Comparisons of New Technologies for Wind Profile Measurements Associated with Wind Energy Applications

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Summary
Measurements of wind speed over the blade sweep are required for turbine site and performance evaluation. The cost of standard mast mounted cup anemometers and vanes increases rapidly with mast height and the alternative is to use ground-based remote-sensing instrumentation: the SODAR (acoustic radar) and LIDAR (laser radar).

Latest SODARs are distinguished by tighter acoustic beam-forming and acoustic baffle design. Additionally, next-generation bi-static pulsed SODARs (having spatially separated transmitter and receivers) are being investigated. LIDARs include the QinetiQ ZephIR focusing laser, and the Leosphere pulsed laser.

Key inter-comparison parameters discussed are: development; accuracy; deployment; calibration; data availability; raw data; use in complex terrain; and cost. SODARs measure wind speed to better than 1%. Recent improvements in data availability and quality are achieved through reducing sensitivity to extraneous echoes and sound sources. New bi-static SODAR development commenced in 2007 as part of the EU UpWind program, and large increases in received signal levels are expected, which will improve data availability and quality. The ZephIR LIDAR shows very good data availability (although filtering is required to remove contamination from reflections off overlying clouds) and is a very compact design. ZephIR wind speed accuracies approach those achieved by SODARs. All instruments currently require field calibration against a mast. The bi-static SODAR design has the potential to give much better accuracy in complex terrain because it samples a single compact volume of air rather than transmitting in widely separated directions. Currently the LIDARs are very much more expensive than the SODARs.

Keywords: remote sensing, SODAR, LIDAR, inter-comparison, complex terrain

1 Introduction

Independent measurements of wind speed are required for turbine site evaluation and turbine power performance monitoring. Because of frictional effects near the ground, it is desirable to provide wind measurements over the full extent of the turbine blade circle, which means that wind profiles are required. In the past, the standard for such measurements has been cup anemometers and wind vanes mounted at several levels on a meteorological mast. These instruments are relatively simple and give a direct output relating to wind speed and direction, and can be calibrated in a moderate-sized laboratory wind tunnel. However, over the last few years the growth in size of turbines means that meteorological masts supporting turbine installations have to be much higher. Although the actual structural design of robust masts and their supporting steel wires is quite complex, the bending moments essentially scale like a moment of inertia and so are proportional to the square of mast height. Wind speeds also generally increase with height, so the result is that the cost of the mast structure can be expected to increase at close to the cube of the height. This means that meteorological masts for wind turbine related work are becoming prohibitively expensive. Additionally, the effort required to install and maintain very large masts, particularly for offshore and complex terrain sites, is considerable.

The alternative is to use ground-based remote sensing instrumentation. These are instruments which sense the air motion based on reflected acoustic or electromagnetic energy which has been transmitted upward by the instrument. There are two types of instruments currently favoured. The first is the sound radar, or SODAR, which records acoustic power reflected by small fluctuations in air density and speed associated with turbulence. The second is the laser light radar, or LIDAR, which records optical power reflected off atmospheric particulates. Since the measurements are no longer direct, it is important that the physics of the energy reflection processes are well understood. Direct calibration in a laboratory of
an instrument which senses at a distance of perhaps 200 m is unlikely to be practical (a rather specialized laboratory of length 200 m would be needed with controlled wind flow through it!). This means that calibrations are generally first required against tall mast cup anemometers and vanes. On-going development of the remote sensing instruments is required until calibrations prove that the relationship between instrument output and the wind profile is thoroughly reproducible and single-valued.

Initially SODARs designed for general purpose use have been evaluated for wind profiling at turbine sites. These inexpensive instruments have traditionally been used to monitor spatial and temporal features of the wind regime in the lowest few hundred meters of the atmosphere, but without the requirement for high accuracy in wind speed. Nevertheless, conventional commercial SODARs have shown real promise for wind energy use [1]. More recently, manufacturers of SODARs have concentrated on producing SODARs targeted more to the high accuracy requirements of the wind energy community. Also, several new LIDAR developments make these instruments very competitive. Finally, a different configuration, the “bi-static” SODAR, is being freshly evaluated since it has some advantages in higher signal strength and in the geometry of the atmospheric profiling. This paper discusses these new developments and gives an overview of the comparative advantages and disadvantages of the differing technologies.

