FS1 SODAR PERFORMANCE VALIDATION

FS1M_1019 Performance Validation

Date: 14 February 2014

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1 Introduction

A Fulcrum3D FS1 Sodar, FS1M1019, has been installed adjacent to a well instrumented 90m met mast located in Northern Tasmania. Terrain at the location is such that it can be assumed that conditions at the mast and sodar are similar and is an appropriate choice as a Sodar validation location.

Data from both sources has been collected and placed through standard filtering processes. This validation aims to confirm the performance of the FS1 Sodar by confirming the accuracy of its measurements against an IEC compliant met mast.

2 Site Description

The monitoring site is located in Northern Tasmania and is generally considered a simple site. Some low vegetation and gentle undulations exist but, in general, the location is appropriate for validating the performance of the Fulcrum3D sodar against cup anemometers. There is some taller vegetation about 2km from the mast but it is not anticipated that this will impact the mast or sodar location for the purpose of this validation. Figure 1 shows the mast and sodar locations approximately 100m apart and on 10m contours.

Figure 1: Site map

3 Mast Description

3.1 Installation details

The mast is a 90m lattice mast which contains instrumentation at a number of heights. Thies First Class Advanced instruments are installed on the mast at 92.6m (x 2), 79.0m, 60.0m, 45.0m and 10.0m. Thies First Class wind vanes are installed at 88.6m, 59.4m and 44.9m. An RM Young vertical wind speed sensor is installed at 89.0m. Temperature and

relative humidity are installed at both 88.0 and 10.0m. All mounting is fully IEC compliant based upon details provided in the mast installation report.

The instruments were commissioned late September 2012 and have to our knowledge been well maintained. More recently, in May 2013, the logger was replaced to repair a communications problem. Met mast logger time stamps have been synchronized with the sodar and confirmed as end timestamps. The mast base elevation is approximately 48m above sea level.

Mast data including calibration certificates has been provided to Fulcrum3D and anemometer calibrations verified by Fulcrum3D. All data has been filtered to remove erroneous data, mainly mast flow distortion at this site and combining the 2 x 92.6m instruments into a single measurement.

3.2 Mast self-correlations

Self-correlations have been carried out between the mast instrument pairs to confirm the performance of each instrument. Only concurrent filtered data in each pairing was carried out (i.e. excluding those direction sectors where lower instruments are affected by mast shadow). The results are shown in Table 1 and Figure 2 and Figure 3.

Table 1: Mast anemometer self-correlations

Instrument A	Instrument B	R-squared	Line of best fit	Discrepancy (%)
92.6m (L)	92.5m (R)	1.000	Y = 0.999x	0.1
92.6m (L)	79m	0.998	Y = 1.025x	NA
92.6m (R)	79m	0.998	Y = 1.026x	NA
79m	60m	0.994	Y = 1.048x	NA
60m	45m	0.995	Y = 1.049x	NA
45m	10m	0.932	Y = 1.263x	NA

No material anomalies have been detected in the mast data and the correlation performance is within expectation.

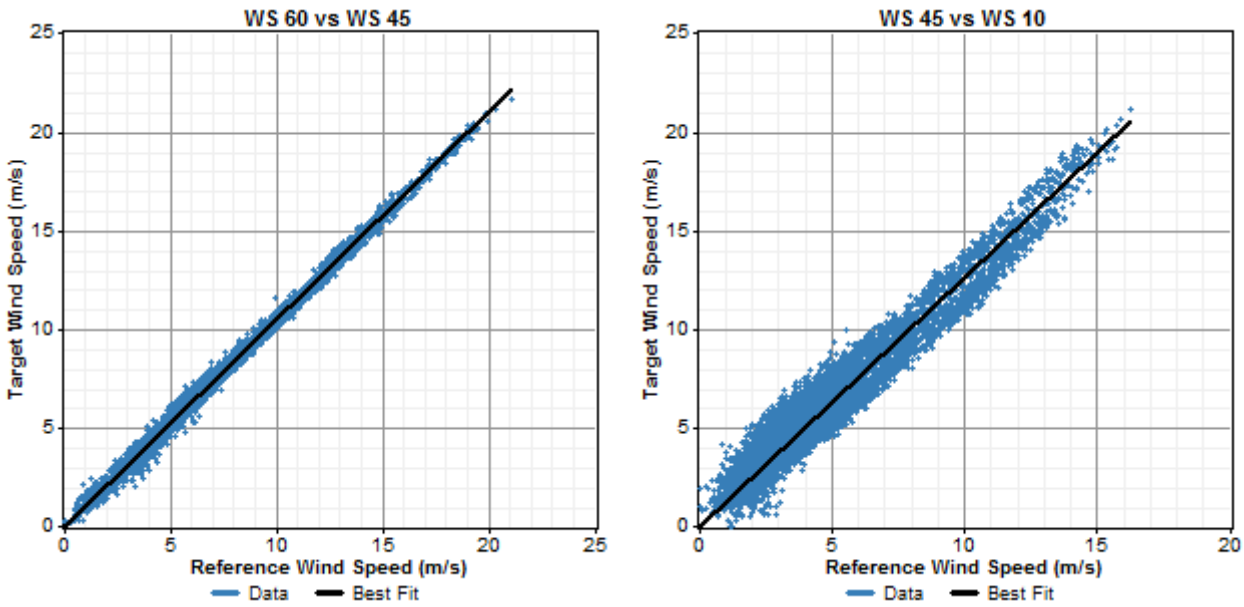

Figure 2: Mast to mast correlations for lower instruments

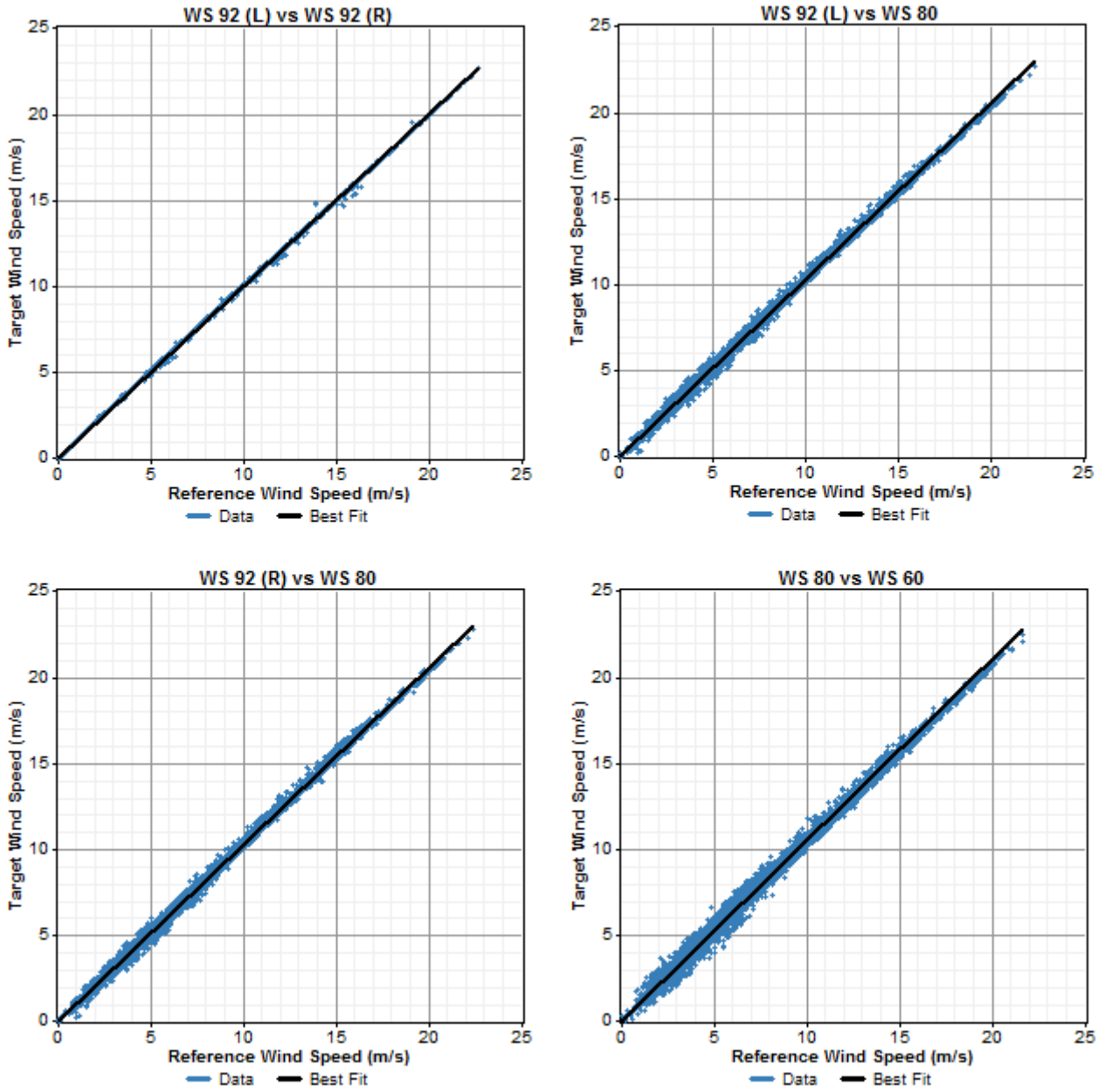

Figure 3: Mast to mast correlations for upper instruments

3.3 Mast data availability

Data from the mast has been used from 24th December 2013 – 2nd February 2014 which gives a reasonable coverage of data from all direction and wind speed bins and is therefore appropriate for validation of the sodar performance.

