A comparison between wind measurements with doppler weather radar and rawinds

Andreas Carlsson

Supervisor: Tage Andersson, SMHI Norrköping
Department of Meteorology
Uppsala University
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Abstract

Comparisons between wind measurement with doppler weather radar and wind measurement with rawinds in different weather situations is done. The study is made in a statistical way with some comparable parameters as outcome. The importance of the weather and different weather situation's effect on the results are discussed, both in form of the winds accuracy and the probability of getting any wind at all as outcome.

The study shows that wind measurement with doppler radar at lower elevations not has so good accuracy, but it becomes better the higher up we measure. At the same time will we lose a lot of the measurements at higher levels by the reason that the reflected power is weakened very fast with the distance the transmitted ray travel.

The doppler effect is explained and the by SMHI used routine for wind measurement with radar is described. At the end of the work are some problems and disadvantages with the radar measurements and the used method discussed.
Errata

Andreas Carlsson

page 1
“5. Results 12” *should be* “5. Results 15”

page 1
all headings containing “avari.” *should be* “aver.”

page 1
“bb” on the 500 hPa level, speed “0.2” *should be* “-0.2”

page 1
“avari.diff” on the 500 hPa level, speed “-0.4” *should be* “-0.3”

page 2
“differ change” *should be* “change”

page 2
“It is yet to early” *should be* “It is yet too early”
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1 Introduction

The beginning of the modern science of meteorology can be set to the early and the middle part of the eighteenth century when a couple of places began to measure some meteorological parameters. The purpose of these measurements can we just guess, but later one began to think about the weather in the future and the possibility to forecast it. It is at the continue of this we are standing today. Today's forecasting meteorologists build their prognoses on various kind of models which are working on many different scales both in room and time. To make these models work well it is of course important that the equations included in the model are well-balanced and as close to the physical reality as they can come. But nearly as important as the equations is the quality of the variables which are put in into the model. One of the most important of these is the wind.

The most common way to measure the wind is having fixed instruments at the ground or in a mast. With these sort of measurements you can get the speed and direction of the wind continuously in the lowest part of the atmosphere, but often it is important to get the wind higher up and then we have to use some sort of balloon or aircraft. The problem with using balloons is that they become rather expensive if you want high resolution in time and space and taking off with a plane is much too expensive to do regularly. At this point the radar is coming up as an alternative. High investments at the build-up of a network is the disadvantage, but when you have got the radar they are quite cheap to run and you can get good resolution in time and space and this might be needed in the future if the models are working on smaller and smaller scales.

If we look at the situation today we see that many of the even before rather few sounding stations have been closed down and today it just remains three of them. During the same time has SMHI in co-operation with the Swedish Airforce built up a network of radar which covers nearly the whole area of Sweden, and there would be a more efficient use of the investment one has done if they could be used for more than the more common looking for precipitation-areas. With the purpose to in the future have the chance to make the radar measurements better I will look at and compare some winds measured with radar with nearby sounding-measured winds. The radar at Hemse on Gotland is used in pair with soundings done on Östergarnsholm just outside Gotland during early summer 1995. The second pair of data is taken from the radar at Jonsered outside Göteborg and soundings done at Landvetter during summer and autumn 1995.
2 Radar

The history of radar (radio detection and ranging) can be said to begin sometimes in the start of the 20:th century. It was developed out of the researches in the field of radio communication. As soon as the military (in many different countries) became aware of the idea of radar they were very interested in it, and their attempts to develop this new field were shortly started. The great developments by the radar occurred during the second world war (W.W.II). This happened mostly by the reason that all the sides now began to utilise aircraft more frequently, and the radar became an important instrument in finding these. By the end of W.W.II the radar had been developed nearly completely in its basic form and after that the changes have been done in smaller parts.

After the end of W.W.II much of the remaining radar equipment became available for civil use. Some of the first to take these in use were the meteorologists. After this the meteorologists have been one of the participant groups in the continuous development of the radar.

The idea of radar is (much simplified) that you can send out a wave of known power and let some of the energy rebound on particles in the air. If you then measure the reflected power at the same time as you measure the time between transmitting and receiving of the same wave you can get the range between the radar and the particles and sometimes even what sort of particles the wave is rebounded at.

A radar basically consists of a couple of different parts. The most important ones are the transmitter, the antenna and the receiver.

Transmitter
The transmitter is the original source of the electromagnetic radiation which is radiated by the radar. It generates and decides the frequency and the power which the radar will work with. Today it exists many different kind of transmitters which work in their own frequency domains. The most used frequency bands for weather radar are the three in table 1.

<table>
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<th>Band</th>
<th>Designation</th>
<th>Frequency</th>
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<tr>
<td>S</td>
<td>2-4 GHz</td>
<td>15-8 cm</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>4-8 GHz</td>
<td>8-4 cm</td>
<td></td>
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<td>X</td>
<td>8-12 GHz</td>
<td>4-2.5 cm</td>
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The quality of a transmitter does not primarily come out in form of higher transmitted power, but through the purity of the transmitted frequency. The most important for measurement of wind with the radar is that it can transmit as near as a single frequency. This is because that is the frequency which the reflected wave is compared with.
Antenna

There exists two types of antennas in the world of radar, the isotropic and the directional antenna. The former is an antenna which sends out radiation equally in all directions, but the most antennas used in meteorology are directional antennas. This latter sort of antenna do in fact consists of two different parts, the feedhorn and the reflector. The feedhorn is the "stick" from where the waves are sent out. After been sent out the wave hits the reflector and get its right direction. The reflector is especially shaped for each antenna and radar and it determines the beam width of the transmitted ray. The form of the reflector is often parabolic in cross-section and circular when it is viewed from the back or the front.

