RECOMMENDED PRACTICE

DNV-RP-J101

Use of Remote Sensing for Wind Energy Assessments

APRIL 2011

This document has been amended since the main revision (April 2011), most recently in November 2011.
See "Changes" on page 3.

The electronic pdf version of this document found through http://www.dnv.com is the officially binding version

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FOREWORD

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CHANGES

Amendments November 2011

- **Appendix A. Uncertainties using the Jack-knife Method**

— In the paragraph below “A.1 Example”, the result of the example was incorrect and has been corrected to 0.025.

CONTENTS

1. Introduction

1.1 Purpose

This document describes DNV's guidelines for using remote sensing to gather data for wind resource and energy assessments.

1.2 Limitations

As technologies evolve, DNV's recommendations and opinions may change.

1.3 Background and Scope

As SODAR (SOnic Detection And Ranging) and LIDAR (LIght Detection And Ranging) technologies mature, more project developers are using these technologies to support wind resource assessments. These remote sensing instruments are relatively easy to use and move from site to site. They provide wind turbine hub-height wind speeds and direction, vertical wind speeds, and wind shear and veer above the heights of typical meteorological (met) tower measurements. They may also provide some measure of turbulence levels.

Unfortunately, users may fail to realize the full value of their remote sensing equipment due to a lack of clarity about best practices to ensure that their data will be useful for reducing uncertainty in future energy assessments. For example, the portability of remote sensing equipment has encouraged many users to measure for short periods at multiple locations in order to capitalize on their investment. Measurement periods that are too short, poor site conditions and a lack of verification of equipment performance can lead to data which are of limited or no use in an energy assessment.

This document provides guidelines on the use of remote sensing (Sodar and Lidar) measurements to support wind resource and energy assessments for wind energy projects. It includes guidelines for instruments on site, documentation and verification, and planning and implementing remote sensing measurements. The document also provides examples of their use. Instruments covered by this Recommended Practice include Sodar and Lidar systems intended to measure wind characteristics up to 200 m above the ground. Activities covered by this Recommended Practice include the collection of wind data for the purpose of wind resource assessments and wind project energy assessments. In this context, wind resource assessments are evaluations of the wind resource available at a wind energy project site and wind project energy assessments are evaluations of the energy generation potential of wind turbines planned for that project.

2. Using Remote Sensing Data in Energy Assessments

In an energy assessment, remote sensing data may be used to evaluate any or all of the following:

- The accuracy of extrapolations from tower data
- Shear coefficients to be used with tower data
- Hub-height wind speeds and directions
- Wind resource variability across the site.

How the data are used in an energy assessment will depend on the quality, quantity and representativeness of the validated data. The degree to which the data improve or reduce the uncertainty of the energy assessment will depend on, among other factors, the data recovery and its correlation to nearby met tower data, the data collection durations and the data collection locations relative to met tower and proposed turbine locations.

Other characteristics of the project will also determine the impact of remote sensing data on an energy assessment. For example, if there is little uncertainty in the energy assessment without remote sensing measurements, then remote sensing measurements may have a marginal impact on the overall energy assessment due to the uncertainties inherent in the remote sensing data. Seasonal variability of the atmospheric conditions at the project may limit the impact of short-term remote sensing measurements on the energy estimate or its uncertainty.

The following important aspects of remote sensing technologies must be taken into account to ensure that data are useful for energy assessments:

- Remote sensing technologies are still maturing. Equipment configuration and software changes may affect measurement accuracy, quality, or consistency.
- Measurement quality may be affected by site positioning. Even perfectly operating Sodars or Lidars may provide incorrect measurements in the presence of complex flow (spatially uneven flow) above the instrument. Complex flow may occur in complex terrain or near surface roughness transitions. Additionally, Sodar measurements may be affected by site-specific ambient noises and echoes from nearby objects and surrounding vegetation ("ground clutter").
- Remote sensing measurements may be different than those of anemometry. Anemometers provide averages of point measurements of wind speed irrespective of wind direction ("scalar averages"). Sodars and Lidars measure average vertical, lateral and horizontal wind speeds. These are usually transformed to provide "vector averages" of wind speed, although some instruments may provide scalar averages. In turbulent

conditions, vector averages are lower than scalar averages. These differences mean that remote sensing and anemometry may not provide the same wind speed values although each may be measuring correctly. Each type of measurement system may also provide slightly biased measurements under certain conditions. For example, in conditions with high shear the volume averages of remote sensing instruments are lower than point measurements. In turbulent conditions, anemometer measurements are biased high.

If these aspects of remote sensing technology are appropriately considered in a measurement campaign, remote sensing data can provide valuable information for an energy assessment. Compliance with the site positioning, documentation and verification practices detailed below provides information required to evaluate the quality of the data and its value with respect to an energy assessment. The value of the data will depend on many factors but can be enhanced with careful planning and consultation with energy analysts before data collection begins (see the guidelines for planning and implementing remote sensing measurements below).

