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The sodar as a screening instrument

Comparison with cup anemometer measurements and long-term correction studies

Anders Nilsson

ABSTRACT

The sodar as a screening instrument - Comparison with cup anemometer measurements and long-term correction studies
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A site assessment including wind measurements is of major importance when planning a wind farm. Small differences in wind speed can determine if a project will be economically viable since the power in the wind is proportional to the cube of the wind speed. It is also important to have knowledge about the long-term wind climate since the technical lifetime of a wind turbine is about 20 - 25 years.

Traditionally, masts mounted with cup anemometers and wind wanes have been used for wind measurements during site assessments. However, an instrument called sodar which measures the wind based on sound waves has entered the market some years ago and offers some advantages in terms of e.g. mobility compared to the mast equipped with cup anemometers and wind vanes. Since the sodar is a relatively new instrument in the wind energy business, it is important to gain knowledge on how the instrument operates and its performance. To do that, sodar measurements have been compared to wind measurements performed by a cup anemometer and a wind vane.

In order to estimate the long-term wind climate at a site, a long-term calculation is performed based on short-term measurements from the site and a long-term reference wind data. At least one year of wind measurements at the site are needed in order to obtain a valid result from the calculation. However, for an early evaluation of a site it is desirable to measure the wind for a shorter period of time. Therefore, it has been studied in this thesis how the result of the long-term correction depends on the length of the site measurement period. The seasonal impact on the results has also been studied to distinguish what season is the most suitable for short measurements.

According to the results, the measurements performed by the sodar used in this study are as valid as those performed by the cup anemometer and the wind vane. Considering the advantages with the sodar compared to the mast equipped with cup anemometers and wind vanes, the sodar is the preferable choice.

The results from the long-term correction calculations improve most rapidly during the first four months of measurements. It is therefore important to measure the wind for at least four months. Best results are obtained when the measurements are performed during the spring and the autumn compared to the summer and the winter.

Keywords: Sodar, long-term correction, wind measurement, wind power

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REFERAT

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En platsbedömning innehållande vindmätningar är en mycket viktig del i projekteringen av en vindkraftspark. Eftersom effekten i vinden är proportionell mot vindhastigheten i kubik kan små variationer i vindhastighet avgöra om ett projekt blir ekonomiskt hållbart. Det är också viktigt att ha kunskap om det långsiktiga vindklimatet då ett vindkraftverks tekniska livslängd är 20 - 25 år.

Traditionellt sett har mätmaster utrustade med skålkorsanemometrar och vindfanor använts för att mäta vinden vid platsbedömningar. För några år sedan har dock ett mätinstrument som kallas sodar slagit sig in på marknaden. Detta instrument använder en teknik som bygger på ljudvågor och erbjuder fördelar i t.ex. mobilitet jämfört med mätmasten utrustad med skålkorsanemometrar och vindfanor. Då sodar är ett relativt nytt instrument i vindkraftsbranschen är det viktigt att skaffa sig kunskap om hur instrumentet fungerar och vilken prestanda det har. Av denna anledning har vindmätningar med sodar jämförts med vindmätningar gjorda med skålkorsanemometer och vindfana.

För att uppskatta det långsiktiga vindklimatet på en plats utförs en långtidskorrigering baserad på kortidsmätningar från den aktuella platsen och vinddata från en längre tidsperiod. Det krävs minst ett års vindmätningar från platsen för att erhålla säkra resultat från långtidskorrigeringen, men för en tidig utvärdering är det önskvärt att mäta vinden under en kortare period. Därmed har det i denna rapport studerats hur resultatet av en långtidskorrektion beror av längden på mätperioden. Det har också studerats om det finns ett årstidsberoende i resultatet som kan visa på vilken årstid som är mest lämpad för korta mätningar.

Enligt resultaten håller vindmätningar utförda med den sodar som användes i denna rapport lika hög prestanda som vindmätningar utförda med skålkorsanemometer och vindfana. En sodar är då att föredra framför en mast utrustad med skålkorsanemometer och vindfana med tanke på sodarinstrumentets praktiska fördelar.

Resultaten av långtidskorrektionerna förbättras markant under de fyra första månaderna av mätningar vilket innebär att det är viktigt att mäta vinden i minst fyra månader. Bäst resultat erhålls då mätningarna utförs under vår och höst jämfört med under sommar och vinter.

Nyckelord: Sodar, långtidskorrektion, vindmätning, vindkraft

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PREFACE

This Master Thesis was performed at Nordex Sverige AB as a completion of the Aquatic and Environmental Engineering program at Uppsala University. The thesis comprises 30 ECTS. Supervisor was Kristian Baurne, Project Engineer at Nordex Sverige AB and subject reviewer was Hans Bergström, PhD in meteorology at the Department of Earth Science, Air, Water and Landscape Science, Uppsala University.

I would like to thank the team at Nordex Sverige AB for the good time at their office and Michael Henriksson for providing me with this opportunity. Special thanks to Kristian Baurne for excellent supervision and all the effort he has put in to my work. I would also like to thank Hans Bergström, Mats Hurtig at AQSystem, Niklas Sondell at Storm Weather Center, Frank Gross at Nordex Energy GmBH and Barry Neal at Atmospheric Research & Technology, LLC, Hawaii for providing me with information and valuable input. Finally, I would like to thank Beau Boekhout for many laughs at the office and for proofreading of this report.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Sodar som ett screeninginstrument - Jämförelse mot mätningar med skålkorsanemometer och studier av långtidskorrigeringar.
Anders Nilsson

Vindkraft är en förnyelsebar energikälla där den kinetiska energin i vinden omvandlas till elektricitet. 2008 var Sveriges årliga produktion av elektricitet från vindkraft är 1,6 TWh men regeringen har som mål med vindkraft att årligen producera 30 TWh år 2020. Detta innebär att det planeras för en omfattande utbyggnad av vindkraften i Sverige.

När en vindkraftspark skall byggas är det viktigt att en utförlig platsbedömning genomförs. Denna platsbedömning består av allt från att beräkna ljudutbredning från verken till att inventera fåglar och fladdermöss, men framförallt utförs vindmätningar för att kunna beräkna hur mycket energi det går att få ut från den aktuella platsen. Om det inte blåser tillräckligt mycket på den tänkta platsen är det ingen idé att bygga några vindkraftverk då det inte kommer att vara ekonomiskt lönsamt. Eftersom vindkraftverk har en livstid på 20 – 25 år är det viktigt att ha kännedom om det långsiktiga vindklimatet då detta kan ändras mycket från år till år.

Vindmätningar har traditionellt sett utförts med mätmaster utrustade med skålkorsanemometrar och vindfanor på olika höjder. Nackdelen med denna metod är att den praktiskt sett inte är mobil för att flyttas till en annan plats samt att den enbart ger uppgifter om vindhastighet och vindriktning på de höjder som det finns mätutrustning på. Ett nytt sätt att utvärdera vindklimatet på en plats är att använda en sodar. Sodar står för Sound Detecting and Ranging och mäter vindhastighet och vindriktning genom att skicka ut ljudpulser och analysera de mottagna ekona. Denna metod erbjuder en del fördelar jämfört med det traditionella sättet att mäta vind på, bl.a. en vindprofil upp till 200 m med ett värde för hastighet och riktning var femte meter. Eftersom en sodar ryms på en släpvagn är den även mobil och kan lätt flyttas mellan olika platser.

Då det är otänkbart att mäta vinden under 20 – 25 år för att få kunskap om det långsiktiga vindklimatet på en plats utförs en så kallad långtidskorrigering av vinddata. I en långtidskorrigering kombineras vindmätningen från den tänkta platsen med en vindreferens som t.ex. kan vara en närliggande vindmätning som pågått under längre tid. På så sätt kan man uppskatta det långsiktiga vindklimatet för en viss plats utan att mäta vinden för hela den tiden.

Fördelarna med sodar gör instrumentet till ett intressant alternativ, men eftersom tekniken är relativt ny i vindkraftssammanhang är det viktigt att lära sig hur instrumentet fungerar och att undersöka dess prestanda. I den här rapporten har detta gjorts genom att studera litteratur om sodarteknik och genom att jämföra vindmätningar utförda med sodar och med skålkorsanemometer samt vindfana monterade på en mätmast. Jämförelsen har skett på tre platser och de faktorer som har jämförts är vindhastighet, vindriktning, samt i viss mån turbulens.

För att erhålla säkra resultat av en långtidskorrektion måste mätperioden på platsen vara minst ett år lång. Det är däremot önskvärt att få en tidigare uppfattning om vindklimatet på platsen utan ett behöva vänta på mätningar i ett år. Med hjälp av en tidig uppskattning av vindklimatet kan en bedömning göras om det är lönt att fortsätta med projekt. Därav har det i detta arbete studerats hur bra långtidskorrigeringar som är baserade på färre antal månader än ett år stämmer överens med en långtidskorrigering som är baserad på ett år. Det har även studerats om olika årstider kan tänkas ha någon inverkan på resultatet när en uppskattning av det långsiktiga vindklimatet baseras på kortare mätperioder än ett år.

I dagsläget är inte vindmätningar utförda med enbart sodar accepterade av banker eller vindkraftstillverkare, men eftersom en sodar är ett mobilt instrument skulle det kunna användas som ett screeninginstrument i syfte att ge en tidig utvärdering om vindklimatet på platsen.

Resultatet av jämförelsen mellan sodarmätningar och vindmätningar utförda med skålkorsanemometer och vindfana visar att mätningar med sodar håller lika hög kvalitet som mätningar med skålkorsanemometer och vindfana, vilka i dagsläget anses som standard i branschen. På en av de tre platser som vindmätningar jämförts på var avståndet mellan sodar och mast så stort att inga slutsatser kunde dras men på de andra två platserna var skillnad i medelvindhastighet mindre än 0,1 m/s, vilket är mindre än de båda instrumentens mätosäkerhet. Bra överensstämmelse erhölls även i vindriktningsmätningar och korrelationen i vindhastighetsmätningarna mellan de båda instrumenten låg mellan 0,89 och 0,98 för samtliga höjder.

Som väntat visade det sig att långtidskorrigeringarna gav ett bättre resultat ju fler månader som de baserades på. Det som var intressant var att resultat förbättrades markant upp till en fyra månader lång mätserie för att sedan endast förbättras något för längre mätperioder. Detta leder till att långtidskorrigeringar bör bygga på minst fyra månaders mätdata från den aktuella platsen för att kunna ge underlag till en tidig uppskattning av vindklimatet. Ett årstidsberoende kunde påvisas i resultatet av en långtidskorrelation. Vindmätningar under vår och höst representerar vindklimatet under ett helt år bättre än mätningar utförda under sommar och vinter.

Sammanfattningsvis visar resultaten i denna rapport att vindmätningar med en sodar är likvärdiga med vindmätningar utförda med skålkorsanemometer och en vindfana monterade på en mast. Därmed är det möjligt att använda en sodar som ett screeninginstrument för att få en indikation om huruvida en plats lämpar sig för vindkraft eller ej. Vinden bör då mätas i minst fyra månader med vetskapen om att vår och höst ger bättre uppskattningar jämfört med sommar och vinter.

TABLE OF CONTENT

1 INTRODUCTION

Wind is a renewable energy source and a wind turbine converts the kinetic energy in the wind to electricity. Currently (2008), Sweden's annual electricity production from wind power is just over 1.6 TWh (Vindforsk, 2009). However, the government goal is to annually produce 30 TWh by the year of 2020. This goal states that wind energy will play an important role in the transformation of the Swedish energy system (Swedish Energy Agency, 2009).

A site assessment including wind measurements is of major importance when planning a wind farm. The power in the wind is proportional to the cube of the wind speed, hence, small differences in wind speed can determine if a project will be economically viable. So far, cup anemometers and wind wanes mounted on masts have been used for wind measurements during site assessments (Antoniou et al., 2007), but recently other types of instruments for wind measurements have entered the market. One of these instruments is called sodar (Sound Detecting and Ranging) and uses a remote sensing technique based on sound propagation. The sodar is mobile and offers some advantages compared to the met mast. One advantage with the sodar is that it measures the wind at several heights e.g. every fifth meter and thereby reports a vertical wind profile, compared to the mast which only reports values for the heights equipped with anemometers. However, since the sodar is a relatively new instrument in the wind power industry, it is necessary to study the performance and other features of the instrument.

As the technical lifetime of a wind turbine is about 20 - 25 years (Wizelius, 2007), it is important to have knowledge about the long-term wind climate. A single year of measurements is not representative for the whole lifetime of the turbine, therefore the measurements made on site are combined with a longer reference series of measurements in order to estimate the long-term wind climate. This is called a long-term correction and the result is a time series of wind measurements for the specific site but with the same length as the reference series. The wind measurements at the site should consist of at least one year of measurements in order to obtain a reliable estimate of the long-term wind climate (Baurne, pers.coum. 2009).

In an early stage of the project it is desirable to get an estimation of the wind potential at the site in order to decide on whether to proceed with the project or not. For that purpose it is not realistic to measure the wind for a whole year. It is therefore necessary to study how long a site measurement period has to be in order to receive a somewhat reliable estimation.

Nordex Sverige AB, the company where this thesis was performed, has thought of using the sodar instrument as a screening tool in order to perform an early evaluation of a project. For this purpose it is important to have knowledge about the sodar instrument in general and to assure that the measurements are of high standard. Since the sodar is supposed to be used in an early project evaluation, it is also necessary to know for how long time the sodar must be positioned at each site in order to get reliable long-term estimations.

1.1 PURPOSE

The purposes of this thesis are as follows:

- Provide general information about the sodar instrument and at three different sites evaluate the sodar performance compared to a mast.
- Study how the length of the short-term site measurement affects the correlation between long-term corrected wind data series based on 12 months of short-term measurements and long-term corrected wind data series based on fewer months of short-term measurements.
- Study if the correlation described above varies with season.

2 THEORY

This chapter will describe some basic meteorology related to wind power, the two wind measuring instruments studied in this thesis and the long-term correction concept. There is also a brief site description of the different sites used in this study.

2.1 WIND ENERGY METEOROLOGY

In the field of wind energy, meteorology plays an important role. Differences in air pressure due to differences in temperature are the primary driving force for the wind. At lower levels of the atmosphere the winds are affected by friction from the ground, which give rise to turbulence (Wizelius, 2007). Wind characteristics are different between turbulent and laminar wind. Knowledge about these characteristics is important when trying to extract energy from the wind with a turbine. There are also seasonal variations in wind speed with lower wind speeds during the summer and higher during the winter (SMHI, 2008).

2.1.1 Turbulence

Turbulence can be described as stochastical variations in wind speed and direction. When measuring the wind, turbulence is shown as short-term fluctuations in wind speed and wind direction (Wizelius, 2007).

Turbulent air may be due to several reasons. Friction between the wind and the ground causes turbulence in the wind which propagates upwards. A rougher surface and more obstacles on the ground imply more friction and thereby more turbulence. For example, a forest or a city slows down the wind and creates a lot more turbulence compared to an open plane surface like water. Another reason for turbulence is buoyancy forces in thermally non-neutral air. Warm air near the surface rises and cold air at higher levels sinks giving rise to turbulent winds. When wind is blowing through a turbine, turbulence is caused by the rotor. The area behind the turbine with turbulent air is called a wind wake (Wizelius, 2007).

Turbulence intensity (T_I) is the most basic measure of turbulence and is defined as the ratio between the standard deviation of wind speed (σ_U) and the mean wind speed (U).

$$T_I = \frac{\sigma_U}{U} \tag{1}$$

The highest values of turbulence intensity generally occur at low wind speeds, but high wind speeds do not always result in low turbulence intensities. At a given location, the lower limiting value will depend on the specific terrain features and surface conditions on the site (Manwell et.al., 2004).

