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Evaluation of wind measurement technologies

Oxhult
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Summary

A number of various wind measurement technologies are presently commercially available. In this project we have investigated and compared wind data simultaneously obtained with traditional mechanical instruments mounted on a 60m mast and data from a AQS SODAR placed a few hundred meters away.

We conclude that the AQS500 sodar is correlating well with anemometer measurements at 60m for mean wind speed as well as wind direction.

The sodar data are limited in averaging time to 10 minutes, while the anemometer can give data at much shorter time series. Therefore the anemometer can potentially be used to measure turbulence and wind fluctuations at short time scales whereas the sodar can not. A lidar system would be superior and probably the only commercially available system to measure turbulence on small size scales.

The anemometer measures the wind speed and direction in the horizontal plane only whereas the sodar gives the wind vector in three dimensions. This is crucial to determine upwinds and correct attack angle to the blade.

The anemometer is limited to give a few data point in altitude, and is limited by the physical height of the mast. This is a severe limitation when turbines of 90m or more are planned with a central point at 105m above ground. The sodar measures the full wind profile over the area of the wind turbine blade span. We consider also this to be crucial for estimating the suitability of a specific site for wind power plants.

The sodar needs to be situated at minimum 30-50m from any high obstacle such as a mast or a forest edge. The sodar is easy to transport and mount while mast must be transported and raised in a dense forest area.

In general, we suggest that the sodar system is superior in all aspect except the availability of short time data and the requirement of a clear area of 30-50 m around the instrument. However, the sodar system does measure the more important wind shear parameters. This, together with the ease of use and service, suggest that the sodar is a better choice to determine wind parameters for locations of large wind turbines.

We suggest that the build-up of Swedish wind power industry is of such magnitude that standardization of wind parameters and certification of wind measurement systems must be prioritized.

1 Introduction

Wind power is one of the fastest growing industries in Sweden, and in the world, of today. Wind power is seen as a clean generation of electrical power and new taxes on green house gas emissions will make it a competitive source of energy. Large wind power parks are planned in Sweden, and especially the coastal and high plateau landscape of Halland and surroundings have generated great interests for investors.

Wind is a natural resource which is depending on geographical site location and of the structure of the landscape both in near and far field. The regional wind conditions can be rather well modeled using fluid dynamic code, but local conditions have to be measured due to the inability to analytically model more turbulent gas flows. Hills, forests and sudden changes in the landscape agricultural use and vegetation will affect wind conditions locally. These conditions have to be measured and followed over long times in order to properly asses the optimal positions of wind parks and individual wind turbines.

Measurements of wind speed, direction, wind shear, and to some degree turbulence therefore need to be measured and assessed for each planned wind power site. These measurements need to be performed at the sites, before they have been developed. This calls for a large number of robust and correct wind measurement instruments. They are required to be robust for weather and be able to measure in all kinds of weather conditions such as rain, fog, high winds and sow and ice. The measurements also have to be continuous and scientifically appropriate and correct. Because of the large number of instruments required, they need to be low price, easy to install and access and with minimum of maintenance.

2 Project goal

A number of various wind measurement technologies are presently commercially available. In this project we have investigated and compared wind data simultaneously obtained with traditional mechanical instruments mounted on a 60m mast and data from a AQS SODAR [1] placed a few hundred meters away.

3 Required measurements

The Troposphere is a mixture of molecules in gas form. The molecules move in Brownian motion with speeds determined by the temperature of the gas. The Troposphere is usually divided into three regions [2]. Coriolis forces and large scale horizontal pressure gradients create a flow at heights over about 500 m in the Geostrophic layer. Very close to the ground, at 0 to a few cm, the gas flow is laminar and viscous. Above this up to a few tens of meters is the mixed or Prandtl layer [2] where the wind is affected by friction to the laminar viscous ground layer. Over a few tens of meters up to 500 m is the Ekman layer [3], which is the interface layer between the ground layer and the Geostrophic layer. This is characterized by that the wind is less turbulent, that the wind speed is increasing with height and that the wind direction is slowly turning in a Ekman spiral from the ground friction region to the jet wind in the Geostrophic layer [4].

Local variations in pressure formed by the wind hitting hills and other obstacles are affecting the wind in the mixed layer. Such locally induced winds are at shorter distances and create turbulent eddies, where the wind is behaving locally different, but which move together as coherent atmospheric cells [5]. The size of such turbulent eddies is important for the physical stability of wind turbines.

Wind shear, i.e. difference in wind direction (impact angle to blade) and wind speed, over the wind turbine surface area is also important. Large wind shear may cause severe loss of power output and also, in severe cases, damage to the turbine wings [6].

For best effect, a wind turbine should be situated above the mixed layer, in the Ekman layer where wind direction and wind speed are more constant and where turbulence is less.

4 Wind parameters

4.1 Definitions

Wind data are usually measured as:

u = mean horizontal wind speed taken over 10 mins.
v = mean vertical wind speed taken over 10 mins.
Δu = standard deviation of horizontal wind speed over 10 mins average
Δv = standard deviation of vertical wind speed over 10 mins average
θ = wind direction with 0 degrees to North
Γ = Δu/u is the turbulence index over 10 mins. Note that this is in reality the noise-to-signal ratio where ALL noise contributors within 10 mins are included (instrumental as well as real gas flow fluctuations).

The wind speed is assumed to have a Weibull distribution P with scale parameter A and shape parameter k as:

$$P = A * k * u^{(k-1)} * e^{-A*u^k}$$

α = shear coefficient for level 2 relative level 1 as:

$$\frac{v_1}{v_2} = \left(\frac{Z_1}{Z_2}\right)^{\alpha}$$

4.2 Standardization

Measurements of wind data need to be standardized and made by specifically certified instruments. There is work ongoing to decide on a standard. This is lead by IEC [14]. The only use we have seen of this work as today is that the wind measurements should be made within 2.5% of the height of the turbine rotation center.

We note the lack of standard of wind measure at this time. A number of parameters are used such as Weibull coefficients, turbulence index, mean wind speed over 10 minutes etc.. Especially the turbulence parameter needs to be firmly defined. Turbulence may mean a number of different variations in wind speed and needs to be defined as to time scale and why it is required. Also shear needs to be defined as to time scale and what part of wing.