No guidelines can ensure how data will be used in an energy analysis. The analysis will be driven by the data results. Nevertheless, attention to each of the steps below will ensure, as much as possible, that the value of the data will not be jeopardized by a lack of awareness of the needs of the energy analysis process.

2.1 Guidelines: Site and Operation

Site positioning of the remote sensing equipment should comply with the manufacturer's site instructions and those in general site guidance documents. In addition, as instrument positioning at site and software or hardware upgrades can affect measurements, the following practices should be followed.

2.1.1 Requirements for On-Site Met Tower

— There should be on-site wind-resource-quality met tower data to confirm correct equipment operation. The tower data are used to identify outliers caused by operational problems and electrical or acoustic noise and to identify the effects of ground clutter, echoes, and complex flow. The nearby tower need not be directly beside the remote sensing equipment but should be within the footprint of the wind energy project and at a location with a wind resource similar to that at the remote sensing instrument.
— DNV strongly discourages the use of stand-alone remote sensing data collection when the data are to be used for future energy assessments. As noted above, DNV recommends that at least one nearby wind-resource-quality met tower be used to provide confidence in the positioning at site of remote sensing instruments and to record the annual wind resource at the site.

2.1.2 Positioning at site Requirements to Avoid the Effects of nearby Obstacles and Noise

— In forested areas, when measuring with a Sodar, trees must be cleared in a large circle around the instrument to avoid ground clutter contamination of data. Clearing trees to a distance 20 m greater than the highest measurement height (for example, 140 m at sites where measurements are desired to 120 m above the ground) is the most conservative approach. Depending on the beam orientation and the instrument these conditions may be relaxed.
— In forested areas, when measuring with a Lidar, a clearing with a radius as great as the height of the surrounding trees is adequate.
— Locating a Sodar 20 m farther from solid structures that could reflect signals than the greatest desired measurement height is the most conservative positioning at site approach. Depending on the instrument design, these conditions may be relaxed. If possible, the Sodar should also be oriented such that the acoustic beams are not directed toward these objects.
— Sodar locations with significant ambient noise should be avoided.
— Sodar mounting or anchoring schemes should not cause wind-generated noise or resonate with the acoustic signal.

2.1.3 Positioning at site Requirements to Avoid Complex Flow Effects

— Locations with complex flow (often caused by complex terrain or non-uniform roughness) should be avoided, if possible. Locations with complex flow are locations with changes in flow conditions within the volume used to measure the wind. This is roughly a circular volume with a radius that may be between 15 m and 60 m and a thickness that may be between 1 m and 20 m, depending on the instrument and measurement height. If the spatial variation of the horizontal or vertical wind speeds is expected to be greater than 1% over the measurement volume, DNV should be consulted for a more detailed analysis of possible measurement biases resulting from the complex flow.

2.1.4 Operational Requirements

— If appropriate, the latest hardware and software upgrades available from the manufacturer should be reviewed and installed before measurements are initiated.
— If hardware or software upgrades are made before measurements are completed, a new verification test is recommended (see below).
— No configuration changes should be made during a measurement campaign unless absolutely necessary.

2.2 Guidelines: Documentation

The remote sensing documentation should include:

2.2.1 Remote Sensing Instrument Placement

- Instrument coordinates and elevation to within a few meters, including datum.
- Confirmation that the instrument is level (within ± 0.5°).
- Beam orientation with respect to true north.

2.2.2 Remote Sensing Instrument Configuration

- Instrument manufacturer, model, and serial number.
- Measurement of the cone angle.
- If a Sodar, confirmation, if possible, that the transmit frequency is correct, that any temperature sensor is operating correctly and that any software or firmware is using the measured ambient temperature for calculations
- Confirmation that the clocks of the anemometer and remote sensing loggers are were within five seconds of each other.
- Type, transfer function and manufacturer of auxiliary sensors (e.g., rain gauge, solar insolation).
- Software and hardware configuration of the instrument and any changes to those during the measurement period.

2.2.3 Remote Sensing Instrument Site Conditions

- Photo documentation of surrounding terrain and surface features in 45° direction sectors.
- Azimuth, distance, height, elevation angle and subtended angle, as seen from the remote sensing instrument, of surface features and obstacles to flow within visible range.
- Azimuth, distance and elevation angle, as seen from the remote sensing instrument, of the nearby tower.
- If a Sodar, documentation of possible sources of echoes.
- Magnitude and orientation of any slope at the site.
- If a Sodar, ambient noise sources, such as nearby roads, crickets, etc.
- Upwind changes in surface roughness and slope within 3 km of the site and in 45° direction sectors.

2.2.4 Tower Sensor Locations and Configuration

- Tower location and elevation to within a few meters.
- Tower height and dimensions.
- Instrument manufacturers, serial numbers, and calibration documentation.
- Sensor installation heights, boom dimensions and azimuth angles.

2.2.5 Tower Site Conditions

- Photo documentation of surrounding terrain and surface features in 45° direction sectors.
- Azimuth, distance, height, elevation angle and subtended angle, as seen from the tower, of surface features and obstacles to flow within visible range.
- Magnitude and orientation of any slope at the site.
- Upwind changes in surface roughness and slope within 3 km of the site and in 45° direction sectors.

