FS1 SODAR PERFORMANCE VALIDATION

Fleet-wide Performance Summary

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1 Introduction

The Fulcrum3D FS1 Sodar has been specifically designed to service the renewable energy sector. It is of monostatic design that operates by sending sound pulses (“chirps”) upwards into the atmosphere. Each chirp passes through the air with some of the sound backscattered to the sodar. This returned signal is analysed to determine the wind speed, direction, standard deviation, inflow angle and other wind statistics at multiple height range bins above the sodar.

Converting the pulsed sound returns into meaningful data requires a number of steps. First, the signal is processed using proprietary software to derive a wind vector at each height bin above the ground. Post corrections are then applied to adjust for the temperature’s effect on the speed of sound and to covert the vector/volume wind speed to a scalar/point measurement (like an anemometer). Finally, automatic filtering is applied to the data to remove spurious data points.

Figure 1 FS1 Sodar undergoing validation

The Fulcrum FS1 Sodar has been deployed at a number of sites adjacent to tall masts in various locations around Australia. The purpose of these deployments has been to verify performance of the unit in a range of conditions. Included here is a summary of the key performance characteristics of these validation sites.

It should be noted that the sites against which the sodar has been tested are active wind farm development sites. Accordingly, they show characteristics which are typical of field operation, rather than “ideal” test facilities. Not all sites have IEC-compatible met masts for comparison, with a variety of instrumentation on each site. Some met masts exhibit logger timestamp drift due to the type of logger installed. Other have poorly chosen anemometers (e.g. using anemometers known to be affected by vertical inflow in complex terrain areas where vertical inflow is expected). Many sites exhibit additional challenges such as local vegetation, complex terrain, or background noise (e.g. crickets).

These effects all impact the potential for ideal correlations between sodar and mast. However, this real-world testing also provides a strong indication of the results that could be expected on a typical wind farm site.

2 Validation Background

Wind industry standard practice has been to use met masts with conventional anemometry for wind monitoring. This practice has evolved and a considerable body of knowledge developed around the accuracies and inaccuracies of this method. Accordingly, it is reasonable to compare the performance of the FS1 Sodar against traditional anemometry.

It is not practical to validate the performance of a sodar in a wind tunnel, due to the practicalities of building a wind tunnel over 200m high. Accordingly, to confirm the performance of a sodar it is necessary to carry out validation tests against well instrumented met masts. While in practice it is difficult to do this in ideal conditions, considerable confidence can be gained by developing a multitude of studies in different terrains and meteorological conditions.

This comparison serves two purposes:

- A fleetwide validation confirms that there is no inherent bias or error in the performance of the sodar design, a fact confirmed through development of a body of knowledge from a large number of validation studies in a variety of terrains and meteorological conditions; and,
- Individual unit validation which confirms that each unit is built to spec - various consultants recommend comparison against a met mast before (and sometimes after) a monitoring campaign for this reason.

This report provides an analysis of the fleetwide performance of the Fulcrum3D Sodar on the basis of accumulated results from a variety of validation studies. Deployment of the unit has been carried out at adjacent to a number of tall masts in varying terrain. The Sodar data has been processed using Fulcrum3D’s proprietary *CoreIP V3.3*.

3 Considerations in Validation Exercises

In this type of comparison there will always be differences between the met mast and sodar measurements. This is influenced by a number of factors including errors in measurements of cup anemometers, terrain or siting differences between the met mast and the sodar, and differences in the way that a cup and a sodar measure the wind flow. Each of these can be affected by the 'design' of the validation exercise, with a corresponding variability in the quality of results achieved. The primary differences to be considered in establishing the validation exercise are as follows:

- *Spatial differences* – The mast and sodar are located away from the tower 1.5 -2 times the height of the tower. This can result in differences in base height and exposure to different terrain and other features.
- *Height differences* -The base heights and measurement heights of the anemometers and sodar range bins may be different, meaning correction and approximation is required, however some differences will remain.
- *Clock synchronization* – Clock variation between the met mast logger and the sodar can result in the sodar and met mast recording over different periods. The larger the offset, the larger the difference. Aligning the clocks improves the correlation result, and in Fulcrum3D's experience even a time offset of a few minutes can impact the correlation coefficient (r-squared) by more than 1%.
- *Anemometer age and quality* – Anemometers which have been installed for a period of time can have degradation since the original calibration report, often through increased drag in bearings or more erratic performance. This can sometimes be detected by comparing two instruments on the same mast.
- *Overspeeding of anemometers* – Inherent in any anemometer is the feature that it responds more quickly to increasing wind speed than decelerating wind speeds. This delay in deceleration in called overspeeding which is dependent upon the square of the horizontal turbulence intensity.
- *Inflow angle impacts* - Different anemometer models are known to have errors as a result of inclined (off horizontal) flow which often occurs on complex sites or where high thermal mixing exists. The characteristics of this error is different for each anemometer model, but can exceed 10% on instantaneous measurements.
- *Mast shadow* – As with any wind assessments, mast shadow effects must be removed from the met mast data or erroneous results will occur.
- *Vector vs scalar measurement* – The FS1 Sodar records a vector average wind speed while cup anemometer records scalar averages. The vector wind speed is more representative of what wind turbines see during their operation. The difference on simple sites is often up to 2% while on complex sites can be as much as 5%.
- *Volume vs point measurement* – The FS1 Sodar records wind speeds over a volume while cup anemometers measure at a single point. These are two alternate measurement methodologies and result in output wind speed differences, even if recording at identical locations.
- *Sodar siting* – If a Sodar is located in an area which exhibits high flow curvature (known to artificially reduce apparent wind speeds) or significant vegetation (likely to increase fixed echoes and therefore reduce availability) the quality of the comparison will be affected.
- *Neutral atmospheric conditions* – These conditions can impact performance of the unit. When thermal turbulence is low, backscattering is reduced and so too is the ability of the unit to resolve a wind speed, resulting in lower availability and (sometimes) high correlation scatter. This is site and season specific.

Many of these possible differences are more likely to occur in complex terrain or when more complex wind flow exists at a site through things like stratification, high shear etc. It is therefore expected that the FS1 sodar would agree more closely with an adjacent tall mast on simple sites. For this reason, wind consultants generally apply broader criteria as being an acceptable performance in complex terrain. For example, DNV GL generally accepts performance within 2% (correlation slope) on simple terrain and 5% (correlation slope) on complex terrain.

4 Validation Process

The following process has been followed in order to derive the summary statistics present here.

1. Mast data was collected and fully checked. All bad data was removed through standard F3D processes including removal of mast shadow, check anemometer correlations and time series, verify direction, clock checked and transfer functions applied as required. Any other site specific checks undertaken. Any suspect data has been removed.

2. Sodar data was collected and standard F3D filtering applied and standard F3D QA applied including clock check, manual filtering of spurious values using sodar data only etc. These manually identified points were identified when comparing the sodar to other sodar range bin heights as well as the mast.

3. Data sets were time synchronized and compared using standard correlation and plotting techniques. Only concurrent heights between sodar and mast have been used in this comparison. In some case the sodar wind speed has been synthesized to match the mast height and this is clearly marked.

All statistics outlined in this document have been prepared by Fulcrum3D using a consistent approach. In parallel, external consultants including DNV-GL (formerly Garrad Hassan), Entura and Parsons-Brinckerhoff have also carried out a number of independent validations at various sites, and the results of these studies are generally consistent with the results outlined in this document.

5 Summary of Validation studies

The following table includes a summary of FS1 Sodar validation studies carried out to date, and shows the performance through slope, R2 and data availability (post filtering) over a number of deployments. The validation results included in this report are all based on Fulcrum3D's *CoreIP V3.3* processing software with its standard filters applied.

The following defines the column headings:

- *Site* – Sodar Serial Number and Site reference (in brackets)
- *Terrain* – simple or complex
- *Start Date / End Date* - refer to the comparison period
- *Weeks* – the number of weeks of comparison data available
- *Sodar Avail* – the percentage of time the sodar unit was operating during this period
- *Comparison* – sodar and mast height being compared, for example:
  - S60 = sodar at 60m AGL
  - S45* = synthesized sodar data at 45m (linear interpolation from other sodar range bins)
  - M84.5 = mast anemometer at 84.5m AGL
  - U80 = mast ultrasonic anemometer at 80m AGL using scalar averaging of ultrasonic anemometer
- *Slope* – sodar vs mast correlation based on the correlation of 10 minute samples. A value less than 1 means the sodar is reading less than the mast and vice versa
- R^2 – correlation coefficient squared based on the correlation of 10 minute samples.
- *Data Avail* – availability of the respective sodar range bin height for available data. Note, availability can be affected by siting issues (background noise, proximity to mast or other objects, met conditions) and is not particularly important for the validation study other than to ensure that sufficient data points exist for the purposes of the assessment.

