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Sodar wind measurement verification

Fulcrum 3D Sodar

E303463
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Executive summary

Fulcrum 3D is the developer of a sodar wind measuring device for the wind energy industry. To assist in the development and industry acceptance of this product, Fulcrum 3D has engaged Entura to independently evaluate its performance.

For this study, Fulrum3D has provided Entura with sodar data from two different sodar units at different locations adjacent to a single wind monitoring 80 m mast (referred to as Site #1a and Site #1b), and a third unit adjacent to a 70 m mast at a different project (referred to as Site #2). Entura has undertaken an independent analysis of this data in reference to the IEA's recently published recommendations the use and verification of remote sensing devices.

Sodar data recovery rates - 86%, 87% and 86% at 80 m at the three sites after filtering, were lower than mast data recovery rates. Data loss generally occurred for short periods (e.g. several hours) scattered throughout the measurement period. A preliminary observation is that the frequency of loss varies with factors such as 'time of day' and wind speed, and is not randomly distributed.

Overall the sodar wind speed averages were similar or slightly less than the mast wind speed averages at the levels compared. The measured differences are acceptable given the measurement uncertainty. Wind direction measurements were consistent.

Entura's analysis of the sodar data from each of the three sites showed a very high correlation with the mast data for wind speed and direction measurements, with R^2 values above 0.99.

The average shear derived from mast and sodar measurements was compared. While only coincident measurement levels were verified, we note that the range of sodar measurement levels would likely be used to calculate wind shear exponent in practice. Provided that any impacts of reduced data availability are considered, Entura has identified no reason to suggest that other measurement levels are more or less accurate than those considered here.

Entura recommends that further study across multiple sites is undertaken on the characteristics of missing data from the sodar unit, to determine whether any bias (systematic or varying) is introduced through the regular loss of short periods of data. Analysis of the data availability and any bias will ultimately inform uncertainty estimates for a system, when assessed over a number of sites. A robust process for this is included in the draft IEC 61400-12 standard.

Based on this analysis, Entura's opinion on the usefulness of the Fulcrum 3D sodar for various wind measurement applications is summarised below. As a preface to all our comments on application suitability – final determination of bankability depends on satisfying the lender's engineer in the specific situation.

Application	Suitability	Limitations
Site prospecting	Yes	Potential bias in wind speed due to lost data.
Bankable wind report – stand-alone use	Only for low risk applications	Further verifications studies (including potential bias of missing data), and industry acceptance required. May currently be useful stand-alone for very small wind projects where potential bias in wind speed due to lost data can be addressed.
Bankable wind report – site infill	Yes	Industry acceptance required.
Bankable wind report – shear extrapolation	Yes	Industry acceptance required, and verification of higher levels.
Bankable wind report – long term record	Yes	Potential bias in wind speed due to lost data.
Inflow angle measurement	Not assessed	
Mast measurement uncertainty reduction	Yes	Subject to site specifics

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1. Introduction

Fulcrum 3D is the developer of a sodar wind measuring device for the wind energy industry. The device enables remote sensing measurement of the wind speed and direction at a range of heights above ground level. To assist in the development and industry acceptance of this product, Fulcrum 3D has engaged Entura to independently evaluate its performance.

Traditionally, wind resource assessment data has been obtained from fixed wind monitoring masts with cup anemometers measuring wind speed, and wind vanes measuring wind direction. In recent years, 'remote sensing devices' such as sodar and lidar have been increasingly accepted as a useful tool for measuring wind resource. Remote sensing devices have some very clear advantages over fixed masts, but acceptance is currently only gained through direct comparison and verification with data from fixed masts.

Recently, the International Energy Agency (IEA) published an expert group study on recommended practices for remote sensing devices [1]. The comparison of sodar data with mast data in this report follows the IEC recommended verification practices where practicable.

For this study, Fulrum 3D has provided Entura with sodar data from three test sites, and Entura was involved in testing at a fourth site which is covered by a separate report [14]. Entura's independent analysis of data from two different sodar units at different locations adjacent to a single mast, and a third unit adjacent a different mast provided by Fulcrum 3D is presented, and conclusions are presented regarding the usefulness of the Fulcrum 3D sodar for wind resource assessment.

The structure of this report is as follows:

- Section 2 summarises the characteristics of the three test sites and their suitability for verification of the sodar
- Section 3 describes the data filtering techniques applied to mast and sodar data
- Section 4 discusses the results
- Section 5 discusses potential applications for the Fulcrum 3D sodar
- Section 6 presents the conclusions
- Section 7 lists the references

Detailed analysis of the data is presented in the Appendices.

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2. Description of test sites

This section discusses the main characteristics of the three test sites.

Entura has been provided documentation and data relating to three sodar test locations: Site #1a (1007), Site #1b (1014) and Site #2 (1011), but was not involved in the data acquisition.

2.1 Site #1a – Fulcrum site 1007

Site #1a was a flat, open paddock to the north east of Meredith, Victoria, displayed in Figure 2.1. A Fulcrum 3D sodar unit was operated 105 m to the north of an 84.5 m mast, at a location with an elevation above sea level 3 m higher than the mast location.

The surrounding terrain is simple, and significant differences in actual average wind speed are unlikely between the sodar and mast locations over this distance. As such, this test site is a good location for verifying the absolute accuracy of the sodar data against the mast data.

Figure 2.1: Sites #1a and #1b, aerial image (from Google Earth)

The test period provided was from 18/04/2012 00:00 to 11/06/2012 00:00 (UTC +10:00).

Further details of the site are provided in Appendix A.

2.2 Site #1b – Fulcrum site 1014

Site #1b was tested against the same mast as Site #1a. A flat, open paddock in the vicinity of Meredith, VIC, displayed in Figure 2.1. A Fulcrum 3D sodar unit was operated 140 m to the south-east of the 84 m mast at a similar elevation to the mast base.

The surrounding terrain is simple, and significant differences in actual average wind speed are unlikely between the sodar and mast locations over this distance. As such, this test site is a good location for verifying the absolute accuracy of the sodar data against the mast data.

The test period provided was from 22/06/2013 10:00 to 31/07/2013 00:00 (UTC +10:00).

Further details of the site are provided in Appendix 0.

2.3 Site #2 – Fulcrum site 1011

Site #2 was a ridgeline near Gundagai, NSW, displayed in Figure 2.2. A Fulcrum 3D sodar was placed 96 m to the south east of a 71 m wind monitoring mast, and within 5 m altitude.

The surrounding terrain is relatively complex, and differences in actual wind speed are likely between the sodar and mast locations over this distance. As such, verifying the absolute accuracy of the sodar data against the mast data is difficult at this site. Nonetheless, a comparison can be made, and aspects of the data acquired can be discussed.

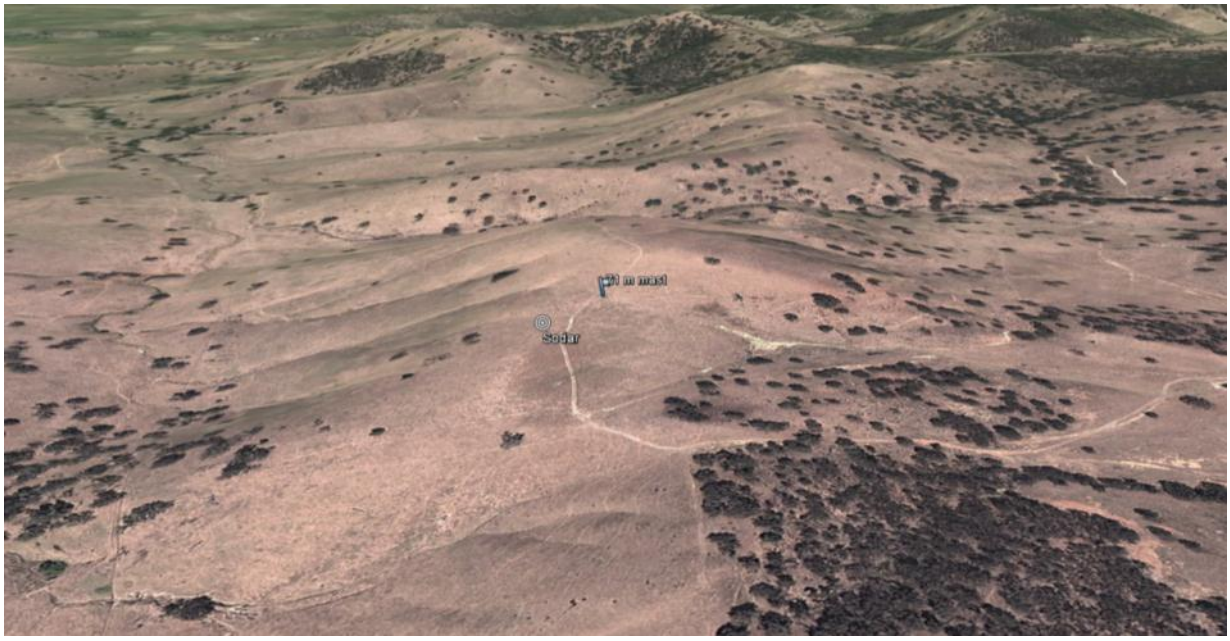

Figure 2.2: Site #2, aerial image looking West (from Google Earth)

The test period provided was from 27/05/2012 00:00 to 15/07/2012 08:50 (UTC +10:00).

Further details of the site are provided in Appendix 0.

3. Summary of data filtering

A critical aspect of the verification of remote sensing technology such as sodar is the data filtering applied to the mast data, and particularly the sodar data. This section provides an overview of general data filtering applied to all datasets, consistent with the recommendations of [1].

The resulting verification data sets include only coincident data (mast and sodar), such that direct comparisons can be made.

3.1 Mast data

In general, the following filters are applied to wind monitoring mast data to remove any low quality or erroneous data:

- Removal of data impacted by flow distortion from the mast, as identified by information on the mast setup and data analysis.
- Removal of erroneous sensor data.

3.2 Fulcrum 3D sodar

The Fulcrum 3D sodar data has been processed, in an attempt to remove any low quality or erroneous data. Fulcrum 3D has included with the data 3 filter columns for each height. Sodar data filtering is reliant on Fulcrum's recommended data filtering process [5], consisting of:

- F1_v01 < 1 – Signal Quality Flag;
- F2_v01 < 1 – Processing Quality Flag ; and
- F3_v01 < 1 – Consistency Check Flag.
- Translation of data from UTC 0:00 to UTC+10:00.

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4. Discussion of results

This section presents a discussion of the results across all test sites, structured around the key performance measures which should be considered when judging the performance and usefulness of a remote sensing device. These results are very reliant on the accuracy of the mast data, although currently comparison with a met mast is the accepted methodology for testing remote sensing units.

4.1 Data sufficiency and quality

For validation of sodar against mast data sufficient data should be acquired to meet the following criteria [1]:

- At least one hour of data should be acquired in each (0.5 m/s) wind speed bin
- No less than 40% of data should be acquired from either night-time or day-time
- Wind speed data should not exhibit a strong diurnal cycle

The data recorded at each site was of sufficient quantity and sufficient quality to form comparisons between the sodar and mast data. However these criteria were not strictly met at Site #2 as sufficient data was only available for wind speed comparisons up to 14 m/s.

The data recovery rates for the mast and sodar are displayed in Table 4.1. For the purpose of reporting data recovery, Entura does not distinguish between data lost through operational downtime, and data lost through filtering. The sodar data has only had the standard filtering applied as discussed in Section 3.

Table 4.1: Fulcrum 3D sodar data recovery by height

Height AGL (m)	Site #1a Data recovery (%)	Site #1b Data recovery (%)	Site #2 Data recovery (%)
60	88	88	87
70	87	90	87
80	86	87	86
90	86	83	87
100	84	79	86
110	83	72	84
120	80	63	80
130	72	51	77
140	71	40	71
150	64	33	62

The sodar data recovery is lower than the mast data recovery, which was at or close to 100% for all periods (if tower shading is disregarded), however this is expected. Generally the sodar data recovery decreases with height above ground level, which is also expected.

The data from Site #1b had a lower recovery rate above 90 m than the other two sites, despite being located next to the same mast as site #1a. Looking at the signal to noise ratio (SNR) for each level, it is lower than at each of the other sites. This could be due to factors such as different atmospheric conditions, rain or insects but it is not possible to determine this from the data provided.

A preliminary review has been undertaken to investigate the level of measurement bias introduced by the sodar measurements. Figure 4.1, Figure 4.2, and Figure 4.3 display the wind speed distributions measured by the mast during the whole period (left), in comparison with the wind speed distribution for the time steps where Fulcrum 3D sodar data is missing or has been removed through filtering (right). This comparison suggests the missing sodar time steps are biased towards lower wind speed time steps during these time periods, but also with some of the highest wind speeds missing.

The accuracy of long term wind resource estimates, whether from mast, sodar, or other source, can be impacted by missing data in the record, where that missing data has the potential to bias the data set. The lower availability of the sodar units than the mast at these sites means there is greater potential to introduce a bias if the missing data is not uniformly distributed. This is most likely to occur where sodar availability is correlated with a particular conditions such as wind speed but could also depend on other factors such as or direction; temperature; air pressure; air density; sun angles; background noise etc. Analysis of the data availability and any bias will ultimately inform uncertainty estimates for a system, when assessed over a number of sites. A robust process for this is included in the draft IEC 61400-12 standard.

Accordingly, before the data from a remote sensing device, or other source such as a met mast, can be used in financing decisions, consideration should be given to any bias which may be introduced. This impact is more applicable where remote sensing devices are used in stand-alone applications and any bias cannot be detected by comparison with a met mast.

Entura notes that these comparisons do not necessarily address the fundamental site conditions that may cause data loss, and the results cannot be generalised or applied to other sites. Considering a range of other parameters (e.g. atmospheric stability, turbulence intensity, wind shear, and wind direction, etc.) as listed in the draft IEC 61400-12 standard may be of interest, but is beyond the scope of this current assessment.

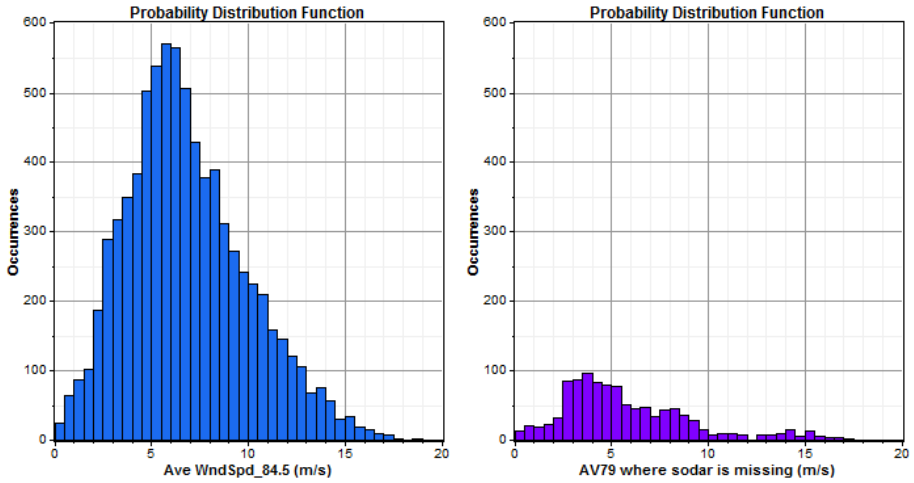

Figure 4.1: Site #1a wind speed distribution of mast data for i) the whole test period, and ii) the 14% of time steps where Fulcrum 3D sodar data at 80 m is not available

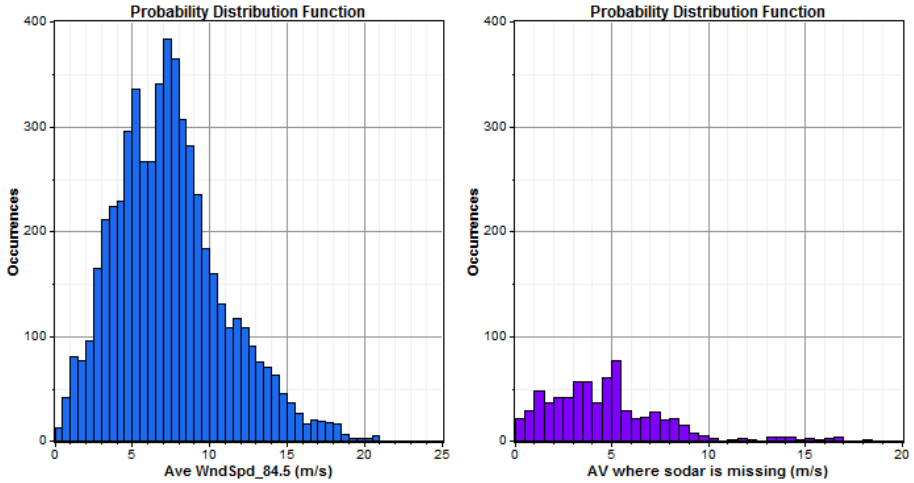

Figure 4.2: Site #1b wind speed distribution of mast data for i) the whole test period, and ii) the 13% of time steps where Triton sodar data at 80 m is not available

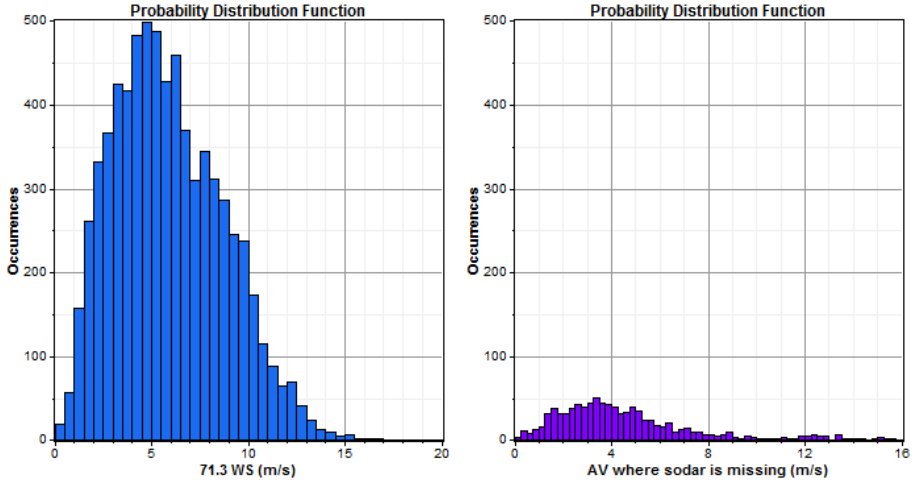

Figure 4.3: Site #2 wind speed distribution of mast data for i) the whole test period, and ii) the 13% of time steps where Fulcrum 3D sodar data at 70 m is not available

4.2 Time series comparison

The direction data from the sodar units has been corrected for the magnetic declination at Site #1a and Site #1b of 11° and Site #2 of 12°. It was noted by Fulcrum 3D that Site #1a was installed facing east [5], not north, and Entura has corrected the data for this.

