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Recommended Practices for the Use of Sodar in Wind Energy Resource Assessment

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1.0 Introduction

1.1 Significance and Use

This document provides guidelines for the use of sodar for wind energy resource assessment. The guidelines are intended to encourage the collection of accurate and representative sodar data on wind resource characteristics within the operating height range of wind turbine rotors. Principles of sodar application presented herein will be of interest to most wind resource professionals, although some topics may have more restricted application. Some recommendations are aimed at the meteorological quality control process, which will often require input from a specialist trained in this area.

For application in wind energy resource assessment, sodar is primarily used to (1) measure the characteristics of the wind shear profile at heights above ground where wind turbine rotors operate, and/or (2) compare the wind conditions at selected sites relative to one or more reference wind measurement locations (typically meteorological masts). Sodar can also be used in wind energy applications for micrositing, for model evaluation, and to determine certain turbulence characteristics. Because wind energy is a very sensitive function of wind speed, the application of sodar to wind energy resource assessment requires particular attention to certain details that may affect the absolute accuracy by less than 5%.

Although sodar offers a wide array of valuable information, it is a very different measurement system than conventional anemometry. The differences in the underlying physics of both types of measurement system must be accounted for when comparing wind characteristics determined by the two techniques. Furthermore, sodar measurements are more time-intensive in terms of resources needed for data quality checking (there are more parameters to check) and in terms of analysis. For this reason sodar typically is not used for long-term monitoring at proposed wind energy sites; rather it is more likely used for intensive campaigns over a period of a few weeks to a few months at any particular site.

The IEC standard 61400-12[1] is being revised as of this writing. It is anticipated that the revised standard will include some perspective on the possible roles for ground-based remote sensing in wind turbine power curve testing and power performance testing. In anticipation of this revision, these subjects will not be treated in this version of the recommended practices.

1.2 Scope and Background

Sodar (<u>so</u>nic <u>d</u>etection and <u>r</u>anging) is a ground-based remote sensing technology that uses acoustic pulses (i.e., chirps or beeps) to measure the profile of the three-dimensional wind vector in the lower atmospheric boundary layer (Coulter and Kallistrova, 1999; Crescenti et al., 1997). After each pulse, the sodar listens for the backscattered sound and determines the wind speed from the Doppler shift in the acoustic frequency. Sodars vary

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[1] Wind turbines—Part 12-2: Power performance measurements of electricity producing wind turbines. IEC, Geneva, Switzerland.

in the acoustic frequencies they use. Some use several tones, while others use a single frequency. Some models allow the user to select one or many frequencies. The frequencies used range from 2 to 5 kHz.

In general there are two techniques implemented in sodar design: phased arrays or a 3-antenna configuration. Phased array sodars consist of a phased array of emitters (speakers), which acts to steer the acoustic pulses such that the individual components of the wind (two horizontal and one vertical; or u, v, and w) can be resolved. Three-antenna sodars use three transceivers to emit and record the backscattered signal. The antennas are configured such that the three components of the wind can be acquired. For the most part the sodars in use for wind resource assessment are monostatic, i.e. the same array is used for transmitting and receiving. Reviews of the theory of sodar measurements are provided in Antoniou, et al. (2003) and Bradley (2007).

For the purpose of this document, only sodars having a maximum vertical range of 500 m or less (i.e., mini-sodars) are addressed.

1.3 Principles of Operation

The principles of sodar operation have been addressed in recent standards, including the ASTM standard (ASTM, 2005) on sodar operation, the German VDI standard, and in recent publications (Antoniou et al., 2003, Bradley et al., 2005). As such, it is not necessary to provide a detailed description of sodar principles of operation here, but only to summarize.

Sodar relies on scattering of an acoustic pulse back to the source (monostatic) or toward a receiver displaced horizontally from the source (bistatic). In the case of monostatic sodars, the scattering elements are small-scale temperature inhomogeneities resulting from atmospheric turbulence, whereas for the bistatic case, either temperature or velocity fluctuations can contribute to the scattering. The largest amount of backscattering results from turbulent fluctuations with length scale of about ½ of the wavelength of the sound pulse; this type of scattering is known as Bragg scattering (Neff, 1990). A monostatic sodar equation can be expressed as (Underwood, 2003):

$$P(R) = P_o \frac{A}{R^2} L_v \exp(-2\bar{\alpha}R)\sigma(R)_E$$

where $P(R)$ is the received power, P_o is the transmitted power, α is the atmospheric attenuation, and $\sigma(R)_E$ is the scattering cross-section at range R. The term P_oAL_v can be described as a "system function" which is specific to each sodar.

1.4 Overview of sodar/anemometer comparisons

Numerous comparisons of sodar with anemometry have been published, for example in Bradley et al., 2006, Crescenti 1997, and in the proceedings of the American Wind Energy Association and the European Wind Energy Association. Many studies have shown that where adequate compensation for the differing physics of sodar and anemometry has been done, wind speeds from sodar agree with mechanical anemometry within the uncertainty of the anemometry in the field.

