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Can a meteor measure vertical winds?

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Acknowledgment

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Abstract

In the first part of this thesis the zonal and meridional tilt of the SKiYMET Meteor Radar at Dragvoll (63.4° N 10.5° E) has been found using two different methods.
The average zenith angle model found the zonal tilt to be 0.22 ± 0.11 degrees towards the east and the meridional tilt to be 0.09 ± 0.11 degrees towards the north. The results of this model should be treated with skepticism as the seasonal variations of especially the meridional tilt was large.
The zenith angle model found the zonal tilt to be 0.15 ± 0.21 degrees towards the east and the meridional tilt to be 0.62 ± 0.24 degrees towards the south.
In the second part the tilt found from the zenith angle model was used to investigate the changes such a tilt would cause to the meridional, zonal and vertical winds. And whether the vertical wind would show a strong correlation with either the meridional or zonal wind.
The vertical wind seems to be oscillating with a main period of 24 hours while the meridional and zonal wind has a 12 hour oscillation period, this might show that the contamination from the horizontal winds are not the dominant driving force in the winds. The changes the tilt had on the vertical wind showed an oscillation with the same period as the meridional winds. The changes to the zonal and meridional wind due to the tilt was neglectable.
The daily vertical background wind was obtained and analyzed. The seasonal vertical background wind for the fall of 2012 was found to be weak and downwards, winter was stronger and downwards, spring 2013 was approximately zero and for summer 2013 a upwards wind was measured.
The data was compared to data found by Balsley and Riddle (1984). The result of the comparison was that the resulting winds from this thesis was stronger and has the opposite direction of the data by Balsley and Riddle (1984).

Sammendrag

I den første delen av denne masteroppgaven ble den zonale og meridionale tilten av SkiYMET meteor radaren på Dragvoll ($63.4°$ N $10.5°$ E) bestemt ved å bruke to forskjellige modeller. Den gjennomsnittlige zenith vinkel modellen fant den zonale tilten til å være 0.22 ± 0.11 grader mot øst og den meridionale tilten til å være 0.09 ± 0.11 grader mot nord. Resultatet fra denne modellen bør behandles med skepsis da spesielt den meridionale tilten var svært sesongavhengig.
Zenith vinkel modellen fant den zonale tilten til å være 0.15 ± 0.21 grader mot øst og den meridionale tilten til å være 0.62 ± 0.24 grader mot sør.
I den andre delen av oppgaven ble tilten som ble funnet av zenith vinkel modellen brukt til å se på endringene som en slik tilt ville gjøre på den meridionale, zonale og verticale vinden. Det ble også utforsket om den vertikale vinden ville ha en sterk korrelasjon med den meridionale eller zonale vinden.
Den vertikale vinden ser ut til å oscillere med en hovedperiode på 24 timer mens den meridionale og zonale vinden har en 12 timers oscillasjonsperiode, dette kan være tegn på at innflytelsen fra de horisontale vindene ikke er de dominante faktorene for den vertikale vinden. Endringen som tilten hadde på den vertikale vinden hadde samme oscillasjonsperiode som den meridionale vinden. Endringen på den zonale og meridionale vinden ved endring i tilten var neglisjerbar.
Den daglige vertikale bakgrunnsvinden ble funnet og analysert. Sesongverdien for de vertikale bakgrunnsvindene ble funnet til å være svake og nedadgående på høsten, sterkere og fortsatt nedadgående på vinteren, omtrentelig null på våren og oppadgående på sommeren.
Disse sesongverdiene ble sammelignet med data av Balsley and Riddle (1984). Resultatet av denne sammenligningen var at vindene funnet i denne masteren var sterkere og hadde motsatt retning av dataene ifra Balsley and Riddle (1984).

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Chapter 1

Introduction

The horizontal winds in the mesosphere have been well documented by the SKiYMET meteor radar at Dragvoll. The vertical winds however are harder to measure. This is because the vertical winds are very small compared to the horizontal winds, and therefore errors you can neglect when computing the horizontal winds might have a large impact to the small vertical winds.
One of the errors that might have a large impact on the vertical winds while no impact on the horizontal winds is a tilt of the radar equipment. If the radar is tilted the horizontal winds will not change but if a small component of a 100 $\frac{m}{s}$ horizontal winds adds to a 0.1 $\frac{m}{s}$ vertical wind the change will be large. Therefore the objective of the first part of this thesis will be to determine if the radar is tilted or not and what direction and magnitude the tilt has.
The second part of this thesis is to analyze the impact this tilt of the radar has on the vertical winds, and to determine how big the contamination from the horizontal winds are.

Chapter 2

Data collection

2.1 The SKiYMET Meteor Radar

The data used in this thesis was gathered by the SKiYMET Meteor Radar at Dragvoll, Trondheim (63.4° N 10.5° E). This radar has been collecting data since August 2012. The radar consist of a 30 kW transmitter array of 8 transmitting antennas and 5 receiving antennas. The receivers is set up in a cross shape with 4 receivers surrounding one in the center. 2 of the surrounding receivers are set up a distance of approximately 18 meters (2 times the wavelength of the signal) from the center receiver. The other 2 are set up 22.5 meters (2.5 times the wavelength of the signal) from the center receiver. The setup can be seen in Figure 2.1.

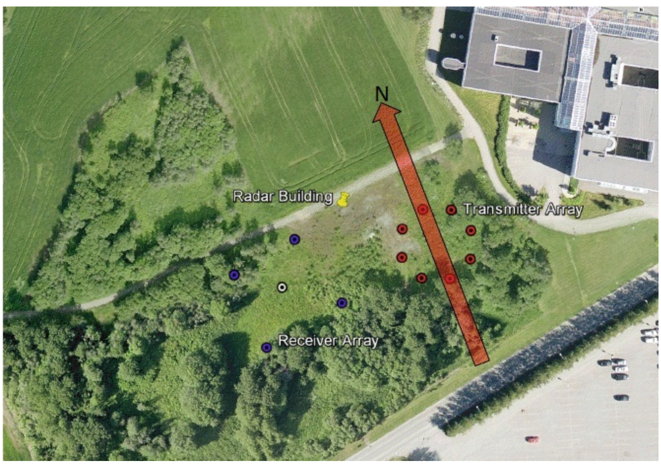

Figure 2.1: Overview of the radar area

The setup detects the majority of meteor trails at zenith angles between 15° and 50° with a peak around 35° off zenith. As seen in Figure 2.2 the setup experience destructive interference every 45° azimuth angle.

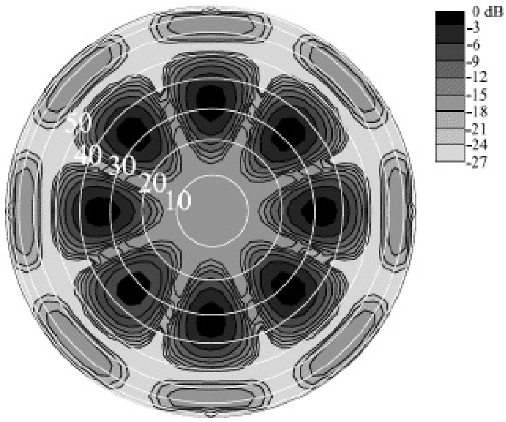

Figure 2.2: Intensity distribution for the meteor radar

The transmitting antennas are transmitting at a pulse repetition rate of 1kHz and the receiving frequency is approximately 32 Hz. The transmitted signal is a radio wave with a frequency of 34,1 MHz and a wavelength of about 9 meters R. De Wit (2013). The radar detects meteor trails that are perpendicular to the line of sight in the range between 70 and 120 km, with most detections between 80 and 100 km, see Figure 2.3.

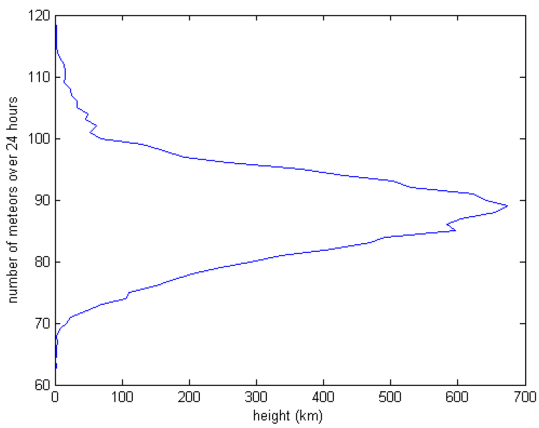

Figure 2.3: Number of meteors detected at different heights (data from January 20th 2013)

2.2 Data from the radar

The raw data from the meteor radar comes in a .mpd file with 17 data components for each meteor detection, see Figure 2.4. The major components used in this thesis is the date and time of the detection, the radial drift velocity, the zenith angle and the azimuth angle. Data which could have more than one origin (ambig > 1 in Figure 2.4) was removed from the analysis.

Data Field	Description
Date	The date of the detection CCYY/MM/DD relative to UTC.
Time	The time of the detection HH:MM:SS.XYZ in UTC where XYZ is the millisecond of the detection. (Note that this represents the relative accuracy of the detection, not the absolute accuracy which, in the normal mode of operation, is +/- 1 second).
File	The file name extension used to store the raw data for this detection (VWXYZ characters from [0..9, A..Z]).
Rge	The range of the detection in km to one decimal place (WXY.Z).
Ht	The corrected height above ground of the detection in km (WXY.Z).
Vrad	The radial drift velocity of the trail in m/s (WX.YZ).
DelVr	The standard deviation of the radial velocity measurement obtained from the 5 antenna pairs in the interferometer. Note that the analysis rejects data with delVr > 5.5 m/s so that this represents a limiting value for this field in the MPD file.
Theta	The zenith angle of the detection in degrees (XY.Z).
Phi0	The azimuth angle of the detection in degrees measured anticlockwise from East (WXY.Z).
Ambig	The number of locations this detection could have originated from (X).
Delphase	The worst phase error between antennas if the measured azimuth and zenith of the detection are correct (XY.Z). Measured in degrees.
ant-pair	The antenna pair with the worst phase error (XY).
IREX	The receive channel used in the analysis for certain single-channel data quality tests. This is always "1" during normal operation.
amax	The peak value of the amplitude of the meteor echo in digitiser units. This may be greater than 32767 if channel saturation has occurred (VWXYZ).
Tau	The decay time of the meteor in seconds. This is a half-life, *not* a 1/e time constant (.XYZ).
vmet	The entrance speed of the meteor in km/s. Bad values are characterised with "-9.99" (WX.YZ).
snrdb	The signal-to-noise ratio for this meteor (X.YZ).

Figure 2.4: Data recorded by the meteor radar

2.2.1 Radial drift velocity

The radial drift velocity or line of sight velocity is used in this thesis. The radial drift velocity is the velocity measured in the line of sight from the radar. The radial drift velocity is used in fit routines to get the meridional, zonal and vertical wind velocity.

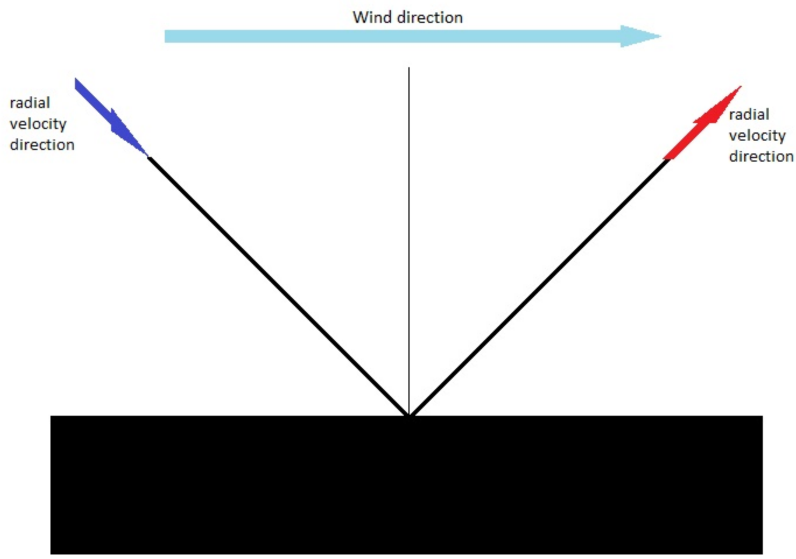

Figure 2.5: Two line of sight velocities from one wind direction

2.2.2 Zenith and Azimuth angle

The zenith and Azimuth angles are used extensively in this thesis. The zenith angle is the angle downwards from the zenith(directly above) while the azimuth is the angle measured counterclockwise from the east.

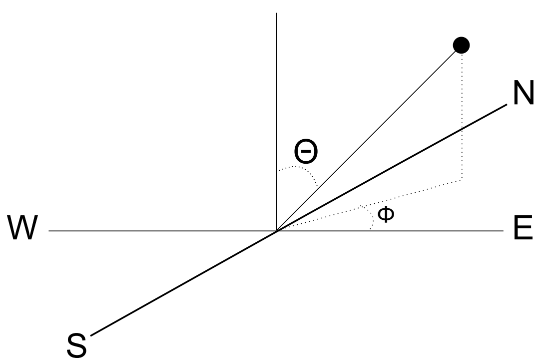

Figure 2.6: The zenith angle seen as the angle coming down from the zenith, and the azimuth as the angle counterclockwise from the east

2.2.3 Change of vertical wind velocities due to tilt of radar

The vertical wind velocities in the mesosphere are very small compared to the horizontal winds. If the radar is tilted slightly off zenith there should be a component of the horizontal winds that would seem like a vertical component to the radar. If the wind direction is the same as the tilt direction an upwards vertical wind component will be added and if the wind is blowing in the opposite direction an downwards vertical wind component will be added. I.e. if the meridional tilt is directed towards the south and the meridional wind is directed the same way one would expect an upwards vertical motion added to the real vertical wind (see Figure 2.7).

