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VALIDATION OF SODAR MEASUREMENTS FOR WIND POWER ASSESSMENT

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ABSTRACT
A ground-based SODAR has been tested for 1½ years together with a traditional measurement set-up consisting of cups and vanes for measuring wind data for wind power assessment at a remote location. Many problems associated to the operation of a remote located SODAR have been solved during the project and a new remote power system has been designed. A direct comparison between SODAR and cup measurements revealed a limitation for the SODAR measurements during different weather conditions, especially since the SODAR was not able to measure wind speeds above 15 m/s due to an increasing back-ground noise. Instead, using the SODAR as a profiler to establish representative wind speed profiles was successful. These wind speed profiles are combined with low height reference measurements to establish reliable hub height wind speed distributions. Representative wind speed profiles can be establish by use of a SODAR during short term campaigns taking into account the local topography and stratification distributions.

INTRODUCTION
Modern wind turbines have reached a size that makes hub height wind speed measurements rather expensive. The cost of masts increases rapidly with height (distinctly more than linearly) and their installation is subject to a (often) lengthy authorization procedure. A ground-based SODAR (**So**nic **d**etection **a**nd **r**anging) [1] is able to measure at many levels simultaneously and is economically competitive with other forms of measurements.
The main objectives of the project have been to optimize the SODAR availability and the quality of the SODAR readings. Based on the SODAR readings the reliability, accuracy, limits and limitations of the SODAR have been determined. A validation program with a SODAR has been performed for 1½ years at a remote location without any access to an electricity grid. The program will study whether the SODAR wind measurements are accurate enough for wind power assessment and whether the SODAR is applicable as a stand-alone instrument or as a “profiler” in combination with reference instruments on a 30-50m tower. These issues in particular will be addressed in the present paper.
Remote operation of the SODAR system was tested against traditional wind resource measurement set-up equipment. The test set-up consisted of a 50 m mast, equipped with three calibrated cup-anemometers, 1 wind vane and one 3-D ultrasonic anemometer sampled at 10 Hz using a low- power industrial computer. Statistics were transmitted every 10 minutes using SMS telegrams.
The SODAR was a METEK PCS-2000.24 low power version, Figure 1. All equipment was powered by a commercial off-grid power system designed to continuously provide 120 watt. The equipment was installed on gently rolling, open farmland with few windbreaks.
A SODAR provides approximately 20 instantaneous scans every minute. This is much less than a traditional cup anemometer / data logger setup. In addition, the instantaneous values do not have any inherent temporal averaging (rather vertical spatial averaging) and are often noisy. For good statistical reliability it is necessary to compare at least ten-minute average values.

SODAR MEASUREMENT SET-UP
The complete SODAR system set-up is listed in Table 1, where the top mounted cup anemometer at 50 meter is used as a reference instrument. Additional meteorological instruments have been included for validating the SODAR properties during different weather conditions and atmospheric stability situations.

Table 1: SODAR system set-up summary.

Component	Manufacturer	Comments
SODAR and SODARpc (SPC)	METEK, D	Low power version (100 W)
Remote Power System (RPS)	Polar Power Inc., US	Based on 1200 pW solar panels and a battery pack with a capacity of 4 x 24 hours
Meteorological mast	HRAFNKEL SarL, F	height 50 m
3 Cup anemometers	ED-Service &	Calibrated and located at height 50, 48/31 & 16 m

	Thies	
Addidional equipment	Misc.	Temperature, Rain, relative humidity, atmospheric pressure & wind direction
Datalogger	Wilmers, D	Dedicated to cup anemometers and vane
3-D Ultrasonic anemometer	METEK, D	Located at height 47 m
Datalogger	MetSupport Aps, DK	Dedicated to logging of the sonic anemometer, the operation parameters and data transfer.

System

All the selected components were standard components except for the Remote Power System (RPS), which has not been used for this purpose previously, since it was difficult to locate a standard remote power system with a capacity of 120 Watt for approximately 100 hours. The necessary power wiring system for supplying both AC 230V and DC 24 V voltage is shown on Figure 2.

