EXPERT GROUP STUDY ON
RECOMMENDED PRACTICES

15. GROUND-BASED VERTICALLY-PROFILING REMOTE SENSING FOR WIND RESOURCE ASSESSMENT

FIRST EDITION, JANUARY 2013

Submitted to the Executive Committee
of the International Energy Agency Implementing Agreement
for
Co-operation in the Research, Development, and Deployment of
Wind Energy Systems

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Remote sensing devices. Photo credit: Andrew Clifton, USA.

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Foreword

The International Energy Agency Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems (IEA Wind) is a vehicle for member countries to exchange information on the planning and execution of national, large-scale wind system projects and to undertake co-operative research and development projects called Tasks or Annexes.

As a final result of research carried out in the IEA Wind Tasks, Recommended Practices, Best Practices, or Expert Group Reports may be issued. These documents have been developed and reviewed by experts in the specialized area they address. They have been reviewed and approved by participants in the research Task, and they have been reviewed and approved by the IEA Wind Executive Committee as guidelines useful in the development and deployment of wind energy systems. Use of these documents is completely voluntary. However, these documents are often adopted in part or in total by other standards-making bodies.

- A Recommended Practices document includes actions and procedures recommended by the experts involved in the research project.
- A Best Practices document includes suggested actions and procedures based on good industry practices collected during the research project.
- An Experts Group Studies report includes the latest background information on the topic as well as a survey of practices, where possible.

Previously issued IEA Wind Recommended Practices, Best Practices, and Expert Group Reports can be found on the IEA Wind website at www.ieawind.org, on the Task 11 pages.

Preface

Wind turbines have become taller, and rotor diameters have steadily increased over the past decades as developers seek to extract more energy from the wind. This trend has led to a need for vertically-resolved wind profiles, with wind speed and wind direction data at multiple heights. Traditionally the wind speed and direction profile was provided by meteorological towers, and if the turbines that were installed were taller than the towers, the tower data were extrapolated vertically. However, extrapolation of data adds uncertainty to the wind resource estimation process.

Ground-based, active remote-sensing of winds is now seen by the wind industry as a useful tool to reduce the uncertainty in wind speeds at hub-height and higher. Two remote sensing technologies have become popular for wind energy applications. These are sodar (or SODAR, short for SOnic Detection and Ranging), and lidar (or LIDAR, short for LIght Detection and Ranging). Although different implementations of the technologies exist, vertical-profiling of wind often involves measurements of wind speed in a cone of the atmosphere, and the calculation of the wind vector at different heights.

The purpose of this recommended practice is to document the steps required to collect high-quality, well-documented remote sensing data for use in wind resource assessments on land. Because of the similarities between sodar and lidar, and the frequently similar sources of uncertainty that are observed in both technologies when used to measure winds, recommendations are made that apply to both lidar and sodar. Where important differences do exist between remote sensing technologies and corresponding data analysis methods, these have been highlighted in the document. Examples of data processing and presentation are given. The importance of documenting the entire process of data acquisition and analysis is emphasized.

Executive Summary

Vertically-profiling wind remote sensing technologies such as lidar and sodar potentially allow the collection of wind speed and direction data at heights up to typical wind turbine hubs, and beyond. Traditionally, wind data have been collected using cup anemometers and vanes on meteorological towers. It is therefore necessary to compare and verify the performance of sodar and lidar to these traditional traceable technologies and standards before using the data for a wind resource assessment. Care also needs to be taken that the remote sensing device is correctly installed, operated and maintained. This document includes recommended practices for the characterization, verification, installation, operation and maintenance, and data analysis of a remote sensing device for the purposes of wind energy assessments. Recommended practices for vertically-profiling lidar and sodar are often identical, and so only recommended practices that differ between the two technologies refer to a specific technology.

The following is a broad summary of the specific recommended practices in this document:

- Remote sensing device technologies, techniques and methods should be clearly characterized by manufacturers.
- Remote sensing devices should be verified periodically against calibrated reference devices that can be traced back to a national standard.
- Remote sensing devices should be installed by trained personnel following an installation checklist.
- The use of the remote sensing device should be documented, including verification activities, site deployments, servicing and data analysis.
- Remote sensing devices should be able to operate reliably and accurately in a defined range of ambient and atmospheric conditions.
- Data obtained from remote sensing devices should be analyzed within defined limits of application.

The recommended practices are listed on page **??** and defined in detail in the text.

Nomenclature

Abbreviations

AEP Annual Energy Production

ASTM American Society for Testing and Materials

CFD Computational Fluid Dynamics

CDL Coherent Doppler Lidar

DBS Doppler Beam Swinging

DTU Danish Technical University

GPS Global Positioning System

IEA International Energy Agency

IEC International Electrotechnical Commission

LIDAR LIght Detection and Ranging

LOS Line of Sight

TOF Time of Flight

LASER Light Amplified by Stimulated Emission of Radiation

NREL National Renewable Energy Laboratory

OLS Ordinary Least Squares

RP Recommended Practice

RSD Remote Sensing Device

SNR Signal to Noise Ratio

SODAR SOnic Detection and Ranging

UPS Uninterruptible Power Supply

UTC Coordinated Universal Time

UTM Universal Transverse Mercator (co-ordinate system)

VAD Velocity-Azimuth Display

VDI *Verein Deutscher Ingenieure*
(The Association of German Engineers)

Variables

A_R receiver area

f frequency

λ wavelength

L_v acoustic pulse length

P_0 transmitter power

P_R received power

R^2 Square of correlation coefficient

r range

Ti turbulence intensity

U time-averaged horizontal wind speed

u west-to-east wind speed

v south-to-north wind speed

v_{LoS} line-of-sight wind speed

w vertical wind speed

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1 Introduction

Important wind farm development decisions are based on the stable and accurate measurement of a variety of atmospheric variables. Traditionally, sensors mounted on meteorological towers[1] have been used to characterize local wind regimes in advance of constructing a large wind farm development.

At the time of writing (2012), there is no formal wind resource assessment standard. Instead, processes for estimating the wind resource and subsequent performance of a wind turbine at that site are largely based on the International Electrotechnical Commission (IEC) 61400 family of standards (International Electrotechnical Commission, 2005a,b). These standards require that wind speed measurements be made using calibrated mechanical, cup anemometers that have a documented response to changes in environmental conditions. The standards also require that wind direction measurements be made using wind vanes. The use and deployment of cup anemometers and vanes is backed up by calibrations (e.g. MEASNET, 2009), an extensive and well-developed body of knowledge about how they perform under different environmental conditions, well-established standards for use, and an experienced user-community.

1.1 The need for a recommended practice

Lidar (also 'LIDAR', from LIght Detection and Ranging) and sodar (also 'SODAR', from SOnic Detection and Ranging) technologies have emerged as useful wind resource assessment tools. They can characterize the wind resource at multiple heights from near ground to above typical wind turbine hub heights. The deployment of remote sensing may provide wind project developers with useful information that can be used to reduce the costs associated with wind data collection at heights greater than can be achieved using traditional monitoring towers. The use of remote sensing as part of a well-planned and properly implemented wind resource measurement campaign involving a diverse suite of measurement techniques may also contribute to the overall reduction of uncertainty in a formal wind energy production assessment. Compared to the use of cups and vanes for wind resource assessment, there are few documents that describe how a lidar or sodar should be deployed to get the best quality data for a wind resource assessment. A recommended practice document is therefore required to guide the use of remote sensing as a data source in wind resource assessments that lead to predictions of annual energy production.

1.2 Document goal

The goal of this document is to codify existing industry and academic best practices to help ensure that the best quality remote sensing data are made available for use in the wind energy resource assessment process.

1.3 Applicability

This document is designed to guide the use of ground-based, fixed scan geometry, vertically-profiling wind remote sensing using lidar and sodar for the resource assessment phase of an on-shore wind farm development. Lidar and sodar that use these methods are referred to generically in the document as remote sensing devices, or RSD.

Other types of lidar and sodar are available but are not covered by this recommended practice. These include, but are not limited to: nacelle-mounted, forward-looking lidar; offshore remote sensing on fixed or floating platforms; lidar that use variable scan geometries to probe volumes not directly above the device. It is anticipated that as more experience is obtained with other types and uses of RSD, specific recommended practice documents will be produced or this document will be expanded.

Although the deployment of RSD offshore is not covered within this document, some of the practices presented are directly applicable to an offshore deployment on a fixed platform and could be used to help guide deployments in those environments.

1.4 Limitations

The recommended practices in this document are intended to complement training and documentation provided by device manufacturers or suppliers. This document has been written assuming that the reader is familiar with the

[1] Meteorological 'masts' and 'towers' are often used interchangeably, but both indicate a structure that is used to support reference devices.

basic process of wind resource assessment and typical wind instrumentation, and is not intended to be a 'how-to' guide for the process of wind resource assessment.

An overview of wind resource assessment methods using remote sensing is given for information only. It is suggested that rapid changes in resource assessment methods would render irrelevant any recommended practices for the use of the data.

1.5 Using this document

This document highlights two different results in the text with an underlined, bold label and number. For example:

- **Note 1**. These points are for information only and may explain or expand on a recommended practice. They may also highlight where more research or development is required.
- **RP 1**. These points are the specific recommended practices that should be followed to give low-uncertainty data.

1.6 Origins and historical perspective

An initiative to develop recommended practices for lidar and sodar arose in 2007 at the 51st IEA Wind Topical Expert Meeting on remote wind speed sensing techniques, under the IEA Wind Task 11 on Base Technology Information Exchange (Thor, 2007). At that meeting, there was a common understanding that more experience from remote sensing was needed to increase the accuracy and repeatability of measurements, especially when comparing the performance of lidar and sodar with cup anemometers. Two ad-hoc groups were formed to put together proposals for the proper operation of lidar and sodar devices and began work on the development of recommended practices.

The 59th IEA Wind Topical Expert Meeting in 2009 on lidar and sodar remote sensing techniques included many presentations on a number of different topics relevant to remote sensing, and an update on preliminary work for the recommended practices (Aranda, 2009). At the conclusion of that meeting, it was decided that the highest priority should be placed on completion of recommended practices for lidar/sodar remote sensing in wind resource assessment applications. There was also general consensus that the recommend practices document should be focused on obtaining low-uncertainty data for resource assessment. Two separate ad-hoc groups, one for lidar and one for sodar, committed to finishing the work on the recommended practices.

In mid-2011, the ad-hoc groups drafted separate recommended practices for lidar (Jaynes and Courtney, 2011) and sodar (Moore, 2011) that were sent to IEA Wind for review. The basic content of the sodar and lidar documents was acceptable. However, it was decided that the two separate documents should be re-worked into a single document and produced in a consistent format and style with a clearer structure, similar to other recommended practice documents. Staff at the National Renewable Energy Laboratory (NREL) and the Danish Technical University (DTU) lead the development of a revised document.

1.7 A note on 'bankability'

Low-uncertainty data is often referred to as 'bankable' data by the wind industry, which implies that it can be used to obtain financing for a wind power plant. However, it should be noted by the reader that 'bankability' is not conferred by using a particular product, instrument, or service provider. Instead, achieving bankability requires two things:

- The level of Annual Energy Production (AEP) considered sufficiently reliable on the basis of the uncertainty analysis is adequate for financial purposes, and
- The resource assessment and related uncertainty analysis upon which this level of production has been predicted is robust, complete, and unbiased. That is, bankability does not require that a specific instrument is used; rather it requires that whatever instrument is used has been operated correctly and that its performance in the circumstances in which it has been operated is adequately understood. Bankability has clear, open, transparent and specific technical requirements relating to project risk and uncertainty. These are described in the Boulder Protocol article 4.1, as submitted to the 59th IEA Wind Topical Expert Meeting.

In this respect, following the recommended practices set out in this document does not confer 'bankability' on the data obtained by a remote sensing device as part of a wind resource assessment. Instead, following the recommended practices helps provide confidence that the deployment and use of the remote sensing device conforms to a widely accepted norm, and that information and experience from one deployment can be transferred to another (see e.g. Clive, 2011, for more discussion of this). Specifically, these recommended practices do the following:

1. Quantify the uncertainty of the RSD against a reference device using a well-defined method.
2. Set out methods and procedures to ensure that the RSD is deployed and used in a way that minimize the uncertainty with the deployment site compared to the verification site.
3. Describe documentation and metadata to be collected that allow maximum data traceability.

1.8 Status

This draft was prepared for review by the IEA Wind Executive Committee. This version was prepared on 22nd February 2013. A detailed change log can be found in Appendix C.

1.9 Authors

This document was drafted by:

- Andrew Clifton (NREL)
- Dennis Elliott (NREL)
- Mike Courtney (DTU Wind Energy, Risø Campus)

This recommended practice builds on information that is publicly available, including recommended practices from consultants (e.g. DNV, 2011), IEA Wind Topical Expert Meetings (Aranda, 2009; Jaynes and Courtney, 2011; Moore, 2011; Thor, 2007), and peer-reviewed journal and conference papers. All sources are cited in the text and a complete list of references is given in the Bibliography (page 42). The reader is recommended to consult documentation provided by the RSD manufacturer in addition to these materials.