2.0 Calibration and Testing

Since sodar measures the wind speed in an elevated layer of air not typically accessed by other measurement systems (such as meteorological masts), calibration and test techniques often differ from those used for mechanical anemometry (EPA, 2000). For the purposes of this document, the word "calibration" refers to a process that gnerates a transfer function relating an input such as an independently measured wind speed or acoustic frequency, to an output number, e.g. wind speed in m/s. Since sodars measure the Doppler shift in acoustic frequency, and there is a fixed physical relationship between Doppler shift and the motion of air, a fixed "calibration" is implied. "Validation" or "verification" on the other hand, refer to testing the sodar's output against other, known measurements, but without the implication that any adjustment or transfer function will result.

The available techniques are described below:

2.1 Performance Audit or System Verification Techniques

Sodar system verification testing. Some sodars have audit tools and techniques specific to the type or model of sodar. In these cases, it is possible to test one or more of the following characteristics:

a. the sodar array's response to known input frequencies. The results should be expressed as m/s wind speed per Hz of frequency shift. Check for both accuracy and resolution.
b. the output pulse length, frequency and quality, to see if they conform to what they are supposed to be. Beam steering for phased-array systems should also be confirmed by making phase angle measurements.
c. the condition and output of individual array elements (in phased-array systems) to ensure that all are operating properly
d. input "challenge" pulses with programmed delays and frequencies (transponder test) to verify system-derived wind speed and direction at specified heights.
e. user-accessible test points where an oscilloscope can be used to check on the condition of electronic components.
f. Some sodars have self-test capabilities, especially for array element function, but also for timing, transmit frequency stability, etc.. The results of any such self-tests should be documented on a regular basis.

The tests above provide confidence that the electronics, software and certain mechanical aspects of the sodar function correctly independent of the atmospheric input or site-specific issues. They do not evaluate performance related to the magnitude of side lobe energy, sensitivity to echoes and signal contamination from side-lobe leakage, signal strength, the effects of signal rejection algorithms, etc.

2.2 Comparison with Mechanical Anemometry

Comparison with mechanical anemometry on nearby tall masts. Sodars in general must be placed at some distance from obstructions such as masts to eliminate fixed echo interference. When comparisons with tall towers are done as a means of calibration, the comparison should be done in simple terrain with low or at least uniform roughness. Additionally, the calibration of the mechanical anemometers must be well documented, and any sources of bias between the two resulting from differing measurement techniques, physics and exposures must be accounted for. (Bradley et al., 2005).

The statistical comparison with anemometry should include an evaluation of the coefficient of determination (R^2) between the two measurements, indications of any bias between the two, and an evaluation of whether bias is dependent on wind speed.

The accuracy of a comparison with nearby anemometry will depend on the uncertainty of the anemometer measurements (including considerations related to anemometer measurement error, tower effects, turbulence, and vertical wind flow), the uncertainty of the sodar measurements (including instrument uncertainty, the effects of any software features that may be chosen by the user, ambient noise and echoes), upwind terrain and surface roughness conditions that results in different wind resources at the tower and sodar locations and any effects of spatially variable flow within the measurement volume of the instrument (see below).

Comparisons with rawinsonde data. Comparisons of wind conditions measured by sodar and rawinsondes are feasible, although balloon soundings of the atmosphere typically have low vertical resolution in the first 100 m above ground level. Balloons also move horizontally and vertically with the wind, and there will be low temporal resolution as well. Therefore this technique has very limited application and is best done in areas consisting of simple, homogeneous terrain.

Comparisons with tethered balloons. Tethered-balloon systems equipped with a meteorological sensor package can also provide a general check on sodar performance, although for wind energy resource assessment applications, this method is not sufficiently accurate for verification or calibration purposes.

Performance audits, inter-comparisons, and calibration procedures and schedules should be documented thoroughly to support the use of sodar in any wind resource assessment program. The documentation should include dates and locations of calibration tests, the names of personnel involved, detailed description of the site, including a sector-wise summary of the terrain, and the test set-up, and documentation of the test equipment including serial numbers and calibration certificates.

System verification audits should be done at the start and end of a measuring campaign and upon any re-location of the SODAR. For longer measuring periods, system verification or re-calibration should be done every six months or less. These procedures should also be done if harsh weather or environmental conditions near the extreme rated tolerances given by the manufacturer have been experienced by the sodar.

2.3 Verification of sodar performance against standard models

Another testing procedure would involve the use of standard instruments for testing, requiring three steps:

a. The verification of a reference instrument by each manufacturer. Manufacturer's verification would include the internal audit procedures using traceable standard test instruments and components, followed by a comparison with mast anemometry at a test site.

b. Subsequent models of the same sodar make and model should be verified by the manufacturer on their own test site, with third-party certification of the test validity.

c. The reference sodar system should be retested regularly (at least annually) to verify that there is no drift or wear in the components or calibration.