4.3 Certification

Certification of wind measurement should follow the ISO9001 format. A part of this is included as Appendix A. In short, the certification can be summarized as:

1. Verification of the technique and technology.
2. Validation of the system.
3. Calibration of each unit.

The organization also needs to be certified as to learning and use of the system.

We suggest that the build-up of Swedish wind power industry is of such magnitude that standardization of wind parameters and certification of wind measurement systems must be prioritized.

5 Technologies

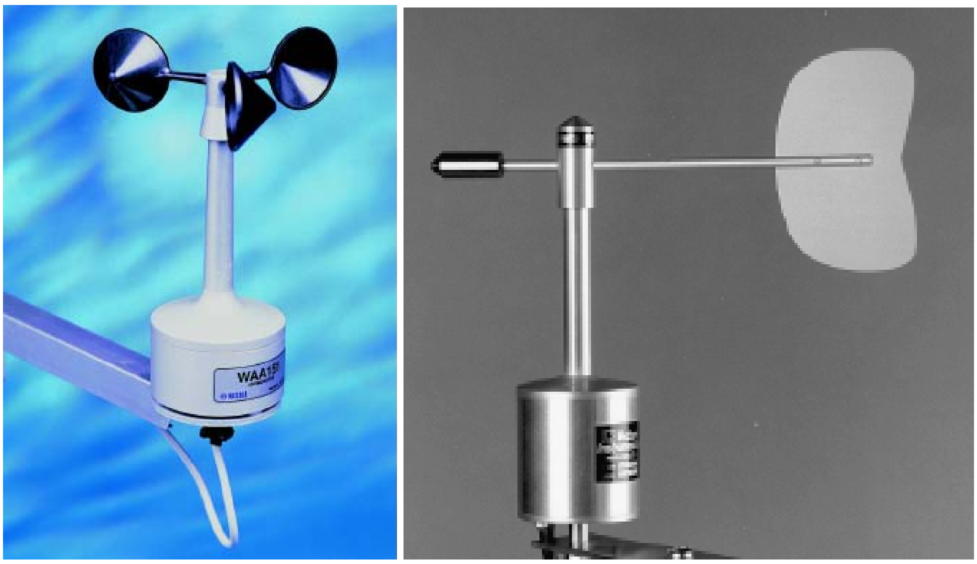
Wind flow parameters can be measured in many ways. Usually flows are measured in wind tunnels using seed particles and background light. This is not possible in free atmospheric conditions. The most used methods are summarized below.

5.1 Mast

The most common practice is to mount mechanical wind devices on a high mast. Small cups mounted on rotating arms are used to measure the wind speed. The rotation speed induced by the wind is directly proportional to the wind speed. A small 'sail' is mounted on another arm. This directs itself along the horizontal wind vector and is used to measure the wind direction. These devices measure only the horizontal wind speed and direction. They cannot measure any vertical vector of the wind. Measurements can be taken at high frequency, and small scale variation in wind can therefore be measured. All measurements are local, and only at the height above ground where the instruments are mounted. Also, measured wind parameter may be affected by the wind flow around the mast. The devices are mechanical and mechanical wear, friction and mass will affect the measurements. Fast changes in wind speed and direction may not be measured correctly because of the inherent mass of the moving cups and sail.

The instruments have to be physically mounted at each observational level. This requires very high masts to be hoisted in difficult terrains. The measurements should be taken over the full height of the wind turbine, in the case of Oxhult up to at least 150m. The instruments also have to be serviced at regular intervals, usually 1-2 times per year.

The system at Oxhult consists of instruments mounted at 40m and 60m. The instruments are Vaisala WAA151 anemometer [7] and W200P potentiometer [8] wind vane as shown below.

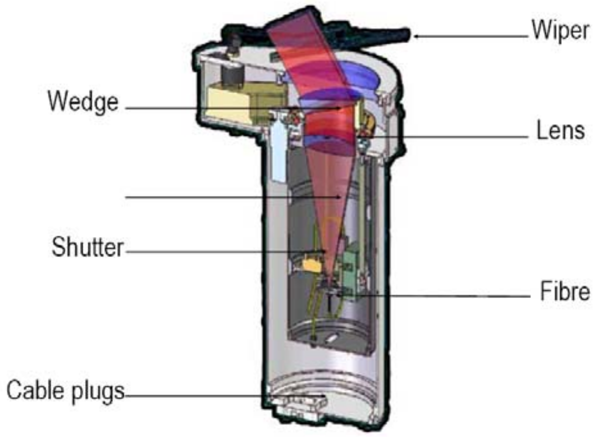


Figur 1 – WAA151 anemometer (left) and W200P wind vane (right).

5.2 Lidar

Lidar is a fairly modern concept [9]. Monochromatic light, usually in the infrared, is emitted by a laser and focused at a defined distance from the source. The light is reflected by aerosol molecules back towards the Lidar instrument. The light is detected and the spectrum is determined. The frequency of the reflected light is Doppler shifted by the motion of the reflected molecules to the height where the beam has been focused. The Doppler shift is determined and converted to velocity. The velocity is then determined as a function of height by focusing at different heights and the determined Doppler shift, i.e. velocity, at each. This gives the velocity distribution along a certain direction. This is then repeated in a number of directions along a circle at a small zenith angle, usually 16 degrees. By combining all such directions, the velocity vector distribution can be determined in three dimensions.

The Lidar system has the advantage of being small and transportable. It is also fairly robust to weather conditions, but rain and fog can have severe impact on the availability of data [10]. The data rate is very fast, and sampling can be done at 1 Hz or better. The intrinsic accuracy is very high and has been proven to be so also in field tests. The opening angle of the system is very small and it can therefore be placed very close to trees, masts or other obstacles. The cost of a full system is around € 150 000.



Figur 2 – Principle of Lidar system.

Figur 3 – Principle of Lidar system.

