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Boris Radeljic Jakic BSc.
Born in Travnik, Yugoslavia

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Microwave Sensing, Signals and Systems Group
Department of Microelectronics
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology
The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled “Development of Processing Algorithms for the Detection and Estimation of Multi-Layered Structures of a Windfield with Polarimetric Doppler Weather Radar” by Boris Radeljic Jakic BSc. in partial fulfillment of the requirements for the degree of Master of Science.

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Chairman:

Prof. Dsc. O. Yarovoy

Advisor:

Dr. O.A. Krasnov

Committee Members:

Christine Unal

Dr. Yann Dufournet
The Technical University of Delft has started a project in the form of a Master Thesis to improve their existing and develop new algorithms for processing the measured data with the PARSAX radar for 2D-Windfield monitoring. A new algorithm is developed that detects and estimates the multi-layered structure of a windfield using the measured polarimetric Doppler weather data.

It is studied which variables can be used and within which boundaries they will be for the measurement of precipitation targets. The processing of the measured data is improved and higher quality data is obtained. The high quality data is used to make a Velocity Azimuth Display (VAD) and study the pattern of a windfield. An existing algorithm is studied and tested to obtain the direction and strength of the windfield from the VAD. A model is developed that uses the radar configuration and a user divined weather model as input to simulate the Doppler velocity pattern that the radar would measure with this configuration. This model is used to simulate the pattern that would be observed in case of a multi layered windfield, to be used as input for the testing of the newly developed algorithm. The developed algorithm is finally tested on a real dataset. The obtained windfield parameters with the existing and developed algorithm are used as input for the developed Doppler velocity pattern simulation model to compare the simulated Doppler velocity patterns with the measured one. It can be concluded that the existing algorithm has problems and gives wrong results when more windfields are present. The developed algorithm gives more realistic results, retrieving wind characteristics for every vertical layer, and producing high resulting correlation between simulated and observed patterns on VAD.
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Boris Radeljic Jakic BSc.
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5.9 Doppler velocity pattern belonging to the obtained windfield parameters by the algorithm of Lhermitte and Atlas (1961)
Doppler radars have been used since the mid 1950s to study weather phenomena’s that range from clear air to severe thunderstorms (Atlas, 1990). These radars were initially used by the weather research and engineering communities. Later the aircraft industry also used it to monitor wind, with special attention to turbulence, wind shears and wake vortexes in the vicinity of the airport. The information obtained with the Doppler radars would have a great impact on the management of the air traffic.

These radars make use of the Doppler effect to get information on the velocity of a target. Since these radars only measure the radial component of the targets velocity in the direction of the radar, which changes with azimuth angle, elevation angle and time, visual patterns are used to understand the measurements. A horizontal scan is made by the radar to make a well known plan position indicator (PPI) of the measured velocity components. Algorithms are used that process this data to obtain some information about the weather, but because of the complexity nowcasters/forecasters are still needed to interpret these Doppler velocity patterns. There are different models that use predefined weather conditions and then simulate what a radar would measure to study the azimuthal Doppler velocity that would come from it (Brown and Wood (2007) and Bayton (1979)). These models assume that the beamwidth and the vertical fall velocity of observed hydrometeors are equal to zero (in practice, the last assumption can only be correct for very small elevation angles).

The Technical University of Delft has started a project in the form of a Master Thesis to improve their existing algorithms for processing the measured PARSAX radar data for 2D-Windfield monitoring. The PARSAX is a worldwide unique high resolution polarimetric Doppler radar with a flexible, software defined architecture, which can be used in many applications, including real-time atmospheric and ground remote sensing, aerial and ground traffic monitoring, and as information provider and test bed for the development and validation of advanced radar signals and processing algorithms. These algorithms will take care of the filtering of the raw data and the processing of the filtered data to obtain a azimuthal Doppler velocity display, to estimate the azimuthal Doppler velocity pattern that a radar would measure in case of a given radar configuration and presented windfield, and, finally, to detect and estimate a multi-layered structure of a windfield. The algorithm for the detection and estimation of a multi layered structure of a windfield could be used as a warning system for the readers of a VAD to know that the values on the screen are incorrect. This is especially important in cases where this information is used for safety reasons as on airports. The probability of having these problems is present because they typically use fan beams to quickly scan the air for presence of traffic. Further it could be used to get a better understanding of what the radar has measured.
1.1 Signal processing within a Polarimetric Doppler radar

The PARSAX radar makes use of FMCW complex signals to simultaneously measure the elements of the targets’ polarization scattering matrix. To achieve this, two signals with orthogonal modulating waveforms are simultaneously transmitted on orthogonal polarizations, one with a horizontal and the other with a vertical polarization. On parallel reception the two orthogonally polarized scattered signals are supplied to two mixers with two original signals. After the mixing there will be the four scattering elements, two co-polarized \( S_{hh} \) and \( S_{vv} \) and two cross-polarized \( S_{hv} \) and \( S_{vh} \) scattering elements of the observed radar object. In equation 1.1 \( S \) is the scattering matrix and \( h \) and \( v \) are the horizontal and vertical polarization respectively, where the SM-element \( S_{hv} \) means that a vertical signal is transmitted and a horizontal is received.

\[
S = \begin{bmatrix}
S_{hh} & S_{hv} \\
S_{vh} & S_{vv}
\end{bmatrix}
\]

In this section the basics of the FMCW (Frequency Modulated Continuous Wave) principle are explained. The PARSAX radar eventually makes use of a more complex system, but this is to illustrate the principle. The signals that are transmitted will be linearly frequency modulated in time. During the transmission of the signals, backscattered energy is already being received. For this reason two antennas are required, one for transmission and one for reception. The transmitted signal will hit an object and the received signal is delayed by \( \Delta t \) because it is situated at a distance \( R \) from the radar. This is illustrated in figure 1.1a, where the bold line is one of the transmitted signals. The frequency is linearly increased over a frequency range \( F \) (the sweep frequency) during a sweep repetition interval \( T \). The dashed line is the received signal that is delayed by \( \Delta t \). When these two signals are applied to a mixer, the beat signal is obtained as in figure 1.1b. By having a low-pass filter after the mixer there will be a maximum beat frequency that can be obtained. From equation 1.4 it can be seen that this gives restrictions to the maximum range that can be measured.

\[
f_b = \frac{F}{T} \Delta t
\]

\[
f_b = \frac{2F}{cT} R
\]

\[
R = \frac{T c f_b}{F} \frac{2}{2}
\]

Here \( c \) is the speed of light and \( \Delta t = 2R/c \). To get the frequency spectrum of the beat signal a FFT is applied to it and a result as in figure 1.1c is be obtained. With this knowledge the range and reflectivity can be extracted from the frequency and the amplitude of the beat signal respectively. The output of the FFT exists out of 5100 range bins with a resolution of 3m. This resolution is obtained with equation 1.5.

\[
\Delta R = \frac{c}{2F}
\]
Where $F = 50$ MHz, so that a range of approximately 15 km is obtained with these settings. Every bin now contains the amplitude and phase of the received signal at that range.