A protocol for sodar verification is outlined in Appendix A.

3.0 Operating Requirements

Retrieving and evaluating sodar data daily using remote communications (digital, analog, or satellite) is recommended. Some expertise and experience is required to assess the quality of sodar data.

Sodar should be operated at a site for a sufficient period of time to collect a representative and statistically robust sample of meteorological conditions for the desired range of wind speeds and directions. When comparing sodar data with a reference wind measurement location, the data recording interval for both systems should be the same. Clocks within the data recorders for both systems should be synchronized.

Because the backscattered sound measured by sodar is dependent upon spatially distributed turbulent temperature fluctuations, and these fluctuations are not necessarily evenly distributed within a height interval (i.e., range gate), very short measurement periods (less than a few days) are generally not very useful. Temporal averaging will smooth out the variation and provide better reliability and comparability with other measurements. Initial evaluation of the quality of sodar data generally requires at least 12 hours' data, preferably when wind speeds are 4 m/s or greater at the height level of interest (e.g., wind turbine hub height). Initial data quality checks and the subsequent adjustments made should be documented.

3.1 Temperature

All sodars require some kind of temperature setting or measurement as input. Most sodars now acquire this temperature automatically from an onboard sensor, but for those that don't, a mean temperature must be entered. This setting allows the sodar to accurately compute the speed of sound, which in turn determines both the altitude assigned to returned echoes, and, for phased-array systems, the vertical tilt of the acoustic beams. Because the sodar determines the horizontal components from the component radial velocities in the tilted beams, the beam tilt angle variation with temperature can contribute to statistical error in the derived horizontal speed. Therefore, a realistic mean ambient temperature setting should be entered and updated at least monthly, or, if the temperature setting is updated automatically from a sensor logged with the sodar, this option should be chosen in software. The functionality and accuracy of the onboard sensor should be verified.

3.2 Precipitation

Precipitation can cause acoustic noise and/or scattering of sound back to the sodar, which can result in erroneous wind data from the sodar. For this reason, in most instances, periods of precipitation should be removed from the sodar data stream. In some sodars, data acquisition can be automatically turned off when precipitation is sensed. For others, it is necessary to screen the data during post-processing in order to remove periods that are affected by rain or snow. Having an independent measurement of precipitation allows for the careful consideration of whether precipitation is adversely affecting the data.

At mid- and high-latitudes, a provision must be made for the removal of accumulated snow or ice from the sodar's acoustic array and/or the reflector board. In some sodars a heater is provided which can be activated automatically when it snows. However, for sodars operated off-grid, it may not be practical to provide sufficient power to do this. Propane heaters can be used to melt snow from sodar reflector boards. In the absence of a means of melting the snow manual removal of snow will be necessary to maintain a quality data stream. Field notes should be kept on snow accumulation in the sodar, so that data quality during those periods can be scrutinized. Even a light accumulation of snow can result in damped acoustic signals and poor altitude performance.

3.3 Vertical Range and Resolution

The maximum vertical range of sodars in common use for wind energy resource assessment varies from 200 to 500 m. The maximum range for a particular sodar depends largely on the emitted power; however, the actual maximum height achieved at a particular site is determined by ambient atmospheric and noise conditions, and by the software settings, for example the threshold for acceptable signal-to-noise ratio. Very dry or very noisy conditions, for example, will tend to limit the maximum achievable altitude performance. Altitude performance can also be affected by transient events such as the nocturnal low-level jet.

Sodar produces acoustic pulses of discrete physical length (i.e. the pulse period in seconds multiplied by the speed of sound in m/s). The backscattered sound received from the atmosphere at any given time represents an integral of the sound through a depth related to the length of the pulse. The vertical resolution of the sodar wind measurement, or the ability to distinguish between signals returned from different heights above the ground, depends primarily on three things: the acoustic pulse length, the sampling rate, and the number of samples required to convert from the time domain to the frequency domain (Fast Fourier Transform, or FFT). The choice of pulse length affects both the vertical resolution and the total height to which measurements can be made. The number of samples in each range gate affects the frequency resolution and hence the overall system accuracy. A frequency resolution and accuracy of about 1 Hz is desirable to obtain the required accuracy of wind speed and direction.

Some, but not all, sodars allow the user to make choices in software settings that affect vertical resolution and frequency resolution. For those sodars that do allow changes to these settings, users should be aware of the tradeoffs that are inherent in making these choices. An optimal set of choices for any given instrument and measurement protocol should reflect this balance among altitude performance, frequency resolution and vertical resolution.

Although most sodars will output a data point for every 5 m depth, the actual vertical resolution is not better than 10 m (± 5 m) in most circumstances, and it may be closer to 20 m (± 10 m), because of the issues just cited. At adjacent range gates closer than the vertical resolution there is ”overlap” of information among the data. In a “regular” wind profile, the samples in the center of the range gate will tend to be weighted more than the samples at the extremes.