Note, the correlation results outlined below related to a time-based correlation of coincident 10 minute samples. This approach differs from the approach proposed in the draft IEC standard which refers to correlation of 0.5m/s binned averages., and the results are not comparable. A binned averages approach would produce a significantly higher R2 (>0.99) which, while it appears improved, provides less information on the level of scatter apparent in the results.

As indicated earlier, there is expected to be greater variation between the sodar and mast on complex sites. This is evident in the results shown. On simple sites the slope is consistently within 2% of the masts in terms of wind speed value and R^2 are often over 0.97. On complex sites the slope us consistently within 5% and often within 2 % of the mast in terms of wind speed magnitude and R^2 is consistently over 0.96.

6 Conclusions

1. 20 separate validation trials have been carried out in both simple and complex terrain and across a variety of site conditions, meteorological conditions and seasons.

2. The median correlation slope from validations in simple terrain is 1.001, showing performance within 0.1% of mast anemometry.

3. The median correlation slope from validations in complex terrain is 0.996, showing performance with 0.4% of mast anemometry. This greater difference is to be expected in complex terrain. The slope being slightly below 1.00 is also expected as in complex terrain met masts are usually installed at the windiest location (top of ridge), hence terrain differences between the met mast and sodar would normally see the sodar measuring slightly below the met mast.

4. Median correlation coefficients (R^2) on a concurrent 10min time sample basis are 0.976 (simple sites) and 0.966 (complex sites) showing excellent scatter performance when compared with existing anemometry.

5. Data availability is acceptable at a median of 90% across all sites.

6. These results demonstrate excellent and consistent performance of the Fulcrum3D sodar unit in both simple and complex terrain across a variety of sites.

Table 1 – Validation results in simple terrain

Unit (Site)	Terrain	Start Date	End Date	Weeks	Sodar Avail	Comparison	Slope	R^2	Data Avail
FS1M_1004 (BALC)	Simple	22-Sep-12	16-Nov-12	7.9	100%	S60-M60	1.000	0.954	80%
						S85*-M84.5	1.017	0.977	92%
FS1M_1005 (BALB)	Simple	28-Nov-12	6-Dec-12	1.1	95%	S60-M60	1.017	0.969	91%
						S85*-M84.5	1.017	0.976	97%
FS1M_1005 (MTF)	Simple	10-Jul-13	28-Oct-13	15.7	100%	S70-M70	0.992	0.980	92%
						S80-M80	0.992	0.982	91%
FS1M_1007 (BALA)	Simple	18-Apr-12	10-Jun-12	7.6	99%	S60-M60	0.995	0.963	88%
						S85*-M84.5	0.998	0.972	89%
FS1M_1010 (BAD)	Simple	23-Jan-13	21-Mar-13	8.1	100%	S80-M78	1.002	0.976	93%
						S80-M80	1.013	0.974	93%
FS1M_1014 (BALD)	Simple	22-Jun-13	30-Jul-13	5.4	99%	S60-M60	0.972	0.973	88%
						S85*-M84.5	0.993	0.980	88%
FS1M_1016 (DUNA)	Simple	26-May-13	20-Oct-13	21.0	95%	S60-M60	0.995	0.982	89%
						S85*-M84.5	1.002	0.991	90%
FS1M_1018 (LWL)	Simple	27-Sep-13	14-Nov-13	6.9	98%	S60-M60	1.000	0.971	90%
						S80-M79	1.010	0.974	88%
						S80-M81	1.000	0.975	88%
FS1M_1019 (LHD)	Simple	24-Dec-13	2-Feb-14	5.7	100%	S90-M92	1.001	0.986	96%
						S80-M80	1.011	0.986	96%
						S60-M60	1.011	0.984	96%
						S45*-M45	1.003	0.984	97%
MEDIAN (SIMPLE SITES ONLY)							**1.001**	**0.976**	**91%**
MEAN (SIMPLE SITES ONLY)							**1.002**	**0.977**	**91%**
MINIMUM (SIMPLE SITES ONLY)							**0.972**	**0.946**	**76%**
MAXIMUM (SIMPLE SITES ONLY)							**1.017**	**0.986**	**97%**
STANDARD DEVIATION (SIMPLE SITES ONLY)							**0.011**	**0.008**	**4.1%**