Looking at the time series sodar wind speed and direction data in comparison with the mast data for similar levels at each of the three sites they track each other reasonably well. However in all the sodar datasets there were individual outliers when compared to the measured 10 minute time series, particularly for levels above 100 m.

4.3 Wind speed

A concurrent dataset was created from the filtered wind speed data from the sodar and the mast for comparison. A comparison of the average wind speeds is shown in Table 4.2.

At Site #1a mast and sodar wind speeds are in very good agreement at the 60 m level, and the mast 84.5 m level wind speed is bracketed by the 80 m and 90 m sodar wind speeds, indicating very good agreement.

At Site #1b sodar mean wind speed at 60 m is slightly less than at the mast, and the mast 84.5 m level wind speed is bracketed by the 80 m and 90 m sodar wind speeds, indicating good agreement.

At Site #2 sodar mean wind speeds are slightly lower than mast mean wind speeds.

Table 4.2: Average wind speed comparison, concurrent wind speeds

Height AGL (m)		Mean wind speed (m/s)					
		Site #1a		Site #1b		Site #2	
Mast	Sodar	Mast	Sodar	Mast	Sodar	Mast	Sodar
60.3,60.4	60	6.44	6.44	7.19	6.96	5.79	5.69
71.5	70	-	-	-	-	6.09	5.93
84.5	80	7.01	6.91	7.83	7.64	-	-
84.5	90	6.97	7.10	7.96	8.02		

In accordance with the IEA verification guidelines [1] the data was then binned using the reference mast data into 0.5 m/s wide bins starting at 3.75 m/s. An Ordinary Least Squares (OLS) fit was used to determine the gradient, offset and coefficient of determination (R^2) for the bin-means of the time averaged values for the mast and sodar data. Bins containing less than one hour of data, six 10-minute timesteps, were excluded from the OLS fit.

Scatter plots and binned results are displayed in Figure 4.4 to Figure 4.9.

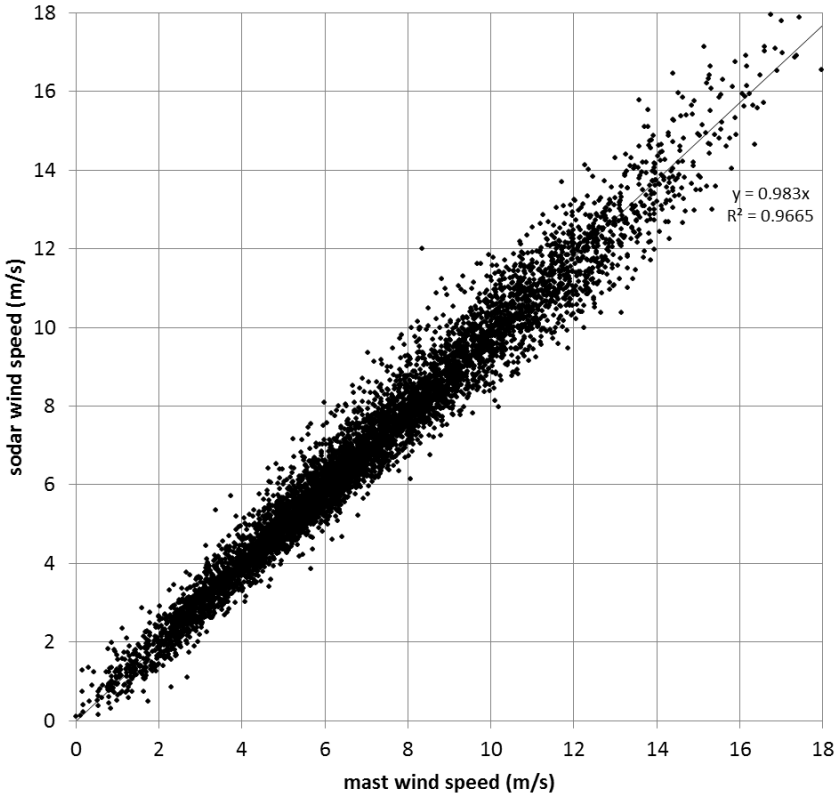

Figure 4.4: Site #1a Sodar 80 m wind speed vs. Mast 84.5 m wind speed, 10-min data

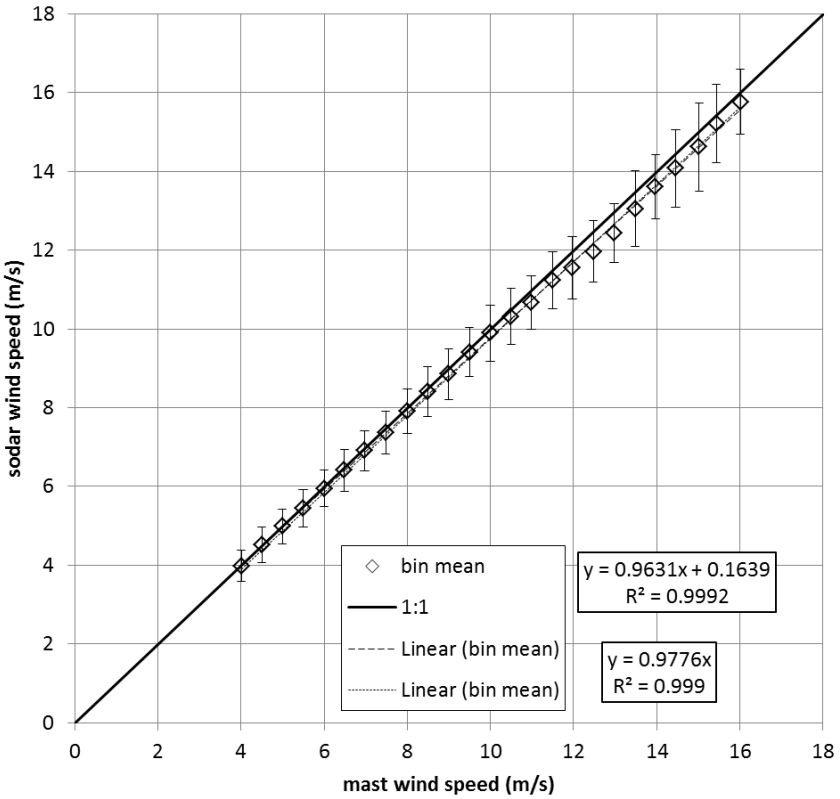

Figure 4.5: Site #1a Sodar 80 m wind speed vs. Mast 84.5 m wind speed, binned correlation

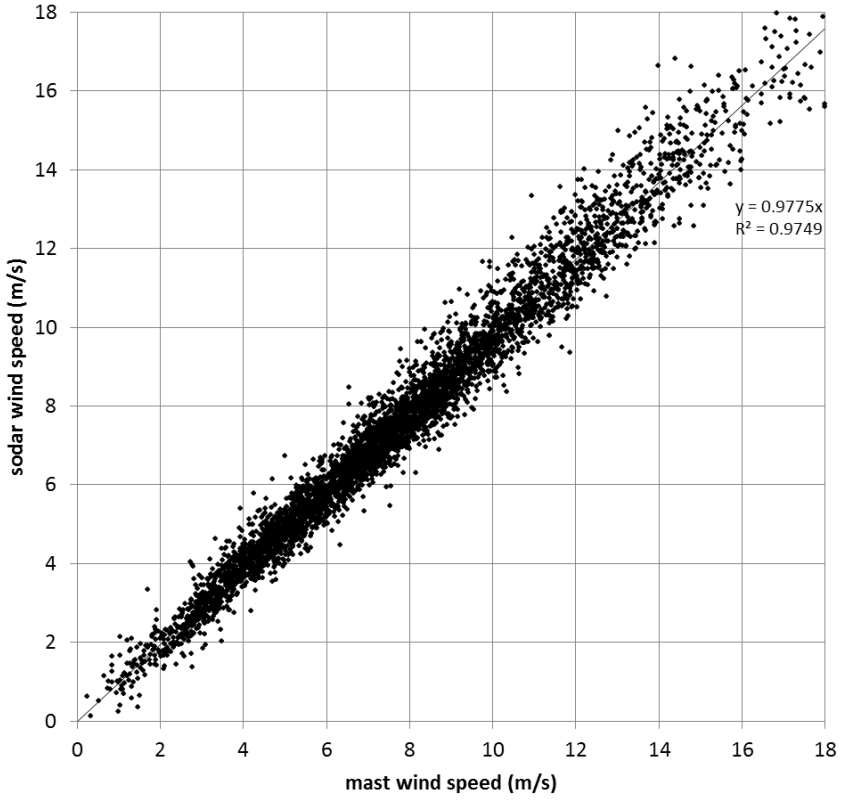

Figure 4.6: Site #1b Sodar 80 m wind speed vs. Mast 84.5 m wind speed, 10-min data

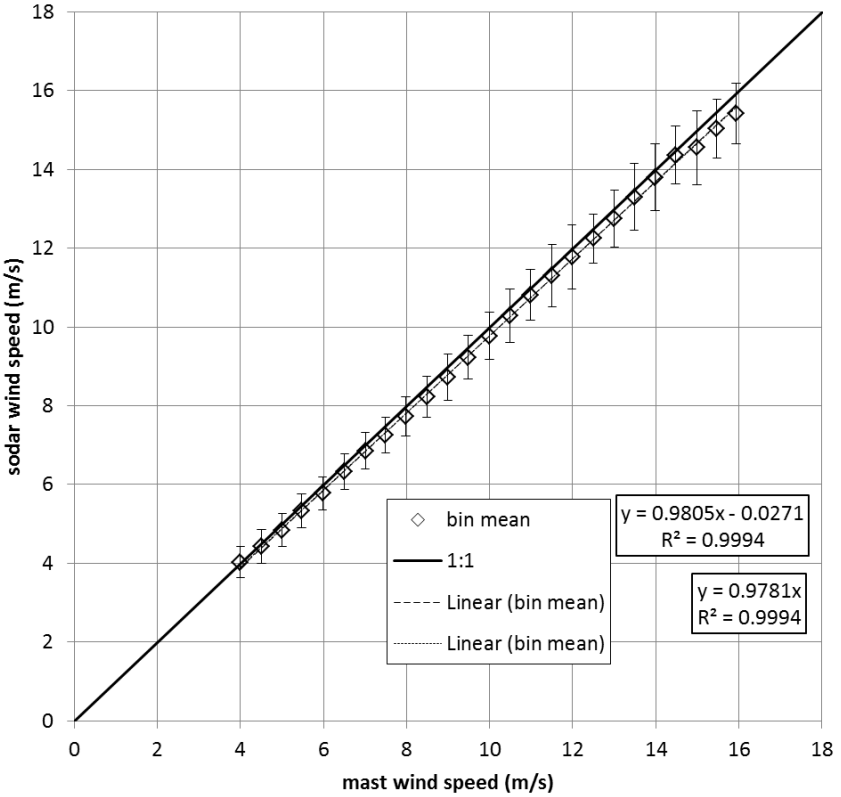

Figure 4.7: Site #1b Sodar 80 m wind speed vs. Mast 84.5 m wind speed, binned correlation

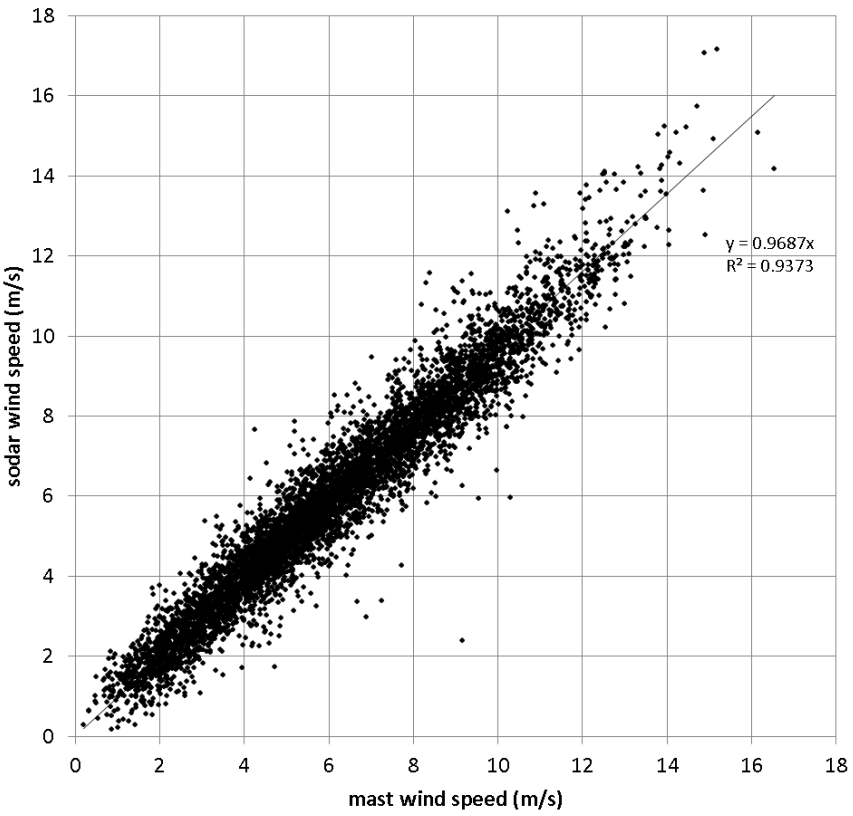

Figure 4.8: Site #2 Sodar 70 m wind speed vs. Mast 71.3 m wind speed, 10-min data

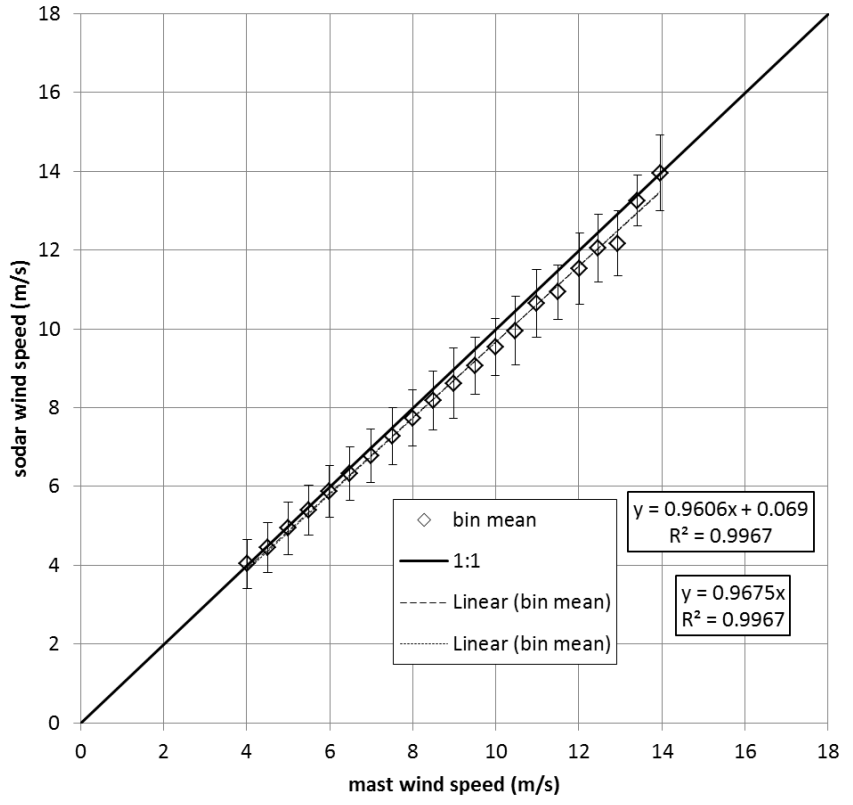

Figure 4.9: Site #2 Sodar 70 m wind speed vs. Mast 71.3 m wind speed, binned correlation

The correlation results are presented in Table 4.3, further analysis is shown in the Appendices.

Table 4.3: Wind speed correlation results

Site	Level (m)	linear best fit			forced through origin	
		Slope	Offset	R^2	Slope	R^2
Site #1a	84.5 vs 90	0.9888	0.2110	0.9994	1.0075	0.9990
	84.5 vs 80	0.9631	0.1639	0.9992	0.9776	0.9990
	60.3 vs 60	0.9566	0.3007	0.9989	0.9841	0.9980
Site #1b	84.5 vs 90	1.0041	0.0158	0.9996	1.0055	0.9996
	84.5 vs 80	0.9805	-0.0271	0.9994	0.9781	0.9994
	60.3 vs 60	0.9804	-0.0758	0.9997	0.9737	0.9997
Site #2	71.3 vs 70	0.9606	0.069	0.9967	0.9675	0.9967
	60.4 vs 60	0.9777	0.0077	0.9930	0.9785	0.9930

The results of the correlations show a very high R^2 values, above 0.99, for all sites and measurement levels. The correlations are very high using both constrained, forced through the origin, and free fits. This shows that there is a high correlation between the mast and sodar wind speed measurements.