If a target has a constant velocity the returned signal will also have a constant Doppler shift. This Doppler shift will give an estimation error on the range of the
target (this will not be handled in this thesis). To extract the velocity of the targets, one measurement is insufficient, it can be extracted from the change in return signal phase between the modulation sweeps. To obtain this change in return phase an FFT is used again. The PARSAX radar makes use of 512 sweeps to estimate the velocity. The maximum velocity that can be seen by the radar is calculated with equation 1.6.

\[ V_{\text{max}} = \pm \frac{\lambda}{4T_s} \]  

(Doviak and Zrnic, 1984)  

Here \( \lambda \) is the wavelength for a frequency of 3.315GHz, and \( T_s \) is the sweep repetition interval which equals 1 ms. This gives a maximum velocity of \( \pm 22.6 \text{m/s} \) and according to equation 1.7 a velocity resolution of 0.088m/s, with \( N \) being the number of Doppler cells.

\[ \Delta V = \frac{2V_{\text{max}}}{N} \]  

(1.7)

The output of the FFT now contains information on every range with the velocity of the targets and the reflectivity belonging to it.

By making use of the spectral moments of the Doppler spectrum (Atlas et al., 1973), the mean Doppler velocity and the peak width can be obtained. The total reflectivity that is measured is just the sum of all the reflectivities belonging to every velocity cell. The \( n \)th moment of the Doppler spectrum is then defined as

\[ \langle v^n \rangle = \int_0^\infty v^n Z_v(v) \, dv / \int_0^\infty Z_v(v) \, dv \]  

(1.8)

where if \( n=1 \) and \( n=2 \) the mean Doppler velocity and the Doppler spectrum width are obtained respectively. The variance of the spectrum is then equal to

\[ \sigma_v^2 = \langle v^2 \rangle - \langle v \rangle^2 \]  

(1.9)

This variance can be a measure for the turbulence in the air, but care needs to be taken because with different precipitation the spectrum will also have another shape and variance. Snow will, for example, have a different spectrum than rain, and differences between rain spectra itself with different median drop size distribution can also be expected (Russchenberg and Ligthart, 1989).

1.2 Outline of the thesis

First of all it is explained what the radar is measuring and what variables can be used for the processing of the raw data in chapter 2. Knowing what the properties of the targets that need to be measured are the data processing algorithm is explained. It is wanted that all the noise and other non-wanted targets are filtered out of the data after this filtration process. The high quality data that is available after this process is used in chapter 3 to make a velocity against azimuth display (VAD). This VAD is used by an algorithm that is explained and tested in the chapter to obtain the direction and strength of the windfield(s) present at the moment of measuring. It will
be clear that this algorithm has problems when there are multiple windfields present. To detect these multiple windfields and estimate the structure of them a new algorithm is developed. This algorithm also works with the data from a VAD. It is wanted that this algorithm is first of all tested on a simulated Doppler velocity pattern and later on a real measurement. To obtain a simulated Doppler velocity pattern, for a user defined weather model, an existing simulation model is studied in chapter 4. This model is used by Doppler radar users to study patterns that come from different types of weather. The model is improved and it is explained why the new model is more realistic and what problems can come with the existing one. After this the developed algorithm to detect and obtain the structure of a multi-layered windfield is explained in chapter 5. This algorithm is first of all tested on a modelled Doppler velocity display from the previous chapter. The algorithm is then tested on a real dataset and the thesis work is finally concluded and recommendations are given for future work in chapter 6.
In this chapter a short description about the shape and orientation of a raindrop is given in section 2.1. The SM-elements are used to obtain a number of variables that will differ depending on the observed target. Because the shape of the precipitations particles is known, it can be expected that the value of these variables will have a certain range. This is used to determine if the measured data came from precipitation or not. In section 2.2 these variables and some extra processing steps are evaluated on a real dataset to obtain the best possible processing method, and, finally, the chapter is concluded in section 2.3.

2.1 Precipitation characteristics and Scattering Matrix variables

The shape of a raindrop can be approximated by an oblate spheroid, having an axial ratio of b/a (with b being the minor axis and a the major axis). This ratio will depend on the volume-equivalent spherical diameter of the drop. An accurate description is given by Beard and Chuang (1987) with the shapes given as in figure 2.1 for diameters ranging from 1-6mm. The maximum drop diameter used in literature varies between 6 and 10mm, with 8mm commonly used (Bringi and Chandrasekar, 2001). Knowing this and using the available models by Beard and Chuang (1987), and Pruppacher and Beard (1970), that tell what diameter has what axial ratio, the SM-elements are used to determine if these ratios are exceeded because the signal is reflected from another type of target.

Another important point is the orientation of the drop. When falling in absence of wind shears and turbulence the drops symmetry axis will be vertical. If there exists an airflow relative to the displacement of the drop this will cause a canting angle of the symmetry axis (Brussaard, 1976). This angle is proportional to the inclination of the airflow and the vertical as can be seen in figure 2.2. This angle will depolarize the transmitted signals.

As discussed earlier the SM-elements are used to describe the measured targets. Three of these variables are the Spectral Linear Depolarization Ratio (sLDR), Spectral HV2VH ratio and the Spectral Differential Reflectivity (sZdr). These are defined as
Figure 2.1: Drop shape for an equilibrium drop diameter of 1-6mm (Beard and Chuang, 1987)

\[ s_{LDR_{vh}}(f) = 10 \log \frac{|S_{vh}(f)|^2}{|S_{hh}(f)|^2} \]  
(2.1)

\[ s_{HV2VH}(f) = \frac{|S_{hv}(f)|}{|S_{vh}(f)|} \]  
(2.2)

\[ s_{Z_{dr}}(f) = 10 \log \frac{|S_{hh}(f)|^2}{|S_{vv}(f)|^2} \]  
(2.3)

Where \( S_{vh}(f) \) is the SM-element with a horizontally transmitted and vertically received signal for the used frequency. These variables are spectral because they are defined for every Doppler velocity resolution cell. If they were not spectral they would be related to the mean shape, which is not always representative of the measured particles. To obtain these spectral variables the power Doppler spectra of the related SM-elements are needed. Because these variables are now defined for every Doppler velocity resolution cell it gives us more and detailed information about the shape of the measured targets. Using the reciprocity theorem (Van Bladel, 1985), which states that \( S_{hv} = S_{vh} \) for any observed radar target, the \( s_{HV2VH} \) ratio should thus be equal to unity. This criterion can be used to distinguish weak targets from thermal noise.