2.3 Guidelines: Verification

Verification refers to comparisons against co-located tower data that are used to verify the correct operation of the remote sensing instrument. The accuracy of comparisons with the tower data is dependent on the quality of the tower sensors and is limited by spatial variation of the wind between the tower and the remote sensing device should they not be co-located. Verification against accurate sensors and at sites in uniform terrain and surface roughness conditions will enable analysts to better evaluate the quality of the data and may reduce any uncertainties with respect to the data. This could be of critical importance should questions arise about the site or the data.

When conducting the verification, DNV recommends:

2.3.1 Frequency of Verification

- A verification test every year or within six months of any data collection, or after any software, hardware or firmware change.

2.3.2 Instrument/Sensor Placement and Configurations

- Positioning at site, operation and documentation guidelines should be followed for a verification.
- Placement of a Sodar as close to the tower as possible while avoiding echoes (typically between 60 m and 150 m from the tower). For Lidars, the device can often be placed directly next to a tower.
- The instrument elevation should be within 5 m of the base of the nearby tower.
- Verification against a tower in as uniform terrain and surface roughness as possible.

2.3.3 Tower Sensors

— Verification against well-documented and sensors that have been calibrated within two years, if possible. The accuracy and value of verification is directly related to quality of the anemometry.
— Multiple sensors at comparison heights.

2.3.4 Data Processing

— Collecting data long enough to ensure that the uncertainty of the verification results is within an acceptable band (see below for methods for estimating uncertainty).
— Careful validation of all tower data used in the verification to remove any periods of icing, tower influence or sensor malfunction.
— Elimination of data from those direction sectors for which the remote sensing and tower data are not comparable (due, for example, to tower shadow, upwind terrain or surface roughness effects, wind turbines upwind of either sensor, etc.).
— Careful validation of all remote sensing data used in the verification to remove any periods of low signal-to-noise ratios, echoes, system malfunction or faulty measurements due to precipitation or clouds.
— Application of corrections to the remote sensing data to account for shear and/or vector averaging, if appropriate.
— Correction for measurement error of the anemometers used as the reference instrument (see below for methods to correct the results).
— An estimation of the uncertainty of the slope and the offset of the relationship between the instrument and tower sensors (see below).
— For “bankable” energy assessments to be issued by DNV, DNV shall process the data.

2.4 Details of Instrument Verification

2.4.1 Accounting for Anemometer Measurement Error

Comparison of remote sensing with anemometry is complicated by the fact that the measurement error of both instruments are of a similar magnitude. A variety of approaches can be used to account for measurement error in the sensor system that is used as the standard in verification [1)]. One easy-to-implement approach is to start with a linear regression fit to the data and from this to determine the appropriate slope and offset based on estimates of the tower anemometer measurement error.

1) Carroll, R., Ruppert, D., Stefanski, L., Crainiceanu, C. Measurement error in nonlinear models: a modern perspective. 2nd edition. CRC Press, 2006.

First, the slope and offset of the linear regression formula for the relationship between the tower data and the remote sensing data are estimated. Using a least-squares approach, a linear regression model of the form $y = mx + b$ is determined from the validated and filtered data. Here y is the remote sensing wind speed, x is the tower wind speed, and m and b are the coefficients of the fit.

Next, the relationship between the remote sensing data and the true wind speed, z, is estimated. The linear relationship between the remote sensing data and the true wind speed which takes the measurement uncertainty of the anemometry into account is assumed to be of the form:

$$y = \hat{m}z + \hat{b}$$

A reliability ratio is defined as:

$$\lambda = \frac{\sigma_x^2 - \sigma_u^2}{\sigma_x^2}$$

where, σ_x is the standard deviation of all of the tower measurements and σ_u is the measurement error (one standard deviation) of the tower sensors. The desired slope, $\hat{m}$, and offset, $\hat{b}$, are then calculated using the reliability ratio:

$$\hat{m} = \frac{m}{\lambda} \quad \text{and} \quad \hat{b} = \bar{y} - \hat{m}\bar{x}$$

where, $\bar{x}$ and $\bar{y}$ are the means of all of the concurrent tower and remote sensing measurements. Standard practice in the wind industry is the use of 10-minute wind speed and direction averages. In this case, the measurement error of the tower sensors, σ_u, should be the uncertainty of 10-minute averages, including tower and mounting effects and sensor measurement error and biases.

2.4.2 Duration of Verification

The duration of the verification needs to be long enough to ensure that a representative number of wind speed samples have been collected and that the uncertainty of the slope and the offset are within acceptable bounds. Based on the analysis of a number of data sets, DNV recommends the following criteria for determining the length of a verification test.