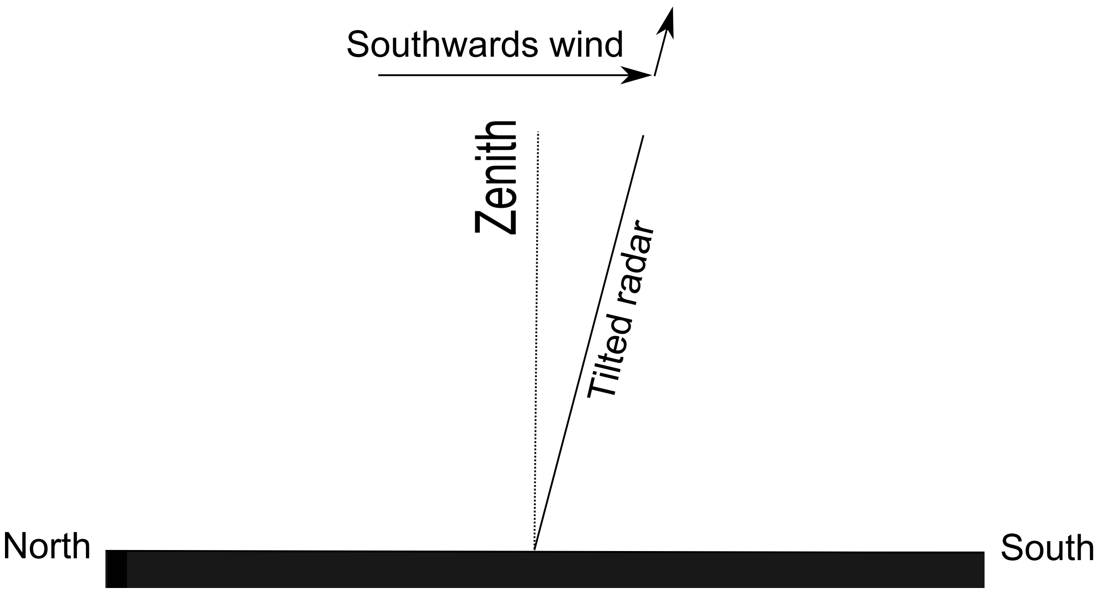

Figure 2.7: Illustration of the added vertical component due to a tilt of the radar

Chapter 3

Methods

3.1 Average Zenith Angle model

The first model used in this thesis to determine the tilt of the radar is a very easy and quick approach. The approach is to look at the range between 88 km and 92 km and split the sky in two parts, first east and west then north and south, then compare the average zenith angle in the two parts. The assumption of this model is that the meteor trails should be uniformly distributed at the sky and hence if the radar is perfectly aligned with the zenith the average zenith angle in the east and west (or north and south) part of the sky should be the same. But if the radar in fact has a small tilt the average zenith should differ slightly. Since the tilt of the radar will add a $\Delta zenith$ in one part and subtract the same $\Delta zenith$ in the other this leads to the following equations for the zonal and meridional tilt.

$$\frac{\overline{Zenith}_{west} - \overline{Zenith}_{east}}{2} = tilt_{zonal} \tag{3.1}$$

and

$$\frac{\overline{Zenith}_{north} - \overline{Zenith}_{south}}{2} = tilt_{meridional} \tag{3.2}$$

where $\overline{Zenith}$ is the average zenith angle. If $tilt_{zonal}$ is positive the radar will be tilted towards the east, while a positive $tilt_{meridional}$ would be evidence of a radar tilted towards the south.

3.2 Horizontal Wind fit

In the first part of the study the zonal and meridional wind velocities is needed. To get the zonal and meridional wind velocities from the radial velocity recorded by the radar a fit routine is needed (see A.2 for Matlab code). The Horizontal wind fit-routine is based on the assumption that the vertical wind velocity is very small compared to the horizontal and therefore may be neglected. With this assumption equation (3.3 is minimized for meteor trail detections in a three hour interval (the time-stamp for the velocity is the hour in the middle of the time interval). If there is fewer than 4 meteor trails detected in the time period there will be no velocities recorded.

$$\sum V_{rad} - u\sin(\theta)\cos(\phi) - v\sin(\theta)\sin(\phi) \tag{3.3}$$

where V_{rad} is the radial velocity, u is the zonal wind velocity, v is the meridional wind velocity, θ is the zenith angle and ϕ is the azimuth angle. A positive zonal wind velocity will have a wind direction towards east, while a positive meridional wind velocity will be directed towards north.

3.3 Zenith Angle Model

The second model used in this thesis to determine the tilt of the radar is a bit more complicated and a lot more time consuming than the first one. The start of this approach is the same as the first one; to look at the range between 88 km and 92 km and split the sky in two parts, first east and west then north and south. But in this model the zonal(meridional) wind velocity in the west and east(north and south) part is compared.

3.3.1 Assumptions

The assumption of this model is that there should be a wind vector blowing in the same direction over the entire sky. So if one look at the zonal (meridional) wind velocity in the west and east (north and south) part of the sky separately they should be the same. On the other hand if the radar is tilted one should see a slight difference in the velocities in the different parts. Therefore the equations,

$$|u_{west} - u_{east}| \tag{3.4}$$

and

$$|v_{north} - v_{south}| \tag{3.5}$$

where u is the zonal wind speed and v is the meridional wind speed, should be equal to zero for a radar that is perfectly aligned with the zenith.

3.3.2 Displacement model

In the work towards getting the tilt of the radar, a model for simulating an "untilting" of the radar was created. This model finds the zenith and azimuth angle of the meteor trail detections corresponding to where they should be if the radar was "untilted" by $\Delta\theta$. The model is easiest explained in the zenith-azimuth plane, where the meteor trail detections is simply displaced by a displacement vector $\Delta\theta$ towards the east(south) in the zonal(meridional) tilt model (see A.5.1 for Matlab code). How the model moves meteor trail detections in the zenith-azimuth plane can be seen in figure(3.1)(zonal) and (3.2)(meridional).

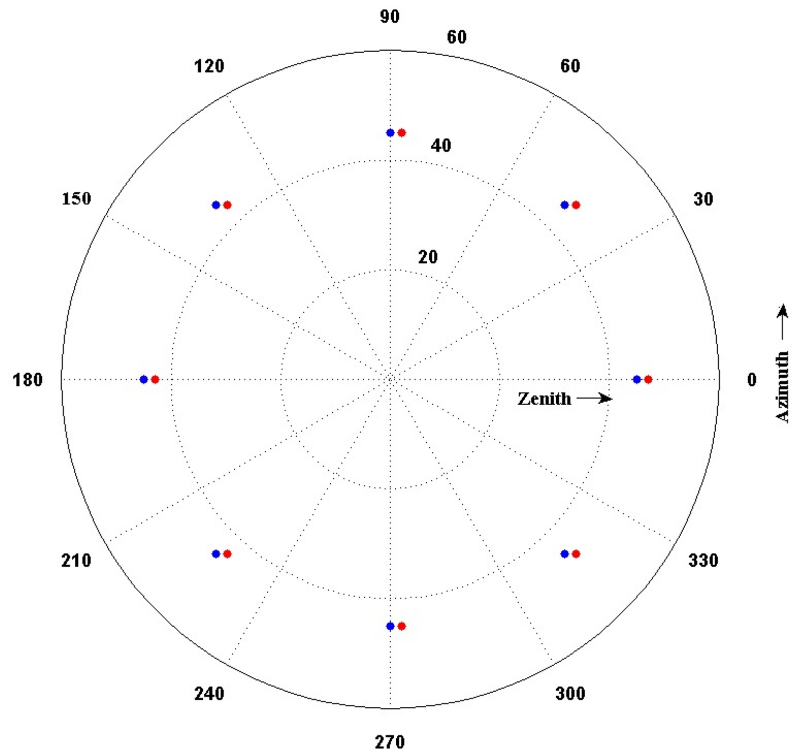

Figure 3.1: The change of zenith and azimuth angle due to a zonal "untilting". The blue dots are the original and the red dots are the position after the displacement has taken place

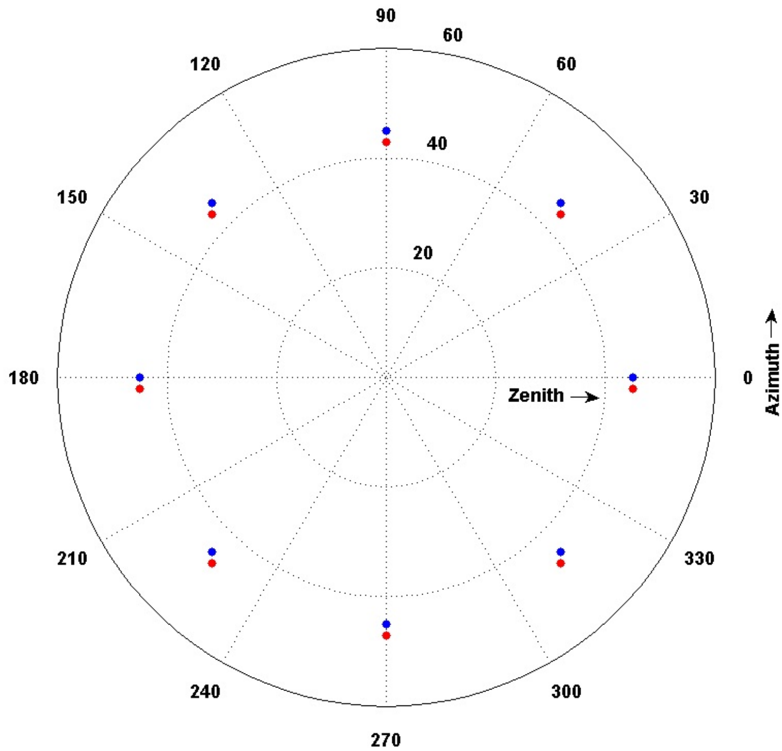

Figure 3.2: The change of zenith and azimuth angle due to a meridional ”untilting”. The blue dots are the original and the red dots are the position after the displacement has taken place

3.3.3 Tilt model

It will only be explained how to obtain the zonal-tilt of the meteor in detail, but the meridional tilt has the exact same form except the use of meridional components of the displacement vector and wind velocity, the use of equation (3.5) instead of (3.4) and the sky is split into north-south instead of west-east.
To use equation (3.4) and the displacement model to get the zonal tilt of the radar a number of horizontal wind fits has to be performed each hour. In order to perform these wind fits the displacement model is used multiple times, each time with a

different zonal displacement vector $\Delta\theta_1$. For each of these zonal displacement vectors $\Delta\theta$ the new zenith and azimuth angles are recorded, then the sky is split into two parts, west and east, and a horizontal wind fit is performed using the new zenith and azimuth angle. The zonal wind component is then recorded for each of the two parts of the sky. When the zonal wind for each part of the sky has been recorded another zonal displacement vector $\Delta\theta_2 = \Delta\theta_1 + 0.1$ is used on the original zenith and azimuth data. This leads to new zenith and azimuth angles which are recorded, the same splitting of the sky as for $\Delta\theta_1$ is performed and finally a new horizontal wind fit is performed with the new zenith and azimuth. This horizontal wind fits gives two new zonal wind velocities that are recorded. This is done for a range between -20 and 20 degrees, in total 401 fits are performed on each part of the sky. After all of the wind fits are performed, equation (3.4) comes to use. If the assumption that this equation should be zero when the radar is aligned with the zenith is correct, then one specific zonal displacement vector $\Delta\theta$ should lead to a minimization of equation (3.4). This is used in the model and the $\Delta\theta$ that minimizes equation (3.4) for the given hour is recorded. To ensure that the minimization actually is close to zero and not just a minimization of a big difference (if this is not the case the assumption of a uniform wind vector would not be true and the entire model will not work), equation (3.4) must give a result which is smaller than 0.1 $\frac{m}{s}$ and the standard deviation of u_{west} and u_{east} must be smaller than 5 $\frac{m}{s}$ to be recorded. This recording of $\Delta\theta$ is done for each hour every day for the entire period. The entire list of recorded $\Delta\theta$ is put in a histogram plot and finally a Gaussian function

$$Ae^{-\frac{(x-b)^2}{2\sigma^2}} \tag{3.6}$$

is fitted to this histogram, from that Gaussian fit the tilt of the radar is extracted as the center of the peak (b in equation(3.6) of the Gauss function. If the gauss fit gives a positive number the radar would be tilted towards the east (south for the meridional fit)

3.4 Vertical Wind fit

To get the vertical wind velocity a similar fit routine to the horizontal wind fit (see section 3.2) is needed. This time the vertical component is not neglected and the equation

$$\sum V_{rad} - u\sin(\theta)\cos(\phi) - v\sin(\theta)\sin(\phi) - w\cos(\theta) \tag{3.7}$$

where V_{rad} is the radial velocity, u is the zonal wind velocity, v is the meridional wind velocity, w is the vertical wind velocity, θ is the zenith angle and ϕ is the azimuth angle, is minimized. As for the horizontal fit this is done using v_{rad} from meteor trail detections in a three hour interval (the time-stamp for the velocity is still the hour in the middle of the time interval). And as for the horizontal fit, time intervals with less than 4 meteor trail detections leads to no recorded velocity.