Assuming that the maximal drop diameter is 8mm and using the linear formulas of Beard and Chuang (1987), and Pruppacher and Beard (1970) the axial ratio will be greater than 0.53 for rain drops. This will approximately give a maximum \( s_{LDR_{vh}} \) of -15 dB and a \( s_{Z_{dr}} \) of 6 dB according to the models of Bringi and Chandrasekar (2001).
Straka et al. (2000) have used precipitation models which specified characteristics of the hydrometeors such as size distribution, concentrations, shape, orientation, dielectric constant and others with scattering models to compute the backscattering that would be produces by these different hydrometeors. The outcome of these models are also compared with observations made by different radars and the $sLDR_{vh}$ will depend on the precipitation characteristics, but will have a maximum of about -10 dB and the $sZ_{dr}$ will vary between -2 and 6 dB. It can be seen that these results are similar to those of Bringi and Chandrasekar (2001). These criteria can be used for distinguish hydrometeor targets from ground clutter, pointed targets and external interfering signals.

Knowing that hydrometeors will produce these values for the $sLDR_{vh}$, sHV2VH ratio and $sZ_{dr}$, other values outside of these boundaries can be filtered out because they will probably come from other types of targets or noise.

2.2 Processing and filtration choices

In this section the received high resolution data will be filtered based on noise, sLDR, sHV2VH ratio, $sZ_{dr}$, Zero-Doppler and on out-shooters. It will be evaluated if all of these filters are needed and if so, what the best filtering thresholds are. These thresholds should be chosen carefully, because if they are too high, valuable data will be filtered out, and if they are too low there will be interference from thermal noise and other types of targets in the data. To avoid the problem that these thresholds are perfect for
one particular dataset and wrong for the rest of the measured data, 8 different sets are taken from one circular scan and the thresholds that have the best impact on the most of these sets are used. With a dataset it is meant, the data that is measured for one particular angle, of all the measured angles from the circular scans. The thresholds are tested on 8 different angles that are equally separated from their neighbouring angles. To get a good impression of how well the filtering worked, the mean velocity and the standard deviation are plotted over the original image. If the thresholds are correct, the mean velocity will be in the centre of the good data, and the standard deviation will enclose it. If this isn’t the case the mean velocity will be incorrect and the standard deviation will be much wider or narrower, because it takes other targets and noise, or doesn’t take enough data into consideration. On following figures the mean Doppler velocity is plotted with black dots in the range cells and the Doppler width is plotted with white dots. The Doppler width is expressed as the width between \( \mu_v - \sigma_v \) and \( \mu_v + \sigma_v \). Where \( \mu_v \) is the mean velocity and \( \sigma_v \) the standard deviation of the velocity.

As discussed earlier, a range-Doppler plot is made for one particular angle (one dataset). In this plot it will be visible what velocity components are present in a range cell and what the reflectivity of these components are. The range-Doppler plot for the unprocessed data can be seen in figure 2.3. It can be seen that there is a strong zero-Doppler component and that there are high reflectivities of precipitation below 3km with a positive Doppler, and some precipitation around the zero on the higher ranges. It can also be seen that there is another target on approximately 2km with a Doppler velocity of -15m/s. When the mean velocity and the Doppler width are plotted on the image as in figure 2.4 is can be seen that the mean velocity is as one would expect around the strong zero-Doppler component and the width is very wide because the noise and the other targets are still present in the data.

The next step is that the user would like to know what the noise in the figure is and what the other targets are. For this the Signal to Noise Ratio (SNR) (which is defined as in equation 2.4) is plotted in this image rather than the reflectivity. It tells one with what fraction the measured signal is greater than the measured noise. For this the noise power needs to be known first. This is measured with the radar by having it only in receive mode to measure the atmospheric noises. In figure 2.5 the range-Doppler plot is available, but this time with the SNR plotted. The mean velocity and Doppler width of this image can be seen in figure 2.6

\[
\text{SNR} = \frac{\text{Signalpower}}{\text{Noisepower}} \tag{2.4}
\]

From figure 2.5 it can be seen that there are some out-shooters present that make the image unclear because of the great diversity on reflectivity (approximately from -70 to 100dB). These out-shooters are lowered to a maximum value so that a better image is obtained. First of all the histogram of the data is studied in figure 2.7. A lower value is set to 0dB because it is wanted to know what signals are stronger than the noise that is measured and based on the histogram a upper value is set to 40dB. The result of processing these out-shooters on the range-Doppler image and its mean Doppler velocity and width can be seen in the figures 2.8 and 2.9 respectively. It can be seen that the user already has a good idea of what the precipitation looks like after
these processing steps.

Next the noise is filtered out of the data. As seen earlier the noise is measured by
having the radar only in receive mode, and the noise threshold is simply the mean of these measured signals. The filtering threshold for the noise is set to 5 times the noise
threshold to get rid of as much as possible noise without filtering out the precipitation data. The result of this filtration step can be seen in figure 2.10. It can be seen that
almost all the noise is out of the image, except for the target that is still present at -15m/s. In figure 2.11 one sees that the quality of the data has been improved with a great amount. It can also be seen that the Doppler width is too narrow. This is because the strong zero-Doppler component is still present in the data. The other filtration steps that are left should take care of the other targets and the zero-Doppler to improve the quality of the data further.

Now the Zero-Doppler velocities are filtered out because their reflectivity is too high, which is a cause a of totally wrong mean velocity and narrowing of the Doppler width. The result of adding this filter to the previous processing steps can be seen in the figures 2.12 and 2.13. It can seen that the Doppler width is now enclosing the precipitation data (except for the part where the other target is present).

Finally the $sZ_{dr}$, $sHV2VH$ ratio and sLDR filtering are evaluated. In figure 2.14 the effect of using a sLDR filter is shown. It can be seen that the target at -15m/s and the rest that was left of the strong reflectivity at the lower altitudes are filtered out successfully. It also looks like that a great amount of the good data is filtered out, but when figure 2.15 is studied it can be seen that the mean velocity and the Doppler width that belong to this data are as wanted: A positive Doppler for low ranges, and Doppler velocities around zero for higher ranges. The Doppler width is also as expected enclosing the precipitation for the greatest part of the data. The sLDR threshold was set to -12dB (which was expected as seen in section 2.1). A possible solution to filter out less of the good data is to make a mask of the resulting image and place this above the data that was used before this step as a filter. For this morphological filtering can be used to fill holes and to filter out the rest of the noise (Zheng et al., 2004).
Figure 2.10: Noise filtered data with a threshold of 5 times the noise threshold

Figure 2.11: Mean velocity and Doppler width of the noise filtered data

The $sZ_{dr}$ and $sHV2VH$ ratio are also considered and they also filter out small parts of the unwanted data. They are not used because the unwanted data that they have
Figure 2.12: Noise + zero-Doppler filtered data with a threshold of 5 times the noise threshold

Figure 2.13: Mean velocity and Doppler width of the noise + zero-Doppler filtered data

filtered out are also filtered out with the sLDR-filter. If the sLDR-filter is used in combination with one of these filters only an extra amount of good data is lost. For
Figure 2.14: Noise + zero-Doppler + sLDR filtered data with a threshold of 5 times the noise threshold and an sLDR threshold of -12dB

Figure 2.15: Mean velocity and Doppler width of the noise + zero-Doppler + sLDR filtered data
this reason the data is not filtered on the $sZ_{dr}$ and $sHV2VH$ ratio.