The mast booms are located at approximately 162 and 330 degrees depending on the instrument. Wind recovery plots indicated that data in the range 145 to 180 degrees is affected for all instruments except the 92.6m which was 310 to 350 degrees. All data within these ranges was removed from this analysis. Mast disturbance can be seen in the mast ratio plot in Figure 4. Since 2 x instruments were installed at 92.6m it is possible to remove mast influences at this height by using an average at that height.

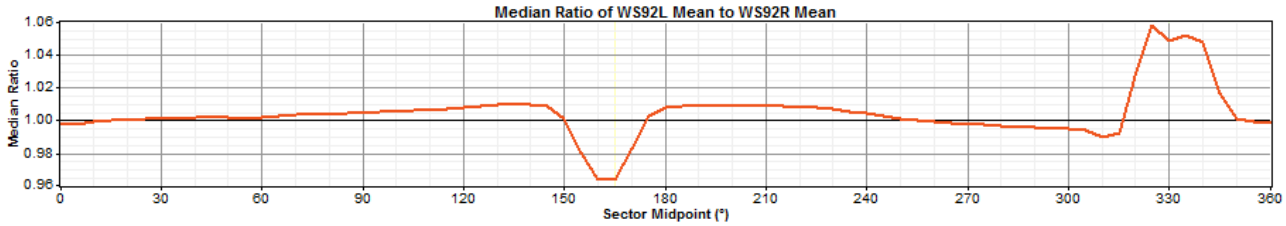

Figure 4: Wind speed ratio by direction indicating mast flow impacts

Removing this data does have the effect of reducing data availability of the mast to roughly 96% at all heights except 92.6m where data capture was 100% during the overlap period with the sodar since the top two instruments have been combined.

While lower heights of the met mast have reduced availability, these are not uniformly distributed with direction and accordingly could potentially introduce a bias (e.g. in extrapolating wind shear at the site).

4 Sodar Description

4.1 Installation Details

The Fulcrum3D FS1 sodar FS1M_1019 was deployed 102m approx. south west of the mast location. It was set up oriented to true north and leveled. The unit was recording data in single beam mode and in 10m range bins from 40m – 150m above ground level in order to maximize overlap with the adjacent mast.

Figure 5: Mast and Sodar locations with aerial image (mast in red and sodar in blue)

The sodar was commissioned on the afternoon of the 23 Dec 2013 and no changes to sodar configuration have occurred since that date. The sodar timestamp is automatically set to UTC+Offset based on the internet time protocol. The sodar base elevation is approximately 52m.

The data from the FS1 Sodar has been processed using V3.3 software and filtered according the standard Fulcrum3D FS1 filtering recommendations (see Appendix A). A manual check of the data was also carried out and a small number of erroneous/outlying data points were removed.

4.2 Sodar SNR

The average SNR for each FS1 Sodar range bin height is included in Figure 6 below. Of note is the general trend of the SNR to reduce with height, with the exception of the 40m range bin. Generally an SNR above 7 is deemed to be acceptable. In this case data from 40 – 150m is of acceptable SNR.

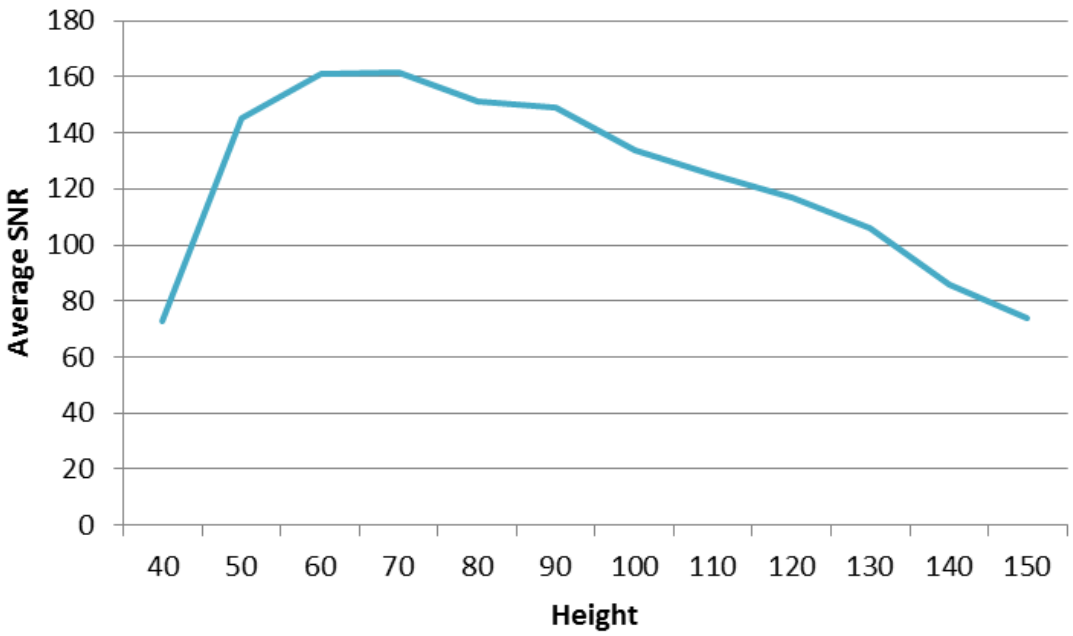

Figure 6: Average Sodar SNR by range bin height

4.3 Sodar self-correlations

Sodar self-correlations have been carried out between adjacent height range bin. As can be seen in Figure 7, data above 40m shows strong correlations, notwithstanding some useful data being available below the recommended data range. The coefficient of determinations R^2 are within the range 0.976 to 0.986 indicating strong agreement between the range bins on the FS1.

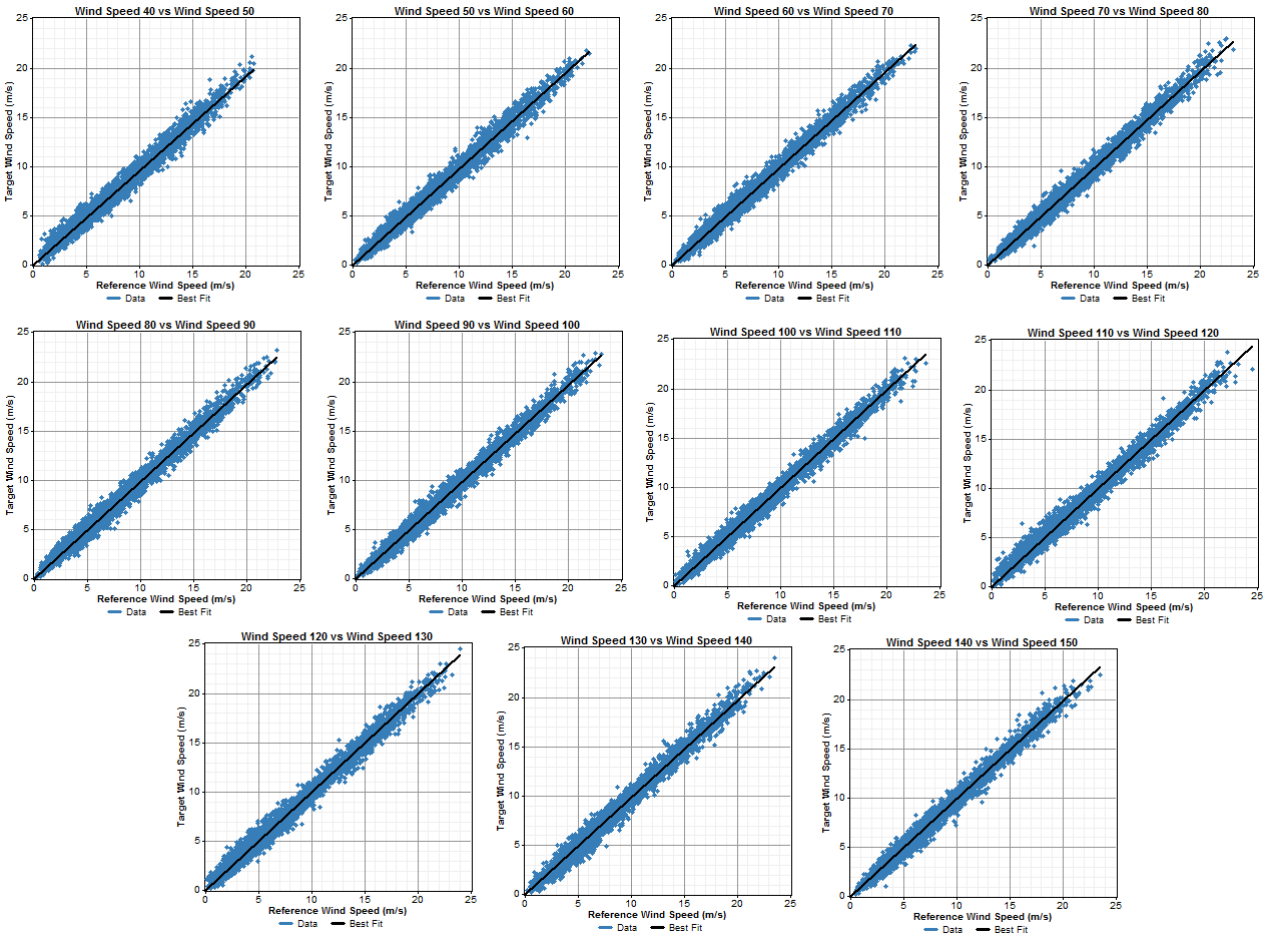

Figure 7: Sodar to Sodar scatter plots

4.4 Sodar data availability

Data from the FS1M_1019 unit has been included from 24th December 2010 to 2 February 2014.