5.3 Sodar

The Sodar system is similar to the Lidar system, but works with sonic waves instead of light [11]. The frequency is usually around 3000 – 4000 Hz. A short pulse is transmitted in a direction and then received with the same antenna. The time delay between transmission and reception is the travel time to the reflected layer and back. The sonic pulse is reflected by small pressure, density or temperature gradients in the troposphere. Such layers exist abundantly and sonic waves will therefore be reflected at all heights. The signal is received in time bins, each representing a distance. With a sonic speed in air of around 300 m/s, the time of travel back and forth to the maximum required level of 150 m will be 1 second. The pulse repletion speed can therefore not exceed 1 second. The spectrum of the received signal is obtained in each delay bin, and the velocity of the reflected layer is determined from the Doppler shift. This is done sequentially in three directions with a small, about 16 degrees, zenith angle and at 120 degrees azimuth angle to each other. The three dimensional wind speed vector can then be determined from these data at each present level bin. The bins are usually set to every 5 m of height from 0 to 150m.

The Sodar has, as the Lidar, a very high intrinsic accuracy in determination of the speed vector. The great advantage to the mast mounted mechanical instruments, is that it does measure multiple levels and do not require any mast. The Sodar can, as the Lidar, be placed directly on the ground, but needs to be carefully leveled. The Sodar beam has, due to the longer wavelength, a much larger opening angle than the Lidar beam. The opening angle is about 20 degrees, and the Sodar must be positioned well away from any nearby obstacles which can reflect the sonic pulse in the near field. The Sodar therefore must be placed at least 20-50 m from the mast and any nearby trees.

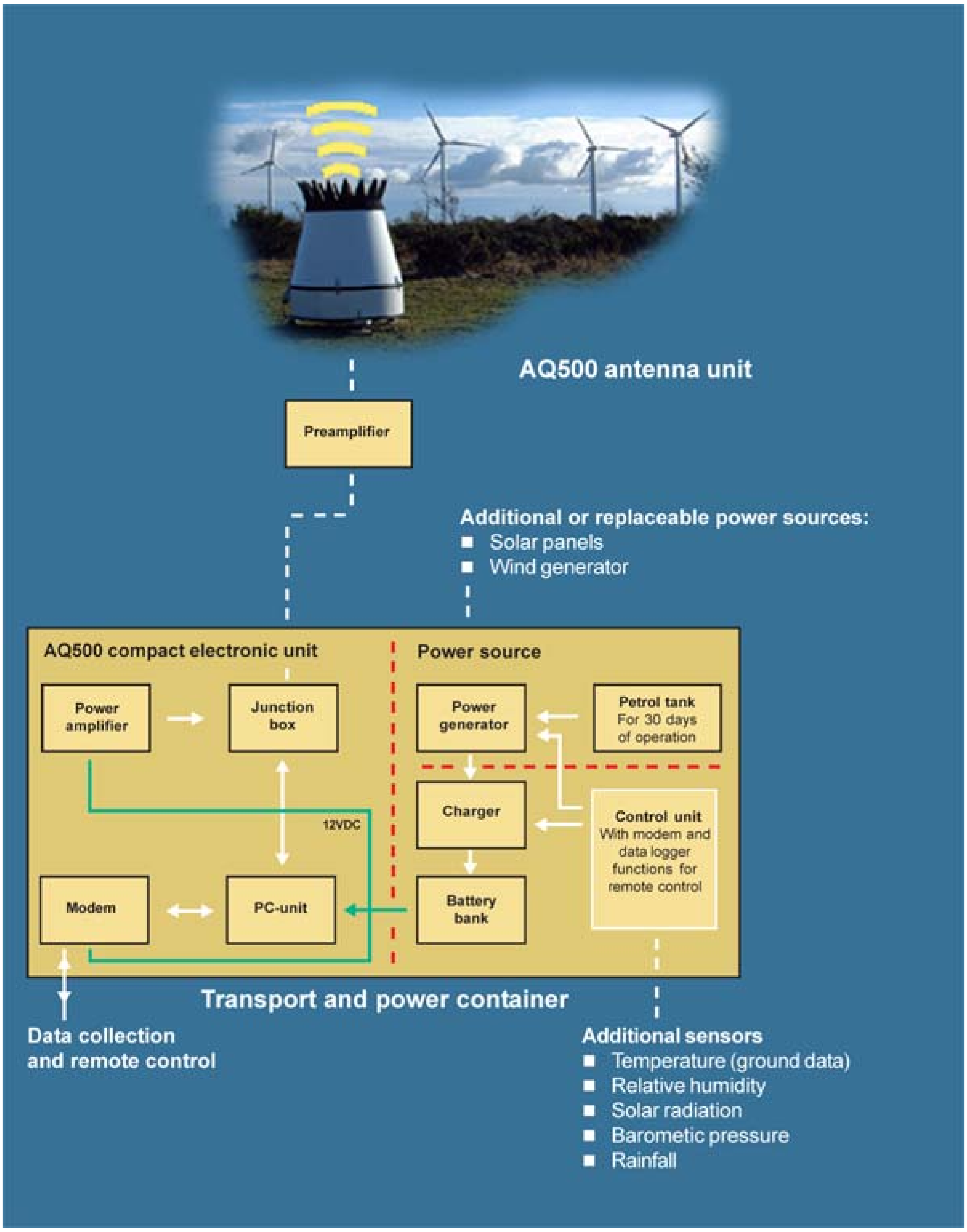
The large beam of the Sodar also spreads the signal with distance. The footprint is increasing with distance, and therefore the observational, or reflecting, spot is larger with distance. Care therefore must be taken when interpreting data at large distances. However, we estimate that the size of the spot at 150 m is smaller than the turbulent eddy size which we need to observe, and that the beam size is thus not a limiting factor.

The data is obtained in three directions which are along a circle of 17 m radius at the altitude of 60m. The wind data are therefore averaged over this size scale and this also has to be included in any comparison with the small size scale area of the anemometer.