3.5 Background winds

The background wind for both horizontal and vertical winds will be used in this thesis. The background wind is what you get when you remove what is called atmospheric tides from the wind speeds. These atmospheric tides are global periodic oscillations of the atmosphere. There are several atmospheric tides, each with its own period, phase and amplitude. The major ones (the ones that will be extracted from the fitted winds in this thesis) has periods of 8, 12 24 and 48 hours. The driving forces of these atmospheric tides is well explained in (Lindzen and Chapman, 1969). To extract the background wind a fitting routine is needed. The fitting routine used in this thesis is loading 4 days (96 hour) of wind data and fits equation (3.8) to this data (if the 4 days contains under 48 hours of data no fit will be performed). From this fit the daily background wind and the standard deviation of this background wind is obtained and recorded. The day of the recorded background wind is set as the first day of the 4 day period.

$$A_8 \sin(\frac{2\pi t}{8} - b_8) + A_{12} \sin(\frac{2\pi t}{12} - b_{12}) + A_{24} \sin(\frac{2\pi t}{24} - b_{24}) + A_{48} \sin(\frac{2\pi t}{48} - b_{48}) + w \tag{3.8}$$

where A_{period} is the amplitude of the tide with the given period, b_{period} is the phase, t is the time and w is the vertical, zonal or meridional background wind (depending of which wind you are fitting)

3.6 Statistical analysis

In this thesis statistical analysis of data is performed In most parts the standard deviations used is derived by the Matlab fit routines. But in some parts of the thesis, especially the parts where data with a given standard deviation is used in further analysis, the weighted mean and weighted standard deviation is used. The weight used in this thesis is

$$w_i = \frac{1}{\sigma_i^2} \tag{3.9}$$

where σ is the standard deviation. This weight is also used when fit routines are performed on data with a standard deviation. The chosen weight gives the following weighted mean

$$\bar{x} = \frac{\sum_{i=1}^{n} \frac{x_i}{\sigma_i^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}} \tag{3.10}$$

and the weighted standard deviation

$$\sigma_{\bar{x}} = (\sum_{i=1}^{n} \frac{1}{\sigma_i^2})^{-\frac{1}{2}} \tag{3.11}$$

Chapter 4

Results and analysis

4.1 Average Zenith Angle model

4.1.1 Zonal

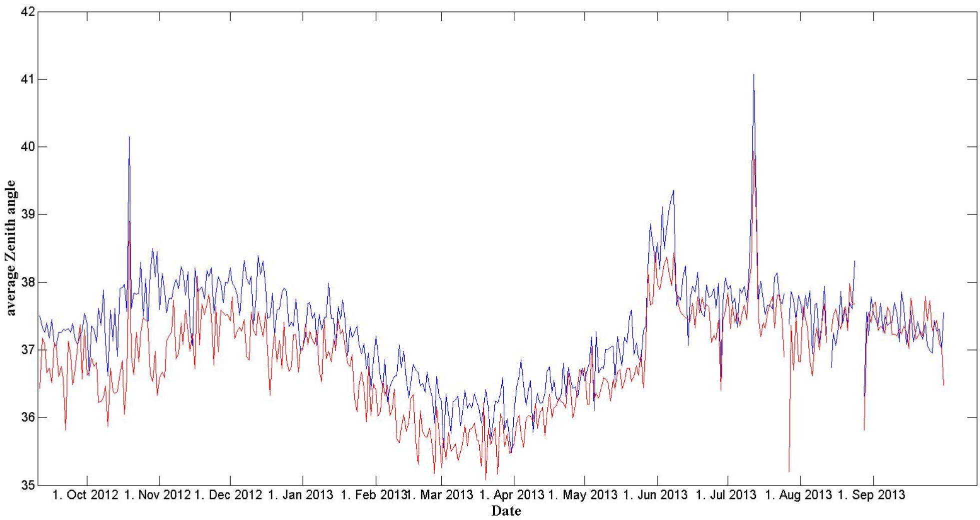

Figure 4.1: Daily average Zenith for the west(blue) and east(red) part of the sky

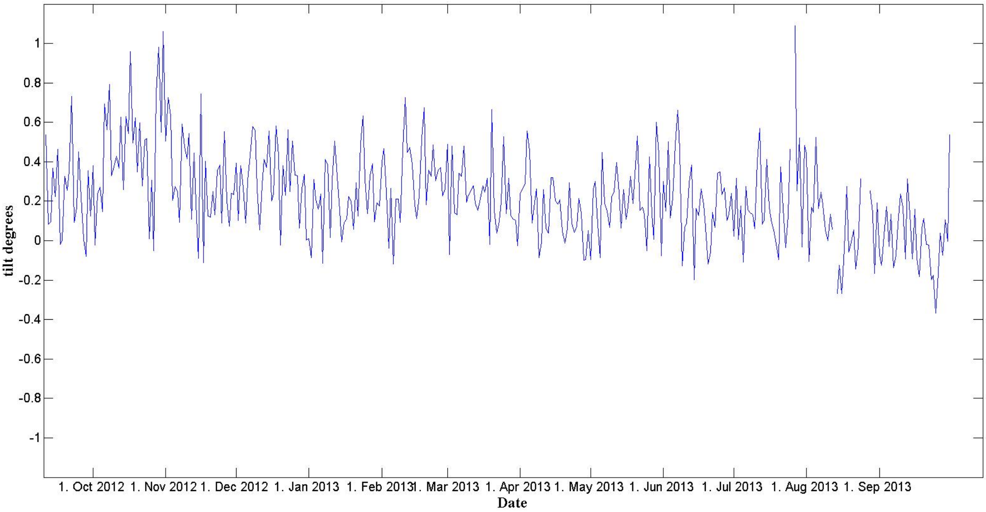

Figure 4.2: The daily recorded zonal tilt of the radar

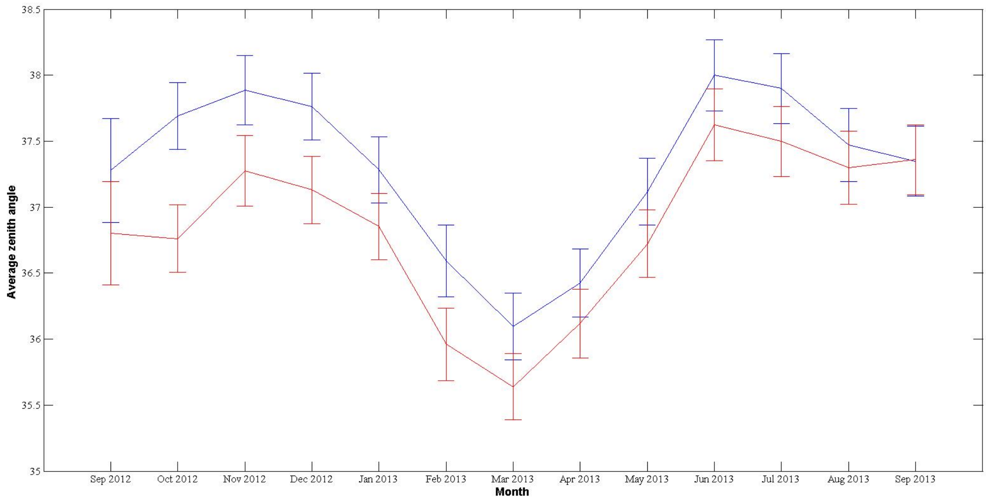

Figure 4.3: Plot of the weighted monthly average zenith for the west(blue) and east(red) part of the sky with weighted standard error

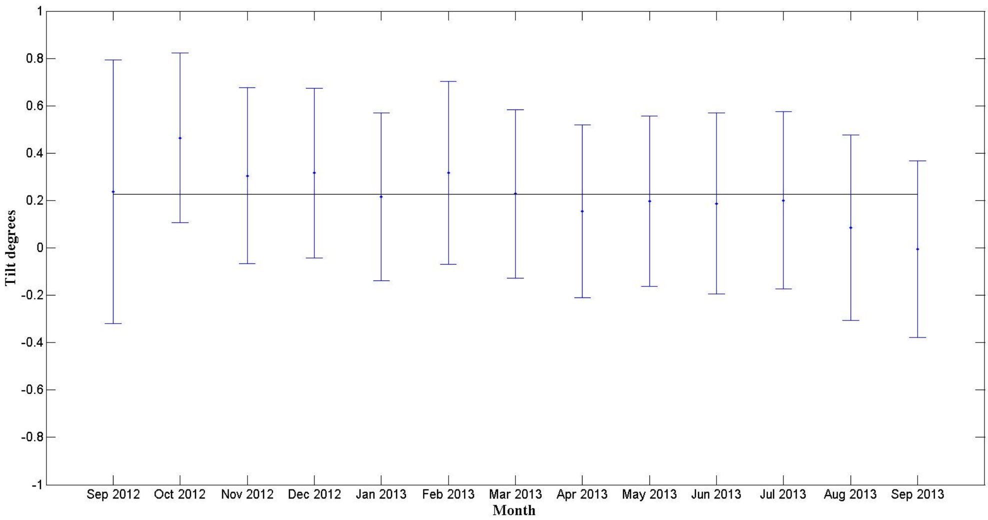

Figure 4.4: Monthly zonal tilt with weighted standard error, the black line is the total weighted zonal tilt(0.22 with weighted standard error of 0.11) for the entire period

Figure 4.1 shows that the average zenith angle of the radar in the west and east part of the sky varies. Especially one can see a seasonal variation on both the west and east part of the sky with minima around the vernal and autumnal equinox (20^{th} of March and 22^{nd} of September) and maxima around winter and summer solstice (21^{st} of December and 21^{st} of June). It seems like the west part of the sky has a greater zenith angle average than the east part has, the exception seems to be in late August 2013 and September 2013 where the two have approximately the same value. This can also be seen in figure 4.3. When it comes to the tilt of the radar, figure 4.2 shows varying values around 0.2 degrees. The exceptions seems to be late October 2012 to early November 2012 where there seems to be a general higher value and late August 2013 through September 2013 where there seems to be a general lower value. This is also shown in figure 4.4 where most weighted monthly means varies around 0.2 degrees, October 2012 seems to be higher while August 2013 and September 2013 seems to be lower. The total weighted mean of the entire period of 0.22 ± 0.11 degrees (tilted towards the east) seems to give a good picture of a stable zonal tilt.

4.1.2 Meridional

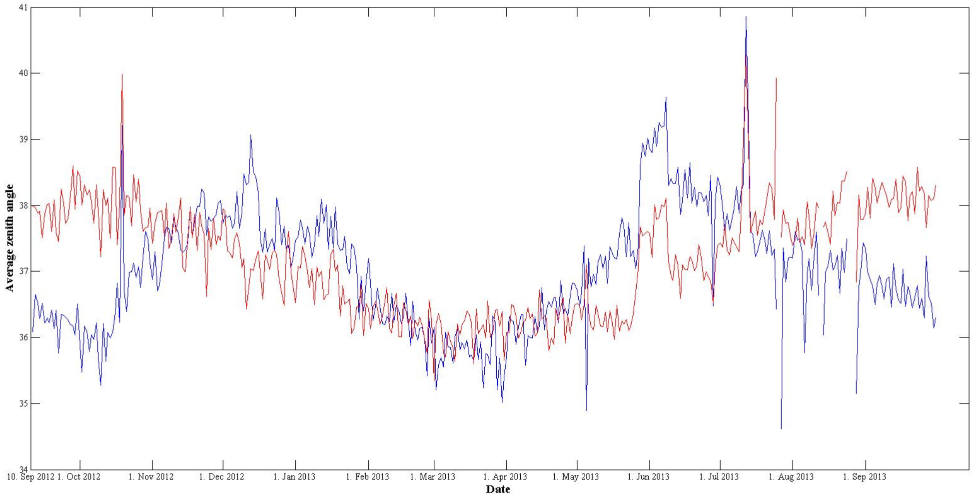

Figure 4.5: Daily average Zenith for the north(blue) and south(red) part of the sky

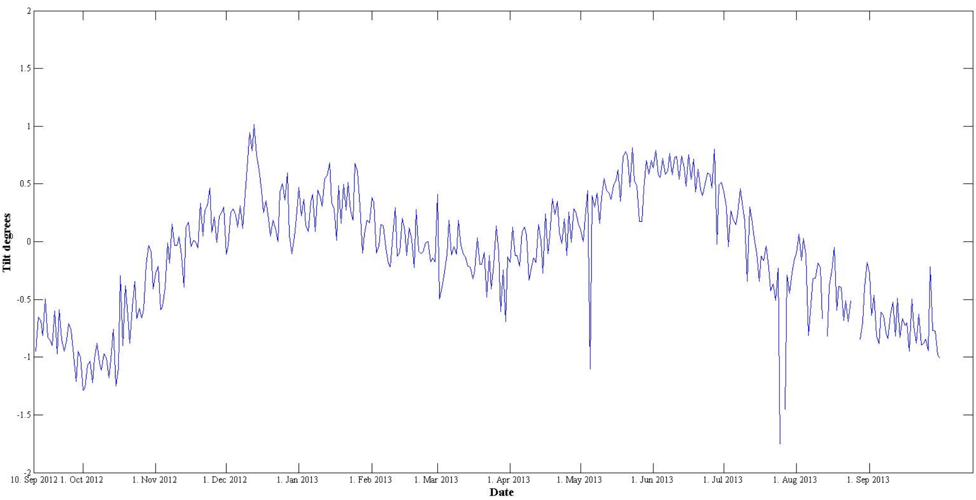

Figure 4.6: The daily recorded meridional tilt of the radar

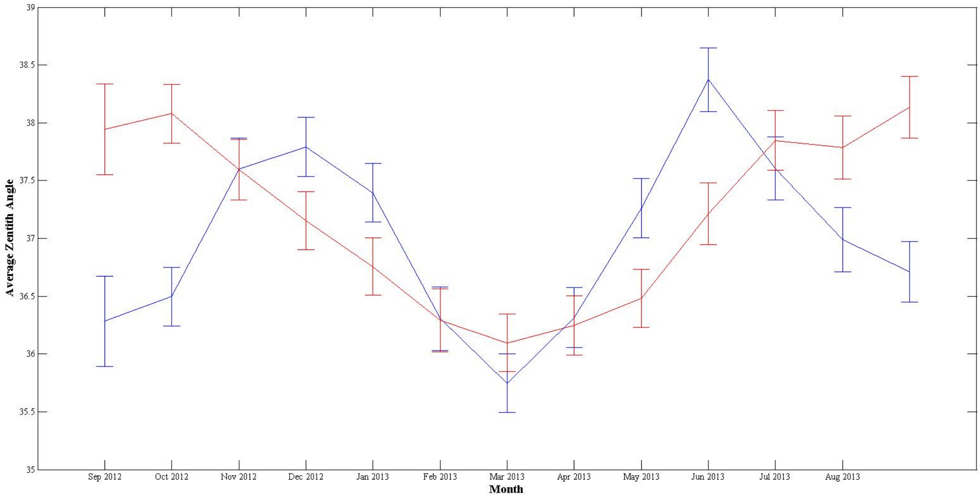

Figure 4.7: Plot of the weighted monthly average Zenith for the north(blue) and south(red) part of the sky with weighted standard error