1.10 Reviewers

This document has been reviewed by participants in the IEA Wind Task 11 59^{th} Topical Expert Meeting, IEA Wind Task 32 'Wind Lidar', and subject matter experts in national laboratories, academia, and the wind energy industry. These reviewers are identified (in no particular order) in Table 1.1. All comments and contributions were helpful and appreciated.

Table 1.1 Contributors to the IEA Wind 59^{th} Topical Expert Meeting (TEM) and this recommended practice (RP)

Country	Organization	Expert	59^{th} TEM	RP
Canada	GL Garrad Hassan	Dariush Faghani		✓
Denmark	DTU Risø	Mike Courtney	✓	
	DTU Wind Energy	Mike Courtney		✓
		Rozenn Wagner		✓
	Vestas	Esben Haldrup Eriksen		✓
Finland	VTT Wind Energy	Andrea Vignaroli	✓	
France	Leosphere	Rémy Parmentier		✓
		Matthieu Boquet		✓
		Jean-Marc Thevenoud		✓
Germany	DEWI	Andreas Beeken	✓	
		Beatriz Canadillas		✓
	U. Stuttgart	David Schlipf	✓	✓

– Continued on next page –

Country	Organization	Expert	59th TEM	RP
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		Ines Würth		✓
		Martin Hofsäß		✓
	U. Oldenburg	Matthias Wächter	✓	
	Frauenhofer Institute	Julia Gottschall		✓
Japan	Itochu Techo-solutions Corporation	Nobuyuki Hayasaki	✓	
Korea	POSTECH	Yeongmi Ji	✓	
	Korea Institute of Energy Research	Hyun-Goo Kim	✓	
Netherlands	ECN Unit Wind	Jan Willem Wagenaar	✓	
Norway	U. Bergen	Joachim Reuder	✓	
Spain	Acciona Energia	Xabier Comas	✓	
	CENER	Félix Avia	✓	
		Paul Gomez	✓	
Sweden	Vattenfall AB	Daniel Gustafsson	✓	
UK	Oldbaum Services	Andy Oldroyd	✓	✓
	Sgurr Energy	Peter Clive	✓	✓
	ZephIR Ltd.	Edward Burin des Roziers		✓
		Mike Harris		✓
		Tony Rutherford		✓
		Will Barker		✓
USA	Atmospheric Research & Technology	Barry Neal	✓	✓
	Atmospheric Systems Corporation	Ken Underwood	✓	✓
	DNV KEMA	Anthony Rogers		✓
	AWS Truepower	Matthew Filippelli	✓	✓
	GL Garrad Hassan	Daniel Jaynes	✓	
	Iberdrola Renewables	Jerry Crescenti	✓	
	Integrated Environmental Data	Kathleen Moore	✓	✓
	Lawrence Livermore National Lab.	Julie Lundquist	✓	
	National Renewable Energy Lab.	Neil Kelley	✓	
		Dennis Elliott	✓	✓
		Andrew Clifton		✓
	NRG Systems	Thomas Nostrand	✓	
		Evan Osler		✓
	Catch the Wind	Fred Beelen	✓	
	RES Americas	Jeffrey Fine	✓	
	Second Wind	Niels La White	✓	
		Barry Logue		✓
	Sandia National Lab.	Regina Deola	✓	
	Siemens Energy	John Obrecht	✓	
	U. Colorado (Boulder)	Rod Friedrich	✓	
		Julie Lundquist		✓

2 Characterizing remote sensing devices

Many different technologies have been developed to measure the wind speed and direction profile at different heights in the atmospheric boundary layer. The two types of remote wind sensing to which this recommended practice document applies are ground-based sodar and lidar. A description of these technologies and the methods used to measure the wind at different elevations above ground is given in Appendices A and B.

Note 1: This document covers the use of vertically-profiling lidar with fixed scanning geometries.

Note 2: Lidar that utilize a variable or user-defined scanning pattern to measure the wind speed and direction at different height are not covered by this document. Where a lidar with a variable scanning pattern is being used and this document is being used for guidance, it is suggested that the same scan pattern must be used for all measurements and for the verification of the lidar, and the verification must be at a similar range between the lidar and tower (See Chapter 6).

Note 3: This document covers the use of sodar with fixed scanning geometries, including monostatic and bistatic devices. Where bistatic devices are being used, it is suggested that the same arrangement of emitters and detectors must be used for all measurements and for the verification of the sodar (See Chapter 6).

There is large variation between different RSD. Therefore, it is important that the technology used in the RSD is well characterized for future reference.

RP 1: The RSD should be clearly characterized by the manufacturer. This information should be included in the data package that is made available for later use. The required characterization information depends on the basic technology used by the RSD.

1 a) For both sodar and lidar:

- Minimum and maximum height that can be sensed (with specified range resolution).
- Number of heights that can be sensed and how these are selected.
- Heights sensed ‘simultaneously’ or if sequentially, dwell time at each height.
- At any given height, the maximum rate (1/s) of data reported.
- The nominal number of samples used to recover data at this rate.
- Manufacturer’s stated nominal accuracy of wind speed and direction.
- Definition of the range over which wind data are acquired.
- Tabulated range resolution throughout the measurement height range.
- Speed range.
- Quality metrics and acceptable ranges.
- Safety constraints due to the energy emitted by the RSD.
- Scanning geometry (beam inclinations, beam spacing, scan patterns, *etcetera*).
- Conditions in which measurement performance may be degraded (for example: low aerosol counts, neutral stability, complex flow, cloud, rain, fog, background noise, *etcetera*).
- Power consumption under defined conditions.
- Weight (assembled and packed).
- Communication protocols and media supported.

1 b) For lidar:

- Continuous wave or pulsed.
- Doppler or direct detection.
- Wave length.

1 c) For sodar:

- Monostatic or bistatic.
- Antenna design.
- Acoustic frequency or frequencies used.

Note 4: Other differences exist between RSD. These may be related to the installation or operation of the RSD, and RSD data analysis, and are described in the following sections of this document.

3 Installing remote sensing devices

3.1 Training

All remote sensing manufacturers and sellers offer training for their devices. Users are encouraged to take specialist training on the RSD before deploying the device.

RP 2: All workers involved with the installation, operation and analysis of data from the RSD should be trained by the manufacturer or their representative to work on (or with data from) the RSD. The training provider should document this training.

3.2 Site selection

The RSD should be installed in an area where flow inhomogeneity in the measurement volume is minimal. Complex flow can result in a variation of the winds above the RSD through divergence, convergence, recirculation or instability (Figure 3.1) which can introduce uncertainty in the flow vector measurement by the RSD. Complex flow will also make comparison with traditional cup anemometer measurements at the same site harder, as the cup anemometer measurements are from a single point, while the RSD measurements are volume-averaged (see Appendixes A and B, and e.g. Bradley, 2008b).

RP 3: Flow heterogeneity may impact the accuracy of RSD measurements.

3 a) Flow heterogeneity in the measurement volume should be estimated before deployment.

3 b) Potentially heterogenous flow (for example, when the RSD is deployed where flow may be curved, diverges or converges) should be recorded in the installation report.

3 c) If RSD data will be used as part of a resource assessment campaign, heterogenous conditions may introduce unknown uncertainties. The user should follow the manufacturer's guidelines on RSD siting in heterogenous conditions. If no guidelines are available, the user should avoid these conditions.

Note 5: In the absence of other methods for estimating flow heterogeneity, the method of assessing flow heterogeneity as a result of terrain in the most up-to-date IEC 61400-12 standard for wind turbine power curve measurements is suggested. This is Annex 'B' in IEC 61400-12-1. Flow may be considered heterogenous if the predicted uncertainty exceeds 1%.

3.3 Transport

An RSD may be sensitive to knocks and shocks, and should be handled with care during transit between sites. This includes transit from the manufacturer's facility to the owner's facility, and from the owner's facility to the measurement site.

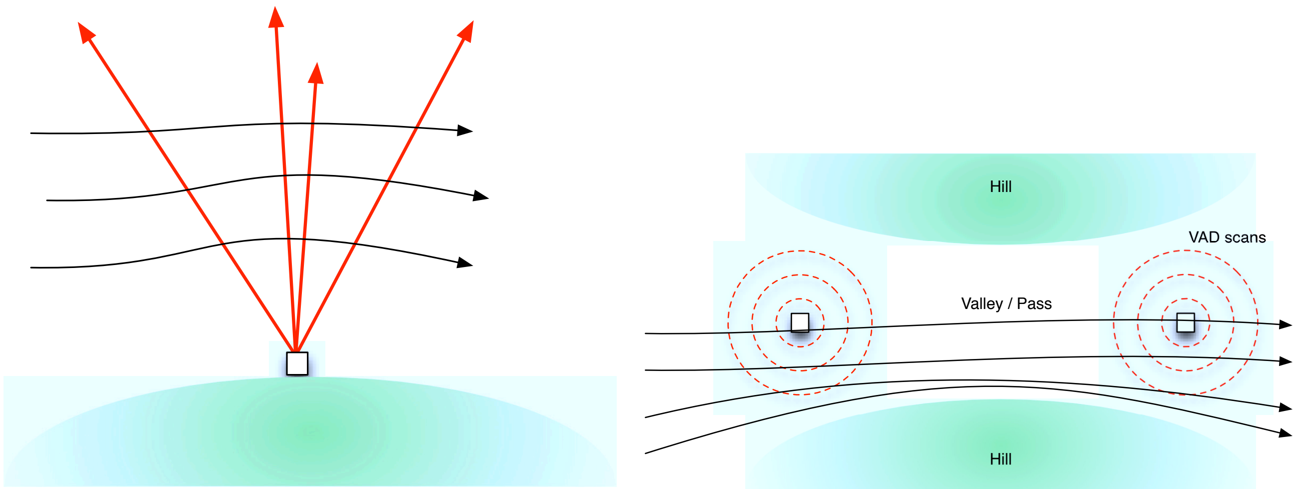
RP 4: The RSD should be supplied in reusable, protective packaging. This packaging could include flight boxes, a shipping container or specially equipped trailer. As far as practical, this packaging should be used for all transport of the RSD to and from deployment sites.

RP 5: The RSD should be designed to withstand shocks and impact that may occur during shipping and installation. Shock detectors or simplified accelerometers should be installed on the RSD to show that a shock event has occurred, that may result in reduced accuracy or a device failure but that may not leave visible evidence. The magnitude of the shock that will be detected depends on the device design and should be set by the manufacturer at a suitable, conservative, level.

3.4 Site preparation

The installation site should give the RSD a clear view of the sky and be largely free of obstructions.

RP 6: The RSD should be situated in a location that maximizes the sky view.



(a) Flow curvature over terrain (elevation view)

(b) Flow convergence and divergence through terrain (plan view)

Figure 3.1 Visualization of some types of flow heterogeneity that could effect remote sensing measurements. Flow streamlines are shown as arrows.

6 a) All site installations should be preceded by a reconnaissance site visit and report. This report should then form the basis of an installation method statement which should be based on user experience, site conditions and manufacturer guidelines.

6 b) If a clearing needs to be made in forested areas, or a structure erected to increase sky view in an existing clearing, the preparation of the clearing or temporary structure should be done according to local guidelines and legislation, and should meet the RSD manufacturer's guidelines.

6 c) Care should also be taken to avoid measurements in tower or structure wakes.

6 d) Avoid interactions between beams and obstructions. The device should be located and rotated so that the beam(s) of the RSD do not intersect or otherwise interact with obstructions.

6 e) For sodar:

- To avoid high levels of echoes, clearings in forestry should be irregular if possible. The sodar should also be positioned away from the geometric focus or center of the clearing.
- Special attention to both the shear and spectral return should be taken to ensure fixed echo contamination is minimized.

3.5 Orientation

The RSD orientation angle (or rotation angle) is the angle between the RSD internal zero azimuth angle or the reference axis of the instrument, and North (Figure 3.2). Documentation at the start of a measurement campaign can reduce or eliminate installation accuracy concerns and help produce a more certain wind rose.

RP 7: The RSD orientation should be recorded in both the installation report and the RSD data stream.

- Check and record the offset with respect to true North at the time of deployment using a trusted hand-held compass or other device.

- RSD manufacturers should specify how the orientation angle corrections are applied to their data sets.

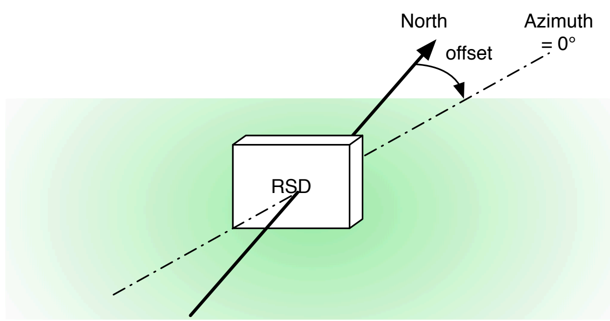


Figure 3.2 Visualization of RSD offset from North

3.6 Tilt and roll

The RSD should be installed on a nominally level site and adjusted as close as possible to horizontal. If the RSD is installed with a tilt or roll, the probe volumes may be skewed (Figure 3.3). This may lead to incorrect estimates of the wind speeds and inflow angles.

RP 8: The RSD should be installed in such a way that the effect of tilt on the quality of the final measurements is minimized. This could include:

8 a) Coarse leveling. Site the RSD in a generally level area. If a level area is not available for the installation of the device, then it may be necessary to create a small and level clearing to host the RSD.