The Sodar works sequentially with the three directions, and a full scan therefore takes at least 3 seconds. The signal reflected at large distance is also low in intensity, and data have to be integrated over some time to secure detection. The sequential procedure also requires integration to avoid systematic errors in the three dimensional recovering of the wind vector. The data are stored at 10 minutes integration times with a standard deviation calculated and stored for each such data point. This means that data at shorter time intervals are not available, and turbulence cannot be determined at higher frequencies than 10 mHz. However, Sodar does give the full three dimensional wind vector and upwind and wind shear can determined with high accuracy. We suggest that this may be of more importance to wind turbines than short scale turbulent eddies.

The AQS500 sodar system costs about € 50 000 or about 1/3 of a lidar system.

The figure below shows the AQS500 system [1] as is used at Oxhult.



Figur 4 – Principle of Sodar system.

6 Comparison of technologies

6.1 Mean wind speed

The anemometer measures the wind with mechanical cups. The gas pressure will be higher on the concave side of the cups as compared to the convex side. The cups are mounted on a vertical axis and therefore will rotate around this. The anemometer is therefore measuring the true flow of the gas.

The Sodar system measures the sonic wave reflected at pressure and/or temperature changes in the gas. These are due to turbulence eddies within the compessible gas flow. The Sodar is therefore also measuring the flow of the gas.

The Lidar systems measures the signal reflected from aerosols or particles in the air. This is similar to the seeding of flow with microballons in flow visualization. Such seeder particles are not compressible, are large and heavy compared to the gas molecules and therefore have different thermodynamic properties than the gas. It has been shown that such particles are not directly representing the gas flow, especially not the velocity of the gas. Tracking of microparticles in a flow usually underestimates the flow velocity of the gas.

6.2 Velocity vector

The anemometer measures the wind speed in the horizontal plane only. Any vertical wind component will cause the anemometer to wobble and will be observed as increased noise in the measurements.

The Sodar and the Lidar systems measure the wind speed in three directions and then convert to both the horizontal and the vertical components. The standard deviation is available for both components.

6.3 Measurement errors and turbulence

The anemometer is a mechanical device. The measurements are made on a rotating axis, with concern for the weight of the cups and friction of the mechanical rotation. The weight of the cups influences the measurements in that the momentum of the cups will be large, especially at high wind speeds. Small and rapid changes in wind speed will therefore not be registered at high mean wind speeds. Friction will be a severe factor at low wind speeds. Friction can here cause large intrinsic errors in wind speed as well as a underestimation of turbulence.

The Sodar system measures the wind speed directly with the Doppler effect. However, the data requires long integration times to be measured and short term turbulence can therefore not be measured. Also, the main reflection layer may be at different height within the delay channel (usually 5 metres) between different measurement points and the turbulence may therefore be overestimated since the mean velocity changes with height.

The Lidar system measures reflection from aerosols and particles at a specific height as determined by the focusing lens. Also here the main reflection may vary from scan to scan. The beam is small and therefore the turbulence can be either over- or underestimated depending on local conditions. The scanning time is much shorter for the Lidar system as compared top the Sodar system and standard deviations can therefore be measured at short time scales.

7 Site

The tests have been performed near Oxhult in Laholm kommun, Sweden. The location is
X = 1345872
Y = 6261834
Z = 100 (mast)
Z = 93 (sodar)

Figur 5 – Position of the Oxhult site.

7.1 Mast

The mast at Oxhult is 60m. Instruments are mounted at 40m and 60m. These consist of a Vaisala WAA151 anemometer and a Campbell Vector V200P wind vane. Temperature is measured at 60m. All data are collected with a CR200 data logger. The data are then downloaded to a local computer over a telephone modem line. Available data are 10 minutes averaged in the form of horizontal speed and direction. Standard deviations are given for each 10 minutes interval.

7.2 Sodar

The Sodar is an AQS500 system with three beams. The sonic signal is alternating between 3067.485 Hz, 3144.65 Hz and 3267.97 Hz. The data are collected locally at 10 minutes interval. The data are then downloaded via modem and a proprietary communication program.

Wind speed, direction and standard deviation for these are given for each 5 m interval between 20m and 150m and for both the vertical and horizontal axes. The on-line program in the AQS system flags data which are deemed to be unreliable. The data are then filtered off-line to include only such times where the data for all levels are available and not flagged.

8 Observed wind data

All data are taken into Matlab for analysis. The mast data and the Sodar data are analyzed separately and then brought together for consistency analysis and comparison. Only such data where the exact observing times fully agree are used in the comparison. The data used for this analysis range from 31 July 2007 to 29 January 2008.

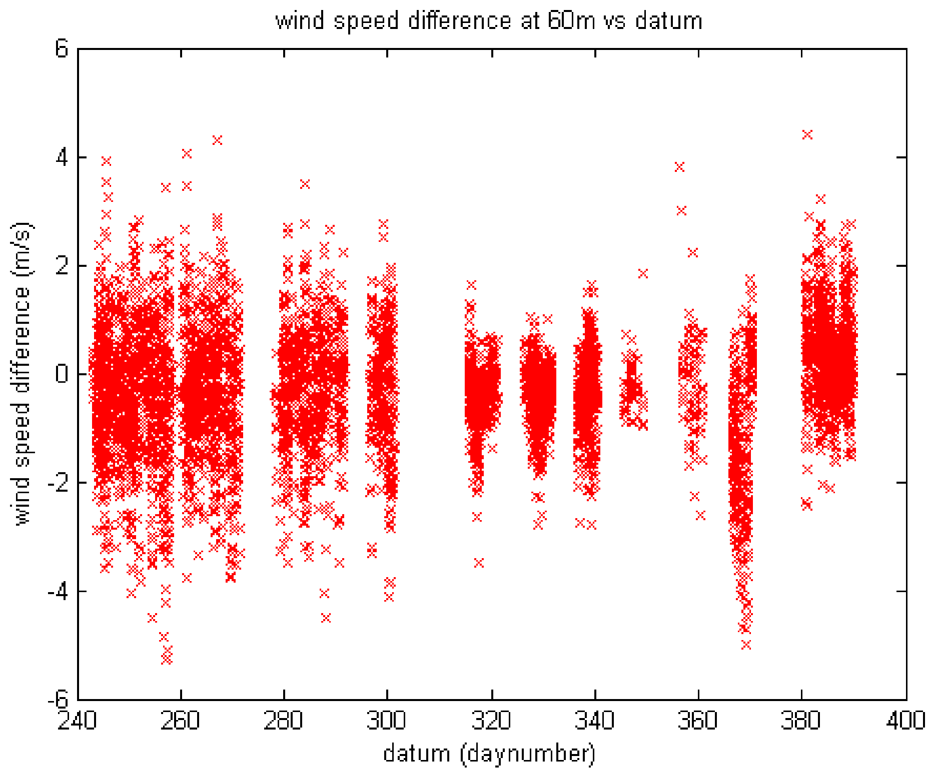
8.1 Mean wind speed

The mean wind speed at 40m and 60 are (standard deviation in parentheses):