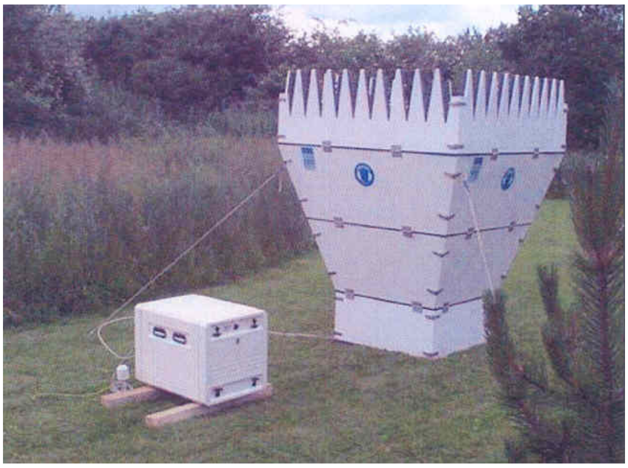

Figure 1: METEK Doppler PCS-2000/24 low power version SODAR.

Test site

The selected measuring site in the eastern part of France is farmland with open appearance with a moderate complexity in terms of hill effects in the northern direction.

The test site was equipped with a 50 m meteorological mast and a standard Wilmers logger. The SODAR is equipped with a pc for operating and logging the SODAR measurements. An additional logger was included to measure the 3D ultrasonic signals with 10 Hz, standard meteorological signals and operational signals e.g. battery voltage and current with 1 Hz and upload the 10-minute statistics to a data server using short message packages (SMS) see Figure 3. This strategy provides internet access for the partners to monitor the system operation in close to real-time. Furthermore the high frequency recordings are stored on a flash card, with a capacity of 2-3 months.

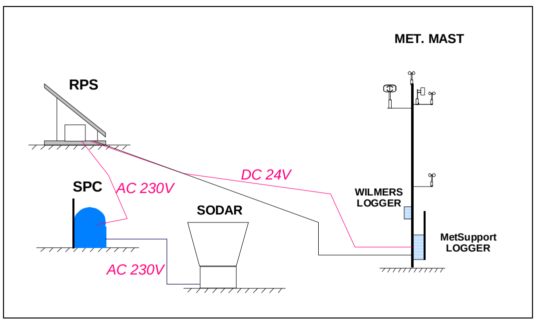

Figure 2: Wiring of SODAR system.

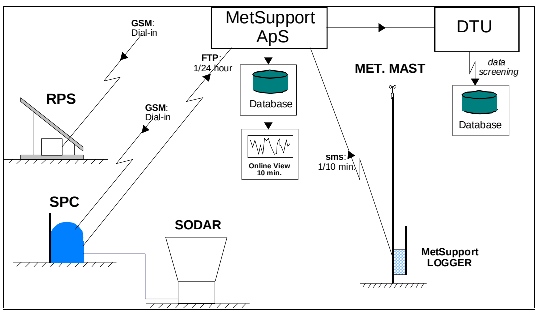

Figure 3: Remote system access and automatic data transfer.

The basic statistics are uploaded to a central server with a database every 10 minutes and displayed graphically through a web-server. This facility has enabled supervision of the operational parameters and the measurements for all partners throughout the project.

SODAR configuration
The SODAR configuration enables measurement of horizontal and vertical wind speed together with the horizontal wind direction at a number of heights (20, 30, 40,… 150, 160m) above ground level. The statistical values are stored for each 10 minute period together with error codes and S/N ratios for each signal. Detailed description of the theory [1] and definition of the SODAR output are given in the METEK® documentation [2,3].

SYSTEM OPERATION
The SODAR availability during the test period of 19 months (1 April 2004– 30 October 2005) has been limited due to the problems with both the remote power supply and the SODAR system. A summary of the SODAR availability is presented in Figure 4.