![Diagram of a directional antenna](image)

Fig 1: Example of how a directional antenna consisting of feedhorn and reflector can look like

Receiver

The receiver is simply an apparatus which can detect and amplify the power and frequency of the, now very weak, signals which are reflected back by the particles in the atmosphere.

Beside these three parts there are several different devices used to evaluate the signals and at the end show the result in an understandable way, for instance on a display.

If we concentrate us to the type of radar used by meteorologists it comes up a couple of different types which all are specialised to just do one thing. Of these it is two which are of major interest for us here in Sweden. It is the radar which send out a signal and measure the power which is coming back and the time between transmitting and receiving. By doing this one can the distance to the reflecting object and sometimes what sort of object it is. This is the usual way to find areas of precipitation with help of radar. The second one, and the interesting for this work, is the doppler-radar.
3.1 Doppler-radar

The use of doppler-radar builds on the theory of the so called doppler-effect. This effect was first noticed and described by the Austrian physicist C. J. Doppler during the first half of the nineteenth century. The first times he recognised it was in sound-waves sent out from moving sources.

The doppler-effect describes a change in frequency at waves. This change occurs when the source of the waves is moving with respect to the observer of the waves or when the observer is moving with respect to the source or when both the source and the observer are moving.

This phenomenon can easily be understood if we look at an example with a moving source which transmits pulses of known frequency and a little distance away we are having an observer which also is moving. In this example we will see which frequency \( f' \) a moving observer with speed \( v_0 \) (positive to the right) will measure if the source is moving with speed \( v_s \) (positive to the right) while it is transmitting waves with the frequency \( f_0 \) and the speed of the transmitted waves is \( w \) and its wavelength is \( L \).

We start at time \( t = 0 \) when the first wave is transmitted. After \( 1/f_0 \) seconds the next wave is transmitted and then the first wave has moved \( w \times (1/f_0) \) meters and the source has moved \( v_s \times (1/f_0) \) meters. Then we can see that the wavelength \( L_0 \) of the wave train will be (if we only care about the moving source)

\[
L_0 = w \times \frac{1}{f_0} - v_s \times \frac{1}{f_0} = \frac{w - v_s}{f_0}
\]

As already said the observer at the other end is moving with speed \( v_0 \) which is positive to the right. In this case the time-difference between two waves approaching the observer is going to be

\[
dt_1 = \frac{L_0}{w - v_o} = \frac{w - v_s}{f_0 \times (w - v_o)}
\]

The frequency is defined as the inverse of the time and the frequency measured by the observer \( f_b \) will be

\[
f_b = \frac{1}{dt_1} = f_0 \times \frac{(w - v_o)}{w - v_s}
\]

This \( f_b \) is the frequency the observer will see, but what we are interested in when we are looking at the doppler-radar is which frequency the source itself will measure after the wave has been reflected by the observer. To get that frequency we just have to go through this procedure again, but now the speeds of both the source and the observer have changed sign compared to the wave.
On the way back to the starting-point for the wave former source will now serve as observer and former observer will serve as source and our initial frequency will be the one which we got with equation (3) because in the case of the radar the observer is just a reflecting medium and it is sending out waves with the same frequency as these which is approaching it. If we go the same way as we did in equations (1) to (3) we just need to change the speeds (with change of sign due to the change in direction of the wave speed) and frequencies to these which we are interested in now. If we do so the three equations will become these following three.

Eq (1) ⇒ (4) \[ L_1 = \frac{w}{f_b} + v_0 * \frac{1}{f_b} = \frac{w + v_0}{f_b} \]

Eq (2) ⇒ (5) \[ dt_s = \frac{L_1}{w + v_s} = \frac{w + v_o}{f_b * (w + v_s)} \]

Eq (3) ⇒ (6) \[ f' = \frac{1}{dt_2} = \frac{f_b * (w + v_s)}{w + v_o} \]

After that we put in equation (3) in equation (6) to get the final frequency as a function of the starting-frequency

(7) \[ f' = \frac{f_0 * (w - v_o) * (w + v_s)}{(w - v_s) * (w + v_o)} \]

This (eq (7)) is the general equation for the frequency change due to the doppler-effect and out of that we can calculate the frequency the source itself measure after the waves have been reflected back. With help of this equation and knowledge about the speed of the source can we easily also get the speed radial out from the source for the reflecting material. It is this last way of using the doppler-effect which makes it possible to measure the winds speed and direction with help of a radar.

### 3.2 Wind-measurement with doppler-radar

As already described can we get the radial speed of the wind seen from the radar by using a radar with doppler-mode. The idea is to take this radial wind-vector and divide it into its three spatial co-ordinates. This can be done with several ways of thinking, and they all give a little different results and types of wind if we compare them. Some of the algorithms give a value of the wind in every point which the radar scans in. These methods will give an output in form of a wind map for the volume around and above the radar. This seem to be the ultimate result
of a wind measurement, but comparisons (Andersson 1995) have shown that the results of this kind of measurements are relatively incorrect when they are checked against the real wind. Then we have the kind of models where for instance the routine from Norrköping can be placed. It is a way of calculate which as outcome gives the horizontal mean wind for each of the heights which are scanned and a vertical wind profile straight above the antenna. It is the horizontal part of this last sort of model I have studied and done some comparisons with. The gathering name for these models which give the horizontal mean wind is "Velocity Azimuth Display" (VAD) and will be explained more detailed later.