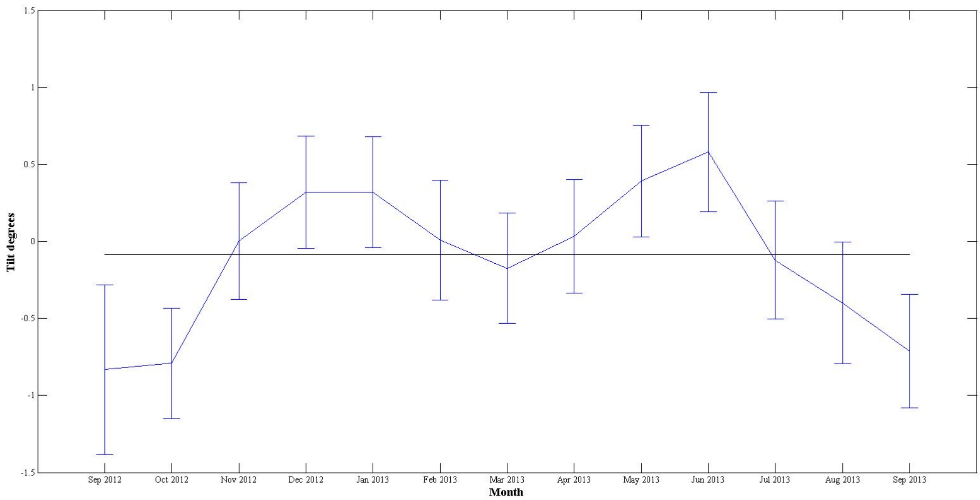

Figure 4.8: Monthly meridional tilt with weighted standard error, the black line is the total weighted tilt (-0.09 with weighted standard error of 0.11) for the entire period

From figure 4.5 one can see that the average zenith angle of the radar in the north and south part of the sky varies. Especially one can see a seasonal variation where the north and south part seems to follow different patterns. The north parts average zenith seem to follow a similar pattern as the west and east part with minima around the vernal and autumnal equinox and maxima around winter and summer solstice. While the southern part seems to have maxima at the autumnal equinox and minimum at the vernal equinox. This leads to no ”dominant” part that has a greater average zenith angle than the other. Figure 4.7 further enhances this picture where its clear that the south part has a greater weighted monthly average zenith angle around the equinoxes. When it comes to the tilt of the radar it seems from figure 4.6 to be having seasonal variations with negative values around the equinoxes and positive values around the solstices. This is also evident in figure 4.8. The total weighted mean of the entire period of -0.09 ± 0.11 degrees (tilted towards north) does not seem to give a good picture of a stable meridional tilt of the radar as the seasonal variations are to large.

4.2 Zenith Angle Model

4.2.1 zonal

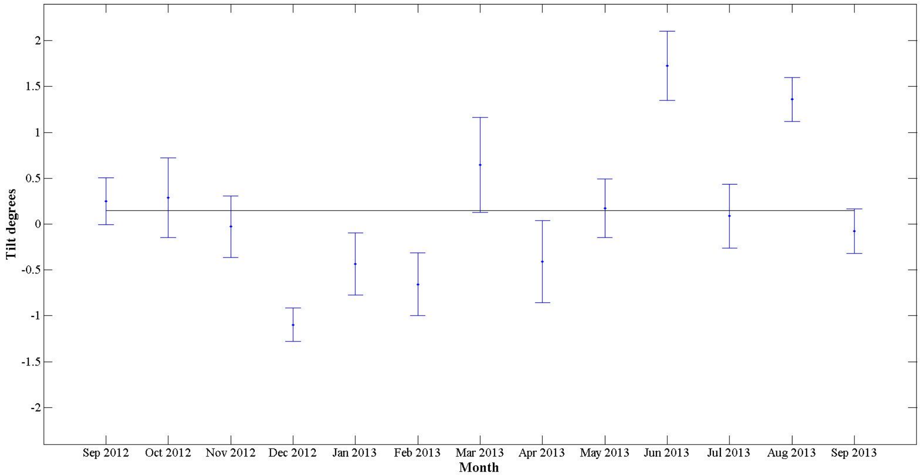

Figure 4.9: Monthly variations in the zonal tilt from fitting gauss curves to data from each month. The black line is the zonal tilt found from figure 4.10

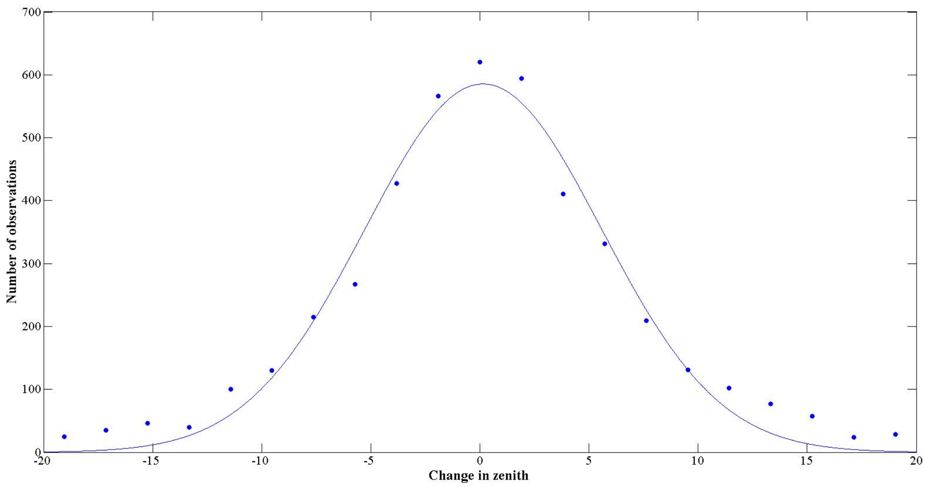

Figure 4.10: Gauss fit of the zonal tilt for the whole period of data collection

Figure 4.9 shows that there are variations in monthly tilt obtained by fitting gauss curves on data from each month. There is no consistent tilt direction for the monthly values. These variations are to be expected since the problem is mainly a statistical one, where lack of data can make contributions from gravity waves and other disturbances greatly influence the result. These disturbances should however influence a lot less when the amount of data increases. Therefore the tilt of the radar found from the gauss fit of all data collected during the period, shown in figure 4.10 of 0.15 ± 0.21 should be a more reliable result. But also in this result we see a standard deviation which is bigger than what was hoped for. The zonal direction of the tilt could not be decided using the data acquired for an entire year. This shows that the amount of data needed to decide the tilt is large, and that the monthly variations obtained by only fitting a month worth of data should be treated with skepticism.

4.2.2 Meridional

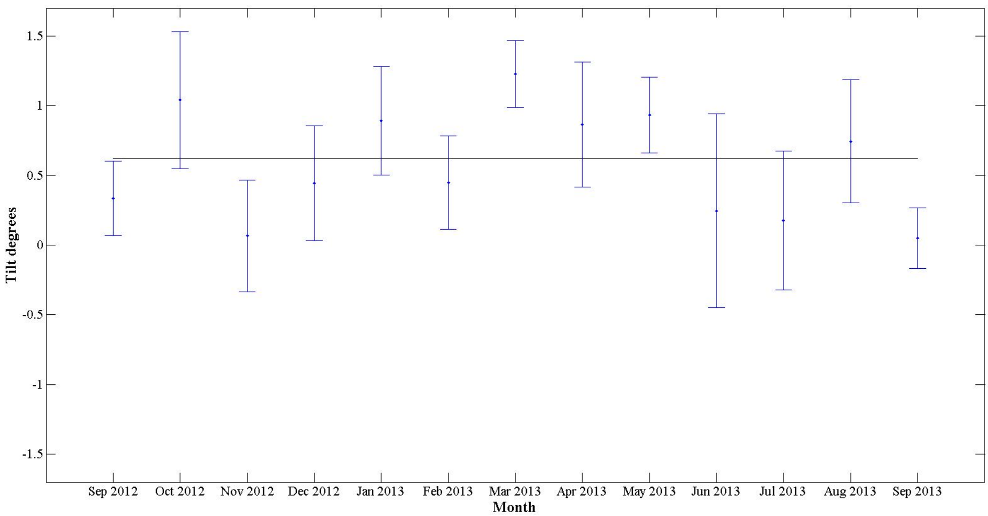

Figure 4.11: Monthly variations in the meridional tilt from fitting gauss curves to data from each month. The black line is the zonal tilt found from figure 4.12

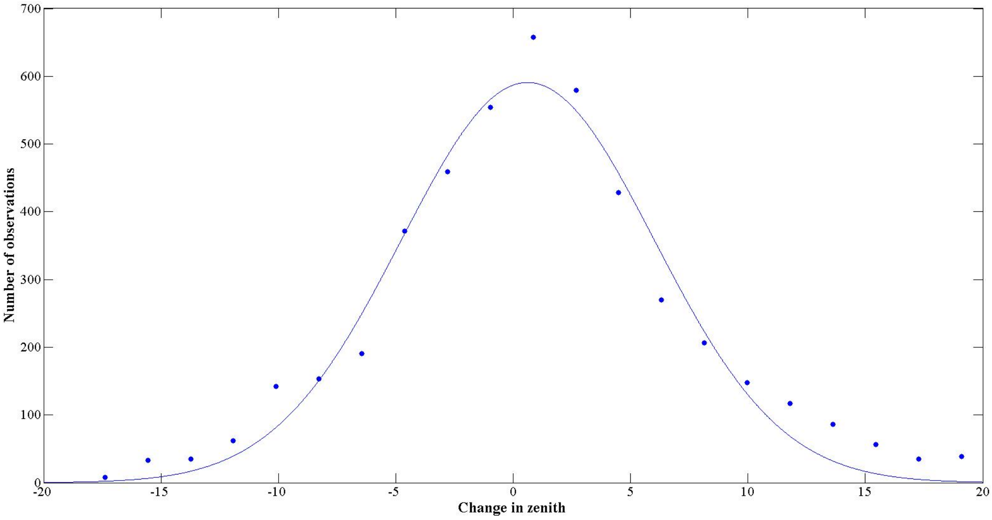

Figure 4.12: Gauss fit of the meridional tilt for the whole period of data collection

Figure 4.11 shows that there are variations in monthly tilt also for the meridional tilt, but the variations are smaller than for the Zonal component. The meridional tilts obtained by the monthly gauss fits are tilted in the same direction. The tilt of the radar found from the gauss fit, shown in figure 4.12, of 0.62 ± 0.24 gives a result that the radar is pointing towards the south, however the standard deviation is to high to ensure that there in fact is a great influence of the meridional wind in the vertical component. The range between 0.62% and 1.5% of the meridional wind contaminating the vertical wind is larger than what was hoped for.

4.2.3 Contamination of the vertical wind

The two fits gives an indication that the meridional wind will contaminate the vertical wind more than what the zonal wind will. In the vertical fits in this thesis the zonal tilt was 0.15 and the meridional tilt 0.62. These tilts indicates that 0.2% of the zonal wind and 1.1% of the meridional wind is influencing the vertical wind component.

4.3 Vertical wind fit

A displacement vector of 0.62 towards south and 0.15 towards east (both obtained using the zenith angle model) was used to produce the corrected data in this section.