2.3 Conclusion

A better understanding, of what the radar is measuring and within which boundaries the values of the obtained SM-element variables will be, is obtained. The existing processing algorithm is improved by using different filtration steps and having different thresholds. The high quality data, obtained with this processing algorithm, will be used in the next chapter to make a Doppler velocity azimuthal image, which is needed for the algorithms that will obtain the wanted windfield parameters.
Estimation of the windfield parameters

In this chapter the filtered and processed data is used for further signal processing to obtain the wanted parameters of the windfield. First of all two different methods are explained in section 3.1 and one of these methods is chosen for the algorithm that will be used. This algorithm is then tested in section 3.2 on the measured dataset to obtain the wanted windfield parameters from it. And finally, this chapter is concluded in section 3.3.

3.1 Theory and algorithm

In the literature there are two methods that are commonly used for the estimation of windfield parameters with the help of radar data. As discussed before, a radar only measures the radial velocity of a target. To get an understanding of how the windfield looks the users needs to look at azimuthal patterns. These patterns are obtained by rotating the radar about a vertical axis at a fixed elevation angle as in figure 3.1, where $\alpha$ is the elevation angle and $\beta$ the azimuth angle of the scan. $V_r$ is the obtained radial velocity, which depends on the elevation angle, the fall speed of the particles ($V_f$), the horizontal speed of the particles ($V_h$) and the direction of the wind w.r.t the x-axis ($\theta$).

Lhermitte and Atlas (1961) described a method that could be used in widespread precipitation cases to obtain the wind speed and direction from it when the wind and fallspeed are horizontally homogeneous. As the radar rotates it makes an image of radial velocity measured of the falling precipitation (wind) against azimuth. This image is called a Velocity Azimuth Display (VAD). They have described that the mean radial velocity of the wind is a sine function of the azimuth. This is also illustrated in figure 3.2. If the wind is heading away from the radar (at $\theta = 0$) the radial velocity will be negative. It will on the other hand be positive when the wind is heading towards the radar ($\theta = \pi$). When the radar beam is pointing perpendicular to the wind direction ($\theta = \frac{\pi}{2}$ and $\theta = \frac{3\pi}{2}$) the radial velocity will be 0. With this information the wind direction can be obtained. The speed of the wind is hidden in the amplitude of the sine function. Later, Browning and Wexler (1968) extended these ideas and showed that a VAD could also be used when the wind isn’t linear horizontally. The divergence, deformation and dilatation could also be obtained.

The second method is developed by Waldteufel and Corbin (1979) and is called Volume Velocity Processing (VVP). It makes the same horizontal scans around a vertical axis as the VAD, but it makes these scans for multiple elevation angles. With this scanning procedure a volume is scanned. If these data are recorded they can be processed simultaneously if the acquisition time is short enough. The data belonging to the same narrow range of altitudes of the volume is processed at once. With this method there will be more data available for the calculation of the windfield parameters.
Figure 3.1: Schematic of a vertical VAD scan with x, y and z being the coordinate system. α the elevation angle of the radar, β the azimuth angle and θ the angle the wind makes with respect to the x-axis. \( V_r \), \( V_f \) and \( V_h \) are the radial velocity, the fall velocity and the horizontal velocity respectively.

Figure 3.2: Up-view of the schematic during the measurement, with the direction of the wind shown and the mean radial velocity (sine function) of the wind for this situation.

per height layer. Having this extra data per height layer, the horizontal mean windfield is obtained without any contamination of any altitude or elevation angle.

One of the objectives of this Thesis is to study the existing methods of simulating
Doppler velocity displays that a weather radar would produce during a measurement and make a new improved model for it. The existing models simulate the displays for the measurement at a single elevation angle, and it is explained what problems can come with these simulation methods and how these are improved. The new model and algorithms are finally tested on a real dataset. Besides that, Waldteufel and Corbin (1979) have concluded from simulations of the VAD and the VVP method that the errors made in the horizontal windfield are similar. Because the horizontal wind parameter is wanted and one elevation angle is used the VAD will be used.

Knowing that the VAD will be used, this method is now studied further. When the direction of the wind with respect to the x-axis is taken to be 0, there will be a wind parallel to it and the side-view of the schematic will look as in figure 3.3. Studying this image the radial velocity is the sum of the projection of the fall velocity and the horizontal wind velocity on the radars looking direction and can be expressed as in equation 3.1. Taking the dependency of the fall speed $V_f$ and the horizontal speed $V_h$, to the azimuth angle $\beta$, direction of the windfield with respect to the x-axis $\theta$ and the elevation angle $\alpha$ into account equation 3.2 is obtained. The equation is further rewritten in the form of the $V_x$ and $V_y$ component in equation 3.3.

$$V_r = V'_f - V'_h \quad (3.1)$$

$$V_r(\beta) = V_f(\beta) \sin \alpha - V_h(\beta) \cos(\beta - \theta) \cos \alpha \quad (3.2)$$

$$V_r(\beta) = V_f(\beta) \sin \alpha - V_x \cos \alpha \cos \beta - V_y \cos \alpha \sin \beta \quad (3.3)$$

Equation 3.3 can be decomposed into a Fourier series in the form of

$$V_r = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} (a_n \cos n\beta + b_n \sin n\beta) \quad (3.4)$$

and providing that the windfield per range and fall speed are horizontally homogeneous,
the non-zero Fourier coefficients are given by

\[ a_0 = 2V_f \sin \alpha \]  
\[ a_1 = -V_x \cos \alpha \]  
\[ b_1 = -V_y \cos \alpha \]  

These coefficients can for example be computed for the case that every 10° a measurement is conducted by

\[ a_0 = \frac{1}{18} \sum_{i=1}^{36} V_{R_i} \]  
\[ a_1 = \frac{1}{18} \sum_{i=1}^{36} V_{R_i} \cos n \beta_i \]  
\[ b_1 = \frac{1}{18} \sum_{i=1}^{36} V_{R_i} \sin n \beta_i \]