Sodar availability vs time of day has been investigated to determine whether any local site effects (background noise, local site atmospheric conditions) have affected data recovery in a way which may introduce a diurnal bias. By adding up the number of records in each hour of the day during the entire deployment the range was found to be 224 to 246. The narrow range indicates excellent data capture throughout the day, with no potential for diurnal bias present.

Availability has also be investigated by wind speed bins and direction sectors. Again the results show a uniform distribution of data availability and accordingly the typical reduction in availability does not appear to introduce any bias.

5 Analysis

5.1 Data Availability

Both the mast and the sodar have had 100% operating availability during the monitoring period.

Figure 8 below summarises the data availability of both the mast and sodar during the monitoring period. These values show the remaining data available after filtering over the full deployment date range.

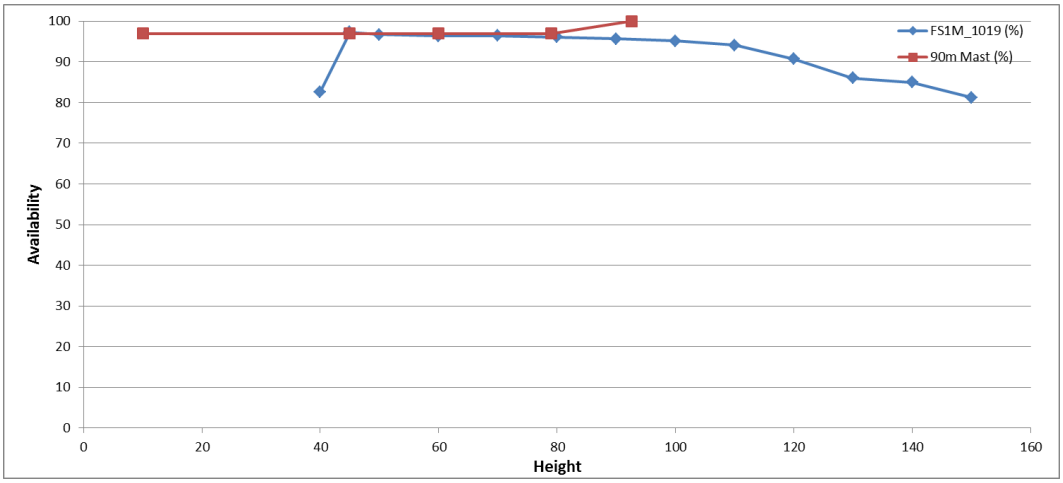

Figure 8: Mast and Sodar availability plot

Of note is that a synthesized sodar height of 45m has been calculated and used throughout this validation in conjunction with other concurrent heights. This height was synthesized by applying log law between 40m and 50m for each 10 minute period using Windographer v3.1.11.

Due to the proximity of measurements:

- the 79m mast has been directly compared with the 80m Sodar range bin. Accordingly the sodar measurement would be expected to measure very slightly more than the mast measurement; and

- the 92.6m mast has been directly compared with the 90m Sodar range bin. Accordingly the sodar measurement would be expected to measure slightly less than the mast measurement.

For relevant aspects of this analysis (in particular the shear comparison) a concurrent data set has been produced. This includes only time stamps where all devices between 40m and 110m recorded valid data. This process has resulted in a lower availability for some aspect of the validation but is deemed appropriate for the purpose of the shear comparison.

5.2 Wind Speed Comparison

It is important when validating the performance of any device that representative wind speeds exist during the monitoring period. Table 2 below shows the data counts for Sodar data above and below 10m/s. Of note is that there is a significant number of data points above 20m/s and good coverage of the wind speed range.

Table 2: Valid data count above and below 10 m/s

Height	4-10m/s	>10m/s
40	3,709	1,170
45 (Synth)	4,421	1,327
50	4,382	1,327
60	4,363	1,326
70	4,368	1,325
80	4,347	1,327
90	4,324	1,323
100	4,303	1,316
110	4,246	1,308
120	4,067	1,290
130	3,863	1,215
140	3,916	1,101
150	3,804	994

5.3 Horizontal wind speed validation

5.3.1 Horizontal wind speed correlations

There are a number of heights where concurrent filtered data exists for both the mast and sodar. Presented here are the wind speed correlations for these heights.

Figure 9 demonstrates the strong correlation that exists at the concurrent heights of 90, 80, 60 and 45m. Figure 10 shows correlations for non-concurrent heights. On each plot the best fit fixed through the origin and coefficient of determination (R^2) are included. In each case the sodar is on the y axis and mast on the x axis.