8 b) Fine leveling. Fine-tune the RSD tilt to set it as close as possible to zero on all horizontal axes. Use a digital level if the RSD cannot detect and compensate for small tilts.

RP 9: The RSD should be instrumented by the manufacturer with a 2-axis clinometer to quantify and monitor the device tilt. The clinometer should be affixed to a horizontal plane in the RSD and have an accuracy of better than 1°. Tilt should be recorded in all data streams to allow checking for settling over time or to estimate errors due to tilt and roll.

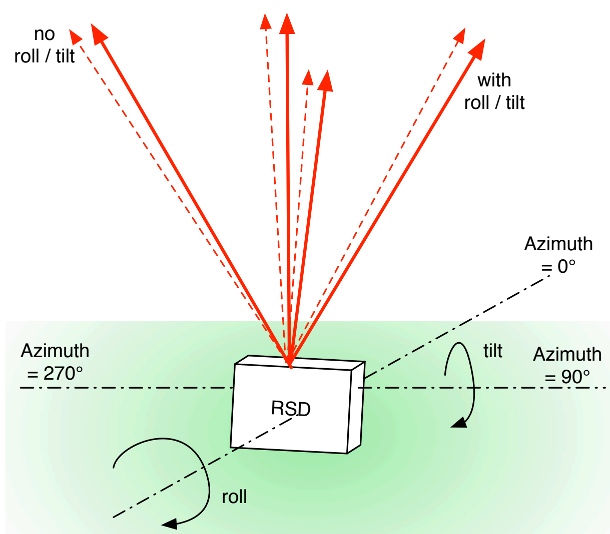


Figure 3.3 Visualization of RSD tilt and roll, and the effect on probe beams

3.7 Time synchronization

Comparing data from multiple sources (for example, an RSD and a traditional tower) requires that the different data be sychronized. Large time differences (on the order of hours, which could be caused by an incorrect time zone or treatment of summer time) may cause unreal lags between sites, while small differences (on the order of seconds) may impact the quality of the data used for the verification.

RP 10: The RSD should be equipped with a means of synchronizing its clock with an external time reference (e.g. network time server, radio clock or GPS receiver).

10 a) The RSD clock should be synchronized to the external reference at system start up and then at a regular interval, at least daily, afterwards.

10 b) The correct function or malfunction of the synchronization mechanism should be clearly indicated in the RSD data.

Note 6: The use of Coordinated Universal Time (UTC) or local standard time may help avoid synchronization errors that may be introduced by the use of daylight savings time.

Note 7: The use of 'bus' data transfer protocols (for example, Can-bus or Mod-bus) to transmit and collate RSD data streams may be beneficial in some applications to better ensure synchronization between multiple devices.

3.8 Power supply

Power requirements for an RSD may vary significantly from device to device. Supplying power in remote locations can be difficult, requiring careful forethought in advance of deployment. Options exist for remote power packages that incorporate power sources including:

- Fuel cells
- Generator sets
- Small wind turbines
- Battery banks
- Solar panels or arrays
- Combinations of the above

A robust remote power system can contribute a significant portion of the cost of a commercial RSD. RSD have been operated successfully in remote locations, but in order to maximize the data recovery rate of an RSD measurement campaign it is recommended to carefully choose a mature and proven power supply option for any site without grid-supplied electricity.

RP 11: Remote power systems require careful design and engineering to reliably supply power to an RSD. Design considerations include:

11 a) The power supply should have a dedicated, independent reporting system that can be remotely or locally interrogated to see or control system status. The reporting system should also report system warnings, for example low temperature faults, failure to start, or low battery levels.

11 b) An uninterruptible power supply (UPS) avoids loss of data, in case of short-circuit conditions or short duration power loss.

11 c) In case of power failure or low battery a message should be sent to the operator and the system should shut down to a safe condition.

11 d) Provision of lighting rods, surge protection and resettable over-voltage protection can reduce or prevent damage to both the power supply and RSD from lightning.

11 e) Suitable provision for power system survival in extreme events, such as:

- High winds
- Hail
- Icing
- Deep snow
- Torrential rain
- High or low temperatures
- High dust levels
- Fog and mist
- Minor earthquakes
- Fuel or acid spill

RP 12: Remote power systems that have any kind of on-site fuel require special care and preparation.

12 a) Permits for on-site fuel should be obtained as required by local legislation and guidelines.

12 b) As with any fuel source there exists the potential for accidental fires to occur as a result of human error, malfunction or *Force Majeure*. Therefore, a fire protection contingency plan is suggested for any remote sensing measurement campaign that requires the presence of flammable substances on site.

12 c) A spill kit should be kept on site and used to minimize environmental hazard and potential impact of leaks or spills (for example, liquid fuel or engine oil) into the local environment.

Note 8: Extensive testing of the power supply before deployment on site is recommended. The exact nature of the power supply testing is beyond the scope of this document.

3.9 Protection from interference

An RSD and its power system may be deployed in a remote location and operate unattended for long periods of time. The RSD and power system may then be at risk of vandalism. Also, if an RSD is deployed in an area shared with livestock, then the RSD could be moved or damaged by livestock. Wild animals and rodents may also damage equipment, particularly exposed cabling. Care should be taken to minimize the risk to the RSD and impact on the measurements.

RP 13: Provide a secure location for the RSD and power system that is protected from interference by people or livestock.

13 a) An enclosure such as a crate, shed, or transport trailer may reduce the risk of vandalism and damage from livestock and wild animals. The enclosure should not interfere in any way with the function of the RSD, including any measurements that are made on the device itself. Care should be taken to prevent animals entering an enclosure.

13 b) Install a fence that surrounds the immediate area around the RSD and power system to prevent animals interfering with the RSD and power system. Fencing and other barriers should be able to withstand strong winds and snow loading without being damaged or coming loose.

13 c) Contact details of the RSD owner or operator should be posted on the fence or enclosure.

13 d) Anchors may help to ensure RSD and power system safety in high wind conditions.

13 e) Passive protection to prevent perching (for example, installation of bird spikes) may help in some locations.

3.10 Safety signs and interlocks

Properly operated and maintained remote sensing devices should pose little or no hazard to the public, outside of the enclosure.

RP 14: The RSD should be designed to operate safely.

14 a) The RSD enclosure should be marked with safety signage in a way that satisfies locally-applicable guidelines and legislation.

14 b) The RSD enclosure should be marked with the contact details of the RSD operator.

14 c) The RSD should be equipped with safety interlocks to reduce the risk of harm to users or the public who enter safety enclosures while the device is energized. These interlocks should meet or exceed the requirements of local guidelines and legislation.

14 d) The RSD should only be serviced by properly trained and authorized individuals.

3.11 Function check

After the RSD has been successfully transported and installed at the measurement site, it is important to ensure that the RSD is operating properly before leaving the site.

RP 15: Manufacturers should supply an installation checklist that installers can follow to show correct function of the RSD.

15 a) The checklist could include (but is not limited to) checking the following:

- Site leveling and beam / obstruction interference requirements
- Power supply status
- RSD status metrics
- Data quality
- Data storage
- Communications
- Data collected in the period up to 24 hours after installation

15 b) Equipment installers should follow the manufacturer's installation function checklist. Installers should sign, date and archive the completed document.

3.12 Installation report

An installation report can add value to the final data set that is used in the wind resource assessment by reducing uncertainty.

RP 16: The RSD installation should be documented in a comprehensive report. Information required in the installation report includes:

16 a) Location:

- Site name and unique identifier
- Nominal Latitude / Longitude or Universal Transverse Mercator (UTM) coordinates
- Time and date, with time zone of installation

16 b) Log of site visits during the installation period, including:

- Site reconnaissance report
- Installation method statement
- Staff names and activities

16 c) RSD installation and configuration:

- RSD type, serial number, hardware and firmware versions
- Date and reason for last verification test (see RP 30)
- Function checklist
- RSD clock check against a reference time signal or reference meteorological tower data logger (if available on the same site)
- Screenshots of device status if possible, including software/firmware version
- Measurement heights [m]
- RSD datum level with respect to ground [m]
- Power supply system configuration

16 d) Photographs:

- Device transport and installation
- Device location and surrounding terrain
- General arrangement of equipment, including power supply
- Known or potential obstructions to flow of air over the site or to measurement signals

16 e) Maps, sketches, photographs, and surveys of the site:

- Locations of RSD, towers, buildings, and possible echo sources
- Distances and heights of potential obstructions
- Elevation of the ground below the RSD above sea level
- Elevation of the ground below the RSD relative to ground level at a nearby tower (if any)
- Site conditions, including estimates of roughness lengths and changes in different sectors and directions
- For sodar:
  - Local background noise level
  - Local noise sources (if any), such as fans, oscillating motors with characteristic frequencies, horns, etc.

4 Operating remote sensing devices

4.1 Communications

Communications refers to data transmission between the remote sensing device and an offsite location. Communications can be used to monitor the unit performance, and retrieve measurements. Being able to remotely retrieve measurements not only minimizes physical trips to the device for data retrieval, but also provides redundant storage of the measurements.

RP 17: Where possible, arrange for remote access to the remote sensing device operating system via cellphone modem, satellite phone modem, radio, Ethernet, or other technology.

17 a) Remote access should include the following capabilities:

- Ability to check and adjust RSD configuration and operation.
- Ability to retrieve high-frequency and time-averaged wind vector data (see Section 5.1.2 and 5.1.3). This information should be available for transfer but stored locally for a significant amount of time so that it could be retrieved. Optionally the high frequency data could be transferred on a hard disk, data card or other device.
- Ability to start and restart the RSD remotely.
- Ability to resynchronize the RSD internal clock.

17 b) If data cannot be transmitted from site, then a routine site visit is recommended to recover measured data, and check the RSD security and performance.

Note 9: RP 11 describes the ability to communicate with, and control, a remote power system.

4.2 Sensitivity to ambient conditions

4.2.1 Variation in back-scatterer concentration

Lidar relies on the backscatter from aerosols carried in the wind to estimate the wind speed. Variations in the vertical concentration of backscattering particles may cause uncertainty in wind speed measurements. An example of this is the presence of cloud. If cloud or fog is present along the line of sight, there is a risk that a strong return from the cloud or fog could swamp the Doppler return from the height of interest, introducing error in the wind speed estimate. Fog- and cloud-detection signal-processing algorithms have been developed to detect, reduce or remove the extraneous returns from cloud and fog.

RP 18: Lidar: algorithms to ensure the detection and/or rejection of the signal from fog or cloud are recommended.

18 a) Manufacturers should document the methods used or that such algorithms are unnecessary. The algorithms should be demonstrated against reference meteorological towers, showing measurements with and without cloud detection algorithms (where applicable) compared to high-quality cup anemometers. For these manufacturers' tests, the cloud presence and height should be documented using a ceilometer.

18 b) The use of algorithms to correct for the presence of cloud or fog should be recorded in the lidar data. This could be recorded as a specific quality code or as a true / false flag, but should be distinguishable from other quality control measures.

Note 10: Manufacturers are not required to release or document in detail algorithms for back-scatter signal processing that are considered 'intellectual property'. However, algorithms should be given a version number and documented in such a way that it is possible to track developments in signal processing methods that may influence the data from the RSD.

4.2.2 Precipitation

Both lidar and sodar may be affected by precipitation. Precipitation can affect the emitter and receiver, causing a reduction in the signal return. Strong backscatter from falling hydrometeors may cause a false vertical component in the signal. For these reasons, care should be taken to account for the effects of precipitation and where possible, mitigate them.

RP 19: Manufacturers should mitigate effects of precipitation on the measurement quality.

19 a) The RSD should be able to withstand most types of precipitation event, either liquid or solid.

19 b) Electronics should be sealed against water ingress. The RSD manufacturer should specify the protection provided, using a suitable standard.

19 c) The device should include heaters, wipers or other methods as appropriate to remove precipitation from the optical or acoustic path.

19 d) Precipitation should not affect the data that are used by the end user. This requires either:

- Measurement accuracy (quantified with the same metrics that are used for verification) during precipitation is not impacted compared to dry conditions.
- Precipitation is measured or detected and periods when data quality may be impacted are flagged.

4.2.3 Local speed of sound

All sodar require an estimate of the speed of sound to determine both the altitude assigned to returned echoes, and, for phased-array devices, the vertical tilt of the acoustic beams. Because the sodar determines the horizontal velocity 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. The speed of sound is a function of the temperature and humidity, which are used to compute the virtual temperature. The speed of sound varies with the square root of the virtual temperature.

RP 20: Sodar: ambient temperature and humidity measurements should be input to the sodar and used to estimate the speed of sound.

20 a) If a temperature and humidity sensor is installed in the sodar, or temperature and humidity measurements are automatically obtained from another sensor on site:

- Manufacturers should document how the ambient temperature and humidity is measured, the procedures to verify that the temperature and humidity sensor is operating properly, and how the measured ambient temperature and humidity are used.
- The temperature sensor should be calibrated annually to a relevant standard (for example ISO 17025, International Organization for Standardization, 2005).
- The make and model of the temperature and humidity sensor(s) and the calibration results and dates should be included in the RSD information.

20 b) In the absence of an accurate temperature or humidity sensor in the sodar device, or local data:

- The method used for measuring and setting the ambient temperature and humidity, and then determining speed of sound should be documented by the manufacturer.
- The procedures used on site to periodically check and update the ambient temperature and humidity should be documented by the user.

