Fulcrum 3D
precision sensing

Fulcrum3D Sodar | complex site performance

state of the art remote sensing

what is a complex site?

Many wind farms are located at complex sites where wind flows can quickly change over a small area, height or period of time. Examples include sites with:

- steep terrain either on or close to the site;
- forested areas close to the measurement location;
- high wind shear, or highly non-linear or extreme shear measured on the site (e.g. low level jets which are common in some areas). See examples in Figure 1.

These sites pose challenges for all wind measurement campaigns due to the highly complex wind flows:

- anemometers are affected by non-horizontal wind flow, turbulence and other influences (in complex terrain Fulcrum3D has measured errors of >10% between high class anemometers and adjacent reference instruments);
- shear estimation above a met mast has high uncertainty as the normal log and power law fits may fit lower heights on the mast, but may not apply above the mast.

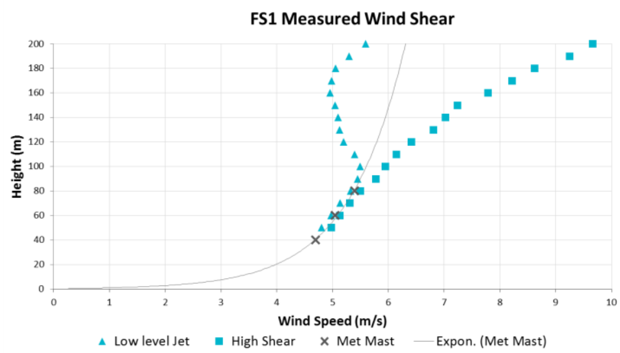

Figure 1: *Examples of FS1 measured complex wind shear that would not be captured with a typical mast (but would impact wind turbines).*

impact on remote sensing

The science behind remote sensing units relies on the assumption that wind flow is homogenous across the sensing area (i.e. that the wind speed and direction as it enters and moves through the sensing area is the same as when it leaves the sensing area).

Any inhomogeneity in wind flow has a tendency to introduce measurement errors in remote sensing systems. Fortunately, unlike anemometers, inflow angles generally do not affect remote sensing systems so long as the wind flow is linear.

Accordingly, well designed remote sensing systems can perform better than met masts (with cup anemometers) in complex terrain.

Where a remote sensing system is located on the top of a hill, it is common for a convex wind flow to occur where the flow follows (to an extent) the line of the hill. In this scenario, a remote sensing system's assumption of homogeneity tends to reduce the measured wind speed compared with the actual wind speed, leading to under-estimation of the resource.

While post-measurement corrections using complex wind analysis (CFD) can improve accuracy, these modelling tools introduce their own errors and cannot eliminate the errors entirely.

Fulcrum3D Sodar: specifically designed for complex terrain

narrow beam angles reduce errors

The key to accuracy of remote sensing in complex terrain is to reduce the potential for inhomogeneity within and especially between beams. This is most easily achieved by reducing the angle of each beam from the vertical axis.

The Fulcrum3D FS1 Sodar uses a very narrow beam angle (9°/12° from vertical axis) compared with competing units which typically have beam angles up to ~30° from vertical axis. This concentration of the beams substantially reduces the potential for inhomogeneity across the measured area.

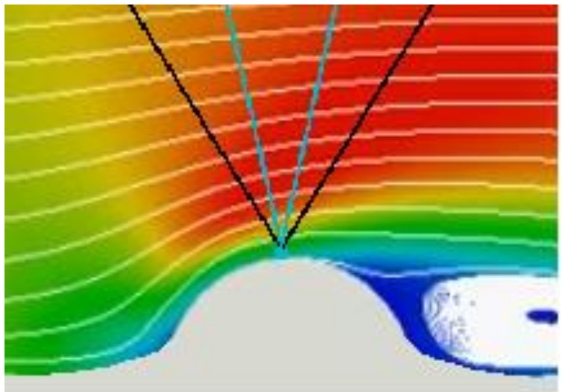

Figure 2: *Wind flow over a hill showing beam locations for a 30 degree unit (black) and the Fulcrum3D FS1 Sodar (blue)*

An example of the Fulcrum3D FS1 Sodar in comparison to a 30 degree beam angle sodar can be seen in Figure 2. Note the difference in the angle the wind flow (white lines) passes the black beams in comparison to the FS1's blue beams. The larger incidence angle to the 30 degree beam and the large difference between beams significantly increases the error compared to the FS1's narrower beam design.

Reducing the angle between beams is challenging as it substantially reduces the manufacturing tolerances required to ensure accurate results. Fulcrum3D has demonstrated its ability to achieve these tight tolerances through excellent performance in its ongoing validation campaigns.

simultaneous sampling: multi-beam mode

When operated in multi-beam mode, each beam is sampled simultaneously rather than the sequential sampling usually used in lidars and sodars.

This has particular benefits in complex sites where wind can vary over small periods of time and further reduces errors of measuring complex and rapidly changing wind flows.

siting is still important

Correct siting of a Fulcrum3D Sodar on complex sites is still important to ensure maximum data accuracy, and to improve the accuracy of wind flow modelling using that data.