1) **Minimum duration criterion**: *Data collection should proceed for at least one month.* This measurement duration criterion is meant to ensure that data collection spans a number of types of atmospheric conditions and that the data are not all correlated with each other.
2) **Minimum quantity criterion**: *At least 48 hours of validated data should be collected over the speeds and wind directions for which the tower data will be compared to the remote sensing instrument.* This minimum quantity criterion is meant to ensure that the data that have been collected are representative of conditions at the site.
3) **Range of data criterion**: *At least 12 hours of data should be collected in each of two wind speed bins with a range spanning 4 to 16 m/s.* This criterion is meant to ensure that the range of wind speeds at the site is well represented and that the range of wind speeds over which a wind turbine would operate is well represented. Thus, one might collect 12 hours of data between 4 and 8 m/s and 12 hours of data between 8 and 16 m/s. At a site with higher wind speeds, bins from 4 to 10 m/s and 10 to 16 m/s might be chosen.
4) **Uncertainty criterion**: *Collect data until the estimate of the uncertainty (standard error) of the slope and the offset is less than a desired threshold limit.* DNV recommends that the standard error of the slope should be less than 2% of the slope and the standard error of the offset should be less than 0.25 m/s. The standard error (uncertainty) of the slope and offset should be derived using a method that is insensitive to the correlation of the wind data. A variety of such methods are available such as the jack-knife estimate of variance and the bootstrap method. The jack-knife method is described in Appendix A.

2.4.3 Sample Results of a Verification

A verification results in an estimate of the relationship between the remote sensing and tower data and the uncertainty of that relationship. The results of a verification example are shown in Figure 2-1. In this case, the uncorrected slope and offset of the linear fit were 0.979 and 0.12 m/s. The standard deviation of all of the data used in the analysis was 3.13 m/s and the estimated anemometer measurement error was 0.20 m/s. The final estimated slope and offset of the relationship between the remote sensing measurements and the true wind speed were 0.984 and 0.07 m/s. The uncertainty of the slope and offset were ± 0.024 and ± 0.21 m/s, respectively.

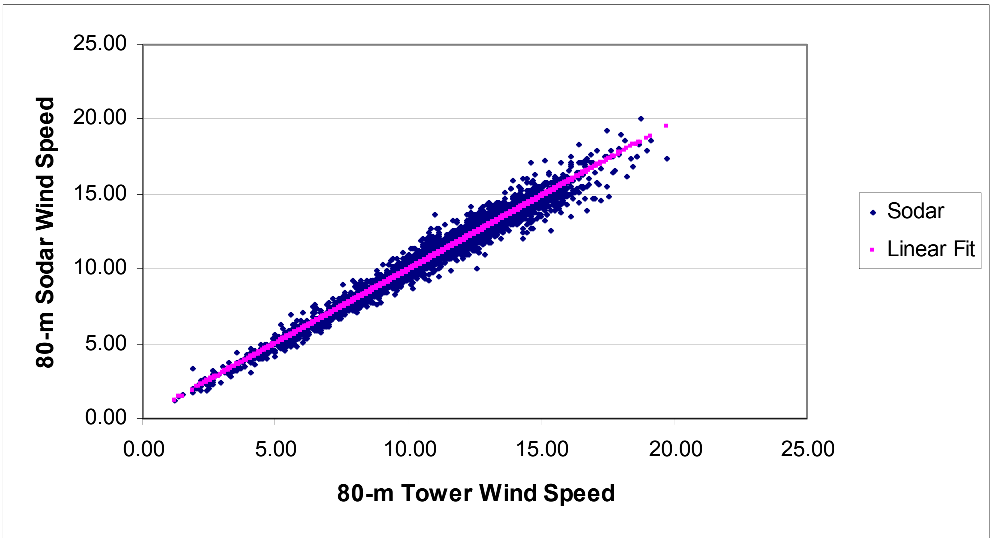

Figure 2-1
Sample Results from Verification of a Sodar

3. Planning and Implementing Remote Sensing Measurements

Energy assessments are usually based on one or more years of met tower data from one or more met towers within a project area. These data are then used to estimate the wind resource at turbine locations and hub heights. There may be enough topographic variability of the wind resource that the estimates of wind speeds at some turbine locations are quite uncertain. There may also be uncertainty as to whether the shear exponent as measured using tower data represents the shear behaviour above the tower or at the proposed turbine locations.

Remote sensing data can be used to define the relationships between the longer-term tower data and the wind resource at remote sensing measurement sites and heights. These data can potentially reduce energy assessment uncertainties if the data collection is well planned and implemented.

A well-planned measurement campaign:

— Addresses the sources of uncertainty in an energy assessment that are expected to be the greatest.
— Provides a data set that is as representative as possible of the annual conditions at the site.

Often a remote sensing instrument is deployed at one or more sites for less than a year. The instrument might be returned to a previous measurement site one or more times in a year to ensure that annual conditions have been measured (this is referred to as seasonal sampling). If seasonal sampling is not employed and if data are collected only for part of a year, there may still be uncertainty about how well these results represent the behaviour over a full year. This may be acceptable if the data, in spite of the uncertainty, provides valuable new information. An examination of numerous data sets indicates that seasonal variations may be significant at many sites. Thus, to adequately characterize the conditions over a year, either seasonal sampling or longer measurement durations are usually needed.

