Correction of sodar wind speed bias in complex terrain situations

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Abstract
The performance of sodar technology for wind resource measurement is well documented in simple terrain with good relationships and high levels of accuracy expected for lidar and sodar due to the homogenous flow fields found in such terrain. When remote sensing is used in complex terrain, for comparison with conventional anemometry, the potential for error increases due to the variation in the flow field through the measurement volume. Methodologies are available to correct the volumetric measurements obtained through the use of lidars to their equivalent point source with the aim to compensate for the bias in the error from the variation in flow through the measurement volume. This paper describes a technique incorporating computational fluid dynamics (CFD) to investigate the correction of this measurement bias made using remote sensing equipment. An example of a typical lidar comparison with anemometer measurements is shown as well as a comparison with a sodar measurement. The results of applying the correction technique to these comparison cases are also described. The measurements from this work have shown that care in the deployment and operation of this technology is key to getting good results. The developed technique shows the uncertainty around determining the wind resource in complex terrain using remote sensing technology can be reduced.

Keywords: Sodar, lidar, resource assessment, CFD modelling

1. Introduction
For wind farm development in complex terrain it is important to be able to compare remote sensing volumetric based measurements with conventional anemometry measurements to enable spatial validation of larger scale CFD site climate assessments. Lidar remote sensing has shown some success in correction of error bias resulting from the variation in flow through the measurement volume. Overall uncertainty from the use of remote sensing can therefore be reduced based on an evaluation of the flow field. The methodology described in this paper is based on the research work undertaken by Bingöl, Mann and Foussekis[1],[2] from Risø DTU.

For our measurement cases we have focused on the Natural Power ZephIR 150 lidar and the Second Wind Triton sodar because these were available for our site measurements. The ZephIR lidar measures the radial velocity at the height of interest by a laser scanning a circular pattern with a cone angle of 30.4 degrees from the vertical. The Triton measures the radial velocity as well but is based on three acoustic beams (cone angle of 5 degrees from vertical) evenly spaced 120 degrees apart with each beam at a tilt angle from the vertical of 11.4 degrees.

Both of the remote sensing devices used derive the horizontal wind speeds at each height from the measured radial velocities with the algorithms based on the key assumption that the flow is homogenous through the measurement volume. In complex terrain the variation in flow through the measurement volume will introduce an error in the measured wind speeds when compared to point measurements such as cup anemometry measurements.
Using high resolution computational fluid dynamic modelling it is possible to model the wind flow through the remote sensing measurement volume to determine the potential error for each type of device due to the surrounding terrain. This enables an estimation of the error bias and the scale of the error to be understood, even prior to deployment of the equipment. It is also possible to apply a correction to the measurements with the aim of reducing the overall uncertainty of the collected measurements.

2. Background and description

In homogenous flow through the measurement volume, such as flow over simple terrain, it is expected that the vertical velocity is insignificant. In complex terrain however there is likely to be not only reasonable vertical velocities but also variation in these vertical velocities across the measurement volume if the flow is sufficiently complex. From investigation of the vector diagrams for different terrain situations an understanding of the significance of the error bias can be found. The vertical velocity component contributes to a change in the length of inlet and outlet radial velocities measured by the sensing device, thus affecting the measured velocity relative to the horizontal velocity.

![Figure 2: Up slope to hilltop flow field – potential for underestimate](image)

![Figure 3: Hilltop flow field – underestimate](image)

![Figure 4: Down slope from hilltop flow field – potential for underestimate](image)

![Figure 5: Valley flow field – potential for overestimate](image)

Some examples of this can be found in Figure 2 to Figure 5. From these figures and also investigation of other scenarios it is expected that an underestimate of the wind speed would be found if the sensing device is placed on the top of a steep ridge, on a hilltop or with flow through a steep saddle. Based on a left to right flow as described in the diagrams a clockwise curvature in the flow is seen. Alternatively if the sensing device is placed in a valley or saddle with flow along the ridge it is expected that there would be an overestimate of wind speed due to the anti-clockwise curvature of the flow, again with a left to right flow direction as shown in Figure 5.