Plots of the absolute and relative wind speed differences between the sodar and the mast data are provided in Figure 4.10, Figure 4.11 and Figure 4.12. These show the difference between the mast and sodar data is low, particularly for the flat, non-complex Site #1a and Site #1b.

Site #1a and Site #1b are compared with the same mast, but give slightly different results. The cause of this difference is unknown, however it can generally be said that sodar and mast wind speed measurements at these sites agree well.

For Site #2, wind speeds measured by sodar are less than measured by the mast, and the reason for this difference cannot be conclusively determined. However for this mast, the booms and upstands are shorter than ideal, which increases the mast effects on the measurements. And the terrain is relatively complex, which may cause different wind speeds to be seen by the mast and the sodar, and differences due to the nature of the measurement devices.

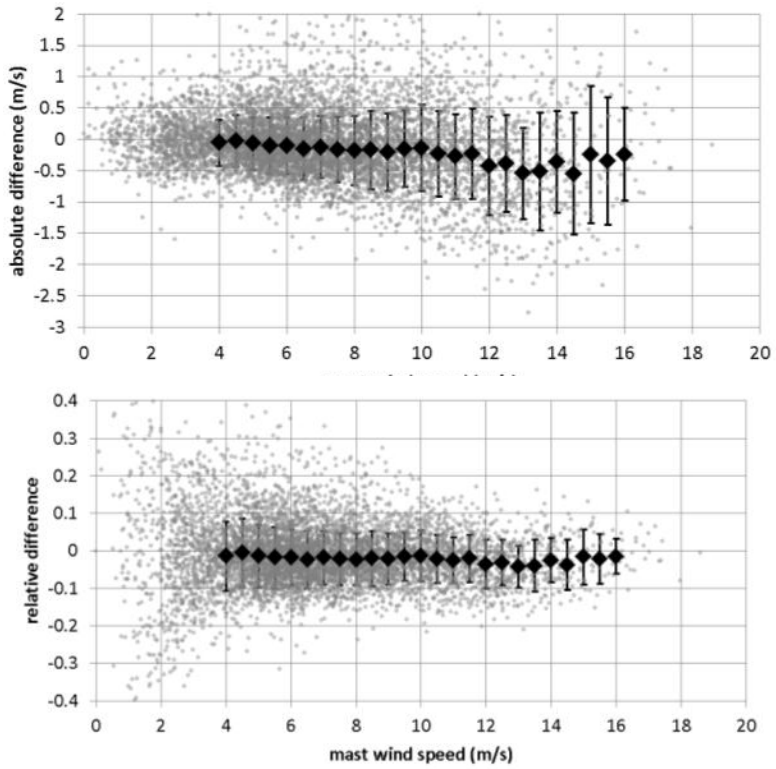

Figure 4.10: Sodar 80 m - Mast 84.5 m absolute (top) and relative (bottom) wind speed difference vs. mast wind speed, Site #1a

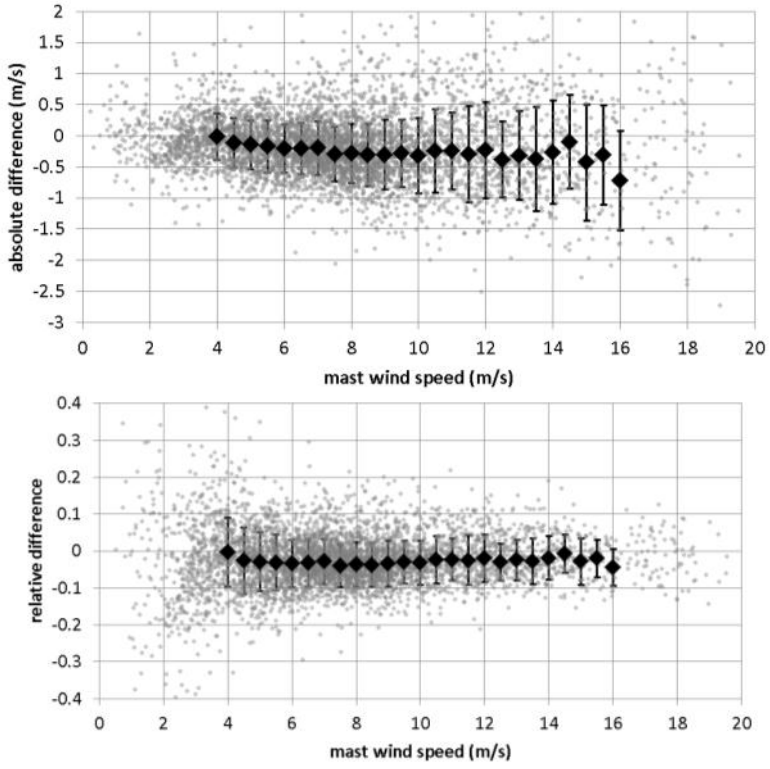

Figure 4.11: Sodar 80 m - Mast 84.5 m absolute (top) and relative (bottom) wind speed difference vs. mast wind speed, Site #1b

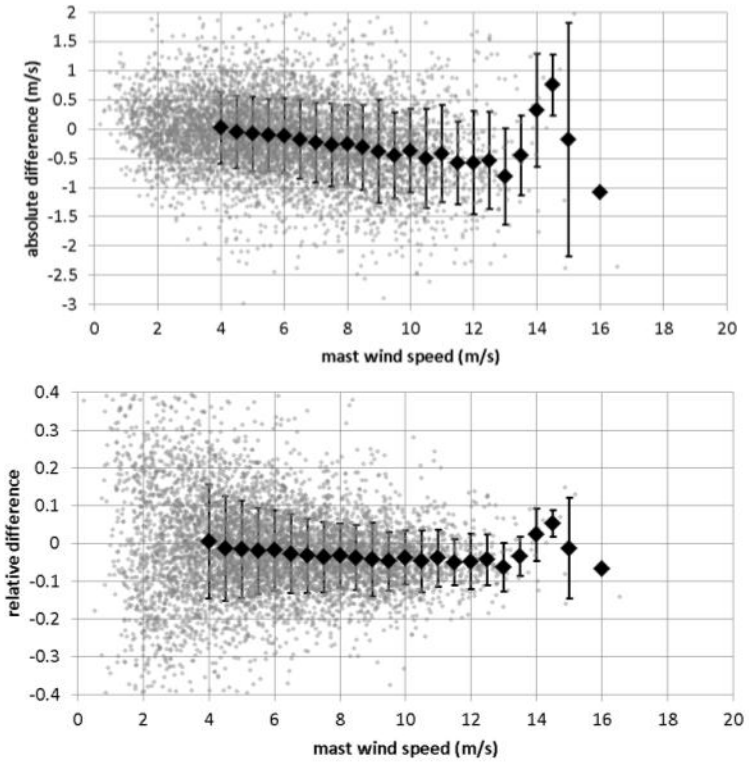

Figure 4.12: Sodar 70 m - Mast 71 m absolute (top) and relative (bottom) wind speed difference vs. mast wind speed, Site #2

4.4 Wind speed uncertainty

The methodology outlined in the IEA report [1] has been used to calculate uncertainties for the sodar wind speed measurements for each wind speed bin. The uncertainty values calculated are as a percentage of the wind speed measurements. The full analysis is detailed in Appendix A.8, B.8 and C.8, with some key observations summarised below:

- The range of total uncertainty measured at Site #1a at 80 m is 3.0% – 5.1% as a percentage of wind speed
- The range of total uncertainty measured at Site #1b at 80 m is 2.9% – 4.4% as a percentage of wind speed
- The range of total uncertainty measured at Site #2 at 70 m is 4.0% – 7.2% as a percentage of wind speed
- The uncertainties are higher at the complex site, Site #2, this is partly due to higher uncertainties to account for the site complexity, however the uncertainties calculated based purely on the comparison with the mast data (excluding the uncertainties for Mast, Sodar mounting and Site effects) are also higher.
- Uncertainty does not decrease or increase with increasing wind speed.
- The IEA document [1] states the uncertainties calculated in this verification should be considered the 'best case' as sodar units are typically moved around wind farm sites and it is

possible that they may perform differently at a new site either due to damage during transport or local wind flows or terrain conditions.

4.5 Wind direction

The correlation of the wind direction data between the mast and sodar was generally very good with R^2 values above 0.99. At Site #1a, Figure 4.13, the direction from the sodar is less than the direction from the mast from 25° to 165°, this is also the case, although not as significant, at the 60 m level, see Figure A.15. The largest deviation of the bins is 8°. This is likely due in part to the limited number of points in some of these bins. Site #1b shows more scatter up to 200° although the differences are small, the largest deviation of the bins is 6.5°, see Figure 4.14,

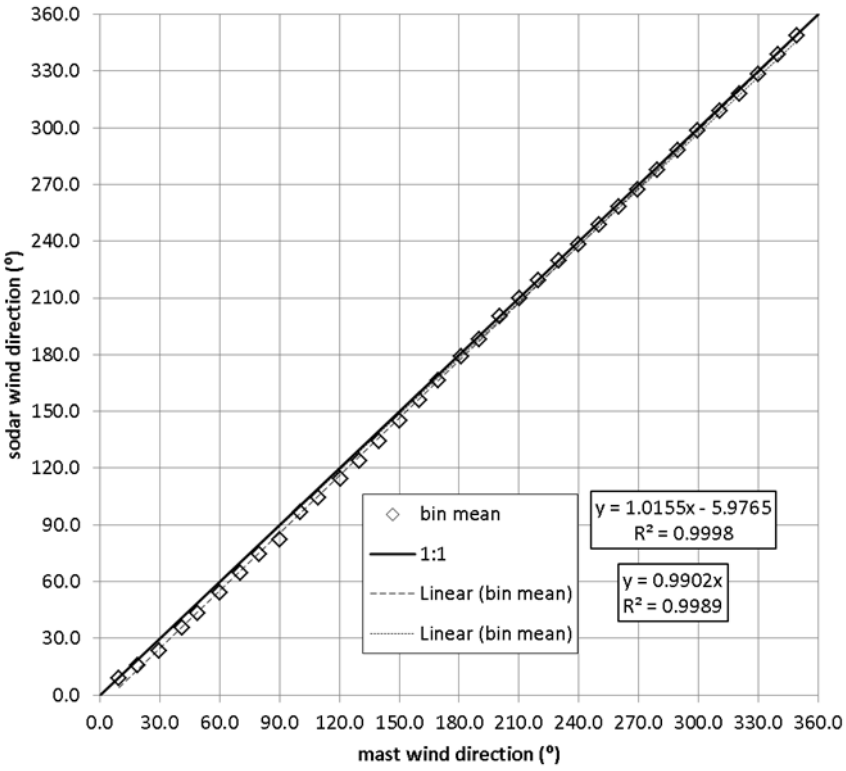

Figure 4.13: Site #1a - Sodar 80 m wind direction vs. Mast 82.5 m wind direction, binned correlation

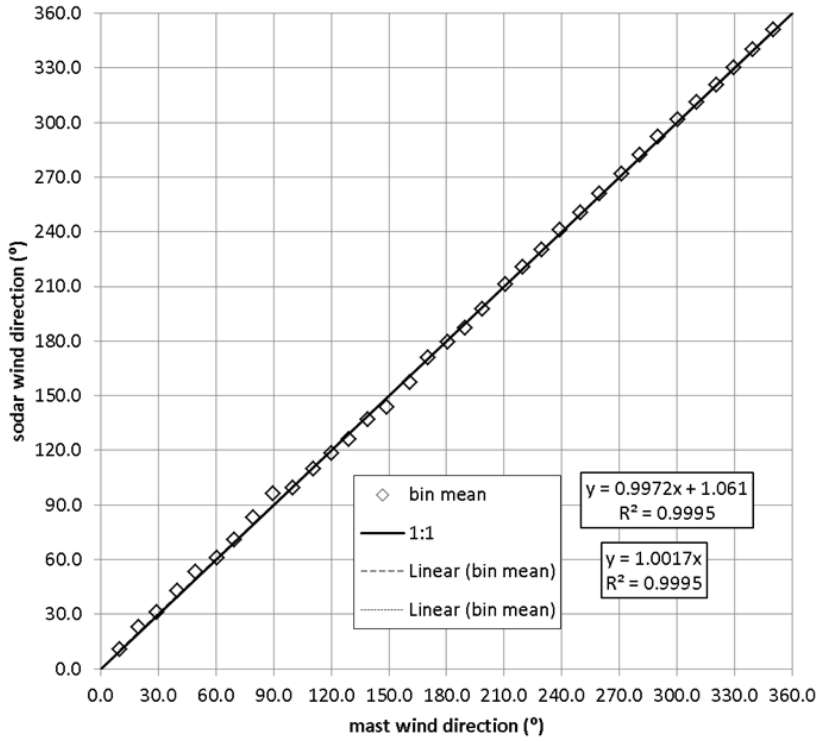

Figure 4.14: Site #1b - Sodar 80 m wind direction vs. Mast 82.5 m wind direction, binned correlation

Site #2 has a high correlation between the directions despite being in complex terrain, Figure 4.15. The largest deviation of the bins is 6°.

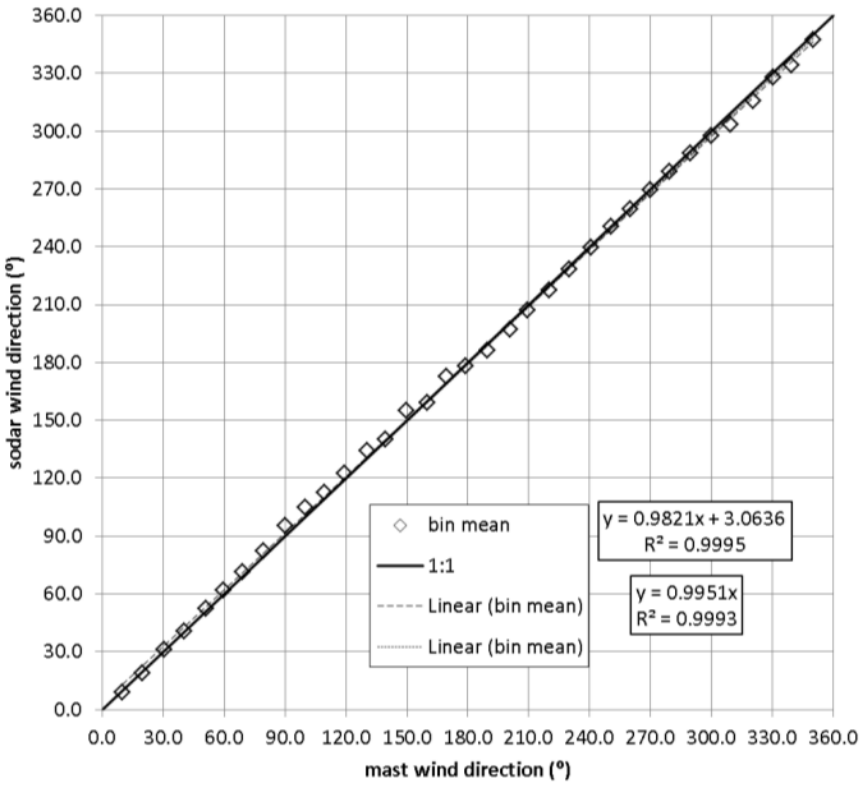

Figure 4.15: Site #2 - Sodar 70 m wind direction vs. Mast 68.4 m wind direction, binned correlation

4.6 Wind shear

The vertical wind shear exponent (power law) was compared between the two levels on the mast which matched levels measured by the sodar, 60 m and 80 m heights for Site #1a and Site #1b and 60 m and 70 m heights for Site #2, for concurrent wind speeds greater than 3.0 m/s.

As seen in Table 4.4, the derived wind shear results for Site #1a and Site #2 match up very well between the mast and sodar, with the sodar even matching the day and night shear variation. However the derived shear results for Site #1b do not match up well as the results based on the sodar measurements are significantly higher than the shear based on the mast.

As wind shear is a derived parameter based on measured wind speeds, these observations are in line with the differences in measured wind speed between the sodar and the mast, see Section 4.3. In particular, the sodar 60 m wind speed at Site #1b is less than the mast 60 m wind speed, which results in a different shear profile.

There are factors in the mast set up which may influence this result, the top anemometers are mounted above the masts while the 60 m anemometers may be affected by mast shading (although 60 m data from the sector most affected has been removed for the assessment). While the mast nearby Site #1a (and Site #1b) has suitable boom lengths and upstand heights for the anemometers, the booms and upstands on the mast at Site #2 are quite short, which is likely to be increasing the mast effects on the measurements. However it is not possible to conclusively determine a cause for the differences in wind speed measurements.

While only coincident measurement levels can be verified, we note that the range of sodar measurement levels would likely be used to calculate wind shear exponent in practice. Provided that any impacts of reduced data availability are considered, Entura has identified no reason to suggest that other measurement levels are more or less accurate than those considered here.

Table 4.4: Shear comparison

	Site #1a			Site #1b			Site #2		
Time	**Mast (60.3–84.5 m)**	**Sodar (60–80 m)**	**# data points**	**Mast (60.3–84.5 m)**	**Sodar (60–80 m)**	**# data points**	**Mast (60.4–71.3 m)**	**Sodar (60–70 m)**	**# data points**
All	0.30	0.31	5,705	0.24	0.31	4,131	0.24	0.22	4,591
Day (06:00 – 18:00)	0.23	0.24	3,052	0.19	0.27	1,820	0.19	0.18	2,502
Night (18:00 – 06:00)	0.38	0.39	2,653	0.29	0.36	2,311	0.29	0.27	2,089

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5. Application suitability

Entura has analysed data from the three sites in this report, and a fourth site in Western Victoria [14]. Based on our experience with the data from the Fulcrum 3D, Entura provides comments in this section on the wind monitoring applications where a Fulcrum 3D sodar may provide valuable data.