Having the Fourier coefficients, the wind speed is obtained with equation 3.11 and the direction of the windfield with the equations 3.12 and 3.13, depending on the coefficient \( b_1 \).

\[ V_h = -\sqrt{\left(\frac{a_1^2 + b_1^2}{\cos \alpha}\right)} \]  
\[ \theta = \frac{\pi}{2} - \tan^{-1}\frac{a_1}{b_1}, \text{when } b_1 \text{ is negative} \]  
\[ \theta = \frac{3\pi}{2} - \tan^{-1}\frac{a_1}{b_1}, \text{when } b_1 \text{ is positive} \]

Using this method to obtain the wind direction and speed it should be known that there are some points of attention because of errors that can be made. Until now it is assumed that the fall speed of the particles is horizontally homogeneous. This isn’t always the case because of two reasons. It is due to variations in the vertical air velocity and variations in the shape and width of the terminal fall speed spectrum of the precipitation. Rain will, for example, have a wider spectrum than snow. This will induce an error in the fall speed that induces an error in the horizontal speed that is obtained. For this Browning and Wexler (1968) mention that in the presence of extreme fall speed variations the elevation angle should be kept low. \( \alpha < 27^\circ \) for snow and \( \alpha < 9^\circ \) for rain. Another source of error it that the elevation angle isn’t constant, by which different heights are measured. For this reason it is important to have a constant elevation angle. The absolute accuracy of \( \alpha \) isn’t important, but how constant \( \alpha \) remains during the scan. Finally an error can also be induced by the inhomogeneities in the reflectivity distribution because the mean radial velocity is in favour of the velocities that have the highest reflectivity.
3.2 Test on real data

The algorithm is tested on real data in this section. The data used was measured with the PARSAX radar of the TU-Delft on 2011-10-12 at 08:27 AM. The radar is located at a height of 92m and an elevation angle of 2° was used. The range resolution of the radar is 3m and the maximum range is 15km. The radar rotated clockwise with a speed of 30° per min., the measurement took 12 min. and began at −10° to 350° from the perspective of the North.

The mean velocity of the Doppler spectrum for every rangebin and every azimuth angle is obtained with equation (1.8) from the filtered data as seen in chapter 2. The velocity data is first of all studied because it still has to be filtered for outshooters. Studying the histogram of the velocity data in figure 3.4, the thresholds for the minimum and maximum velocity are set to -4 and 4m/s respectively. The values that exceed these thresholds are lowered to it. Using this filtered Doppler velocity data a VAD as in figure 3.5 is obtained.

![Histogram of Doppler Velocity component $V_{hh}$](image)

The center of the image is where the radar was located and as can be seen there is a North-Western wind present in the vicinity of the radar. It also looks like there is another layer of air above this first layer which looks like a wind from the East. In the figures 3.6a, 3.6b and 3.6c three successive images of the Buienradar (2011) are shown from which the lower windfield is very clearly seen, and it can also be seen that the outer parts of the clouds are moving slowly to the South-West. With this check it can be seen that the VAD obtained with the filtered data gives a correct image of the movement of the precipitation at that particular moment. From the images of the Buienradar (2011) it can also be seen that the rain cover was not completely homogeneous, which could explain the holes that were also present in the PARSAX’ VAD. These holes could give a problem to the algorithm that is used.
The data is very complete up to a range of approximately 5km. Beyond it the holes are present. The algorithm is extracted and the direction and speed of the wind with respect to range can be seen in the figures 3.7 and 3.8 respectively. Even with the presence of the holes, the extracted direction is as expected for the greatest part of the image. Up to 5km a North-Western wind has been present and further than 9km there was approximately a wind from the East. The jump in direction at 8km isn’t
really a jump because it jumps from 0 to 360°, which is, actually, the same direction. For the range between the two windfields that can be seen clearly it can be seen that the direction shifts from the first to the second one. It is hard to see this shift in the VAD image because of the holes in the data. If this, what looks like a logical shift, is correct, the algorithms is extremely useful because the direction of the wind isn’t clear for the user due to the great amount of holes that are present in that range segment.

The algorithm was also applied on another dataset, which is not shown in this report, and it can be concluded that the direction that is obtained with the algorithm is very accurate for both datasets without spatial holes in the data. Even when such holes are present, the algorithm gives a result that is expected. The obtained windspeed is probably correct for the first windfield. For the second windfield, it is probably incorrect because the magnitude of it is obtained by using the strength of the mean velocity of both the windfields that are present in the data. Even from the VAD it can be seen that the windspeed is not equal to a speed of less than 0.5m/s.

Figure 3.7: Extracted wind direction with the VAD-algorithm. The direction is read clockwise with respect to the North and is the direction to which the wind is blowing.

Figure 3.8: Extracted wind speed with the VAD-algorithm.
3.3 Conclusion

In this chapter two different methods, that can obtain the parameters of a windfield, are studied. A choice is made to use one of the methods, and this method is studied further. The algorithm is tested on a real measurement and the direction and strength of the windfield are obtained from it. The estimated direction is compared to images of the Buienradar (2011) which showed the same results. It is also explained why the algorithm has problems with multiple windfields. An algorithm is needed that can deal with these problems. This algorithm needs to be tested on a simulated Doppler velocity azimuthal image. For this an existing Doppler velocity pattern simulation model is studied and improved in chapter 4.
In this chapter an existing model is studied which simulates the Doppler velocity pattern that a radar would measure for a given weather model in section 4.1. In section 4.2 this simulation model is improved and it is showed why the current model gives problems. It will be shown what effect multiple windlayers, the elevation angle and beamwidth of the radar have on the obtained pattern that the radar would measure. With this it will also be explained why and for which conditions the algorithms of chapter 3 will not work to estimate the windfields direction and strength. The chapter is finally concluded in section 4.3.

### 4.1 Current model

Brown and Wood (2007) have made a guide to help Doppler radar users become proficient in pattern interpretation through the use of simulated patterns that represent air flows in clear air and widespread precipitation. The simulations are said to be based on analytical functions similar to their earlier work (Wood and Brown, 1986). These functions are similar to equation 3.3, with the difference that they neglect the fall velocity because a low elevation angle is used. The other assumption is that the radar’s beamwidth is set equal to zero.