3.1 Guidelines: Planning and Implementing Measurements for Energy Assessments

A measurement plan should be developed prior to installing the equipment to ensure, as much as possible, that the data will achieve the goals of the measurement campaign. The plan should at a minimum:

1) Identify the greatest sources of uncertainty in an energy assessment.
2) Provide a plan for the deployment of the instrument.
3) Define metrics for quantifying when enough data have been collected.
4) Establish a method for measuring uncertainty of the metrics.
5) Establish a method for determining short-term measurement durations.
6) Define a plan for addressing seasonal changes in conditions.

Each of these aspects of the measurement plan is described below.

3.1.1 Determining Sources of Uncertainty

Preliminary estimates of uncertainty can be determined in consultation with the party completing the energy assessment. Such a consultation should include assessment of the greatest sources of uncertainty that are anticipated in a particular energy assessment. This assessment would be based on terrain features and met tower and turbine locations and heights. Those sources of uncertainty might be the spatial variation of the wind resource across the site (“topographic uncertainty”) or the shear above the tower (“shear uncertainty”). As data are collected and analyzed, the sources of greatest uncertainty should be re-evaluated.

3.1.2 Planning Instrument Deployment

The sequence of measurement locations and approximate measurement durations should be determined in advance of measurements. Available information on monthly or seasonal variations in wind speeds and directions, shear and ground cover should be used to guide the timing of measurements at each location in order to ensure useful data sets. For example: if the wind resource is expected to be different at Site A than at the nearby tower when winds are from the north, then the measurement plan should ensure that the remote sensing instrumentation will be at site A when those winds are more frequent. Upcoming measurement locations may change as data are collected and evaluated.

Seasonal sampling may reduce the total measurement period required to characterize the wind resource or may improve confidence in results [1)]. Seasonal sampling is important to include in a measurement plan if there are reasons to believe that the relationship between the wind resource and the tower varies significantly over the year. This is almost always the case. Seasonal changes could be due to changes in surface roughness, ground cover, stability, foliage, wind direction or solar insolation. In spite of the apparent advantages of seasonal sampling, careful consideration should be given to planning for a short initial data collection period on the assumption that later data collection will provide the rest of a useful data set. Possible operational problems, weather-related access or delays getting crews to the site and the cost of moving and re-commissioning the remote sensing instrument should be taken into consideration when planning for seasonal sampling.

1) Lackner, Matthew, A., The streamlined site assessment methodology: A new approach for wind energy site assessment, Thesis for Doctor Of Philosophy, February 2008.
Department of Mechanical and Industrial Engineering, University of Massachusetts Amherst, Amherst, MA.

3.1.3 Defining Metrics

Once the sources of uncertainty have been determined, it is useful to choose a metric with which to track the progress of measurements and the uncertainty of the measurements with respect to goals. For example:

— The reduction of shear uncertainty can be measured with the average of the ratio of the shear exponent above the tower, as measured by remote sensing, to the shear exponent as measured by the tower. Alternately, one might use the average ratio of the hub-height wind speeds measured with remote sensing to those extrapolated from tower data.
— The reduction of topographic uncertainty can be measured with the average ratio of hub-height wind speeds at the remote sensing location to those extrapolated from a nearby tower. One could also use the difference in wind speeds at two sites to characterize topographic uncertainty.

3.1.4 Measuring Uncertainty of the Metrics

DNV recommends that uncertainty of the metric (as characterized by the standard error) be used as one criterion to determine when short-term measurements include enough data to characterize site conditions during the measurement period. The uncertainty of the metrics should be derived using a method that is insensitive to the serial correlation of the wind data. Similar methods to those used for verification tests can be used. The details of one choice, the jack-knife method, are included in Appendix A. Such methods provide uncertainties based on the variability of the results during the measurement period. It is important that the data are validated to avoid erroneous data increasing the uncertainty estimate. Seasonal sampling results in a data set that is not continuous in time. Seasonal sampling does not require an adjustment to the method of estimating uncertainty. If using the jack-knife method, data can be divided into segments that may overlap the measurement gap. The uncertainties are determined based on the measured data. Additional uncertainty related to conditions beyond the measurement period is discussed below.

DNV recommends analyzing data by direction bin. Results can then be weighted by the annual wind direction frequency to get a direction-weighted mean metric and its uncertainty. This direction-weighted metric and its uncertainty characterize the annual average wind resource based on the remote sensing measurements. The method for generating the direction-weighted results is described here.

If N is the total number of data points in a year, n_i is the number the data points in each direction bin and $\bar{x}_i$ is the average metric in each direction bin (based on the remote sensing instrument), then the overall direction-weighted metric $\bar{x}$ can be expressed as:

$$\bar{x} = \sum \frac{n_i}{N} \bar{x}_i$$

Also, if σ_i is the uncertainty of the averages for each direction bin, then the uncertainty of the direction-weighted metric, σ, can be expressed as:

$$\sigma = \sqrt{\sum_i \left(\frac{n_i}{N} \sigma_i \right)^2}$$

3.1.5 Defining Short-Term Measurement Durations

A critical part of the data collection process is ensuring that enough data have been collected to provide value to the user. The data need to be representative of site conditions and be useful for reducing energy assessment uncertainty.