3.4 Reliability Criteria

One output of most sodar systems is a measure of the signal-to-noise ratio (SNR), which is an indicator of data quality. In normal operation, SNR varies with the time of day because the amplitude (strength) of the backscattered acoustic pulse is dependent on the presence of turbulent temperature fluctuations. Periods when there is little or no sensible heat flux[2] in the boundary layer (neutral conditions), and therefore little in the way of temperature variations, will produce less backscattered signal, and lowered signal-to-noise ratio. Low SNR can also result from very low humidity conditions. In addition, both acoustic noise and electronic noise can degrade the SNR or lead to false signals (see Section 4.0). Therefore an important reliability criterion for for sodar is the SNR; it is a key indicator of data quality.

Absolute values of the computed SNR vary with sodar manufacturer, site conditions, and atmospheric conditions. Plotting time series and vertical profiles of SNR can aid in establishing appropriate settings and the later identification of suspect data periods. The choice of threshold SNR to use for acceptable data depends to some degree on the site and conditions. A very noisy site may require a higher SNR to achieve quality data, while a quiet site may allow for a lower SNR threshold. When the sodar is set up at a particular site a good practice is to observe spectral data and SNR to determine if sufficient data of good quality are being acquired with acceptable altitude performance. Another technique available with some sodars is to operate in “listening” mode with the transmit signal off; the SNR threshold can be set to a value that is higher than that obtained when the sodar is not transmitting.

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[2] “Sensible heat flux” refers to the vertical turbulent transfer of heat that occurs when there is a vertical gradient in temperature. “Neutral conditions” means there is very little vertical gradient in temperature.

4.0 Siting and Noise

Sodar should be located at a site that is representative of the prevailing wind conditions for the area of interest, similar to the way in which meteorological masts are sited for wind resource assessment. The sodar should be placed on firm and level ground, and should be anchored if there is a risk of toppling due to high winds. Sodar siting must also take into account unwanted sources of ambient noise, fixed echoes, and sources of electrical noise, which can deteriorate data quality. Regardless of whether the sodar is being deployed operationally for wind resource assessment, or for system test and verification, the same siting criteria should be applied. All noise related evaluations are to be documented.

4.1 Acoustic Noise (passive and active)

It is good practice to develop an understanding of the acoustic environment in which the sodar is operating, and optimize settings for that environment. When siting a sodar system, consideration should be given to the location and spatial distribution of all potential acoustic sources and scatterers, whether atmospheric or not.

Fixed echoes, or passive noise, must be avoided when siting sodar. Any backscattered sound coming from fixed objects (masts, trees, buildings, etc.) is returned to the sodar with zero Doppler shift. If this signal is as strong as or stronger than that from the atmosphere, the sodar wind speed measurement will contain a low bias. Although most sodar manufacturers provide software options for the detection and elimination of fixed echoes, the best practice is to avoid them in the first place by observing adequate setback distances, if at all possible. A starting point is to observe a setback distance no closer than the height of any fixed object in the vicinity; a better practice would be to assure that there are no tall objects within a distance equivalent to the highest measurement height of interest. However, other considerations must be accounted for as well.

Knowledge of the sodar's acoustic beam geometry can be used to orient the sodar such that the side lobes strike objects such as buildings at an oblique angle. In this case, the echo is not reflected directly back to the sodar, and the fixed echo effect can often be minimized. However, with obstacles such as trees, it can be difficult to find an orientation in which fixed echoes are not occurring. Trees also present a large amount of surface area for reflection of sound, which can result in multiple scattering of sound. The required distance to obstacles depends on the site, and how many obstacles there are (i.e. how much total surface area).

A further consideration in the sodar beam geometry is the tilt angle. A smaller tilt angle from the vertical for the horizontal velocity components should result in less interference from obstacles at lower heights. In some sodars, this option may be chosen to mitigate fixed echoes. However, strong winds can refract (bend) acoustic beams, resulting in fixed echoes from objects that are theoretically below the main acoustic lobes. Some mitigation of the fixed echo effect may be achieved with additional acoustic baffling around the sodar.

Detection of fixed echoes can be done by examining vertical profiles of wind speed, signal amplitude, and SNR. In general, in flat terrain and at midday the wind speed should increase with height, while the amplitude and SNR should decrease with height.

However in sloping terrain negative shear (decreasing wind speed with height) is commonly observed, and in strong stability at night there can be variations due to the presence of the low-level jet and other phenomena. A consistent deviation from these conditions at a particular height is diagnostic of a fixed echo at the distance corresponding to that height.

Acoustic noise (active noise) can interfere with sodar measurements by presenting false signals near the sodar's acoustic frequency(ies) or by causing a degradation of the SNR, which results in degraded altitude performance. Active noise sources can include machinery such as generators or air conditioners, insects and birds, and even the wind itself blowing through and around trees or guy wires (Crecscenti, 1998).