Note 11: A 1°K error in the virtual temperature at 0°C is approximately equivalent to a 0.18% error in the speed of sound or 0.092% error in the corresponding height estimate.

4.2.4 Acoustic interference (passive and active)

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

Fixed echoes and passive noise should be evaluated when siting sodar. Any backscattered sound coming from fixed objects such as masts and towers, trees, or buildings, 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 from a device that uses Doppler shift to measure wind speed could 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 between the sodar and fixed objects.

An important metric for both lidar and sodar performance is the signal-to-noise ratio, or SNR. The signal of interest is the back scattered, Doppler-shifted sound or light from the height of interest, while the noise is typically measured at the detector before a pulse is emitted. As SNR decreases the signal is less distinct compared to the noise, and so it becomes harder for signal processing routines to accurately extract meaningful data. Hence, accuracy may be reduced as SNR decreases (Bradley, 2008b).

Acoustic noise (active noise) can interfere with sodar measurements by presenting false signals near the acoustic frequency(ies) or by causing a degradation of the SNR. Active noise sources can include machinery such as generators and air conditioners, insects and birds, and wind blowing through and around trees or guy wires (Crescenti, 1998).

Wind-induced ambient noise under high wind conditions may reduce the SNR of samples during high wind speed gusts. These data may be deleted from the data set with the result that the time average reported by the sodar may be based only on data during lulls, and so the wind speed may be biased low compared to cup anemometers. This ambient noise can be mitigated by the use of baffling.

RP 21: Sodar siting and operation should consider the potential impacts of local acoustics.

21 a) The sodar should have adequate setback distances to fixed objects in the vicinity. In the absence of guidance from the manufacturer, the sodar should be positioned so that no fixed objects are within a 45° cone with its apex on the sodar.

21 b) Sodar siting should also take into account unwanted sources of ambient noise, fixed echoes, and sources of electrical noise, which can deteriorate data quality.

- Ambient noise sources should be noted and an audio record made, if possible. The record should cover a continuous twenty four hour period and be repeated monthly to capture seasonal variation in insect activity.
- Any obstacles that 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.

21 c) Sodar locations with significant ambient noise should be avoided. The definition of significant will depend on the device being deployed, and maximum noise levels (with or without a corresponding frequency range) should be specified by the sodar manufacturer.

21 d) Sodar housings, mountings or anchors should not cause significant wind-generated noise or resonate with the acoustic signal. The manufacturer should mitigate this where possible.

4.3 Local weather conditions

RSD are often used as stand-alone devices for wind resource assessment purposes. As a stand-alone device, there may not be other sources of data about local weather conditions that may impact the RSD.

RP 22: RSD that are to be used for wind resource assessments could be instrumented with supplementary devices to record data that might assist in 1) understanding RSD performance and 2) predicting AEP. These data could include, but are not limited to:

- Air pressure
- Wind speed and direction (secondary measurement using a different method)
- Temperature

- Humidity
- Presence of precipitation

These devices could be mounted on the body of the RSD or nearby. Data collected by the instrumentation could be recorded in the RSD datastream.

4.4 Servicing and maintenance

RSD require some maintenance, and may require repairs for accidental damage or wear and tear. Maintenance should keep the device operating reliably and repeatably. Some maintenance may involve work on the RSD that could alter the performance of the RSD.

RP 23: The manufacturer should define and document a service interval for the RSD that will help sustain the quality of the data from the RSD.

23 a) Carry out recommended services. The user should comply with the manufacturer's recommendations for servicing or maintenance. If the user chooses not to comply with these recommendations, the user should request an explanation of the possible effect of the missed servicing or maintenance, and document this in the service log.

23 b) Document servicing. If or when an RSD is returned to the manufacturer for any service or maintenance activities, the manufacturer should document all activities that have been carried out. Documentation should include time and date, details of parts replaced or repaired, including serial numbers. Where calibrated parts are used, the calibration documents should be included. A copy of the documentation should be returned to the user. Any modifications that may impact the quality of the data should be identified and reported to the user.

23 c) Re-verification. If a service, maintenance or repair is carried out that the manufacturer deems could significantly alter the performance of the RSD, the RSD should go through a new verification process, as described in Chapter 6.

4.5 Operation and maintenance log

Keep a log of all use and maintenance of the RSD. A log can help to document what has been done to the RSD. The goal of the log is to provide traceability and assist in troubleshooting.

RP 24: Record and describe any use of the RSD in an operation and maintenance log. Information recorded in this log should include, but is not limited to:

- Date and time of all activities.
- Repairs, upgrades or maintenance of the RSD.
- Deployment history, including:
  - Site
  - Dates and times of visits
  - Names of visitors and activities
  - Photographs and observations:
    - RSD location and surrounding terrain
    - RSD state on arrival
    - Power system status
    - Clock time

5 Remote sensing data analysis

Data analysis is the process whereby the raw data acquired by the RSD (Doppler shifts, azimuth and elevation, etc) are converted to data that are useful for the wind resource assessment process.

Note 12: Manufacturers are not required to release or document in detail algorithms to derive instantaneous or time-averaged wind vectors (RP 26 and RP 27), turbulence intensity (RP 28) or gusts (RP 29), that are considered 'intellectual property'. However, algorithms should be given a version number and documented in such a way that it is possible to track developments in signal processing methods that may influence the data from the RSD.

5.1 Wind speed and vector

The wind vector is defined over several different times and scales. The wind vector defines the wind speed, wind direction and inclination with respect to horizontal.

5.1.1 Line-of-sight wind speed

The line of sight velocity is the mean velocity derived by the RSD along a laser or sound beam.

RP 25: If storage space allows, and the user requires it, line-of-sight velocity data should be stored for each height and azimuth direction on the lidar scan with a time stamp that indicates a defined point in the data acquisition process.

5.1.2 Instantaneous wind vector

The instantaneous wind vector is the mean wind vector at a single height above ground at the highest possible temporal resolution that can be achieved by the RSD. This may also be known as the high-frequency wind vector. This wind vector could be obtained from a single VAD or DBS scan, as discussed in Appendices A and B.

RP 26: The ability to generate or report an instantaneous, high-frequency wind vector is not required but may be advantageous for some applications.

26 a) The general method used to derive the instantaneous wind vector from the line-of-sight velocities, together with the interval between instantaneous wind vectors, should be documented by the manufacturer.

26 b) Instantaneous wind vectors should be stored for each height. Data should be given a time stamp that is the start of the acquisition of the measurement.

26 c) The instantaneous wind vector should be converted to a wind speed, wind direction and angle from horizontal for ease of use.

5.1.3 Time-averaged wind vector

The time-averaged wind vector is the mean wind vector at a single height over a period of time. This averaging may be required for compatibility with other data, for example meteorological tower measurements. A typical averaging time is 10 minutes.

RP 27: The time-averaged wind vector should be calculated for a user-defined interval at each measurement height.

27 a) Data should be stored and given a time stamp that specifies a particular point in the averaging interval (for example, the start, middle, or end of the interval).

27 b) If the method used to measure the velocity vector allows, it should be possible to reprocess raw data as required to give the time-averaged wind vector over a different averaging period.

27 c) The method used to derive the time-averaged wind speed, inclination, and direction from the RSD data should be documented by the manufacturer. Documentation should include quality metrics.

27 d) The time-averaged wind vector should be converted to a wind speed, wind direction and angle from horizontal for ease of use.

Note 13: If the standard deviation of the wind direction at each height during the averaging interval is required, this could be calculated using a recognized method such as Yamartino (1984). The method used should be documented.

5.2 Turbulence intensity

The turbulence intensity of the wind at a point is defined as the standard deviation of the streamwise flow $\sigma(u)$, divided by the time-averaged horizontal wind speed U:

$$Ti = 100 \times \frac{\sigma(u)}{U}. \tag{5.1}$$

Note 14: RSD measure winds at many different points at each measurement height, at different temporal resolutions, and using a variety of methods. It is therefore unlikely that the turbulence intensity measured by an RSD will correspond exactly to that measured at a point by a cup anemometer. There are also different methods that can be used to derive the turbulence from the RSD data over a period of time, including spectral methods for sodar that do not use Equation 5.1 (Bradley, 2008a). Extracting more useful turbulence information from remote sensing devices is an area of research that has received considerable attention in recent years. Several studies e.g. Sathe et al. (2011) and Mann et al. (2008) have shown that the turbulence intensity measured by cups differs from that of lidar, and that the relationship depends on atmospheric conditions, measuring height and lidar type.

RP 28: The ability to generate or report an estimate of the turbulence intensity is not required but may be advantageous for some applications.

28 a) If the turbulence intensity is calculated and reported by the RSD in the RSD datastream, this value of Ti should be used in preference to any other calculation of Ti.

28 b) Where turbulence intensity is not calculated by the RSD but a time series of wind speed is obtained by the RSD and Ti is required, Equation 5.1 may be used to calculate Ti. The accuracy of Ti data obtained used by this calculation should be checked against a reference device in the verification process (see Section 6.1.2).

Note 15: Variation of wind direction is not acceptable as a measure of turbulence intensity.

5.3 Extreme gusts

A gust is a temporary and rapid change in the wind speed. One way to quantify gusts is to measure the wind vector with high temporal resolution (e.g. 1 Hz) and then post-process the data to characterize gusts using appropriate metrics (e.g. rise-time, magnitude, duration) as set out in wind turbine design requirements (e.g. International Electrotechnical Commission, 2005a).

Note 16: Remotely sensing the wind speed in a volume of the atmosphere rather than directly measuring wind speed at a distinct point can cause differences in the extreme wind gusts that are measured by RSD compared to cup anemometers. Cup anemometers also have different frequency response characteristics to gust events compared to RSD that further compound measurement differences between the two sensor types. There are also differences in the measurement duty cycle between RSD devices (for example, the time to return to a measurement point compared to the dwell time at that measurement point) that will affect the ability of an RSD to measure short-duration gusts. Therefore, using remote sensing devices to perform extended-period extreme gust analysis to inform wind turbine site suitability assessments, is not recommended at this time. Further investigation of the ability of RSD to measure gusts is suggested.

RP 29: In the event that gust data are required for a site and have to be derived from RSD data, the user should supply data to the end user that shows gust measurements from the RSD compared to a reference tower at a comparable site, or during the verification process. The method used to detect and quantify gusts is the user or RSD manufacturer's choice but should be consistent between sites.

5.4 Correcting for errors due to flow inhomogeneity

Converting raw remote sensing data from several line-of-sight beams to a mean wind speed, direction, and flow angle, may assume a uniform flow field in some types of RSD. However, the flow field can be distorted by terrain or changes in land surface cover. These flow distortions cause differences between RSD measurements that extend over a volume and assume a uniform flow field, and cup anemometer measurements made at a single point (Bradley, 2008b).

Note 17: Flow modeling using Computational Fluid Dynamics (CFD) software packages and other tools have been used to estimate the flow distortion caused by complex terrain or by changes in land cover. Studies suggest that measurement bias introduced to the remote sensing data may be removed in some cases in post processing (Bradley et al., 2012a; Harris et al., 2010). At the time of writing, there are limited peer-reviewed studies of the accuracy of such tools or the resulting AEP.

Further investigations of accuracy and repeatability are required before these tools can be recommended for the correction of RSD data.

6 Verification of remote sensing devices

The following chapter describes the process of verifying the performance of the RSD. Verification is the process whereby the ability of an RSD to measure a parameter is compared to a reference device.

6.1 Reference devices

The mechanical cup anemometer has been, and continues to be, the industry standard for measuring the wind speed at potential wind plant developments. Measurements from high quality cup anemometers mounted on a tower in simple, flat terrain, should therefore be used as the norm against which RSD performance is judged.

It is important to note that wind speed measurements using cup anemometers are vulnerable to many sources of uncertainty:

- Speed accuracy and resolution
- Tower/boom shadow effects
- Cup rotor dynamic over speeding
- Temperature and temporal variation of bearing friction
- Calibration uncertainty
- Vertical turbulence effects
- Anemometer tilt response
- Local conditions such as icing
- Aging
- Temperature dependence

The mechanical wind vane is the industry standard for measuring wind direction. Wind direction measurements are also vulnerable to uncertainty, including:

- Wind direction resolution
- Orientation of the north gap
- Accuracy of reference compass, and errors in alignment
- Tower/boom shadow effects
- Calibration uncertainty
- Bearing friction and aging
- Local conditions such as icing

Uncertainties in measurements from cup anemometers and wind direction vanes can introduce error in the estimation of the true mean wind speed and direction, but are generally understood and the associated uncertainties are well established. Some effects may even be mitigated or corrected. As a result, it is important to show the behavior of the RSD with respect to a calibrated cup anemometer and wind vane where the data has gone through a rigorous, accepted quality assurance routine. This quality assurance routine is described in this chapter.

6.1.1 Wind speed and direction

RP 30: The time-averaged wind speed and direction measured by the RSD (as defined in Section 5.1.3) should be verified with respect to calibrated cup anemometers and wind vanes, or sonic anemometers that measure three wind components, mounted on a tower. The RSD should be situated as close as possible to the tower, following the guidance of the RSD manufacturer.