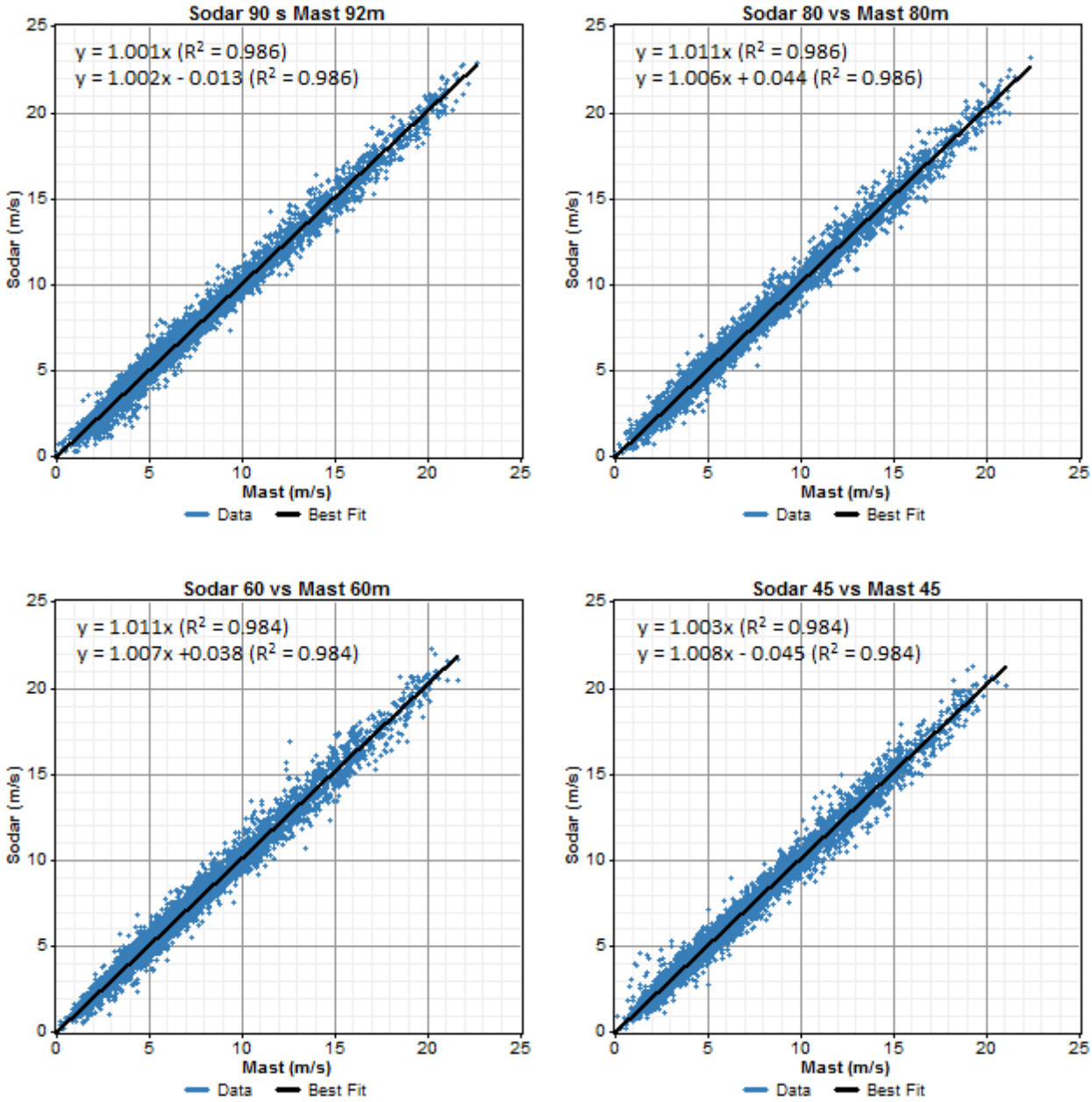

Figure 9: Wind speed correlation between sodar for concurrent heights

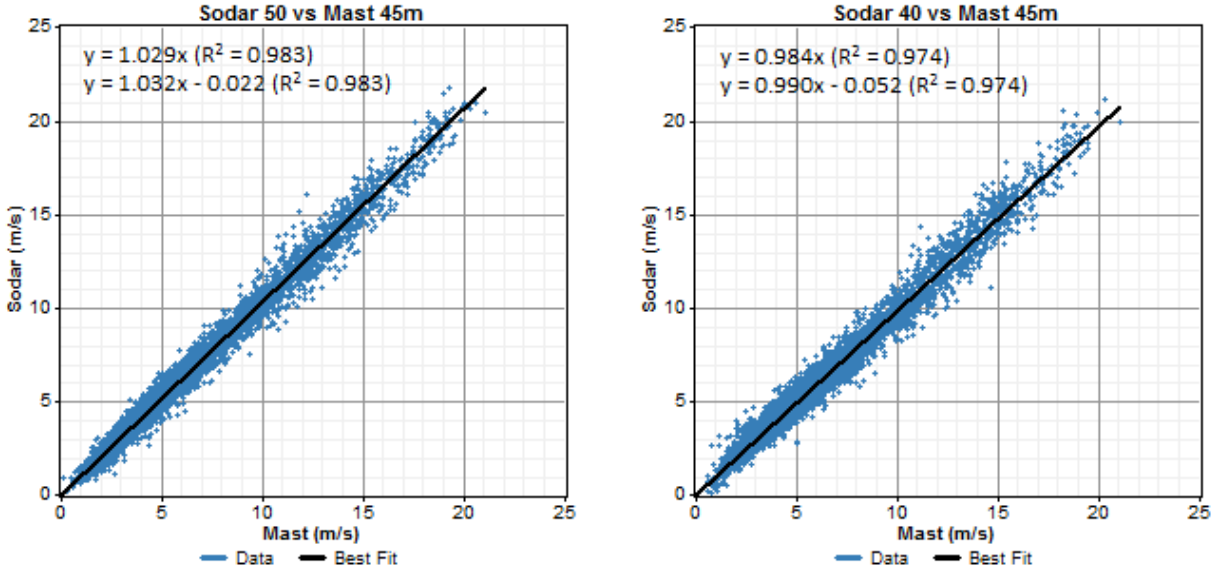

Figure 10: Wind speed correlations between sodar and mast for non-concurrent heights

At all concurrent heights the slope is between 1.001 to 1.011 indicating excellent performance of the sodar in measuring the wind speed magnitude. Coefficients of determination (R^2) are between 0.983 and 0.986 on a 10min sample basis, which is also excellent performance considering the differences in location between the mast and sodar. At non-concurrent heights, the slope is within expectations for the height differences between the mast and sodar and the R^2 remains excellent. Table 3 summarises the performance at the concurrent and non-concurrent heights.

Table 3: Wind Speed correlation summary

Sodar Height (m)	Mast Height (m)	Slope	R2
40	45	0.984	0.974
45 (synth)	45	1.003	0.984
50	45	1.029	0.983
60	60	1.011	0.984
80	79	1.011	0.986
90	92.6	1.001	0.986

These results compare well with the slope and R^2 demonstrated between cup anemometers on the validation met mast which range from 1.001 to 1.011 and 0.983 to 0.986 respectively.

5.3.2 Horizontal wind speed distributions

When validating the performance of the sodar it is important to consider what similarity exists in the wind speed distributions between the mast and sodar. Figure 11 shows these distributions for concurrent heights and all timestamps (ie not necessarily concurrent time stamps) of both the sodar and mast, indicating strong agreement. Considering that the mast and sodar could have different availabilities, agreement is strong and indicates little evidence of bias as a result of availability differences between the mast and sodar. Figure 12 shows wind speed distributions for non-concurrent heights and also indicates close agreement between the mast and sodar.

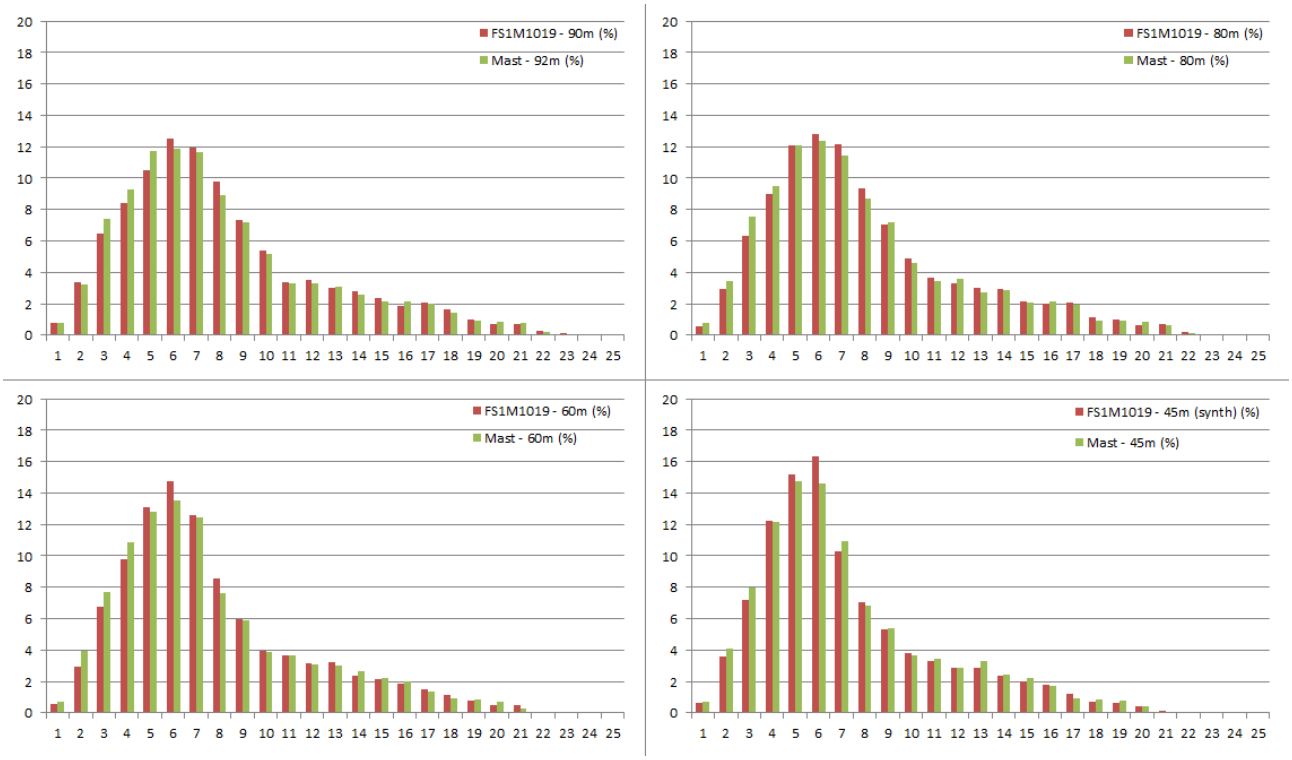

Figure 11: Wind speed distributions for concurrent heights

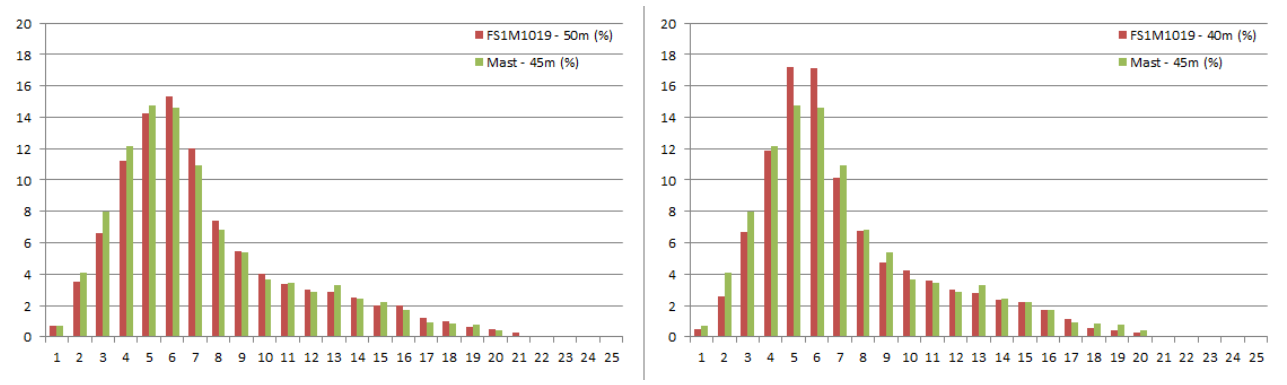

Figure 12: Wind speed distribution for non-concurrent heights

5.3.3 Horizontal wind speed differences

Another measure of spread in the wind speed data is to look at the distribution of the difference between the mast and sodar wind speed to determine if any bias is apparent. Figure 13 demonstrates the difference between the mast and sodar at concurrent heights only. You can see that bias is low and the spread is also low indicating strong performance of the sodar relative to the mast. Figure 14 shows the same for non-concurrent heights. Spread in the data is also low and the bias is as expected for the height difference between the mast and sodar also indicating good sodar performance.