Siting procedures should include an assessment of ambient acoustic noise using a noise meter or the sodar in "listening" mode. For those sodars where this is an option, putting the sodar in "listening" mode periodically, with no outgoing transmit signal, would assure that spurious velocity readings due to noise are not entering the data. Audio recordings that use the sodar's antenna as the microphone input can be especially helpful in assessing the nature and impact of ambient noise. Care should be taken to conduct diagnostic recordings at different hours of the day. Acoustic shielding from some noise sources (e.g. generators) can be effectively obtained from bales of hay or other sound-absorbing material placed around the noise source.

Finally, wind induced ambient noise under high winds conditions may reduce the SNR of samples during high wind speed gusts. These data may be deleted from data set with the result that the 10-mionute average reported by the sodar may based only on data during lulls and this may be biased low.

4.2 Electronic Noise

Input signals should be examined for the presence of radio frequency interference (RFI) or other electronic noise produced by power supplies, inverters, communication equipment, fans, etc. If electronic noise is present, it can sometimes be diagnosed from audio files made through the sodar antenna, with the sodar in "listening" mode, or with the use of an oscilloscope at various test points in the sodar. Depending on the source of electronic noise, it may be necessary to employ filters, shielding, or a different physical spacing of the electronic components in order to reduce it.

4.3 Siting to Avoid Public Annoyance

The ongoing beeping or chirping of a sodar can be an annoyance to people living nearby. If a sodar is going to be operating 24 hours a day for some period of time, it is best to site it far enough from residences so as to minimize this annoyance. This may require ensuring that the sodar is at least 500 m from nearby residences.

5.0 Power Supply

Although power consumption for most sodars has decreased considerably in recent years, sodars still consume more power than the typical mechanical anemometry used in wind resource assessment. Power should be sufficient to maintain continuous operation of the sodar, as well as any communications equipment used for remote access of the instrument. If the sodar is operated off-grid, some means of maintaining battery charge (generator, PV, wind generator) must be supplied. In mid- to high-latitudes, PV charging that is sufficient in summer may have to be supplemented with another charging method in winter.

6.0 Site Documentation

Site documentation should be similar to that done for meteorological mast measurements. Particular attention should be paid to the following items:

- Sodar antenna rotation angle should be measured as accurately as possible with respect to true North. A magnetic compass alone may not give a sufficiently accurate bearing (i.e. better than +/– 2 ^{o}); alternative methods for aligning sensors to true North can be found in Baxter (2001).
- The sodar should also be within 0.5 degree of level.
- Any obstacles which could produce fixed echoes should be documented in an obstacle vista table with entries for azimuth, distance, elevation angle of the obstacle, and the degrees of arc occupied by the obstacle.
- Any obstructions to wind flow and major changes in surface roughness should be noted for each wind direction.
- The coordinates and elevation of the sodar and co-located mast (if any) should be recorded.
- The site's slope and aspect should be measured.
- The distance and azimuth to any local mast used as a reference should be recorded.
- Ambient noise sources should be noted and an audio record made, if possible.
- There should be an onsite rain gauge or precipitation sensor that is logged, to allow either for the suspension of sodar measurements during precipitation, or the removal of those periods from the valid data set.
- If sodar is used near existing wind turbine, it should be placed upwind in the prevailing direction.

7.0 Data Collection and Processing

A sodar's data outputs comprise the basic information sought by a sodar measurement campaign to define certain atmospheric characteristics, such as wind shear. The robustness or temporal representativeness of the results depends on the duration of the measurement campaign, the temporal patterns of atmospheric conditions and on the exclusion of precipitation periods. When comparing results of a sodar campaign with results from another measurement system (e.g., mast), fundamental differences in measurement techniques must be accounted for.

7.1 Data Parameters and Sampling/Recording Intervals

Sodars provide many output parameters. Primary outputs include all three component wind velocities (two horizontal, and the vertical) and their standard deviations. In addition, some combination of the signal amplitude, noise amplitude and/or the signal-to-noise ratio, as well as the maximum height of reliable data, is also provided. There is a wealth of information both about the sodar performance and about the meteorological conditions that can be derived from this assemblage of outputs. Some sodars also provide estimates of meteorological parameters such as the standard deviation of the wind direction, the height of the inversion layer, the sensible heat flux or the momentum flux. The degree of accuracy or reliability for derived parameters depends on the sodar and the environmental conditions; it is best to check such derived parameters against other onsite instrumentation.

Recording intervals should be the same as those being used by other measurement systems with which the sodar will be compared. Where possible, sodar range gates should be selected that correspond as closely as possible to the measurement heights on the meteorological tower to which the sodar is being compared. Another consideration is that setting the maximum desired altitude affects the number of samples included in each recording interval. For example, setting the maximum altitude to 200 m results in about 15% fewer samples (chirps) per 10-minute recording interval, as compared to setting the maximum altitude to 150 m. Choosing a higher maximum range might be desired if for instance greater turbine hub heights are anticipated in the future, or to detect and characterize a low-level jet.