30 a) Instrumentation should be of the highest accuracy, and least sensitivity to changing atmospheric and environmental conditions, that can be obtained. Ideally anemometers should be 'Class 1' when characterized using the classification set out in the most up-to-date IEC 61400-12 standard for turbine power curve measurements (at the time of writing this is International Electrotechnical Commission, 2005b).

30 b) Instrumentation positions, mounting methods and data analysis should correspond to the most up-to-date IEC 61400-12 standard for turbine power curve measurements (at the time of writing this is International Electrotechnical Commission, 2005b).

30 c) Anemometers must be calibrated using a recognized method against a traceable standard. Examples of suitable test protocols include MEASNET (2009).

30 d) In locations where a risk of instrument icing during the verification process exists, it is recommended that heated sensors be used if this does not influence the measurement accuracy. Otherwise, data should be limited to periods where the temperature is greater than 2°C.

6.1.2 Turbulence intensity

As was noted in section 5.2 and RP 28, turbulence intensity reported by an RSD may be different than that reported by a point measurement. However, the RSD may include algorithms that try to scale volumetric measurements so that RSD data are similar to point measurements.

RP 31: If a verification of the turbulence intensity measurement is made, the turbulence intensity reported by the RSD for the time-averaging interval should be verified against calibrated cup anemometers mounted on a tower, as per RP 30.

6.2 Verification heights

The heights of the reference devices to which the RSD performance is compared, should be at heights that are relevant to wind resource assessments. As turbine hub heights may be between 60 m and 140 m above ground, with tip heights up to 200 m, the verification should be carried out considering the likely turbine rotor span.

RP 32: Correlations between RSD measurements and reference measurements should include at least three different vertical positions. The vertical positions should include:

- One position within 25% of the proposed turbine's lower tip height above ground.
- One position at, or higher than, the proposed turbine's hub height.
- One other position between the two measurement heights described above.

6.3 Data sets used in the verification process

Two different data sets are used during the verification process. These are:

1. *The preliminary data set* is the complete time series from the RSD and the reference device, with no quality control beyond that used for the RSD or reference data acquisition.
2. *The verification data set* is the filtered, quality-controlled data set of coincident RSD and reference device data that passes all of the requirements outlined in RP 34.

Each data set will consist of many different records. A record includes many different variables measured during the same time-averaging interval by the reference device or RSD.

6.3.1 Preliminary data set

The preliminary data set includes all of the raw data that were collected during the verification process by the reference device and the RSD.

6.3.2 Verification data set

The verification should be long enough to be statistically meaningful. The verification should also include enough data points in enough bins to span the likely range of operation of the RSD, and the wind resource on site. Finally, the data should be of sufficient duration and quality to generate high confidence statistics.

RP 33: The verification data may be produced directly by the RSD or post-processed from appropriate high-frequency data. The verification data set should include the following data collected from the RSD and reference device:

- Mean wind speed during the time-averaging interval, as defined in RP 27.

- Mean wind direction during the time-averaging interval, as defined in RP 27.

Note 18: The mean reference wind speed and direction should be either a vector or a scalar average and should correspond to the method used by the RSD to determine the time averaged wind vector.

Note 19: Other data may be included in the verification data set as required, for example the turbulence intensity (see RP 28), maximum wind speed (see RP 29), or the standard deviation of wind direction.

RP 34: The RSD and reference device preliminary data set are filtered to form the verification data set:

34 a) Reference data should be filtered to remove records where one or more variable might be incorrect, for example:

- Wakes from a tower, wind turbine, or any other flow anomaly passing through the reference device measurement volume
- Periods of icing
- Lost signal from the wind vane or cup anemometer

34 b) RSD data for use in the verification study should be filtered to remove records where one or more variable might be incorrect, for example:

- RSD data should be filtered according to the RSD manufacturer's guidance on post-acquisition quality control.
- RSD data should be filtered to remove tower shadowing or unusual flow features.

34 c) Valid data are required for each of the variables listed in RP 33 in each time step. For example, if the mean wind direction during the time-averaging interval is from a waked sector, the entire record will be disregarded.

34 d) Filtering of data from the preliminary data set to form the verification data set should be repeatable and rules-based, rather than being subjective. In the event that data are excluded on subjective grounds, the exclusion should be documented so that it is repeatable.

34 e) Bin the filtered reference device wind speed data for wind speeds over 3.75 m s^{-1} into 0.5 m s^{-1} wide bins, centered on integer multiples of 0.5 m s^{-1}, to a maximum of 16.25 m s^{-1}. This will result in bins of reference wind speed from 3.75 to 4.25 m s^{-1}, 4.25 to 4.75 m s^{-1}, etc, to a last bin from 15.75 to 16.25 m s^{-1}.

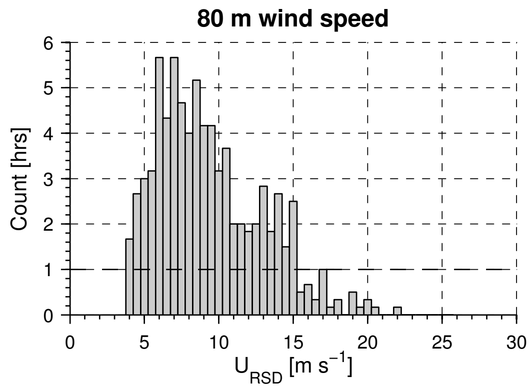
- Data collection should continue until all bins between 4 and 16 m s^{-1} contain at least one hour of data. For example, if ten-minute intervals are used, six, ten-minute intervals are required.
- If the reference device calibration included wind speeds greater than 16 m s^{-1}, data may be included for wind speeds greater than 16 m s^{-1}. However, not all 0.5 m s^{-1}-wide bins with centers above 16 m s^{-1} need to include at least 1 hour of data.

34 f) Bin the verification data by time of day.

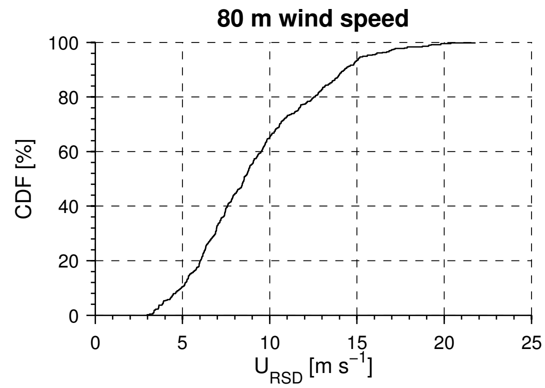
- Data to be used in the verification process should include at least 40% measured during nighttime hours (between local sunset and sunrise) *and* 40% measured during daytime hours (between local sunrise and sunset) at the measurement height nearest the proposed turbine hub-height.
- Data to be used in the verification process should not exhibit a strong diurnal cycle of wind speed at the measurement height nearest the proposed turbine hub-height. A strong diurnal cycle may be indicated by the 25th percentile wind speeds during an nighttime hour exceeding the 75th in a daytime hour.

34 g) Verification durations, amounts of data, and filtering methods should conform to, *or exceed*, requirements for in-situ comparison of anemometers as defined in the most up-to-date IEC-61400-12 standard.

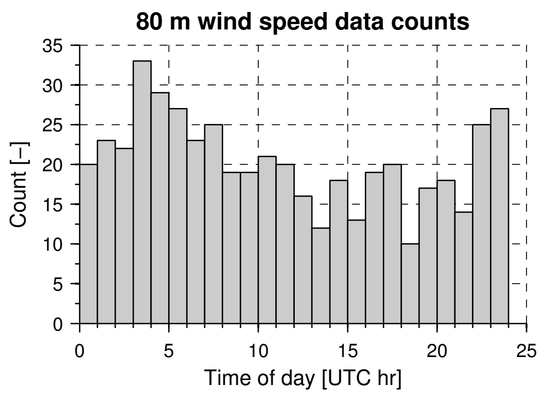
RP 35: Document the reference data used in the verification data set. Tabulate the ranges of the RSD and reference data variables listed in RP 33 that are included in the verification data set, including the median, 25th and 75th percentiles.



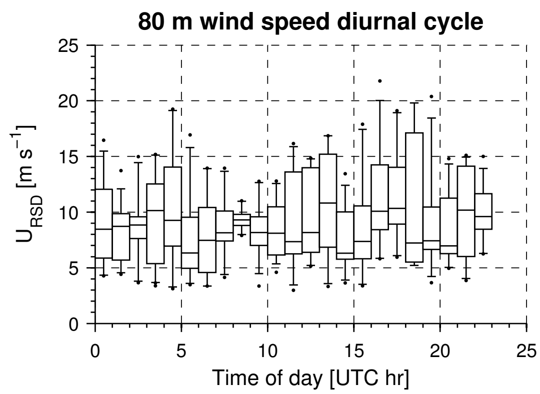
(a) Frequency of filtered RSD data



(b) Cumulative distribution function of RSD data in the verification data set



(c) Time of day that RSD data in the verification data set were obtained



(d) Diurnal cycle of RSD wind speed in the verification data set

Figure 6.1 Example use of RSD data to illustrate RP 34. a) Histogram of all cleaned data. b) CDF of frequency of data in bins with at least 1 hour of data. c) Time of day (UTC) that RSD data were obtained. d) Diurnal cycle of U_{RSD}. Boxes extend from the 25th to 75th percentile. The median is marked as a horizontal bar. Whiskers extend to the 5th and 95th percentiles. Outliers are marked individually.

6.4 Verification process

It is first necessary to establish that a comparison has been made between data that were obtained simultaneously at the RSD and reference device.

RP 36: Show correct clock synchronization between the RSD and reference device by plotting the time series of wind speed or wind direction from the RSD, together with the time series of wind speed or wind direction from the reference device (Figure 6.2).

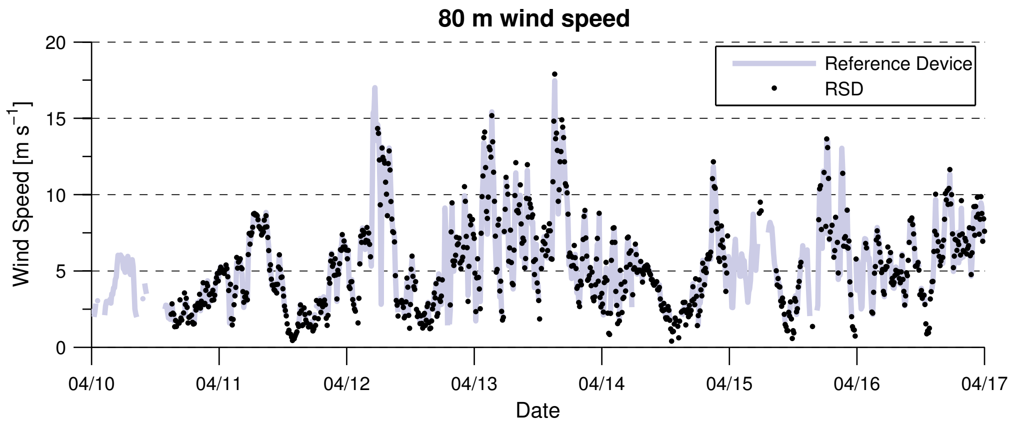


Figure 6.2 Example time series of reference and RSD wind speeds to illustrate RP 36.

Then, the performance of the RSD with respect to the reference device should be shown.

RP 37: Verification results should be reported as:

37 a) Scatter plots of the simultaneous values of each of the variables listed in RP 33 measured by the reference device compared to the RSD.

37 b) The gradient, offset and coefficient of determination (R^2) of ordinary least squares (OLS) fits between the bin-means of time-averaged values of the reference data (abscissa) and the remote sensing data (ordinate), with ('constrained fit') and without fits being forced to pass through the origin ('free fit').

The OLS should be performed for the following data, binned according to the values measured by the reference device:

- Time-averaged wind speed, using reference wind speed binned into 0.5 m s^{-1}-wide bins centered on integer multiples of 0.5 m s^{-1} (i.e. 3.75 to 4.25 m s^{-1}, 4.25 to 5.75 m s^{-1}, etc).
- Vector-averaged wind direction, using 5° bins centered on integer multiples of 5°. To avoid statistical artifacts caused by angles close to north, reference wind directions greater than 352.5°, or less than 7.5°, are not to be used for this correlation.