The real disadvantage with VAD is that they calculate the mean wind for the whole scanned area for a specific height. When the radar is working it is often scanning up to radii of about 30 km. If, for example, the radius is 15 km we get a surrounded area of over 700 km² and assuming that the wind should be uniform or just varying linearly in the whole area is almost never true.

All measurements done with radar builds on the presence of reflecting materials in the atmosphere. When you are looking after areas of precipitation there is no problem because droplets or other precipitation products are rather easy for the radar to "see". When we instead are trying to measure the wind there are two criteria which need to be fulfilled at the same time:

* There must be reflecting particles or materials present.
* These particles have to move approximately with the wind.

These two demands are quite difficult to reach with the same particle. When the first of the two is attained they often become so heavy that they do not follow the wind so well, and when they follow the wind nicely they often reflect very weak. To overcome this problem (make the big particles fly feels impossible) it is necessary to make the radar detect and understand weaker and weaker echoes. Today’s radar are capable of detecting power from three different categories of backscatterer. These three are:

1/ Hydrometeors
2/ Biological and man-made material (clear-air echo)
3/ Refractive index gradients (clear-air echo)

The most frequent of these three and the one which are easiest to detect are the hydrometeors. The hydrometeors are everything which is a natural part of the atmosphere and have water as a basic substance. This become a great variety of meteorological elements such as clouds, snowflakes and many more. Just let us summarise some of them shortly.

Clouds
Clouds which not are precipitating clouds mostly consists of small water droplets or ice crystals. These cloud particles are so small and light that most radar hardly can detect the power they reflect. When the particles in the cloud after a while grow bigger they are getting heavier and easier for the radar to "see". When the particles have grown enough to overcome
the upwind they begin to fall and grow even faster and so on. At this point the former non precipitating cloud has been transformed to a precipitating cloud and is now easier for the radar to detect. As mentioned before clouds can consist of water droplets or ice crystals or both at the same time, depending on, among other things, which height they are on and which temperature they have. Depending on what the cloud consists of it will reflect differently. A cloud consisting of water droplets will reflect noticeably better than a cloud with ice crystals of the same size.

Cloud particles are nice in the sense that they are small and light and can follow the wind quite well, but the problem is that today’s radar have problems to measure the reflected power of these small particles.

**Rain**

Rain can fall with many different intensities, from light drizzle to down-pour. All these intensities will reflect more or less, and they can all be seen with the radar we use nowadays. The more it rains, the bigger are the droplets and consequently it becomes easier to detect. Rain is a good condition when we want to measure the wind with radar. This is because the raindrops are rather big. They are quite easy to detect, and they follow the wind quite well. But when the intensity of the rain gets very high there can be problem because the droplets become big and will not follow the wind so well any longer.

**Snow**

Ice and snow in the form of hail and snowflakes generally give a weaker reflection than rain. This in combination with the fact that the precipitation rates for snow and hail usually are much lower than it is for rain makes the maximum range for detecting snowfalls and hailstorms shorter than likewise for rain.

For wind measurement is snowflakes to prefer to rain because they follow the wind better and can still be detected on a rather long distance.

When we come to the biological and man-made materials we talk about, for example, aeroplanes, birds, insects and the echoes that ground based items will reflect.

**Aeroplanes**

Aeroplanes often give a strong echo which the radar receive and ”understand” quite easily. The reflected power will depend on the distance between the radar and the plane and also on what type of aeroplane it is.

For wind measurements aeroplanes become useless by the reason that the flight routes do not have anything in common with the wind.

**Birds**

To the first approximation birds can, in radar meaning, be considered as spheres of water with the same mass as the bird. Normally water spheres (for example in rain) reflect strongly, but in the case of birds the problem is that they usually are so called point targets and these reflect much less than so called distributed targets do. There is also the case of many birds gathered in flocks. These flocks are easier than the single birds to detect.
Often birds fly with no regard of the wind and do have a goal for their flight, and then they become useless for wind measurements. An example of this sort of behaviour are the migrations of birds that sometimes occur, mostly at nights. But sometimes birds in flocks just fly around randomly. If this is the case one can use the sum of all these movements and this vector might be approximately in the direction of the wind (Wilson et al. 1994).

**Insects**

The problems with insects are mostly the same as these coupled to birds, the insects have to follow the wind passively or fly around randomly so that the sum of all the individual insects velocities become zero relatively the wind.

In the world of insects it exists arts and specimens extending over a great variety of scales. In Sweden they might be from (really just a guess) a couple of millimetres up to maybe a decimetre. These will give totally different echoes and they will also follow the wind with more or less accuracy.

In a study G.L Achtemeier (1991) is looking at insects behaviour in gust front circulations and the accuracy of winds measured with doppler-radar using, among other things, the insects as tracers. In this study Achtemeier shows that there are situations when the insects not are valid as tracers for wind measurements with radar, so just take the combined insect and wind velocity to always be the wind velocity alone is a little risky. He is especially looking at the insects behaviour as they are lifted up to higher altitudes by strong updrafts. One interesting hypothesis is which he tested is that the insects, when they sense strong lift might turn downward, for example by folding theirs wings. This could be seen with dual-polarizating (is not discussed any deeper in this paper) radar as a reorientation of the insects bodies with respect to the radar. This result will make the insects which act like this unreliable as tracers. The same might happen to some insects when they are lifted to altitudes where it is too cold for them to be. In this situation some insect’s metabolic activity declines and the frequency of the wings goes down and it will start to sink.