It is noted that Entura has only assessed limited data sets from four sites, and further documentation of the performance of the Fulcrum 3D sodar is recommended. Further, Entura has not considered aspects of functionality that are important when deploying a wind monitoring technology, such as robustness, maintenance requirements, east of installation, etc.

5.1 Initial site prospecting

The wind resource assessment at the initial site prospecting stage is typically first based on high level modelled wind data or local weather station data. More accurate wind measurements previously required the installation of a wind monitoring mast at the site which can be expensive, often requires a building permit and is difficult to relocate if the site wind resource proves unviable. A remote sensing device (e.g. a sodar unit) has the advantage of being simple to deploy and relocate.

The results of Entura's analysis show the Fulcrum 3D sodar is accurately measuring the wind speed and direction at the sites examined in comparison with the mast data – for the concurrent time steps of measured data. The uncertainties calculated for the wind speed bins are well within those which would be required by developers at the site prospecting stage. It should be noted that the majority of the units assessed by Entura were in simple terrain and this is where the sodar is likely to best match mast data given the lower inflow angles.

A disadvantage of sodar relative to a high quality wind monitoring mast is the relatively low data retrieval rates due to regular short periods of missing data, and the variability of the availability across different sites, although this is an issue for all remote sensing devices, not just the Fulcrum 3D units. Preliminary observation suggests the frequency of data loss varies with factors such as 'time of day' and wind speed, and is not randomly distributed. As such, some bias may be introduced in average wind speed measured for a specific period. For the four test sites considered, small positive biases in average wind speed (i.e. an overestimate of wind resource) were observed.

Given that wind turbine heights above 80 m are available, sodar is a valuable tool to measure wind speeds at these heights. However, additional care would have to be given in the treatment of the missing data at these higher levels (as the data retrieval percentage decreases with height).

The Fulcrum 3D sodar has been shown to provide wind speed data suitable for this purpose. However, Entura recommends that further study is undertaken into characterising the missing data at multiple sites to better understand the uncertainty and any actions to be taken to account for potential bias in missing data.

5.2 Bankable wind report

Subsequent to initial site prospecting, it is reasonable to expect that data acquired during a wind monitoring campaign will be used in a wind resource and wind farm production estimate for the purposes of financing the construction of the wind farm – a 'bankable' wind report. If Fulcrum 3D

sodar data is used in such a report, its performance and accuracy will be subject to a high level of scrutiny, and a track history of previous verification will provide confidence that the data is 'bankable'. In the context of a 'bankable' wind report, Entura provides the following comments on using the Fulcrum 3D sodar data for different aspects of wind resource assessment, stand-alone use, site infill, shear extrapolation, and as a long term record.

As a preface to all our comments on application suitability – final determination of bankability depends on satisfying the lender's engineer in the specific situation.

5.2.1 Stand-alone use

Entura understands there are a limited number of projects worldwide which have been granted finance only on remote sensor data, i.e. without some mast data measured at the site. In Australia, Entura is unaware of any wind farm which has obtained project finance without mast data from the site.

The results of Entura's analysis shows the Fulcrum 3D sodar to measure wind speed and direction at the sites examined is within 1 - 3% accuracy [14] compared to the mast wind speed measurements for varying heights between 60 m up to 80 m, when only concurrent time steps are considered. The uncertainties calculated for the wind speed bins at the assessed sites for 4 – 16 m/s are relatively low and comparable with met masts.

However given the preliminary findings that a wind speed bias may be introduced through lost data, further investigation of this issue is required.

With only a small number of demonstration sites, it is difficult to form a definitive view as to its suitability for stand-alone use. As the number of demonstration sites increases, the variability in accuracy of the sodar predictions across sites will be better characterised, and will result in greater confidence in the uncertainty estimates for stand-alone sodar.

5.2.2 Site infill (in combination with masts)

The portability of a sodar unit (like other remote sensing devices) makes it very useful as a tool to measure the wind speed at a distance from existing met masts on a wind farm site, and developing a long term record based on correlation with the met masts. The results of this analysis show that the Fulcrum 3D sodar provides valid wind speed and wind direction results and therefore could be used to infill measurements across a wind farm site in terrain and flow conditions similar to that at the verification sites. This would reduce the uncertainty relative to wind flow modelling based on mast data alone.

The short periods of missing data are not such a concern for this particular purpose, provided sufficient data is acquired to establish a valid correlation with the mast site.

It is recommended in the IEA [1] and DNV standards [2] that remote sensing devices are periodically verified against a met mast to confirm they are operating correctly.

The Fulcrum 3D sodar has been shown to provide wind speed data suitable for this purpose.

5.2.3 Shear extrapolation

The sodar unit measures data up to 200 m, which is considerably higher than the 84.5, 79.3 m, 80 m and 70 m masts installed at the sites provided.

A sodar unit can potentially be used to extrapolate mast measurements to hub-height, in the case where the mast height is lower than the proposed wind turbine hub-height. Generally, if there is a below hub height mast but within 2/3 hub height, the wind data is already 'bankable', however, the use of a sodar unit will likely decrease the uncertainty in the energy estimate.

And a sodar unit can also be used to assess wind speeds up to tip height, although this data is not yet commonly required or used.

We note that data recovery rates which reduce with increasing height are an issue for the purpose of shear extrapolation, and care must be taken to ensure calculated wind shear profiles are representative.

Subject to the mentioned uncertainties, the Fulcrum 3D sodar has been shown to provide wind speed data suitable for this purpose.

5.2.4 Long term record

The Fulcrum 3D sodar has the potential for quick deployment, relative to the longer lead times for a wind monitoring mast installation. For this reason, the situation may arise where the Fulcrum 3D sodar can be installed before any masts, and therefore commence the recording of a long term site record, which is later correlated with data from the masts.

The primary requirement for this application is that sodar provides a consistent measurement of wind speed over time. Entura has not assessed this specific aspect of performance, however considers this is unlikely to be a problem for the Fulcrum 3D sodar. Previous comments regarding the possibility of bias introduced through the characteristics of missing data are also a consideration. Mitigating this uncertainty is the possibility that subsequent installation of mast could be used to analyse the characteristics of the missing data (during the concurrent period), and hence infer any impacts on the period prior to mast installation.

Subject to the mentioned uncertainties, the Fulcrum 3D sodar has been shown to provide wind speed data suitable for this purpose. Particularly if the alternative is no data at all for a period of several months.

5.3 Mast measurement uncertainty reduction

In the course of a wind measurement campaign, placing a Fulcrum 3D sodar unit adjacent to a wind monitoring mast verifies not only the correct performance of the sodar unit, but also provides an independent check on the correct operation and accuracy of the wind monitoring mast data. Depending on the results, this may enable a reduction to the uncertainty ascribed to cup anemometer wind speeds measurements from the wind monitoring mast.

The Fulcrum 3D sodar has been shown to provide wind speed data suitable for this purpose.

5.4 Noise assessment

Measurement of background noise pre-construction and wind turbine or wind farm noise post-construction typically requires concurrent wind speed measurements at wind turbine hub-height. In many scenarios, mast data or nacelle anemometer data is available, and is sufficient. However there may be some scenarios where the temporary nature of these measurement campaigns means that

sodar is a useful tool. Entura notes that remote sensing has been used in other parts of the world for this purpose.

It is noted that the issues of missing data may raise questions regarding environmental conditions not captured during a noise test. While the likelihood of this is very low, this concern may need to be addressed to ensure that use of sodar data is fully defensible in this application.

Further, regulatory bodies may request assurance that the sodar unit provides valid wind speeds, perhaps through examples of verifications studies.

Subject to the mentioned uncertainties, the Fulcrum 3D sodar has been shown to provide wind speed data suitable for this purpose.

6. Conclusion

Entura has analysed Fulrum3D sodar data from three test sites, in reference to the IEA's recently published recommendations the use and verification of remote sensing devices. Fulcrum3D provided Entura with the raw sodar data and mast data from each mast.

Sodar data recovery rates - 86%, 87% and 86% at 80 m at the three sites after filtering, were lower than mast data recovery rates. Data loss generally occurred for short periods (e.g. several hours) scattered throughout the measurement period. A preliminary observation is that the frequency of loss varies with factors such as 'time of day' and wind speed, and is not randomly distributed.

Overall the sodar wind speed averages were similar or slightly less than the mast wind speed averages at the levels compared. The measured differences are acceptable given the measurement uncertainty. Wind direction measurements were consistent.

Entura's analysis of the sodar data from each of the three sites showed a very high correlation with the mast data for wind speed and direction measurements, with R^2 values above 0.99.

The average shear derived from mast and sodar measurements was compared. While only coincident measurement levels were verified, we note that the range of sodar measurement levels would likely be used to calculate wind shear exponent in practice. Provided that any impacts of reduced data availability are considered, Entura has identified no reason to suggest that other measurement levels are more or less accurate than those considered here.

Entura recommends that further study across multiple sites is undertaken on the characteristics of missing data from the sodar unit, to determine whether any bias (systematic or varying) is introduced through the regular loss of short periods of data. Analysis of the data availability and any bias will ultimately inform uncertainty estimates for a system, when assessed over a number of sites. A robust process for this is included in the draft IEC 61400-12 standard.

Based on this analysis, Entura's opinion on the usefulness of the Fulcrum 3D sodar for various wind measurement applications is summarised below. As a preface to all our comments on application suitability – final determination of bankability depends on satisfying the lender's engineer in the specific situation.

Application	Suitability	Limitations
Site prospecting	Yes	Potential bias in wind speed due to lost data.
Bankable wind report – stand-alone use	Only for low risk applications	Further verifications studies (including potential bias of missing data), and industry acceptance required. May currently be useful stand-alone for very small wind projects where potential bias in wind speed due to lost data can be addressed.
Bankable wind report – site infill	Yes	Industry acceptance required.

Bankable wind report – shear extrapolation	Yes	Industry acceptance required, and verification of higher levels.
Bankable wind report – long term record	Yes	Potential bias in wind speed due to lost data.
Inflow angle measurement	Not assessed	
Mast measurement uncertainty reduction	Yes	Subject to site specifics

7. References

[1] International Energy Agency, Ground-based vertically-profiling remote sending for wind resource assessment, Expert group study on recommended practices, 1st Edition, January 2013

[2] DNV, DNV-RP-J101, Use of Remote Sensing for Wind Energy Assessments, April 2011.

[3] IEC (2005), IEC 61400-12 Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbine.

[4] Fulcrum 3D, Fulcrum3D Sodar Specification Instrument specification V1.01, July 2012

[5] Fulcrum 3D, Fulcrum 3D Sodar Performance Verification Note – V3.30 Data, 4 December 2013.

[6] #### 70m Wind Monitoring Mast Installation Report , October 2009

[7] #### Sodar1 Monitoring Site Commissioning report, 21 March 2012

[8] #### Wind Project Installation Report, #### Meteorological Monitoring Mast, updated February 2011

[9] Instrument installation details, #### 80 m installation report, #### Wind Project, 27 March 2013

[10] Calibration report, #7619, Ecotech, WS-0319 SWR C11551-1B (Cup - Riso P2546A SN-7619).pdf, 19 March 2013

[11] Calibration report, #7621, Ecotech, WS-0322 SWR C11551-3B (Cup - Riso P2546A SN-7621).pdf, 18 March 2013

[12] NATA calibration report, #2099, Ecotech,WS-1088 SWR 10509-8 (Cup - Riso P2546A SN-2099).pdf, 9 June 2011

[13] GDG calibration certificates, GDG_CalibrationCerts.pdf, supplied November 2013

[14] Entura, Fulcrum 3D Sodar Verification Report, E303263-TR02.

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Appendices

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A Site #1a 1007

At Site #1a (1007), a Fulcrum 3D sodar unit was installed adjacent to an 84 m wind monitoring mast, located in simple terrain. This Appendix addresses the following issues:

- The wind monitoring mast setup
- The sodar unit setup
- The comparison of the data sets

A.1 Wind monitoring mast setup

A single wind monitoring mast is installed, and details of the mast setup provided by [8]. From a brief review of this information, Entura has summarised the setup in Table A.1 and Table A.2 and notes the following:

- The physical mast setup appears to be generally compliant with IEC 61400-12-1 [3] standard, however Entura has not verified the site, so independent verification is not possible.
- Throughout the period, corrections were made to logger directional data.

The wind data is considered to be of reasonable quality and suitable for verification of the sodar data.

Typically, Entura would attempt to determine any mast shading effects, and eliminate the data before verification. The 84.5 m anemometer is installed on a boom straight up from the mast in line with IEC standards [3] and is therefore not shaded by the mast. There is a lightning finial installed at the top of the mast, it is installed at 98° magnetic (109° true) with a distance from the spindle centreline of 0.32 m and a diameter of 13 mm. Based on the flow disturbance approximations provided in IEC 61400-12-1 [3] and there being no shading effect visible in the data it is assumed to have negligible effect on the data.

The 60 m anemometer is installed in the direction 227° and therefore data from the directions 45° to 75° has been removed to account for mast shading. Data from the 40 m and 11 m levels of the mast do not have comparable heights in the sodar data record, and have not been analysed.

Table A.1: Site #1a mast setup

Mast Name	Site #1a		
Coordinates and Datum	Confidential		
Altitude	415.3 m Australian Height Datum		
Mast Type	Jennings lattice mast, 81.65 m AGL		
Face Width	450 mm		
Boom Clamping Method	Unconfirmed		
IEC Compliant?	Unconfirmed		
Mast Operating Period	Start: 14/12/2009	End: present	

Surrounding Terrain Description	Flat
Visible Obstructions/Terrain Features Affecting Data	None visible from photos or listed in data supplied
Logger Type	Unidata – Prologger 7001B (512k)
Logger ID	10430
Data Time Step / Offset	10 minutes
Service History	82.45 m wind vane replaced 9/02/2011
Event Log	None
Other Comments	All anemometers on this mast except at the 10 m level were replaced 27/03/2013.

Table A.2: Site #1a mast instrument setup

Height AGL (m)	**Type**	**S/N**	**Calibration Date**	**Boom (*approx.*) (m)**			**Logged Parameters**			
				Length	**Up stand**	**Orient.**	**Ave**	**SD**	**Max**	**Min**
Wind Speed										
84.5	Risø P2546A	2098	24/10/2008	NA	1.8	20°	✓	✓	✓	✓
60.28	Risø P2546A	1879	1/05/2009	2.6	1.2	227°	✓	✓	✓	✓
40.76	Risø P2546A	1878	1/05/2009	2.6	1.2	229°	✓	✓	✓	✓
11.51	Risø P2546A	1164	1/05/2009	2.6	1.2	232°	✓	✓	✓	✓
Wind Direction										
82.5	Vector W200P	55966 (53748)	NA	2.4	1.19	45° (57° true)	✓	✓		
60.27	Vector W200P	53743	NA	2.2	1.19	47° (59° true	✓	✓		
40.75	Vector W200P	53739	NA	2.2	1.19	49° (61° true	✓	✓		
11.50	Vector W200P	53744	NA	2.2	1.19	52° (64° true	✓	✓		
Temperature										
81.4	Fischer 439101						✓			
Pressure										
1.7	Vaisala PTB110	E1510019					✓			

A.2 Fulcrum 3D sodar setup

Based the sodar and location data supplied, Table A.3 summarises the Fulcrum 3D sodar setup.

Table A.3: Site #1a Fulcrum 3D sodar configuration

Device manufacturer	Fulcrum 3D
Serial number	FS1M_1007
Software version	v3.30
Software date	N/A
Measured heights	60, 70,80, 90,100, 110, 120, 130, 140, 150 m
Raw data time zone	UTC +00:00
Time zone for site	UTC +10:00
Tilt X, absolute maximum during period, (within +/- 3°)	N/A
Tilt Y, absolute maximum during period, (within +/- 3°)	N/A
Location: Easting, Northing, Zone	Confidential
Elevation	~417 m (from Google Earth)
Elevation relative to mast base	~3 m (from Google Earth)
Orientation	Sodar direction required an offset of -101^{o} to be applied. The unit was installed rotated on site (facing east, 90^{o}) and the offset for magnetic declination (11^{o}) was also required to be applied.
Description of site:	Flat paddock of grassland, appears to be for grazing.
Obstacles:	Wind monitoring mast: Height 81.65 m Bearing ~179^{o} Distance 105 m
Notes:	• None

The following has been considered in siting the sodar:

- A minimum separation distance of 1.25x mast height, in this case 105 m.
- Sodar beam orientation not directly at the mast.

The placement of the sodar unit is located 105 m to the north of the existing mast location and within 5 m elevation, with uniform terrain and surface roughness in the immediate vicinity. No changes to the sodar firmware or setup occurred during the reporting period.

Photographs of the sodar unit are provided in Figure A.1.

The surrounding terrain is simple, and differences in actual wind speed are unlikely between the sodar and mast locations over this distance. As such, this test site is suitable for verifying the absolute accuracy of the sodar data against the mast data.

Figure A.1: Site #1a surrounding terrain and vegetation
Clockwise; North, East, South and West

A.3 Data recovery

Details of the test period are displayed in Table A.4.

Table A.4: Site #1a data period

Data begin	18/04/2012 00:00, UTC +10:00
Data end	11/06/2012 00:00, UTC +10:00
Number of days	54
Number of 10 minute periods	7,777

As a test of the sufficiency of the data period, Entura has confirmed the recommendations of [1] as listed in Section 4.1 have generally been fulfilled at this test site. Entura has filtered the sodar data based on the recommendations of Fulcrum 3D [5].