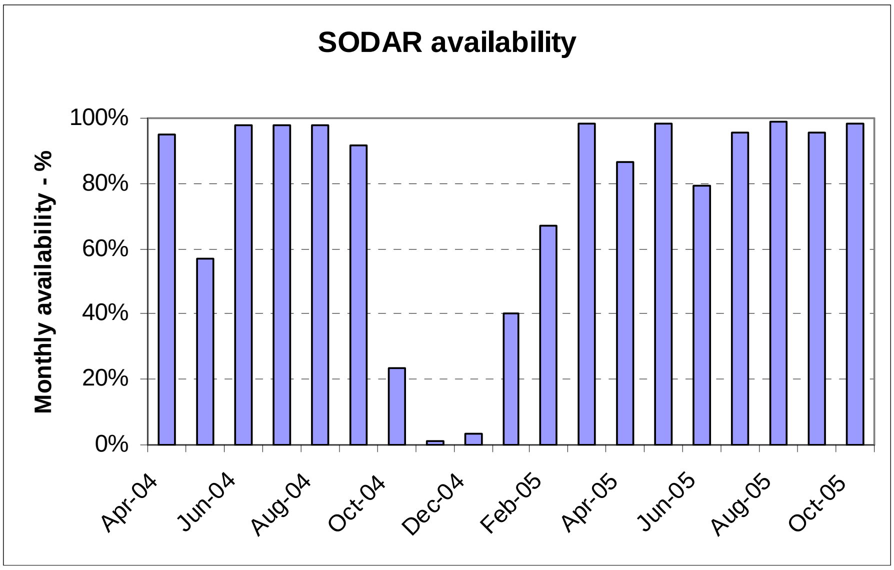

Figure 4: Monthly SODAR availability obtained during the test period.

The SODAR system availability was low during the autumn 2004 and a reduced during winter 2004/05 due to lack of power. The latest measurement period (Jul - Oct 2005) has demonstrated high SODAR system availability combined with a good SODAR signal quality - compared to the previous periods.

SODAR DATA QUALIFICATION
Output statistics from the SODAR system in terms of wind speed, direction S/N ratios and error codes at all levels representing all 10 minute periods (~900 MB/24 hours) has to be organized properly. Afterwards the output is validated against error codes and outliers, which have to be detected and eliminated. A dedicated MySQL® database has been defined to host all the measurements and a data validation procedure has been developed and implemented to identify valid measurements.

Quality of sodar signals
The signal quality represents the usable [SODAR] measurements for given height. The monthly mean SODAR signal quality, which has been obtained through the project is shown on Figure 5. Two different shapes clearly demonstrate the difference between a well-shaped and a mal-functioning SODAR system. The maximum possible availability depends on the height and season, and ranges between 95 – 80% up to 120m. Decreasing availability at low heights (~ 30m) occurs after the [downhill[1]] relocation of the SODAR. Acceptable signal availability has been obtained during Aug - Oct 2005, which reflects that an optimum setting has been implemented.

[1] Relocation of the SODAR was made to eliminate a disturbing fixed echo signal at reference height 50m.

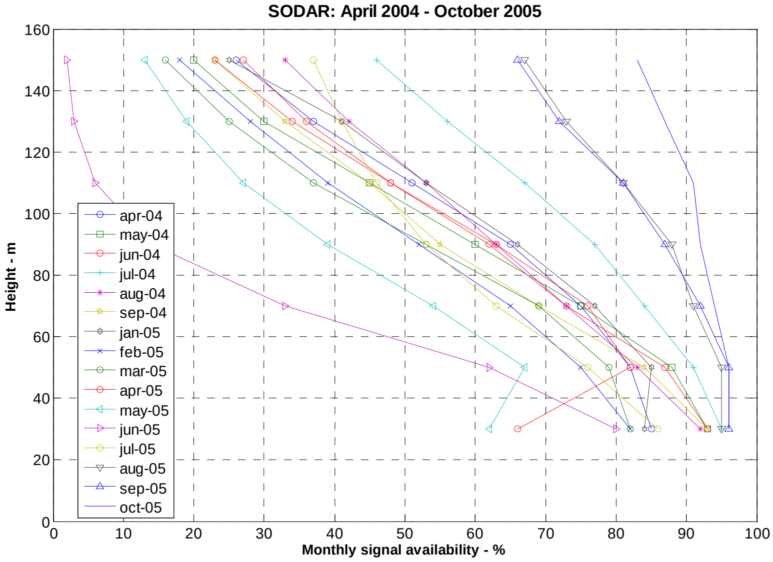

Figure 5: SODAR signal availability.