For this study two cases have been developed based on experimental data collected at two different sites. Both cases place emphasis on the complexity resulting from variations in
orography typical of wind farm sites in New Zealand rather than on other terrain features such as trees or buildings.

The lidar case is an 80m tubular mast with the lidar placed approximately 5m away from the mast. The ZephIR lidar is located to ensure the scanning cone does not impact on any moving mast hardware or instruments. The measurement location is on a ridgeline in steep terrain with only a few small scrub bushes in the surrounding terrain. The lidar is orientated towards north to align with the measured mast wind direction. Some examples of the terrain for this case can be seen in Figure 6 and Figure 7.

For the sodar case an 80m lattice mast and the Triton sodar are placed approximately 100m apart. These are located along a ridgeline in very steep terrain with a large cliff to the northwest. The 100m separation is required here to minimize any interference from acoustic reflections from the lattice tower. The sodar location is optimized to ensure the beams are not aligned with the mast and also that the sodar is not downwind from the mast in prevailing wind directions to ensure good data capture. In this case the Computational Fluid Dynamics (CFD) model has been used to transfer the mast data to the sodar location as well as calculating the flow variation through the sodar volume. Two examples of the terrain for this case can be seen in Figure 8 and Figure 9.

Meteodyn WT is the CFD software package used for the calculations of the flow variations. The CFD models are tailored for each site based on the orography present, computing resources available, accuracy required and modelling convergence requirements. The models use high resolution contours (2-5m contour resolution) with a minimum grid size of approximately 3-5m in the horizontal plane and 1-2m in the vertical plane. The grid used is refined around the areas of interest at the reference masts and also around the measurement volumes for each case.
3. Theory and method

The method described, as mentioned previously, is based on the research work undertaken by Bingöl, Mann and Foussekis\[1\],[2] from Risø DTU. The tilt angle of the lidar laser or sodar acoustic beam from the vertical is defined as $\varnothing$. The CFD model is used to calculate points on the lidar cone ring (72 points used in this case) and for the sodar only three points are calculated based on the beam centres at the measurement height. Each point has an angle of $\beta$ from grid north and each point’s radial velocity $V_{rpt}$ is calculated using the formula (1).

$$V_{rpt} = U_{hpt} \left( -\sin \theta \times \sin \varnothing \times \sin \beta - \cos \theta \times \sin \varnothing \times \cos \beta + \tan \alpha \times \cos \varnothing \right) \quad (1)$$

For each radial point, for each wind direction, from the CFD results $\alpha$ is the inflow angle, $U_{hpt}$ is the horizontal velocity and $\theta$ is the wind direction calculated at the point relative to grid north. The three main velocity components are obtained by fitting the following trigonometric series for each wind direction considered.

$$V_{rpt} = a + b \times \cos \theta + c \times \sin \theta \quad (2)$$

From this best fit of the calculated points the equivalent horizontal wind speed at the required height can be determined and defined as $U_{h_{eq}}$ from the $u$ and $v$ components. This value of $U_{h_{eq}}$ is used with the sensing device centre horizontal velocity $U_{h_{centre}}$ from the CFD results to determine the estimate of the bias.

$$Bias\_Ratio = \frac{U_{h_{eq}}}{U_{h_{centre}}} \quad (3)$$

An estimated correction can be applied to the measurement data based on the inverse of this calculated bias.

4. Results

Both cases investigated showed promising results for the application of the method both in terms of error estimation and potential for the application of a correction. In both cases the data investigated was refined based on sectors with the wind directions where the error due to mast effects on anemometry and sensing device are minimised to reduce overall test uncertainty.
MEASNET calibrated Vector brand anemometers have been used in both cases with boom arrangements designed to meet IEC requirements.

4.1 Study results

For the lidar case the results showed a very good correlation with low scatter in the results, as would be expected due to the close proximity of the measurements with this evident in Figure 11. Approximately 7 ½ days of data (1119 points) were used from the chosen sectors after the collected data was filtered for cloud, rain, quality, low wind speeds and equipment outages. The comparison with the mast data is shown in Figure 13 with the error results in Table 1. The results are presented as errors relating only to the scatter of the data rather than a full error uncertainty analysis to simplify the comparison. Figure 12 shows the correction applied as calculated from the CFD model with Figure 13 showing the results of the correction applied to the sector filtered data.