A number of data sets have been analyzed to determine criteria for data collection. Based on this work, DNV recommends using four criteria, two general criteria and two direction-bin-specific criteria. The direction-bin-specific criteria are to be met in as many direction bins as possible. Data in some direction bins may be more variable or there may be very few data points from some directions. Under these conditions, the criteria may not be met in some direction bins. Experience shows that at least 50% of the total data collected should fall into direction bins that meet the bin-specific criteria. The criteria are:

1) **Minimum duration criterion**: *Data collection should proceed for at least one month at each measurement location.* This measurement duration criterion is meant to ensure that data collection spans a number of types of atmospheric conditions and that the data are not all correlated with each other.
2) **Uncertainty criterion**: *Collect data until the estimate of the uncertainty of the direction-weighted metric is less than a desired threshold limit.* The desired threshold will depend on the energy assessment uncertainties and measurement goals but in many cases, DNV would recommend a threshold limit of approximately 1% of the value of the direction-weighted metric.
3) **Direction-specific criteria**: To be met in enough direction bins that over 50% of the collected data fall in these bins.
4) **Minimum quantity criterion**: *At least 48 hours of validated data should be collected for each wind direction bin.* This minimum quantity criterion is meant to ensure that the collected data are representative of conditions at the site.
5) **Range of data criterion**: *At least 12 hours of data should be collected in each of two wind speed bins with a range spanning 4 to 16 m/s for each wind direction bin.* This criterion is meant to ensure that the range of wind speeds at the site is well represented and that the range of wind speeds over which a wind turbine would operate is well represented. Thus, one might collect 12 hours of data between 4 and 8 m/s and 12 hours of data between 8 and 16 m/s. At a site with higher wind speeds the choice of wind speed bins from 4 to 10 m/s and 10 to 16 m/s might be chosen.

3.1.6 Example

This example is based on 11 months of met tower data from two nearby towers. A variety of time periods of the data were analyzed to illustrate the methods described here.

Goal:	Addressing topographic uncertainty
Metric:	Average of the ratio of the remote sensing-derived hub-height wind speeds to the hub-height wind speeds extrapolated from nearby tower data
Target uncertainty threshold for mean direction-weighted metric:	1%.

Figure 3-1 shows the progression of measurements of the direction-weighted ratio of measured hub-height wind speeds to the hub-height wind speeds extrapolated from nearby tower data. The error bars in the graph indicate the uncertainty (1 standard error) of these results. The figure shows the first 69 days of results.

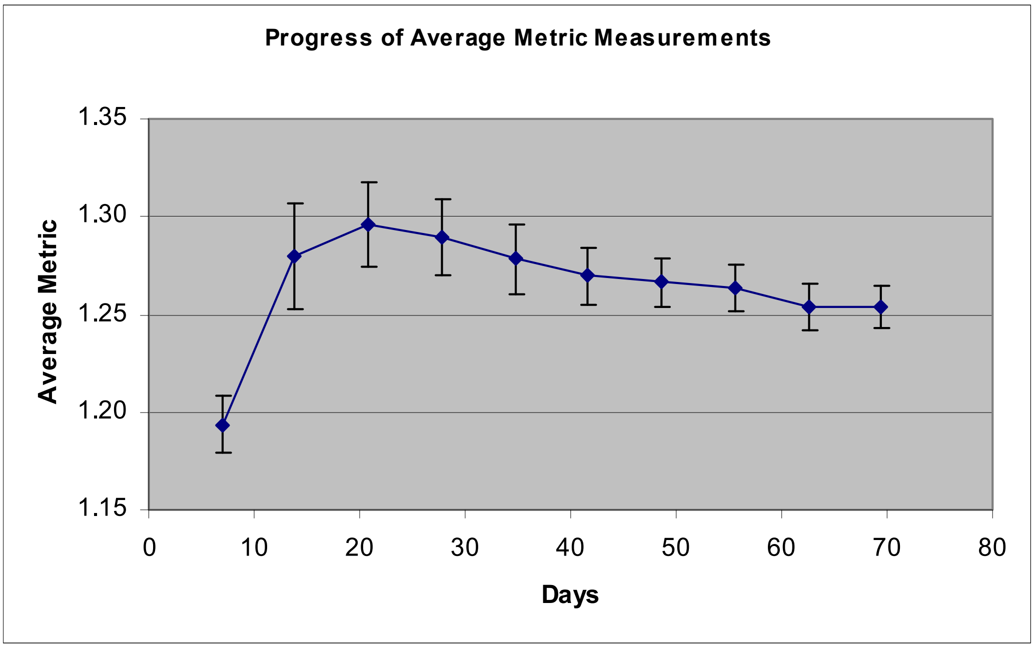

Figure 3-1
Progress of Measured Metric as Data Collection Proceeds over 70 Days

In this example, initial measurements of the direction-weighted metric indicate that the mean annual wind speed at the remote sensing measurement site is about 19% greater than that extrapolated from the on-site tower (the metric is 1.19 after a week). As measurements proceed, the measured value of the metric increases to 1.29 at 20 days and then decreases to about 1.26 after 2 months. The mean metric and its uncertainty, the amount of data in bins that meet the bin-specific criteria and the number of those bins are shown in Table 3-1 for measurement periods of 28 days and greater. In this case, all criteria were met at about two months. It can be seen from the graph that very short-term measurements may not provide results which correctly characterize the wind conditions at the site. In this example, the value of the metric varied significantly over the initial period of measurements.