Height	mast	sodar
40m	5.78 (2.17)	5.47 (2.10)
60m	6.73 (2.34)	6.43 (2.26)

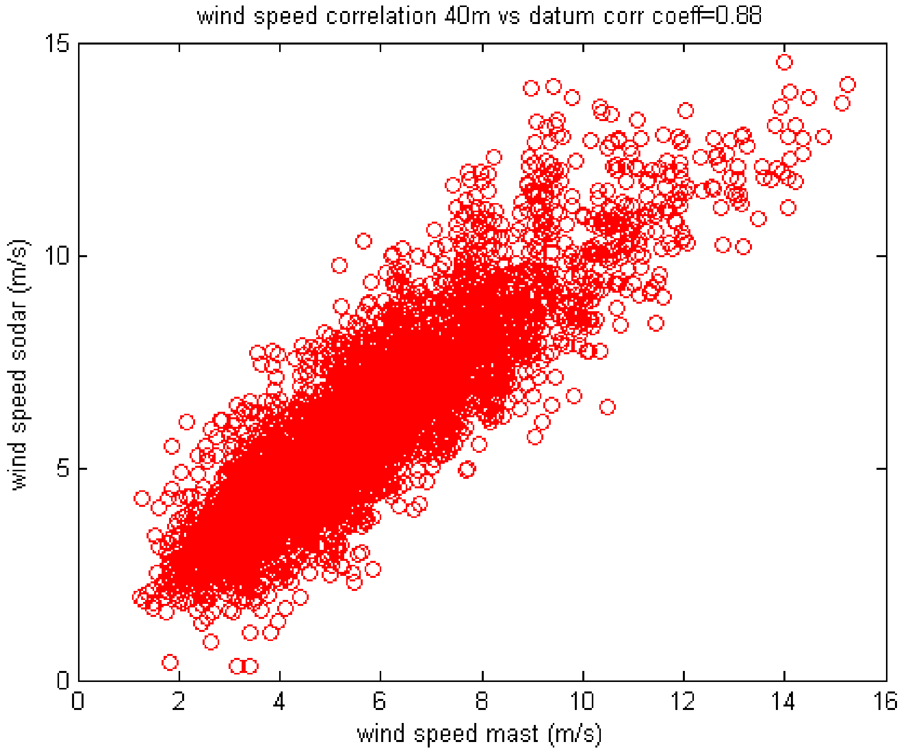
The mean wind speed therefore seems to be about 0.31 m/s or 5% lower from the Sodar than from the anemometers. We suggest that this can be attributed to the altitude difference of about 7m between the sodar and the mast reference levels.

Figure 6 below shows the difference in wind speeds at available times. Note the large gaps in data, probably due to down time of the Sodar because of power generator problems. The data are never the less sufficient to indicate a rms deviation of about 1 m/s. This is within the measured errors of the mechanical device and therefore as expected.

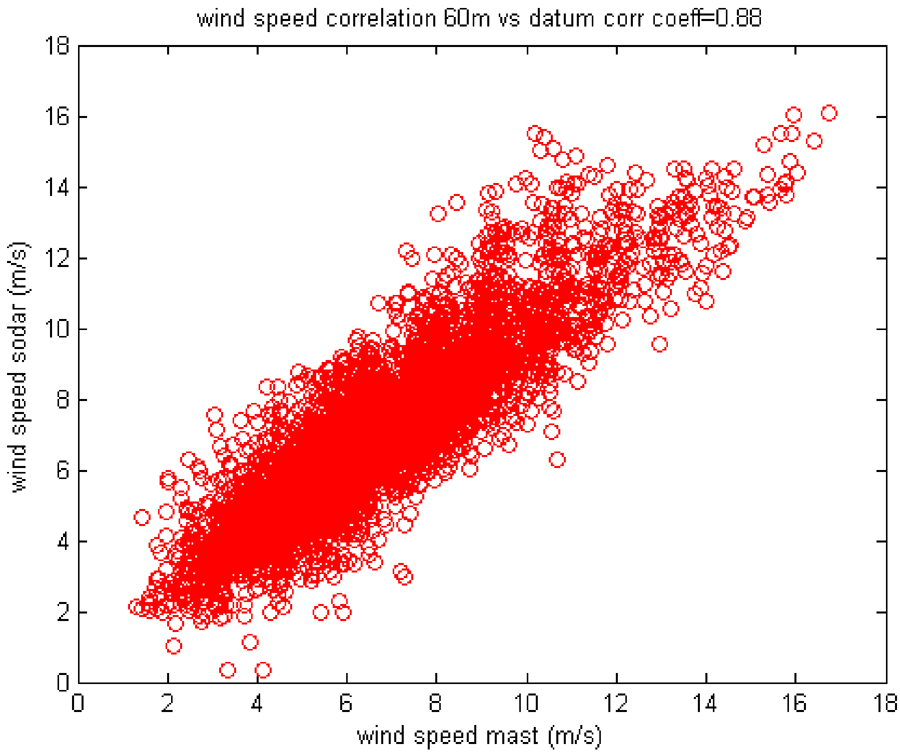


Figur 6 – Wind speed difference at 60m as a function of time.

Figures 7-8 below show the correlation between data observed on the mast and by the sodar at 40m and 60m, respectively. The correlation coefficient is in both cases 88% which is deemed to be a very good correlation and well within the expected uncorrelated error bars of the instruments.