For the sodar case the results also showed a good correlation but with a higher scatter in the results, as would be expected due to the larger distance between the mast and sensing device of the measurements as shown in Figure 14. Close to 19 days of data (2712 points) were used from the chosen sectors after the collected data was filtered for rain, quality (98% factor used), low wind speeds and equipment outages. The comparison with the mast data is shown in Figure 16 with the error results in Table 2. As in the lidar case the results are presented as errors relating only to the scatter of the data rather than a full error uncertainty analysis to simplify the comparison. Figure 15 shows the correction applied as calculated from the CFD model with Figure 16 showing the results of the correction applied to the sector filtered data.

<table>
<thead>
<tr>
<th>Table 1: Lidar measurement results</th>
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<tbody>
<tr>
<td>RMS uncorrected</td>
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<tr>
<td>0.69m/s</td>
</tr>
<tr>
<td>5.3%</td>
</tr>
<tr>
<td>MAE uncorrected</td>
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<tr>
<td>0.61m/s</td>
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<tr>
<td>4.7%</td>
</tr>
<tr>
<td>RMS corrected</td>
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<tr>
<td>MAE corrected</td>
</tr>
<tr>
<td>0.26m/s</td>
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<tr>
<td>2.0%</td>
</tr>
</tbody>
</table>

Figure 12: Lidar measurement location

Figure 13: Lidar measurement results
4.2 Discussion of results

From the results for the lidar it can be seen there is a very good relationship and low scatter of the data in the set. Upon correction of the data, using the CFD based correction method in section 3, the uncertainty of the data is comparable with the expected uncertainty surrounding the mast measurement which is a combination of mounting set-up, terrain flow and anemometer calibration.

The sodar results show a higher level of scatter but still a good correlation between the mast and the sodar measurements. Overall the sodar results show an agreement with the mast measurement with a general relationship that agrees with the proposed bias correction. However more investigation is required into techniques to improve the CFD modelling and reduce the scatter of the relationship to confirm the applicability of the method to sodar use. This relatively large scatter in the sodar data and associated uncertainty (before and after correction) is due to the following key reasons when compared with the lidar case:

Table 2: Sodar measurement results

<table>
<thead>
<tr>
<th></th>
<th>RMS uncorrected</th>
<th>MAE uncorrected</th>
<th>RMS corrected</th>
<th>MAE corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.58 m/s</td>
<td>0.45 m/s</td>
<td>0.52 m/s</td>
<td>0.38 m/s</td>
</tr>
<tr>
<td></td>
<td>7.2%</td>
<td>5.6%</td>
<td>6.3%</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

Figure 14: Sodar measurement location

Figure 15: Sodar measurement location

Figure 16: Sodar measurement results

Correction Ratio for Sodar

<table>
<thead>
<tr>
<th>Sector</th>
<th>Correction Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector 285 to 345 Degrees Grid</td>
<td>0.97, 0.98, 0.99, 1, 1.01, 1.02, 1.03, 1.04, 1.05, 1.06</td>
</tr>
</tbody>
</table>

Wind speed correlation sector fitted - Quality 95 %

Sector 285 to 345 Degrees Grid
• The terrain is generally more complex in the sodar case with associated higher complexity flow fields in the area surrounding the sodar and mast. There is potential that some of the sectors may be affected by complex flow conditions not modelled with sufficient accuracy by the available steady state CFD model.

• In the sodar case the sensing device is positioned further from the reference anemometer due to the requirements of minimising the potential for acoustic reflections from the mast. This spatial separation is also required to reduce the influence of the increased background noise from the wind flow through the mast and over its guy wires at higher wind speeds. This does however reduce the correlation between the data sources as the wind fields are less correlated at the different locations.