**Ground clutter**

A big problem for all measurements with radar is that there will always exist reflecting items which are bound to the ground, for example buildings and heights. This disturbance will often be seen on the display just around the radar. One way to reduce this problem is to set the power which is known to come from ground clutter to 0 before the measurements start.

**Refractive index gradients**

Electromagnetic (EM) radiation travels through different materials with different speeds. It travels through vacuum with a speed of \(299 792 458 \pm 10\) m/s (according to National Bureau of Standards) which usually is referred to as speed of light. This is the highest speed for EM radiation, and when it travels through any other material than vacuum it will keep a little lower speed. The ratio between the speed of EM radiation in vacuum, \(c\), and ditto through a material, \(u\), is called the refractive index for the material and is denoted with the letter \(n\) and is defined as following

\[
(1) \quad n = \frac{c}{u}
\]
Since $c$ always is greater than or equal to $u$, $n$ will always be greater than or equal to 1. The refractive index (RI) differ its value through the atmosphere and usually it is highest in the lower part of the atmosphere and decreases until we come to the top of the atmosphere where it is equal to 1. When $n$ is calculated one can see that it always will have values which differ very little from 1. By convenience one will normally recalculate RI to refractivity, $N$, which is defined as

$$ N = (n - 1) \times 10^6 $$

Refractivity in the atmosphere has been found to mostly depend on pressure, temperature and vapour pressure and can be calculated with following formula:

$$ N = \frac{77.6}{T} \left( P + 4810 \times \frac{e}{T} \right) - 4.03 \times 10^{-7} \times \frac{N_e}{f^2} $$

- $T$ = temperature (Kelvin)
- $P$ = atmospheric pressure (hPa)
- $e$ = vapour pressure of the moist air (hPa)
- $N_e$ = number density of free electrons per m$^3$
- $f$ = operating frequency of the radar (Hz)

If we neglect the last part of the right side (it is just important in the higher parts of the atmosphere) we will get an equation that will change with changes of the three former mentioned meteorological parameters. For the gradient of $N$ to be able to reflect measurable power (also called Bragg scattering) it has to be found on a distance which is small compared to the wavelength of the transmitted ray. On this distance pressure will normally not have any significant change, so the important variables will be the temperature and the vapour pressure. The most common way for these changes to occur on this small scale is with help of turbulence. This could possibly give us a chance to measure the turbulence of clear air, but more often than not the reflected power is so weak that it is nearly undetectable.
The doppler radar has been worked on and developed by meteorologists for nearly forty years. Today we have also seen the doppler radar be set out for operative use, and this was first done in USA for about ten years ago, and there has the radar network of today the capacity to of working in doppler mode. This is also a fact for the Swedish radar network which got this just a couple of years ago.

The ground for the algorithm used by SMHI was first published by T Andersson and P.O.G. Persson in "Promis Report nr. 6" (1987). Development and changes of this routine was made and 1992 the latest publication describing this whole routine came out. This is also the routine used by SMHI nowadays and it will now be described shortly.

With the VAD technique the horizontal wind right above the antenna is calculated, this is done by measuring the radial wind around a circle, the VAD circle, of constant radii and elevation. Around this circle the horizontal radial component of the wind is supposed to change linearly with respect to the azimuth angle, and the vertical speed of the wind is supposed to be horizontally constant. Because of these assumptions will the measured winds form an approximate sinusoid if the wind speed is plotted against the azimuth angle.

When the VAD circle is seen from right above (fig 3) one sees how the horizontal radial component, $U_r$, of the real wind, $U$, can be divided in the north and east component of the real wind.
In figure 3 it can be seen that

\[ U_r = y \cos \theta + x \sin \theta \]  

\( y \) = north component of the wind  
\( x \) = east component of the wind  
\( \theta \) = azimuth angle of the antenna

With help of the sinusoid we have got through the measurements around the VAD circle it is possible to estimate the radial wind, \( \hat{U}_m \), for each azimuth angle. This estimated radial wind can be written as

\[ \hat{U}_{mi} \cdot \cos \alpha = \overline{U}_m \cdot \cos \alpha + U_{ri} = \overline{U}_m \cdot \cos \alpha + y \cos \theta_i + x \sin \theta_i \]

\( \hat{U}_{mi} \) = estimated radial wind for azimuth angle \( \theta_i \),  
\( \overline{U}_m \) = average of the measured radial speed  
\( U_{ri} \) = horizontal radial component of the wind for azimuth angle \( \theta_i \),

To be a good assumption the sum of equation (2) around a whole VAD circle has to be approximately equal to the sum around the VAD circle of the horizontal component of the measured radial wind, \( U_{mi} \). This is done with the least square method, by minimising the sum of the square of the difference between the horizontal components of \( U_{mi} \) and \( \hat{U}_{mi} \) (eq. 3).
\[ Q = \sum (U_{m_i} \cdot \cos \alpha - \overline{U}_m \cdot \cos \alpha)^2 = \]
\[ \sum (U_{m_i} \cdot \cos \alpha - \overline{U}_m \cdot \cos \alpha - y \cdot \cos \theta_i - x \cdot \sin \theta_i)^2 \]