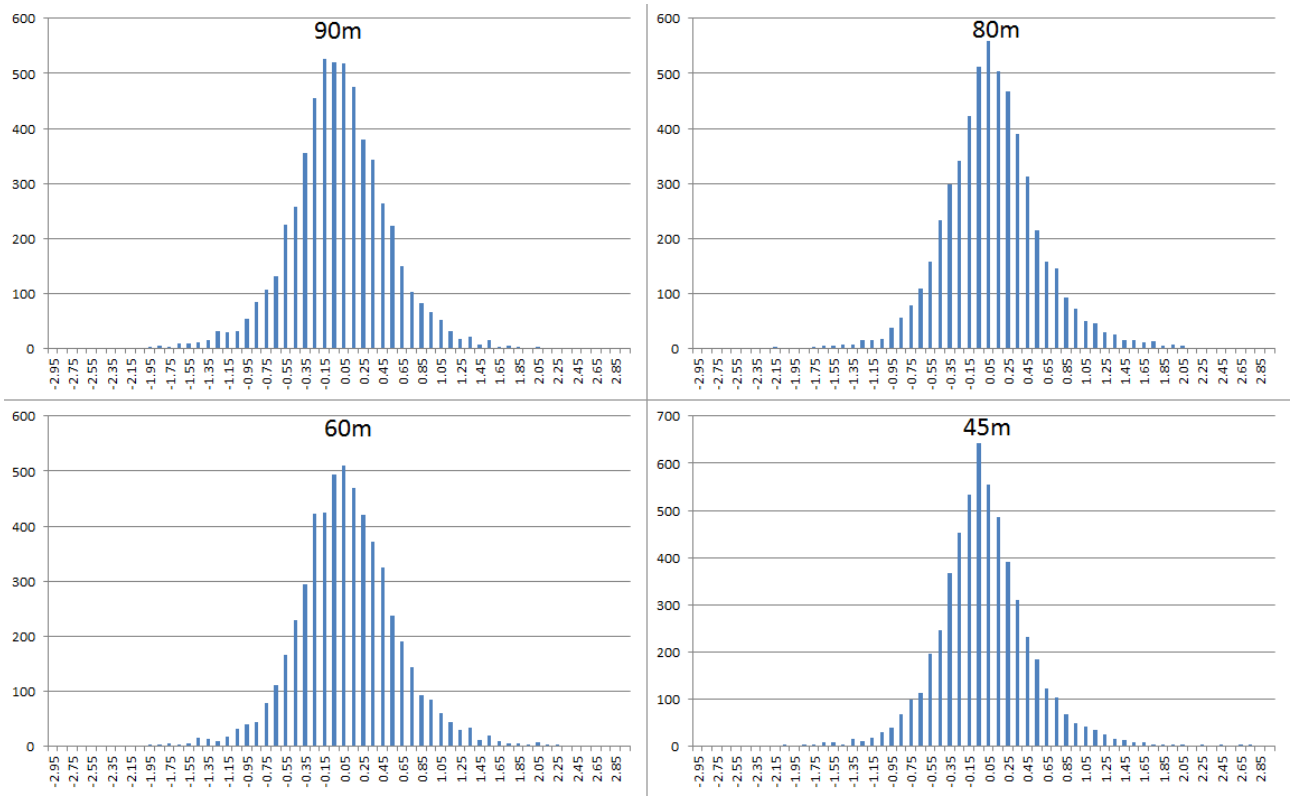

Figure 13: Wind speed difference (sodar - mast) for concurrent heights

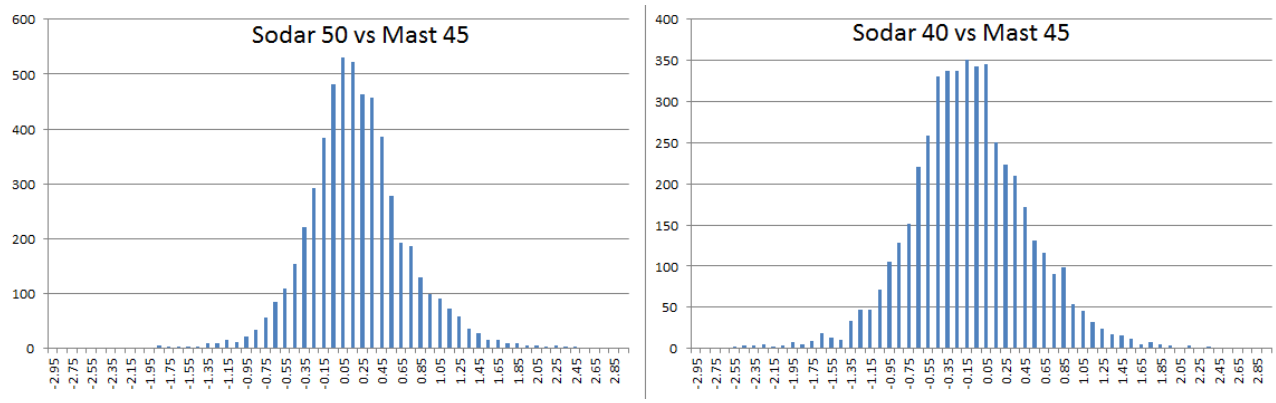

Figure 14: Wind speed difference (sodar - mast) for non-concurrent heights

5.4 Turbulence intensity

Wind speed standard deviation and turbulence intensity are related and important on a wind farm site. Figure 15 shows correlation plots of sodar vs mast wind speed standard deviation. There is a clear correlation evident. These wind speed standard deviation measurement have been used in Figure 16 to apply the IEC 61400-1 3rd edition. Again, there is relative agreement between the FS1 and reference mast.

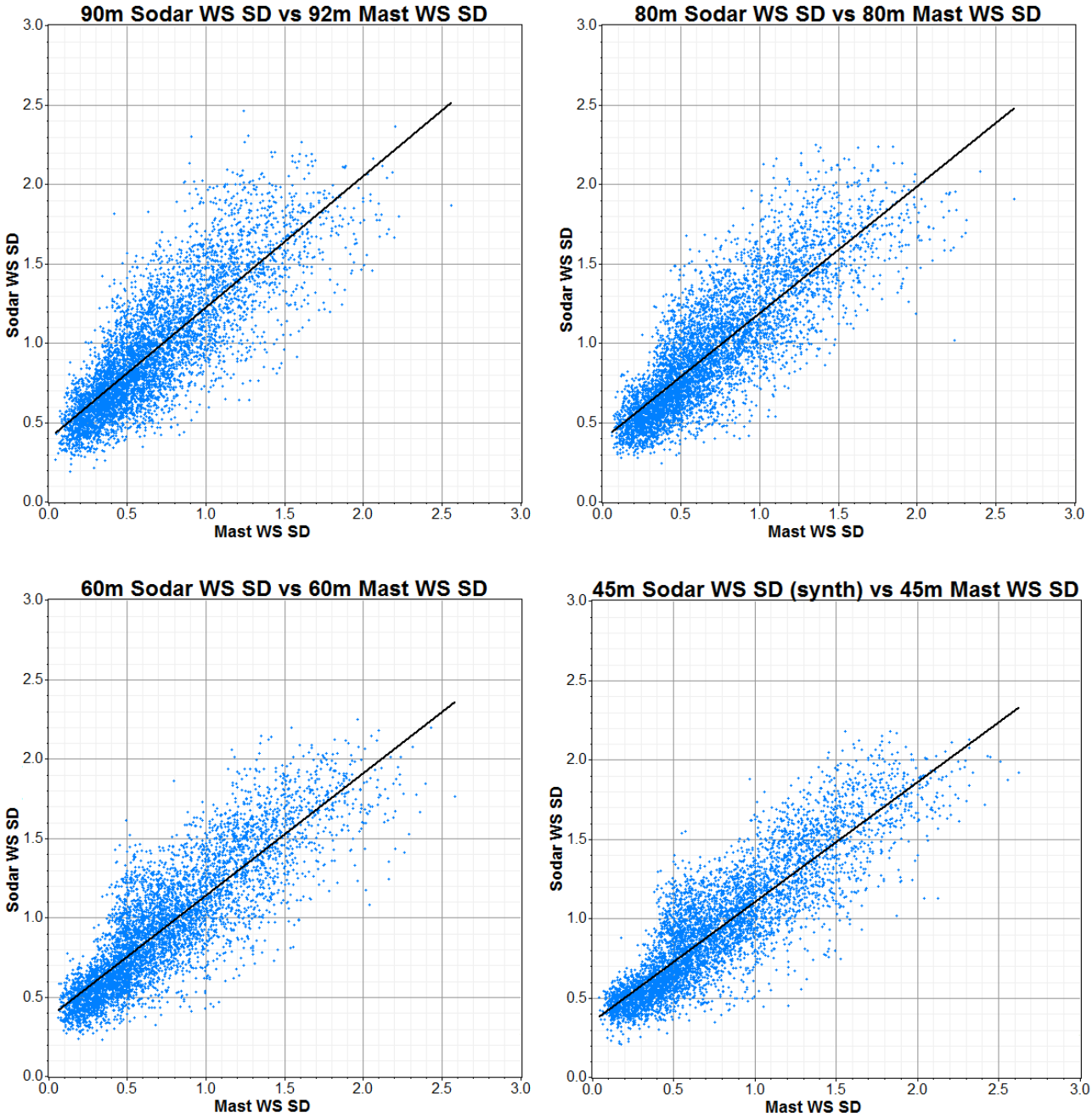

Figure 15: Correlation plots between sodar and mast wind speed standard deviation