**Sodar data synthesized via linear interpolation. Synthetic data is only used where the mast and sodar measurement heights differ by more than 2 metres.*

Table 2 – Validation results in complex terrain

Unit (Site)	Terrain	Start Date	End Date	Weeks	Sodar Avail	Comparison	Slope	R^2	Data Avail
FS1M_1002 (LVP5)	Complex	13-May-13	1-Sep-13	15.9	92%	S80-M81	0.959	0.963	94%
FS1M_1003 (BIR)	Complex	14-Nov-12	15-Sep-13	43.6	84%	S60-M60	0.942	0.962	91%
FS1M_1011 (GDG)	Complex	26-May-12	15-Jul-12	7.1	98%	S60-M60	0.981	0.971	87%
						S71-M70	0.972	0.974	88%
FS1M_1012 (S01R)	Complex	10-Dec-13	6-Jan-14	3.9	100%	S50-M52	0.999	0.961	92%
						S80-M79.5	0.997	0.96	77%
FS1M_1012 (S01T)	Complex	10-Dec-13	6-Jan-14	3.9	100%	S50-M52	0.982	0.963	92%
						S80-M79.5	0.992	0.964	77%
						S80-U79.5	0.998	0.963	77%
FS1M_1013 (S25R)	Complex	10-Dec-13	6-Jan-14	3.9	100%	S50-M52	0.997	0.967	93%
						S80-M79.5	0.999	0.969	86%
						S80-U79.5	1.000	0.972	86%
FS1M_1013 (S25T)	Complex	10-Dec-13	6-Jan-14	3.9	100%	S50-M52	0.993	0.966	93%
						S80-M79.5	0.996	0.97	86%
						S80-U79.5	0.997	0.973	86%
FS1M_1013 (S26R)	Complex	10-Dec-13	6-Jan-14	3.9	100%	S50-M52	1.013	0.969	93%
						S80-M79.5	1.016	0.977	86%
						S80-U79.5	1.009	0.977	86%
FS1M_1013 (S26T)	Complex	10-Dec-13	6-Jan-14	3.9	100%	S50-M52	1.019	0.960	93%
						S80-M79.5	1.015	0.965	86%
						S80-U79.5	1.015	0.965	86%
FS1M_1018 (S65R)	Complex	20-Nov-13	6-Jan-14	6.7	100%	S50-M52	0.988	0.961	88%
						S80-M79.5	1.000	0.971	93%
						S80-U79.5	1.003	0.972	93%
FS1M_1018 (S65T)	Complex	20-Nov-13	6-Jan-14	6.7	100%	S50-M52	0.968	0.953	88%
						S80-M79.5	0.989	0.966	93%
						S80-U79.5	0.991	0.966	93%
MEDIAN (COMPLEX SITES ONLY)							**0.997**	**0.966**	**88%**
MEAN (COMPLEX SITES ONLY)							**0.994**	**0.967**	**88%**
MINIMUM (COMPLEX SITES ONLY)							**0.942**	**0.953**	**77%**
MAXIMUM (COMPLEX SITES ONLY)							**1.019**	**0.977**	**94%**
STANDARD DEVIATION (COMPLEX SITES ONLY)							**0.018**	**0.006**	**5.1%**

Table 3 - Combined validation results in both simple and complex terrain

	Slope	R^2	Data Avail
MEDIAN (ALL SITES)	**0.999**	**0.971**	**90%**
MEAN (ALL SITES)	**0.997**	**0.971**	**89%**
MINIMUM (ALL SITES)	**0.942**	**0.953**	**77%**
MAXIMUM (ALL SITES)	**1.019**	**0.991**	**97%**
STANDARD DEVIATION (ALL SITES)	**0.016**	**0.009**	**4.8%**