2 New sensors

2.1 Improved SODARs

A SODAR transmits a short (typically 50 ms) acoustic sinusoidal wave pulse upward into the atmosphere. Small changes in refractive index due to turbulent temperature and velocity fluctuations cause weak reflections which are detected by sensitive microphones. If the transmitter speakers and the receiver microphones are at the same location, the backward reflections are solely from temperature fluctuations. This is called a “mono-static SODAR” configuration. By directing the transmitted sound beam slightly off-vertical (typically 12°-20°) a Doppler shift change in frequency occurs in the reflected sound. Since this frequency change is proportional to the wind speed component in the direction of the beam, use of at least three beams in different directions provides estimates of the three wind components (i.e. easterly, northerly and vertical components).

There are not many significant sources of error in this basic wind estimation instrument [1]. The most important problems occur due to

- Incorrect estimation of the zenith angle of the acoustic beams
- Echoes from fixed objects such as nearby masts
- Poor signal strength when there is poor temperature contrast
- Echoes from rain

Of these, only the first gives calibration errors (the others can cause lower data availability). The most likely cause of incorrect estimation of the beam tilt angle $\psi$, for a properly installed instrument, is that the volume-weighted maximum of $\sin(\psi)$ has a systematic bias away from the $\sin(\psi)$ value expected on the basis of idealized beam geometry. This type of error is particularly likely to occur in a phased-array of speakers and microphones where the beam is more complex.

![Figure 1. Operational platform for the AQ500 SODAR (left-hand white instrument), the QinetiQ ZephIR LIDAR (central yellow instrument) and the AeroVironment 4000 SODAR (right-hand white instrument) [2].](image-url)
Echoes from stationary fixed objects can give a bias toward lower wind speeds. This problem is reduced by using improved acoustic baffles around the acoustic antenna. Attention to both these aspects have improved the latest generation of SODARs. For example, the AQ500 SODAR uses a dish antenna and horn speakers to obtain a well-defined acoustic beam, and has improved acoustic baffles (see Fig. 1).

2.2 QinetiQ ZephIR LIDAR
A new LIDAR, based on focusing the beam to determine the active range, is being developed by QinetiQ. Results are very impressive, and the instrument is compact in comparison with SODARs (see Fig. 1). However, the beam focusing simply reduces reflections from either side of the focal point rather than eliminating them. This means that there are problems if strong reflectors, such as cloud, are present even at a much larger distance than the focal point. To counteract this problem a “cloud filter” is used to reject cloud-contaminated data. The effect of extended sensitivity around the focal point means too that the along-beam spatial resolution becomes quite course at longer ranges. Also, a rather large swath conical scan is used and this means that the three wind components are determined from quite spatially separated volumes of air.

2.3 Leosphere LIDAR
Leosphere produced a pulsed LIDAR for wind energy use and its performance is currently under evaluation.

2.4 Bi-static SODARs
Bi-static SODARs, in which the transmitter and receivers are spatially separated by usually tens of meters, have been the subject of a number of research evaluations over many years but without a commercial instrument being produced. One reason is that, until recently, bi-static SODARs have had the transmitted acoustic beam and the receiver field of view intersecting at a fixed point in space. This means that wind components can only be obtained from a single height, rather than as a wind profile. Fig. 3 shows the receiver for a recent prototype bi-static SODAR having fixed field of view direction [3].

New bi-static SODARs are being designed for which the receivers are arrays of microphones. These arrays can be electronically scanned to give a receiver field of view which can follow the acoustic pulse at all heights up to the instrument’s useful range. One big potential advantage of bi-static SODARs is their sensitivity to turbulent velocity fluctuations which typically give echo strengths a factor of 100 larger than the conventional mono-static SODARs.

Figure 3. The dish antenna receiver for a recent prototype bi-static SODAR, and the received power spectrum [3].
3 Comparisons
In the following, some key inter-comparisons are given. However, the development of these new remote-sensing instruments is changing rapidly.

3.1 State of development
SODARs are very well-established instruments for measuring wind and turbulence in the lowest km of the atmosphere. Their capabilities and limitations are well known. However, only recently in the wind energy context have they been expected to measure wind speeds to an accuracy of better than 1%. This has caused re-evaluation of the sources of error in SODARs and how to improve designs. For this reason, it can be expected that new instruments will emerge over the next few years having much tighter acoustical design of beams and baffles.

The use of LIDARs for wind energy is very new. An enormous research effort has been expended on the ZephIR LIDAR over the past 3 or 4 years, producing a very high quality instrument. Similar effort is likely on the Leosphere pulsed LIDAR. Rapid further development is therefore expected for these short-range LIDARs.