A number of parameters, which influence the quality of the measurements, have been analyzed as part of the SODAR verification program and some of the most important factors are:

S/N ratio as function of height

The quality of a SODAR measurement depends strongly on a proper signal/noise ratio, and the mean Signal to Noise (S/N) ratio decreases with increasing height. The SODAR measurements with S/N ratio less than 2 dB, usually results in erroneous speed values.

The mean S/N ratio is shown as function of height both during morning hour (5-6) and during the evening hour (sunset) (17-18) on Figure 6 for 3 different settings. The figure shows how the S/N ratio strongly depends of height, optimal SODAR settings and the atmospheric stability[2].

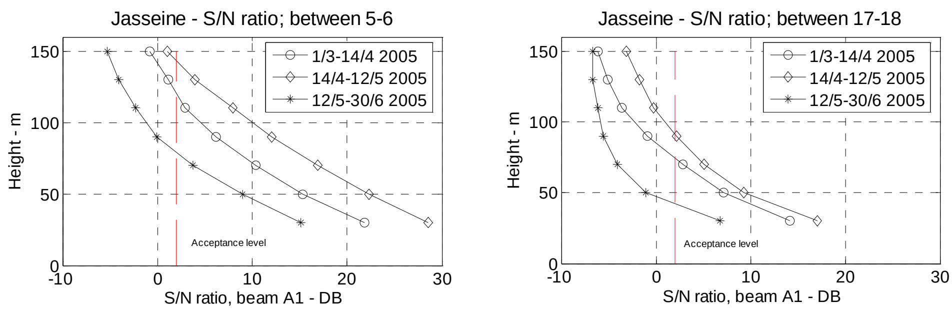

Figure 6: Vertical mean S/N ratio for beam A1 during two different hours and different settings; a) hour = 5:00 – 6:00 and b) hour = 17:00 – 18:00.

Fixed echo

Echo from a [nearby] obstacle is difficult to identify, since this is not reflected directly in the S/N ratio or in the error codes. Plot of the resulting wind speed profile reflects a fixed echo in Figure 7. The change in the profile at height 50 and 60 m is very pronounced compared to the mean wind speed profile and the cup readings. The location of the echo corresponds to the height of the meteorological mast.

[2] During sunset the stability is neutral resulting in very low atmospheric turbulence.

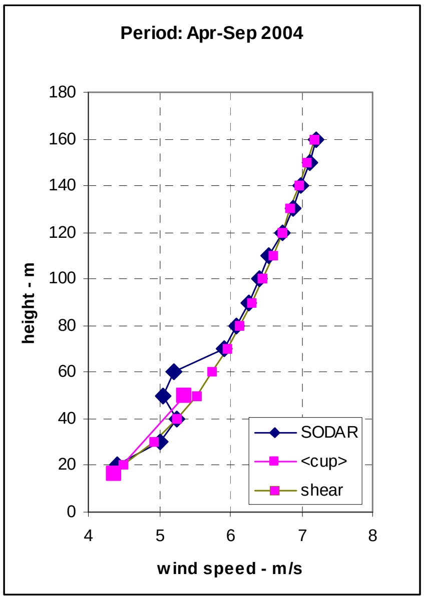

Figure 7: Fixed echo problem
at level 50 – 60 m.

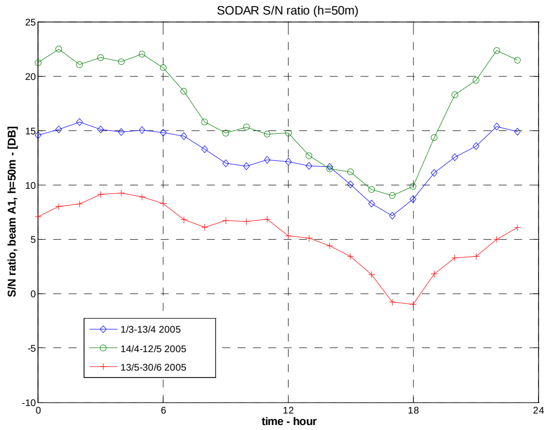

Figure 8: Hourly S/N ratio with 3 different setup, h=50m

Low turbulence
With reference to the measuring principle, the SODAR availability has been correlated with the absolute turbulence level and the correlations indicates at low [absolute] turbulence (<0.5 m/s) the SODAR signal quality is decreasing, which at the test sites corresponds to approximately 5 m/s wind speed at 50 m. The analysis also indicates that the SODAR signal quality decreases strongly for increasing heights - at the same turbulence level (reference 50 m). The SODAR was unable to measure wind speeds less than 5 m/s reliable due to low (absolute) turbulence at these low wind speeds.