To minimise this sum we set the derivatives with respect to \( x \) and \( y \) to 0.

\[
(4a) \quad \frac{dQ}{dy} = -2 \sum \left( \cos \theta_i \cdot \left( U_{m_i} \cdot \cos \alpha - \overline{U}_m \cdot \cos \alpha - y \cdot \cos \theta_i - x \cdot \sin \theta_i \right) \right) = 0
\]

\[
(5a) \quad \frac{dQ}{dx} = -2 \sum \left( \sin \theta_i \cdot \left( U_{m_i} \cdot \cos \alpha - \overline{U}_m \cdot \cos \alpha - y \cdot \cos \theta_i - x \cdot \sin \theta_i \right) \right) = 0
\]

\[
(4b) \quad \sum \left( (U_{m_i} - \overline{U}_m) \cdot \cos \theta_i \cdot \cos \alpha - y \cdot \cos^2 \theta_i - x \cdot \sin \theta_i \cdot \cos \theta_i \right) = 0
\]

\[
(5b) \quad \sum \left( (U_{m_i} - \overline{U}_m) \cdot \sin \theta_i \cdot \cos \alpha - y \cdot \cos \theta_i \cdot \sin \theta_i - x \cdot \sin^2 \theta_i \right) = 0
\]

The interesting variables are the two horizontal components of the real wind, \( x \) and \( y \). To get the mean wind right above the antenna one seek the best fitting constant \( x \) and \( y \) out of this least square summation. If the real wind is constant or changing linearly over the VAD circle, this method will give the best suited north and east component. And since \( x \) and \( y \) are constant they can be taken out from the summations.

\[
(4c) \quad y = \frac{1}{\sum \cos^2 \theta_i} \left( \sum (U_{m_i} - \overline{U}_m) \cdot \cos \theta_i \cdot \cos \alpha \right) - x \sum (\sin \theta_i \cdot \cos \theta_i)
\]

\[
(5c) \quad x = \frac{1}{\sum \sin^2 \theta_i} \left( \sum (U_{m_i} - \overline{U}_m) \cdot \sin \theta_i \cdot \cos \alpha \right) - y \sum (\cos \theta_i \cdot \sin \theta_i)
\]

When the radial wind is measured at \( K \) equidistant azimuth angles the following simplifications will be valid.

\[
(6) \quad \sum_{i=1}^{K} \cos^2 \theta_i = \sum_{i=1}^{K} \sin^2 \theta_i = \frac{K}{2}
\]

\[
(7) \quad \sum_{i=1}^{K} \sin \theta_i = \sum_{i=1}^{K} \cos \theta_i = \sum_{i=1}^{K} (\sin \theta_i \cdot \cos \theta_i) = 0
\]
Equation (6) and (7) will modify equation (4c) and (5c) to the final expressions for the north and east components of the wind.

\[
y = \frac{2}{K} \sum (U_{mi} - \bar{U}_m) \cos \theta_i \cos \alpha_i
\]

\[
x = \frac{2}{K} \sum (U_{mi} - \bar{U}_m) \sin \theta_i \cos \alpha_i
\]

The direction of the wind vector in polar co-ordinates will be

\[
\delta = \arctan \left( \frac{y}{x} \right)
\]

and conversed to the scale of the wind circle we get the following wind directions

\[
\varphi = 270 - \delta \quad \text{if } x > 0
\]

\[
\varphi = 90 - \delta \quad \text{if } x \leq 0
\]

and the horizontal wind speed

\[
v = \sqrt{x^2 + y^2}
\]

By doing this for different elevations can we get the mean wind for all the heights the where the radar will measure. The radar in Norrköping uses a couple of different elevation angles and ranges for the VAD calculation. The elevations are between 0.4 and 20 degrees and the ranges between 3 km and 25 km with range gates of 1 km. This will give a maximum height of about 8550 meters. The gate between two following azimuth angles is 0.857 degrees, so there will be a maximum of 420 points of measure around a whole VAD circle. In the routine is a simple quality control for the wind included. If the wind calculated with the VAD routine not is good enough, compared to one in the routine specified limit, it is not approved.
5 Results

A couple of comparisons between wind measurements with doppler radar and the true wind has been done. In these the true wind has often been represented by wind measurement with rawinds. Data from different comparisons (Andersson et al 1987, Andersson 1992, Andersson 1994, Wilson et al 1994) shows that the VAD winds generally are following the real wind well, but that there also will be differences. The study done by Andersson 1994, which is the most extensive of these, gives a couple of interesting results. This study is done with data from the radar in Norrköping and rawinds done in Bromma. This situation is much the same as the one from where I have got some of my data. The same routine is used for the doppler radar and the distance differs just a couple of kilometres. The main results from the Norrköping - Bromma study are:

* The VAD wind speeds are generally little higher than those from the rawinds
* The difference between the rawind wind speed and VAD wind speed decreases with the height.

The data available for this work are from two pair of places. The radar in Jonsered and the rawinds at Landvetter are compared and so are also the radar at Hemse on Gotland and rawinds from Östergarnsholm just east of Gotland. The distance between the first two is approximately 10 km and between the second pair of places is it about 43 km.