An example of a pattern that would be obtained, in case of the vertically stratified windfield with two layers, which have different wind directions, is given with this model. In figure 4.1 one can see the wind profile on the left with two windfields having a difference of 180° in direction. The right part of the figure shows the corresponding azimuthal Doppler velocity pattern that would be obtained. From the figure it is clear that there are two windfields present with opposite wind directions.
Figure 4.1: Doppler velocity pattern (right) corresponding to a vertical wind profile (left) through a discontinuity between two wind regimes that differ by 180° (Brown and Wood, 2007)

4.2 New model

The new model, which has been developed in the framework of this project, is taking the beamwidth and elevation angle of the radar and the fallspeed of the precipitation into account. The model is written for the case of two vertical windfield layers, where it is assumed that the first windfield is present up to a certain height and the second field will be present above it. In the figures 4.2 and 4.3 different configurations are shown that could have been used during a measurement. The arcs show the ranges within the radar beam that have both windfields within the scanned volume. Because of the possibility that more windfield layers can be present in the beam and because of the fact that the mean velocity of the targets is plotted in the VAD, the pattern that is obtained can give confusing results. It can also be seen that the amount of rangebins that will give confusing results is dependant on the beamwidth, the elevation angle, layers’ height and the direction and magnitude of the windfields.

The developed model is used to simulate the Doppler velocity pattern, that would be measured with the radar, having the configurations of the figures 4.2 and 4.3. It will be seen how the pattern depends on the variables that are added to the new model. The lower windfield for all the simulations will be a wind from the East with a strength of 4m/s and the upper windfield will be a wind from the West with the same strength. The height of separation will be set to 3000m and a fall velocity of 3m/s is used.
The first example can be seen in figure 4.4. This figure corresponds with the configuration of figure 4.2a which uses a pencil beam with a low elevation angle. Because the radars beam is only present in the lower windfield the obtained pattern will only contain the lower windfield. The next example can be seen in figure 4.5. This figure corresponds with the configuration of figure 4.3a which uses a pencil beam with a higher elevation angle. If one studies figure 4.3a it is expected that there will be a small region where the beam of the radar is filled by both windfields. The mean velocity in this part of the beam will give confusing results. This can also be seen in the pattern at approximately 7km, where the image tells that there is no wind present. The next example uses the configuration of figure 4.2b with a fan beam and a low elevation angle. The pattern that belongs to this configuration can be seen in figure 4.6. It can be seen obviously that for further ranges the VAD gives totally wrong results. This is because the beam is filled for a large part with great amounts of both windfields. The final example uses the configuration of figure 4.3b with a fan beam and a higher elevation angle. The pattern that belongs to this configuration can be seen in figure 4.7. Compared to the pattern of the previous example this one gives more information about the upper windfield because of the higher elevation angle that is used. The magnitude of
the windfields is still wrong because the mean is plotted in the image. From these four
simulated patterns it can be seen how important it is to take the beamwidth and the
elevation angle of the radar into account. The studied patterns will as seen depend on
it and if this is not taken into account by the readers of a VAD image, wrong conclusion
can be extracted from it.

Figure 4.4: Doppler velocity pattern corresponding to a vertical wind profile with a lower
wind coming from the east and a upper wind coming from the West with both having a
strength of 4m/s. The beam that is used is a pencil beam of 2.5° with a centre at 2°

Figure 4.5: Doppler velocity pattern corresponding to a vertical wind profile with a lower
wind coming from the east and a upper wind coming from the West with both having a
strength of 4m/s. The beam that is used is a pencil beam of 2.5° with a centre at 25°
Figure 4.6: Doppler velocity pattern corresponding to a vertical wind profile with a lower wind coming from the east and an upper wind coming from the West with both having a strength of 4 m/s. The beam that is used is a fan beam of 30° with a centre at 15°.

Figure 4.7: Doppler velocity pattern corresponding to a vertical wind profile with a lower wind coming from the east and an upper wind coming from the West with both having a strength of 4 m/s. The beam that is used is a fan beam of 30° with a centre at 25°.

To simulate these results, a 3D-windfield is written which will be used to describe the windfields that are present and the fallspeed of the precipitation. It is assumed that the wind and the fallspeed are linearly homogeneous with height and that every drop has the same RCS. The user will define the elevation angle and the beamwidth of the radar. The algorithm will now simulate what a radar would measure with this configuration and weather.
To get these results, first of all a 3D-grid is made with a maximum range of 15km and a resolution of 3m in the x, y and z-direction. Every point in this grid describes the direction and magnitude of the wind at that location. Ideally an algorithm can be made that makes a horizontal scan and calculates if a certain point is within the beam for every rangebin. All the points that are within the rangebin are added to get the radial velocity that a radar would measure in a real measurement. Because this takes too much memory and simulation time an alternative is used. This alternative uses the information that is available of the conducted measurement (elevation angle and beamwidth) to simulate the amount of grid-points (number of scatters) that are within every rangebin. The simulation of what the radar would measure is completed on the following principle: First of all the wind direction is described with help of the map that can be seen in figure 4.8a. The wind is coming from the angle that is given, so 0° mean a Northern wind. The strength of the wind and the fallspeed are given as the speed in m/s and the direction that the radar is pointing to is given by $\beta$. Because the radial velocity, even in the same wind layer, depends on the height (as can be seen in figure 3.3), the rangebins are divided in smaller cells as in figure 4.8b to obtain the radial velocity of each height cell independently. In this figure $\alpha$ is the angle that the centre of the height cell makes with the horizontal.

Figure 4.8: a) Map used to describe from where the wind comes and which angles to use for it, $\beta$ is the direction the radar point to b) Side view of radar beam with a rangebin divided in vertical height cells to obtain the radial velocity per height cell, $\alpha$ is the angle the horizontal makes with the centre of a height cell

Having this information the obtained radial velocity is described by equation 4.2.
\[ V_r = \sum_{1}^{n} V_{rh} \]  \hspace{1cm} (4.1)

\[ V_r = \sum_{1}^{m} mV \sin(\beta + \phi) \cos(\alpha) + mV_f \sin(\alpha) \]  \hspace{1cm} (4.2)

With \( V_r \) being the radial velocity of one rangebin, \( V_{rh} \) the radial velocity in a height cell, \( n \) the number of height cells in a rangebin, \( m \) the number of scatterers in one heightcell (number of gridpoints), \( V \) the wind strength, \( V_f \) the vertical fallspeed and with \( \phi = 90 - \beta \). To get the average velocity: \( V_r \) is divided by the number of scatters that are in the rangebin (simulated number of grid-point for the used beam). Using this and having \( \beta \) go from 0-360 an image as in figure 4.6 can be obtained. From this image it is also obvious that the sine function that could be seen with a VAD for a certain wind isn’t always present. This means that the algorithm of chapter 3 will not work for the ranges that are drastically changed because of multiple windfields in the same beam.