Height resolution
Increasing the SODAR height resolution, Δh from 10 to 20 m increases the S/N ratio at all heights considerably (3-10 DB) as shown in the second period (14/4-12/5 2005) on Figure 6. This enables the SODAR to withstand external disturbances. During sunset, (17-19) all levels are affected by the low atmospheric turbulence as indicated on Figure 8 and in these hours a proper system setting is extremely important to avoid erroneous measurements.

Precipitation
A general observation shows that a small amount of precipitation (light rain) only influences the measurements at the upper levels, but during heavy rain all heights are affected mainly due to the increased background noise.

High wind speeds
The background noise depends strongly on the wind speed level and an increasing background noise level reduces the S/N ratio. Figure 9 presents the measured SODAR signal availability (at all heights) as function of the reference wind speed and shows that the SODAR signal availability drops to zero for wind speeds above 15-16 m/s measured at the reference height.

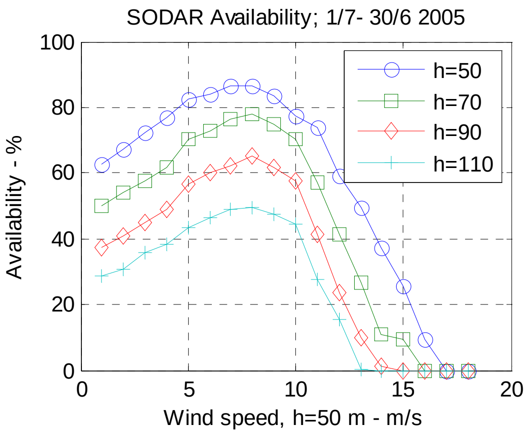

Figure 9: SODAR signal availability at different levels, as function of reference wind speed at height 50 m.

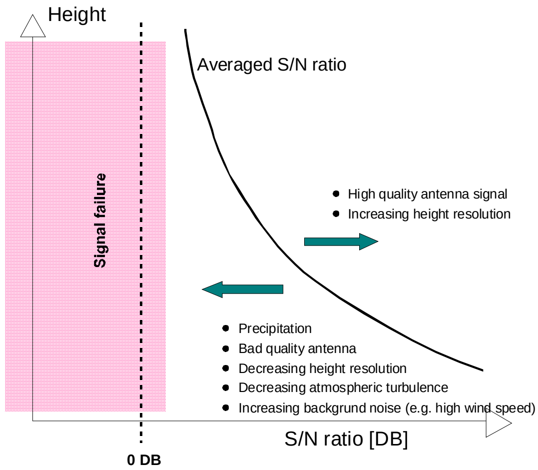

Figure 10: S/N sensitivity due to external factors

Conclusion on the signal qualification

The sensitivity to different types of signal disturbances and system settings are summarized in Figure 10. The main factors, influencing the SODAR signal quality are: precipitation, wind speed level, turbulence, height resolution and finally the quality of the antenna. The first three items are external and site specific, while the last two items are system specific and can be optimized.

DATA ANALYSIS

Examples of measured sector-wise mean profiles are shown in Figure 11a, which have been determined both for the wind speed and the wind direction. Despite the reduced system availability, the profiles illustrate the amount of available and valid SODAR signals. Some of the sectional wind speed gradients are very large (>0.03 m/s/m) compared to what can be expected at a pastoral site (<0.02 m/s/m). The sector-wise directional profiles in Figure 11b, illustrates how the wind direction “rotate clockwise” with increasing heights - corresponding to 20 degrees per 100 meter. The direction for the sector-wise profiles refers to the reference wind vane located at 47 m.