2.1.2 Planetary Boundary Layer and stability

The part of the atmosphere closest to the planetary surface is called the Planetary Boundary Layer (PBL). Within this layer, the wind is affected by the topography and the type of land use at the surface, hence, the wind is always more or less turbulent. The height of the PBL increases with the roughness of the surface and with increasing thermal instability. Above the PBL is the geostrophic wind (Wizelius, 2007), which is the undisturbed laminar wind. The height at which the wind speed is approximately geostrophic depends on the roughness of the land surface and thermal stability but is usually of the order 1000 m (Wizelius, 2007).

Different sorts of thermal atmospheric stability occurs within the PBL. Unstable conditions occur when the vertical temperature gradient of the air is larger than the dry adiabatic temperature lapse rate. Opposite conditions implies a stable atmospheric stability and a neutral stability occurs when the temperature decrease of the air is equal to the dry adiabatic temperature lapse rate. This is valid for unsaturated air and the dry adiabatic temperature lapse rate is approximately 1°C per 100 m (Totalförsvarets forskningsinstitut, 2006).

An unstable stability favours vertical movement of air and occurs when there is heating from below, e.g. during a summer day. On the other hand, if the ground is colder than the air above, the atmosphere will be cooled from below and become stable. This is common during winter and vertical motion is damped. A moderate wind speed is favourable in order to either have an unstable or stable atmosphere since mixing of the air during higher wind speeds leads to a more neutral stability regardless of the cooling or warming effects from below (Totalförsvarets forskningsinstitut, 2006).

2.1.3 Wind profile

A wind profile describes the relation between wind speed and height. The shape of the profile depends on the roughness of the land surface and the thermal stability of the atmosphere. Figure 1 shows conceptual wind profiles over terrains with different roughness.

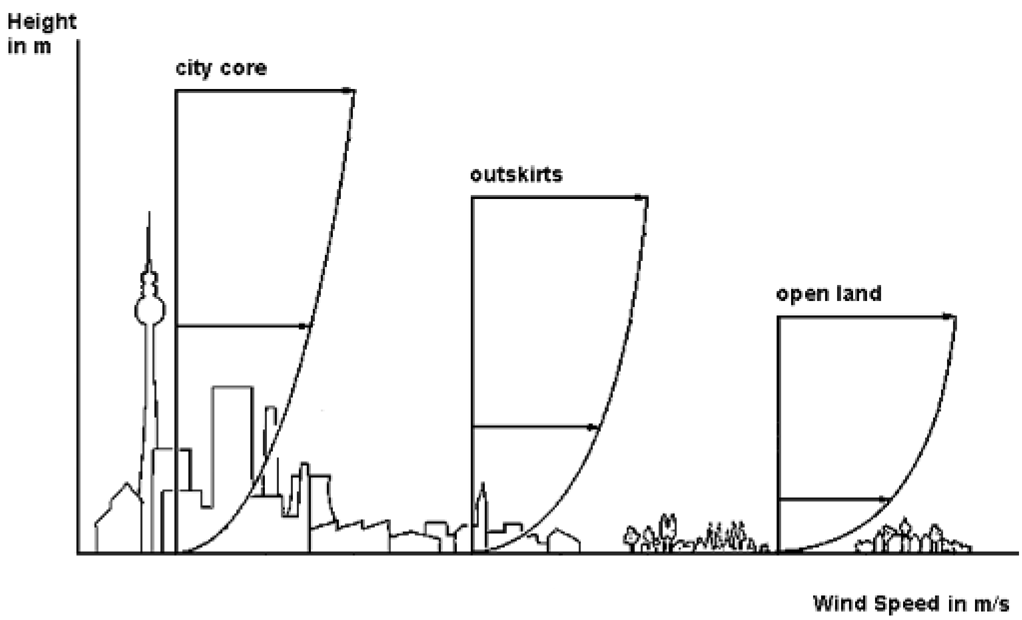

Figure 1. Wind profiles for different types of roughness, edited from Berlin.de (2007).

As shown in figure 1, wind speed increases faster with height in open land compared to rougher land surfaces. The reason for this is the higher occurrence of turbulence above rough surfaces, hence, a higher PBL as well. The wind gradient towards lower wind speed close to the ground is called wind shear (Danish Wind Indunstry Association, 2004).

2.2 ENERGY EXTRACTION FROM THE WIND

A wind turbine extracts the kinetic energy in the wind and converts it into electricity. The energy content in the wind mainly depends on the wind speed, since the power (P) is proportional to the cube of the wind speed (v). Another property that affects the energy content is the density of air (ρ), which varies with height and temperature (Wizelius, 2007).

$$P = \frac{\rho A v^3}{2} \quad [\mathrm{W}] \qquad (2)$$

In equation 2, A stands for the sweep area of the rotor. Figure 2 provides a schematic sketch of the most important turbine components.

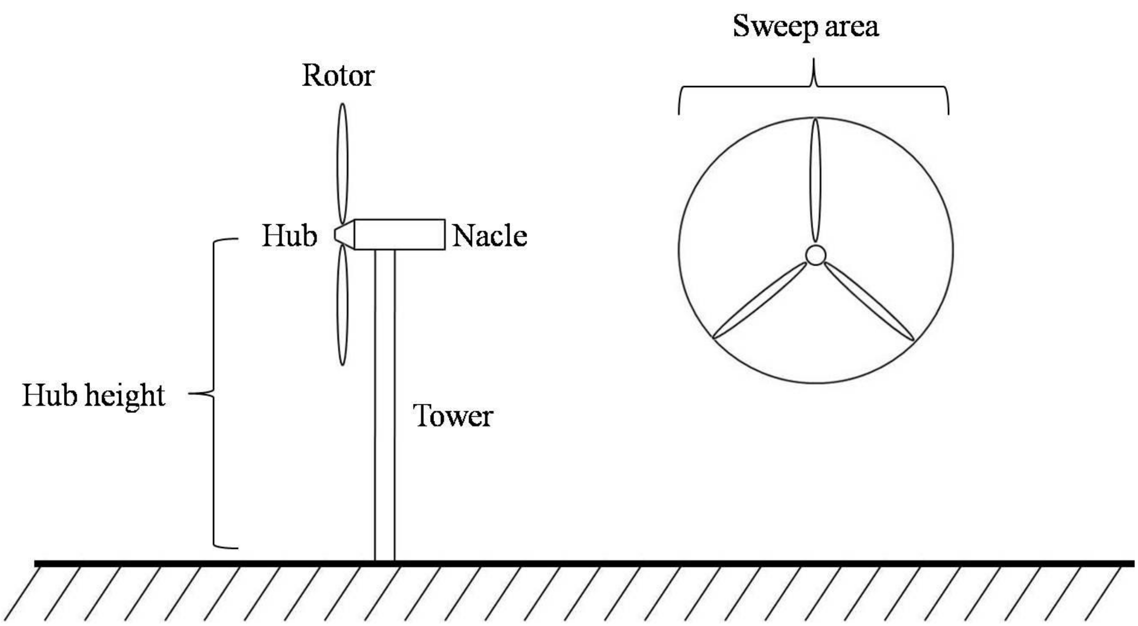

Figure 2. Conceptual sketch of a turbine and the sweep area.

Briefly, the turbine generates electricity when the wind sets the rotor in motion. The rotor is connected to a generator through a gearbox and thereby the generator converts kinetic energy from the rotor to electricity. Some turbines operate without a gearbox. A turbine can only utilize the wind that is blowing through the sweep area and according to Betz' Law, which is related to the deceleration of the air going through a turbine, the theoretically maximum efficiency is 59 %. However, in practice the efficiency is lower due to aerodynamic and mechanical losses. (Wizelius, 2007).

When performing a site assessment with the purpose of building a wind farm it is important to know the mean wind speed for the site, but even more important is to know the wind speed distribution. Since the energy content in the wind is proportional to the cube of the wind speed, energy estimation for a specific site cannot be carried out simply using the mean wind speed as wind data (Wizelius, 2007). Two different sites with different wind speed distributions can have the same mean wind speed, but due to different wind speed distributions generate unequal amounts of energy. To be able to calculate the energy content, the frequency of the different wind speeds must be known. The general way of presenting this is in a graph with wind speed on the x-axis and duration on the y-axis. The annual energy content in the wind is then calculated by multiplying the cube of the wind speed with the corresponding duration. The distribution of the wind usually corresponds quite well with a probability distribution called the Weibull distribution (Wizelius, 2007).

Besides mean wind speed, measurements of turbulence and wind shear are also important during site assessment to evaluate which turbine is the most suitable for the site. This evaluation takes in to account both the optimal energy yield and forces acting on the turbine (Baurne, pers.coum. 2009). There is a certain classification system that divides the turbines into different classes depending on which conditions the turbines are constructed to operate in. The system is called IEC WT 01 and includes regulations concerning dimensioning of the turbine and how performance should be determined. The classes have different maximum mean wind speeds and subclasses for different levels of turbulence (Energimyndigheten, 2007).

2.3 WIND MEASUREMENTS

In the wind power industry wind measurements are used for a number of reasons related to both the site of interest and the turbine (Hunter, Edited 2003). For a site assessment, wind measurements are necessary for estimating the wind resources as well as the wind shear and turbulence intensity. Wind speed is also important when testing a turbine for power performance, mechanical load, power quality and acoustic emission (Hunter, Edited 2003).

The most important step in a site assessment for a project is to determine the energy content in the wind (Wizelius, 2007) and the specific wind characteristics for the site. Other factors such as grid connection, distance to existing roads etc. also have to be taken into consideration, but if the wind speeds are too low there is no point in continuing with the project. When evaluating a site, a rule of thumb can be used for the minimum value of the mean wind speed at hub height. This wind speed must be exceeded in order to have an economically viable project and thereby the option to proceed with the project of constructing a wind turbine or a wind farm (Baurne, pers.coum. 2009). This demands a high accuracy in the wind measurement and knowledge about uncertainties in the wind measurements, especially if the wind speed is close to that specific minimum speed.

The best way to determine the wind resource for a site is through in-situ measurements (The European Wind Energy Assosiation, 2009). In-situ measurements also provide information about wind direction, wind shear and turbulence intensity, which are important for turbine siting according to section 2.2. Traditionally, the most common instruments for these measurements are anemometers and wind vanes mounted on different heights in a mast. However, wind measurements with remote sensing techniques such as sodar, lidar (Light Detection and Ranging) and satellite, which are relatively new for wind energy purposes, are showing promising results (IEA RD&D Wind, 2007).

Turbines are growing both in height and in rotor area, which demands measurements at higher levels as well as the possibility for measurements not only at the center of the rotor but over the whole sweep area. This implies advantages for remote sensing techniques compared to masts since building costs, instrumentation, erection and maintenance increase with the height of the mast. Also, a mast only measures at a few levels compared to the remote sensing instruments (IEA RD&D Wind, 2007).

2.3.1 Anemometers and wind vanes in general

There are several types of anemometers. Some are more responsive and thus suitable for detailed turbulence measurements, whereas others are better fitted to measure mean wind speed. For wind resource assessment purposes the mean wind speed is of interest. Undoubtedly, the three-cup anemometer is the best choice for this application (Hunter, Edited 2003). To be able to receive information on both wind speed and horizontal wind direction, an anemometer usually needs to be used in connection with a wind vane.

An anemometer must be deployed on a meteorological mast, and this is usually done at several heights in order to observe wind shear. Uncertainties related to how an anemometer is mounted on the mast may be as significant as those caused by calibration and design, which will be discussed later on. For example, if an anemometer is measuring the wind speed in the wake of the mast it is obvious that these wind speeds will be a false indication of the undisturbed wind speeds. Significant flow distortions upstream the mast may also occur. To keep this from affecting the instrument it is important to keep enough distance between the tower and the anemometer. The best possible way of mounting an anemometer is to place it on a vertical pole clear of the top of the mast. Since that is not possible at lower heights, booms are used to deploy anemometers at lower heights in mast. These booms are another source of distortion and it is important to know how to deploy them in order to minimize the distortions (Hunter, Edited 2003).

The mast wind measurement data used in this thesis is measured for wind resource assessment purposes using a three-cup anemometer. This is also the type of anemometer that will be compared to the sodar instrument. Therefore a more thorough review of this type of anemometer is needed.

2.3.2 Cup anemometer

Cup anemometers are generally designed as three hemispherical or conical cups attached to a central vertical shaft which drives a signal generator device. Even though the minor differences in design between the different anemometers may seem insignificant, they may have a major influence on behavior and accuracy. For example, a bigger rotor will have greater inertia, thus less responsiveness. However, at the same time a bigger rotor implies better linearity of calibration since mechanical friction becomes relatively unimportant. Common for all cup anemometers are problems connected to dynamic response, calibration and winds with a vertical angle of attack. (Hunter, Edited 2003).

A cup anemometer measures the wind speed independent of horizontal wind direction. Thereby, a wind vane is necessary to obtain the direction of the wind. A wind vane rotates freely around its vertical axis and has the design of an asymmetrical shaped object. Usually, the tail has a larger surface and will thereby offer greater resistance to the wind. This will position the vane so that the front is facing the wind (The Columbia Encyclopedia sixth edition, 2008). In the shaft there is a potentiometer that senses the position of the vane and emits a signal containing information about the wind direction (Wilmers Messtechnik 2, 2003). Figure 3 displays the cup anemometer and the wind vane that has been used for the measurements in this thesis.

Figure 3. Thies Cup Anemometer first class (Wilmers Messtechnik, 2003) and Wilmers Messtechnik Wind Direction Sensor standard (Wilmers Messtechnik 2, 2003).

Most cup anemometers are designed to only measure the horizontal wind speed. That implies that only the two horizontal velocity components of a three dimensional wind vector are used to calculate the wind speed. There are however some cup anemometers which measures the total wind, i.e. even the vertical velocity component. Nevertheless, currently there is no cup anemometer on the market which perfectly meassures either type (Hunter, Edited 2003).

Before a cup anemometer can be used in the field it has to be calibrated. This should be done in a wind tunnel prior to deployment. Ideally, recalibrations or at least field comparisons with newly calibrated instruments should be carried out in case of extended usage (Hunter, Edited 2003).

Cup anemometers differ from many other types of measurement instruments, where the rate at which they respond to a change in an input parameter is determined by a time constant. Generally, the time to react is independent of staring value and the magnitude of the change. Cup anemometers on the other hand have a distance constant instead of a time constant that signify at which rate they are able to respond to a change in the input parameter. The response consists of a given wind-run (Hunter, Edited 2003). A wind-run is the distance or length of an air flow passing the cup anemometer during a given period of time (NovaLynx Corporation). A consequence of this is that a cup anemometer responds more quickly to an increase in wind speed, than to a decrease in wind speed. Another effect is the higher rate of responsiveness at higher wind speeds. Thereby, in fluctuating winds, the cup anemometer will report a mean wind speed that is higher than the true mean wind speed, an error that is known as ‘overspeeding’. However, this is not seen as a major source of error in mean wind speed measurements. The overspeeding error (E) in percentage can according to simple models be approximated as a function of turbulence intensity (T_I) and distance constant (d) (Hunter, Edited 2003):

$$E = {T_I}^2(1.8d - 1.4) \qquad (3)$$

This expression can both act as a base when correcting measured wind speeds and be used for uncertainty estimations (Hunter, Edited 2003).

When using cup anemometers in climates with low temperature, problems due to accumulation of snow and ice in the cups as well as increased friction in the bearings can occur. One solution for these problems is to discard data below a certain temperature, but in cold climates this will lead to huge lack of data and thereby it may be necessary to use heated devices (Hunter, Edited 2003).