### 4.3 Conclusion

In this chapter an existing model for simulating Doppler velocity patterns is studied and improved. The dependency on the beamwidth and the elevation angle of the radar and the fall speed of the hydrometeors are added to the simulation model. The developed model shows how the measured velocity pattern depends on these variables. This also shows the importance of an algorithm that is needed to detects and estimates the presence of a VAD that contains multiple windfields. The improved model will be used in chapter 5 to obtain a Doppler velocity pattern of a multi layered windfield as input for the algorithm that will be estimating the structure of it.
Algorithm for the detection and estimation of the multi-layered structure of a windfield

In this chapter the algorithm that needs to detect and estimate the structure of a multi-layered windfield configuration is explained at first in section 5.1. Then the Doppler velocity simulation model of chapter 4 is used to get the Doppler velocity pattern that would be obtained by the radar during a measurement with a multi-layered windfield configuration. This modelled pattern will then be used as input for the algorithm to be tested in section 5.2. The algorithm is tested on a real dataset in section 5.3 and the chapter is finally concluded in section 5.4.

5.1 The algorithm

Having a Doppler velocity pattern, the direction and strength of the windfields and the height separation of the two fields can be obtained. For this at least two datasets of two different looking directions of the whole Doppler velocity display are needed. This is explained with figure 5.1b: If the wind is heading in the direction of $V_1$ and the radar points to the East it will only measure $V_{1x}$. If on the other hand the radar points to the North it will only measure $V_{1y}$. By combining these two results the magnitude is obtained by equation 5.1 and the direction is obtained by looking from which quadrant the wind is coming and using simple geometry rules.

$$V_1 = \sqrt{V_{1x}^2 + V_{1y}^2}$$  \hspace{1cm} (5.1)

To estimate $V_1$, first $V_{1x}$ and $V_{1y}$ need to be known. If a dataset is used where the radar points to the East as in figure 5.1a an image as below it can be obtained. From this image it can be seen what the radial velocity of the lower windfield ($V_{1x}$) is and up to which point it is present. This can be seen because the windfield will stay constant up to that point because it is the only windfield present in the radars beam. From that point on the second windfield is present in the radars beam and the radial velocity that can be seen in the Doppler velocity display is the mean of those two fields. Knowing this point also means that the height at which the second windfield starts is known. By now using the Doppler velocity pattern simulation model and the data that is now known of this multi-layered windfield (radars beamwidth, elevation angle, height of separation between the two fields and the radial strength of the first windfield in the looking direction) the radial strength of the second windfield can be obtained by iteratively changing its strength until it gives the same curve and end value as the measured one. This process needs to be done for one more angle as explained earlier to
Figure 5.1: a) Map of the wind directions (up) and an estimation of what the radar would measure when it is pointing in the direction of the bold arrow (down) b) Windmap with $V_1$ being one windfield, and $V_{1x}$ and $V_{1y}$ the x and y component of this field respectively

obtain the radial components of the windfields. By using equation 5.1 the magnitude of both the fields are extracted and the direction is obtained as explained before by looking from which quadrant the wind was coming and using simple geometry rules.

Depending on what elevation angle and what kind of beam is used the fall velocity of the particles will change the value of the measured radial velocity with an amount which is not coming from the wind. Compensations should be added to this model that depends on the fall speed. A vertical scan can be made to obtain the fall speed at the moment to compensate for the radial velocity that is added to the measured velocities by the falling particles. There are also other existing methods to obtain the fallspeed.
by Lhermitte (1961) and Harrold (1966), but these are not handled in this thesis.

5.2 Testing algorithm on simulated Doppler velocity pattern

In this section one of the tests that is conducted on the algorithm for a modelled Doppler velocity pattern with a configuration of a multi-layered windfield is shown. A pencil beam of $2.5^\circ$ with an elevation angle of $2^\circ$ is used. The lower windfield is coming from the East with a strength of 4m/s and the upper windfield is coming from the North with a strength of 7m/s. The height of separation is set to 450m and the fall velocity is 3m/s. The simulated Doppler velocity pattern belonging to this configuration can be seen in figure 5.2. Studying this image it is again clear what the direction and strength of the lower windfield are. The algorithm is used on the dataset when the radar pointed to the East and to the South to obtain the direction and strength of both the windfields and the height of separation. The simulated radial velocities of the radar when it pointed to the East and to the South can be seen in the figures 5.3 and 5.4 respectively. When figure 5.3 is studied one first of all sees that the radial velocity of the first windfield is approximately equal to 4m/s as expected. The next thing that can be seen is that the second field comes into the beam at a range of approximately 8km. With equation 5.2 the height of separation is obtained.

$$H_{sep} = R_{2nd} \times \sin(\alpha + \theta/2)$$ (5.2)

Where $H_{sep}$ is the height of separation between the two windfields, $R_{2nd}$ the range at which the second field comes into the beam, $\alpha$ the elevation angle and $\theta$ the beamwidth of the radar. The radial velocity of the first windfield and the $H_{sep}$ in the dataset to

![Figure 5.2: Doppler velocity pattern corresponding to a vertical wind profile with a lower wind coming from the East with a strength of 4m/s and a upper wind coming from the North with a strength of 7m/s. The beam that is used is a pencil beam of $2.5^\circ$ with a centre at $2^\circ$ radian pointed to the East and to the South to obtain the direction and strength of both the windfields and the height of separation.](image-url)
the East are used in the Doppler velocity simulation model with a changing second windfield to obtain the same curve and end value for the radial velocity as the original image. The same process is done for the dataset when the radar points to the South and the obtained direction and strength for the first and second windfield are $91.2^\circ$ with a strength of 4.0m/s and $359.2^\circ$ with a strength of 7.2m/s respectively. The obtained height of separation was 455m. From these results it can be seen that the algorithm gives the correct results with a small error.

![Figure 5.3: Radial velocity when the radar points to the East](image)

![Figure 5.4: Radial velocity when the radar points to the South](image)
5.3 Testing algorithm on real dataset

In this section the algorithm is tested on a real dataset. The pattern of the real measurement can be seen in figure 5.7. It can be seen that there is a lower windfield coming from approximately the West and a upper windfield coming from approximately the East. From the obtained directions in figure 3.7 it can be seen that there is a shift from the lower windfield to the upper one. This could be a real measured shift in the windfield or because of the plotted mean of both the fields that are present in the radars beam. When one studies the range-Doppler image from figure 2.8 it is also clear that after a range of 5km two windfields with an opposite Doppler velocity are present. Because the mean velocity is plotted in the VAD, confusion can come from it.

The datasets that are used for the algorithm are chosen carefully because there are big holes in the data. The datasets are chosen for the directions of $140^\circ$ and $230^\circ$ because of the completeness of the data at those looking directions. The radial velocity and the smoothed version of it for the first dataset can be seen in the figures 5.5a and 5.5b respectively. The same figures are available for the second dataset in the figures 5.6a and 5.6b. Studying these images it can be seen that the perfect straight line that was expected for the lower windfield is not present in the Doppler velocity plot. The velocity plots also don’t have a common point where the second field comes into the beam. In this thesis the algorithm is only tested with the data of two looking directions. If the algorithm is used on all the data that is present and a mean value is taken for the point where the second field comes in, it is expected that a correct height of separation will be obtained. For now the knowledge from the algorithm of Lhermitte and Atlas (1961) from figure 3.7 is used because this algorithm works good up to the point that there is only one windfield present. The range at which the second field comes in is read from this image and with equation 5.2 the height of separation is obtained. The next variables that need to be known are the mean radial value of the first windfield and the end value of the radial velocity of both the datasets. These are read from the radial velocity images of both the datasets.