The data recovery rates for the mast and sodar are displayed in Table C.5. For the purpose of reporting data recovery, Entura does not distinguish between data lost through operational downtime, and data lost through filtering. The sodar data has only had the standard filtering applied as discussed in Section 3.

Entura has noted erroneous sodar data points occurring at levels above 100 m. These data points were not identified with the Fulcrum provided data filtering rules which have been applied to derive the recovery rates in Table C.5. The sodar recovery rates are comparably lower than the mast, as is typical with remote sensing devices.

Table A.5: Site #1a data recovery by height

Mast			Fulcrum 3D sodar	
Height AGL (m)	**Data Recovery (%)**		**Height AGL (m)**	**Data recovery (%)**
11.51	100#		60	88
40.76	100#		70	87
60.28	95*		80	86
84.50	100		90	86
82.03 DIR	100		100	84
60.27 DIR	100		110	83
40.75 DIR	100		120	80
11.50 DIR	100		130	72
			140	71
			150	64

mast shading not removed from these levels, which are not used in this analysis

*data recovery with data affected by mast shading filtered out

A.4 Time series observations

Fulcrum 3D has stated that 1007 was deployed with a 90 degree offset (as measured with the compass on site) and this was not been corrected in the data supplied. The direction data has also not been corrected for the magnetic declination at the site of 11°. Therefore Entura has applied an offset to the sodar direction data of 101°.

The wind speeds at 80 m and 60 m heights from the sodar and mast track each other reasonably well throughout the period, provided the sodar data is appropriately filtered.

Some individual outliers in the dataset are apparent in the comparative measured 10 minute time series.

A.5 Average wind speed

Table A.6 displays a comparison of the average wind speeds measured at the mast and sodar over the period.

'All wind speed data' refers to whatever data is available for the specified time period. 'Concurrent wind speed data' has been filtered so that only time-steps where both mast and sodar data are available for the given level, are considered.

Note that mast wind speeds measured at 84.5 m are compared with both 80 m and 90 m sodar wind speeds, without any adjustment to account for wind shear.

Table A.6: Site #1a comparison of average wind speeds

Height AGL (m)	All wind speed data (m/s)		Concurrent wind speed data (m/s)	
	Mast	Sodar	Mast	Sodar
(60.3) 60	6.31	6.36	6.44	6.44
70	-	6.65	-	-
80	-	6.91	7.01 (84.5 m)	6.91
84.5	6.79			
90	-	7.10	6.97 (84.5 m)	7.10
100	-	7.30	-	-
110	-	7.37	-	-
120	-	7.59	-	-
130	-	7.84	-	-
140	-	8.06	-	-
150	-	8.28	-	-

A.6 Wind speed correlation

Correlations between mast and sodar wind speeds are presented in the following figures.

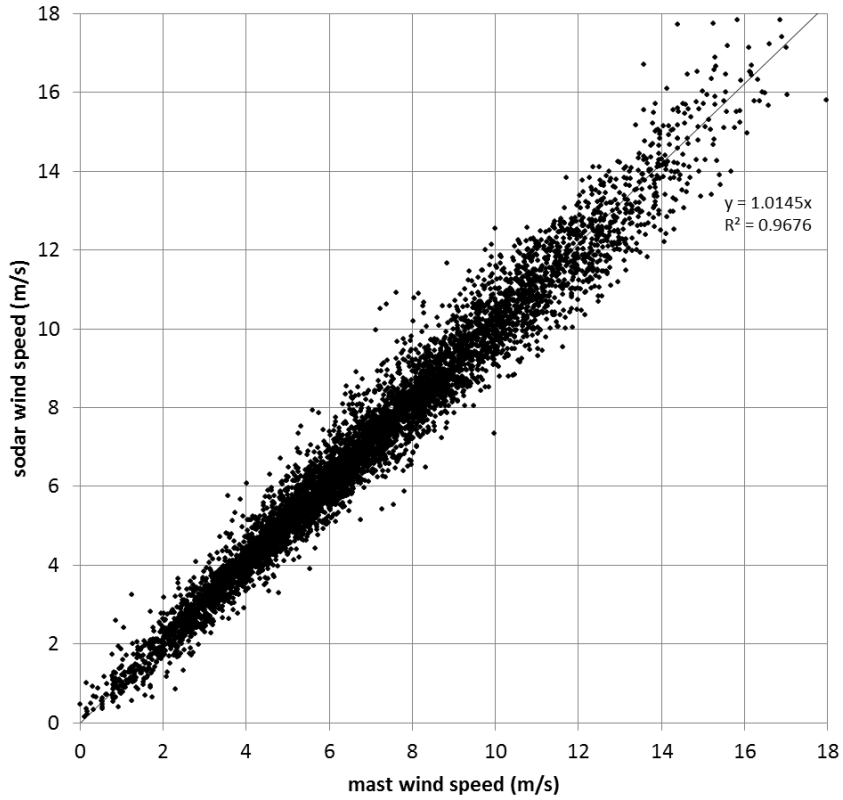

Figure A.2: Sodar 90 m wind speed vs. Mast 84.5 m wind speed, 10-min data

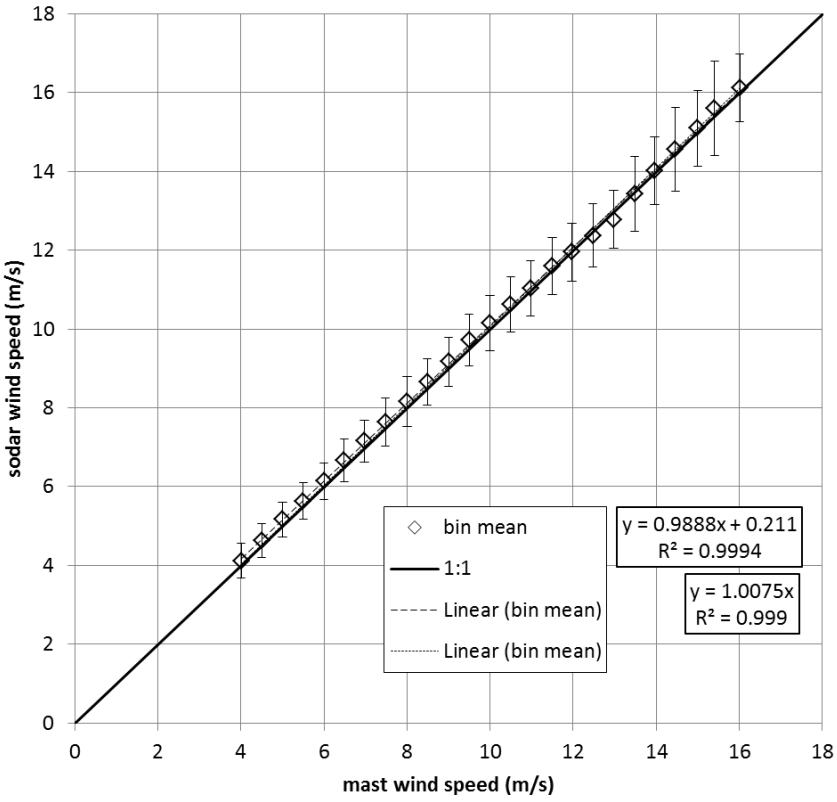

Figure A.3: Sodar 90 m wind speed vs. Mast 84.5 m wind speed, binned correlation

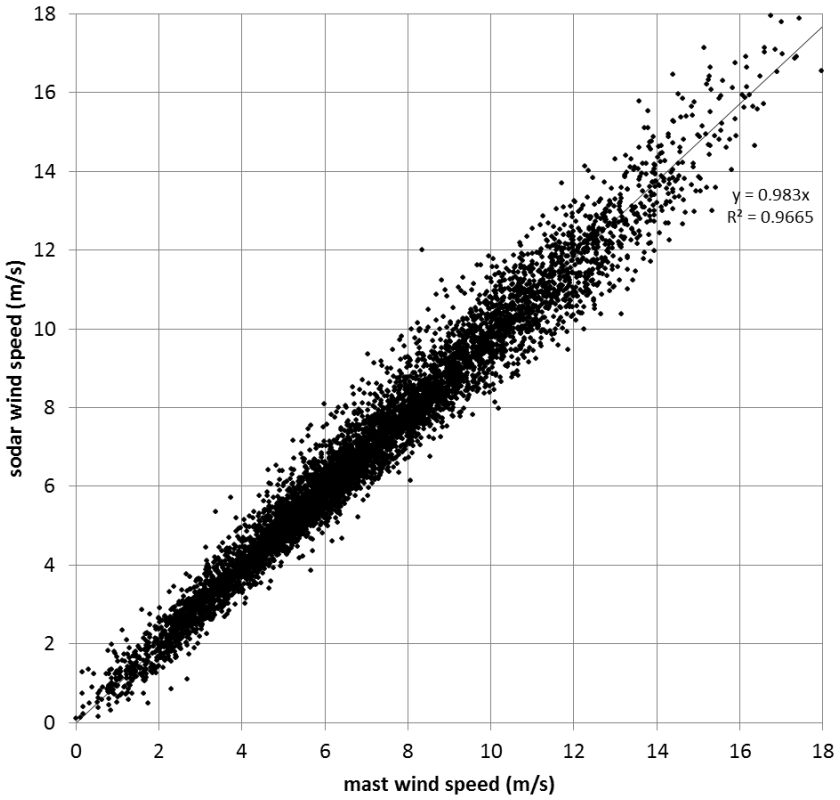

Figure A.4: Sodar 80 m wind speed vs. Mast 84.5 m wind speed, 10-min data

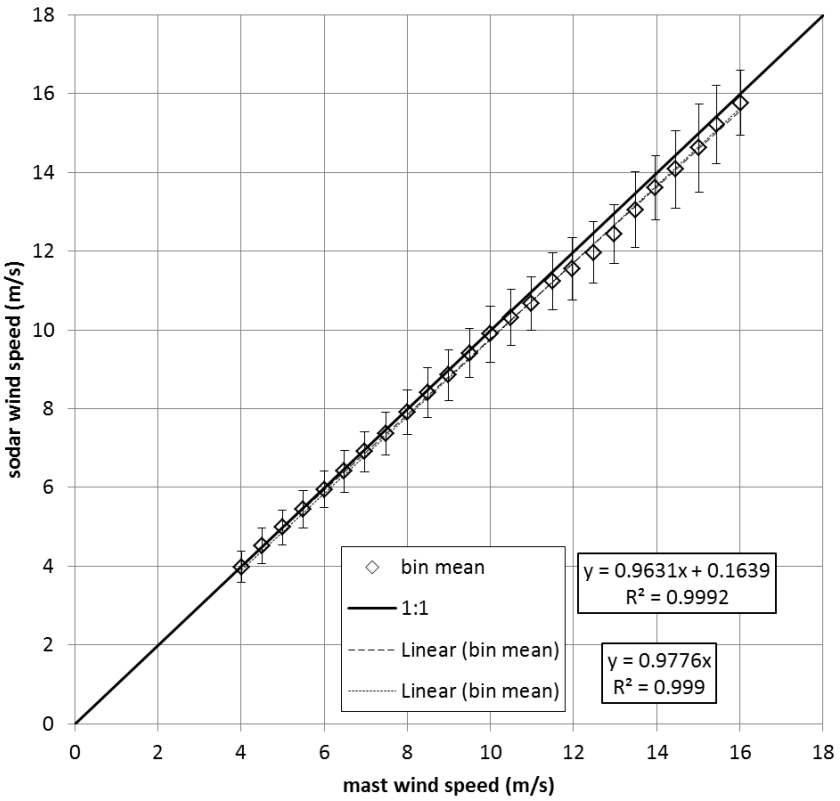

Figure A.5: Sodar 80 m wind speed vs. Mast 84.5 m wind speed, binned correlation

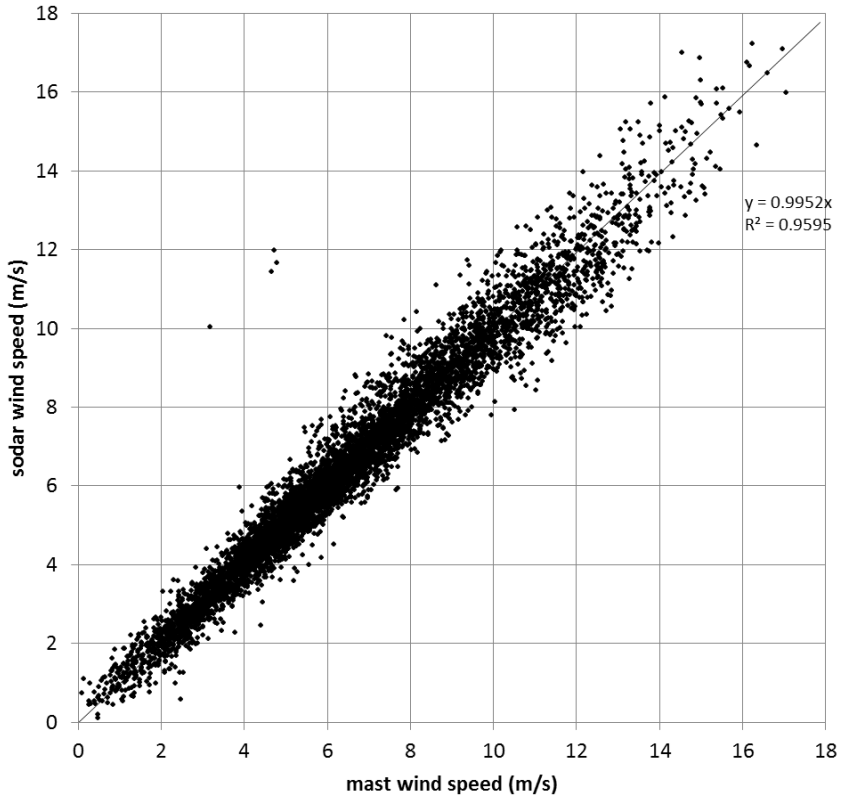

Figure A.6: Sodar 60 m wind speed vs. Mast 60.3 m wind speed, 10-min data

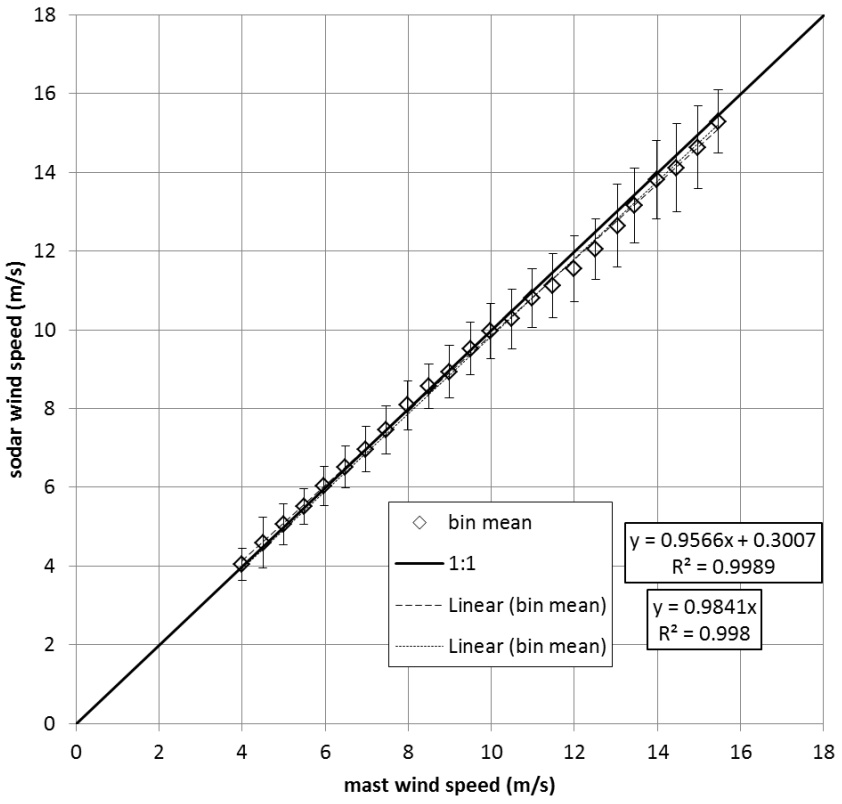

Figure A.7: Sodar 60 m wind speed vs. Mast 60.3 m wind speed, binned correlation

Table A.7: Wind speed correlation results

Level	linear best fit			forced through origin	
	Slope	Offset	R2	Slope	R2
90	0.9888	0.2110	0.9994	1.0075	0.9990
80	0.9631	0.1639	0.9992	0.9776	0.9990
60	0.9566	0.3007	0.9989	0.9841	0.9980

A.7 Wind speed differences

Absolute and relative differences between the mast and sodar wind speeds at the 80 m level are presented in the following figures, which also display the median and standard deviation for each wind speed bin.

Figures for the 60 m height are not shown, but Entura notes these provide similar results.