2.3.3 Cup anemometer and wind vane used for studies in this thesis

The cup anemometer used in this study is manufactured by Thies Clima and called First Class. It has a measuring range of 0.3 to 75 m/s, a resolution of 0.05 m wind run (Thies Clima, 2009) and a distance constant between 3 and 3.9 m depending on starting angle (Westermann & Rehfeldt, 2008). The accuracy is ±0.3 m/s for wind speeds between 0 to 15 m/s and ± 2 % of reading for wind speeds above 15 m/s (Wilmers Messtechnik, 2003) and the data sample rate is set by the logger to 1 Hz (Gross, pers.coum. 2010)

Wilmers Messtechnik GmbH is the manufacturer of the wind vane and it has an output of 0 to 358 degrees, a 0.5 degree resolution, an accuracy of ± 1.5 degrees (Wilmers Messtechnik 2, 2003) and it sample data at the same rate as the cup anemometer (Gross, pers.coum. 2010).

2.3.4 Sodar technology in general

Sodar is an abbreviation of Sound Detecting and Ranging and uses an acoustic remote sensing technology that is based on the Doppler shift of reflected sound waves.

A sodar measures the wind by sending acoustic pulses with certain frequencies in the audible range up in the atmosphere and then analyze the sound that is reflected back. Sound is emitted in a number of beams pointed at different directions. In order to obtain the 3D wind velocity a minimum of three beams in differing directions are needed. The sound pulses are scattered by changes of the turbulent refractive index at all heights and acoustic energy is backscattered and collected by microphones (Antoniou et.al., 2007).

As discussed in section 2.1.1, turbulence can develop from different sources but all sorts of turbulence result in turbulent air parcels or eddies of varying sizes (Neal, 2008).

The Doppler effect allows measurements of the movement of the air at the position of the scattering eddy (Neal, 2008). Since turbulent fluctuations may be assumed to move with the average wind, the Doppler effect shifts the frequency of the transmitted pulse during the scattering process (Antoniou et.al., 2003), and the shift of frequency is proportional to the wind speed in the beam direction (IEA RD&D Wind, 2007). The frequency of the backscattered sound (f_D) collected by the microphones can be described with equation 4 by using the transmitted frequency (f), speed of target (u) and speed of sound (c) (Bradley, 2008):

$$f_D = f\left(1 - 2\frac{u}{c}\right) \qquad \text{[Hz]} \qquad (4)$$

To achieve correct wind measurements it is important to calculate the current speed of sound using the present temperature (Hurtig, pers.coum. 2009). Knowing the temperature (T) in °C, the speed of sound can be determined with equation 5 (Wong, 2000):

$$c = 331.5 + 0.60T \qquad \text{[m/s]} \qquad (5)$$

The current speed of sound for the measurement location is also required to be able to determine from which height a certain echo is reflected from. By knowing the elapsed time since transmitting (t), that height (z) can be calculated with equation 6. A vertical wind profile is obtained by performing this calculation with different values for the elapsed time since transmitting (Antoniou et al., 2007):

$$z = \frac{ct}{2} \qquad \text{[m]} \qquad (6)$$

The time a sodar measures backscattered signals defines the maximum measuring height. For instance, a measuring height of 200 meters requires a measuring time of 1.2 seconds. If the sampling time is too short, backscattered signals from a certain pulse may cause possible contamination on the signal from the next pulse (Noord et.al., 2005).

After the backscattered signal has been recorded by the microphone, noise has to be filtered out because only a small part of the received frequency spectrum contains relevant information. The backscatter that returns from higher altitudes is both weaker and later in time, because the received signal decreases with the distance it has travelled in the atmosphere. Therefore a ramp gain is used to amplify the signals from greater altitudes more than the signals from lower altitudes (Noord et.al., 2005).

Due to insufficient computer capacity, the sampling rate is reduced by mixing down the frequency of the signal to approximately zero from about sending frequency. For example, if the relevant frequency range is from 4 300 Hz to 4 700 Hz with a sending frequency of 4 500 Hz, the range after down mixing will be from 0 to 200 Hz. By studying the in-phase trace and the 90 degree phase trace it is still possible to distinguish between positive and negative Doppler shift after down mixing. Subsequently, a low pass filter is applied to remove all the higher frequency components still present after the mixing. The remaining frequency content represents the received Doppler shift in the signal and therefore the low pass filter limits the maximum wind speed measurable with a sodar (Noord et.al., 2005).

A Fast Fourier Transform (FFT) is carried out after the backscattered signal has been sampled (Noord et.al., 2005). The FFT detects the frequency content in the backscattered echoes and returns a frequency spectrum (Hurtig, pers.coum. 2009). After the FFT is done for a specific height the frequency of the peak containing the Doppler shift has to be determined. This is done by a peak finding algorithm that uses different techniques to distinguish between the signal and noise (Noord et.al., 2005). The frequency of the detected peak is now compared to the frequency of the transmitted pulse. The differences in frequency caused by the movement of the reflecting eddy due to the Doppler effect can be transformed into wind speed, and with three beams in different directions the three dimensional wind vector can be calculated (Hurtig, pers.coum. 2009).

One of the advantages with sodar is that it measures the wind at various heights, also referred to range gates. The maximum height resolution (Δz_V) for these range gates can be derived from either equation 7 or equation 8 (Noord et.al., 2005):

$$\Delta z_V = \frac{c\tau}{2} \quad [\mathrm{m}] \tag{7}$$

$$\Delta z_V = \frac{cN_s}{2f_s} \quad [\mathrm{m}] \tag{8}$$

The maximum height resolution due to pulse length is presented in equation 7, where c is the speed of sound and τ is the pulse length. Equation 8 represents the same height resolution but in terms of number of samples of an FFT in a time series (N_s) and the sampling rate (f_s). The larger value of the above equations determines the height resolution. However, a finer spatial resolution is often presented by the sodar. Even if this looks better on a profile plot no extra information is gained since this is done either by the FFTs using overlapping sequences of samples, or if the resolution is limited by equation 8, using a higher sampling rate (Noord et.al., 2005).

Sodar data may be influenced by phenomenas like fixed echoes and background noise etc., which will be discussed later on, so it is important to reject contaminated data. One way of doing this is to use the signal-to-noise ratio (SNR). The definition of SNR is a ratio of powers or a ratio of logarithmic powers. For data points having a SNR equal to the noise or smaller no peak can be found and therefore the data point is rejected. Users are usually allowed to choose a higher SNR value where the peak finding algorithm is assumed to become unreliable and data points are rejected (Noord et.al., 2005).

Another tool to use for rejecting bad data is a consistency check. This type of check assumes that there is a maximum vertical wind shear that is physically possible or certain inertia of wind profiles in time. Thereby, the wind or the frequency shift of each range gate of a profile can be compared with one or more previous profiles and data can be rejected or smoothed out if the maximum difference is exceeded. A problem becomes apparent when the wind speed is calculated from the instantaneous peaks detected from the spectra. Since the SNR and the backscattered power decreases with the height of the range gate due to absorption of sound in the air, which is explained later, erroneous peak positions will be detected by the peak finding algorithm. As a result the wind profile looks jumpy both in space and time. In this case a consistency check is often performed to treat the problem (Noord et.al., 2005).

Two reasons for attenuation of sodar data are losses due to absorption and spherical spreading of sound. Absorption occurs when the sound pressure along the propagation path compresses and stretches each small volume of air it passes. This causes a change in shape which is resisted by viscous forces. There is also a molecular absorption when a molecule's energy is transferred out of translational motion into vibration or rotation. Sound spreads out spherically from a source and equation 9 shows how the intensity (I) of sound with the transmitted power (P_T) decreases when travelled a distance (r) (Bradley, 2008):

$$I = \frac{P_T}{4\pi r^2} \qquad [\mathrm{W/m^2}] \qquad (9)$$

Background noise can be a problem for sodar systems if the noise is within the same frequency band as the system use to transmit and receive signals (Neal, 2008). Both electrical noise from circuits and acoustic noise from the environment may be the source to background noise (Bradley, 2008). In the case of very strong winds, the surroundings and the enclosure of the instrument may also be a source to background noise. A consequence of this is that loss of data can appear over a certain wind speed. Correct design and acoustic sheltering of the instrument may reduce the loss of data due to high wind speeds (Noord et.al., 2005). The maximum sample height might be reduced due to background noise since the return signal generally varies inversely with target height. Therefore, echoes from greater heights are more readily lost in the background noise. Besides reducing the height of measurements, background noise can also lead to bias in the sodar data. When evaluating a position for sodar measurements it is thereby important to identify potential noise sources and estimate the background noise level (Neal, 2008). Measurements containing background noise show incorrectly high backscatter intensities and have a low SNR. As the sources of background noise are usually not correlated with the wind speed, the filtering algorithm should not eliminate data that has a systematic influence on the measured wind speed (Noord et.al., 2005).

Due to background noise, atmospheric absorption, and spherical spreading of the energy; the echo is after some seconds to weak to detect. Another pulse is now transmitted in a different beam direction in order to estimate a different component of the wind. The conical beam shape implies an increasing volume occupied by the transmitted acoustic pulse propagating upwards (Antoniou et.al., 2007). The wind speed at a certain height is in other words averaged over a volume. An echo from a height (z) is registered at the microphone after traveling the distance $2z$. Combining this with an acoustic pulse duration (τ) and beam width $(\Delta\varphi)$, the volume (V) has a vertical extent of $c\tau/2$ and a horizontal radius of $z(\Delta\varphi/2)$ (Antoniou et.al., 2007):

$$V = \frac{c\tau}{2}\,\pi\left(\frac{z\Delta\varphi}{2}\right)^2 \quad [\mathrm{m}^3] \tag{10}$$

The time (t) it takes to sample the acoustic echo for each frequency spectrum may be dominant in determining the averaging volume, which leads to a vertical spatial resolution for wind speed and direction estimates with the vertical extent determined by $c\tau/2$ and $ct/2$. The various beams are usually tilted in differing directions at an angel φ to the vertical, which means that they are horizontally separated by a distance of $z\varphi$ to $2z\varphi$ according to figure 4. This inflicts a limitation since the separate wind components are not estimated within the same volume (Antoniou et.al., 2007).

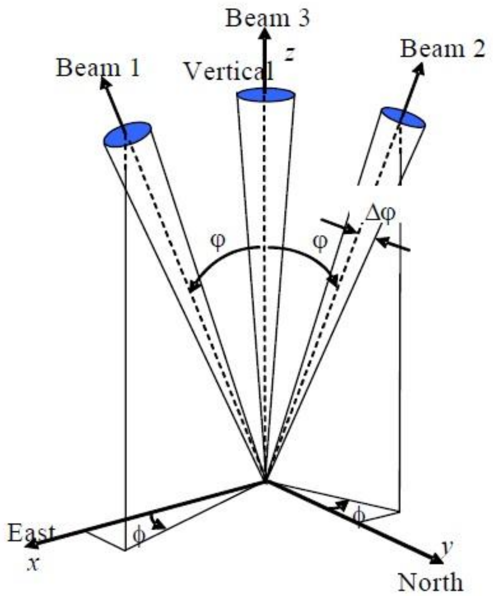

Figure 4. The principle beam orientation of a three beam sodar (Antoniou, o.a., 2007).

Another principal problem for sodar systems is fixed echoes from objects surrounding the instrument. Even if only the side lobes of the sodar beam hit these objects the echoes do have an influence on the measurements since the backscatter intensities are very high. Fixed echoes will normally be shown as a strong peak with zero Doppler shift in the frequency spectrum and the peak finding algorithm often mistake this peak for the wind peek. Because of the high SNR, usual filters often let fixed echoes pass but consistency checks are usually sufficient to reject these echoes. Another way to minimize the influence of fixed echoes is to choose suitable measurement sites (Noord et.al., 2005), or designing the system to substantially eliminate side-lobe energy (Neal, 2008).

Precipitation both in form of snow and rain has influences on the recorded backscattered sound. Detection of incorrect wind speeds are especially the case when the speed of the precipitation particles differ from the speed of the air mass through which they are falling. Rain is also a considerable source of noise due to the impact of the raindrops on the instrument and the surroundings. However, compared to snowflakes raindrops are not so good reflectors for sound waves due to their smaller size. As a consequence of these two facts the signal-to-noise ratio declines during rainfall. Snowflakes on the other hand induce a high signal-to-noise ratio since they provide a good reflectance and a noiseless impact on the instrument. Because of this, filters may let pass these signals and snowfall may thereby lead to detection of downward vertical velocities in the order of 2 m/s. It is important to have a sufficient heating system since longer snowfalls may otherwise lead to a nearly perfect insulation of the antenna unit and thereby failure of further measurements until the snow melts again. In the case of rain, scattering from rain droplets contaminates the spectrum with a second peak. However, the peaks can in theory be separated since medium to large rain droplets fall with a vertical velocity above the usual vertical wind velocity, which is normally not more than 1 m/s. Thereby ignoring data points with a high vertical velocity will erase data contaminated due to rain (Noord et.al., 2005).

There are different technical designs and configurations of sodar systems. The transmitter and receiver can either be separated (bistatic) or co-located (monostatic). For a monostatic sodar the speaker and the microphone are the same unit (Antoniou et.al., 2007). The scattering angle between the sodar and the target eddies are 180 degrees and the backscattered energy is caused by thermally induced turbulence only. A bistatic sodar can receive echoes from other angels than 180 degrees and both thermal and mechanical turbulence can act as a target. However, nearly all commercial sodar systems are monostatic due to their simpler and more practical design (Neal, 2008). It is also possible to divide sodar systems into phased array sodars and multiple antenna sodars depending on how they transmit the sound in different beams. A phased array sodar has an array of transmitters/receivers and transmit sound in beams with different orientation by using a phase shift of the transmitters in the array to amplify and reduce the sound in the different beam directions (Antoniou et.al., 2003). The multiple antenna sodar on the other hand has three fixed antennas which can either be used sequentially or simultaneous with different frequencies to prevent the different signals to interfere with each other (Neal, 2008).

The sodar used in this thesis is a monostatic multiple antenna sodar manufactured by AQSystem AB and called AQ 500 Wind Finder. This particular model will be described further in terms of design and operation.

2.3.5 Monostatic multiple antenna sodar

A monostatic sodar can only receive echoes from thermally induced turbulence since mechanical induced turbulence does not produce acoustic backscatter in the 180 degree direction. This is a drawback when the atmospheric stratification changes from stable to unstable and becomes nearly neutral (Noord et.al., 2005). The atmospheric stratification may also become neutral during strong winds because of a high degree of mixing of the air (Hurtig, pers.coum. 2009). The change of temperature in an air parcel traveling vertically in a neutral atmospheric stratification will almost coincide with the change of temperature in the surrounding air (Totalförsvarets forskningsinstitut, 2006). This will reduce the thermally induced turbulence.

The AQ 500 Wind Finder has three beam sending antennas evenly distributed horizontally with an angle shift of 120 degrees. The transmitting frequency is 3 144 Hz and no down mixing of the signal is necessary since there is enough computer capacity in the AQ 500 Wind Finder to carry out the FFT on the sending frequency (Hurtig, pers.coum. 2009). Unlike many other sodar systems the AQ 500 Wind Finder has no strictly vertical beam, instead all three beams has an inclination of 15 degrees from the vertical axis and a beam width of 12 degrees (AQSystem, 2008). By changing the software it is possible to choose between a wind profile of 20 – 150 m or 50 – 200 m (Hurtig, pers.coum. 2009). The resulting wind profile has a value every 5 m (AQSystem, 2008) with a resolution of ± 6 m (Hurtig, pers.coum. 2009), which results in a range gate of 12 m. Figure 5 displays the beam orientation and measuring volume of the AQ 500 Wind Finder.