While the concept of bi-static SODARs is well-established, designs providing routine accurate wind profiling are only recently under development. They have the potential for better performance than mono-static SODARs in all the key problem areas. The large increase in signal strength for off-axis turbulent scattering means the relative strength of extraneous echoes from fixed objects and from rain is greatly reduced. Work on self-calibrating designs is in progress. But there remains the fundamental disadvantage that distributed transmitter and receiver units are required, perhaps over separation distances of 50 m.

3.2 Accuracy
The calibration work reported for WISE [1] and PIE [4], and more recently as part of UpWind [5] show that SODARs and the ZephIR LIDAR give comparable wind speed estimates when compared with cup anemometer data from a tall mast. Fig. 4 shows one direct comparison between an AQ500 SODAR and a ZephIR LIDAR.

![Figure 4. Inter-comparison between an AQ500 SODAR and a QinetiQ ZephIR LIDAR at a height of 90 m.](image)

More importantly, Fig. 5 shows errors, \( m \), in the calibration slope, \( m \), where \( \frac{V_{\text{instrument}}}{V_{\text{cup anemometer}}} = m \) for the AV4000 SODAR calibrations in PIE and ZephIR-mast calibrations recently reported at the IEA meeting on remote sensing, 23-24 January 2007, Risø, Denmark [6]-[9]. The SODAR calibration has been corrected to the 40 m cup anemometer as described in the WISE report [1]. Not all the LIDAR results allowed estimation of the uncertainty of estimated slopes. Apart from the anomalous results of Kindler, the LIDAR performs similarly to the SODAR and with comparable uncertainty, particularly if the LIDAR results were to be also normalized to the results from a cup anemometer at one fixed height.
Figure 5. The error, 1-\(m\), in calibration slope \(m\), expressed as a percentage, for an AV4000 SODAR and for several field comparisons between the ZephIR LIDAR and cup anemometers on tall masts.

The main limitations to accuracy of SODARs is probably beam-pointing accuracy and this is determined partly by set-up (i.e. leveling the instrument), partly by knowledge of the sound speed (i.e. by measuring the local air temperature), and partly by having good laboratory knowledge of the beam shape. The sensitivity to leveling the instrument is indicated by the second axis in Fig. 5, for the case of a nominal 20° beam zenith angle. The tilt error angles shown, are the angle out of level required to give the percentage error in \(m\) shown on the slope error axis. It can be seen that a 1° leveling error can make a huge difference to the calibration. It is expected that greater accuracy will be achieved in the next 2 years through better treatment of these problems.

The main limitations to accuracy of the ZephIR LIDAR, when operated on flat terrain, is probably also leveling the instrument. For its larger beam zenith angle, the effect of tilt errors are less (1.36° out of level to give a 1% calibration error) but still a viable candidate for the systematic deviations of the LIDAR calibration evident in Fig. 5.

3.3 Ease of deployment
Each of the instruments described will fit in a small 4WD vehicle. SODARs and LIDARs should be able to be installed and be operational within 30 minutes of arrival on site. The installation time for new-generation bi-static SODARs is unknown, but will depend significantly on whether positioning (e.g. GPS) and orientation (e.g. flux-gate compass) interfaces are included in the design.

3.4 Ease of calibration
These instruments all sense air motion at a distance. It is currently not possible to perform a complete laboratory calibration for any of these instruments. For both SODARs and LIDARs though, it is possible to obtain good laboratory measurements of the sensing beam shape, and then by inference determine expected calibration properties. In the case of SODARs, however, full investigation of the acoustic beam is rarely performed because the size of the SODARs is too large for them to fit in most available anechoic test facilities and, even if they can be accommodated within an anechoic chamber, the far-field beam pattern may not be accessible because of the relative size of the acoustic antenna and the width of the chamber.

Efforts are underway in UpWind [10] to design a sophisticated multi-element acoustic transponder which will sense the signals emitted by a SODAR, pass them through a software filter which simulates the atmospheric scattering, and echo the signal back to the SODAR. This should provide a full laboratory (and possibly field) calibration facility.
3.5 Data availability
Mono-static SODARs obtain weaker reflections in neutral atmosphere conditions, as shown in Fig. 6.

![Data availability graph](image)

Figure 6. The data availability of a Scintec SFAS SODAR for Richardson numbers from -100 to 100 [1].

In contrast, the data availability for the ZephIR LIDAR appears to be close to 100% when there is no fog or overlying cloud present. Filtering the data to remove contamination by strong reflections from more distant cloud will reduce the availability.

The data availability of new-generation bi-static SODARs is expected to also be very high. Fig. 7 shows the gain in signal strength of a bi-static SODAR over a mono-static SODAR of similar acoustic power output, based on the known scattering properties of turbulence.