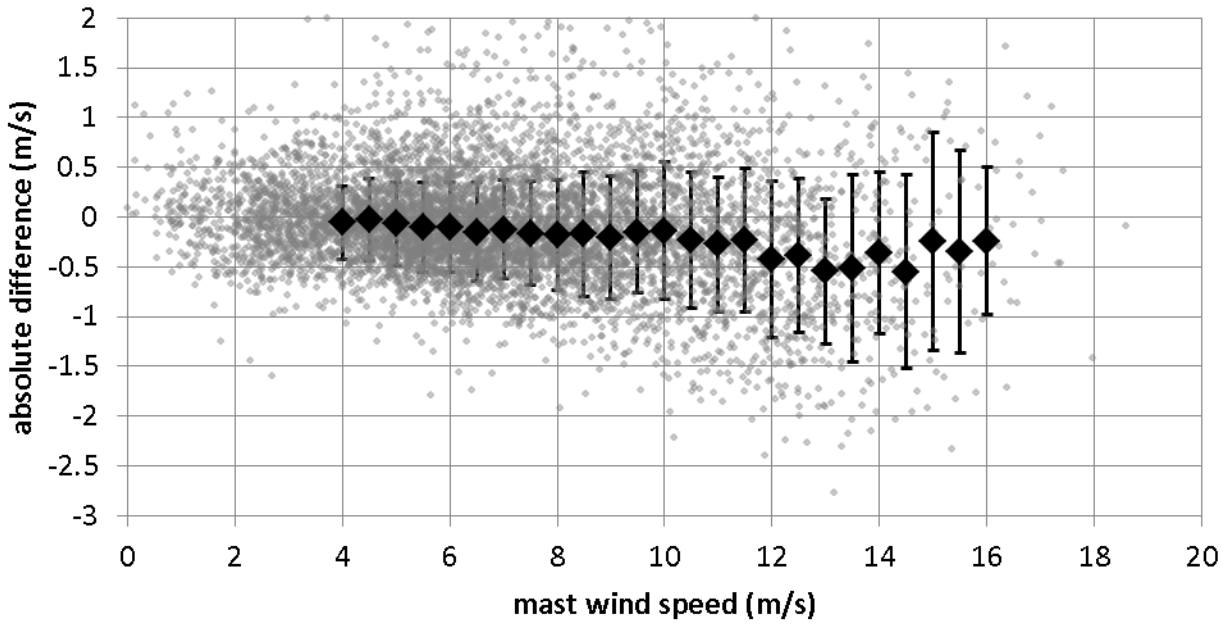

Figure A.8: Sodar 80 m - Mast 84.5 m absolute wind speed difference vs. mast wind speed

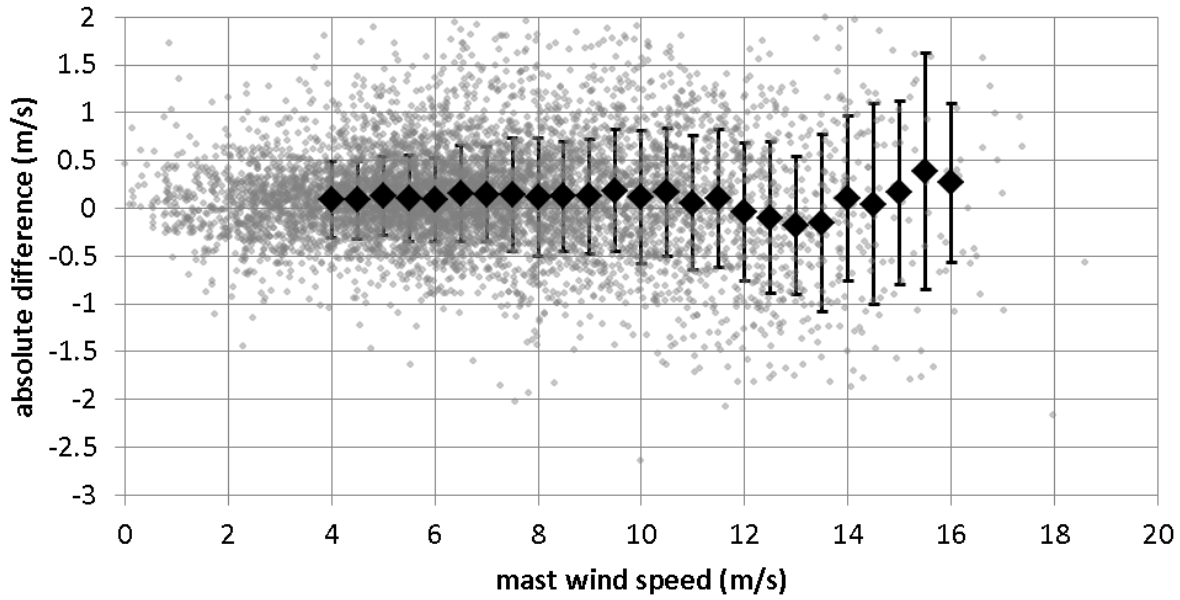

Figure A.9: Sodar 90 m - Mast 84.5 m absolute wind speed difference vs. mast wind speed

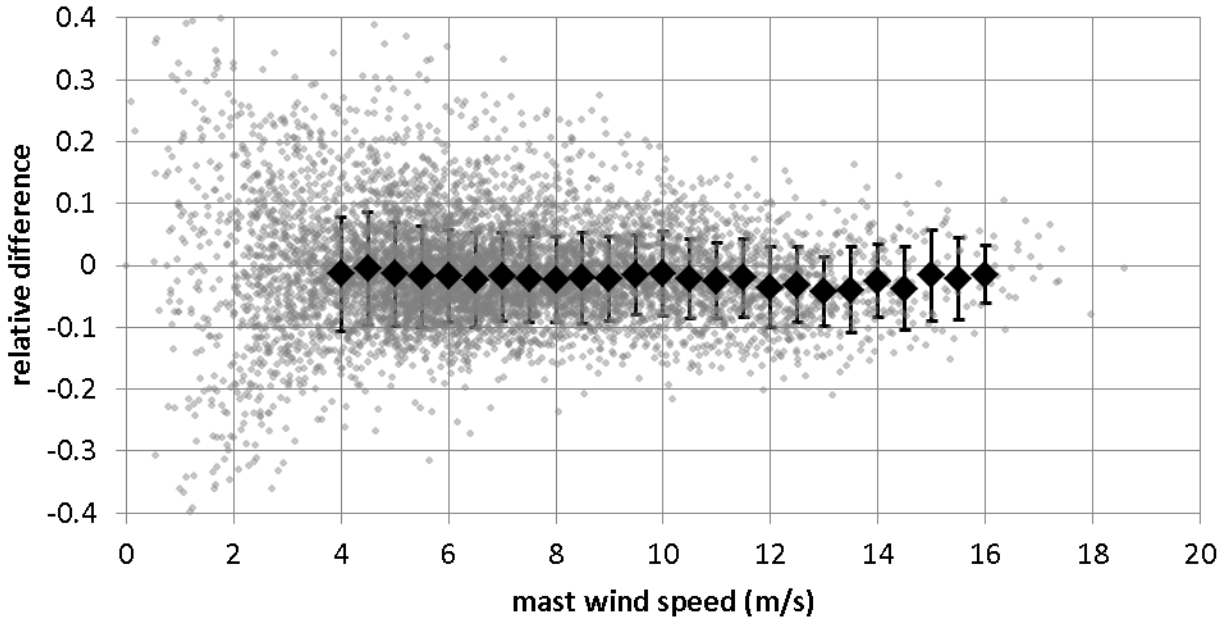

Figure A.10: Sodar 80 m - Mast 84.5 m relative wind speed difference vs. mast wind speed

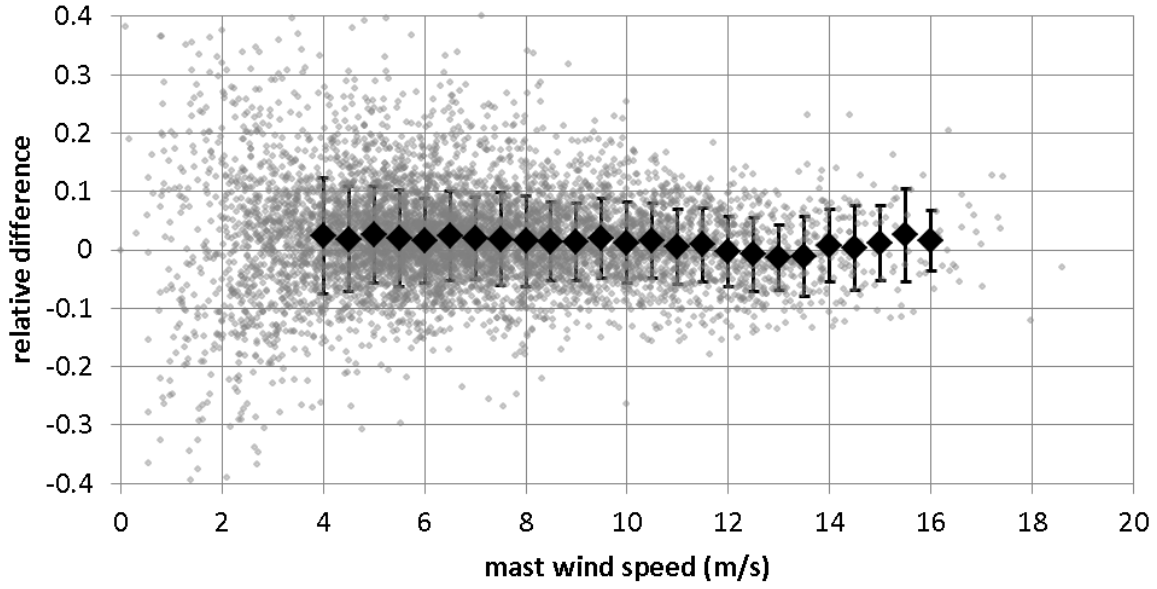

Figure A.11: Sodar 90 m - Mast 84.5 m relative wind speed difference vs. mast wind speed

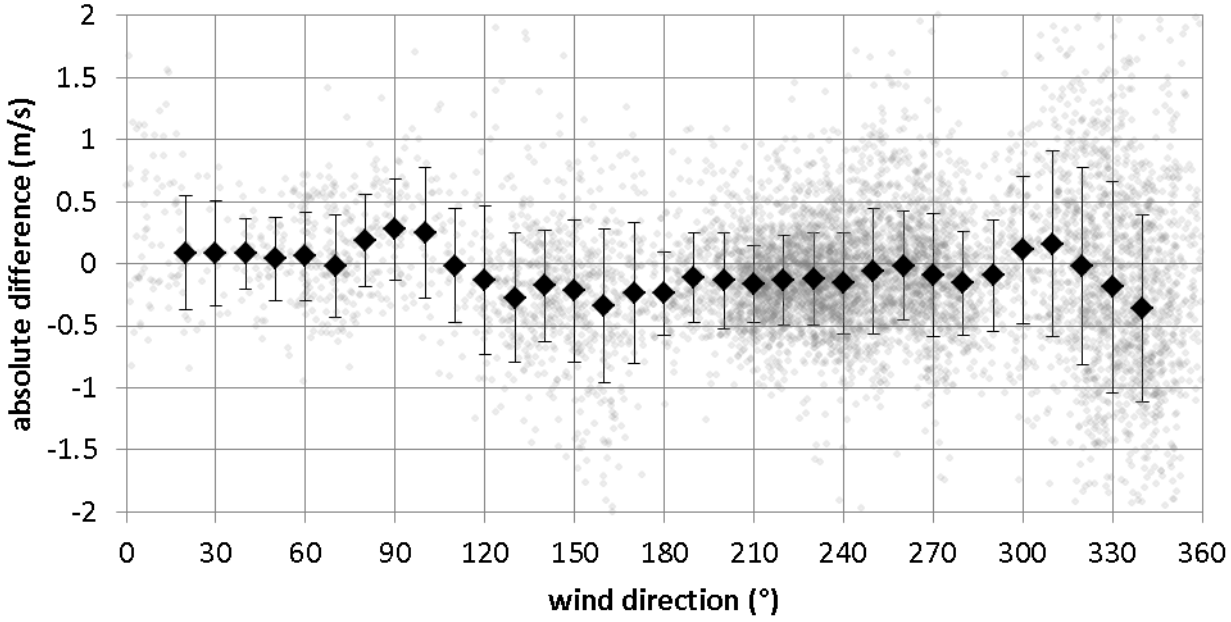

Figure A.12: Sodar 80 m - Mast 84.5 m absolute wind speed difference vs. mast wind direction

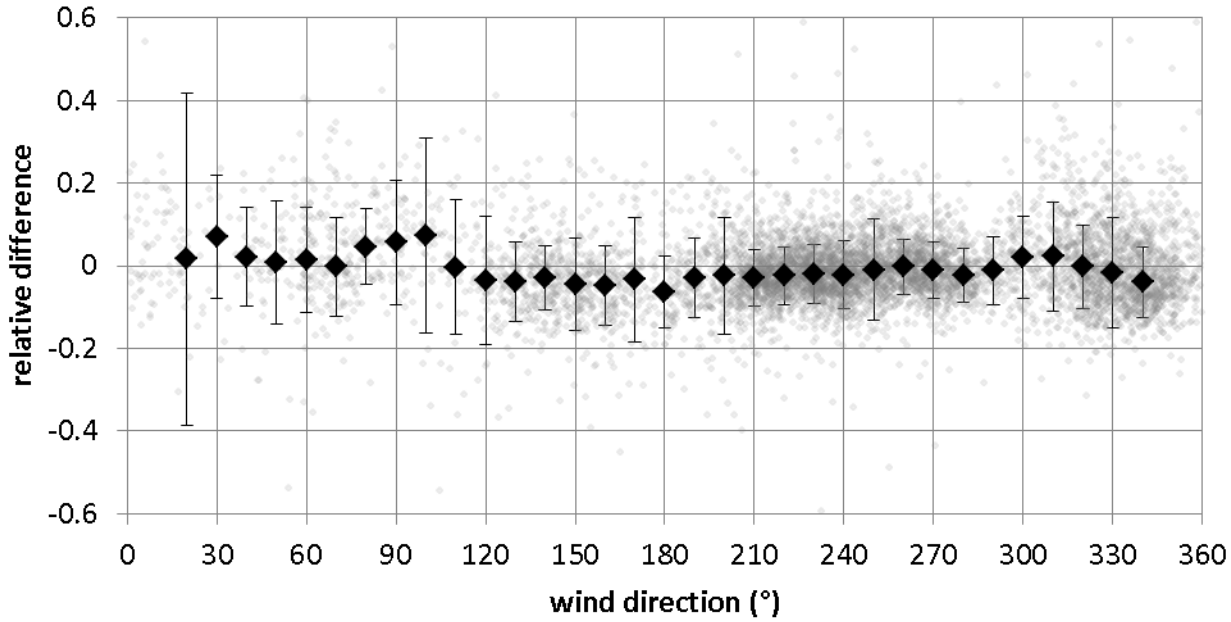

Figure A.13: Sodar 80 m - Mast 84.5 m relative wind speed difference vs. mast wind direction

A.8 Wind speed uncertainty

Table A.8 displays the inputs and the calculated relative uncertainty as a percentage of the bin-mean mast wind speed for the 80 m level. It is assumed that all sources of uncertainty are uncorrelated, and the total uncertainty is the square-root of the sum of the square of the uncertainties.

Estimating the mast anemometer uncertainty includes consideration of the following factors (listed in order of importance):

- Tower, boom and instrument mounting effects – an uncertainty of 2.0% is estimated.
- Complex wind flow and environmental conditions during field measurements, including increases and decreases in wind speed (dynamic overspeeding), turbulence, angled inflows, and rain – an uncertainty of 1.0% is estimated considering the relatively benign terrain at site #1a, and the characteristics of the Risø anemometer [8].
- Anemometer calibration – an uncertainty of 1.0% is estimated based on the anemometer specifications and the calibrations undertaken of the 80 m anemometer [8].
- Anemometer degradation – an uncertainty of 1.0 % is estimated given that the instruments have been in place for over 3 years without recalibration.
- Data processing accuracy – an uncertainty of 0.2% is estimated (a nominal amount).

These individual uncertainties are combined using the root-sum-square technique. The combined uncertainty of the wind speed measurements is 2.7%.

Estimating the sodar mounting uncertainty includes consideration of the following factors (listed in order of importance):

- Instrument uncertainty – an uncertainty of 0.5% is estimated.

- Complex wind flow and environmental conditions during field measurements, fixed echoes, turbulence, angled inflows, and rain – an uncertainty of 1.0% is estimated considering the relatively benign terrain and absence of obstacles visible at site #1a.

The uncertainty caused by the flow variability across the site is estimated to be quite low given the close proximity between the masts and the sodar units, 105 m. Therefore an uncertainty of 0.5% is estimated.

The uncertainty table for the 60 m height is not shown, but Entura notes this provide similar results.