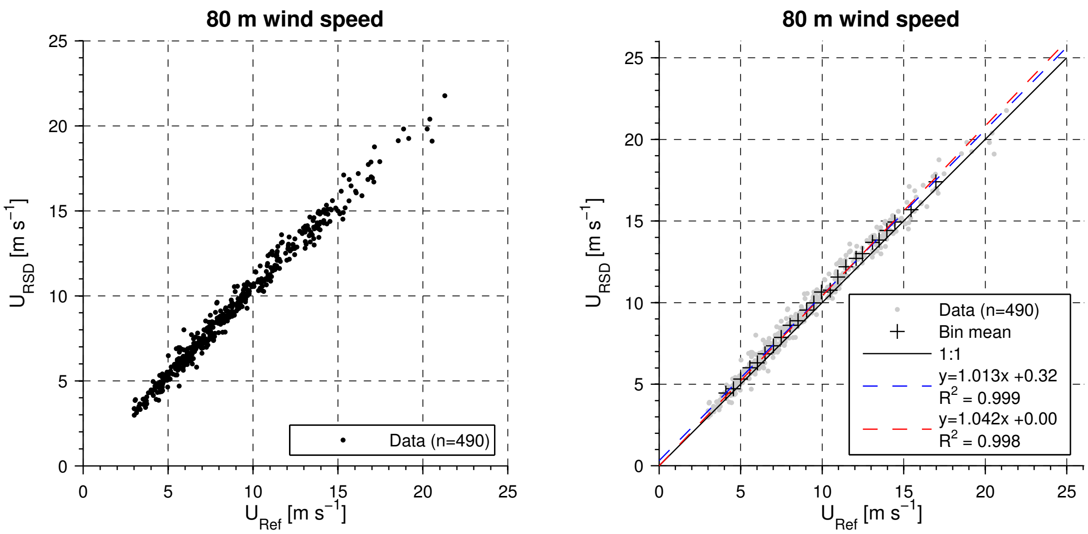
If a verification of other optional variables is carried out, the following bins are suggested:

- Turbulence intensity: 0.01 (1%)-wide reference turbulence intensity bins centered on integer multiples of 0.01 (1%) (i.e. 0.5 to 1.5%, 1.5 to 2.5%, etc).
- Peak wind speed (for example, for gust characterization): as for the time-averaged wind speed.

37 c) Bins that contain in total less than 1 hour of data should not be included in the OLS fit.

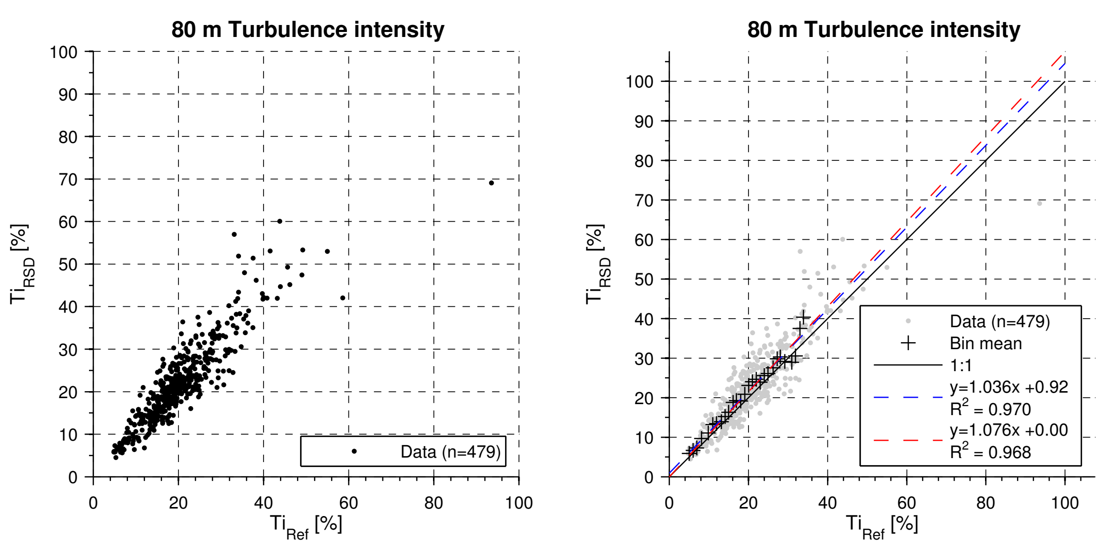
Note 20: Examples of data and correlations between RSD and reference wind speeds are given in Figure 6.3, and for turbulence intensity in Figure 6.4.

Note 21: The OLS fit required in RP 37 is done using the bin means to avoid introducing error by weighting the OLS fit towards the most frequently occurring wind speeds.



(a) RSD versus reference data **(b) RSD to reference device correlation**

Figure 6.3 Example of wind speed verification correlation reporting as required by RP 37. Data shown are for the wind speed at 80 m above ground measured by a reference device and RSD.



(a) RSD versus reference data **(b) RSD to reference device correlation**

Figure 6.4 Example of turbulence intensity verification correlation reporting as required by RP 37. Data shown are for the turbulence intensity at 80 m above ground measured by a reference device and RSD.

Next, the relationship between the verification test flow conditions and the verification results should be shown.

RP 38: The relationship between the results of the RSD verification test and the flow conditions during the test should be reported as:

38 a) Scatter plots of absolute and relative difference of the simultaneous remote sensing data and reference data for each variable, versus flow conditions.

The absolute and relative differences for a variable y are defined as:

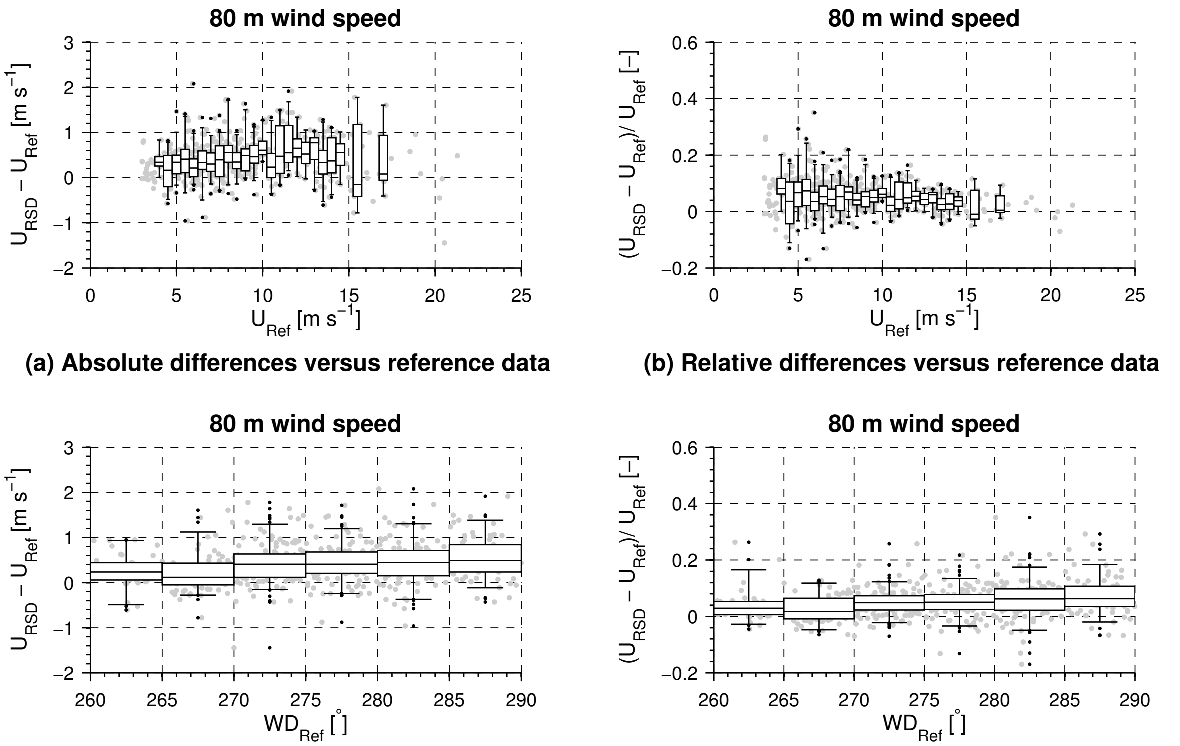
$$\text{Absolute difference}(y) = y_{RSD} - y_{ref} \tag{6.1}$$

$$\text{Relative difference}(y) = \frac{y_{RSD} - y_{ref}}{y_{ref}}. \tag{6.2}$$

The differences should be plotted as a function of the following flow conditions:

1. The reference data for that variable, using the same bins suggested in RP 37 for the OLS fit.
2. The reference wind speed, using the same wind speed bins suggested in RP 37 for the OLS fit.
3. The reference wind direction, using the same wind direction bins suggested in RP 37 for the OLS fit.

38 b) The median, 5^{th}, 25^{th}, 75^{th} and 95^{th} percentiles of the absolute and relative differences in each bin using box-and-whisker plots or some other suitable method. Example plots are shown in Figure 6.5.



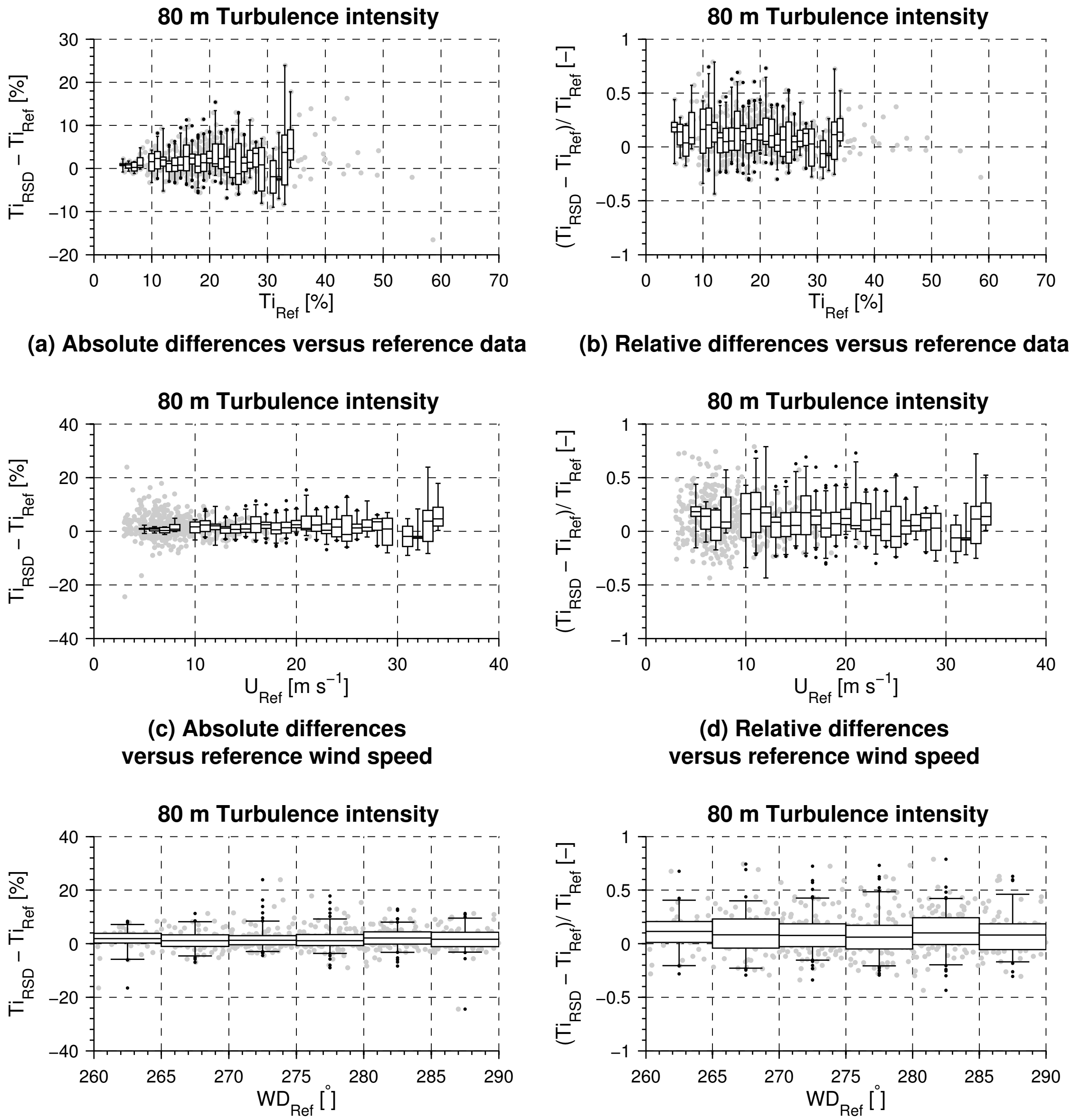
(a) Absolute differences versus reference data

(b) Relative differences versus reference data

(c) Absolute differences versus reference direction

(d) Relative differences versus reference direction

Figure 6.5 Example of wind speed verification results reporting as required by RP 38. Data shown are for the wind speed at 80 m above ground measured by a reference device and RSD. Individual data points are marked with larger solid points. Bin statistics are shown using box and whisker plots. The bin median is marked as a horizontal bar. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentiles for each bin. Outliers are marked with small solid points.



(a) Absolute differences versus reference data

(b) Relative differences versus reference data

(c) Absolute differences versus reference wind speed

(d) Relative differences versus reference wind speed

(e) Absolute differences versus reference direction

(f) Relative differences versus reference direction

Figure 6.6 Example of turbulence intensity verification results reporting as required by RP 38. Data shown are for the turbulence intensity at 80 m above ground measured by a reference device and RSD. Individual data points are marked with larger solid points. Bin statistics are shown using box and whisker plots. The bin median is marked as a horizontal bar. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentiles for each bin. Outliers are marked with small solid points.

6.5 Uncertainty estimates

The total uncertainty of measurements of variable y by the RSD can be estimated by assuming that all sources of uncertainty are uncorrelated. The total uncertainty of the measurement is then the square root of the sum of the square of the uncertainties that are present in that measurement (e.g. Moffat, 1982).