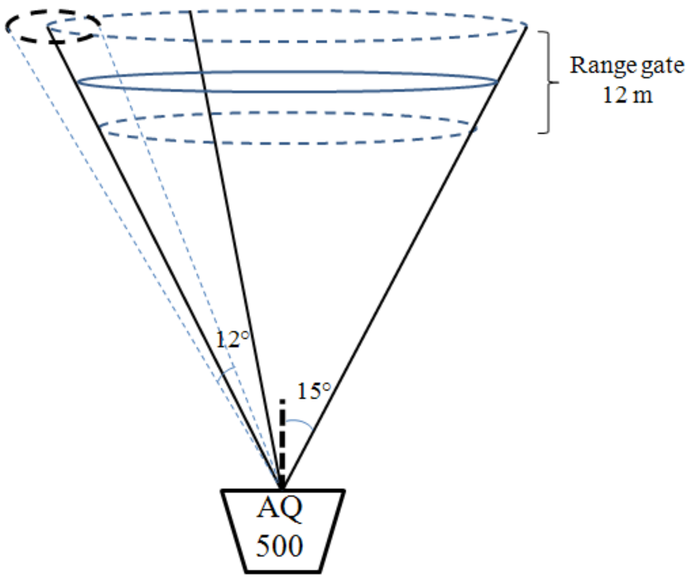

Figure 5. Beam orientation and measuring volume of the AQ 500 Wind Finder.

According to the manufacturer the horizontal speed range is from 0 to 50 m/s with an accuracy of ≤ 0.1 m/s, and the vertical range is ± 10 m/s with a resolution of 0.05 m/s. The reported wind direction has an accuracy of 2 to 3 degrees (AQSystem, 2008).

To prevent data from being contaminated by precipitation in the form of rain, the AQ 500 Wind Finder uses a relatively low frequency which reduces the impact of echoes due to rainfall. The vertical wind speed may be incorrect during snowfall, but the horizontal wind speed component is compensated for that error (Hurtig, pers.coum. 2009).

The AQ 500 Wind Finder is a complete system including sodar antenna, electronics, battery pack and diesel generator. It is installed on a trailer with a casing and it is possible to move the trailer with a car. Solar cells are mounted on the side of the trailer to reduce the diesel generator run time. For use in remote areas without infrastructure, it is possible to deploy the AQ 500 using a helicopter (AQSystem, 2009). Figure 6 displays the trailer and the antenna unit.

Figure 6. The trailer that contains the AQ 500 Wind Finder sodar system and the antenna unit with and without the wind shield (AQSystem, 2008).

2.3.6 Differences between point and profile measurements

Since the extractable energy in the wind is determined by the volume of air passing through the sweep area of a wind turbine during a certain time interval, it is desirable to obtain information about the wind for the whole sweep area. Remote sensing devices, such as sodar, performs volume measurements and provides therefore a better resolution of measurements over the sweep area compared to point measurements i.e. cup anemometers (Antoniou et.al., 2003).

Simultaneous information from different heights is provided by volume measurements using sodar or other remote sensing devices. It is thereby possible to obtain a vertical wind profile across the sweep area without interpolation or extrapolation from point measurements provided by cup anemometers. In case of a met mast that is lower than the hub height, uncertainties are entered in the wind estimation by extrapolation of point measurements up to hub height. A value for wind speed at hub height is not representative for the whole rotor area, which shows the advantages of a vertical wind profile measured by for instance a sodar (Antoniou et.al., 2003).

2.4 COMPARISON OF SODAR AND MAST MEASUREMENTS

First of all, it must be stated that it is difficult to make information from point and volume measurements directly comparable. That would only be possible if a large number of cup anemometers (or other types of point measurement devices) where evenly distributed over the whole measurement volume, which is unrealistic (Antoniou et.al., 2003). A sodar and cup anemometers are thereby not able to give the exact same result but it is still possible to compare them.

When performing this type of comparison it is important to have knowledge about some expected differences in the results. Explaining these factors will help to understand why sodar and cup anemometers measure different values of the wind.

Both instruments present a measurement of the wind that is an average over a certain period, in this case ten minutes. The cup anemometer and the wind vane used for the studies in this thesis are set by the logger to sample data at a rate of 1 Hz (Gross, pers.coum. 2010) and the sodar that has been used completes a cycle of measurements (one measurement in each beam) in about 4 seconds i.e. 0.25 Hz (Hurtig, pers.coum. 2009). This data is then averaged over ten minutes before reported to the user. Although they both use the same average time, the sodar reports a vector averaged wind speed and the cup anemometer reports a scalar averaged wind speed, which result in different values (Bradley, 2008). The theory behind vector and scalar averaging will be addressed further in section 2.4.1.

In the presence of turbulence and vertical winds cup anemometers have a tendency to overestimate the wind speed due to overspeeding (Bradley, 2008). A sodar on the other hand distinguishes between the vertical and horizontal wind components and calculates the mean wind speed only using the horizontal wind components (Antoniou et.al., 2003).

Since the sodar measures the wind speed in a volume of air, unlike the cup anemometer, differences in wind speed will occur if there is a high shear in the wind profile. In the case of high shear a sodar measurement for a certain range gate will report a lower wind speed than a point measurement in the center of the same range gate. This is due to the fact that the wind speed at the lowest height of the range gate will differ more from the center wind speed than the wind speed at the top height of the range gate. The mean wind speed for the range gate reported by a sodar will thereby be lower than the wind speed reported from a cup anemometer at the center height of the range gate. The reason for this is the shape of the wind profile which is approximately logarithmic and therefore the wind shear decreases with increasing height. A result of this is that the sodar will report a higher wind shear. This effect will decrease with increasing height if the shear decreases with increasing height (Bradley, 2008).

In terms of turbulence measurements, the sodar usually reports a lower wind speed standard deviation compared to a cup anemometer since it is a volume measurement (Antoniou et.al., 2007). Another reason for a lower wind speed standard deviation is that a complete measurement cycle is completed in approximately 0.25 Hz while the cup anemometer sample measurements at a rate of 1 Hz. These two factors imply dispersion of the fluctuations in wind speed in both volume and time during a sodar measurement cycle. This will affect the turbulence intensity which is the ratio between wind speed standard deviation and mean wind speed, section 2.1.1 equation 1.

2.4.1 Scalar and vector averaging of wind data

The wind is a vector quantity since it has both a magnitude (speed) and a direction, but the speed and the direction can also be treated separately as scalar values. Wind data is usually measured at a high frequency to be averaged over a certain time period. The data may either be vector averaged, scalar averaged or both depending on the application and instrumentation (Neal, 2009).

Scalar averaging of wind data is used when measurements of wind speed and wind direction are performed independent of each other, typically with a cup anemometer and a wind vane. Data is sampled regularly and the measurements during an averaging period are being averaged using simple arithmetic methods. (Neal, 2009).

A vector average is a vector composed by individual components which are themselves averages obtained over a certain period of time. Hence, remote sensing techniques, in this case the AQ 500 Wind Finder, accumulates data from each beam direction and determines the radial average velocity in each direction for ten minutes before composing the total average wind vector by using data from all three directions (Clive, 2008).

A sodar reports the wind speed as the magnitude of the vector average. That value will differ from the average magnitude of the vector, which is the scalar average reported by the cup anemometer. Using an extreme but instructive example will facilitate the understanding of the differences between scalar and vector averaging: Suppose that the wind is blowing at a constant speed of 6 m/s from the North during half of the averaging interval and at the same constant speed from the South during the other half of the averaging interval. The vector average during this interval would be equal to 0 m/s, whereas the average magnitude of the vector i.e. the scalar speed would be equal to the constant speed of the wind i.e. 6 m/s. To sum up, a sodar takes the wind direction into account when calculating the mean wind speed, as opposed to a cup anemometer which is insensitive to horizontal wind direction (Clive, 2008). Vector averaged speeds will thereby in theory never be larger than scalar averaged wind speeds and greater variations in wind direction will amount to larger differences in wind speed i.e. lower vector averaged wind speed (Neal, 2009).

Previous studies of the differences between scalar and vector wind speed indicates a difference of 2.5 % for a turbulence intensity of 25 % (Antoniou et.al., 2003) and according to Bradley (2008) the vector wind speed can be as much as 5 % lower, but the median difference is generally closer to 2 % to 3 %.

2.4.2 Aspects not related to measuring technique

Besides aspects related to measuring techniques, there are other advantages and disadvantages concerning these two instruments. The specifications on prices and operation presented in this section are for the mast and the sodar used in this study.

The cost for a sodar is about the same as for an equipped met mast including erection (Baurne, pers.coum. 2009). However, increasing height, more equipment and removal/-dissembling of the mast makes the mast more expensive.

A building permit is necessary to be able to erect a mast (Baurne, pers.coum. 2009), whereas it is possible with a simple permission from the landowner to install the sodar trailer on a desired location. In terms of operation, the mast is self supporting with electricity from a battery that is recharged by a small wind turbine and solar cells. A diesel generator with a battery pack is though needed if heating of the anemometers is required. (Baurne, pers.coum. 2009). The sodar runs on a battery which is recharged with a diesel generator and solar cells (Hurtig, pers.coum. 2009).

As the sodar unit is mobile, it is also relatively easy to steal even though the trailer is equipped with solid padlocks. Since the sodar instrument is located at ground level it is also quite easy to sabotage the equipment. However, the logger on a met mast is also often located at ground level and thereby also accessible to sabotage.

An important difference between these instruments is that the measurements performed by a sodar, as opposed to a cup anemometer, is not yet bankable or accepted by the turbine suppliers if not used together with a nearby mast. Some turbine suppliers accept measurements performed by the AQ 500 Wind Finder if the wind profile reported by the sodar has been calibrated to a mast at the site. It is enough with a relatively short mast (40 – 50 m) and a calibration is only necessary if the sodar and the mast do not report the same mean wind speed at a certain height e.g. 50 m (Hurtig, pers.coum. 2009). Bankable measurements are necessary to be able to sell a wind farm (Baurne, pers.coum. 2009).

2.4.3 Previous studies

There have been some previous comparisons between the AQ 500 Wind Finder and cup anemometer measurements. The correlation analyses in all studies are carried out with the linear equation $y = kx + m$.

Arise WindPower and AQSystem performed a comparison at site Markaryd from 2008-04-03 to 2008-04-29. The site is located in a forested area and the meteorological conditions were typical for the spring with large daily variations in temperature and turbulence. Measuring heights on the mast were 40, 60, 80 and 100 m and the coefficient of correlation for mean wind speed measurements were 0.94, 0.95, 0.96 and 0.97 respectively. Mean differences in wind speed when the sodar value is subtracted from the mast value were 0.05, 0.09, 0.08 and 0.12 m/s in that same order. (Bergström, 2008). Thereby, the sodar measures a lower wind speed at all heights compared to the cup anemometers.

Another comparison test between the AQ 500 Wind Finder and a met mast with cup anemometers and wind vanes at 40, 60, 80 m height has been carried out at the flat terrain test site of Havsøre. The coefficients of correlation from the wind speed comparisons are 0.9764, 0.9818 and 0.9811 respectively. The AQ 500 Wind Finder measured higher standard deviations at 40 m compared to the cup anemometer, which was not expected since the AQ 500 Wind Finder measures over a larger volume (Antoniou et.al., 2007). According to the scatter plots in this report the sodar measures a lower wind speed at all heights compared to the cup anemometers.

Vattenfall has also performed a comparison of the AQ 500 Wind Finder and cup anemometers at a forest site in southern Sweden. The cup anemometers measured higher wind speeds compared to the sodar at all heights and the results from the study are presented in table 1 (Gustafsson, 2008).

Table 1 Results from the study carried out by Vattenfall

	25 m	**40 m**	**60 m**	**80 m**	**97 m**	**100 m**
Mean difference [m/s]				0.09	0.11	0.11
Wind speed correlation [%]	0.573	0.769	0.771	0.778	0.828	
Standard deviation [m/s]	0.80	0.54	0.75	0.85	0.78	
Turbulence intensity correlation [%]		0.059		0.16		

2.5 LONG-TERM CORRECTION

Since the technical lifetime of a wind turbine is calculated to be about 20 - 25 years, it is desirable to have knowledge about the long-term wind climate. The wind climate varies from year to year and the energy content in the wind may vary as much as 30 percent between decades. Knowledge about the long-term variations in the wind climate is thereby important when planning to utilize the power in the wind (Wizelius, 2007).

From a meteorological and a climatological point of view, thirty years of measurements is needed to obtain stable values on different climatological parameters. Measurement periods that long are not realistic and thereby it is necessary to determine the climatological mean wind based on measurements from a limited period of time, but with as much certainty as possible (Bergström & Nilsson, 2009). Estimating the long-term wind climate from a short period of measurements is called long-term correction.

The method that is used for performing long-term corrections of wind data is called Measure-Correlate-Predict. This method requires some sort of long-term reference wind data in order to estimate the long-term wind climate at a certain site (EMD International A/S, 2008). Since the long-term reference wind data are supposed to describe the long-term wind climate at the site where the short-term wind measurements have been performed it is important to find a long-term reference wind data with as good correlation as possible with the concurrent short-term limited series of measurements. Long-term reference wind data can both be in the form of wind measurements from e.g. a mast, or in the form of reanalysis data. As long-term wind measurements performed by a mast or other types of measurement instruments are rare in Sweden, reanalysis wind data are often used as a long term reference. This is also the case in this study.

2.5.1 Reanalysis data

Since the long-term reference wind data used in this thesis are in the form of reanalysis data, this type of data will be further discussed in this section.

According to ECMWF (European Centre for Medium-Range Weather Forecasts), reanalysis can be described as re-analyze past observations with a fixed data assimilation system and model (ECMWF, 2008). The observations are both in form of in-situ measurements such as surface stations, radiosondes and aircrafts, but also satellite observations (Poli, 2009).

Reanalysis data is presented in a grid over the entire globe with values in each node. This kind of data can be provided by both NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) and ECMWF. The main difference between the American NCEP/NCAR reanalysis data and European ECMWF reanalysis data is that they are produced with different data assimilation systems and models (Bergström, pers.coum. 2010).

ERA-Interim, which is the latest ECMWF reanalysis with data from 1989 to present (ECMWF, 2008) has been used in this study. The ERA-Interim data must be bought compared to the NCAR/NCEP which is free. On the other hand, ERA-Interim data has a resolution of approximately 0.7 x 0.7 degrees (Sondell, 2010) compared to 2.5 x 2.5 degrees for the NCAR/NCEP data (National Center for Atmospheric Research , 2004).

2.5.2 Measure-Correlate-Predict

The Measure-Correlate-Predict (MCP) technique is a method for estimating the long-term wind statistics by using a limited series of wind measurements from the local site and long-term reference wind data from a somewhat nearby site (EMD International A/S, 2008).

The method creates a transfer function between the local short-term wind data and the concurrent long-term reference wind data (EMD International A/S, 2008). A modeled long-term wind data series for the local site is thereafter created by applying the transfer function on the long-term reference wind data series. This whole procedure is described in figure 7.