Table A.8: Wind speed uncertainty, 80 m

				bin uncertainty (% of mast wind speed)					
mast wind speed	**Sodar wind speed**	**# data points**	**std. dev.**	**sodar precision**	**mean deviation**	**Mast**	**Sodar mounting**	**Site effects**	**Total**
U_{mast}	U_{sodar}	n	$\sigma(U_{sodar})$	$\sigma(U_{sodar})/\sqrt{n}$	$U_{sodar}-U_{mast}$				
4.01	3.98	355	0.39	0.52	0.60	2.7	1.1	0.5	3.0
4.50	4.52	448	0.44	0.47	0.40	2.7	1.1	0.5	3.0
5.00	4.99	553	0.44	0.38	0.26	2.7	1.1	0.5	3.0
5.50	5.46	560	0.48	0.37	0.76	2.7	1.1	0.5	3.0
6.00	5.95	591	0.47	0.32	0.92	2.7	1.1	0.5	3.1
6.49	6.41	537	0.53	0.35	1.25	2.7	1.1	0.5	3.2
6.98	6.91	449	0.52	0.35	1.03	2.7	1.1	0.5	3.1
7.48	7.38	432	0.55	0.35	1.43	2.7	1.1	0.5	3.3
8.01	7.90	396	0.56	0.35	1.27	2.7	1.1	0.5	3.2
8.49	8.41	339	0.63	0.41	0.94	2.7	1.1	0.5	3.1
9.00	8.86	288	0.64	0.42	1.58	2.7	1.1	0.5	3.3
9.50	9.42	261	0.63	0.41	0.84	2.7	1.1	0.5	3.1
10.00	9.89	234	0.72	0.47	1.06	2.7	1.1	0.5	3.1
10.50	10.32	212	0.71	0.46	1.73	2.7	1.1	0.5	3.4
10.98	10.67	183	0.68	0.45	2.84	2.7	1.1	0.5	4.1
11.50	11.25	144	0.73	0.53	2.17	2.7	1.1	0.5	3.7
11.97	11.56	126	0.80	0.59	3.42	2.7	1.1	0.5	4.5
12.48	11.97	125	0.78	0.56	4.07	2.7	1.1	0.5	5.0
12.98	12.44	85	0.75	0.62	4.17	2.7	1.1	0.5	5.1
13.49	13.05	62	0.96	0.91	3.20	2.7	1.1	0.5	4.4
13.97	13.61	73	0.81	0.68	2.61	2.7	1.1	0.5	4.0
14.46	14.08	48	0.99	0.99	2.62	2.7	1.1	0.5	4.0
15.02	14.63	31	1.12	1.34	2.62	2.7	1.1	0.5	4.1
15.44	15.22	25	1.00	1.30	1.38	2.7	1.1	0.5	3.5
16.02	15.77	19	0.83	1.19	1.52	2.7	1.1	0.5	3.5

Table A.9: Wind speed uncertainty, 90 m

				bin uncertainty (% of mast wind speed)					
mast wind speed	**Sodar wind speed**	**# data points**	**std. dev.**	**sodar precision**	**mean deviation**	**Mast**	**Sodar mounting**	**Site effects**	**Total**
U_{mast}	U_{sodar}	n	$\sigma(U_{sodar})$	$\sigma(U_{sodar})/\sqrt{n}$	$U_{sodar}-U_{mast}$				
4.01	4.12	260	0.44	0.68	2.72	2.7	1.1	0.5	4.0
4.50	4.62	361	0.43	0.51	2.76	2.7	1.1	0.5	4.0
5.00	5.16	460	0.44	0.41	3.26	2.7	1.1	0.5	4.4
5.50	5.63	488	0.47	0.38	2.31	2.7	1.1	0.5	3.7
6.00	6.14	537	0.46	0.33	2.25	2.7	1.1	0.5	3.7
6.49	6.67	480	0.54	0.38	2.74	2.7	1.1	0.5	4.0
6.98	7.16	398	0.52	0.38	2.57	2.7	1.1	0.5	3.9
7.48	7.64	384	0.62	0.42	2.11	2.7	1.1	0.5	3.6
8.01	8.15	341	0.63	0.43	1.81	2.7	1.1	0.5	3.5
8.49	8.65	295	0.59	0.40	1.96	2.7	1.1	0.5	3.5
9.00	9.17	250	0.63	0.44	1.86	2.7	1.1	0.5	3.5
9.50	9.72	229	0.67	0.46	2.38	2.7	1.1	0.5	3.8
10.00	10.16	216	0.71	0.48	1.57	2.7	1.1	0.5	3.4
10.50	10.63	201	0.70	0.47	1.22	2.7	1.1	0.5	3.2
10.98	11.03	170	0.70	0.49	0.47	2.7	1.1	0.5	3.0
11.50	11.59	139	0.73	0.54	0.85	2.7	1.1	0.5	3.1
11.97	11.95	122	0.73	0.55	0.17	2.7	1.1	0.5	3.0
12.48	12.38	120	0.80	0.59	0.80	2.7	1.1	0.5	3.1
12.98	12.78	74	0.74	0.66	1.53	2.7	1.1	0.5	3.4
13.49	13.43	54	0.96	0.97	0.42	2.7	1.1	0.5	3.1
13.96	14.02	61	0.86	0.78	0.42	2.7	1.1	0.5	3.1
14.47	14.56	38	1.06	1.19	0.66	2.7	1.1	0.5	3.2
15.00	15.10	17	0.96	1.55	0.62	2.7	1.1	0.5	3.4
15.41	15.60	18	1.20	1.84	1.25	2.7	1.1	0.5	3.7
16.01	16.12	13	0.86	1.48	0.67	2.7	1.1	0.5	3.3

A.9 Wind direction comparison

Correlations between mast and sodar wind speeds are presented in the following figures.

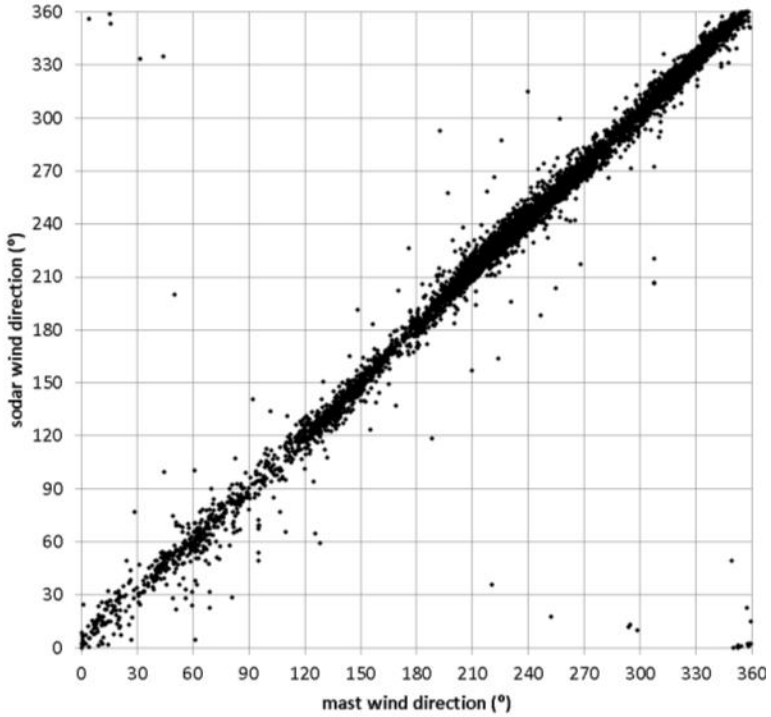

Figure A.14: Sodar 60 m wind direction vs. Mast 60.3 m wind direction, 10-min data

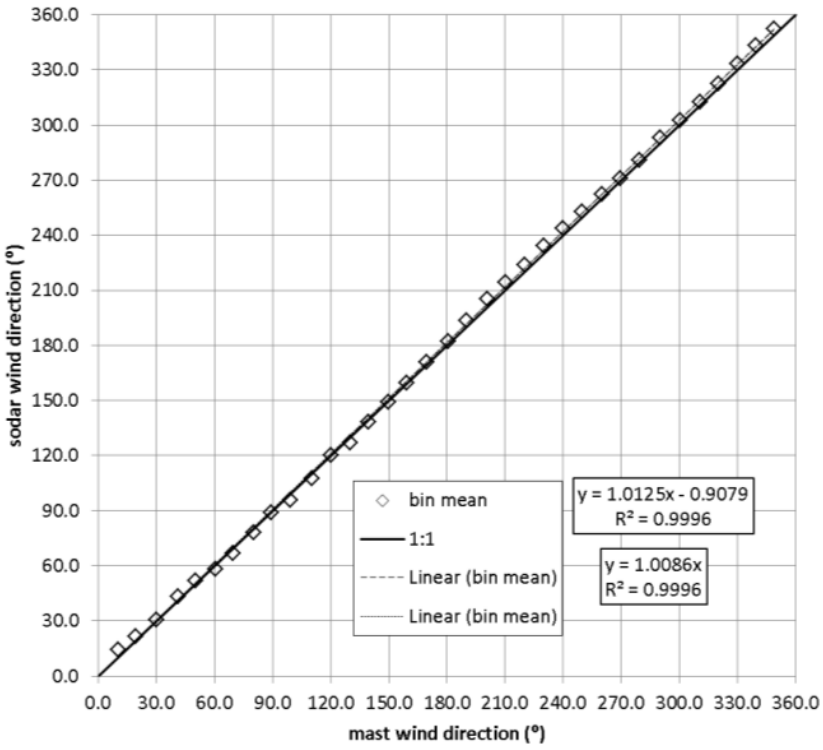

Figure A.15: Sodar 60 m wind direction vs. Mast 60.3 m wind direction, binned correlation

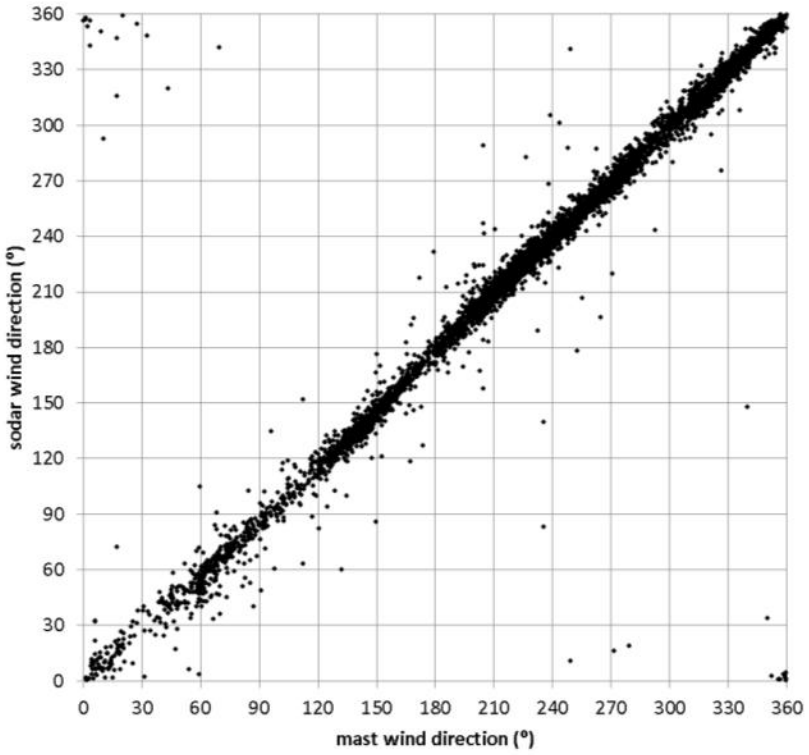

Figure A.16: Sodar 80 m wind direction vs. Mast 82.5 m wind direction, 10-min data

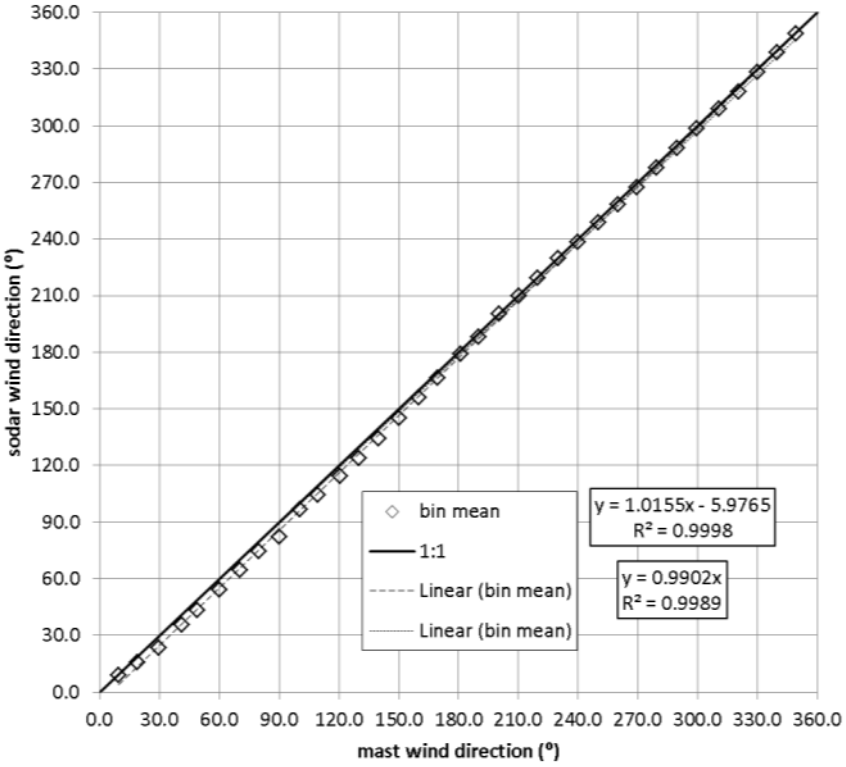

Figure A.17: Sodar 80 m wind direction vs. Mast 82.5 m wind direction, binned correlation

The previous figures suggest some non-linearity in the relationship between sodar and mast wind direction, which may be due to instrument error (mast or sodar) or differences between the two locations. Generally the difference is relatively small.

Comparisons of wind frequency roses, based on 10 minute data at 80 m indicate a close relationship as shown in Figure A.18.

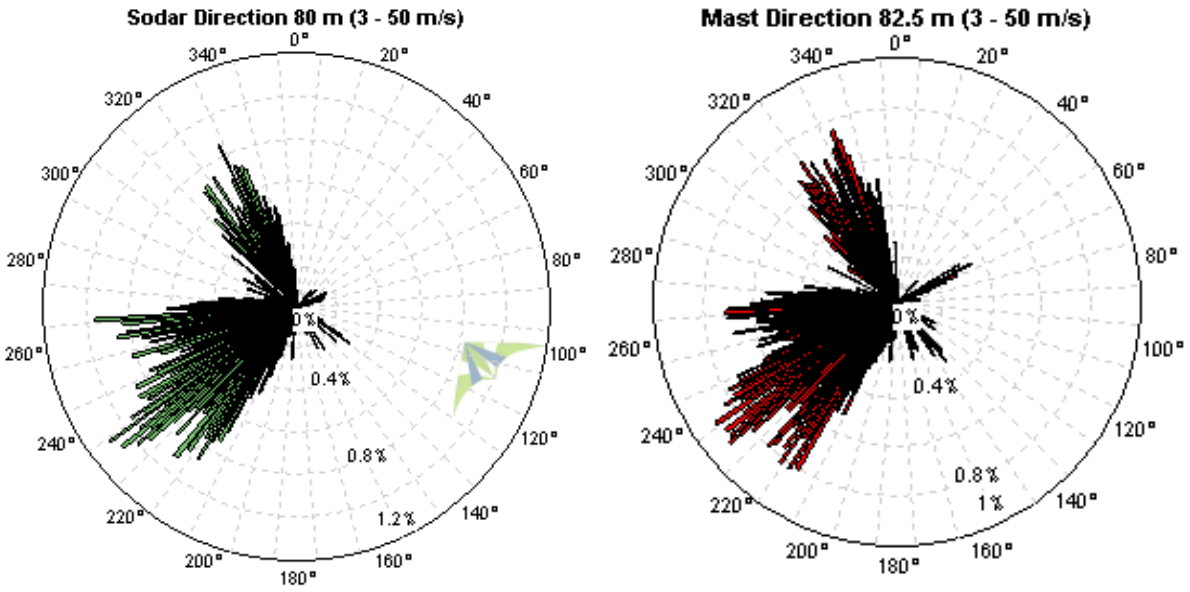

Figure A.18: Wind direction frequency rose, left sodar 80 m, right mast 82.5 m, and 360 sectors

A.10 Wind shear analysis

Vertical wind shear exponent (power law) was compared between the 60 m and 80 m heights of the sodar and mast, for concurrent wind speeds greater than 3.0 m/s and excluding the shaded 60.3 m mast data for the sector 45° to 80°. The results are displayed in Table A.10.

Table A.10: Shear comparison

	Shear exponent mast (all data points)		Shear exponent		
Time	**Mast (60.3–84.5 m)**	**# data points**	**Sodar (60–80 m)**	**Mast (60.3–84.5 m)**	**# data points**
All	0.29	6,735	0.31	0.30	5,705
Day (06:00 – 18:00)	0.23	3,614	0.24	0.23	3,052
Night (18:00 – 06:00)	0.36	3,121	0.39	0.38	2,653

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B Site #1b 1014

At Site #1b (1014), a Fulcrum 3D sodar unit was installed adjacent to an 84 m wind monitoring mast, located in simple terrain. This Appendix addresses the following issues:

- The wind monitoring mast setup
- The sodar unit setup
- The comparison of the data sets

B.1 Wind monitoring mast setup

A single wind monitoring mast is installed, and details of the mast setup provided by [8] and [9]. From a brief review of this information, Entura has summarised the setup in Table B.1and Table B.2 and notes the following:

- The physical mast setup appears to be generally compliant with IEC 61400-12-1 [3] standard, however Entura has not verified the site, so independent verification is not possible.
- Throughout the period, corrections were made to logger directional data.

The wind data is considered to be of reasonable quality and suitable for verification of the sodar data.

Typically, Entura would attempt to determine any mast shading effects, and eliminate the data before verification. The 84.5 m anemometer is installed on a boom straight up from the mast in line with IEC standards [3] and is therefore not shaded by the mast. There is a lightning finial installed at the top of the mast, it is installed at 98° magnetic (109° true) with a distance from the spindle centreline of 0.32 m and a diameter of 13 mm. Based on the flow disturbance approximations provided in IEC 61400-12-1 [3] and there being no shading effect visible in the data it is assumed to have negligible effect on the data.

The 60 m anemometer is installed in the direction 227° and therefore data from the directions 45° to 75° has been removed to account for mast shading. Data affected by mast shading has not been removed for the lower levels (40 m and 11 m) as these are not used in this assessment.

Table B.1: Site #1b mast setup

Mast Name	Site #1b		
Coordinates and Datum	Confidential		
Altitude	415.3 m Australian Height Datum		
Mast Type	Jennings lattice mast, 81.65 m AGL		
Face Width	450 mm		
Boom Clamping Method	Unconfirmed		
IEC Compliant?	Unconfirmed		
Mast Operating Period	Start: 14/12/2009	End: present	
Surrounding Terrain Description	Flat		
Visible Obstructions/Terrain Features	None visible from photos or listed in data supplied		

Affecting Data	
Logger Type	Unidata – Prologger 7001B (512k)
Logger ID	10430
Data Time Step / Offset	10 minutes
Service History	82.45 m wind vane replaced 9/02/2011
Event Log	None
Other Comments	All anemometers on this mast except at the 10 m level were replaced 27/03/2013.