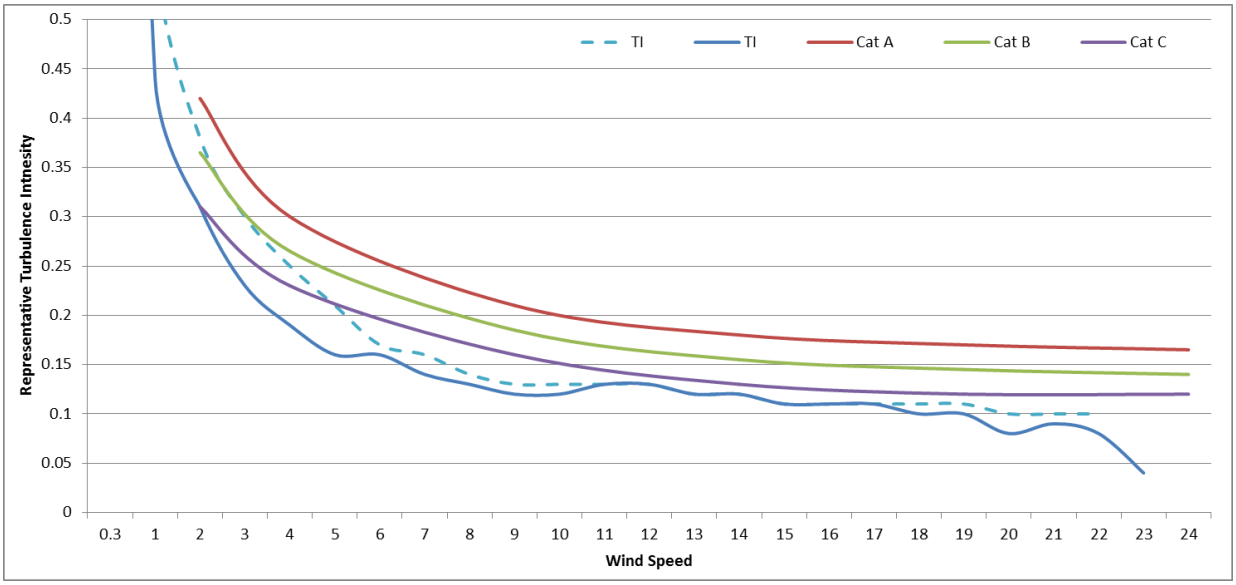

Figure 16: Representative Turbulence from Sodar and Mast relative to IEC standard 61400-1 3rd edition

5.5 Wind Shear

Understanding wind speed with height is important for many aspects of the wind farm process. Concurrent data between 40m and 110m for all devices has been used to calculate shear. Figure 17 shows wind shear at the site with a best fit curve for both the mast and sodar. A close agreement can be seen.

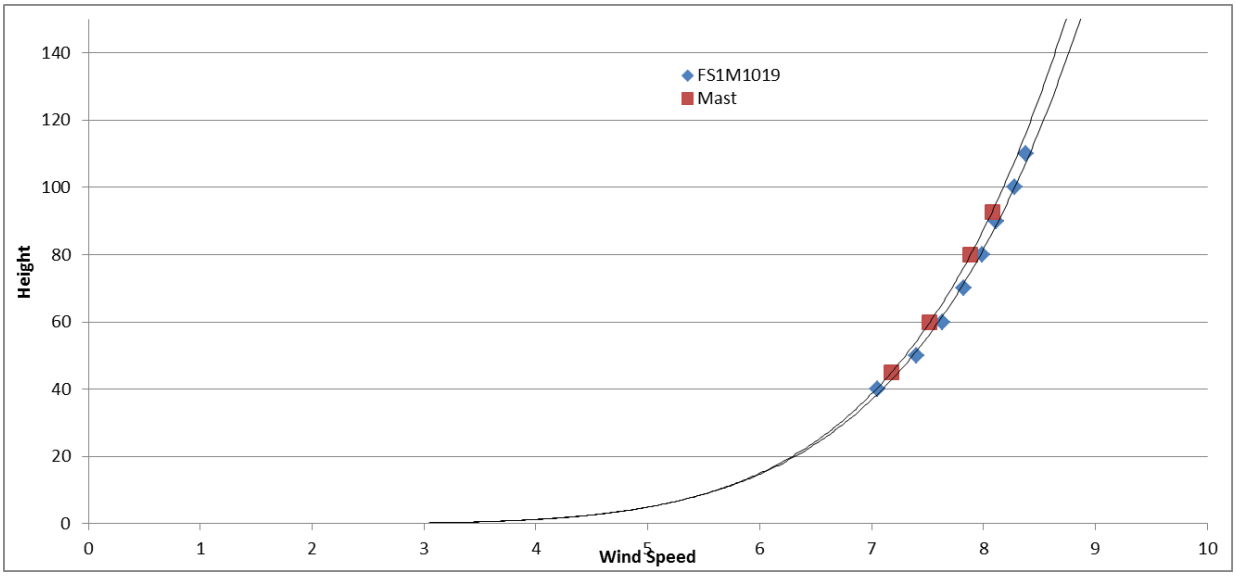

Figure 17: Wind shear plot including best fit curves

Additionally, the shear exponent has been calculated and is shown in Table 4. At this site, the mast and sodar give identical values within the overlapping region indicating excellent performance by the sodar. Also, the shear exponent over the full range of the sodar is very close to that measured by the mast as shows in Table 4 and Figure 18.

Table 4: Shear exponent for mast and sodar

Shear	Mast (45-92.6m)	Sodar (40-110m)	Sodar (40 – 150m)
Shear	0.16	0.17	0.17

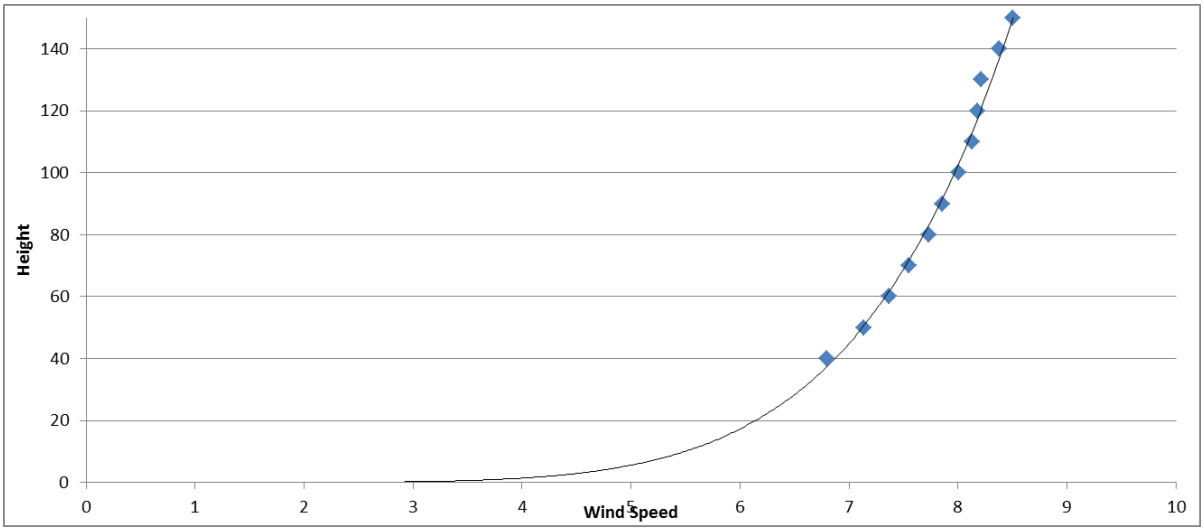

Figure 18: Shear profile as measured by the sodar at all heights

5.6 Horizontal wind direction

Figure 19 and Figure 20 show the wind direction correlation between mast and sodar at concurrent heights. Figure 19 shows the same for non-concurrent heights and Figure 20 the concurrent heights. In each case, strong agreement is evident, as demonstrated with R^2 ranging from 0.992 – 0.999 for concurrent heights and strong linearity. This metric again indicates excellent FS1 sodar performance.