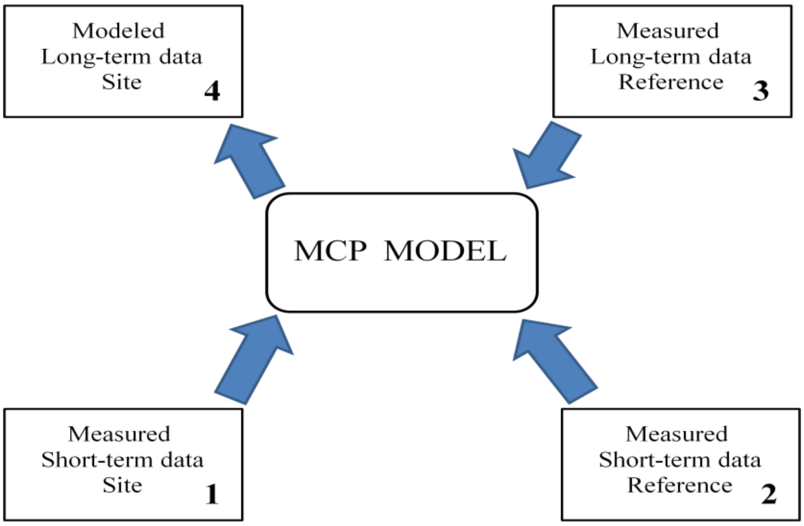

Figure 7. A conceptual model of the MCP procedure.

Box one and box two contains the concurrent short-term data from the local wind measurement and the reference wind data respectively. These two series are input data to the MCP model and a transfer function is created between them. That transfer function is applied on the long-term reference series in box three, which results in the modeled long-term corrected wind data series for the local site in box four. The series in box two and box three are the same long-term reference series, but only the part concurrent with the short-term local series in box one is used in box two. A more graphical explanation of this procedure for a special case is presented in section 2.5.3 figure 8.

Depending on the software, different models for long-term correction are available within the MCP method. Emd WindPRO 2.6, described in section 3, is the software used for long-term correction calculations in this study and it has the following four models: Regression, Matrix, Weibull scale and Wind index. The regression model was chosen in this study since it is a classical MCP model (EMD International A/S, 2008), widely used and relatively easy to interpret. Therefore, only that model will be discussed further.

2.5.3 Regression model

The regression model $(f(x))$ with one dependent variable (y), one independent variable (x) and a residual (e) is based on equation 11 (Thøgersen et al., 2007):

$$y = f(x) + e \tag{11}$$

Usually, a linear model is chosen as the regression model since the linear model has proven to give reasonable results for wind energy estimation. However, the regression model could be polynomials of any order (Thøgersen et al., 2007).

Figure 8 displays an overview of the long-term calculation process when a linear model is used as a regression model. In step 1, the transfer function between the short-term data (y) and the concurrent long-term reference data (x) is calculated. The transfer function consists of the regression parameters (k) and (m) which are calculated by the method of least squares. During step 2, the transfer function is applied on the long-term reference data (x') which results in the estimated long-term corrected site data ($\hat{y}$).

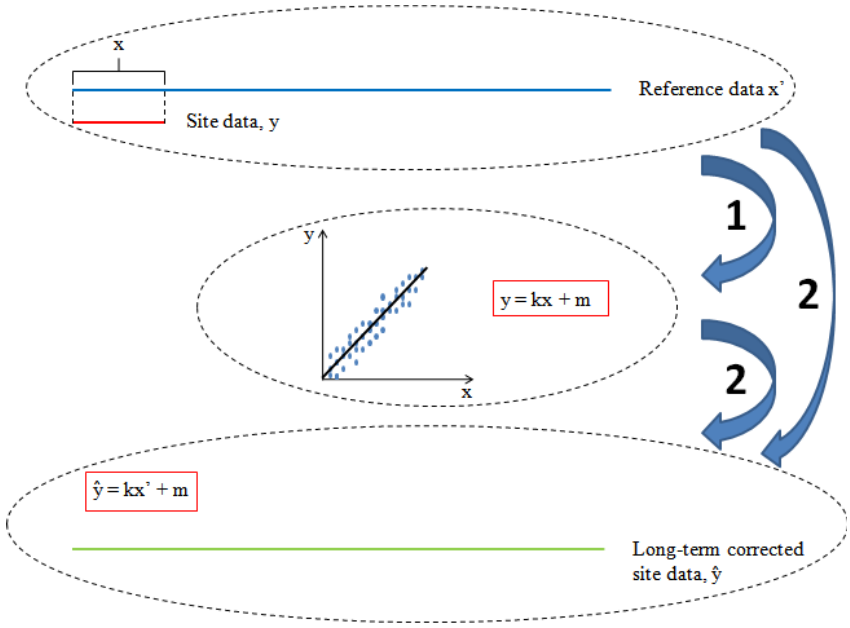

Figure 8. The process of long-term correcting wind data using a linear regression model.

2.5.4 Previous studies

Previous studies of the correlation between a long-term corrected time series based on 12 months of short-term wind data and long-term corrected time series based on fewer months of short-term data has not been found. However, there is a study on the seasonal impact on the predicted wind climate.

A French study in the DEWI (Deutsches Windenergie Institut) Magazin performed long-term corrections based on various lengths of short-term measurements. The predicted energy yield was calculated with these series and compared to the actual energy yield. The results are the error in predicted energy yield as a function of the length of the measuring period and the middle month of the same period. It is obvious from the results that the smallest errors in energy prediction occur when April and October are the middle month of the measuring period i.e. during the spring and the autumn. Measurements performed during the winter and the summer result in the worst estimations. It is also evident that the errors in estimation decreases with an increasing length of the measuring period (Borget et al., 2007).

3 METHODS

The studies were performed by using MS Excel 2007 and Emd WindPRO 2.6. WindPRO 2.6 is a software for wind energy project design and planning (Emd, 2010). Long-term correction calculations and validation of wind data has been performed in WindPRO 2.6, while all other calculations and regression analyses were carried out in MS Excel 2007.

3.1 COMPARISON OF SODAR AND MAST MEASUREMENTS

Sodar and mast measurement comparisons were performed with existing measurement data from three different sites, site A, site B and site C. The com-parisons were concentrated to mainly wind speed and wind direction. Thorough comparisons of turbulence measurements were not carried out due to the differences in measurement technique described in section 2.4. It is complicated to evaluate the turbulence measurements and an adequate evaluation of these measurements is not within the scope of this thesis.

The measurements were compared at the same height except for the 81.5 m mast height which was compared to the 80 m measurements from the sodar. At site B the sodar was located at a 5 m lower elevation compared to the mast. This was corrected for by using the values from the sodar wind profile that are from a height of 5 m above the height of the corresponding cup anemometer on the mast. No filtering for extreme values or under-/over speeding by the cup anemometers was done unless otherwise is stated.

Wind measurement data was downloaded from the sodar and mast respectively and imported into WindPRO 2.6 in order to create continuous time series. These series were then exported to MS Excel 2007 for data conditioning and comparisons. Since both the mast and the sodar lacked some data from time to time the corresponding value for each instrument was rejected in order to make the measurement series comparable.

Data availability from the sodar was studied by calculating the ratio between the number of rejected samples and the total number of samples.

Mean values and standard deviations were calculated in MS Excel and all the plots were created by using the chart tool. The calculation of the overspeeding error by the cup anemometer was carried out by using equation 1 and a distance constant of 3.4 m.

Scatter plots with a linear regression line were used to study the correlation of sodar and mast measurements. The comparison includes wind speed, wind direction and to some extent turbulence intensities for the different sites. The equation used to describe the linear relationship was $y = kx + m$ and the trend line with the corresponding coeffi-cient of correlation (R^2) is calculated with the least square method. The reason for choosing a linear equation allowing an offset on the y-axis is that the two instruments use different measuring and averaging techniques, which was described earlier.

The difference in wind speed related to scalar and vector averaging were studied at height 40 and 80 m by plotting ten minute wind speed averages from the sodar and the cup anemometer together with the standard deviation of the wind direction reported by the wind vane. In theory, the sodar should report a lower wind speed when there is a higher standard deviation of the wind direction, section 2.4.1. The overspeeding error was reduced from the cup anemometer data and the graphs only consist of a randomly selected five day time period in order to make them more readable.

3.2 LONG-TERM CORRECTION

The long-term correction study was performed with reanalysis reference data ranging from 1989 to present that was bought from Storm Weather Center and short-term data from the mast at site D. Storm Weather Center purchased ERA-Interim data from ECMWF at a grid resolution of 0.75 x 0.75 degrees and made it site specific for site D by interpolation of the wind data for the four surrounding nodes to the coordinate of the met mast at site D (Sondell, 2010). The short-term wind data from the mast at site D are from the free mounted cup anemometer at 81.5 m elevation and therefore the reference data was bought from a height of 80 m from Storm Weather Center.

Emd WindPRO 2.6 with its MCP (Measure Correlate Predict) module was used to perform the long term calculations. The first step was to select input data and to make the long-term and short-term data comparable with each other. Since the short-term data was averaged over ten minutes and the reference data over three hours, new three hour averages were made of the short-term data. Next step was to validate the short-term data. During the validation process some data was rejected due to freezing of the cup anemometer. There was also a lack of about one month of mast data in November and December because of the logger that was out of order. After the validation, the time period of short-term data that the long-term correction calculation will be based on was selected. The last step before the calculation was choosing a MCP model. The linear regression model described in section 2.5.3 was used in this study.

Since the purpose was to study how the coefficient of correlation varied between a long-term corrected time series based on 12 months of short-time data compared to a long-term corrected time series based on fewer months of short-term data, a number of long-term correction calculations with the same reference data but with varying length of short-term data were carried out.

The first long-term correction calculation was performed with a whole year of wind measurements as short-term data. The resulting long-term-corrected time series was the series which all the other calculated series based on fewer months was compared to. Long-term corrected time series based on one month of measurements were then calculated. To study if the correlation also varied with the season, long-term corrections were performed for each month of the year. This means that 12 long-term correction calculations based on one month of short-term wind data were carried out. The results of these calculations was exported to MS Excel 2007 and the regression tool in the data analysis Add-In was used to calculate the coefficient of correlation between the long-time corrected series based on 12 month of short-term data and all the series based on one month of measurements. To obtain the coefficient of correlation without any seasonal impact, the mean and the median value of all correlations was calculated. Next step was to perform long-term correlations with two months of measurements as input and after that three months etc. Since the seasonal impact on the correlation was of interest, long-term corrections were carried out with all combinations of adjacent months as short-term data e.g. January - Mars, February – April, Mars - May etc. for the calculations based on three months. Thereby, 12 calculations were performed for every time one month of measurements was added to the short-term data, which resulted in 232 calculations. The results of the calculations were exported to MS Excel 2007 and the correlation to the long-term corrected series based on 12 months was calculated as described earlier.

Due to the loss of data because of freezing of the cup anemometer and a logger that was out of order, some months lacked a considerable amount of data. This needed to be compensated for when the short-term data only consisted of one month. The number of days missing during one month was added from the next month in order to get a full month of measurements. In the case of two month's or longer short-term data no compensation was done since the longer the short-term measurement time series are, the lesser is the impact of the missing days. The total loss of data amounts to 40 days of measurements and the specific dates are presented in appendix I.

3.3 SITE DESCRIPTION

Measurements from four different sites have been used in this study. The following is a short site description of these sites.

3.3.1 Site A

A is an inland site in northern Sweden. There are no obstacles or forest nearby the mast or the sodar, which are separated by about 100 m and installed at the same elevation (Hurtig, pers.coum. 2009). This is probably the best site for the comparison study. The location of the sodar and the mast are displayed in figure 9. After the satellite photo was taken the forest that surrounds the sodar and the mast has been harvested.

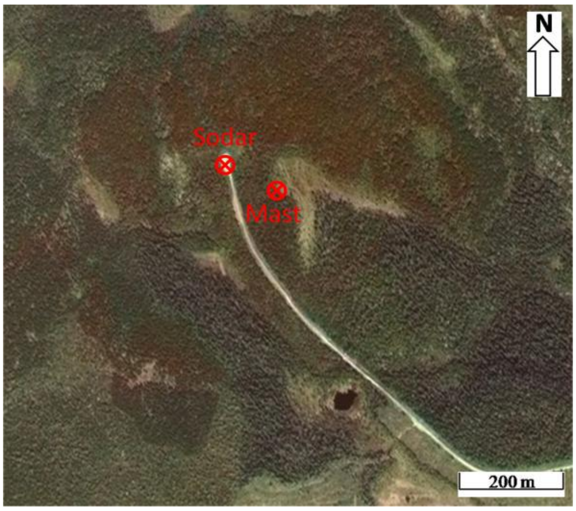

Figure 9. Positioning of the sodar and the mast at site A.

3.3.2 Site B

Site B is located in central Sweden about 4 kilometers from the east coast. The sodar and the mast are separated by a distance of approximately 100 m and the sodar is installed at a five meter lower elevation compared to the mast. This is compensated for in the comparative study. Both instruments are positioned on an area with a sparse forest. The trees are about 10 – 15 m high and the location of the sodar and the mast are marked on the satellite photo in figure 10.

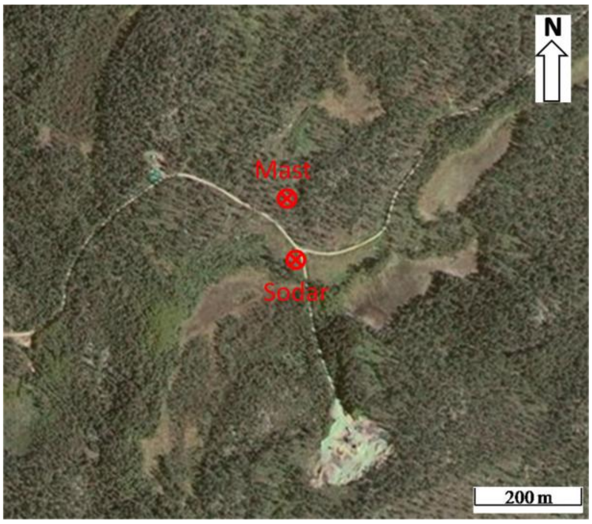

Figure 10. Positioning of the sodar and the mast at site B.

3.3.3 Site C

C is an inland site in southern Sweden. The sodar and the mast at site C are located at the same elevation but separated with a distance of approximately 600 m. Taller trees surround approximately 270 degrees of the location of the mast compared to the location of the sodar where only a few lower trees are in the vicinity, figure 11.

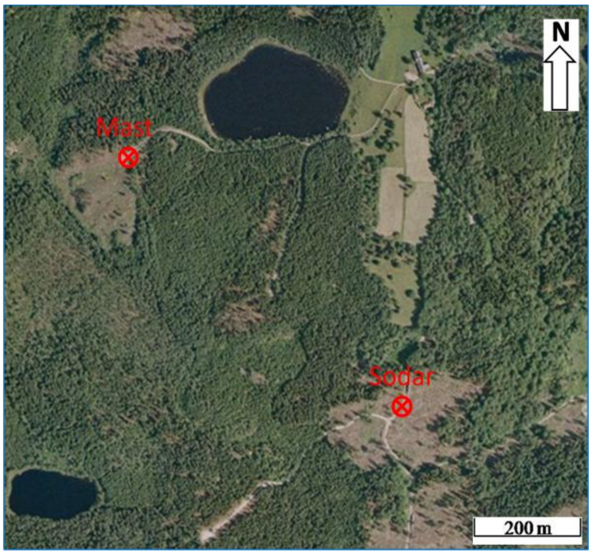

Figure 11. Positioning of the sodar and the mast at site C.

3.3.4 Site D

Site D is located about 15 kilometers south west of the town Söderhamn. There is no sodar at the site but the mast which is positioned in a forested area at the top of a mountain has been used in the long-term correction study.

4 RESULTS

This chapter presents the results from both the sodar and mast comparison and the long term correction study. There will also be some short explanations in order to make the results easier to comprehend.

4.1 COMPARISON OF SODAR AND MAST MEASUREMENTS

Table 2 presents the measuring period for each site.