RP 39: The uncertainty is estimated as the root of the sum of the squares of all uncertainties for each of the bins used for the OLS fit (RP 37):

$$\begin{aligned}\text{Total RSD uncertainty}^2 = {} & \text{reference sensor uncertainty}^2 \\ & + \text{mean deviation } (y_{RSD} - y_{ref})^2 \\ & + \text{precision of the RSD}^2 \\ & + \text{uncertainty caused by the RSD mounting}^2 \\ & + \text{uncertainty caused by site effects}^2, \end{aligned} \tag{6.3}$$

where the precision of the RSD is the standard deviation of the measurements divided by the square root of the number of measurements ($\sigma(y_{RSD})/\sqrt{n}$).

Uncertainties should be summed *either* as relative values (per cent) *or* as absolute wind speeds. An example of an uncertainty calculation for the wind speed measured by an RSD compared to the reference device using relative values is shown in Table 6.1.

Note 22: RSD are not often deployed next to a tower for verification and then left at that tower to continue data collection. Instead, the RSD is deployed to a new location to collect data. This may involve repacking the RSD and transport to the new site. Therefore, there is a risk that the RSD may perform differently at the new site because of accidental damage to the RSD during transport, or because wind conditions may be different as a result of changes in terrain or local flows in ways that alter the ability of the RSD to correctly measure wind characteristics (see Section 3 and e.g. Bradley, 2008a; Mann et al., 2008; Sathe et al., 2011). The combination of the risk of damage and the different wind characteristics mean that the uncertainty estimated using RP 39 should be considered a ‘best case’ value.

Table 6.1 Example of a wind speed uncertainty calculation as described in RP 39. $\%_R$ indicates the relative uncertainty as a percentage of the bin-mean reference velocity, $\overline{U}_{ref}$. Bin uncertainties include the reference device calibration ('Ref'), the uncertainty caused by the RSD mounting ('mounting') and uncertainty caused by flow variability across the site ('site').

Binned measurements					Bin uncertainties					
$\overline{U}_{ref}$ m s^{-1}	$\overline{U}_{RSD}$ m s^{-1}	n -	U_{RSD} range m s^{-1}	$\sigma(U_{RSD})$ m s^{-1}	$\sigma(U_{RSD})/\sqrt{n}$ $\%_R$	$\overline{U_{RSD} - U_{ref}}$ $\%_R$	Ref $\%_R$	Mounting $\%_R$	Site $\%_R$	Total $\%_R$
4.09	4.47	9	4.13 - 4.95	0.24	1.97	9.20	0.5	0.5	0.5	9.4
4.56	4.72	20	3.86 - 5.41	0.45	2.18	3.52	0.5	0.5	0.5	4.2
4.99	5.32	21	4.64 - 6.48	0.36	1.56	6.53	0.5	0.5	0.5	6.8
5.56	6.00	26	4.69 - 6.96	0.52	1.83	7.88	0.5	0.5	0.5	8.1
6.03	6.31	37	5.62 - 8.00	0.41	1.11	4.74	0.5	0.5	0.5	4.9
6.50	6.86	27	5.80 - 7.81	0.48	1.42	5.64	0.5	0.5	0.5	5.9
7.01	7.35	28	6.63 - 8.52	0.38	1.03	4.92	0.5	0.5	0.5	5.1
7.49	7.87	38	6.97 - 8.86	0.43	0.93	5.02	0.5	0.5	0.5	5.2
8.02	8.61	28	7.80 - 9.62	0.42	0.99	7.26	0.5	0.5	0.5	7.4
8.51	8.89	23	7.87 - 9.76	0.38	0.92	4.46	0.5	0.5	0.5	4.6
9.04	9.55	27	8.80 - 10.56	0.44	0.94	5.59	0.5	0.5	0.5	5.7
9.49	9.99	26	9.27 - 10.79	0.38	0.78	5.26	0.5	0.5	0.5	5.4
9.95	10.65	11	10.12 - 11.41	0.42	1.26	7.02	0.5	0.5	0.5	7.2
10.49	10.76	12	10.25 - 11.75	0.42	1.16	2.58	0.5	0.5	0.5	3.0
10.96	11.57	16	10.65 - 12.62	0.63	1.43	5.55	0.5	0.5	0.5	5.8
11.45	12.20	20	11.54 - 13.60	0.61	1.18	6.56	0.5	0.5	0.5	6.7
12.08	12.71	10	12.10 - 13.46	0.40	1.06	5.23	0.5	0.5	0.5	5.4
12.47	13.00	8	12.43 - 13.80	0.42	1.18	4.26	0.5	0.5	0.5	4.5
13.08	13.70	12	12.79 - 14.13	0.45	0.99	4.70	0.5	0.5	0.5	4.9
13.48	13.83	14	12.99 - 14.63	0.51	1.00	2.56	0.5	0.5	0.5	2.9
13.96	14.42	13	13.44 - 15.07	0.49	0.98	3.27	0.5	0.5	0.5	3.5
14.46	14.94	9	14.23 - 15.60	0.43	1.00	3.33	0.5	0.5	0.5	3.6
15.04	15.29	4	14.83 - 16.15	0.59	1.97	1.63	0.5	0.5	0.5	2.7
15.45	15.69	6	14.51 - 17.11	1.06	2.81	1.56	0.5	0.5	0.5	3.3
16.02	16.46	4	16.06 - 17.19	0.51	1.60	2.78	0.5	0.5	0.5	3.3

6.6 Verification report

A remote sensing verification report should be prepared and made available to all users of the remote sensing data.

RP 40: The verification report should include information about the following:

40 a) The RSD that was verified:

- Make and model
- Serial number and year built
- Firmware and software versions
- Operation and maintenance log (see RP 24)
- Reference data

40 b) The verification site:

- Map showing:
  - Contours of altitude above sea level with contours at 5 m intervals
  - Locations of all towers, RSD, and buildings
  - Valid verification sectors
  - Sodar only: other sodar known to be deployed within 2 km of the sodar or tower
- Tabulated locations (latitude and longitude or UTM coordinates) of the reference towers, buildings and RSD, as well as distances between the RSD and reference tower.
- Reference tower, including:
  - Schematic of boom dimensions and positions, and guy wires
  - Instrumentation list
  - Available documentation

40 c) Reference devices used in the verification:

- Types of equipment (e.g. anemometers, wind vanes, temperature sensors)
- Serial numbers
- Calibration certificates

40 d) Results of the verification:

- Ordinary least squares fits to reference data, including the values of the offset, slope, and R^2, as shown in Figures 6.3 and 6.4.
- Variation of absolute and relative difference by flow conditions, as shown in Figures 6.5 and 6.6.
- Binned relative uncertainty for each variable, tabulated as in Table 6.1.
- Verification history (previous verifications, date of next verification, etc.)

6.7 Periodic verification

A regular, documented verification will help to confirm that the RSD is operating correctly and establish a record of performance.

RP 41: Follow the manufacturer's recommendations for periodic device verification.

41 a) If the RSD manufacturer does not offer detailed verification recommendations, then verifications of the RSD should be performed every two years, or more frequently, and documented. These verifications should follow the recommended practices set out in RP 33 to RP 37.

41 b) After verification, any drift in performance compared to the previous verification should be examined and documented. Where possible a source of drift should be evaluated, for example different test location/conditions, or systematic drift. If there is a chance of systematic drift, an estimate should be made of the implications for the RSD uncertainty.

41 c) The RSD user should ensure *before deployment* that the verification that has been carried out is applicable to the new location and task. This suitability should be determined in collaboration with the end user of the data. Depending on the end users' requirements, a new verification may be required.

Appendices

A Ground-based remote sensing of wind using lidar

Lidar uses laser (or 'LASER', from Light Amplified by Stimulated Emission of Radiation) light to probe the atmosphere and measure wind speed. Several different methods of probing the atmosphere to measure the wind vector have been developed. These include:

Direction motion detection uses the time- and range-resolved intensity of the backscattered laser along several beam paths to calculate a velocity vector at different ranges. Changes in intensity from plumes or clouds passing through the domain can be tracked and used to calculate the local velocity vector. See e.g. Mayor et al. (2007).

Doppler shift In a Doppler wind lidar, the emitted laser is reflected by aerosols or particulates in the air. These are microscopic particulates of similar sizes to the wavelength λ of the laser emissions. The reflected light is scattered back towards the light source. The frequency of the emitted light (f_0) that is reflected back to the receiver (f_R) changes as a result of its interaction with the moving aerosols entrained with the wind (Figure A.1). The change in frequency - its Doppler shift, Δf - can be measured, and the speed of the aerosols in the line-of-sight of the laser orientation (v_{LoS}) can then be calculated. Formally, the relationship between the Doppler shift and the aerosol speed in the line of sight is given by:

$$\Delta f = f_R - f_0 \quad \text{(A.1)}$$
$$= -\frac{v_{LoS}}{\lambda} \quad \text{(A.2)}$$

where a decrease in the frequency of the reflected laser light ($\Delta f < 0$) means that the aerosols are moving away from the lidar and so $v_{LOS} > 0$.

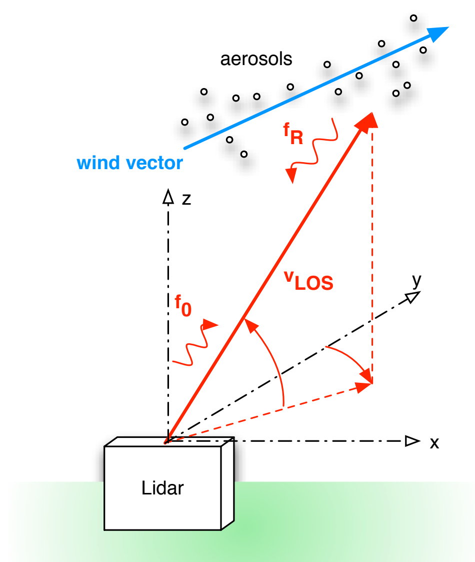


Figure A.1 Using the Doppler effect to measure wind speed in the line of sight.

The change in wavelength due to the Doppler effect can be established by digitally sampling the reflected laser light to estimate the wavelength (an approach known as 'incoherent Doppler lidar'), or by mixing it with a known reference signal (the 'local oscillator', in some cases the emitted laser) to estimate the change in wavelength from the beat frequency. This latter approach is known as 'heterodyne' or 'coherent' Doppler wind lidar (CDL).

Direct detection doppler wind converts the Doppler shift to a change in optical intensity, which can then be directly detected or measured. Unlike normal Doppler lidar, the change in signal frequency is not measured.

Rather than pure line-of-sight speeds, wind resource assessment requires knowing how wind speed and direction vary with height above ground. From this process, other parameters such as wind shear and directional veer can be calculated. Other parameters that are useful for wind energy applications that require time-resolved data such as gustiness and turbulence might also be derived from lidar data, if the refresh rate of the lidar data is high enough.

Several techniques are used with Doppler lidar to calculate the flow vector. These techniques start from the observation that at least 3 line-of-sight measurements v_{LoS} from 3 different directions relative to the wind velocity vector are required to derive three wind velocity vector components u, v, and w, shown in Figure A.2.

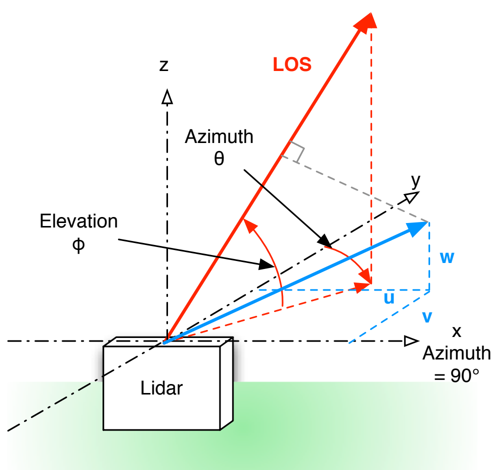


Figure A.2 LOS wind speed measurements and the orthogonal wind velocity components.

Formally, the system of equations that describes the three different measurements of the wind vector from three different viewpoints is:

$$\begin{bmatrix} V_{LoS,1} \\ V_{LoS,2} \\ V_{LoS,3} \end{bmatrix} = \begin{bmatrix} \sin\theta_1 \cos\phi_1 & \cos\theta_1 \cos\phi_1 & \sin\phi_1 \\ \sin\theta_2 \cos\phi_2 & \cos\theta_2 \cos\phi_2 & \sin\phi_2 \\ \sin\theta_3 \cos\phi_3 & \cos\theta_3 \cos\phi_3 & \sin\phi_3 \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{A.3}$$

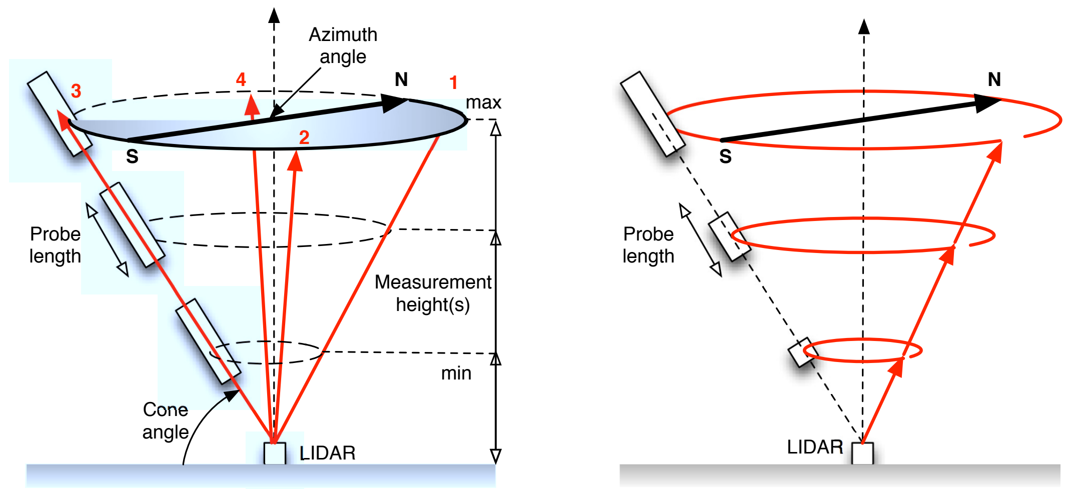
This system of equations can be solved to obtain u, v, and w, if 3 sets of values for θ, ϕ and the corresponding v_{LoS} are available. Two main techniques have been developed to determine the wind vector using lidar. These are doppler beam swinging (DBS) and velocity-azimuth display (VAD), and use different scanning patterns to obtain the wind vector (Figure A.3).