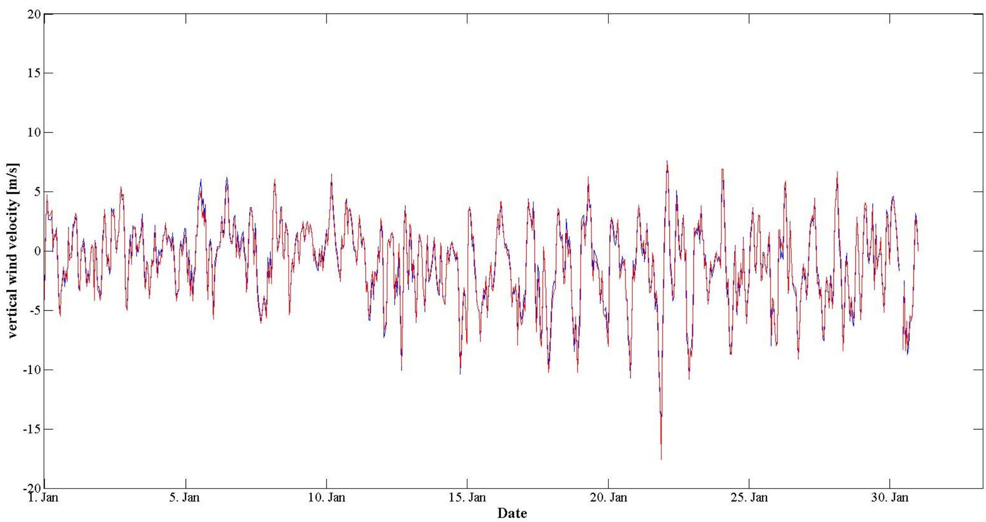

Figure 4.13: Vertical wind from January 2013, blue original red corrected data

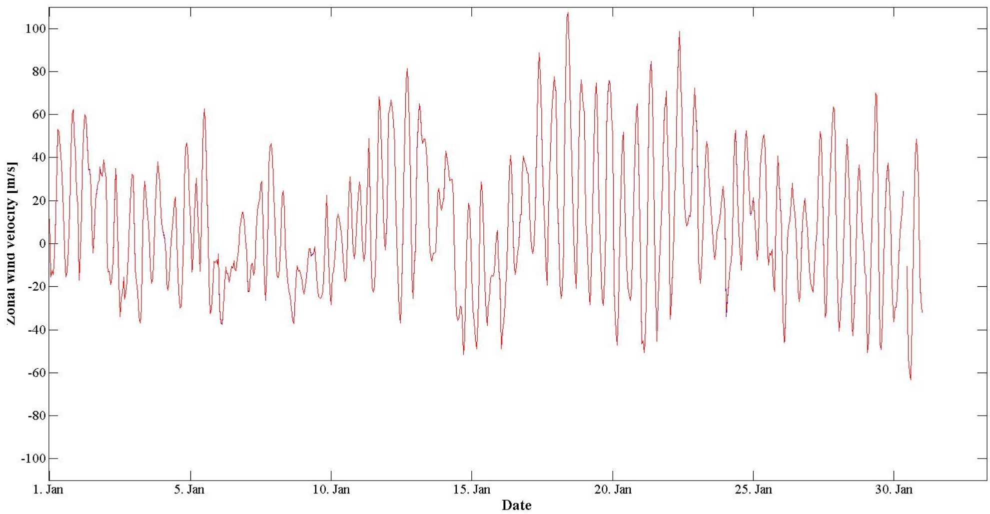

Figure 4.14: Zonal wind from January 2013, blue original red corrected data

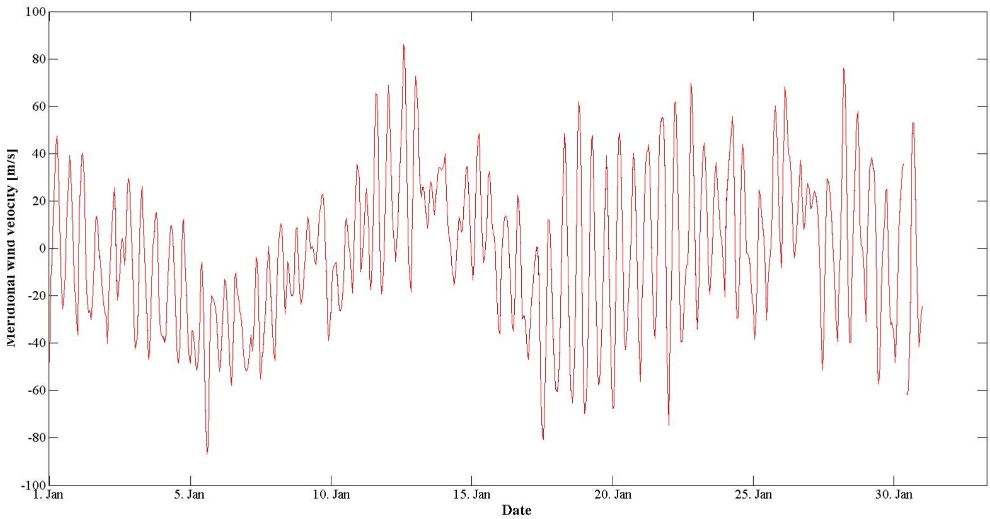

Figure 4.15: Meridional wind from January 2013, blue original red corrected data

Figure 4.13 show the vertical velocities in January 2013 for both the uncorrected and corrected data, this plot shows that there is a small change in the vertical winds between the uncorrected and corrected data. Figure 4.14 and 4.15 show the uncorrected and corrected data for the zonal and meridional wind speed. It is almost impossible to see both lines in the figure as the change between the corrected and uncorrected data is, as one would expect, very small.

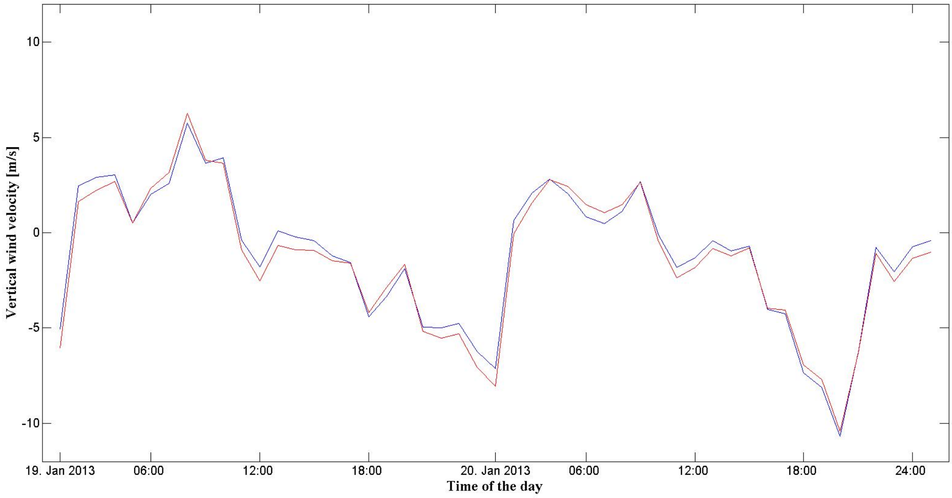

Figure 4.16: Vertical wind from January 19^{th} to 21^{st} 2013, blue is the original and red is corrected data

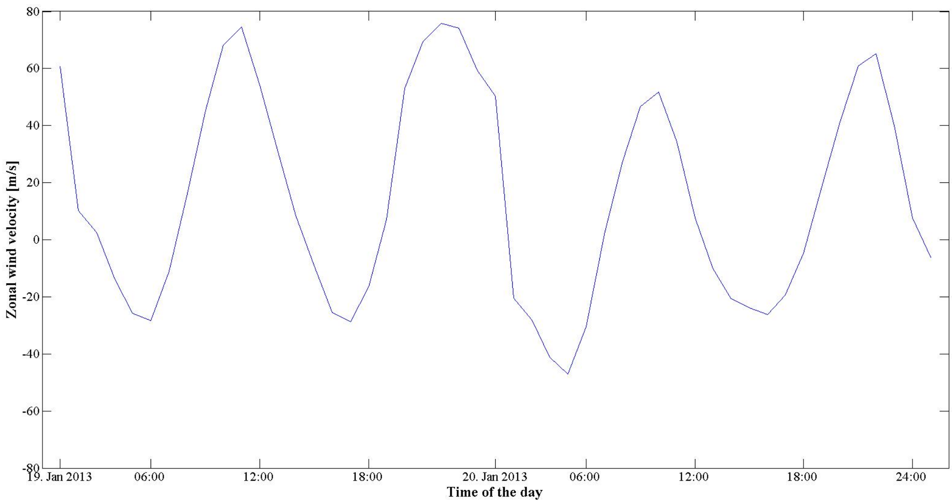

Figure 4.17: Zonal wind from January 19^{th} to 21^{st} 2013

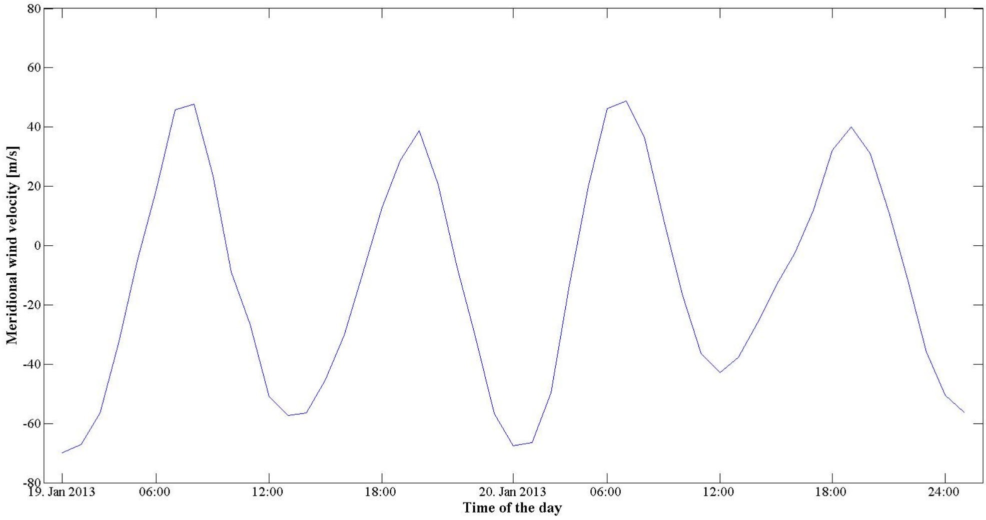

Figure 4.18: Meridional wind from January 19^{th} to 21^{st} 2013

Figure 4.16, 4.17 and 4.18 shows the vertical, zonal and meridional wind in the period between January 19^{th} and January 21^{st} 2013. In these plots it seems like the vertical velocities is oscillating with a period of approximately 24 hours while the zonal and meridional are oscillating with a period of 12 hours. This shows that the contamination of the vertical wind due to the meridional and zonal wind is not greater than other driving forces, as if the contamination was the main part the vertical component should be expected to oscillate with the same period as the meridional wind.

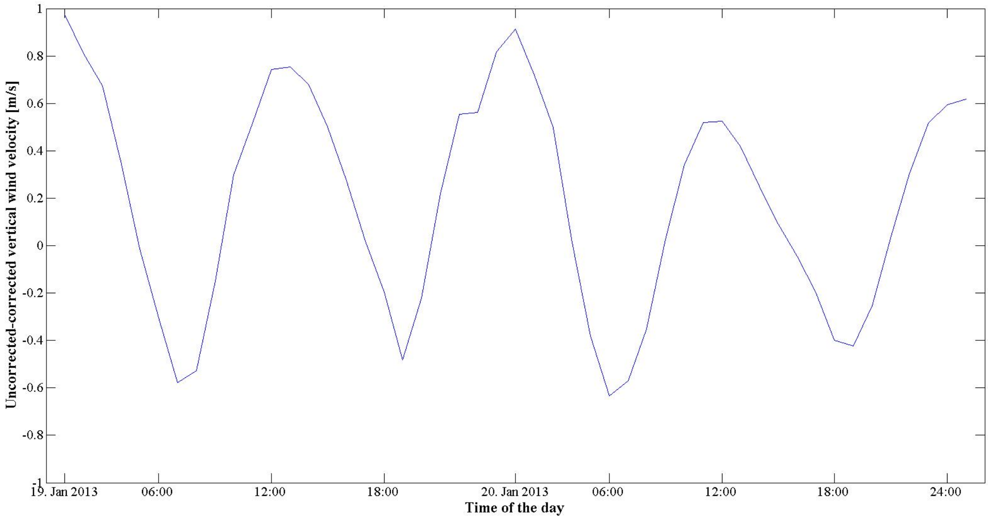

Figure 4.19: The difference in uncorrected and corrected vertical wind velocity

Figure 4.19 shows that the difference ($v_{uncorrected} - v_{corrected}$) in vertical wind speeds of the uncorrected and the corrected data. This is oscillating with the same period as the meridional wind, which is expected as the meridional tilt of the radar was found to be the largest and hence should change the vertical wind the most. When the meridional wind is directed northwards (positive values) the difference is negative and the opposite when its directed southwards, this is the result expected in section 2.2.3.

4.3.1 Background wind

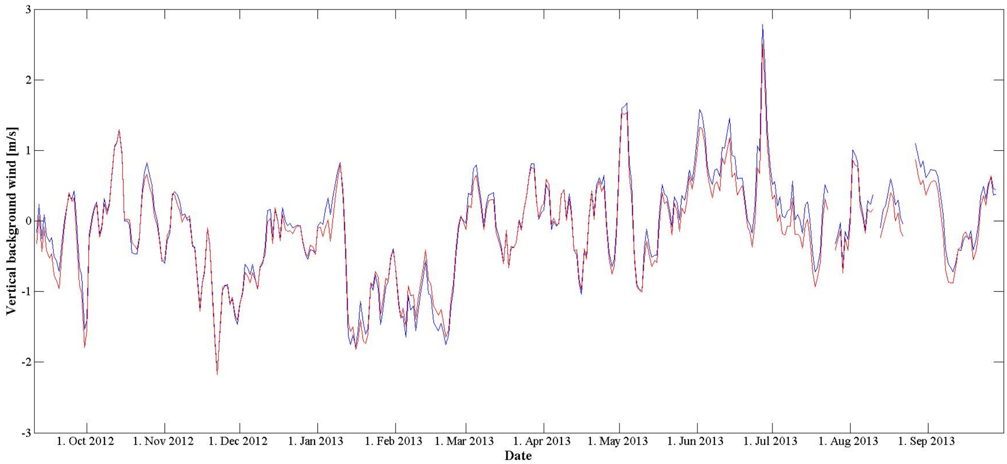

Figure 4.20: Vertical background wind over the entire year

Figure 4.20 shows large variations in the daily background wind through the entire period. It seems to be a overall downwards wind from November until March, with an especially large downwards wind during late January until late February. From March until mid May the background wind seems to vary around 0 with some spikes in both upwards and downwards direction throughout the period. From mid May to late August there seems to be a general upwards direction. The data from late July and August is having some gaps due to problems with the power amplifier of the radar.