Table 2 Measuring period for each site

Site	Measuring period	
A	03-Sep-2009 to 19-Sep-2009	0.6 months
B	17-Jun-2009 to 08-Aug-2009	1.7 months
C	26-May-2009 to 05-Oct-2009	3.4 months

Since the mast and the sodar at site C are located rather far from each other, see section 3.3.3, the most important studies are those carried out at site A and site B.

Required data to perform the data availability study was only available at site B and site C. Figure 12 and figure 13 presents the data availability at site B and site C.

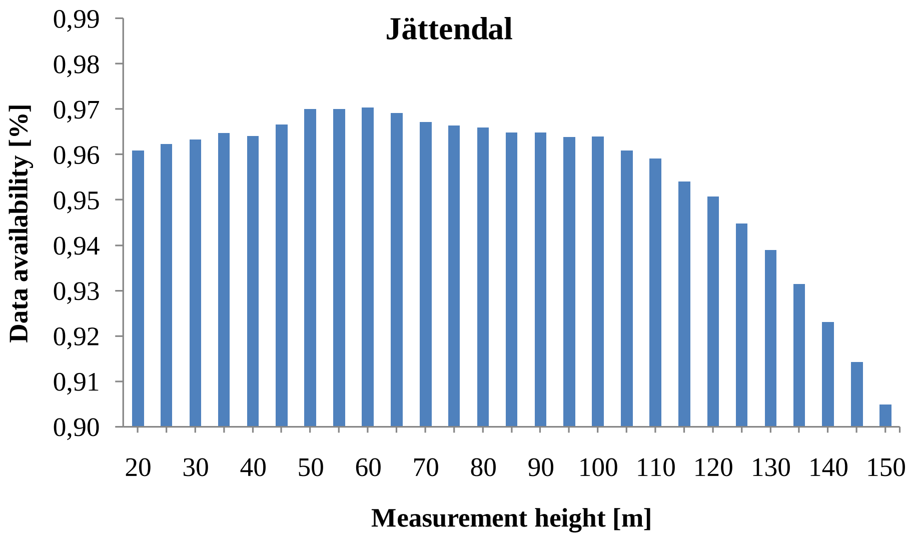

Figure 12. Sodar data availability for different measurement hights at site B.

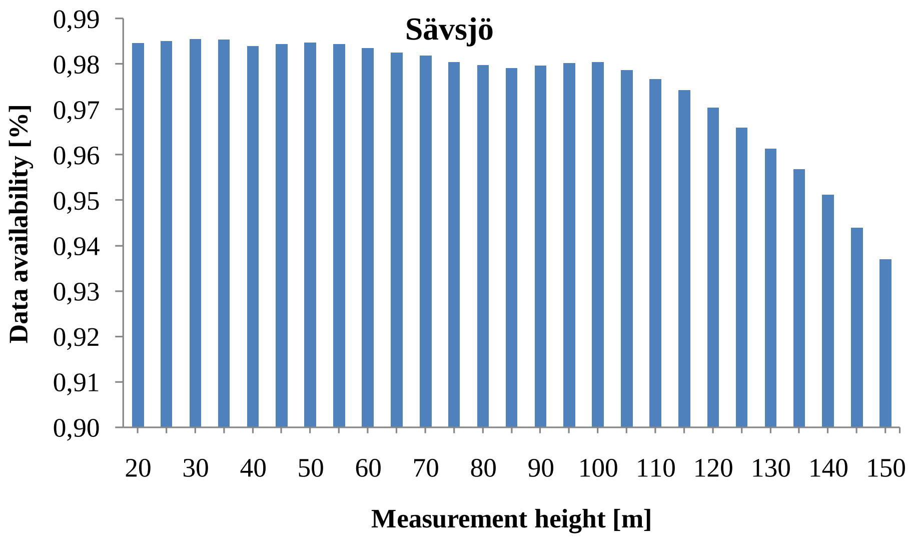

Figure 13. Sodar data availability for different measurement hights at site C.

The sodar at site C has a better data availability compared to the sodar at site B. Besides the expected loss in availability at the top of the wind profile, both sites have a small lack in availability around 80 m height. There is also a lower availability at the bottom of the wind profile compared to the middle of the profile at site B.

4.1.1 Mean wind speed and wind direction

The mean wind speed, mean difference and standard deviation for the three sites are presented in table 3, table 4 and table 5. The mean difference is calculated by subtracting sodar data from cup anemometer data.

Table 3 Mean wind speed, mean difference and standard deviation at site A

	80 m	**120 m**
Mean wind speed sodar [m/s]	6.198	7.057
Mean wind speed mast [m/s]	6.110	7.015
Mean difference [m/s]	-0.099	-0.030
Standard deviation [m/s]	0.589	0.636

Table 4 Mean wind speed, mean difference and standard deviation at site B
a) Corrected for overspeeding

	40 m	**60 m**	**80 m**	**81.5 m**	**81.5m [a)]**
Mean wind speed sodar [m/s]	3.790	4.314	4.703	4.703	
Mean wind speed mast [m/s]	3.771	4.223	4.645	4.701	4.698
Mean difference [m/s]	-0.019	-0.091	-0.058	-0.001	-0.006
Standard deviation [m/s]	0.655	0.596	0.628	0.649	0.650

Table 5 Mean wind speed, mean difference and standard deviation at site C
a) Corrected for overspeeding

	40 m	**60 m**	**80 m**	**81.5 m**	**81.5m [a)]**
Mean wind speed sodar [m/s]	4.362	5.237	5.93	5.926	
Mean wind speed mast [m/s]	4.171	4.864	5.57	5.631	5.625
Mean difference [m/s]	-0.191	-0.372	-0.359	-0.295	-0.303
Standard deviation [m/s]	0.842	0.792	0.818	0.809	0.810

The mean wind speed measured by the sodar and the cup anemometers show a good conformity for site A and site B. At site C there is a greater difference in mean wind speed. The standard deviations do not show any clear significant dependence of measuring height and are rather constant at each site. Site A and site B is within the same magnitude of standard deviation.

The effect of overspeeding has been reduced on cup anemometer data for the top measuring height at site B and site C. Site A lacked necessary data to perform the calculation. According to table 4 and table 5 only a small reduction in cup anemometer mean wind speed and no significant change in standard deviation were obtained.

Analyses of the wind direction are only performed at the heights where the mast has a wind vane deployed and not at site A where data about wind direction was available. Since the wind direction has a value between 1 to 360 degrees, problems may occur when calculating the mean difference and standard deviation. When the sodar for example reports a direction of 360 degrees, the wind vane may report a direction of 1 degree. This is a good conformity in wind direction but will introduce an error in case of mean difference and standard deviation. Therefore, 360 degrees was added to the lowest wind direction value when the difference in wind direction between the sodar and the wind vane was larger than 250 degrees. This implies that the wind vane from the example earlier has a value of 361 degrees which results in a difference of 1 degree instead of 359 degrees.

Table 6 and table 7 presents the mean difference and the standard deviation where the sodar wind direction is subtracted from the mast wind direction.

Table 6 Mean difference and standard deviation of wind direction at site B

	40 m	**80 m**
Mean difference [°]	1.363	-2.855
Standard deviation [°]	18.92	16.68

Table 7 Mean difference and standard deviation of wind direction at site C

	40 m	**80 m**
Mean difference [°]	-3.781	-9.936
Standard deviation [°]	21.82	18.69

There was a smaller mean difference and standard deviation at site B compared to site C. The sodar measures higher wind directions at site C and at 80 m height at site B.

4.1.2 Correlation study

Figure 14, figure 15 and figure 16 present the wind speed correlation between the sodar and the cup anemometers at site A, site B and site C respectively. The data in the scatter plots are ten minute averages reported by the sodar and the cup anemometers

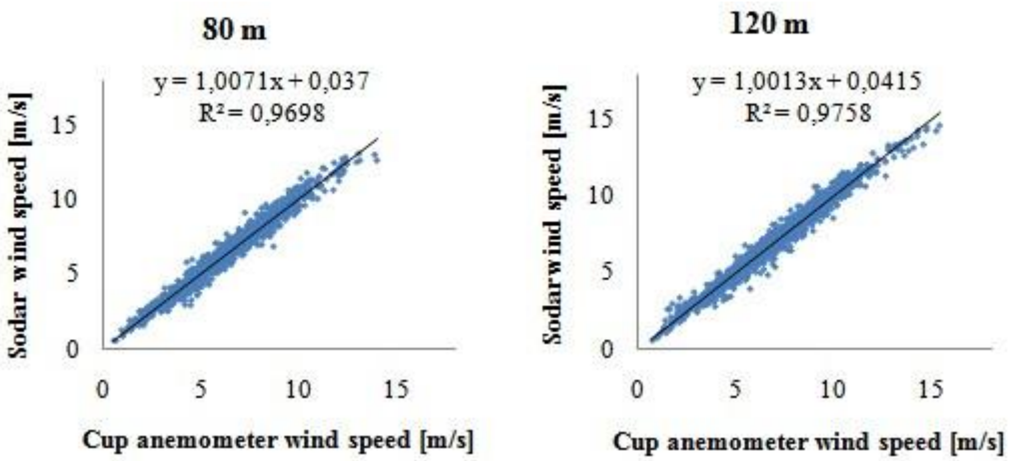

Figure 14. Correlation of wind speed at site A.

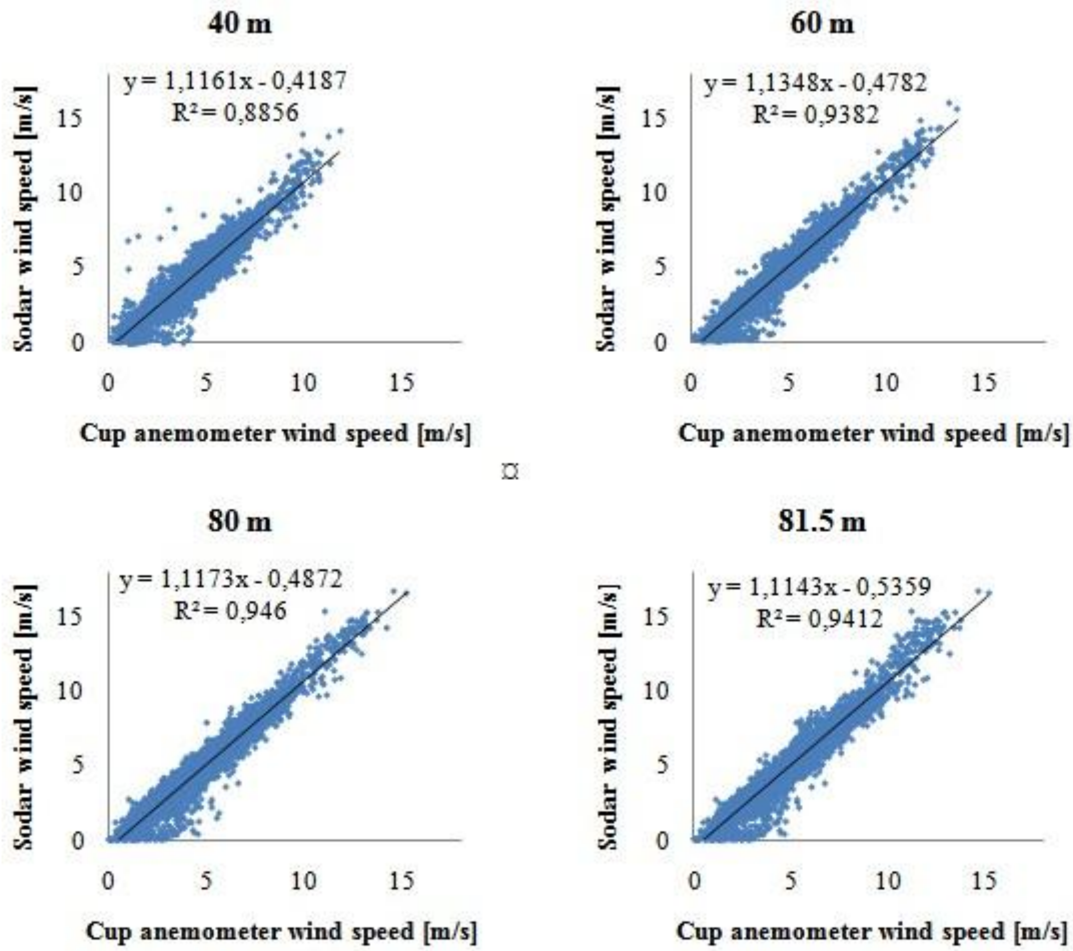

Figure 15. Correlation of wind speed at site B.

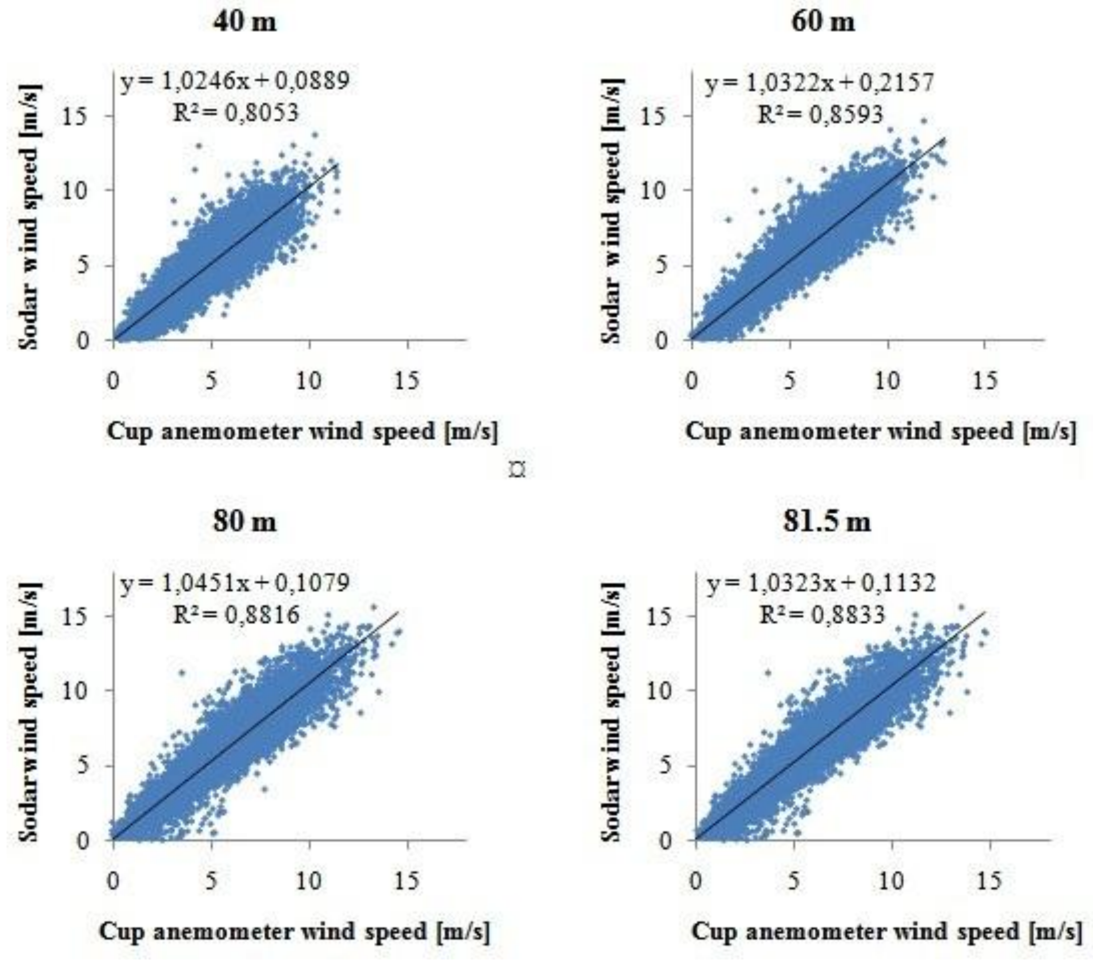

Figure 16. Correlation of wind speed at site C.