Table 3-1 Results for Sample Data Set

Total Days of Data Collection	*Mean Metric*	*Uncertainty of the Mean Direction-Weighted Metric*	*Percent of Data in Bins Meeting Criteria*	*Number of Bins Meeting Bin-Specific Criteria*
28 days	1.29	1.5%	0%	0 bins
42 days	1.27	1.1%	50% data	2 bins
55 days	1.26	1.0%	67%	3 bins
69 days	1.25	0.9%	65%	3 bins

3.2 Estimating Annual Behaviour

As mentioned above, short-term results may or may not characterize the annual average wind resource at the remote sensing measurement site, depending on the nature of seasonal changes in wind conditions at the site. Most sites have significant seasonal changes. Thus, direction-weighted results from a short-term campaign may not characterize annual behaviour very well. Even though measurements may characterize the short-term measurement period quite accurately, they may have an uncertainty of up to 3% when compared with annual results. Reducing that uncertainty requires measuring over multiple seasons. Two methods for reducing seasonal uncertainty of a metric are recommended:

— Measuring for at least eight months or more.
— Seasonal sampling with short-term deployments that each meet the measurement duration criteria above.

Figure 3-2 shows the progression of the direction-weighted metric using the data shown in the example above. In this case, samples at a variety of specific measurement durations are shown, starting after 28 days of measurements. As measurements proceed, the ratio of the measured hub-height wind speed to that extrapolated from the tower data decreases to a final value of about 1.23. Thus, the short-term measurements, when used to estimate annual behaviour, would have greater uncertainty than the initial measurements would indicate. Measurements over 8 months (about 250 days) or more typically provide a good indication of the average annual behaviour.

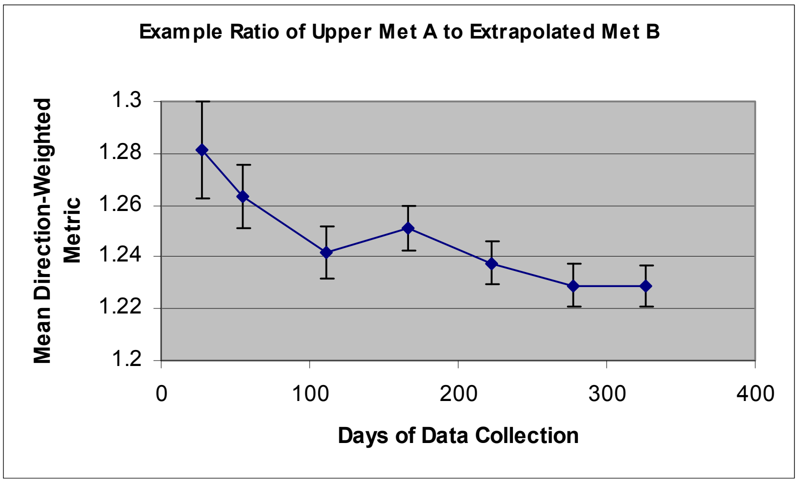

Figure 3-2
Example Results over an 11-Month Period

An alternative to continuous measurements is seasonal sampling. The results of seasonal sampling are illustrated in Figure 3-3. The figure indicates the values of the metrics that would be measured after two and three 1.5-month measurement periods spaced evenly over the year. Two 1.5-month measurement periods spaced a half of a year apart would result in a mean measured metric of 1.25 after a total of three months of measurements (over two 1.5-month periods). Three such measurement periods in the year would result in a mean measured metric of 1.24 after a total of four and a half months of measurements. These results are provided to illustrate results from one specific site. Results at other sites will depend on the specific site conditions.