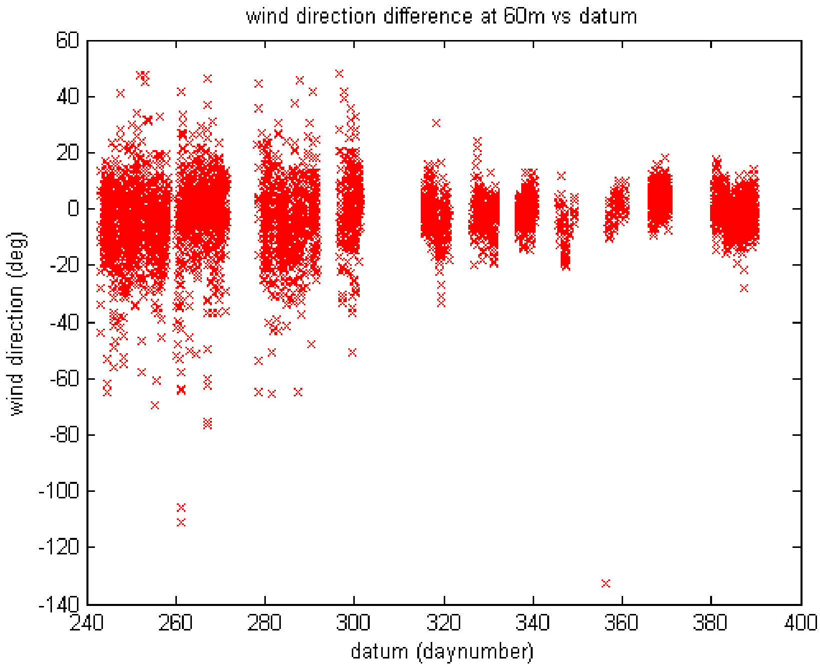
Figur 7 – Wind speed correlation mast-sodar at 40m.



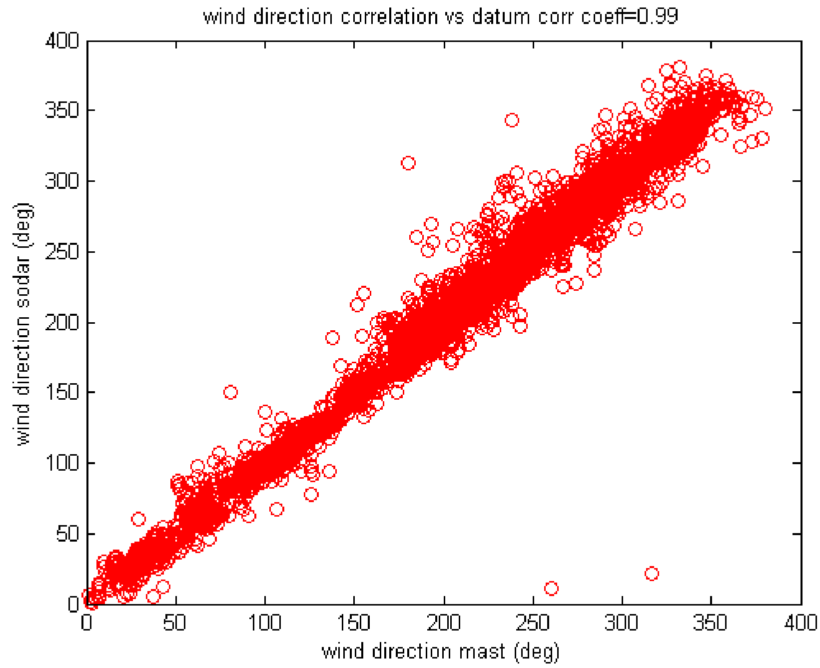
Figur 8 – Wind speed correlation mast-sodar at 60m.

8.2 Wind direction

The difference in wind direction as measured on the mast and by the sodar at 60m is shown in figure 9 below. The correspondence is excellent with a mean offset of about 2.5 degreees and a standard deviation of about 11 degrees, well within the expected instrumental errors. Figure 10 shows the correlation of the wind directions. The correlation coefficient is 99%, which is excellent by any standard of definition.



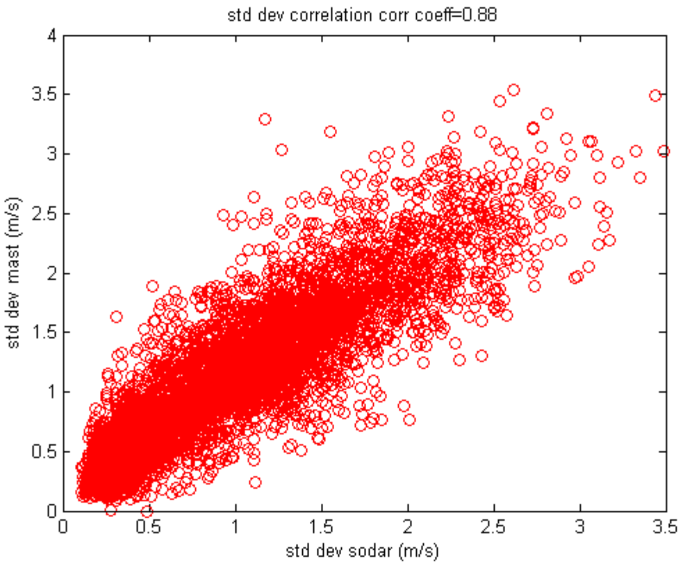
Figur 9 – Wind direction difference mast-sodar at 60m.