The radar in Jonsered is running continuously and is compared with rawinds done each day at midnight, 6 am, noon and 6 p.m. The time used here is between 28:th of July and 31:st of October. The data from Gotland are more irregular in time owing to that the rawind measurements were done during a campaign held by MIUU on Östergarnsholm during late May and beginning of June 1995.

To get an objective comparison of the data they are treated statistically. The measurements from Göteborg was divided in three different categories according to the weather at the time and these were calculated separately. The categories are:

* clear air
* cloud
* precipitation

The weather situation “clear air” is by me taken to occur not just when the air is totally free from cloud particles, but also when there is just one or two eighths of high clouds. This is because these clouds often are placed above the height where the radar is scanning.

The following statistical parameters were calculated.

* arithmetic average: \( \frac{1}{n} \sum a_i \)
* average difference: \( \frac{1}{n} \sum (v_{a_i} - r_{a_i}) \)
* average absolute difference: \[ \frac{1}{n} \sum |va_i - ra_i| \]

* root mean square (RMS): \[ \sqrt{\frac{1}{n} \sum (va_i - ra_i)^2} \]

* constants \( aa \) and \( bb \) in \( y = aa \cdot x + bb \) calculated with 'least square method'
  (VAD measurements on x-axis and rawind measurements on y-axis)

\( va_i \): the value of the \( i \)th VAD measurement
\( ra_i \): the value of the \( i \)th rawind measurement
\( n \): number of observations

All the different parameters were calculated for the measured values for all three weather situations and one calculation was done with all measurements included. The results are the following tables (table 2 - table 8).

When we look at table 2 we can see that the general behaviour for both the wind speed and the wind direction is a decreasing difference between the values from the VAD measurements and the rawind measurements with the height, which show that the VAD measurements is more accurate the higher up we come. This can be seen in two different ways:

* \( aa \) is approaching 1.00 with increasing height at the same time as \( bb \) is nearly constant or approaching 0.
* \( RMS \) and \( average \ absolute \ difference \) for the direction is steadily decreasing with increasing height, and since the wind speed is increasing with the height while \( RMS \) and \( average \ absolute \ difference \) are nearly constant will the relative difference decrease.

### Table 2: Comparisons between VAD winds from Jonsered and rawind winds from Landvetter. All measurements included.

Distance between sites is 10 km. Wind speed (m/s) and wind direction (°).

<table>
<thead>
<tr>
<th>p (hPa)</th>
<th>( aa )</th>
<th>( bb )</th>
<th>avar _ VAD</th>
<th>avar _ rawind</th>
<th>avar _ diff</th>
<th>avar _ abs. diff</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>925 (speed)</td>
<td>0.86</td>
<td>0.6</td>
<td>9.9</td>
<td>9.2</td>
<td>0.7</td>
<td>2.1</td>
<td>3.1</td>
</tr>
<tr>
<td>850</td>
<td>0.97</td>
<td>-0.3</td>
<td>10.0</td>
<td>9.5</td>
<td>0.5</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>700</td>
<td>1.03</td>
<td>-0.4</td>
<td>12.3</td>
<td>12.3</td>
<td>0.0</td>
<td>1.9</td>
<td>2.7</td>
</tr>
<tr>
<td>500</td>
<td>1.01</td>
<td>0.1</td>
<td>16.9</td>
<td>17.2</td>
<td>-0.3</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>400</td>
<td>1.01</td>
<td>0.3</td>
<td>19.5</td>
<td>20.1</td>
<td>-0.6</td>
<td>1.7</td>
<td>2.8</td>
</tr>
<tr>
<td>925 (direction)</td>
<td>0.91</td>
<td>16.6</td>
<td>204.5</td>
<td>201.9</td>
<td>2.7</td>
<td>17.1</td>
<td>28.7</td>
</tr>
<tr>
<td>850</td>
<td>0.89</td>
<td>21.9</td>
<td>212.3</td>
<td>210.5</td>
<td>1.8</td>
<td>16.0</td>
<td>27.5</td>
</tr>
<tr>
<td>700</td>
<td>0.90</td>
<td>21.7</td>
<td>210.3</td>
<td>211.4</td>
<td>-1.1</td>
<td>11.9</td>
<td>24.8</td>
</tr>
<tr>
<td>500</td>
<td>1.02</td>
<td>-3.8</td>
<td>206.0</td>
<td>207.2</td>
<td>-1.2</td>
<td>8.2</td>
<td>13.8</td>
</tr>
<tr>
<td>400</td>
<td>0.98</td>
<td>6.7</td>
<td>212.8</td>
<td>214.6</td>
<td>-1.8</td>
<td>5.2</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Due to this it should be perfect to measure the winds higher up with help of radar, but when we come to higher levels the distance to the scanned volume will be rather big and the reflected power will be quite a lot weakened. This will be seen if we look at how many per cent of all done VAD measurements which give an approved wind.

Table 3: The share of all wind measurements with VAD which gives an approved wind. All measurements included.