7.2 Calculation of Wind Shear

It is still common for wind resource assessments to utilize the shear exponent, α, for extrapolation from towers. One use for sodar is to indicate how the shear parameter changes with height under varying conditions, e.g. stability or wind direction. Sodar produces a complete wind profile in the desired altitude range, with the actual height interval for data output determined by software settings, e.g., every 10 m. As a result, the shear parameter can be determined between any two heights z_1 and z_2, and changes in the shear parameter can be detected throughout the measurement range. The shear parameter (α) is given by:

$$\alpha = \frac{\log(U_2/U_1)}{\log(z_2/z_1)}$$

The underlying assumption in the use of the shear parameter for extrapolation is that a single power law wind profile pertains to the layer of interest. An alternative formulation of the wind profile, with more basis in physics, is the neutral logarithmic profile:

$$U(z) = \frac{u_*}{k} \ln(\frac{z}{z_0})$$

Where U(z) is the wind speed at any given height above the ground, u_* is the friction velocity, *k* is the von Karman constant, and z_0 is a roughness length. There are several benefits to examining the entire profile, plotted against a logarithmic height axis: 1) instead of relying on a single shear parameter calculated between two discrete levels, the degree of uniformity in the profile can be assessed. Such non-uniformity can be due to upwind changes in roughness or terrain. 2) the upper limit of the meteorological surface layer can be determined as a function of, for instance, stability and 3) the roughness length z_0 as a function of wind direction can be derived. Deviations from the logarithmic profile nearer to the surface can be accounted for with a displacement height parameter *d*:

$$U(z) = \frac{u_*}{k} \ln(\frac{z-d}{z_0})$$

This parameterization, mainly used as a convenience for computational purposes, is commonly interpreted to mean that the displacement height is a kind of "virtual surface" representing the mean height of momentum absorption.

As with shear calculations based on mechanical anemometry, only wind speeds greater than 4 m/s should be considered in the calculation of the wind shear at a site for wind energy purposes. This is the wind speed below which most wind turbines do not produce power.

7.3 Measurement Period

The decision about how much sodar data to collect at a site depends on the objective of the study, and the nature of the site and the local wind regime. For example, if the primary goal is to assess how the shear parameter changes above tower top under varying stability or wind direction, one criterion might be to collect enough qualified data to achieve 95% confidence bounds of ±0.02 around the mean shear exponent, or the difference between shear exponents in different layers, for the prevailing wind direction sector(s). For this analysis, statistical methods need to be used that are not sensitive to the serial correlation (autocorrelation) of wind data or one can get false confidence in the results. This criterion can often be achieved in as little as 3 weeks to one month, if there are enough observations with wind of sufficient speed from the important energy-producing wind direction sectors. However, in other cases, either a longer period might be required or measurement periods in different seasons may to necessary, to achieve sufficient representation of varying conditions in the data.

Another approach to determining the duration of a sodar study is to achieve target confidence limits around the speed difference with a reference meteorological mast located some distance from the sodar site. Whether the criterion is based on confidence bounds around the shear or the speed differences, it is best to use whatever pre-existing information there is about a site, such as seasonal variability in shear, atmospheric stability, or wind direction distribution, to help determine the period duration (and number of seasonal periods) needed to achieve a representative data set.

7.4 Exclusion of Precipitation Periods

Acoustic signals can be scattered back to the sodar from hydrometeors (rain drops or snow flakes), depending on the intensity of precipitation and the acoustic frequency. In addition, there can be noise from raindrops striking the exposed area of antenna or transceiver. It is best to check with the manufacturer regarding the effect of precipitation on sodar data quality; for most sodars, periods of precipitation must be removed from the data. Even after removal of periods with recorded rain or snowfall, the data should be screened for periods of excessive negative vertical velocity, which may indicate that light precipitation, unrecorded by a gauge, was occurring. Such screening can be achieved through examination of the time series of vertical velocity.

7.5 Comparisons with Mechanical Anemometry

Since sodar data are almost always referenced to ongoing mechanical anemometry and because power curves us anemometer measurements as a standard, whether co-located or at some distance from the sodar site, bias between mechanical anemometry and sodar wind speeds arising from differing underlying physics between the two should be addressed in data processing. Bias between the two can be attributed to several factors:

- Sodars generally report a vector-average wind speed, while cup anemometers yield scalar average or mixed vector-scalar average, depending on the type. The vector average can be as much as 5% lower than the scalar average, but the median difference is generally closer to 1-3%. A conversion between the two can be made using the standard deviation of the wind direction, or wind speed and direction, if an anemometer and mechanical wind vane are present, or using an empirical relationship with the sodar sigma-w (standard deviation of the vertical wind velocity), for instance.
- The tilt angle of the off-vertical acoustic beams of the sodar phased array is subject to variation due to temperature. Most sodars have an onboard temperature sensor that will do beam tilt calculations using the current temperature. However, some still use an ambient temperature setting that is generally set to some average value for the period of measurement. However, depending on the acoustic beam geometry, greater wind speed measurement accuracy will be achieved if *either* a correction based on the temperature-tilt angle relationship is made after the data are collected, *or* an in-situ temperature measurement is used to calculate and adjust the tilt angle as the data are being collected.
- Mechanical anemometers can overestimate the wind speed due to overspeeding resulting from turbulence or off-horizontal flow. The magnitude and characteristics of overspeeding vary with the anemometer. These effects should be accounted for when making comparisons between sodar and anemometers.
- The geometry of the sodar acoustic beams may be such that in cases where there is an inhomogeneous wind field, the different off-vertical beams may be probing flows of different characteristics. This could be detected by gross discrepancies in the wind direction, compared to a nearby tower.
- Sodar calculates the wind speed in a volume of air, in contrast to the “point” measurement provided by mechanical anemometers. If the wind profile has very high shear in it, this will cause the sodar speed at the lowest heights to be lower

than a point measurement centered in the sodar volume, by as much as 3 to 4%. This will result in a concomitant increase in the shear of as much as 5%, depending on the surface roughness. If the shear decreases with increasing height, then this effect will also decrease with height. This example supposes a volume average 20 m in depth, and a 50/30 m shear parameter (point measurement) of 0.40. Corrections for shear biases will be based on the instrument configuration, shear exponent and measurement height.

- Missing data in the either the sodar or anemometer data sets may make direct comparisons more difficult. Data gaps may result in selective sampling of certain atmospheric conditions (no rain, stable atmosphere) which could introduce errors in a comparison between instruments. Only concurrent data points should be compared.

Comparisons between sodar and mechanical anemometry should include a careful examination and verification of the location and characteristics of the anemometry. Characteristics to examine or verify include measurement levels of mast-mounted sensors, directional orientations of sensor booms from the mast, distances between sensors and mast hardware, sensor calibration constants, changes in instrumentation, etc. Valid measurements for the anemometry should exclude periods of detectable mast-induced flow interference (e.g., tower shadow), periods when icing is occurring, or periods when other types of measurement problems are occurring.

8.0 Complex Flow and Other Considerations for Incorporating Sodar Information into a Resource Assessment Program

The use of sodar in complex flow can introduce bias into the measurement of the horizontal wind speed. Complex flow is spatially variable flow within the measurement volume of the instrument. This may be caused by complex terrain or upwind surface roughness and terrain features which result in a non-homogenous wind resource above the sodar. This is primarily due to the fact that the radial measurements used to derive the horizontal and vertical speeds are displaced from one another. The same principle affects both sodar and lidar measurements in complex terrain (Bradley, 2008). For example, for a 3-beam sodar with an 18^{o} tilt angle, at 100 m each tilted beam is displaced about 30 m from the vertical velocity measurement used to derive the horizontal from the radial. If there is flow inhomogeneity (that is, if there is a gradient in the actual vertical velocity) on this scale, then the derived horizontal velocity components will have some error. Various modeling studies (Boquet, et al., 2010, Harris et al., 2010) have proposed that the error can be corrected using CFD models. The error has been modeled using CFD models to be on the order of 1% to 6% across a range of terrain complexities. The siting of sodar in complex terrain should be done in such a way as to minimize the impact of complex terrain. Where complex terrain cannot be avoided, an effort to understand its impact on sodar measurements should be made, and any accompanying uncertainties must be accounted for in the wind energy resource assessment process.

For many applications, sodar will likely be used for relatively short periods of time and the results compared to longer-period measurements taken by ongoing meteorological masts. Evaluation of the seasonal representativeness of the sodar measurement period should be done by examining the seasonal changes in the shear at the site of interest. In many cases no adjustment need be made, but in cases where the shear is expected to change significantly by season, sodar should be deployed accordingly.

Beyond the factors described in Section 6.5, significant discrepancies between results obtained by sodar and conventional mast anemometry may still occur and understanding of the source(s) of such discrepancies should be sought. An obvious potential source of discrepancy can be the separation distance between the two measurement systems and the corresponding differences in upwind fetch, surrounding surface roughness, ground-base elevation, and other physical factors. Differences in location between measurement systems, therefore, must be accounted for when utilizing sodar to estimate wind shear conditions above existing meteorological masts.

9.0 Uncertainty and “Bankabilty” of Sodar Measurements

It can be demonstrated that, in the absence of influences such as fixed echoes and complex flow, sodar has an inherent accuracy that is comparable to anemometry in the field, and therefore, if certain conditions are met, sodar data should be bankable. Those conditions include verification of the individual sodar’s performance by the methods discussed above in this document. A formal protocol for verification of the sodar performance, and a definition of bankability in this context, is presented in Appendix A.