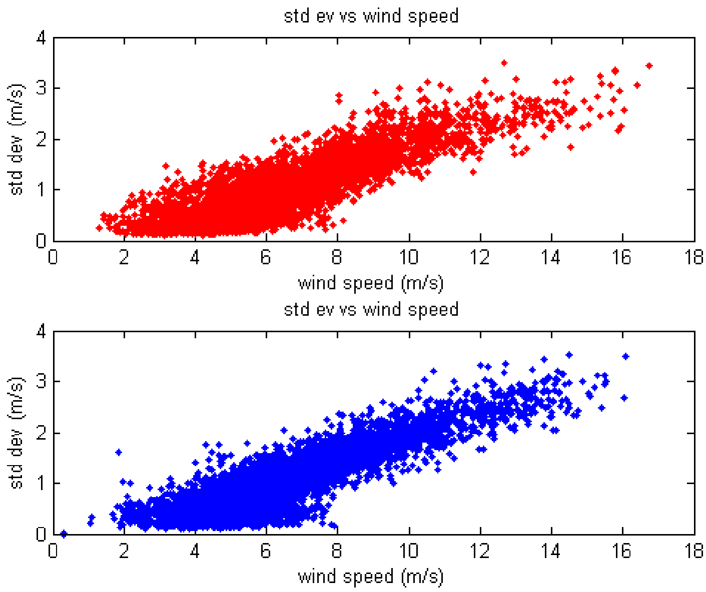
Figur 10 – Wind direction correlation mast-sodar at 60m.

8.3 Turbulence

The turbulence cannot be measured by any of the two systems. A true turbulence measurement would require statistics to be made over various time scales on data with short integrating times. Only data of 10 minutes average are available and therefore statistics can be made over frequencies of 10mHz or more. The data presented are therefore the standard deviations given by the instruments over the 10 minutes of averaging time. Figure 11 below shows the scatter diagram of the standard deviation of the mast versus the sodar. This has an excellent correlation of about 88%. However, figure 12 below shows that the standard deviation of the wind speed is highly correlated with the wind speed for both the mast and the sodar. Since the wind speed measurements are highly correlated, than the standard deviations will also be correlated since they are functions of the wind speed. We therefore consider this test to be of no value to estimate any correlation of the turbulence measure.

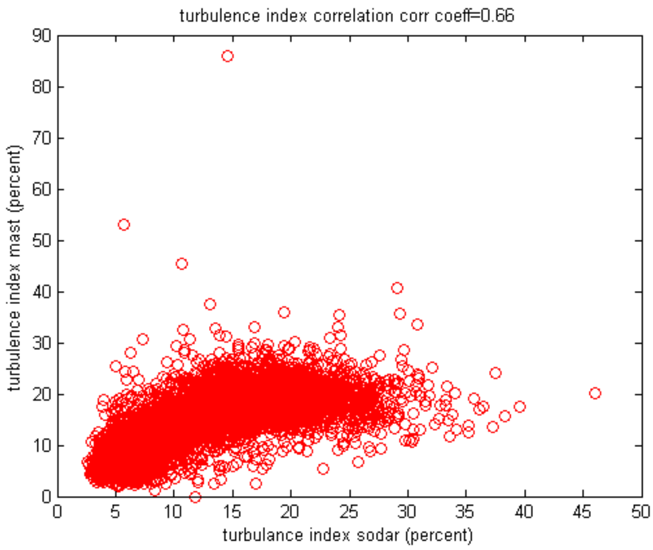


Figur 11 – Scatter plot of the standard deviation of the mast versus the sodar at 60m.



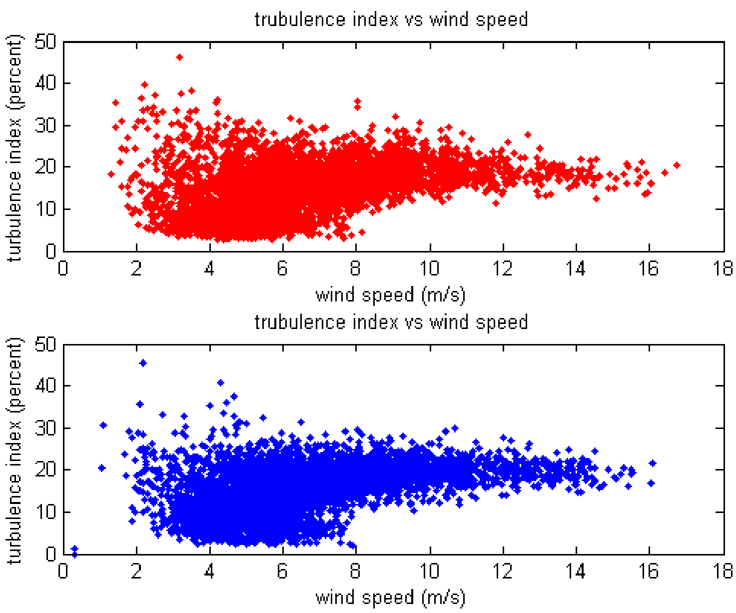
Figur 12 – Standard deviation versus wind speed of the sodar (top) and mast (bottom).

Instead we show in figure 13 below the turbulence index, defined as the ratio of the standard deviation over the wind speed. This parameter will not be affected by the wind speed and is expected to show a more realistic measure of correlation between turbulence measures. The correlation coefficient is 66%, which is good, but would be expected to be higher.



Figur 13 – Correlation plot of the turbulence index of the mast versus the sodar at 60.