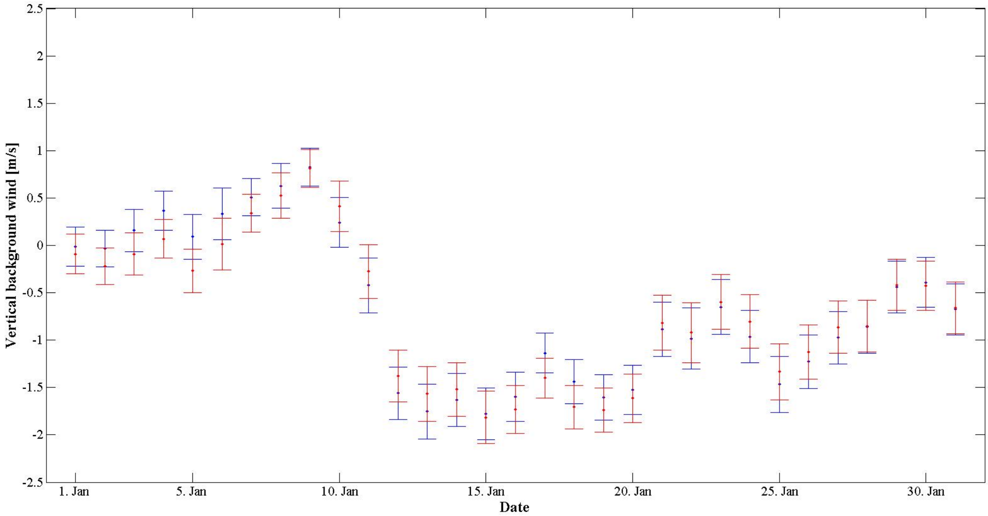

Figure 4.21: Vertical background wind over January with errorbars

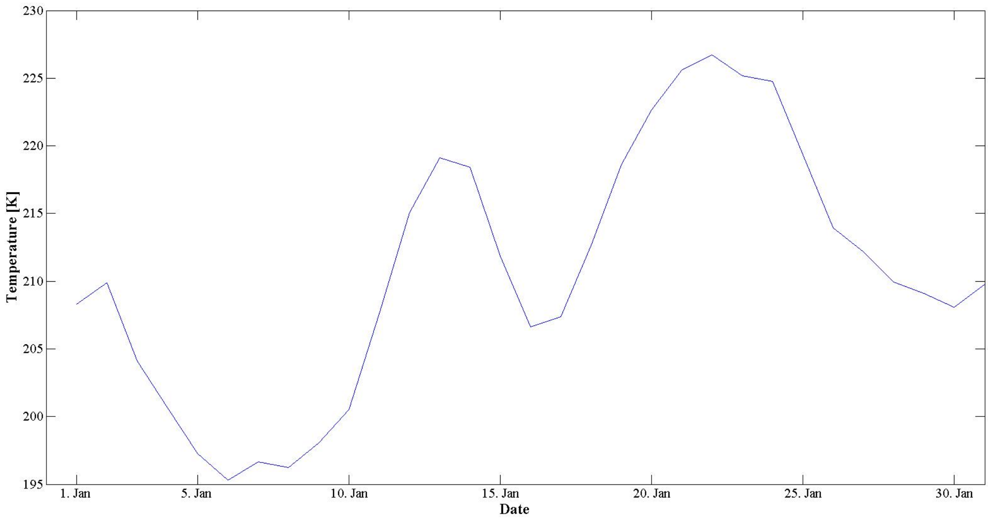

Figure 4.22: The average temperature over meteor ablation altitudes

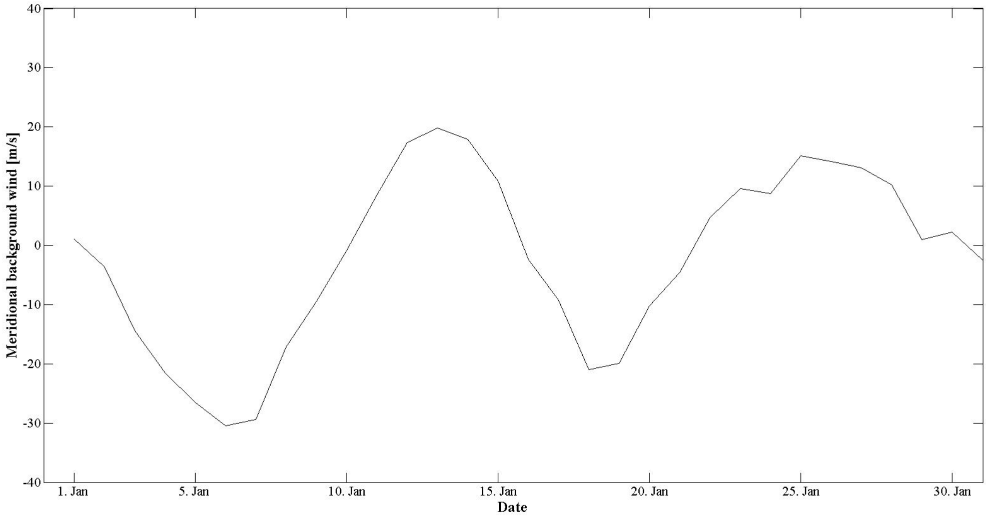

Figure 4.23: Meridional background wind in January 2013

Figure 4.21 is showing how the vertical winds in January 2013 are slowly increasing towards a strong upwards velocity until suddenly at January 10^{th} the wind is decreasing rapidly until January 13th where it settles on a strong downwards wind. This seems to be related to a sudden stratospheric warming (see Hoffmann et al. (2007) for more information) that happened around January 6^{th} 2013. The stratospheric warming can also be seen on the average temperature over meteor ablation altitudes (this is the temperature at approximately 90 km) seen in figure 4.22. It is possible to see similarities in the temperature and vertical velocity behavior, around the 10^{th} of January the temperature rises quickly and at the same time the vertical velocity is dropping from an upwards to a downwards direction, this might suggest a strong correlation between the temperature changes and the vertical wind velocities. However the second rapid rise in temperature (around January 18^{th}) is not spotted in the vertical velocity. Even though the meridional background wind was not the focus in this thesis, its worth to take notice of the similarities between the temperature (figure 4.22) and meridional background wind (figure 4.23) during January 2013.

4.3.2 Weighted mean background wind

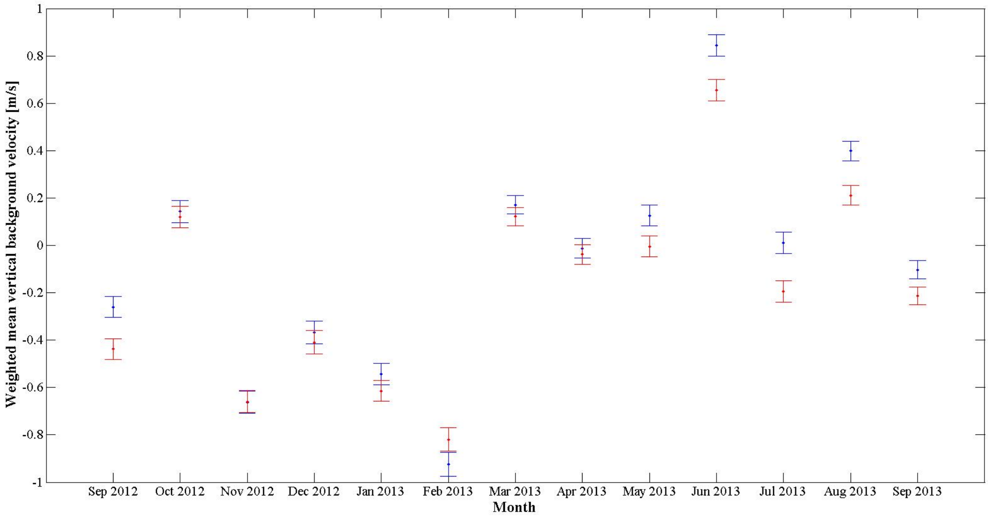

Figure 4.24: Weighted mean vertical background wind

Figure 4.24 shows that there are seasonal variations in the monthly weighted mean vertical background wind. From November to February a downwards direction of the weighted mean background wind can be seen, in March to May the motion is approximately zero before a very strong upwards motion can be seen in June. July is approximately zero while in August the direction is upwards. The corrected and uncorrected data agrees well on of the direction of the monthly weighted mean background winds, the exception is July where the uncorrected data shows a small upwards wind while the corrected data shows a stronger downwards wind. The general difference between the uncorrected and corrected monthly mean background wind seems to be an extra downwards component in the corrected winds, the exception is February where the downwards velocity of the corrected data is smaller than the downwards velocity of the uncorrected.

Table 4.1: Table of the seasonal weighted background winds

Season	uncorrected data	corrected data
	$\frac{m}{s}$	$\frac{m}{s}$
Fall 2012	$-0,07 \pm 0.03$	$-0,17 \pm 0.03$
Winter 2012/2013	$-0,62 \pm 0.02$	$-0,62 \pm 0.02$
Spring 2013	0.1 ± 0.02	0.03 ± 0.02
Summer 2013	0.42 ± 0.03	0.23 ± 0.03

In these calculations fall consist of September and October, Winter is November 2012 until February 2013, Spring is March through May and Summer is June, July and August.

The seasonal weighted mean vertical background winds seen in Table 4.1 shows a strong downwards wind in the winter, approximately zero wind in spring and upwards wind in the summer. The fall of 2012 shows approximately zero vertical wind. There are differences between the corrected and uncorrected data. The difference in general seems to be a stronger downwards and a weaker upwards velocity in the corrected data.

Chapter 5

Discussion

5.1 Tilt of the radar

The tilt of the radar was decided using two different models. The zonal tilt found from the two models were approximately the same which could indicate that the two models would be as good to use for this task. However the meridional tilt differed greatly from one model to the other. The meridional tilt found from the average zenith angle model must be treated with a lot of skepticism due to the large seasonal variations, and the tilt from this model was therefore not used in the later corrections. The error in the zenith angle model is larger than what was hoped for. The large error in both the zonal and meridional tilt is believed to be due to lack of data, and with more data available the error should be smaller.

5.2 Vertical wind

The vertical wind found did not have the same oscillation period as the meridional or zonal wind and the contamination from a possible tilt of the radar is therefore not believed to be the largest factor of the vertical winds recorded. The difference between the vertical wind found from the uncorrected and the corrected data was found to oscillate with the same period as the meridional wind velocity, which is what was expected since the meridional tilt used in the model was the greatest.

5.3 Vertical background wind

The weighted mean vertical background winds shows a downwards wind during winter and upwards wind during the summer. Spring has a small upwards wind

while fall has a small downwards wind. The direction of these winds is what to be expected by the radiative-dynamical balance models however the values are to big.
The difference in the value from what would be expected from radiative-dynamical balancing models and what is obtained in this thesis might be cause by the difference in what velocity the radar is measuring and what velocity is used in models. The radar is measuring the Eulerian mean velocity while the models are using the Lagrangian mean velocity. The difference in these are that the Lagrangian mean velocity is a vector sum of the Eulerian mean and Stokes drift due to atmospheric waves. Under similar conditions the downwards Eulerian mean vertical wind velocity found in this thesis has been explained by taking the Stokes drift into account Coy et al. (1986), however the upwards wind during summer can not be explained by the equations found by Coy et al. (1986).
Another way of interpreting the result is to think of the winds measured by the radar to be local values of a large stationary planetary wave. To look at this possibility values of the vertical winds found at Poker Flat, Alaska (65° N 147° W.) from Balsley and Riddle (1984) can be compared to the winds in this thesis. The values obtained in this thesis are overall larger than the vertical background winds found by Balsley and Riddle (1984), but still has the same order of magnitude. The direction found by Balsley and Riddle (1984) is the opposite of what was found in this thesis. This might show that the data collected at each radar is not the same as the zonally-averaged vertical velocity used in radiation balancing models, but rather local values of a large stationary planetary wave.

5.4 Future work

5.4.1 tilt of the radar

To get a more precise tilt of the radar the amount of data needs to be increased. This can be solved by letting the time go by, as this will increase the number of days worth of data that is available. Another solution to this problem might be to perform the zenith angle model on multiple layers of the atmosphere. E.g. perform it on data between 80 to 84 km, 84 to 88 km , 88 to 92 km and 92 to 96 km and then perform a gauss fit on the data collected by the 4 ranges combined.

5.4.2 Vertical background wind

The vertical background wind could be compared with more recent date data from other meteor radars at the same latitude to investigate the possibility of a large stationary planetary wave.