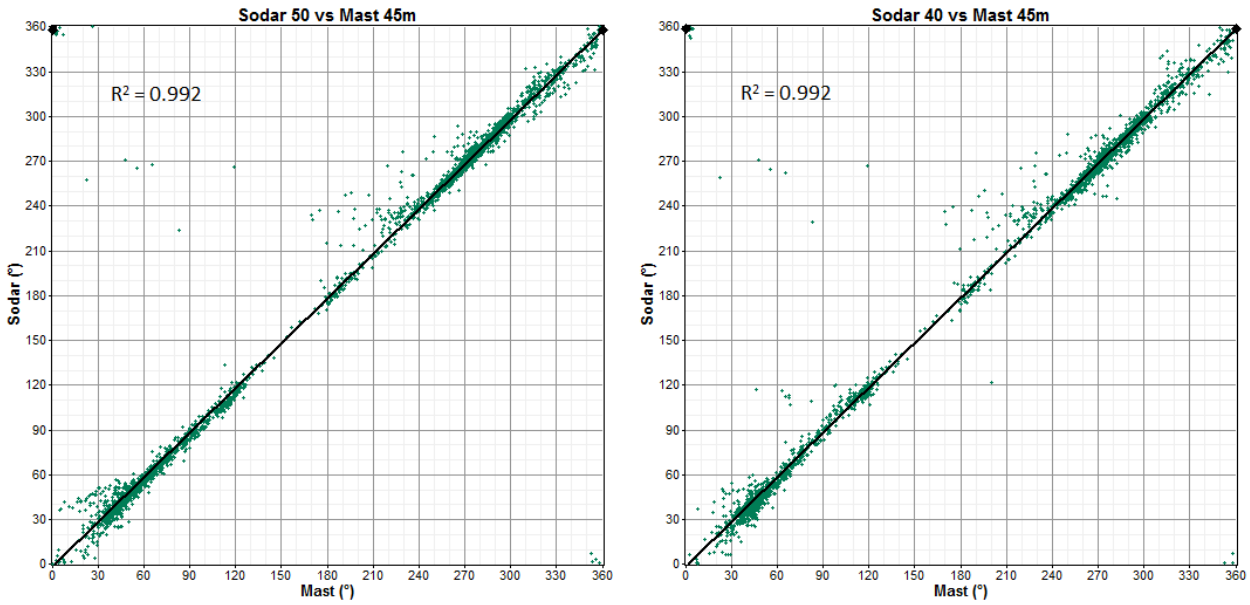

Figure 19: Wind direction correlation for non-concurrent heights (only wind speed above 5m/s)

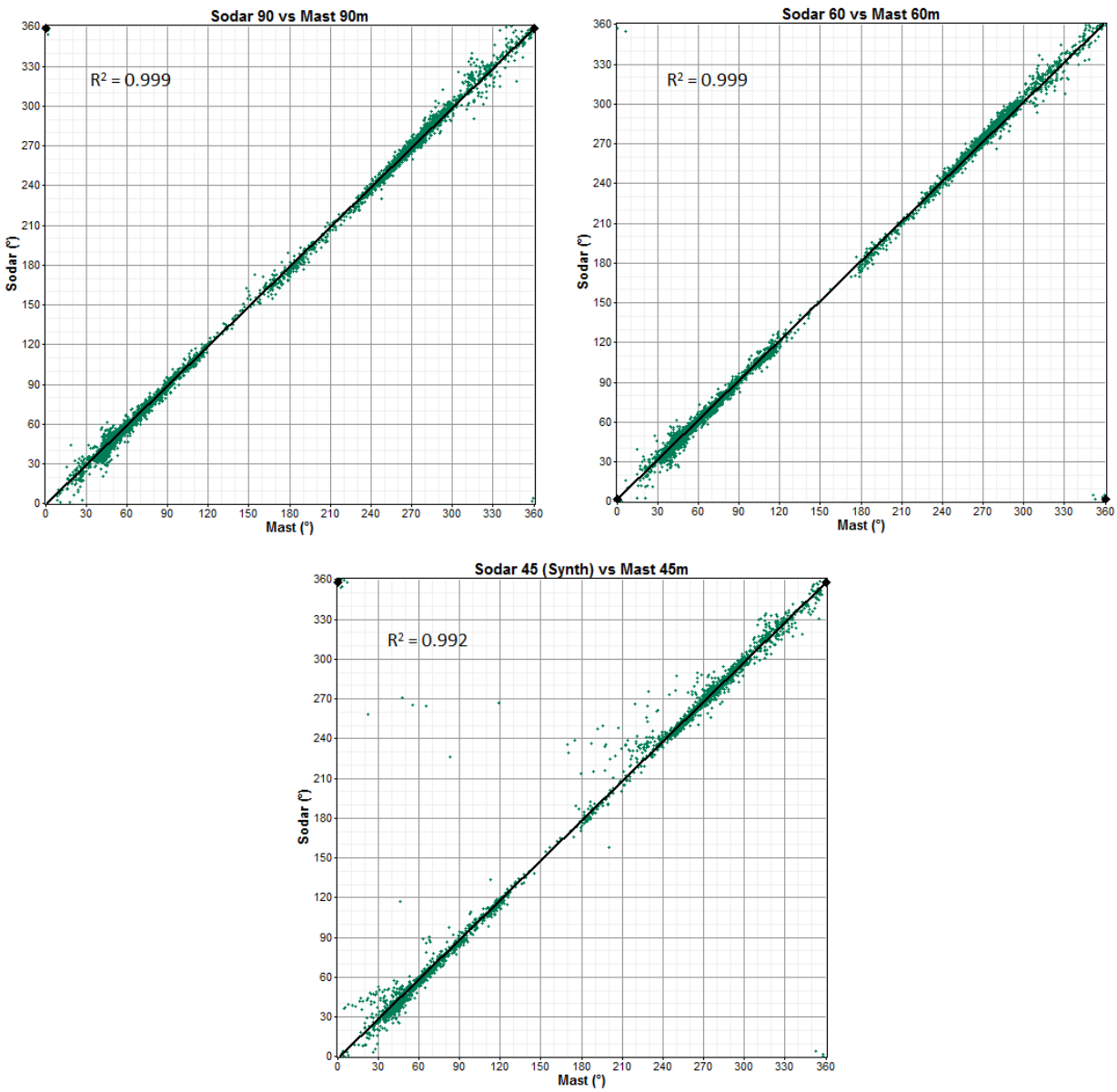

Figure 20: Wind direction correlation for concurrent heights (only wind speed above 5m/s)

5.7 Vertical wind flow

One of the key benefits of the FS1 sodar is that it can measure inflow angles. This mast is equipped with a vertical wind speed propeller at 89m. Given the flat conditions at the site it would be expected that consistent inflow angles would be measured regardless of direction or horizontal wind speed, and that these inflow angles would be approximately zero.

Figure 21 shows inflow angle as a function of horizontal wind speed. It demonstrates that the mast vertical inflow angle measurements are dependent on the horizontal wind sped while that measured by the FS1 are not. While the mast sensor is theoretically unaffected by the horizontal component, any error in its installation (tilt) would expose the sensor to horizontal wind speeds affecting its vertical plane, introducing errors, perhaps similar to what is being seen at this site. Figure 22 further demonstrates a dependency between mast vertical wind speed and horizontal wind speed in showing mast vertical wind speed as a function of direction and coloured by horizontal wind speed. Perhaps more telling in Figure 22 is , however, the sinusoidal pattern of the vertical wind speeds, further supporting an installation tilt of the instrument. By contrast, no dependency is evident in the sodar as shown in Figure 23. Whilst this

assessment is not conclusive in determining performance of the sodar or the mast, it is clear that installation tilt is impacting the mast measurements of this parameter and the sodar measurements are in line site expectations.