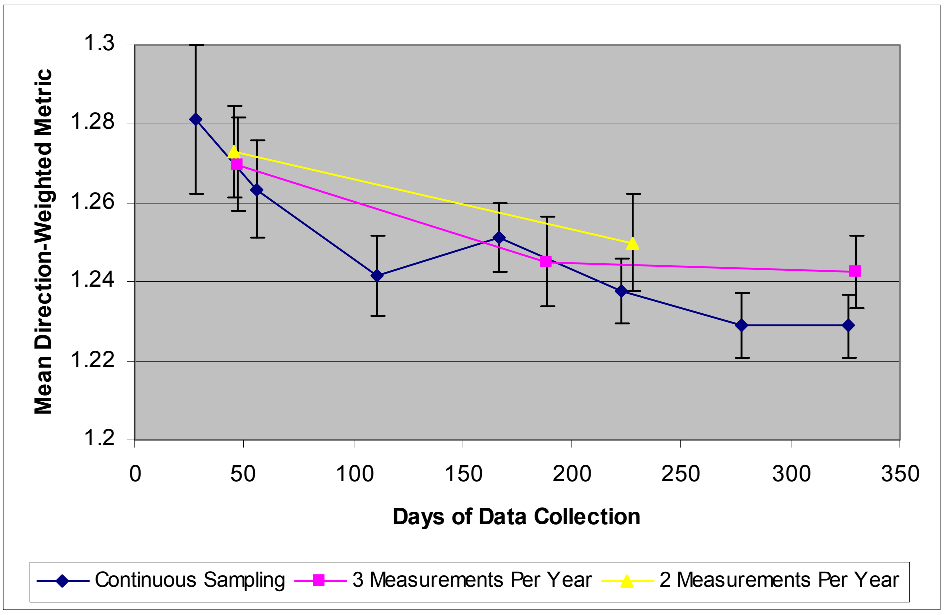

Figure 3-3
Results Using Seasonally Sampling over an 11-Month Period

4. Summary

DNV has developed guidelines for positioning at site, documentation and verification of remote sensing instruments and for planning and implementing remote sensing measurement campaigns to ensure that the results have the greatest value in an energy assessment.

Each of these elements is critical to maximizing the value of the data:

— Appropriate positioning at site helps ensure that the data provide valid measurements of the wind resource at the site.
— Careful and complete documentation helps to ensure that there is sufficient information to properly evaluate the data.
— Verification of equipment against tower measurements helps to ensure that the remote sensing equipment was operating correctly during the measurement period.
— Careful planning of measurement locations and durations ensures that the data collection will have been targeted at the greatest sources of uncertainty and, thus, will have the greatest value in the energy analysis process.

Finally, no guidelines can ensure how data will be used in an energy analysis. The analysis will be driven by the data results. Nevertheless, attention to each of these steps will ensure, as much as possible, that the value of the data to the process has not been jeopardized by a lack of awareness of the needs of the energy analysis process.

APPENDIX A
UNCERTAINTIES USING THE JACK-KNIFE METHOD

When the results of an analysis use input data which are serially correlated, then an estimation of the uncertainty of those results requires methods that are insensitive to the correlation of the data. A variety of methods could be used to estimate the uncertainty of the measurements, including the jack-knife estimate of variance and the bootstrap method. The jack-knife method is simple to use, directly addresses the goals of the measurement campaign (the reduction of uncertainty) and is relatively insensitive to serial correlation.

The jack-knife estimate of variance is described here. It can be used to estimate the uncertainty of the slope and offset of a linear fit to data or of estimates of mean wind speeds, ratios of mean wind speeds, etc., as illustrated in Figure A-1. In the figure, time series data, from beginning to end, are represented as a bar indicating that all of the data are used in an analysis.

Figure A-1
Illustration of Process for which the Jack-knife Method Applies

The jack-knife estimate of variance estimates the uncertainty of the results of an analysis by considering the variability of results when subsequent subsets of the data are removed from the analysis, as is illustrated in Figure A-2. Six results are calculated each using, in this case, a different 5/6 of the whole data set. The uncertainty of the results are then determined from these results.

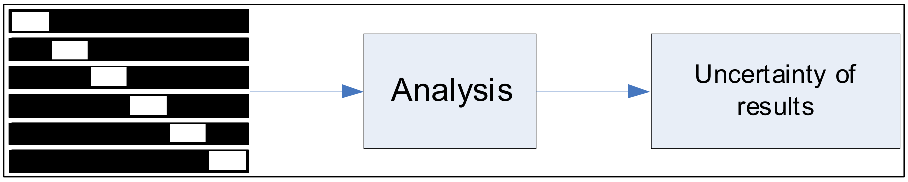

Figure A-2
Illustration of Analysis for Determining the Uncertainty of Analysis Results

Specifically, if R is an analysis result (uncertainty-corrected slope, mean ratio of remote sensing to tower wind speeds, etc.) and if R_i are n results based on data sets that each have a different, non-overlapping $1/n$th of the data file missing, then the jack-knife estimate of the standard error (uncertainty) of the result, is:

$$\sigma_R = \sqrt{\frac{(n-1)}{n}\sum_{i=1}^{n}(R-R_i)^2} \qquad \text{(A1)}$$

The approach assumes that the n subsets that are removed are independent. This may not be true if the n subsets are of such short duration that they are correlated. In that case, the serial correlation of the data will affect this method. In practice, six data subsets have proven to provide adequate results with a minimum of analytical effort and data collection for one month or more minimizes the danger that any of the subsets are correlated.

A.1 Example

The slope of the relationship determined from a verification is 0.979. The slopes when one of six data subsets was removed from the data set are listed in Table A-1. The resulting uncertainty, using equation A1 is 0.025.

Table A-1 Example of Using Jack-knife Method to Estimate Uncertainty of Slope

Index of Missing Subset	*Slope*
1	0.983
2	0.964
3	0.989
4	0.983
5	0.982
6	0.998