• CFD is required to transfer the reference wind speed and direction to sodar location due to the complexity of the terrain and the distance between the sodar and reference anemometer. This adds an additional component to the uncertainty of the comparison.

• There is a different sampling rate of the flow field when using the different remote sensing technologies. The sodar has a sampling rate driven by the physical nature of the acoustic pulse and the time required to cycle through the different direction beams (approximately 86 pulses for each beam per 10 minutes [3]). Whereas the lidar is not constrained by the speed of the laser, only by the scanning time at each height and the time required to refocus the laser between the measurement heights which is dependant on the number of the heights utilised.

• The volume size and shape measured by the two remote sensing technologies are different. The lidar ZephIR 150 is scanning a ‘donut’ shaped ring with a depth of approximately 11.5m at 80m [4] resulting in a volume in the region of 30600m$^3$. In comparison the sodar is scanning three cone shaped volumes each with a depth of approximately 20m at 80m resulting in a total volume of approximately 10000m$^3$. More modern lidars are available which have a smaller probe length and hence smaller scanning volume which is comparable to the sodar volume.

• In the sodar case the correction is modelled using three discrete points which may lead to a more coarse result while the lidar is modelled by a ring of 72 points. Suggestions for further investigation include modelling of additional points to represent the sodar measurement volume.

• There is potential for the different terrain complexities in each case to have affected the anemometer performance to different extents due to the different gust factors, turbulence, inflow angles and other local climatic conditions at each site. It is expected that this will add to the overall uncertainty of the results in each case.

With the method requiring the use of CFD in complex terrain this adds additional scope for uncertainty that is not typically required when using remote sensing measurements in simple terrain. In this investigation the steady state CFD software Meteodyn WT has been used for the CFD model. For the lidar case the sensing device has been modelled using the Meteodyn WT lidar tool for forcing the grid refinement to the measurement volume of the lidar. Additional points of interest have been added to produce calculation and result points in the volume of the lidar. For the sodar case the sensing device has been modelled using Meteodyn WT with an array of points being used to produce calculation and result points in the volume of the sodar as well as at the mast location.

From the CFD analysis work it became evident that a balance has to be made in the CFD modelling to optimise the calculations for the best overall outcome. Difficulties occur from
complex terrain in regards to determining the correct flow model for the conditions, obtaining calculation convergence in complex flow, defining the grid appropriately and optimising the calculation speed versus model accuracy while limited by the computing resources available. In our case based on 36 sectors for each calculation with two processors we aimed at producing a convergent solution for all sectors in approximately 24 hours. A balance has to be found in the following key aspects when modelling with CFD and these are our recommendations:

- Refinement of the grid to minimise the grid at the areas of interest, such as the sodar measurement volume, while still maintaining a large enough domain to include dominant terrain features but minimising overall model size to speed up calculation time. The size and number of points in the grid typically defines the speed of the calculation and also the computing resources required to undertake the calculation. In our models we have used 3-5m for the minimum horizontal grid size and 1-2m for the minimum vertical grid size. Grids that have a high resolution and are refined vertically and horizontally about the measurement volume are desirable. Our domain size used is typically approximately 2.5km x 2.5km but this should be evaluated on a site-by-site basis.

- Contour accuracy is also important as the volume of the sodar is relatively small when looking at the large scale maps of most wind projects. It is recommended that contours of 1-5m height resolution be used with a preference towards 2m especially in the area around the sodar location itself. This is based on the balance between information normally obtained for wind farm developments where contours in the 2m to 20m ranges are fairly typical and the need for accuracy around the sodar and mast location.

- CFD models should be assessed for accuracy against site measurements if possible. This may also include checks for comparison with climatic stability effects, turbulence/wind shear effects with direction, wind veer accuracy and also the effect of variations in the grid chosen to check for grid independence of the results. Assessment may be required as to whether the average steady state results are appropriate for the entire measurement period or whether seasonal patterns/climate conditions that occur at a site require different models to be associated with the measurement data from these periods for more accurate results.