The coefficient of correlation is increasing with altitude, except for the 81.5 m measurement height at B where the value is almost the same as for 80 m. The best correlation is achieved at site A but the correlation for site B is also quite good. The correlation at site C is not as good as the other sites. Using an equation not allowing any offset, i.e. $y = kx$, only gave a negligible difference in the coefficient of correlation.

When compensating for the overspeeding error at 81.5 m measuring height at site B and site C there is no change in the coefficient of correlation.

Measurements below 5 m/s at site B seems to differ more compared to higher wind speeds. Since measurements below 4 m/s are under the normal cut-in speed of a turbine, they do not affect the energy yield calculation and were therefore excluded at 81.5 m to see if the correlation improved. The result of doing this however was a lower coefficient of correlation 0.913 instead of 0.941. The mean deviation was increased to -0.213 m/s from -0.001 m/s, but the standard deviation did not change significantly. Since the mast measures higher wind speeds compared to the sodar below 5 m/s, a possible explanation for the differences might be overspeeding of the cup anemometers. Therefore, the correlation at 81.5 m was calculated for the wind speeds between 0 – 5 m/s both when the cup anemometer data was compensated and when it was not compensated for the overspeeding error. The results showed no significant difference in correlation or in mean wind speed and standard deviation.

The wind direction correlation study is performed with wind direction data that is not compensated for the problem around zero degrees. No coefficient of correlation was therefore calculated. However, the shape of the chart indicates the correlation between the two instruments, figure 17 and figure 18.

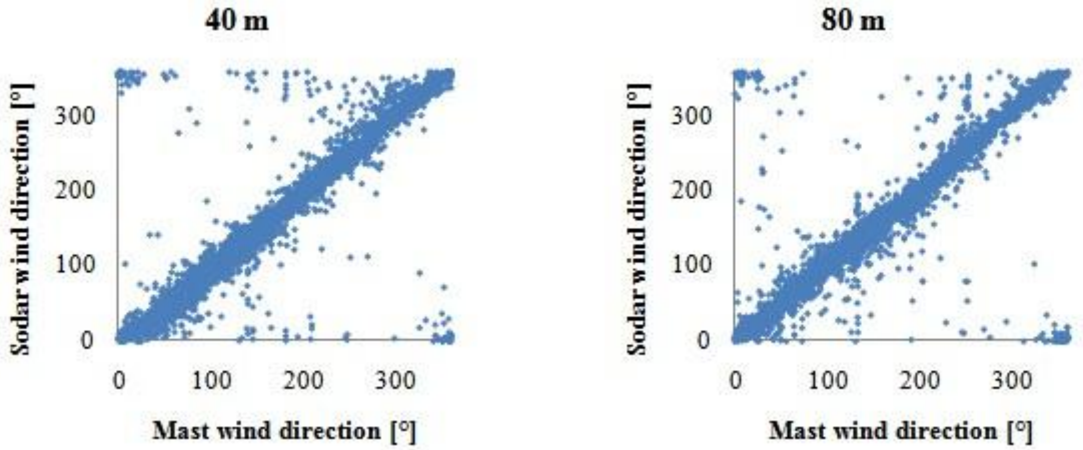

Figure 17. Correlation of wind direction at site B.

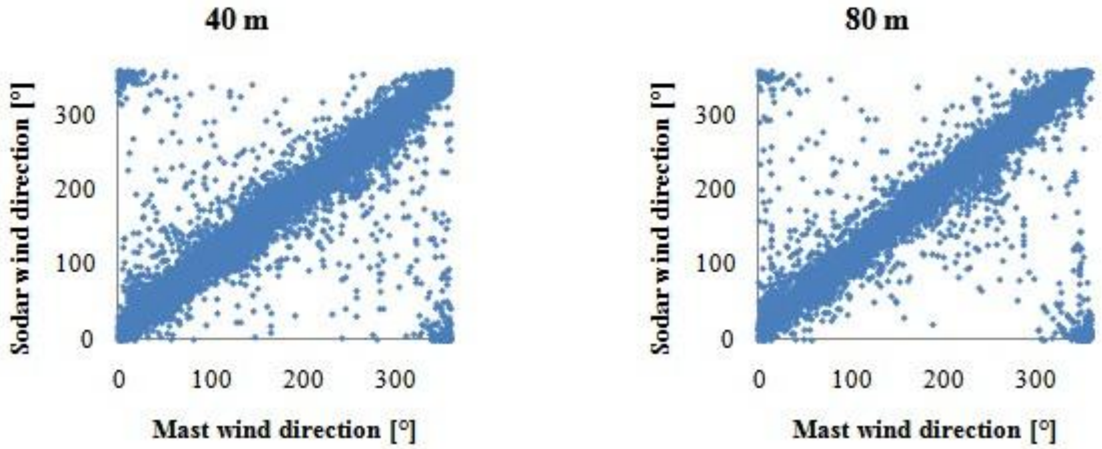

Figure 18. Correlation of wind direction at site C.

The measurements are less scattered in figure 17 than in figure 18, which signifies a better correlation of wind direction at site B than at site C. The problems around zero degrees are displayed in the upper left and the lower right corner of each plot.

Turbulence intensity data were only available at site B and site C. Correlation analyses are performed at 40 and 81.5 m measuring height and presented in figure 19 and figure 20.

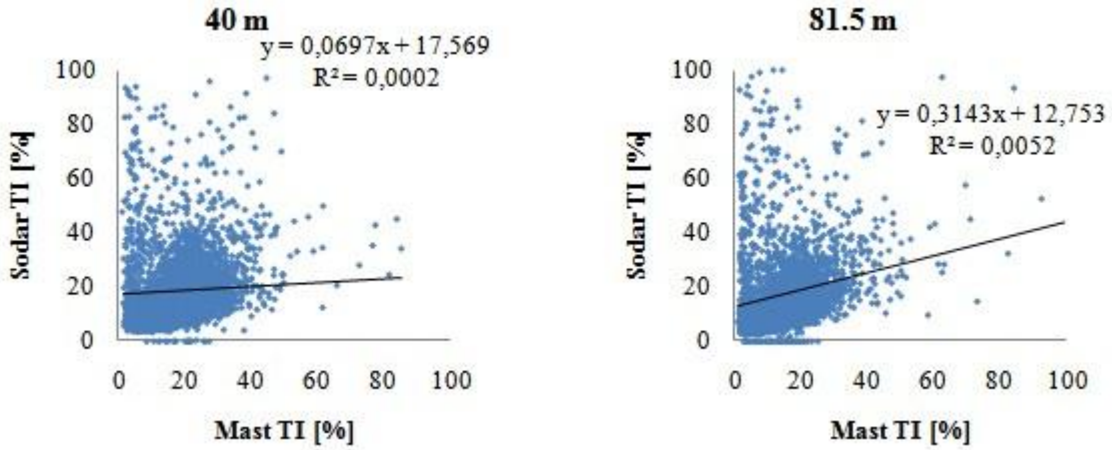

Figure 19. Correlation of turbulence intensity at site B.

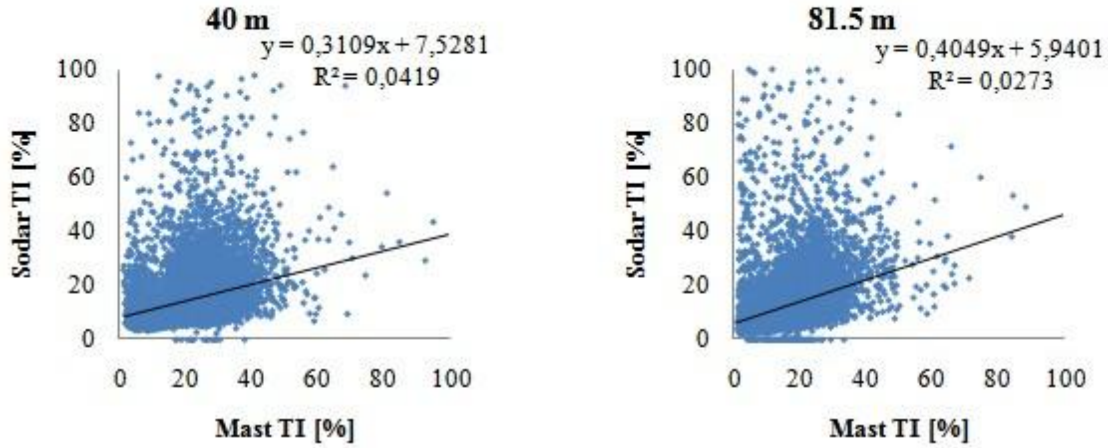

Figure 20. Correlation of turbulence intensity at site C.

There is a very low coefficient of correlation at both sites. The reason for an extremely low correlation at site B is a number of outliers from the sodar not within the range of the plot. Since the turbulence intensity is the ratio between the wind speed standard deviation and the mean wind speed, low values of mean wind speed will result in high turbulence intensities. The turbulence intensity values with a mean wind speed below 4 m/s were therefore rejected to study if the correlation improved. At site B the coefficient correlation improved to 0.38 at 40 m height and to 0.22 at 81.5 m height. Corresponding results for site C was 0.11 at 40 m height and 0.32 at 81.5 m height. This is still a low coefficient of correlation. The result from both before and after the rejection of data indicates that the sodar measures a lower turbulence intensity compared to the cup anemometers.

4.1.3 Scalar and vector averaging

By studying the scatter plots from site B it is noticeable that the sodar has a tendency to measure lower wind speeds below 5 m/s compared to the cup anemometers. One of the reasons for that might be the differences between scalar and vector averaging of wind data as discussed in section 2.4.1. This was studied at height 40 and 80 m, figure 21 and figure 22.

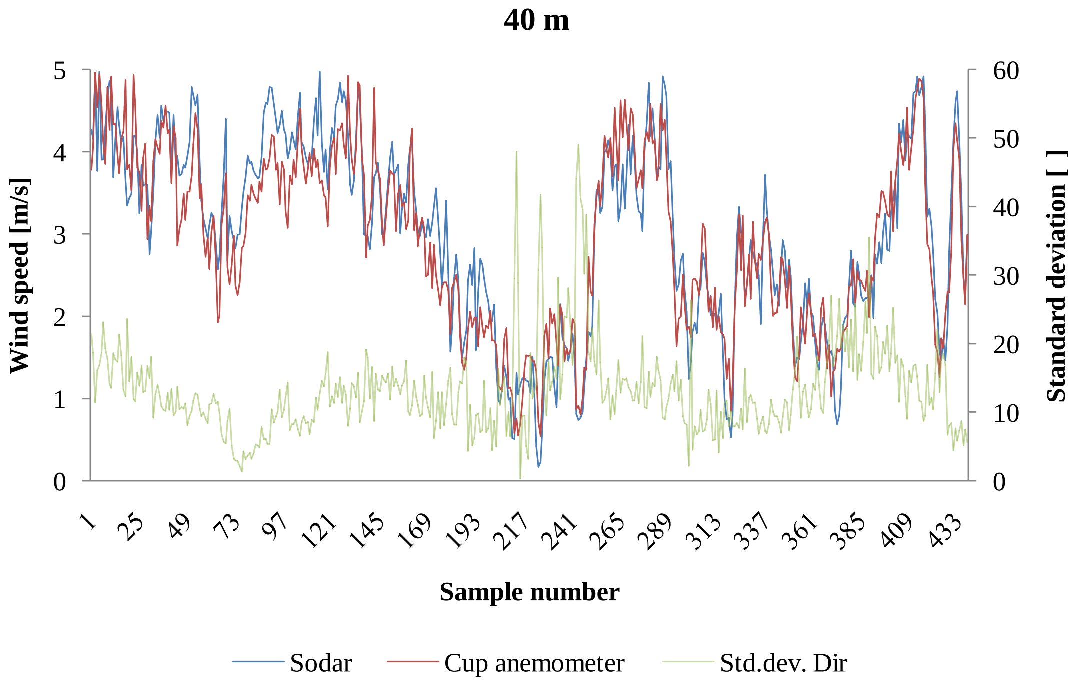

Figure 21. Vector and scalar averaged wind speed, i.e. sodar and cup anemometer wind speed together with the standard deviation of wind direction at 40 m height at site B.

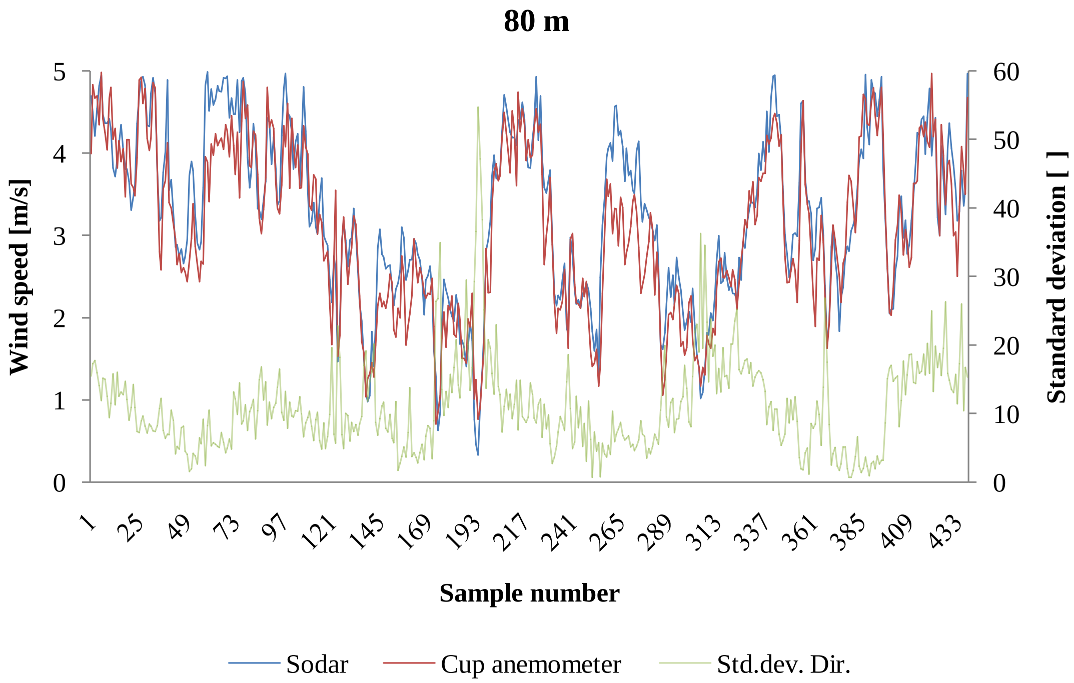

Figure 22. Vector and scalar averaged wind speed, i.e. sodar and cup anemometer wind speed together with the standard deviation of wind direction at 80 m height at site B.

There are some results supporting the theory that the sodar should report a lower wind speed when there is a higher standard deviation of the wind direction, especially at 40 m height around sample number 230 where the standard deviation is high. However, there is no distinct trend in these measurements that indicates that the different averaging methods are the reason for the somewhat lower wind speed measured by the sodar below 5 m/s.

4.2 LONG-TERM CORRECTION

The result of the long term correction study is presented in figure 23. A mean and median value of all the coefficients of correlation for a specific measurement period has been calculated in order to prevent any seasonal impact on the result.