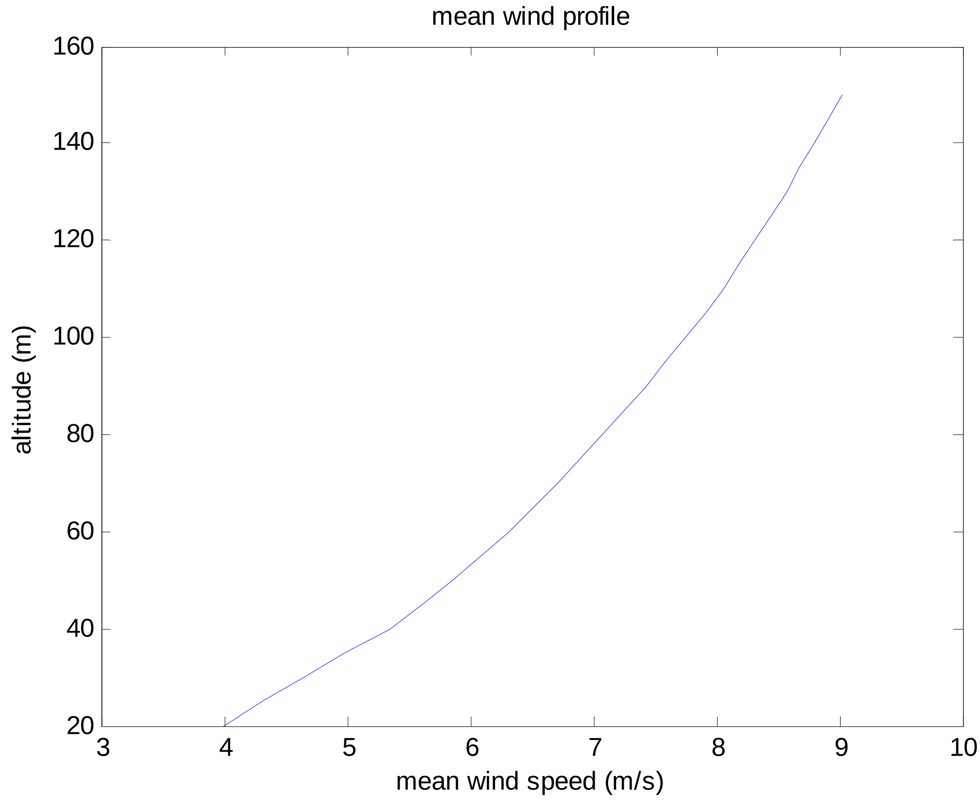
The scatter plot of turbulence index shows that the sodar measurements have a larger spread than the mast measurements. The mast measurements are leveling out at about 30%. This is usually indicative of a physical limitation in the device, such that large percentage variations are squashed by friction or other mechanical or computational problems. Figure 14 shows the turbulence index as a function of wind speed for the mast and the sodar. We note here that the spread in turbulence index is significantly larger for the sodar than for the mast at low wind speeds. Our interpretation of this is that the anemometer has a limitation in noise level caused by mechanical weight and friction which will appear at low wind speeds, where the rotation speed of the axis is low, dampen rapid changes in wind speed. We therefore suggest that this inconsistency is coming from the anemometer rather than from the sodar.



Figur 14 –Turbulence index versus wind speed for the sodar (top) and the mast (bottom).

8.4 Shear

Wind shear is the differential wind speed and attack angle over the sweep area of the wind turbine. This cannot be measured with the existing mast since the wind blades start at 60m. We therefore cannot measure or compare this important wind parameter. Figure 15 shows the wind speed distribution with altitude as measured by the sodar. A shift with a about 7m in altitude would change the mean wind speed by the appropriate amount 0.31 m/s to fit with the mast value at 60m.



Figur 15 – Wind speed versus altitude as measured by the AQS sodar.

9 Discussion

Our data show that the correlations between the mast and sodar wind speed and wind direction are excellent (88% and 99%, respectively). Such high correlation is generally considered in science to be indicative of that the data can be considered to be the same and only one of the data sets is required to be measured.

The standard deviation of the difference in the wind speed data is on the order of 0.7 - 1 m/s which is at the same order as is expected from the standard deviations given by the instruments.

The horizontal, or azimuth, wind direction is measured with extremely high correlation, also clearly indicating that the flow is only weakly turbulent over the area.

There is a variation in turbulence index between the two instruments. We suggest this is caused by mechanical friction and large mass of the cups of the anemometer which limits the noise at low wind speeds. There could also be a variation in turbulence cells of up to 10m in diameter at the two sites.

One of the most important parameters is wind shear as differential wind speed and attack angle over the area swept by the wind turbine blades. We note that this can only measured by the sodar, where data from the mast must be extrapolated to higher altitudes. Any such data from the mast are therefore model dependent whereas the sodar data are direct measurements.

Lidar is a possible option to measure wind data. The Lidar system can measure data at short time intervals, and therefore can get a closer estimate of the turbulence profile. The time delay channels are longer though, and the resolution in Z-axis is lees than that of the Sodar. The Lidar system measures the motion and speeds of particles and aerosols in the wind flow, which has been shown to be different from the motion of the interface regions which is measured by the Sodar [10]. Lidar is definitely an option, but is more technically complicated and more expensive than the Sodar.

Sodar systems have been previously investigated by several groups. Moore, Bailey and Bernadett [12] show the use of the measurement of full wind profiles as important to wind turbine performance. Hansen et al. [13] investigated a Sodar in a 18 month long test program. Their data showed that the Sodar data were in good agreement with mast data and that the Sodar showed representative wind profile data. At that time the Sodar data were not available above a wind speed of 15 m/s. We cannot see any such limit in our data and therefore conclude that the Sodar system used by us is different and probably more evolved than what was used by the Riso group.

10 Conclusion

We conclude that the AQS500 sodar is correlating well with anemometer measurements at 60m for mean wind speed as well as wind direction.

The sodar data are limited in averaging time to 10 minutes, while the anemometer can give data at much shorter time series. Therefore the anemometer can potentially be used to measure turbulence and wind fluctuations at short time scales whereas the sodar can not.

The anemometer measures the wind speed and direction in the horizontal plane only whereas the sodar gives the wind vector in three dimensions. This is crucial to determine upwinds and correct attack angle to the blade.

The anemometer is limited to give a few data point in altitude, and is limited by the physical height of the mast. This is a severe limitation when turbines of 90m or more are planned with a central point at 105m above ground. The sodar measures the full wind profile over the area of the wind turbine blade span. We consider also this to be crucial for estimating the suitability of a specific site for wind power plants.

The Lidar system is presently superior in measuring turbulence. However, the Lidar system is more complex and much more expensive. The resolution in Z-direction is also less than for the Sodar, and the Sodar will therefore present a more detailed wind profile.

The sodar needs to be situated at minimum 30-50m from any high obstacle such as a mast or a forest edge. The sodar is easy to transport and mount while mast must be transported and raised in a dense forest area.

We also suggest that the Sodar can be further developed to also give turbulence data at the time scales 10-60 seconds, which are important to the design of the turbine for the site.

In general, we suggest that the sodar system is superior in all aspect except the availability of short time data and the requirement of a clear area of 30-50 m around the instrument.

We also conclude that standardization of wind measurements are of greatest importance and that the build-up of Swedish wind power industry is of such magnitude that standardization of wind parameters and certification of wind measurement systems must be prioritized.

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