4.3 Practical recommendations

It was found during our sodar deployments that the guidelines [5] produced by Second Wind Inc. are very useful in locating the sodar unit to maximize the available data and minimize the quantity of data that is excluded in the filtering process. The concept is to place the sodar in a location that provides high quality sodar measurements resulting from a low level of influence from local background noise sources. In complex terrain some of the key considerations include the following:

- Siting of the sodar – this is important to maximize the data collected and reduce any correction that should be applied. Consideration should be made for siting the sodar unit in an appropriate location that is representative of the locations that you wish to use the data for, while minimizing the wind flow over the unit itself. For siting on ridgelines the sodar unit should be placed in a small hollow, dip or on the lee side of the ridge if practical. In low wind shear sites wind flow over the sodar unit itself should be avoided as this will reduce the quality of the available measurements due to higher background noise levels reducing the signal to noise ratio. Sources of noise such as farm equipment, wildlife habitat areas (frogs, birds, etc.) or locations with wind flow noise such as trees, buildings, mast and fences should also be avoided, particularly if they are at similar distances to the intended measurement heights. CFD models for assessment of the complexity of the flow and terrain prior to deployment would also provide useful results. Areas of high variation in wind shear or turbulence should be identified and avoided in prevailing wind directions. Care should be taken to avoid re-circulation zones.
or areas with very complex flow conditions that will significantly increase the modelling and measurement error.

- **Fencing and mounting** – fencing around the sodar unit should be kept to a minimum to reduce the background noise from wind flow over the sodar surroundings. Ideally there would be no fencing around the sodar but this option needs to be based on a risk assessment of potential damage to the sodar from stock, wildlife or vandalism. Any trailer or mounting frame and the anchoring system should be designed to maintain the portability of the unit and ease of set-up but also consideration needs to be made to minimise the wind flow noise from the system. Suggestions here would be to remove tie-down straps, keep mounting gear close to the ground, close off open ended tubes, reduce wire lengths, anchor poles close to the ground and ensure the installation is secure to minimise any movement of components.

- **Quality filtering** – in complex terrain a higher level of filtering may be required. From data collected to date, at lower quality factor levels and higher wind speeds, there is a trend to decreasing sodar wind speed when compared with anemometry measurements. This is likely to be due to higher levels of background noise around the sodar unit at higher wind speeds. Using higher quality levels (>95%) when filtering provides data sets with a lower scatter and reduces the high wind speed trend effect as shown in Figure 18 and Figure 19. However higher levels of filtering reduce the available data set size so a balance has to be found between data collected, accuracy required, minimizing the monitoring period, required direction sector set size and size of post-filtered data sets. When filtering sodar data for rainfall in complex terrain the vertical wind speed filter range may need to be increased when compared with simple terrain due to the greater magnitude of the terrain induced vertical wind speeds that will occur.

![Figure 18: 60% level filtered sodar data set](image1)

![Figure 19: 98% level filtered sodar data set](image2)

5. **Conclusion**

While the bias correction appeared to improve the accuracy of the sodar when compared with a cup anemometer there is still reasonable scatter in the data. A similar technique has been applied to another remote sensing device (ZephIR lidar) in complex terrain which shows promising results. Key sources of uncertainty in this investigation include;

- Steady state CFD modelling error between mast and sodar including resolution of the grid and representation of volume of beams by centre points.
- Impact of filtering and quality factors on data sets (higher quality level filters should be used in complex terrain, particularly at low wind shear sites).
- Distance between reference and sodar location.
• Different characteristics of anemometer versus sodar measurement such as sampling frequency, inflow angle response and gust/turbulence response.
• Siting of sodar in complex flow conditions which cannot be modelled accurately with steady state CFD.

Additional research into the uncertainties involved and developing more experience in different situations is expected to improve the results. Further investigation is proposed for this sodar study in regards to looking at alternative CFD options for flow field calculation, investigating unstructured mesh, grid refinement options and also investigation into different volumetric measurement distributions based on higher resolution CFD models. Further development of techniques to improve the accuracy of this type of measurement, both lidar and sodar, in different wind industry applications will be the key to its widespread use within the industry enhanced by its versatility and decreasing cost.

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References