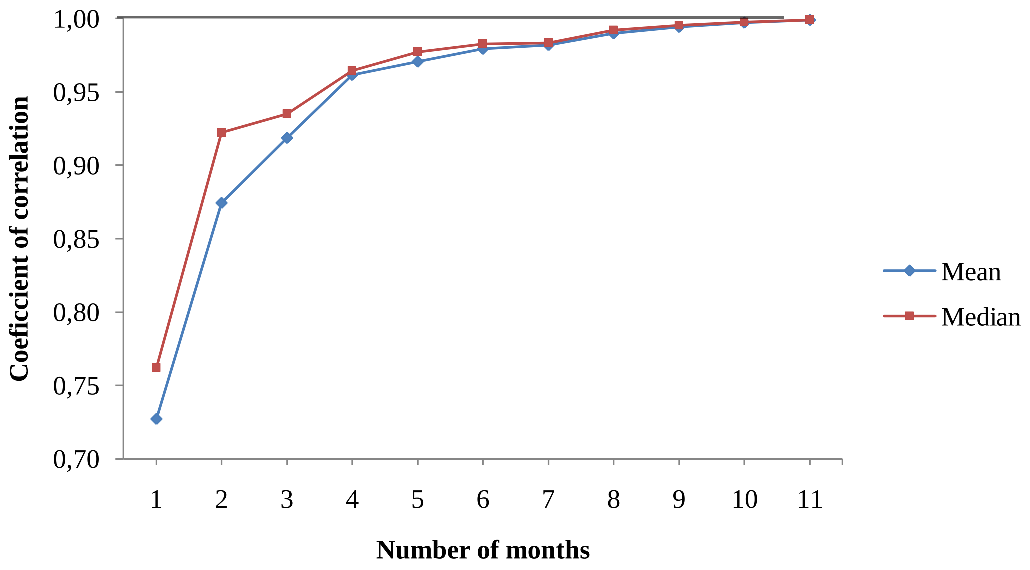

Figure 23. Mean and median value of the coefficients of correlation depending on the length of measurement period.

Figure 23 shows that the largest increase in the coefficient of correlation occurs during the first four months. The increase in correlation between the measurement period of six months and seven months is smaller compared to the general trend for adjacent measurement periods. The difference between the mean and the median values are only significant during the shorter periods since extreme values are more common there.

The result from the study of seasonal impact on the correlation is presented in figure 24. The x-axis represents the middle month in each measurement period, e.g. 3 means that March is the middle month in all five series.

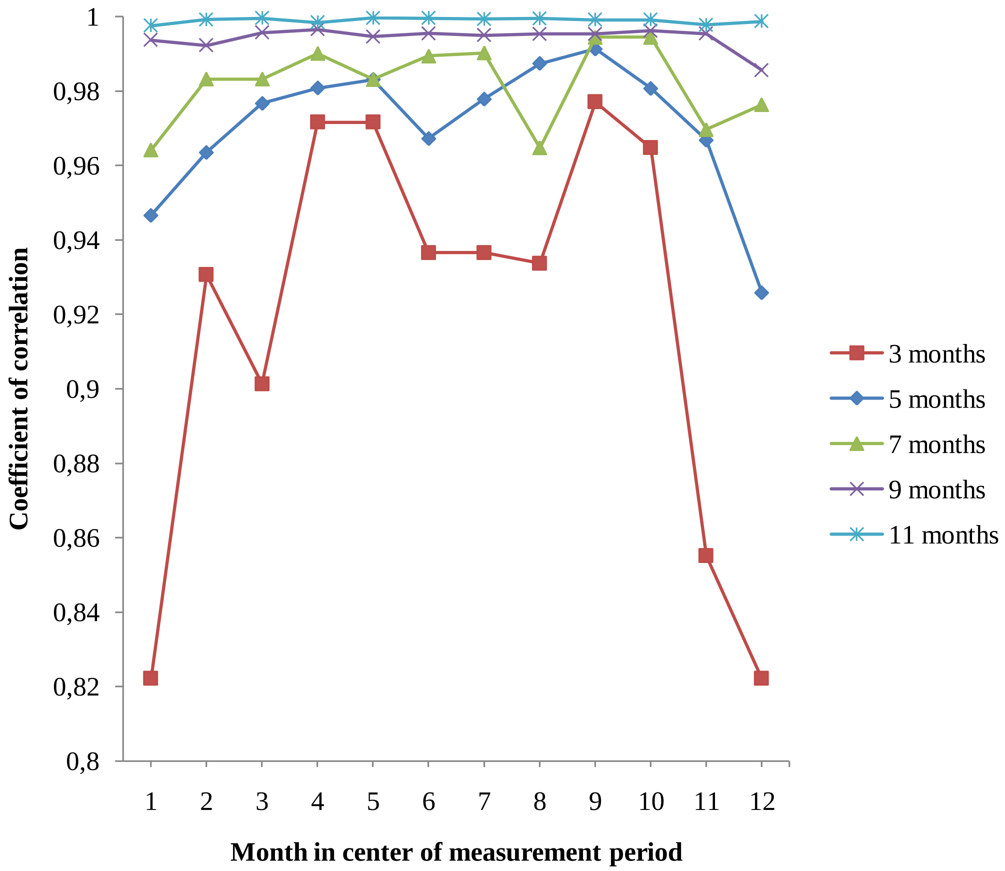

Figure 24. Seasonal impact on correlation for measurement periods of various lengths.

According to figure 24 there is a trend in the three shortest series that indicates a higher coefficient of correlation during spring and autumn compared to summer and winter. There is also a slightly better correlation during the autumn compared to the spring. The two longest series do not show any distinct trend.

5 DISCUSSION

As this thesis is divided in to two parts, these parts will also be treated separately in the discussion chapter.

5.1 COMPARISON OF SODAR AND MAST MEASUREMENTS

Information about the presence of fixed echoes, background noise and the attenuation of sodar data at the top of the wind profile was obtained from the study of the sodar data availability. Two reasons for better sodar data availability at site C compared to site B might be that there are more fixed echoes and background noise present at site B. The loss of availability in the lower parts of the wind profile at site B was probably due to fixed echoes. However, no explanation was found for the small lack in availability around 80 m height at both sites.

5.1.1 Wind speed

With respect to the distance between the instruments at the test sites, conclusions should only be drawn from measurements at site A and site B. Measurements from these sites indicated a good agreement between the sodar and the cup anemometer wind speed measurements. The mean difference in mean wind speed at all heights was less than 0.1 m/s, which is equal to or below the accuracy of the sodar and the cup anemometer respectively. There was a relatively big difference in measured wind speed (1.2%) between the cup anemometer at 80 and 81.5 m height at site B and the reason for that might be that the anemometer at 81.5 m was top mounted and thereby less disturbed by the mast structure.

According to this study the sodar measured a higher mean wind speed compared to the mast at all sites. This was in contrary to both the theory and previous studies. The reason for this was difficult to determine. However, the previous studies have been carried out at one site each whilst this study was performed at three sites, indicating that the sodar may measure higher wind speeds as well.

The differences in reported wind speed by the sodar and the mast below 5 m/s at site B could not be explained by the overspeeding of the cup anemometer. Nor was it possible to entirely explain the differences with the results from the study of scalar and vector averaging. However, to make a proper study about the differences in wind speed between scalar and vector averaging, it is necessary to have a software in the mast or the sodar logger that reports both scalar and vector averaged wind speed. Otherwise, the distance between the two instruments has an impact on the results. The vector averaged wind speed may be more relevant in terms of energy yield calculations since the turbine cannot respond to fast fluctuations in wind direction. A more detailed study of the differences in wind speed between scalar and vector averaging would be an interesting subject for further studies.

5.1.2 Wind direction

In terms of wind direction, it was only possible to evaluate the results from the comparison at site B since the distance between the sodar and the mast at site C was too far and because there were no data from site A. According to the results from the study at site B there was a good conformity in wind direction between the sodar and the wind vane. It was not possible to conclude that one of the instruments measured higher or lower values of wind direction compared to the other instrument since the wind vane measured higher values at 40 m and the sodar measured higher values at 80 m height. There was a smaller mean difference at 40 m height but a higher standard deviation compared to 80 m height. This implies more extreme values in wind direction differences at 40 m height which might be due to a higher degree of turbulence at lower heights.

5.1.3 Turbulence

Since the comparison of turbulence measurements in this thesis were not detailed enough, no certain conclusions could be drawn. However, as expected from the theory it was possible to determine that the sodar measured lower turbulence intensities compared to the mast. This lower value should not be interpreted as incorrect since the cup anemometer provides the value for turbulence intensity on a small scale and the sodar reports turbulence intensity measured on a larger scale. It is a matter of what is desired and at least for the time being turbulence measurements performed by a sodar are not valid for the IEC WT 01 classification discussed in section 2.2. The result from the turbulence study in this thesis indicated a significantly lower coefficient of correlation compared to three non public previous studies (Bergström, pers.coum. 2010). However, the result from the turbulence study carried out by Vattenfall showed resemblance with the results in this study (Gustafsson, 2008). A more detailed turbulence comparison study is of interest for further work.

5.1.4 Aspects not related to measuring technique

All measurements in this were been carried out during the summer and the autumn which eliminates the possibility of under speeding by the cup anemometers due to icing of the cups and freezing of the bearings. This implies reliable data, but to be able to make a more thorough study it would be desirable to compare sodar and cup anemometer data during the winter time as well. A source of error in this type of study was the distance between the two instruments, but since it is impossible to have them located on the same spot because of fixed echoes and wind wakes due to the mast structure, it cannot be completely eliminated.

In terms of output data from the two instruments the sodar reports a wind profile for the whole sweep area, whilst the mast usually only have a measurement at hub height and one or maybe two at the lower part of the sweep area. A wind profile for the whole sweep area enables a better estimation of the energy yield and provides more information about the wind shear. As rotors are growing in size this becomes more and more important. The towers are also growing in height which demands higher and thereby more expensive met masts.

The mobility of the sodar enables a faster deployment and the possibility to measure the wind at different locations within the future wind park area. A sodar is also easy to use at a new site, compared to the mast which in addition to a new building permit also needs to be disassembled and erected once again. Therefore, it is possible to use the sodar as screening instrument and measure the wind during a relatively short period of time at a new site to get an idea if the site is good enough to continue working with. Since the price is about the same for a sodar and a mast (80 m), the sodar will probably be the more cost efficient alternative because no extra cost is added when using it at a new site. A disadvantage of the sodar is the need for more maintenance in terms of refueling the diesel tank during periods of insufficient sunlight.

Using a sodar will eliminate the problems of over- and under speeding by the cup anemometers and the wake effect due to the mast. On the other hand, it is important to make an adequate positioning of the sodar to reduce the influence of background noise and fixed echoes. This limits in a sense the use of sodar, but on the other hand the instrument is possible to use in remote areas with no infrastructure.

A problem for the time being is that measurements from a sodar alone are not bankable or accepted by turbine suppliers. This implies that a mast needs to be used to acquire valid wind measurements. Perhaps all the comparative studies of sodar and already accepted wind measuring instruments will change that fact.

5.2 LONG-TERM CORRECTION

Since this study was only carried out at one site, the results must be seen as site specific and may not be generally valid. However, the tendency in the results might very well be valid for other sites as well. It must also be kept in mind that the loss of data totally amounts to 40 days of measurements. This implies that the long-term corrected reference series based on 12 months of short-term measurements actually only consists of about 10.7 months.

5.2.1 Correlation study

The result of the correlation study shows a better correlation with an increasing length of measurement period. This was expected since adding months to the measurement period will make it more similar to the reference period consisting of 12 months. What was more interesting though was that the fastest increase in correlation occurred during the first four months. After that, the result shows a smaller and smaller increase in correlation for every month added, except for the measurement period consisting of seven months. The reason for a slightly smaller increase in correlation between the measurement period of six months and seven months compared to the general trend for adjacent measurement periods has no explanation and could be a coincidence for the specific data used. A reason for the rapid increase in correlation during the first four months might be due to the fact that every month added made up for a greater part of the total measurement period when the period was relatively short. The rapid increase in correlation during short measurement periods might also be due to the fact that lost or rejected data has a greater impact on a shorter measurement period.

Since the correlation study was carried out between a long-term corrected measurement series based on 12 months of short-term data and long-term corrected measurement series based on fewer months of short-term data, the results are an indication on how good a long-term correction with a shorter measurement period as short-term data represented a long-term correction based on a whole year of measurements. It is important not to confuse that with the correlation between the concurrent data of a long-term corrected measurement series and the original site measurement series, which has not been studied in this thesis but is a common comparison. Another important thing to keep in mind is that there are still uncertainties in the results even after a year of measurements (Bergström & Nilsson, 2009).

5.2.2 Seasonal impact on the correlation

From the study on seasonal impact on the correlation it is evident that wind measurements during the spring and the autumn represented a whole year of measurements better than wind measurements performed during the summer and the winter. It is difficult to explain this tendency but one possible reason might be the daily variations in atmospheric thermal stability discussed in section 2.1.2. During the winter the nights are longer than the days and there is a low heating of the ground. This implies a mostly stable atmospheric thermal stability. Opposite conditions occur during the summer, which means that an unstable stability dominates. The bias in atmospheric thermal stability might be a reason for the lower correlation compared to spring and autumn where the day and night are of a more equal length and both types of stability are common. This theory is supported by an article in the DEWI Magazin in which a similar study with analogous results was carried out (Borget et al., 2007).

The difference in correlation between the winter and the summer was larger for the measurement period consisting of three months compared to the other measurement periods. This might be due to the loss of data which only occurs during the winter and has a greater impact on short measurement periods compared to longer periods. Consequently, there were fewer measurements to base the long-term correction calculation on during the winter.

The seasonal impact decreases with increasing length of measurement period because longer periods contained more than one season. It should be kept in mind that this study does not present the time of year with the highest wind speeds, but the time of year with the most representative wind climate for a whole year.

6 CONCLUSIONS

From the comparative study of sodar and cup anemometer measurements it is possible to draw the conclusion that the measurements performed by the AQ 500 Wind Finder sodar are as valid as those performed by the cup anemometer and the wind vane. Considering other aspects such as mobility, no need for permits, cost efficiency and the fact that the sodar presents a vertical wind profile the sodar is the preferred choice. However, if the aim is to perform long term wind measurements at a certain site a mast might be more suitable due to its low demand for maintenance, unless heating of the anemometers is required. Measurements performed by cup anemometers and wind vanes are also bankable and accepted by the turbine suppliers.

The long-term correction study shows a large increase in correlation during the first four months of measurements. It is therefore important to measure the wind for at least four months in order to get a result from the long-term correction that somewhat represents the result for a whole year of measurements.

It has been shown that there is a seasonal impact on the correlation. This impact becomes less important with an increasing length of the measurement period but is evident up to a measuring period of seven months. The tendency is a better correlation during the spring and the autumn compared to the summer and the winter.

The overall conclusion of this thesis is that the sodar measurements are equivalent to those obtained by a cup anemometer and that at least four months of measurements are needed in order to perform an early evaluation of the long-term wind climate. It is also concluded that measurements performed during the spring and the autumn represents the wind climate for a whole year better than measurements carried out during the summer and the winter.

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APPENDIX I

Table 1 presents the data that was lost in the long-term correction study due to an out of order logger and freezing of the cup anemometer.

Table 1 The dates that were lost in the long-term correction study

Reason for loss	**Date**
Out of order logger	20-Nov-2008 - 14-Dec-2008
Freezing of the cup anemometer	23-Jan-2009 - 02-Feb-2009
Freezing of the cup anemometer	05-Mar-2009 - 09-Mar-2009