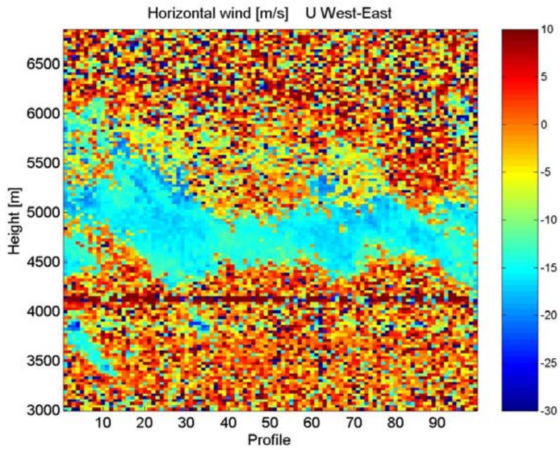

Fig. 17 Horizontal wind West-East (m/s)

6. CONCLUSION

A retrieval method of the three dimensional wind velocity field based on Doppler spectrum and polarimetric measurements is being developed. Because it makes use of multiple beams of a single radar, aliasing problem appears as the main disadvantage of this technique. This disadvantage is enhanced if different polarization acquisitions are added. Therefore the focus of the paper is on solving aliasing problems. We have discussed the worse case scenario, where the sequence of 5 measurements is carried out, with a single measurement time of 1 ms. In this case, the maximum unambiguous Doppler velocity is equal to 4.5 m/s. The polarimetric dealiasing technique gives very good results. As a result the maximum unambiguous Doppler velocity is increased to 22.5 m/s for the main beam measurements. For the offset beams the reference velocity estimation is a critical issue and is still being improved. The terminal fall velocity removal algorithm must be developed to obtain the vertical wind velocity. It is intended to carry out these measurements in real time in the near future.

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