<table>
<thead>
<tr>
<th>p (hPa)</th>
<th>share approved winds (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>925</td>
<td>80.3</td>
</tr>
<tr>
<td>850</td>
<td>64.0</td>
</tr>
<tr>
<td>700</td>
<td>23.5</td>
</tr>
<tr>
<td>500</td>
<td>14.3</td>
</tr>
<tr>
<td>400</td>
<td>14.8</td>
</tr>
</tbody>
</table>

Table 4 is the same as table 2, but just for weather situations with precipitation. Here we can see, if we compare with table 2, that all the values (except for 400 hPa) are better than the same for all measurements. The failure at 400 hPa depends on that there is one pair of measurements which is relatively bad, and there are so few situations with precipitation so this “bad” pair will cause big harm. If this pair was taken out of the calculation we should instead get the following values of $aa$ and $bb$ at the 400 hPa level.

wind speed: $aa = 1.06$; $bb = -0.6$
wind direction: $aa = 0.96$; $bb = 9.3$

Table 4: Comparisons between VAD winds from Jonsered and rawind winds from Landvetter in situations with precipitation.

<table>
<thead>
<tr>
<th>p (hPa)</th>
<th>$aa$</th>
<th>$bb$</th>
<th>avar. VAD</th>
<th>avar. rawind</th>
<th>avar. diff</th>
<th>avar. abs diff</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>925 (speed)</td>
<td>0.78</td>
<td>2.6</td>
<td>13.1</td>
<td>12.8</td>
<td>0.3</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>850</td>
<td>1.01</td>
<td>0.7</td>
<td>12.6</td>
<td>13.4</td>
<td>-0.8</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>700</td>
<td>1.01</td>
<td>0.1</td>
<td>13.9</td>
<td>14.2</td>
<td>-0.3</td>
<td>1.4</td>
<td>1.9</td>
</tr>
<tr>
<td>500</td>
<td>1.03</td>
<td>0.2</td>
<td>17.7</td>
<td>18.0</td>
<td>-0.4</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>400</td>
<td>1.13</td>
<td>-1.4</td>
<td>19.7</td>
<td>21.0</td>
<td>-1.3</td>
<td>2.1</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Table 4: Comparisons between VAD winds from Jonsered and rawind winds from Landvetter in situations with precipitation.

Distance between the sites is 10 km. Wind speed (m/s) and wind direction ($^\circ$).


If we look at the share of winds which are approved in precipitation (table 5) we will see that these are very high, which show what is already said, that precipitation can be detected rather easily and on long distances. But this does not really help so much, because the share of all measurements which were done in precipitation only come up to about 8 %.

If we look at the share of winds which are approved in precipitation (table 5) we will see that these are very high, which show what is already said, that precipitation can be detected rather easily and on long distances. But this does not really help so much, because the share of all measurements which were done in precipitation only come up to about 8 %.
Table 5: The share of VAD wind measurements in precipitation which gives an approved wind.

<table>
<thead>
<tr>
<th>( p ) (hPa)</th>
<th>925</th>
<th>850</th>
<th>700</th>
<th>500</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>share approved winds (%)</td>
<td>91.9</td>
<td>89.2</td>
<td>78.4</td>
<td>59.5</td>
<td>51.4</td>
</tr>
</tbody>
</table>

Table 6 gives us the statistics for situations with clouds. The values here show the same tendencies as the calculations with all the measurements do, which means that the difference between VAD and rawind is getting smaller as we come up to higher altitudes. We can here see bad values for the wind speed at the 400 hPa level. This is also due to the small number of values and that one pair of values is not so good. The per cent approved winds for cloudy situations will be approximately as high as it is with all measurements included (table 3).

Table 6: Comparisons between VAD winds from Jonsered and rawind winds from Landvetter in situations with clouds.
Distance between the sites is 10 km. Wind speed (m/s) and wind direction (°).

<table>
<thead>
<tr>
<th>( p ) (hPa)</th>
<th>aa</th>
<th>bb</th>
<th>avar VAD</th>
<th>avar rawind</th>
<th>avar diff</th>
<th>avar abs diff</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>925 (speed)</td>
<td>0.86</td>
<td>0.8</td>
<td>9.8</td>
<td>9.2</td>
<td>0.6</td>
<td>2.1</td>
<td>3.1</td>
</tr>
<tr>
<td>850</td>
<td>0.96</td>
<td>-0.3</td>
<td>10.2</td>
<td>9.5</td>
<td>0.7</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>700</td>
<td>1.05</td>
<td>-0.7</td>
<td>12.1</td>
<td>12.1</td>
<td>0.0</td>
<td>2.1</td>
<td>3.0</td>
</tr>
<tr>
<td>500</td>
<td>1.00</td>
<td>0.2</td>
<td>17.1</td>
<td>17.3</td>
<td>-0.2</td>
<td>2.3</td>
<td>3.3</td>
</tr>
<tr>
<td>400</td>
<td>0.84</td>
<td>3.5</td>
<td>19.0</td>
<td>19.4</td>
<td>-0.4</td>
<td>1.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>

| 925 (direction) | 0.89 | 22.6 | 212.3 | 211.4 | 0.9 | 17.4 | 29.1 |
| 850 | 0.87 | 26.9 | 222.5 | 220.3 | 2.2 | 16.2 | 28.9 |
| 700 | 0.87 | 32.2 | 213.5 | 217.3 | -3.9 | 14.3 | 30.3 |
| 500 | 1.03 | -5.6 | 197.9 | 198.3 | -0.4 | 18.7 | 13.3 |
| 400 | 1.02 | -2.2 | 222.3 | 223.5 | -1.2 | 4.9 | 6.1 |

The measurements in clear air show a result which is relatively bad (table 8). If we compare this with the situations with clouds and precipitation (especially precipitation) we can see that for most of the parameters will the clear air echo situation have the least accurate value. We can also look at how many of the winds which get approved (table 7), and see that already at the 700 hPa level it will be down to 11%, and at 500 hPa and 400 hPa there are so few approved winds (2 respectively 0 winds) that there is no idea to calculate the parameters.