![Gain in signal strength graph](image)

Figure 7. Typical echo signal strength of a bi-static SODAR compared to a mono-static SODAR of comparable transmitted power output. The height scale is based on a separation distance of 50 m between the transmitter and receiver antennas.
3.6 Quality of raw data

Fig. 8 shows SODAR raw data from the WISE project [1] in which rain contamination (higher SODAR winds) is most evident for the higher frequency AV4000, and echoes from fixed objects (lower SODAR winds) are most evident for the lower frequency Metek. These artifacts can be removed by software filters.

![Figure 8: Mast windspeeds vs raw SODAR windspeeds. (a) AV4000 (b) Scintec SFAS (c) Metek SODAR/RASS [1]](image)

The spectra from the ZephIR are relatively noise-free and the largest problem is the extended range over which the instrument is sensitive, due to the focusing method used. Strongly reflecting cloud can contribute to the signal expected from a much lower height. ZephIR removes most of these contaminated records by also focusing at the extreme height range to detect whether cloud is there. The pulsed bi-static SODARs have potentially cleaner raw data than mono-static SODARs, but not just because of increased signal strength. The configurations being developed transmit only in the vertical direction, allowing for a tighter acoustic baffle design and reducing sound transmitted at low elevations. Also the angular scattering pattern for sound from rain has a minimum at the centre of the normal operating scattering angle for the bi-static design.

3.7 Use in complex terrain

Mono-static SODARs and all LIDAR designs use off-vertical transmissions so that the radial component of the scattering object’s velocity includes a component of the horizontal wind. But this necessarily means that information on different wind components (e.g. the easterly and northerly components) comes from spatially separated volumes of air. In contrast, the new-generation bi-static SODARs sample a single volume of air, as shown in Fig. 9.

![Figure 9: The acoustic beam configuration for a mono-static SODAR (left-hand diagram) and for a new-generation bi-static SODAR (right-hand diagram).](image)

A simple potential flow model of wind flow over a Gaussian-shape hill gives information on how a conically-scanning instrument might respond to the wind speed gradients present. Fig. 10 shows an example for a LIDAR transmitting in a ±30° cone at a height 50 m above a 50 m high hill. Errors can be significant even for this relatively gentle terrain case.
Figure 10. The wind speed error arising from using a ±30° conical scan in the wind shear region above a small hill.

3.8 Relative cost
The costs for all remote sensing instruments are likely to change depending on demand by the wind energy sector. Currently, even in a period where the LIDAR manufacturers are attempting to establish a new technology, the LIDARS are very much more expensive than SODARs.

4 Conclusions
In [1] conventional mono-static SODARs have been found to be able to give wind speeds to an accuracy better than 1%, providing they are first calibrated against a cup anemometer. The need for this comparison against a direct-measuring instrument is probably related to acoustic beam pointing errors and, given that carefully laboratory testing can determine beam shape, the remaining source of error is most probably leveling in the field installation. Since the error due to a slightly out-of-level instrument depends on wind direction, it is also likely that this source of error accounts for some of the spread of SODAR measurements at a fixed wind speed. Latest SODAR models appear to have calibration slopes closer to 1 and less data spread, so perhaps have better defined beam characteristics. Also evident is the reduced influence of echoes from fixed objects such as masts and turbines.

LIDARs, particularly the ZephIR, have undergone rapid development. The ZephIR is compact, reliable, and accurate. It does have problems with fog and cloud: these have not been particularly evident in presentations of the ZephIR because field investigations have mostly not included fog and cloud events. Also, both mono-static SODARs and LIDARs may experience reduced performance in complex terrain because of their obtaining wind component information from widely separated target volumes. This contrasts with the new-generation bi-static SODARs, which analyze data from a narrow vertical column. These SODARs also have advantages of echo strength up to 100 times greater than that of the mono-static designs, and reduced sensitivity to signal contamination by rain. They have a substantial disadvantage though of requiring spatially distributed sensors on the ground.

Given the entry into the market of the latest LIDAR technology, the next 2 years are likely to see introduction also of much more sophisticated SODAR technology. This is likely to comprise self-orientation hardware and much tighter specification of the acoustic design aspects.

Currently all SODAR and LIDAR instruments require field calibration against cup/vane instruments on a mast. Efforts are in progress for both technologies to develop robust laboratory calibration methods. These will be calibration ‘analogues’ designed to check instrument specifications, rather than full-scale 200 m Doppler ranges.

References
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