- In a DBS scan, the laser beam is swung from north to vertical to east, and the doppler shift of the laser is used to measure the line of sight velocity along the vectors $N(0°, \phi)$, $E(90°, \phi)$ and $Z(\theta, 90°)$. This gives three unit vectors in the line-of-sight; $\vec{e}_N = (0, \cos\phi, \sin\phi)$, $\vec{e}_E = (\cos\phi, 0, \sin\phi)$, and $\vec{e}_Z = (0, 0, 1)$. The product $\vec{v} \cdot \vec{e}$ for each line of sight gives simultaneous equations that can be solved for u, v and w:

$$v_{LoS,N} = v\cos\phi + w\sin\phi \tag{A.4}$$
$$v_{LoS,E} = u\cos\phi + w\sin\phi \tag{A.5}$$
$$v_{LoS,Z} = w \tag{A.6}$$

  A DBS scan using the lidar shown in Figure A.3a might perform multiple scans, for example from north to vertical to west, or west to vertical to south, and so on. An estimate of the wind vector can be made for each group of scans.

- In a VAD scan, the laser beam is elevated at a constant angle to the horizon and swung around an arc of azimuth, describing a cone with the lidar at its apex on the ground. The line-of-sight measurement has a



(a) Pulsed DBS lidar **(b) Continuous Wave VAD lidar**

Figure A.3 Different possible lidar scanning techniques.

sinusoidal dependence on the azimuthal angle θ:

$$v_{LoS} = u\sin\theta\cos\phi + v\cos\theta\cos\phi + w\sin\phi \tag{A.7}$$

$$= \left(u^2+v^2\right)^{\frac{1}{2}}\cos\phi\sin\left[\theta + \arcsin\left(\frac{v}{\left(u^2+v^2\right)^{\frac{1}{2}}}\right)\right] + w\sin\phi \tag{A.8}$$

Noting that $\left(u^2+v^2\right)^{\frac{1}{2}}$ is the horizontal wind speed U, it is possible to convert this into a sinusoidal variation of the the line of sight wind speed with azimuth angle:

$$v_{LOS} = \underbrace{U\cos\phi}_{A}\underbrace{\sin\left[\theta + \arcsin\left(v/U\right)\right]}_{\sin(\theta+B)} + \underbrace{w\sin\phi}_{+C} \tag{A.9}$$

where A is the horizontal wind speed times the cosine of elevation angle ϕ, B is the wind direction, and C is the vertical wind speed times the sine of the elevation angle ϕ. A fit of the line-of-sight radial velocity at each azimuth angle θ to observed line-of-sight radial velocities can be used to estimate the ambient wind velocity vector components u, v and w from A, B and C. An example of a fit to artificial line of sight wind speed data from a VAD system sampling at 60° azimuth intervals is shown in Figure A.4.

When carrying out a measurement of the wind vector, it is important to know the height at which the measurement was carried out. This height can be derived from the elevation angle and the range to the measurement. Two main methods of determining the range to the measurement (and thus measurement height) exist:

- Analyzing a small time slice of reflected light starting at time Δt after the beam is emitted. The time of flight (ToF) of the pulse from emission to detection of the back-scattered return corresponds to the distance it has traveled along the line of flight to the region where the scattering occurred and back. This method of wind speed retrieval is typically used with a pulsed device, where a pulse of light is emitted by the lidar in a single azimuthal direction at a time (Figure A.3a). Pulsed devices are also capable of getting data from many different heights nearly simultaneously by emitting one pulse and then listening at multiples of Δt.
- Setting the focus of the optics of the telescope assembly that concentrates the laser emissions at a waist in the beam at the focal point, such that the focal length along the line of sight corresponds to the height at which measurements are required. This is typically used with a continuous wave device, where the laser continuously emits and scans a single measurement height before refocussing at the next measurement height (Figure A.3b).

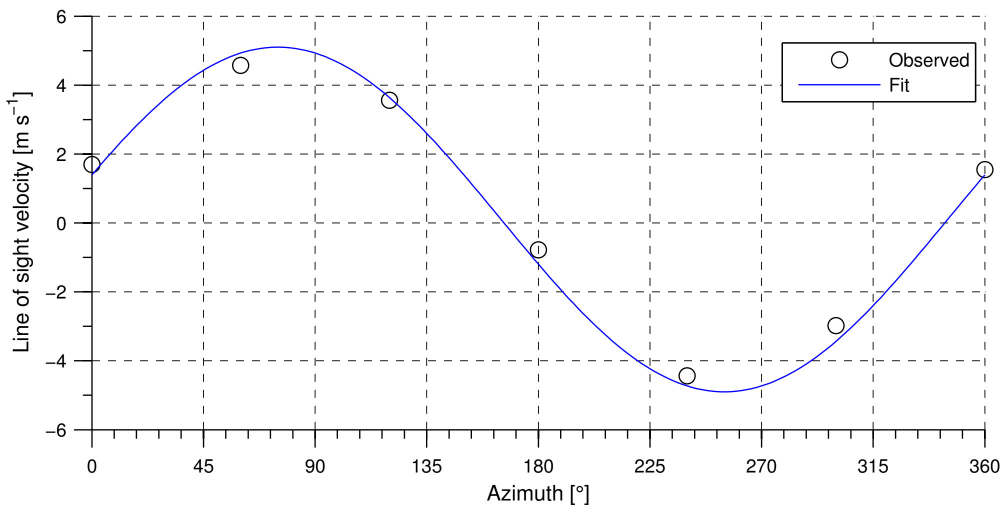


Figure A.4 Line of sight velocity versus azimuth for an arbitrary wind field sampled at 6 azimuthal points. Points show simulated observations of the wind field using a VAD lidar. The line shows the fit to data. In this example, the horizontal wind speed was 10 m s^{-1}, vertical wind speed was 0.2 m s^{-1}, and the wind direction was 75°.

The 'probe volume' is the region from which a single constituent physical measurement of Doppler shift (giving line of sight velocity) is acquired, several of which are typically required to derive a wind speed measurement. The probe volume is a characteristic of the basic physical interaction of the RSD with the atmosphere, and is defined by the scan geometry, device configuration or arrangement of the multiple beams penetrating the volume in order to acquire that measurement.

A 'probe length' can also be defined for the lidar. This is a representative length for the volume from which photons are scattered back towards the emitter and detected. The probe length is a function of the measurement technology that is used in the lidar:

- In a pulsed lidar device, the probe length is approximately the product of the pulse duration and the speed of light. The probe length is typically constant (Figure A.3a).
- In a continuous wave lidar device, the probe length is defined by the optics of the telescope assembly and the measurement height. The probe length varies and depends on the focus as the focal depth and Rayleigh Length (the length after the area of the probe doubles compared to the narrowest point) change, as the focus and measurement height changes (Figure A.3b). The probe length typically increases with the square of measurement range.

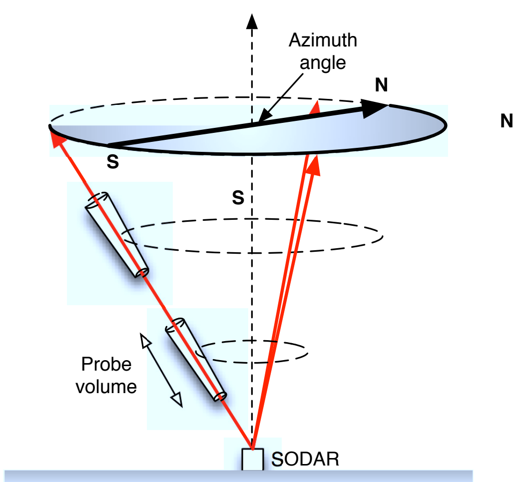
B Ground-based remote sensing of wind using sodar

Sodar is a remote sensing technology that uses acoustic pulses (‘chirps’ or ‘beeps’) to measure a three-dimensional wind vector in the atmospheric boundary layer. After emitting a pulse, the sodar listens for the backscattered sound and determines the wind speed from the Doppler shift in the acoustic frequency. Sodar vary in the acoustic frequencies they use; some use several tones, while others use a single frequency, and some models allow the user to select one or many frequencies. Sodar operating principles are documented in considerable detail in peer-reviewed publications such as Bradley (2008a); Bradley et al. (2012b) and Crescenti (1998). Several standards also exist for sodar use for environmental monitoring, including American Society for Testing and Materials (2005) and VDI Technical Division Environmental Meteorology (1999). The reader is referred to those sources for more details if required.

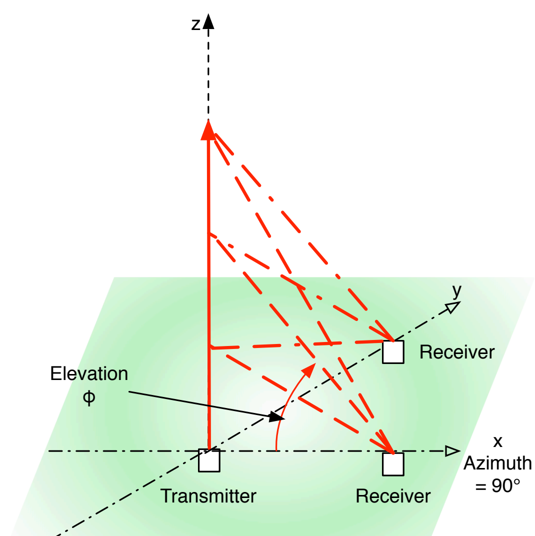
Commercial sodar devices are built in a variety of configurations:

- Monostatic phased array sodar have an array of transceivers, usually arranged in a rectangular grid. By inserting phase delays between individual transceivers, the emitted sound pulses can be steered in a particular direction. Similarly, a phase delay can be used to make a sodar ‘listen’ in a particular preferred direction.
- Monostatic multiple independent antenna sodar use three or more transceivers to emit and record the backscattered signal. The antennas are configured such that the three components of the wind can be acquired using a multi-beam, constant azimuth scan (Figure B.1a).
- Bistatic sodar use a separate transmitter and receiver to probe the atmosphere. Both the transmitter and receiver can scan the same vertical volume to provide vertical resolution of the wind field, or the transmitter can emit vertically and the receivers can alter their azimuth to measure at different elevations (Figure B.1b).

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 sodar, the scattering elements are small-scale temperature inhomogeneities resulting from atmospheric turbulence, whereas for bistatic sodar, either temperature or velocity fluctuations can contribute to the scattering. Sodar used for wind resource assessment are mostly mono-



(a) A multi-antenna monostatic sodar using 3 sonic beams to probe the atmosphere. The beams are separated by 120°.



(b) Bistatic sodar using one vertical beam and 2 scanning receivers to probe the atmosphere

Figure B.1 Different possible sodar measurement approaches. For other terminology used in the text, see Figure A.3.

static. The largest amount of backscattering results from turbulent fluctuations with length scale of about half of the wavelength of the sound pulse. This type of scattering is known as Bragg scattering. The power of the signal received by the detector is a function of the emitted power and the scattering that occurs:

$$P_R = P_0 \frac{A_R}{r^2} L_v e^{(-2\overline{\alpha} r)} \sigma(R)_E \tag{B.1}$$

where P_R is the received power, P_0 is the transmitted power, $\overline{\alpha}$ is the atmospheric attenuation, A_R is the effective area of the receiver, L_v is probe length (analogous to the lidar probe depth), and $\sigma(R)_E$ is the scattering cross-section at range r. The term $P_0 A_R L_v$ can be described as a 'system function' which is specific to each sodar.

C Change history

Table C.1 details the changes that have been made to this document. Requests for changes or updates should be directed to IEA Wind.

Table C.1 Document change log

Date	Version	Notes
January 2013	1st Edition	Submitted to the IEA Wind Executive Committee for adoption.
October 2012	1st Draft	Submitted to the IEA Wind Executive Committee for review.
September 2012	0.9	Distributed to attendees of the IEA Wind Task 11 59th Topical Expert Meeting, and members of Task 32, for comments in advance of submission to the IEA Wind Executive Committee.
June 2012	0.1	Distributed electronically to attendees of the IEA Wind Task 32 (lidar) meeting at DTU Wind in Roskilde, Denmark.

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