Equally important is the design and location of any met mast used for validation campaigns in complex terrain. Fulcrum3D has developed specific siting guidelines for these purposes.

validation in complex terrain

Validation in complex terrain is challenging due to errors introduced in met masts in complex terrain, as well as wind flow differences between the met mast and sodar locations. Real wind flow speedups can occur over even short distances, therefore correlation (R^2) may be high while the correlation slope can differ substantially from unity. Sodars must be located some distance from the validation mast and therefore real wind flow differences are to be expected.

The Fulcrum3D Sodar has been deployed on a number of complex sites as part of our ongoing validation program. Detailed results from this campaign are available via a fleet-wide summary report as well as individual case studies. A number of independent validations in complex terrain have also been completed by consultants including DNV-GL and PB Power and are available from Fulcrum3D.

detailed case study

In a key case study, a number of units were deployed on a complex site where power performance testing of a wind farm required pairs of met masts approx. 300m apart. Each sodar was located equidistant between the mast pairs (~150m from each mast), with one sodar located equidistant between four tall met masts. The results confirm the accuracy of the Fulcrum3D unit in complex terrain:

- strong correlations between sodar and each mast were demonstrated;
- these correlations were consistent with the correlations between mast-mast pairs, indicating the sodar correlated as well as the power performance test masts;
- the correlation slope between sodar-mast and mast-mast pairs indicated that the slope differences in sodar correlations were consistent with real-world wind flow differences and that the sodar was measuring accurately;
- the test was done in the vicinity of operating wind turbines with no material impact on sodar performance;

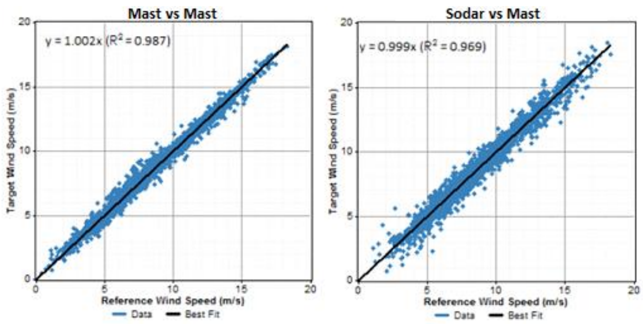

Figure 3: *mast:mast (L) and sodar:mast (R) correlation result at 80m*

Figure 3 indicates typical mast:mast and sodar:mast correlations from this trial. It can be seen that the mast and sodars broadly agree and the level of scatter between masts is similar to the level of scatter from sodar measurements.

The detailed case study and related wind and terrain data is available from Fulcrum3D, allowing 3rd parties to carry out their own performance assessments at this site.

performance in complex terrain

wind speed accuracy

Figure 4 indicates a typical comparison between the sodar and mast in complex terrain. Note that the bias is close to 1 indicating excellent wind speed accuracy and that the correlation is also excellent at ~0.97.

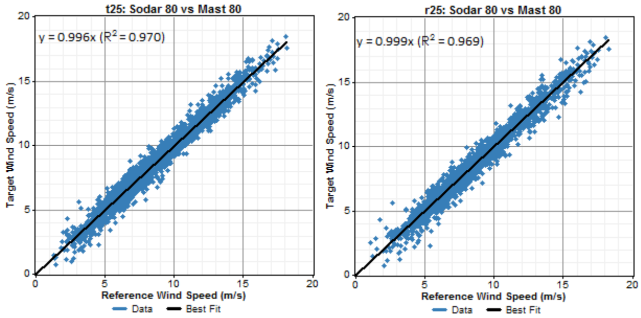

Figure 4: *80m correlation between mast and sodar ~300m apart*

In addition to the case study, a fleet-wide assessment of all deployments on complex sites is shown in Table 1. This demonstrates a low level of wind speed bias and high levels of correlation. Please ask Fulcrum3D for a full copy.

Table 1: *Fleet-wide performance on complex sites*

Shear	Slope	R^2
Median	0.997	0.966
Mean	0.994	0.967
Minimum	0.942	0.953
Maximum	1.019	0.977
Standard Deviation	0.118	0.006

wind shear accuracy

Measuring wind shear is a key application of the FS1 Sodar. In this case study a number of masts were in proximity to the sodar's deployed providing ideal validation. Table 2 indicates that the sodar was in close agreement with the adjacent masts and well within the range of expectations for overlap heights with the mast.

Table 2: *wind shear comparisons between mast and sodar*

Shear	Mast (25.4-79.5)		Sodar (50-80m)
	Reference mast	Turbine mast	
Location 1	0.06	0.04	0.04
Location 25	0.09	0.10	0.09
Location 26	0.11	0.10	0.10
Location 65	0.15	0.13	0.16

This case study is an extract from a full analysis by Fulcrum3D in the complex site validation report dated March 2014. The raw data that was used for analysis is also available on request from Fulcrum3D.

Who is Fulcrum3D?

Fulcrum3D combines the strengths of Fulcrum Energy's firsthand renewable energy project experience with the specialist technical design and manufacturing expertise of Orang-utan Engineering.

The result is unique technology designed specifically to support the renewable energy sector.

Our range of remote sensing products includes:

- Wind monitoring using our compact beam Sodar;
- High speed data logging of weather sensors;
- Integrated noise / weather monitoring;
- Solar resource monitoring;
- CloudCAM cloud tracking and cloud monitoring systems.

Our technology platform is based on a robust telemetry system, designed for maintenance free operation in remote environments.

All data is available for web download via our *Flightdeck* portal.

We look forward to providing you with great Australian technology supported by first class service and support.

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