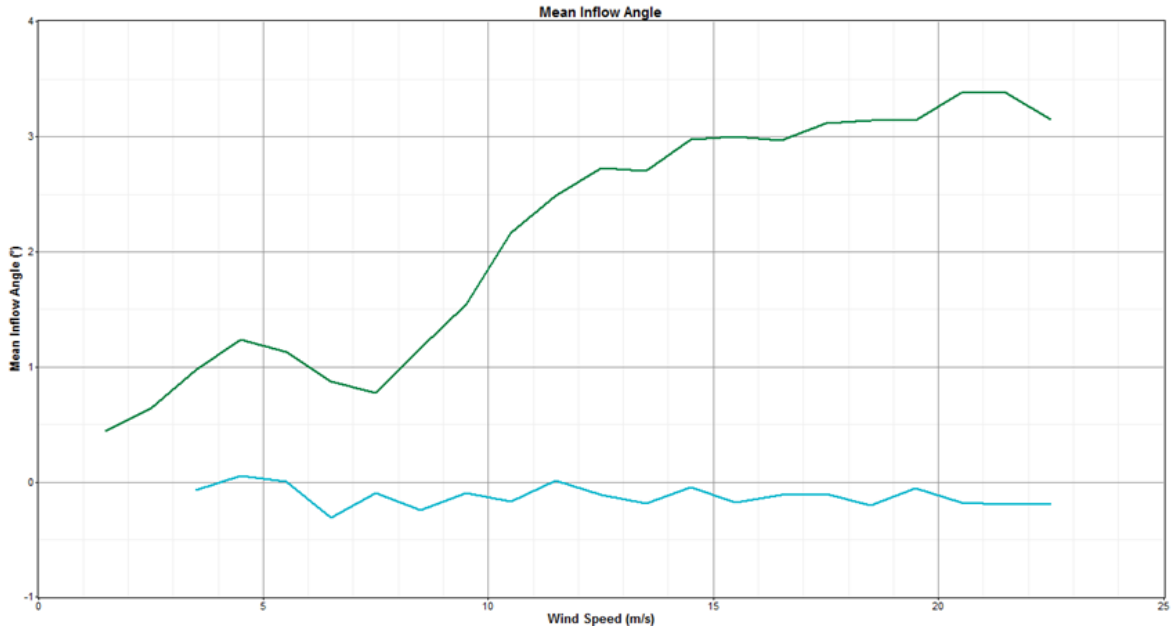

Figure 21: Mean inflow angle as a function of wind speed (blue is sodar and green is mast)

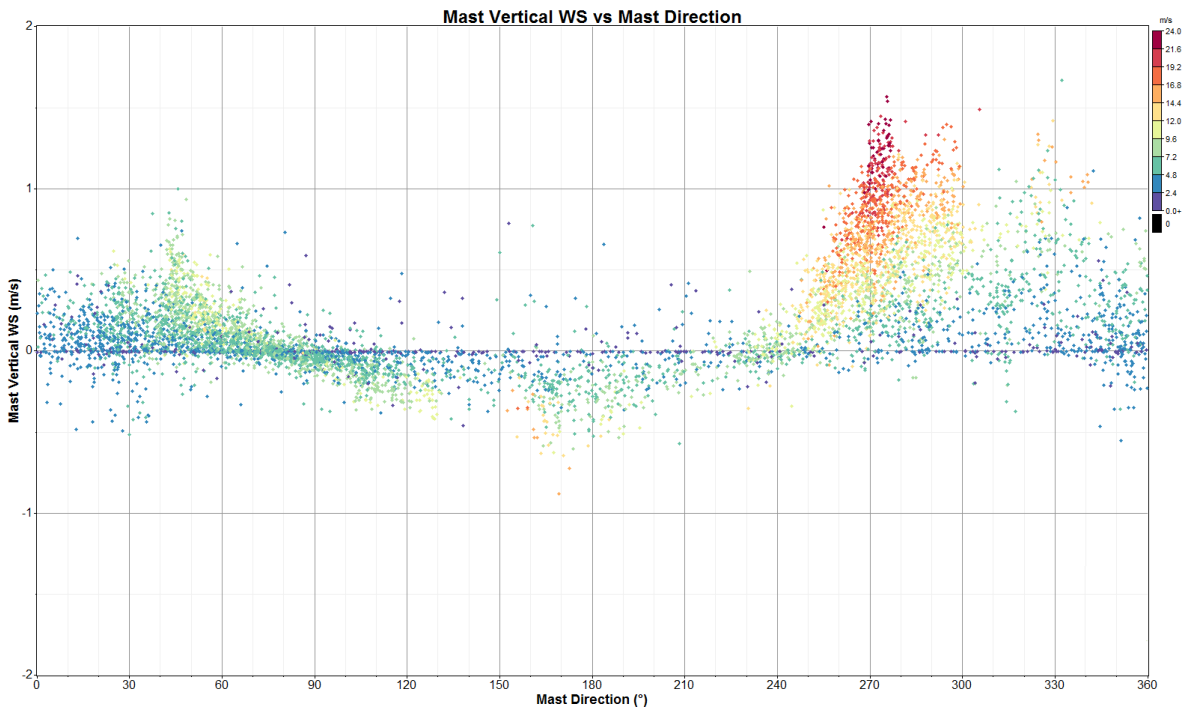

Figure 22: 89m Mast Vertical Wind Speed vs Mast 89m direction (colour coded by Mast 92m wind speed)

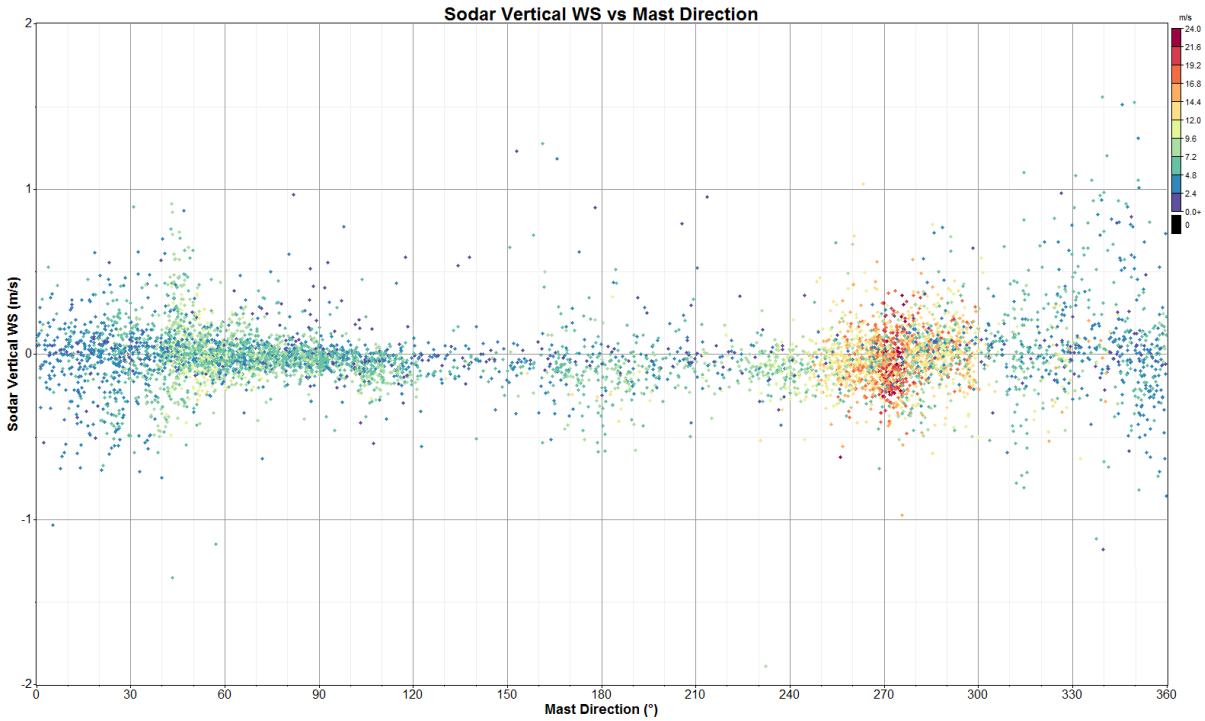

Figure 23: 90m Sodar Vertical Wind Speed vs Mast 89m direction (colour coded by Mast 92m wind speed)

6 Conclusions

A Fulcrum3D FS1 sodar has been placed adjacent to a 90m tall mast in Northern Tasmania for the purpose of validating sodar performance against an adjacent met mast. The site is simple and the mast is well instrumented and consistent with IEC recommendations, making it appropriate for validation of the sodar performance.

A number of standard processes have been followed to assess the sodar performance against cup anemometry. The key outcomes of the validation are summarized below:

1. Acceptable wind data availability has been demonstrated from the sodar in the range 40m to 150m.

2. Horizontal wind speed correlations at concurrent heights indicate coefficients of determination in the range 0.983-0.986 and slopes of between 1.001 and 1.011 indicating an excellent degree of accuracy in the sodar data. This demonstrates that the FS1 sodar is within the accuracy/uncertainty range of the anemometers.

3. Horizontal wind speed distributions at concurrent heights agree closely between the mast and sodar.

4. Horizontal wind speed difference histograms show a low degree of spread and no discernible bias in the data.

5. A strong relationship exists between the mast and sodar when measuring wind speed standard deviation and turbulence intensity at this site. The mast and sodar produced similar turbulence intensity classification results when assessed using IEC 61400-1 3rd edition.

6. Wind shear curves agree extremely closely and shear exponents are almost equal for both the mast and sodar (0.16 and 0.17 respectively) over concurrent heights indicating strong agreement between the two sources.

7. Wind direction at concurrent heights agrees strongly as shown by the coefficient of determinations (R^2) ranging from 0.992-0.999.

8. The FS1 sodar produces vertical wind speed and inflow angle data that looks more believable than the propeller anemometer installed on the mast which is experiencing bias due to installation tilt.

Based on this validation process the performance of the Fulcrum3D FS1 sodar is excellent over the height range 40 – 150m and is comparable to the adjacent IEC compliant met mast.