Chapter 6

Conclusion

In this thesis the zonal and meridional tilt of the SKiYMET Meteor Radar at Dragvoll ($63.4°$ N $10.5°$ E) has been found using two different methods.
The average zenith angle model found the zonal tilt to be 0.22 ± 0.11 degrees towards the east and the meridional tilt to be 0.09 ± 0.11 degrees towards the north. The results of this model should be treated with skepticism as the seasonal variations of especially the meridional tilt was large.
The zenith angle model found the zonal tilt to be 0.15 ± 0.21 degrees towards the east and the meridional tilt to be 0.62 ± 0.24 degrees towards the south.
The tilt found from the zenith angle model was used to investigate the changes such a tilt would cause to the meridional, zonal and vertical winds. The changes to the zonal and meridional wind was neglectable. The changes this tilt had on the vertical wind showed an oscillation with the same period as the meridional winds. The vertical wind seemed to have a major oscillation period of 24 hours while the meridional and zonal winds had a major oscillation period of 12 hour. The daily vertical background wind was obtained and analyzed. The seasonal weighted mean vertical background wind was found. Fall 2012 had a -0.07 ± 0.03 $\frac{m}{s}$ wind for the uncorrected (without the change in azimuth and zenith angle due to the tilt found) and -0.17 ± 0.03 $\frac{m}{s}$ for the corrected data, winter 2012/2013 had -0.62 ± 0.02 $\frac{m}{s}$ wind for both the uncorrected and corrected data, spring had 0.1 ± 0.02 $\frac{m}{s}$ wind for the uncorrected and 0.03 ± 0.02 $\frac{m}{s}$ for corrected and the summer of 2013 had 0.42 ± 0.03 $\frac{m}{s}$ for uncorrected and 0.23 ± 0.03 $\frac{m}{s}$ for corrected.

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Lawrence Coy, J Weinstock, and David C Fritts. The stokes drift due to vertically propagating internal gravity waves in a compressible atmosphere. *Journal of Atmospheric Sciences*, 43:2636–2643, 1986.

P Hoffmann, W Singer, D Keuer, WK Hocking, M Kunze, and Y Murayama. Latitudinal and longitudinal variability of mesospheric winds and temperatures during stratospheric warming events. *Journal of Atmospheric and Solar-Terrestrial Physics*, 69(17):2355–2366, 2007.

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Appendix A

MATLAB code

A.1 Average Zenith

A.2 Horizontal Wind Fit

```
function [uWind,wWind,uWindMin,uWindMax,wWindMin,
    wWindMax,AvgHeight,noOfMet,AvgZen] = fitWind(
    Height,inc,Data,timer,k,originalAzi,originalZen)
     AvgHeight = zeros(1,24);
     AvgZen = zeros(1,24);
     noOfMet = zeros(1,24);
     uWind = zeros(1,24);
     wWind = zeros(1,24);
     uWindMin = zeros(1,24);
     uWindMax = zeros(1,24);
     wWindMin = zeros(1,24);
     wWindMax = zeros(1,24);
     timeMat = zeros(1,24);
     ConfConst = 0.682;
     HeightInd = findInd(inc,Data,Height,k,originalZen)
         ;
     for time = 1:24
         [startAt,endAt,testEnough] = FindTimeInd(timer
             (HeightInd), time-1);
         if testEnough == 0;
```

```
            AvgHeight(time) = mean(Data{5}(HeightInd(startAt:endAt)));
            AvgZen(time) = mean(Data{8}(HeightInd(startAt:endAt)));
            noOfMet(time) = length(Data{5}(HeightInd(startAt:endAt)));
            x = Data{8}(HeightInd(startAt:endAt))*pi/180;
            y = Data{9}(HeightInd(startAt:endAt))*pi/180;
            z = Data{6}(HeightInd(startAt:endAt));
            [xData, yData, zData] = prepareSurfaceData(x,y,z);
            ft = fittype( 'u*sin(x)*cos(y) + v*sin(x)*sin(y)', 'independent', {'x', 'y'}, 'dependent', 'z' );
            opts = fitoptions( ft );
            opts.Display = 'Off';
            opts.Lower = [-Inf -Inf];
            opts.StartPoint = [0.0975404049994095 0.278498218867048];
            opts.Upper = [Inf Inf];
            fitInfo = fit( [xData, yData], zData, ft, opts);
            TempCoeff = coeffvalues(fitInfo);
            uWind(time) = TempCoeff(1);
            wWind(time) = TempCoeff(2);
            TempConfinterval = confint(fitInfo, ConfConst);
            uWindMin(time) = uWind(time)-TempConfinterval(1);
            uWindMax(time) = TempConfinterval(2)-uWind(time);
            wWindMin(time) = wWind(time)-TempConfinterval(3);
            wWindMax(time) = TempConfinterval(4)-wWind(time);
            timeMat(time) = time;
        else
            uWind(time) = NaN;
```

```
            wWind(time) = NaN;
            uWindMin(time) = NaN;
            wWindMin(time) = NaN;
            uWindMax(time) = NaN;
            wWindMax(time) = NaN;
            AvgHeight(time) = NaN;
            noOfMet(time) = NaN;
            AvgZen(time) = NaN;
        end
    end
end
```

A.3 Vertical Wind Fit

```
function [uWind,vWind,uWindMin,uWindMax,vWindMin,
   vWindMax,wWind,wWindMin,wWindMax,AvgHeight,noOfMet,
   AvgZen] = fitVertWind(Height,inc,Data,timer,
   originalZen)
    AvgHeight = zeros(1,24);
    AvgZen = zeros(1,24);
    noOfMet = zeros(1,24);
    uWind = zeros(1,24);
    vWind = zeros(1,24);
    wWind = zeros(1,24);
    uWindMin = zeros(1,24);
    uWindMax = zeros(1,24);
    vWindMin = zeros(1,24);
    vWindMax = zeros(1,24);
    wWindMin = zeros(1,24);
    wWindMax = zeros(1,24);
    timeMat = zeros(1,24);
    ConfConst = 0.682;
    HeightInd = findInd(inc,Data,Height,originalZen);
    for time = 1:24
        [startAt,endAt,testEnough] = FindTimeInd(timer
            (HeightInd), time-1);
        if testEnough == 0;
            AvgHeight(time) = mean(Data{5}(HeightInd(
                startAt:endAt)));
```

```
        AvgZen(time) = mean(Data{8}(HeightInd(startAt:endAt)));
        noOfMet(time) = length(Data{5}(HeightInd(startAt:endAt)));
        x = Data{8}(HeightInd(startAt:endAt))*pi/180;
        y = Data{9}(HeightInd(startAt:endAt))*pi/180;
        z = Data{6}(HeightInd(startAt:endAt));
        [xData, yData, zData] = prepareSurfaceData(x,y,z);
        ft = fittype( 'u*sin(x)*cos(y) + v*sin(x)*sin(y) + w*cos(x)', 'independent', {'x', 'y'}, 'dependent', 'z' );
        opts = fitoptions( ft );
        opts.Display = 'Off';
        opts.Lower = [-Inf -Inf -Inf];
        opts.StartPoint = [0.485375648722841 0.8002804688888 0.141886338627215];
        opts.Upper = [Inf Inf Inf];
        fitInfo = fit( [xData, yData], zData, ft, opts);
        TempCoeff = coeffvalues(fitInfo);
        uWind(time) = TempCoeff(1);
        vWind(time) = TempCoeff(2);
        wWind(time) = TempCoeff(3);
        TempConfinterval = confint(fitInfo, ConfConst);
        uWindMin(time) = uWind(time)-TempConfinterval(1);
        uWindMax(time) = TempConfinterval(2)-uWind(time);
        vWindMin(time) = vWind(time)-TempConfinterval(3);
        vWindMax(time) = TempConfinterval(4)-vWind(time);
        wWindMin(time) = wWind(time)-TempConfinterval(5);
        wWindMax(time) = TempConfinterval(6)-wWind(time);
```

```
            timeMat(time) = time;
        else
            uWind(time) = NaN;
            vWind(time) = NaN;
            wWind(time) = NaN;
            uWindMin(time) = NaN;
            vWindMin(time) = NaN;
            uWindMax(time) = NaN;
            vWindMax(time) = NaN;
            wWindMin(time) = NaN;
            wWindMax(time) = NaN;
            AvgHeight(time) = NaN;
            noOfMet(time) = NaN;
            AvgZen(time) = NaN;
        end
    end
end
```

A.4 AverageZenith

```
function [averageZenith,stderrZenith,stddevZenith,
    mntlydeltaMeanZen,mntlyStd,mntlyStdErr,
    monthlydiffStdErr,wgtTotMean,wgtTotStdDev,
    wgtTotStdErr] = AverageZenith()
    a = datenum({'10-sep-2012 00:00:00';'30-sep-2013
        00:00:00'});
    list = datevec(a(1):a(2));
    monthDays =
        [1,21,52,82,113,144,172,203,233,264,294,325,356,386];

    height=88;
    inc = 4;
    for i = 1:length(list(:,1))
        Data = getData(list,i);
        for k = 1:2
            inds = findInd(Data,k,height,inc);
            averageZenith{k}(i) = mean(Data{8}(inds));
            stderrZenith{k}(i) = std(Data{8}(inds))/
                sqrt(length(Data{8}(inds)));
            stddevZenith{k}(i) = std(Data{8}(inds));
```

```
        end
    end
    for i = 1:(length(monthDays)-1)
        for k = 1:2
            mntlydeltaMeanZen{k}(i) = nansum(averageZenith{k}(monthDays(i):(monthDays(i+1)-1))./stddevZenith{k}((monthDays(i):(monthDays(i+1)-1))).^2)/nansum(1./stddevZenith{k}((monthDays(i):(monthDays(i+1)-1))).^2);
            mntlyStd{k}(i) = sqrt(1/nansum(1./stddevZenith{k}((monthDays(i):(monthDays(i+1)-1))).^2));
            mntlyStdErr{k}(i) = mntlyStd{k}(i)/sqrt(monthDays(i+1)-monthDays(i));
            monthlydiffStdErr(i) = sqrt(mntlyStd{1}(i)^2+mntlyStd{1}(i)^2)/sqrt(monthDays(i+1)-monthDays(i));
        end
    end
    for k = 1:2
            wgtTotMean{k} = nansum(mntlydeltaMeanZen{k}./mntlyStd{k}.^2)/nansum(1./mntlyStd{k}.^2);
            wgtTotStdDev{k} = sqrt(1/nansum(1./mntlyStd{k}.^2));
            wgtTotStdErr{k} = wgtTotStdDev{k}/sqrt(length(mntlydeltaMeanZen{k}));

    end
%           for k = 1:2
%                wgtTotMean{k} = nansum(averageZenith{k}./stddevZenith{k}.^2)/nansum(1./stddevZenith{k}.^2);
%                wgtTotStdDev{k} = sqrt(1/nansum(1./stddevZenith{k}.^2));
%                wgtTotStdErr{k} = wgtTotStdDev{k}/sqrt(length(stddevZenith{k}));

end
```

```
function [Data] = getData(dates,i)
    fileName = strcat('E:\Skole\Master2013\MPD-Data\mp',sprintf('%02d',dates(i,1)),sprintf('%02d',dates(i,2)),sprintf('%02d',dates(i,3)),'.trondheim.mpd');
    fileID = fopen(fileName);
    Data = textscan(fileID,'%s %s %s %f %f %f %f %f %f %f %f %f %f %f %f %f %f','Headerlines',29);
    fclose(fileID);
end

function y = findInd(data,k,height,inc)
     if k == 1
         y = find(data{10} == 1 & data{5}<=height + inc & data{5}>=height & data{8}<=60 & data{8} >= 15 & data{9} <=270 & data{9} >=90);
     else
         y = find(data{10} == 1 & data{5}<=height + inc & data{5}>=height & data{8}<=60 & data{8} >= 15 & (data{9}<90 | data{9}> 270));
     end
end
```