Table 7: The share of VAD wind measurements in situations with clear air which gives an approved wind.

<table>
<thead>
<tr>
<th>( p ) (hPa)</th>
<th>925</th>
<th>850</th>
<th>700</th>
<th>500</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>share approved winds (%)</td>
<td>83.5</td>
<td>60.6</td>
<td>11.0</td>
<td>1.8</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Table 8: Comparisons between VAD winds from Jonsered and rawind winds from Landvettter in situations with clear air.

Distance between the sites is 10 km. Wind speed (m/s) and wind direction (°).


<table>
<thead>
<tr>
<th>p (hPa)</th>
<th>$a_a$</th>
<th>$a_b$</th>
<th>avar VAD</th>
<th>avar rawind</th>
<th>avar diff</th>
<th>avar abs.diff</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>925 (speed)</td>
<td>0.82</td>
<td>0.2</td>
<td>8.9</td>
<td>7.4</td>
<td>1.5</td>
<td>2.3</td>
<td>3.3</td>
</tr>
<tr>
<td>850</td>
<td>0.85</td>
<td>0.1</td>
<td>8.2</td>
<td>7.1</td>
<td>1.1</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>700</td>
<td>0.65</td>
<td>2.4</td>
<td>9.4</td>
<td>8.5</td>
<td>0.9</td>
<td>2.5</td>
<td>3.2</td>
</tr>
<tr>
<td>500</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>400</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>925 (direction)</td>
<td>0.91</td>
<td>7.3</td>
<td>193.4</td>
<td>184.1</td>
<td>9.3</td>
<td>20.3</td>
<td>32.9</td>
</tr>
<tr>
<td>850</td>
<td>0.89</td>
<td>22.3</td>
<td>189.8</td>
<td>191.4</td>
<td>-1.6</td>
<td>21.4</td>
<td>30.8</td>
</tr>
<tr>
<td>700</td>
<td>0.90</td>
<td>12.0</td>
<td>202.4</td>
<td>194.3</td>
<td>8.1</td>
<td>16.4</td>
<td>22.2</td>
</tr>
<tr>
<td>500</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>400</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

These results will confirm what T Andersson showed in his study 1994, namely that the difference between the VAD measurements and the rawind measurements will decrease with elevation. It will also confirm that the higher elevation we use the fewer approved VAD winds will we get. This is due to the weakening of the transmitted power as the distance to the reflecting material is growing bigger.

Another result coming out of this study is how good the situations with precipitation are for the possibility to get many and accurate wind measurements at high elevations and how bad the clear air situations are for the same.

One explanation to the decrease in difference with elevation can be that the wind is relatively turbulent at lower levels and the used VAD routine will get the mean wind for a big area. If we go up to higher levels the movements of the air will occur on bigger and bigger scales and therefore not will differ change so much from one point in space to another, or anyway change approximately linearly. This will make the mean value measured with the VAD technique accurate for a bigger area.

The measurements done on Gotland turned out to be very difficult to do anything useful with. First of all were there few contemporaneous measurements, and most of the times have there been early failures in either the VAD measurements or the balloon measurements. This ended in 9 comparable values on the 925 hPa level and 5 on the 850 hPa level. To calculate statistics on these few measurements will (in my opinion) give quite uncertain values. The individual measurements which could be compared were mostly very different both in direction and speed. This can most likely be explained by the fact that Gotland is an island and Hemse (where the radar stands) is situated in the central of the southern part of this and Östergarnsholm where the balloon measurements were made is situated on a small island just outside the east coast of Gotland. Because of this the radar will have two totally different wind conditions at the two coasts to measure at the different parts of the VAD circle. This will give many rejected VAD circles and few approved winds and the winds which will be approved will most often have very little in common with the real wind at the coast.
6 Conclusions

A qualitative and quantitative study of wind measurement with doppler radar has been done. The work was made in a statistical way by calculating a couple of parameters both for the different wind measurements themselves and the difference between rawind measurements and the wind measured with radar. The comparison was done on one hand in a quantitative way by using all measurements at the same calculation, on the other in a more qualitative sense by dividing the measurements in different weather situations and compare these with each other.

The results coming out of this study build up a picture of the radar’s advantages and disadvantages when it is used for wind measurements. The biggest advantage compared to rawinds is that it has a much better covering in both time and space. The problem is that the result in form of winds today not is totally reliable, both because of the problem to detect the weak reflected power which is a result of reflection both in clear air conditions and situations with clouds. This problem can only be solved by getting better radar which can detect the for today’s radar too weak reflected power. If we work on in this field and develop the algorithms, is it possible that we in the future will have the chance to measure winds on much smaller scales but still cover the big area which today is the radar’s advantage. It is yet to early to take away the rawinds and the ground based wind measurements, but maybe in the future.

My purpose with this study was to was to give a little piece to the big puzzle which many other persons are working on in the field of doppler radar. I have showed on some advantages with the radar and some parts where development is necessary and hope this work will give something to the future.

Acknowledgements:

Many thanks to Tage Andersson for giving me the chance to look into the field of radar. Also many thanks to Hans and Stefan for their inexhaustible hunt for my virus.
7 References