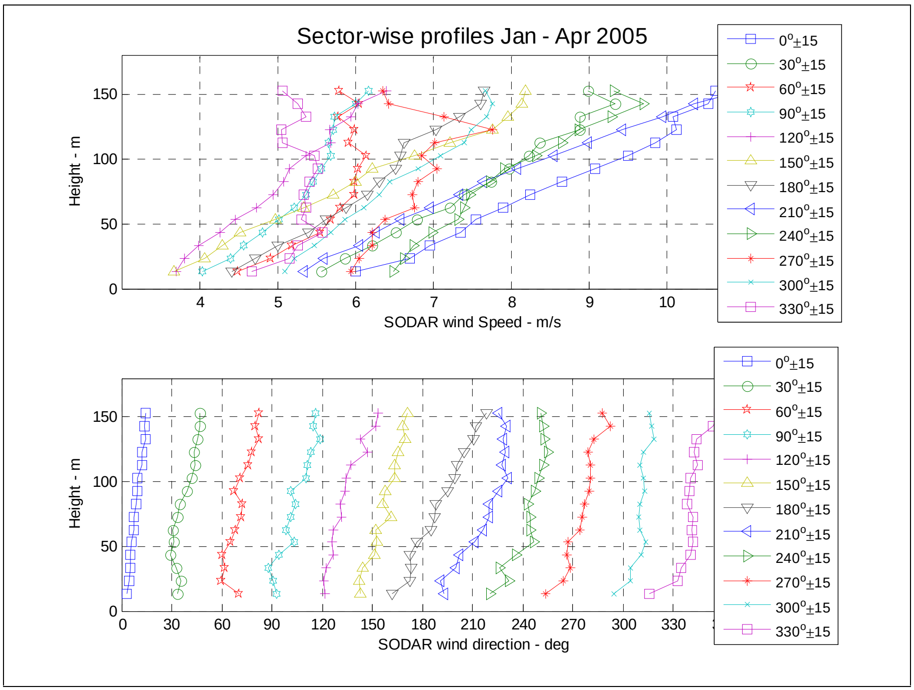

Figure 11: Sector-wise profiles;
a) SODAR wind speed profile; b) SODAR wind direction.

The data analysis will be performed with respect to two different applications: 1) stand-alone-operation and 2) profiler operation.

Stand-alone-operation: The "raw" SODAR readings are used to establish a wind speed distribution at hub height, but due to the limited number of available data the representation is as low as 45%. The fitted Weibull distribution is shown on Figure 12 together with the distribution for the reference cup anemometer, which is based on 8760 hours of measurements. The mean wind speed is almost equal within 0.2 m/s, but the Weibull shape factor (k) differs considerably, mainly due to the lack of SODAR high wind recordings. This difference will be even more pronounced for increasing heights. Establishing a qualified wind speed distribution representing different heights requires [as minimum] a complete year of measurements.

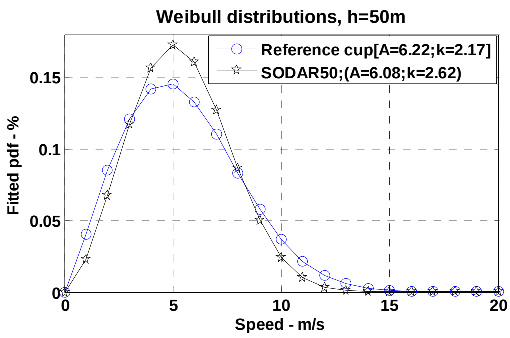

Figure 12: Weibull distributions based on
10-minutes SODAR measurements, h=50 m.

Profiler operation:

In this case the mean wind speed profile[3] is determined for every [measurement] hour. The mean wind speed profile represents minimum 3 x 3 valid readings from 3 heights and 3 consecutive 10 minute periods. This enables an elimination of problematic data points, e.g. fixed echo. The mean wind speed profiles, representing one year of SODAR measurements (~4748 hours) is shown on Figure 13a together with one year of reference measurements from 16 and 50 m height. The averaged wind speed profiles with formula (2).