![Figure 5.5: a) Radial velocity of the real measurement for a looking direction of $140^\circ$ b) Smoothed radial velocity of the real measurement for a looking direction of $140^\circ$](image)

These variables and the known elevation angle and beamwidth of the radar are used for the algorithm to detect and estimate the structure of a multi-layered windfield configuration. A lower windfield that is blowing towards a direction of $114^\circ$ with a
strength of 2.3m/s and an upper windfield that is blowing towards a direction of 263° with a strength of 5m/s are obtained. These results are used in the Doppler velocity pattern simulation model and the resulting pattern can be seen in figure 5.8. The holes that were present in the original measured image are also added in this image. It can be seen that this simulated pattern looks a lot like the measured one.

The direction and strength for the lower windfield are as expected the same as with the algorithm of Lhermitte and Atlas (1961) because up to that point there is only one windfield present. The algorithm of Lhermitte and Atlas (1961) obtained almost the same direction for the second windfield, but with a strength of 0.3m/s for further ranges. If the windfield parameters that are obtained by the old algorithm are used for the simulation of the Doppler velocity pattern the image in figure 5.9 is obtained. It can be seen that the correlation between the measured pattern and this simulated one is very low. This is due to the totally wrong wind strength estimated by the old algorithm because it is calculated from the mean of two windfields. From these observations it
Figure 5.8: Doppler velocity pattern belonging to the obtained windfield parameters estimated by the algorithm for the detection and estimation of multi-layered structures of a windfield, with the holes added present at the measured VAD. Height of separation is set to 283m, first windfield: towards 113° with a strength of 2.3m/s, second windfield: towards 263° with a strength of 5m/s

can be concluded that the algorithm of Lhermitte and Atlas (1961) works good when there is only one windfield present, or in the case of multiple windfields, up to the point that only the first field is present. The new algorithm obtains good estimates of the second windfield with which a high correlation is obtained between the simulated Doppler velocity pattern and the measured Doppler velocity pattern.

Figure 5.9: Doppler velocity pattern belonging to the obtained windfield parameters by the algorithm of Lhermitte and Atlas (1961)
5.4 Conclusion

In this chapter the developed algorithm is explained and tested. It is first of all tested on a simulated Doppler velocity pattern that is obtained with the model of chapter 4. For the simulated tests the results were very good. This is because of the completeness of the data and the homogeneousness of the fields and fall velocity. For the test with the real measured data, the algorithm had some problems with finding a common point for the height of separation between the two windfields for the two used datasets. This could be improved by using all the data that is available. The algorithm gave a far more realistic value for the strength of the second windfield. The old algorithm had problems with this because it calculates it based on the mean of both the fields that are present within the radars beam. The obtained parameters, with the developed algorithm, gave a correct pattern that had high correlation with the measured pattern, which shows the correctness of the obtained parameters.
Conclusion and recommendations

In this chapter the thesis work is concluded in section 6.1 and recommendations for future work are given in section 6.2.

6.1 Conclusion

The Technical University of Delft has started a project in the form of a Master Thesis to improve their existing and develop new algorithms for processing the measured data by the PARSAX radar for 2D-Windfield monitoring. The existing algorithms of the TU-Delft are processing the measured raw data so that a VAD can be plotted with it. It is studied what the radar is measuring and what variables can be used for the processing of the raw data. An understanding is obtained of these variables and within which boundaries these variables will be when precipitation is measured. The processing is improved and a better image with higher quality data is obtained. This high quality data is used to get a VAD and study the pattern of the windfield(s).

Next an algorithm is added that estimates the direction and the strength of the wind from the measured data. This is an existing algorithm based on the algorithms of Lhermitte and Atlas (1961), it estimates these windfield parameters based on the mean Doppler velocity from a VAD. This algorithm works well if only one windfield is present, or in the case of multiple windfields, for the ranges that only one windfield is present in the radarbeam. For the other ranges the algorithm gives confusing results because the mean velocity is a mix of multiple windfields.

After this an existing Doppler velocity simulation model is improved which simulates the Doppler velocity pattern that a radar would measure, based on the configuration of the radar and the a written weather model. The new model gives a more realistic pattern of what the radar would measure because the elevation angle and the beamwidth of the radar and the fall velocity of the precipitation are taken into account.

Next an algorithm is developed and tested that detects and estimated multi-layered structures of a windfield. The algorithm obtains the direction and strength of multiple windfields and the height of separation between them. For this it also uses a VAD as input as the algorithm explained earlier. The algorithm is first of all successfully tested with tested simulated Doppler velocity patterns that is written.

Finally the algorithm is tested on the measured data by the radar. The direction and strength of the second windfield obtained with it were far more realistic than with the algorithm of Lhermitte and Atlas (1961). The direction and strength of both windfields, obtained by both the algorithms, are used by the Doppler velocity pattern simulation model to see how the pattern would look like with these parameters and to compare these results with the measured pattern. The parameters obtained by the new algorithm gave a correct pattern that had a high correlation with the measured one.
The pattern obtained with the parameters with the algorithm of Lhermitte and Atlas (1961) had low correlation as expected because of the fact that more windfields were present in the radars beam.

6.2 Recommendations

Because of the limited time for the Thesis work, not all the ideas could be worked out. First of all the processing of the raw data is completed for a dataset for a rainy day. It would be interesting to study with what amount, or how this process would be impacted by the use of a dataset with other weather conditions. Besides that, the quality of the data could also be improved by using morphological processing (Zheng et al., 2004). Here a mask is made over the processed data to understand where the good data is and where the noise is. By using this mask during the processing, a smaller amount of good data can be filtered out of the raw dataset.

The Doppler pattern simulation model is written for a wind model of two windfields with a constant direction and strength. This is done because only two windfields are needed for the developed algorithm. It would be interesting to extend this pattern simulation model by having the possibility to model more complex weather models, with for example a direction and strength that change with height. It would be interesting to study what kind of patterns would come from these weather models.

The developed algorithm can also be improved by having the algorithm work on all the available data to have a more reliable result. Finally a combination of the algorithm of Lhermitte and Atlas (1961) and the developed one could give better results because of the fact that the old algorithm works very well when there is only one windfield present, or in the case of multiple windfields, up to the point that there are two windfields in the radars beam.


Buienradar (2011).