Uncertainty and bankability are tightly linked. One of the main objectives in using sodar for wind resource assessment is to reduce uncertainty in wind speed estimates at hub height and throughout a turbine rotor plane. In order to demonstrate that uncertainty has been reduced, it is necessary to properly account for all the sources of uncertainty that are present in with sodar measurements included, and in their absensce. For instance, the use of sodar measurements should reduce or eliminate uncertainty due to shear extrapolation.

The impact of availability on uncertainty should also be addressed. Anemometry and remote sensing measurements have different causes for being unavailable. Sodar data availability usually decreases above 60 to 80 m or so, depending on the atmospheric conditions. This differential availability must be accounted for when using sodar for wind resource assessment.

10.0 Acknowledgements

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A second IEA Topical Expert Meeting was held at the National Renewable Energy Labortory in Golden, CO in October of 2009. The participants at that meeting provided further suggestions for changes to this document. The participants at that meeting are listed in Appendix B.

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12.0 Appendix A: A Protocol for Verification of Remote Sensing Instrument Performance

This Appendix outlines a protocol for establishing that remote sensing data are acceptable for use in either a) wind resource assessment work or b) power performance or power curve testing. The requirements for acceptability are:

0: General Requirements

A preliminary requirement is that the data are acquired during a measurement campaign that meets the standards or recommended practices established for the technology.

1: Verification of Performance

The performance of the remote sensing device has been independently verified by comparing measurements made using it with concurrent and co-located measurements of the same wind flow parameters made using reference instruments which would have been deemed acceptable for conducting the wind resource investigation.

1.1: Reference instruments, calibrated and tested under certifiable conditions meeting relevant standards, support traceability of device performance. The calibration of reference instruments must itself have sufficient documentation to be traceable.

1.2: The manufacturing processes and provenance of the remote sensing device and its components will also be adequately documented to support traceability.

1.3: The degrees of concurrency and co-location are those that enable the most precise and well understood relationship between the device and reference measurements to be determined. So, for example,

- The same averaging intervals are used for the device and reference datasets being compared;
- Regression methodologies accommodate errors in all instruments;
- The device is sited and analysis of the measurements conducted in a manner that minimizes extraneous influences such as
    - flow perturbations;
    - fixed echoes;
    - real variations in the flow between the device and reference instrument measurement locations;
    - divergent levels of data coverage within averaging intervals.

1.4: The verification exercise has been conducted recently enough for its results still to be valid, and not more than a period of 12 months in the past.

2: Verification of Methodology

The measurement campaign in which the device is operated to acquire data for the wind power investigation is conducted according to the methodology adopted during performance verification.

2.1: Methodology is adequately documented to ensure repeatability of the measurements. The statement of the methodology details any dependence of device performance on the prevailing conditions. For example, the impact of flow inhomogeneity in the volume penetrated by the remote sensing measurements and the influence of other parameters such as temperature and precipitation is described.

3: Verification of Conditions
The conditions prevailing during the element of the measurement campaign in which the device is operated to acquire data for the wind power investigation are considered sufficiently similar to those prevailing during the performance verification period that a divergence in the performance of the device from the performance observed during performance verification would not be expected.

3.1: The influence of the deviation of conditions during the measurement campaign from the conditions during the verification period is understood and documented sufficiently to enable remote sensing measurement uncertainties and biases arising as a result to be reported and adequately supported with reference to current understanding of device response.

3.2: If conditions deviate and the influence of this deviation is not adequately understood, remote sensing is inapplicable. For example, flow inhomogeneity, variable flow inclination, and non-uniformity in the volume defined by the remote sensing measurements, possibly induced by complex terrain, may render remote sensing inapplicable.

3.3: Filtering and data availability are not correlated with conditions such that a bias is introduced into the results.

4: Robust Uncertainty Analysis
The uncertainty analysis on which energy yield percentiles are based is accurate and adequately represents the uncertainty introduced by the instruments and methods used during the measurement campaign.

4.1: "Bankability". It is acknowledged that these considerations may have a bearing on whether an investigation is judged to be "bankable" or not. For clarification, bankability is defined as follows:

- The long-term energy yield estimate, based upon the wind resource measurements, is sufficient for servicing debt raised to finance the project's development or acquisition;
- The threshold percentile for financing (P90, P85 etc.) is based on an uncertainty analysis that adequately represents the measurements and methods employed for the long-term energy yield assessment.

5: Compliance with IEA Guidelines
The specific remote sensing technology, such as Sodar or Lidar, adopted for the purposes of the wind power investigation, is operated in compliance with the most current IEA Recommended Practices published in relation to the technology, as formulated by the relevant IEA Topical Expert Committees.

5.1: Recommended Practices for sodar are presented above; a separate document provides Recommended Practices for lidar.

12.0 Appendix B: List of Participants in IEA RD & D Wind Topical Experts Meeting #59

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