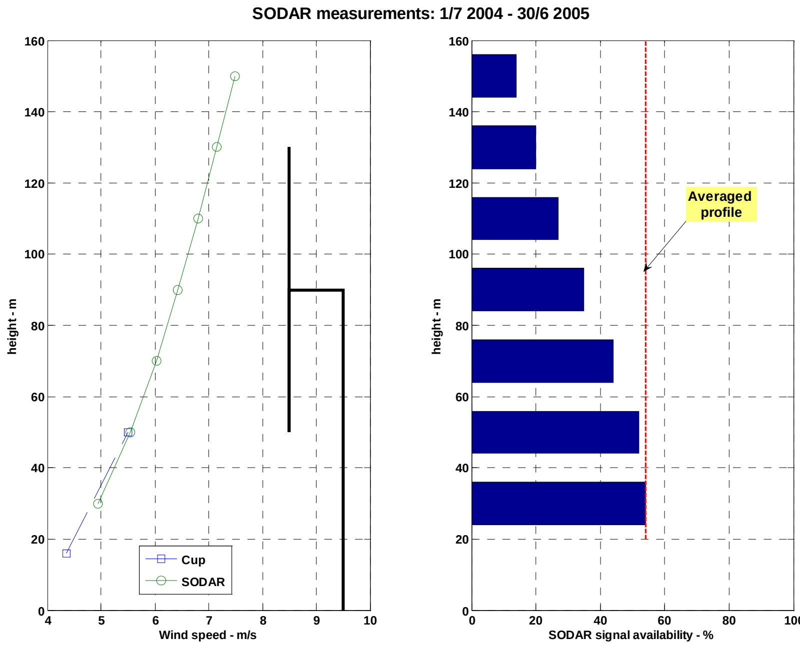

Figure 13: Averaged wind speed profile including reference measurements;
a) mean wind speed profile; b) availability of SODAR measurements.

The annual mean wind speed profile based on valid SODAR measurements presented at Figure 13a are fitted according to the power law, using a least square fit method (2).

$$V_h = 5.53 \times \left(\frac{h}{50}\right)^{0.25} \tag{2}$$

The mean difference between the SODAR estimate (V_{ref}=5.53 m/s) and the reference cup at 50 m level is lesser than 0.2 m/s. Figure 13b indicates how the signal availability decreases with height, but the amount of available data is increased when including all valid measurements in the hourly profile estimate.
The derived wind speed profile will also have a lack of high wind speed measurements, but using bin-averaged profile values for a number of representative sectors will enable us to estimate the wind speed at a given height, based on the reference wind speed signal. For high speed larger than 15 m/s, the wind profiles are based on extrapolations. The SODAR signal availability decreases with increasing height as shown on Figure 13b.

ANNUAL ENERGY PRODUCTION
The annual energy production has been calculated for 5 different distributions, representing the wind climate at 90 m height, as listed in The reference height listed in Table 2, refers to the height or height range where the wind speed has been recorded. Both cup datasets (16 and 50 m) are of high quality and the difference in the estimated (WindPro/WASP) AEP is mainly due to variation in the stability.
, where the power curve represents a standard 2MW, D=80m wind turbine with a hub height of 90m.

- WindPro/WASP(8.3)® wind climate estimates (cup16,h=16m and cup50,h=50m) are based on a full year cup measurements.

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[3] The wind speed profile is represented according to the power law, with two variables (V_{ref} and α) referring to 50 m height.

- SODAR10,h=90 represents 19122×10-minute observations, recorded at 90 m height with the SODAR. As mentioned previously the Weibull shape factor is high due to the missing high wind speed representation in the distribution.
- SODAR60,h=90 represents 4748 hourly mean values determined with the profiler method mentioned above recorded on a 30 -150 m height range.
- Profiler represents 52560×10-minute observations, which are based on the reference cup (h=50 m) and the sectional profile properties (using 4 sectors).

The resulting AEP estimates on Figure 14 shows ±4% scatter, but the results based on SODAR10 and SODAR10,90 underestimates the production due to the high Weibull shape factor. Reducing the shape factor to an "acceptable" level will increase the estimated production further. The profiler results seems to be rather robust since it combines the reliable reference measurements with profiler and only a small part of the high wind speed measurements (~28 hours) need to be extrapolated.
The data analysis will be focusing on estimating the wind resource at a potential wind turbine hub height (90m) and compare the result with the WindPro/WASP wind climate prediction based on reference cup measurements and site characteristics.