A.5 Zenith Angle Model

A.5.1 Change coordinates of meteor detection

Code for change in west-east direction

```
function [AzimuthsNew,ZenithsNew] = fixZenAndAziWestEast(Azimuths,Zeniths,deltaZen)
    AzimuthsNew = zeros(1,length(Azimuths));
    ZenithsNew = zeros(1,length(Zeniths));
    for k = 1:4
        if k == 1;
            inds = find(Azimuths < 90*k & Azimuths >=90*(k-1));
            AzimuthsNew(inds) = atan(sin(Azimuths(inds)*pi/180)./(cos(Azimuths(inds)*pi/180)+deltaZen./Zeniths(inds)))*180/pi;
```

```
        ZenithsNew(inds) = sqrt((cos(Azimuths(inds)*pi/180).*Zeniths(inds)+deltaZen).^2+(sin(Azimuths(inds)*pi/180).*Zeniths(inds)).^2);
        if deltaZen < 0
            testInds = find(cos(Azimuths(inds)*pi/180).*Zeniths(inds) < abs(deltaZen));
            if ~isempty(testInds);
                ZenithsNew(inds(testInds)) = sqrt((abs(deltaZen)-cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2+(sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2);
                AzimuthsNew(inds(testInds)) = atan((abs(deltaZen)-cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))./(sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))).*180/pi + 90;
            end
        end
    elseif k == 2;
        inds = find(Azimuths < 90*k & Azimuths >=90*(k-1));
        Azimuths(inds) = Azimuths(inds)-90*(k-1);
        AzimuthsNew(inds) = atan((sin(Azimuths(inds)*pi/180)-deltaZen./Zeniths(inds))./(cos(Azimuths(inds)*pi/180)))*180/pi;
        ZenithsNew(inds) = sqrt((sin(Azimuths(inds)*pi/180).*Zeniths(inds)-deltaZen).^2+(cos(Azimuths(inds)*pi/180).*Zeniths(inds)).^2);
        AzimuthsNew(inds) = AzimuthsNew(inds) + 90*(k-1);
        if deltaZen > 0
```

```
            testInds = find(sin(Azimuths(inds)*pi/180).*Zeniths(inds) < abs(deltaZen));
            if ~isempty(testInds);
                ZenithsNew(inds(testInds)) = sqrt((abs(deltaZen)-sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2+(cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2);
                AzimuthsNew(inds(testInds)) = atan(cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))./(abs(deltaZen)-sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))).*180/pi;
            end
        end
        Azimuths(inds) = Azimuths(inds)+90*(k-1);
    elseif k == 3;
        inds = find(Azimuths < 90*k & Azimuths >=90*(k-1));
        Azimuths(inds) = Azimuths(inds)-90*(k-1);
        AzimuthsNew(inds) = atan(sin(Azimuths(inds)*pi/180)./(cos(Azimuths(inds)*pi/180)-deltaZen./Zeniths(inds)))*180/pi;
        ZenithsNew(inds) = sqrt((cos(Azimuths(inds)*pi/180).*Zeniths(inds)-deltaZen).^2+(sin(Azimuths(inds)*pi/180).*Zeniths(inds)).^2);
        AzimuthsNew(inds) = AzimuthsNew(inds) + 90*(k-1);
        if deltaZen > 0
            testInds = find(cos(Azimuths(inds)*pi/180).*Zeniths(inds) < abs(deltaZen));
            if ~isempty(testInds);
```

```
                ZenithsNew(inds(testInds)) = sqrt((abs(deltaZen)-cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2+(sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2);
                AzimuthsNew(inds(testInds)) = atan((abs(deltaZen)-cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))./(sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))).*180/pi + 270;
            end
        end
        Azimuths(inds) = Azimuths(inds)+90*(k-1);
    elseif k == 4;
        inds = find(Azimuths < 90*k & Azimuths >=90*(k-1));
        Azimuths(inds) = Azimuths(inds)-90*(k-1);
        AzimuthsNew(inds) = atan((sin(Azimuths(inds)*pi/180)+deltaZen./Zeniths(inds))./(cos(Azimuths(inds)*pi/180)))*180/pi;
        ZenithsNew(inds) = sqrt((sin(Azimuths(inds)*pi/180).*Zeniths(inds)+deltaZen).^2+(cos(Azimuths(inds)*pi/180).*Zeniths(inds)).^2);
        AzimuthsNew(inds) = AzimuthsNew(inds) + 90*(k-1);
        if deltaZen < 0
            testInds = find(sin(Azimuths(inds)*pi/180).*Zeniths(inds) < abs(deltaZen));
            if ~isempty(testInds);
                ZenithsNew(inds(testInds)) = sqrt((abs(deltaZen)-sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2+(cos(Azimuths(inds(testInds)).*
```

```
pi/180).*Zeniths(inds(testInds))).^2);
                AzimuthsNew(inds(testInds)) = 270-atan((abs(deltaZen)-sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))./(cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))).*180/pi;
            end
        end
        Azimuths(inds) = Azimuths(inds)+90*(k-1);
    end
end
AzimuthsNew = AzimuthsNew.';
ZenithsNew = ZenithsNew.';
end
```

Code for change in the north-south direction

```
function [AzimuthsNew,ZenithsNew] = fixZenAndAziWestEast(Azimuths,Zeniths,deltaZen)
    AzimuthsNew = zeros(1,length(Azimuths));
    ZenithsNew = zeros(1,length(Zeniths));
    for k = 1:4
        if k == 1;
            inds = find(Azimuths < 90*k & Azimuths >=90*(k-1));
            AzimuthsNew(inds) = atan(sin(Azimuths(inds)*pi/180)./(cos(Azimuths(inds)*pi/180)+deltaZen./Zeniths(inds)))*180/pi;
            ZenithsNew(inds) = sqrt((cos(Azimuths(inds)*pi/180).*Zeniths(inds)+deltaZen).^2+(sin(Azimuths(inds)*pi/180).*Zeniths(inds)).^2);
            if deltaZen < 0
                testInds = find(cos(Azimuths(inds)*pi/180).*Zeniths(inds) < abs(deltaZen));
                if ~isempty(testInds);
```

```
                ZenithsNew(inds(testInds)) = sqrt((abs(deltaZen)-cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2+(sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2);
                AzimuthsNew(inds(testInds)) = atan((abs(deltaZen)-cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))./(sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))).*180/pi + 90;
            end
        end
    elseif k == 2;
        inds = find(Azimuths < 90*k & Azimuths >=90*(k-1));
        Azimuths(inds) = Azimuths(inds)-90*(k-1);
        AzimuthsNew(inds) = atan((sin(Azimuths(inds)*pi/180)-deltaZen./Zeniths(inds))./(cos(Azimuths(inds)*pi/180)))*180/pi;
        ZenithsNew(inds) = sqrt((sin(Azimuths(inds)*pi/180).*Zeniths(inds)-deltaZen).^2+(cos(Azimuths(inds)*pi/180).*Zeniths(inds)).^2);
        AzimuthsNew(inds) = AzimuthsNew(inds) + 90*(k-1);
        if deltaZen > 0
            testInds = find(sin(Azimuths(inds)*pi/180).*Zeniths(inds) < abs(deltaZen));
            if ~isempty(testInds);
                ZenithsNew(inds(testInds)) = sqrt((abs(deltaZen)-sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2+(cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))
```

```
)).^2);
            AzimuthsNew(inds(testInds)) = atan(cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))./(abs(deltaZen)-sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))).*180/pi;
        end
    end
    Azimuths(inds) = Azimuths(inds)+90*(k-1);
elseif k == 3;
    inds = find(Azimuths < 90*k & Azimuths >=90*(k-1));
    Azimuths(inds) = Azimuths(inds)-90*(k-1);
    AzimuthsNew(inds) = atan(sin(Azimuths(inds)*pi/180)./(cos(Azimuths(inds)*pi/180)-deltaZen./Zeniths(inds)))*180/pi;
    ZenithsNew(inds) = sqrt((cos(Azimuths(inds)*pi/180).*Zeniths(inds)-deltaZen).^2+(sin(Azimuths(inds)*pi/180).*Zeniths(inds)).^2);
    AzimuthsNew(inds) = AzimuthsNew(inds) + 90*(k-1);
    if deltaZen > 0
        testInds = find(cos(Azimuths(inds)*pi/180).*Zeniths(inds) < abs(deltaZen));
        if ~isempty(testInds);
            ZenithsNew(inds(testInds)) = sqrt((abs(deltaZen)-cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2+(sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2);
            AzimuthsNew(inds(testInds)) = atan((abs(deltaZen)-cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))./(sin(
```

```
                        Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))).*180/pi + 270;
            end
        end
        Azimuths(inds) = Azimuths(inds)+90*(k-1);
    elseif k == 4;
        inds = find(Azimuths < 90*k & Azimuths >=90*(k-1));
        Azimuths(inds) = Azimuths(inds)-90*(k-1);
        AzimuthsNew(inds) = atan((sin(Azimuths(inds)*pi/180)+deltaZen./Zeniths(inds))./(cos(Azimuths(inds)*pi/180)))*180/pi;
        ZenithsNew(inds) = sqrt((sin(Azimuths(inds)*pi/180).*Zeniths(inds)+deltaZen).^2+(cos(Azimuths(inds)*pi/180).*Zeniths(inds)).^2);
        AzimuthsNew(inds) = AzimuthsNew(inds) + 90*(k-1);
        if deltaZen < 0
            testInds = find(sin(Azimuths(inds)*pi/180).*Zeniths(inds) < abs(deltaZen));
            if ~isempty(testInds);
                ZenithsNew(inds(testInds)) = sqrt((abs(deltaZen)-sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2+(cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds))).^2);
                AzimuthsNew(inds(testInds)) = 270-atan((abs(deltaZen)-sin(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))./(cos(Azimuths(inds(testInds)).*pi/180).*Zeniths(inds(testInds)))).*180/pi;
            end
        end
```

```
                Azimuths(inds) = Azimuths(inds)+90*(k-1);
            end
        end
        AzimuthsNew = AzimuthsNew.';
        ZenithsNew = ZenithsNew.';
end
```

A.5.2 Find zonal and meridional winds for different tilts

```
function [uWind,wWind,uWindMin,uWindMax,wWindMin,
    wWindMax,AvgZen,noOfMet] =
    ChangeZenithHourlyNorthSouth()
    a = datenum({'10-sep-2012 00:00:00';'30-sep-2013
        00:00:00'});
    list = datevec(a(1):a(2));
    Height = 88;
    inc = 4;
    for i = 1:length(list(:,1))
        disp(list(i,:));
        Data = getData(list,i);
        timer = str2double(strtok(Data{2},':'));
        originalZen = Data{8};
        originalAzi = Data{9};
        for k = 1:2
            j = 1;
            for deltaZen = -20:0.1:20
                [Data{9},Data{8}] = fixZenAndAzi(
                    originalAzi,originalZen,deltaZen);
                [uWind{k}{j}(1+24*(i-1):24+24*(i-1)),
                    wWind{k}{j}(1+24*(i-1):24+24*(i-1))
                    ,uWindMin{k}{j}(1+24*(i-1):24+24*(i
                    -1)),uWindMax{k}{j}(1+24*(i-1)
                    :24+24*(i-1)),wWindMin{k}{j}(1+24*(
                    i-1):24+24*(i-1)),wWindMax{k}{j
                    }(1+24*(i-1):24+24*(i-1)),avgHeight
                    {k}{j}(1+24*(i-1):24+24*(i-1)),
                    noOfMet{k}{j}(1+24*(i-1):24+24*(i
                    -1)),AvgZen{k}{j}(1+24*(i-1)
                    :24+24*(i-1))] = fitWind(Height,inc
                    ,Data,timer,k,originalAzi,
```

```
                    originalZen);
                j = j + 1;
            end
        end
    end
end
```

A.5.3 Find the tilt that minimizes the difference in u and v

```
function [nEl,centers,nElAll,centersAll] =
    FindMinChangeZenithHourlyWestEast(uWind,uWindMax)
deltaZen = -20:0.1:20;
monthDays =
    [0,21,52,82,113,144,172,203,233,264,294,325,356,386];

numNaN = 0;
normal = 0;
numUnder = 0;
numOver = 0;
months = cellstr(['10. to 30. September 2012';'1. to
    31. October 2012   ';'1. to 30. November 2012  ';'
    1. to 31. Desember 2012  ';'1. to 31. January 2013
      ';'1. to 28. February 2013  ';'1. to 31. March
    2013     ';'1. to 30. April 2013     ';'1. to 31.
    May 2013        ';'1. to 30. June 2013       ';'1. to
     31. July 2013       ';'1. to 31. August 2013    ';'
    1. to 30. September 2013 ']);
    for i = 1:length(uWind{1}{1})
        for k = 1:length(deltaZen)
            if uWindMax{1}{k}(i)<5 && uWindMax{2}{k}(i
                )<5 && abs(uWind{1}{k}(i)-uWind{2}{k}(i
                )) <0.5
                    Diff(k) = uWind{1}{k}(i)-uWind{2}{k}(
                        i);
                    err1(k) = uWindMax{1}{k}(i);
                    err2(k) = uWindMax{2}{k}(i);
                    normal = normal + 1;
             else
                    Diff(k) = NaN;
                   numNaN = numNaN + 1;
             end
```

```
            end
        if length(find(isnan(Diff)))==length(Diff)
            error1(i) = NaN;
            error2(i) = NaN;
            minDiff(i) = NaN;
            minDeltaZen(i) = NaN;
        else
            [minimumDiff(i),minInd] = min(sqrt(Diff
                .^2));
            error1(i) = uWindMax{1}{minInd}(i);
            error2(i) = uWindMax{2}{minInd}(i);
            minDiff(i) = Diff(minInd);
            minDeltaZen(i) = deltaZen(minInd);
        end
    end
     [nElAll,centersAll] = hist(minDeltaZen,21);
     hist(minDeltaZen,21)
     for i = 1:(length(monthDays)-1)
         figure
         [nEl{i},centers{i}] = hist(minDeltaZen(1+
             monthDays(i)*24:monthDays(i+1)*24),21);
     end

end
```

A.6 Load data from .mpd file

```
function [Data] = getData(dates,i)
    fileName = strcat('E:\Skole\Master2013\MPD-Data\mp
        ',sprintf('%02d',dates(i,1)),sprintf('%02d',
        dates(i,2)),sprintf('%02d',dates(i,3)),'.
        trondheim.mpd');
    fileID = fopen(fileName);
    Data = textscan(fileID,'%s %s %s %f %f %f %f %f %f
        %f %f %f %f %f %f %f %f','Headerlines',29);
    fclose(fileID);
end
```

A.7 Find indices for both time and height

A.7.1 Time indices

```
function [startAt,endAt,testEnough] = FindTimeInd(timer, time)
    testEnough = 0;
    x = find(timer <= (time + 1) & timer >= (time-1));
    if length(x) <= 4
        testEnough = 1;
        startAt = 0;
        endAt = 0;
    else
        startAt = x(1);
        endAt = x(length(x));
    end
end
```

A.7.2 Height indices

```
function y = findInd(inc,data,height,originalZen)
        y = find(data{10} == 1 & data{5}<=height + inc & data{5}>=height & originalZen<=60 & originalZen >= 15); %
end
```