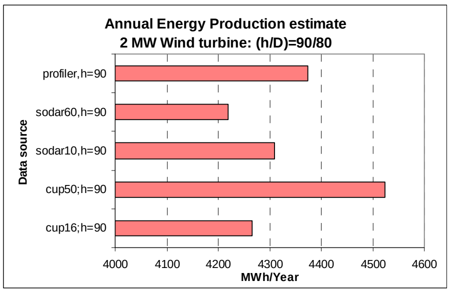

Figure 14: Estimate of Annual Energy Production for different settings.

Table 2: Annual energy production for 2MW wind turbine, h=90m.

Data	Reference height	A	k	AEP	Comments
profiler,h=90	50	7.31	2.47	4374 MWh	Extrapolation for V>15 m/s
sodar60,h=90	30-150	7.27	2.80	4220 MWh	54% availability
sodar10,h=90	90	7.48	2.77	4310 MWh	35% availability
cup50m;h=90	50	7.4	2.42	4524 MWh	WindPro/WASP calc.
cup16m;h=90	16	7.2	2.39	4266 MWh	WindPro/WASP calc.

The reference height listed in Table 2, refers to the height or height range where the wind speed has been recorded. Both cup datasets (16 and 50 m) are of high quality and the difference in the estimated (WindPro/WASP) AEP is mainly due to variation in the stability.

DISCUSSION

SODAR operation
High quality SODAR measurements require a careful selection of the SODAR antenna location (away from possible sources of fixed echo), fully functioning antennas and a proper system setup for maximizing the S/N ratio. The main recommendations are:

i) Recommended distance from obstacle (mast) should be larger than the height of the obstacle to eliminate fixed echo problems.
ii) Increased height resolution (>10 m) will increase the signal availability at all heights.
iii) Include a proper signal screening and a data averaging procedure.

Correlation of SODAR and cup anemometer measurements
Linear regression binned wind speeds from the reference cup anemometer and the SODAR profile results a high correlation ($R^2 \approx 0.999$), with a slope between 0.90-0.94 and an offset of 0.2-0.4 m/s, where the slope and offset depends on the sectors. This means the SODAR will underestimate for all wind speeds above 4 m/s, which has to be compensated afterwards.

Stand-alone operation
Stand-alone operation for wind resource measurements with the SODAR is possible, but the quality of the SODAR measurements is reduced during three specific situations: i) low turbulence, ii) at high wind speeds and iii) precipitation.

i) The lack of low turbulence measurements, which occurs at very low wind speeds, is not critical.

ii) The lack of high wind measurements is very important for the wind speed distribution, because the Weibull shape factor (k) increases, resulting in a decreased power density value.

iii) The lack of wind speed measurements during heavy rain is assumed to be randomly distributed and it therefore does not influence the estimated power density value significantly.

Profiler operation:
Operating the SODAR as a short-term profiler in combination with an anemometer at low height requires a period with wind measurements in representative sectors, the required number depends on the local topography and atmospheric stability. The sector-wise shear values are used to adjust the wind speed distribution to other heights with reference to long-term cup/sonic/vane measurements, recorded at lower height (<50 m).

CONCLUSION

A SODAR has been tested in pastoral terrain with low to moderate turbulence and a limited amount of precipitation, suitable for a potential wind turbine installation site in the Eastern part of France.
Based on the experience obtained during 1½ years of operation, it is obvious to limit the SODAR operation to a short-term profiler, since the SODAR is unable to measure high wind speed (>15 m/s) and this influences the wind speed distribution.
Performing complete long-term resource measurements is costly especially with a SODAR since such a complicated system (power supply unit, reference instrumentation and SODAR) requires a high level of operational supervision.
The benefit of short-term profiler measurements combined with long-term mast measurements is much higher and the output is sufficiently robust to be used in wind resource assessment.
The operation during the latest period (Aug-Oct 2005) has given acceptable system reliability and resulted in a high SODAR signal quality.

ACKNOWLEDGEMENTS

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