Table B.2: Site #1b mast instrument setup

Height AGL (m)	**Type**	**S/N**	**Calibration Date**	**Boom (*approx.*) (m)**			**Logged Parameters**			
				Length	**Up stand**	**Orient.**	**Ave**	**SD**	**Max**	**Min**
Wind Speed										
84.5	Risø P2546A	7621	18/03/2013	NA	1.8	20°	✓	✓	✓	✓
60.28	Risø P2546A	2099	9/06/2011	2.6	1.2	227°	✓	✓	✓	✓
40.76	Risø P2546A	7619	19/03/2013	2.6	1.2	229°	✓	✓	✓	✓
11.51	Risø P2546A	1164	1/05/2009	2.6	1.2	232°	✓	✓	✓	✓
Wind Direction										
82.5	Vector W200P	55966	NA	2.4	1.19	45° (57° true)	✓	✓		
60.27	Vector W200P	53743	NA	2.2	1.19	47° (59° true	✓	✓		
40.75	Vector W200P	53739	NA	2.2	1.19	49° (61° true	✓	✓		
11.50	Vector W200P	53744	NA	2.2	1.19	52° (64° true	✓	✓		
Temperature										
81.4	Fischer 439101						✓			
Pressure										
1.7	Vaisala PTB110	E1510019					✓			

B.2 Fulcrum 3D sodar setup

Based on the sodar and location data provided, Table B.3 summarises the Fulcrum 3D sodar setup.

Table B.3: Site #1b Fulcrum 3D sodar configuration

Device manufacturer	Fulcrum 3D
Serial number	FS1M_1014
Software version	v3.30
Software date	N/A
Measured heights	60, 70,80, 90,100, 110, 120, 130, 140, 150 m
Raw data time zone	UTC +00:00
Time zone for site	UTC +10:00
Tilt X, absolute maximum during period, (within +/- 3°)	N/A
Tilt Y, absolute maximum during period, (within +/- 3°)	N/A
Location: Easting, Northing, Zone	Confidential
Elevation	~417 m (from Google Earth)
Elevation relative to mast base	~0m (from Google Earth)
Orientation	The offset for magnetic declination (11^{o}) was required to be applied.
Description of site:	Flat paddock of grassland, appears to be for grazing.
Obstacles:	Wind monitoring mast: Height 81.65 m Bearing ~10^{o} Distance 140 m
Notes:	None

The following has been considered in siting the sodar:

- A minimum separation distance of 1.25x mast height, in this case 105 m.
- Sodar beam orientation not directly at the mast.

The placement of the sodar unit is located 140 m to the south of the existing mast location and within 5 m elevation, with uniform terrain and surface roughness in the immediate vicinity. No changes to the sodar firmware or setup occurred during the reporting period.

Photographs of the sodar unit are provided in Figure B.1.

The surrounding terrain is simple, and differences in actual wind speed are unlikely between the sodar and mast locations over this distance. As such, this test site is suitable for verifying the absolute accuracy of the sodar data against the mast data.

Figure B.1: Site #1b surrounding terrain and vegetation
Clockwise; North, East, South and West

B.3 Data recovery

Details of the test period are displayed in Table B.4.

Table B.4: Site #1b data period

Data begin	22/06/2013 10:00, UTC +10:00
Data end	31/07/2013 00:00, UTC +10:00
Number of days	38
Number of 10 minute periods	5,556

As a test of the sufficiency of the data period, Entura has confirmed the recommendations of [1] as listed in Section 4.1 have been fulfilled at this test site.

Entura has filtered the data based on the recommendations of Fulcrum 3D [5].

The data recovery rates for the mast and sodar are displayed in Table B.5. For the purpose of reporting data recovery, Entura does not distinguish between data lost through operational downtime, and data lost through filtering. The sodar data has only had the standard filtering applied as discussed in Section 3.

Sodar recovery rates are comparably lower than the mast, as is typical with remote sensing devices.

Entura has noted erroneous sodar data points occurring at levels above 100 m. These data points were not identified with the Fulcrum provided data filtering rules which have been applied to derive the recovery rates in Table B.5.

Table B.5: Site #1b data recovery by height

Mast			Fulcrum 3D sodar	
Height AGL (m)	**Data Recovery (%)**		**Height AGL (m)**	**Data recovery (%)**
11.51	100#		60	88
40.76	100#		70	90
60.28	97*		80	87
84.50	100		90	83
82.03 DIR	99		100	79
60.27 DIR	99		110	72
40.75 DIR	100		120	63
11.50 DIR	100		130	51
			140	40
			150	33

mast shading not removed from these levels, which are not used in this analysis

*data recovery with mast shading excluded

B.4 Time series observations

The wind speeds at 80 m and 60 m heights from the sodar and mast track each other reasonably well throughout the period, provided the sodar data is appropriately filtered.

Some individual outliers in the dataset are apparent in the comparative measured 10 minute time series, particularly at levels above 100 m.

B.5 Average wind speed

Table B.6 displays a comparison of the average wind speeds measured at the mast and sodar over the period.

'All wind speed data' refers to whatever data is available for the specified time period. 'Concurrent wind speed data' has been filtered so that only time-steps where both mast and sodar data are available for the given level, are considered.

Note that mast wind speeds measured at 84.5 m are compared with both 80 m and 90 m sodar wind speeds, without any adjustment to account for wind shear.

Table B.6: Site #1b comparison of average wind speeds

Height AGL (m)	All wind speed data (m/s)		Concurrent wind speed data (m/s)	
	Mast	Sodar	Mast	Sodar
(60.3) 60	7.00	6.88	7.19	6.96
70	-	7.24	-	-
(84.5) 80	7.43	7.63	7.83	7.64
(84.5) 90	7.43	8.01	7.96	8.02
100	-	8.37	-	-
110	-	8.70	-	-
120	-	9.01	-	-
130	-	9.36	-	-
140	-	9.62	-	-
150	-	9.64	-	-

B.6 Wind speed correlation

Correlations between mast and sodar wind speeds are presented in the following figures.

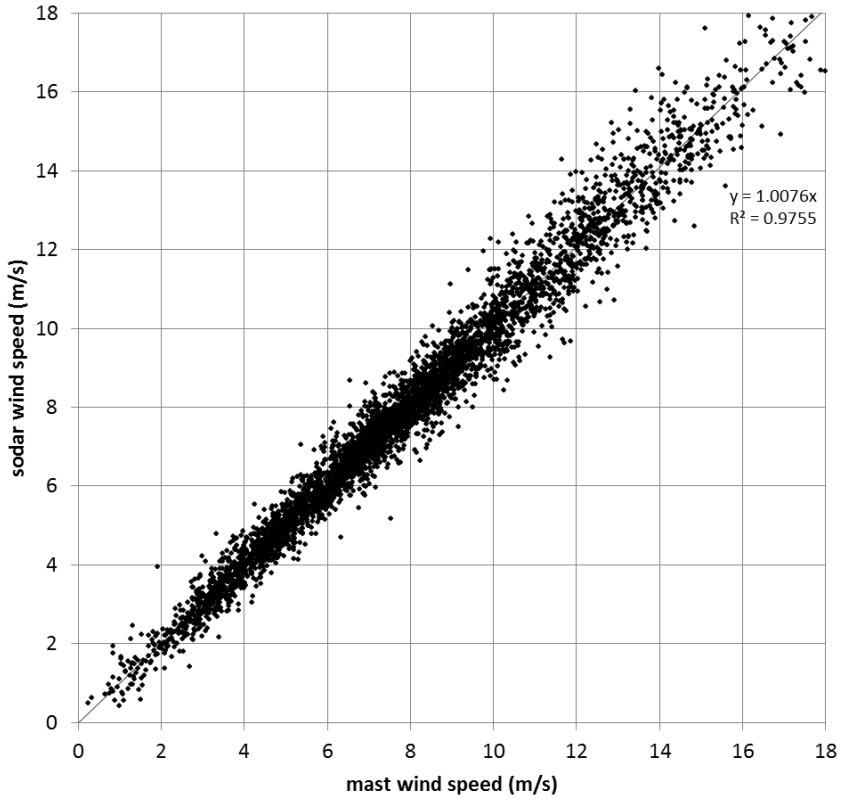

Figure B.2: Sodar 90 m wind speed vs. Mast 84.5 m wind speed, 10-min data

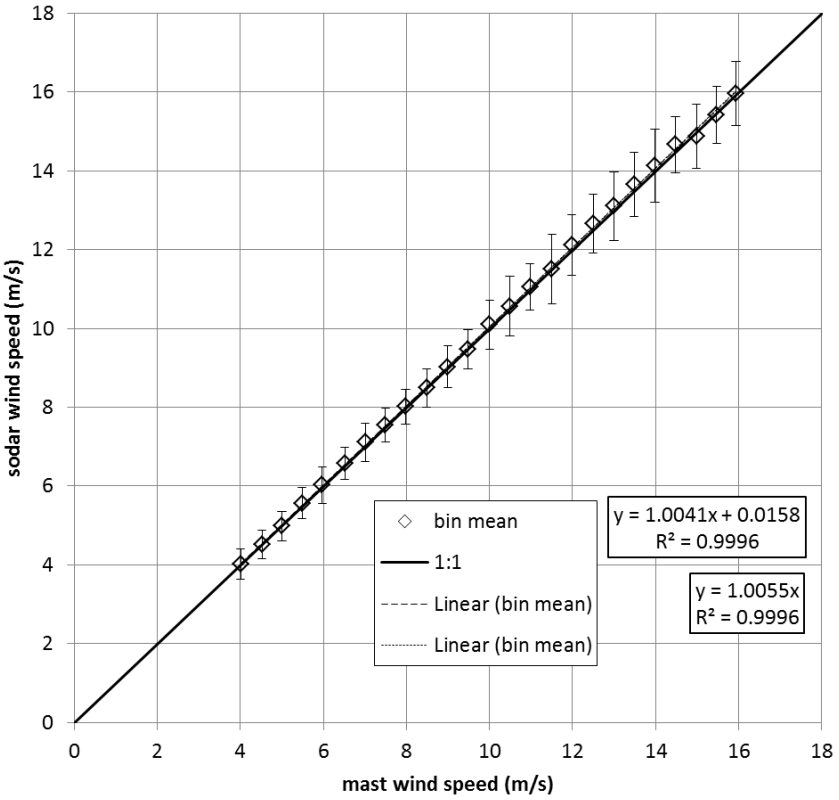

Figure B.3: Sodar 90 m wind speed vs. Mast 84.5 m wind speed, binned correlation

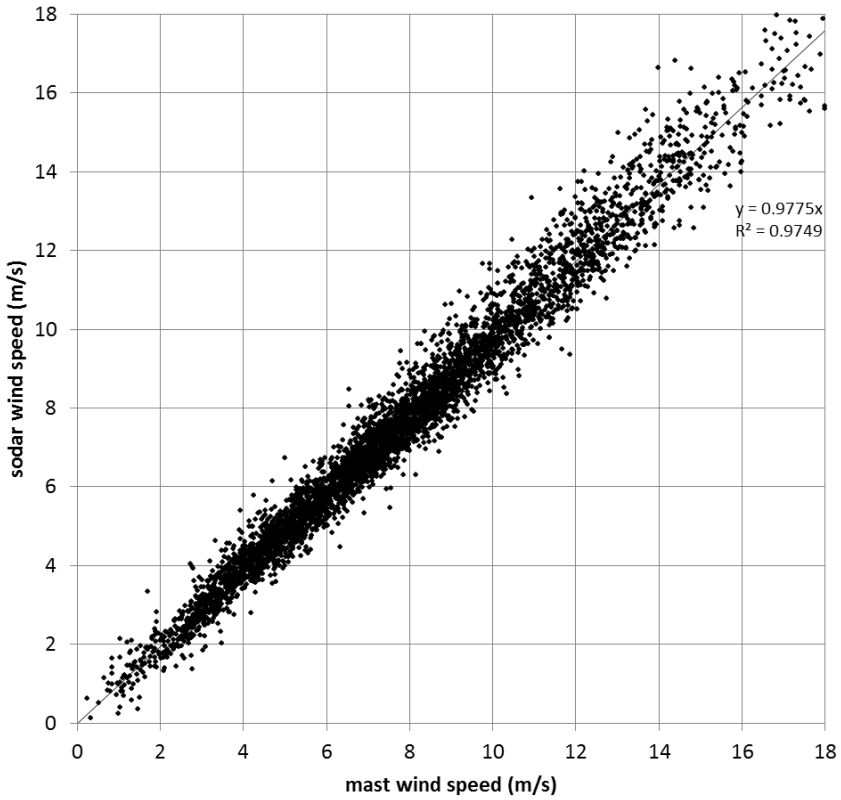

Figure B.4: Sodar 80 m wind speed vs. Mast 84.5 m wind speed, 10-min data

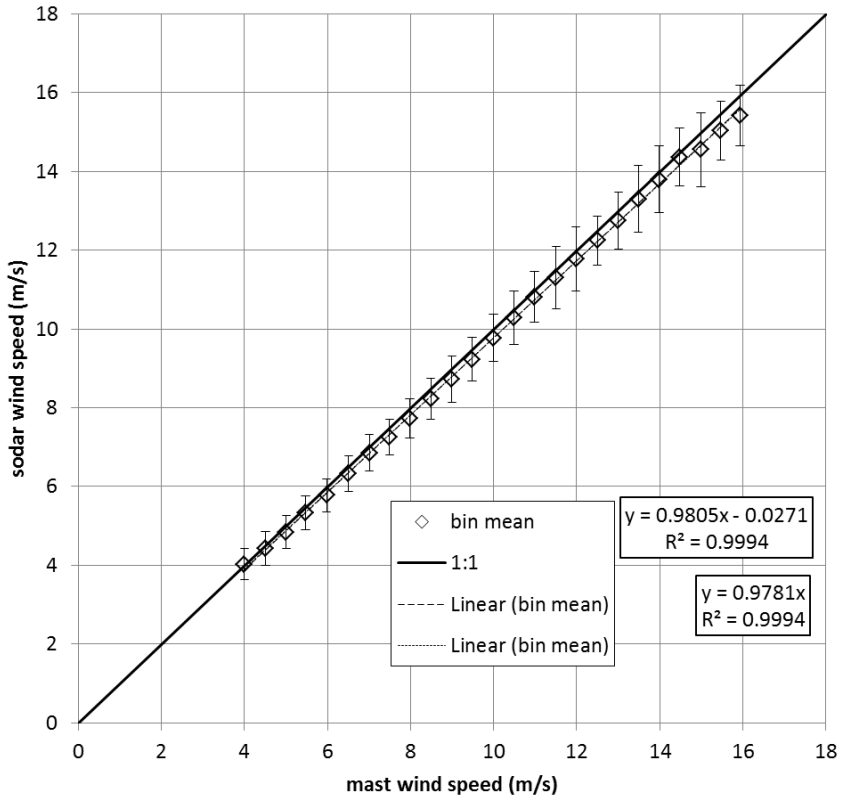

Figure B.5: Sodar 80 m wind speed vs. Mast 84.5 m wind speed, binned correlation

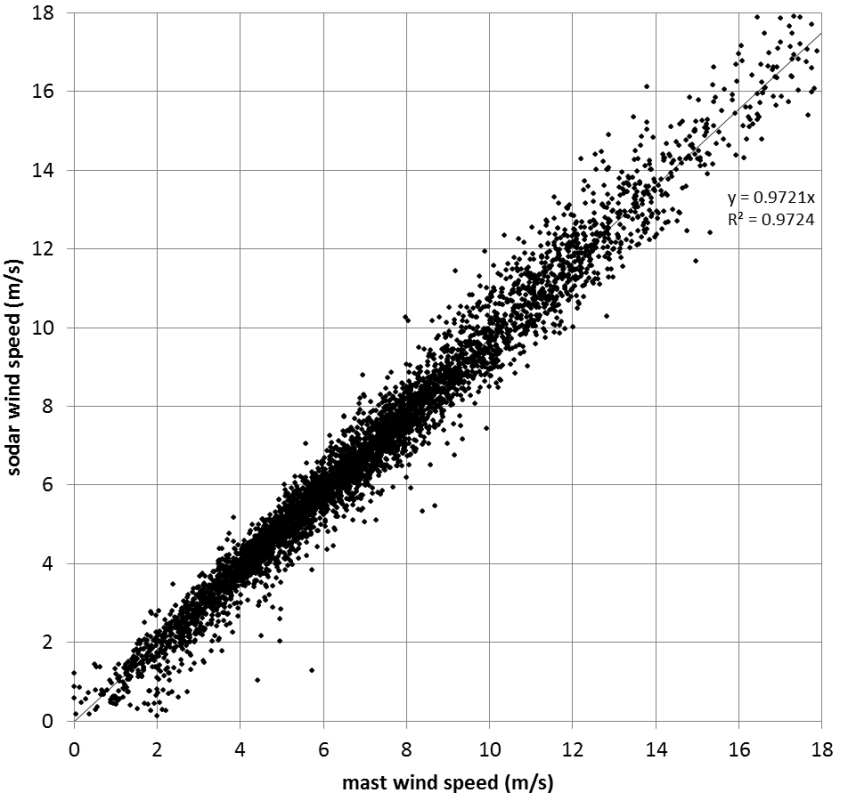

Figure B.6: Sodar 60 m wind speed vs. Mast 60.3 m wind speed, 10-min data

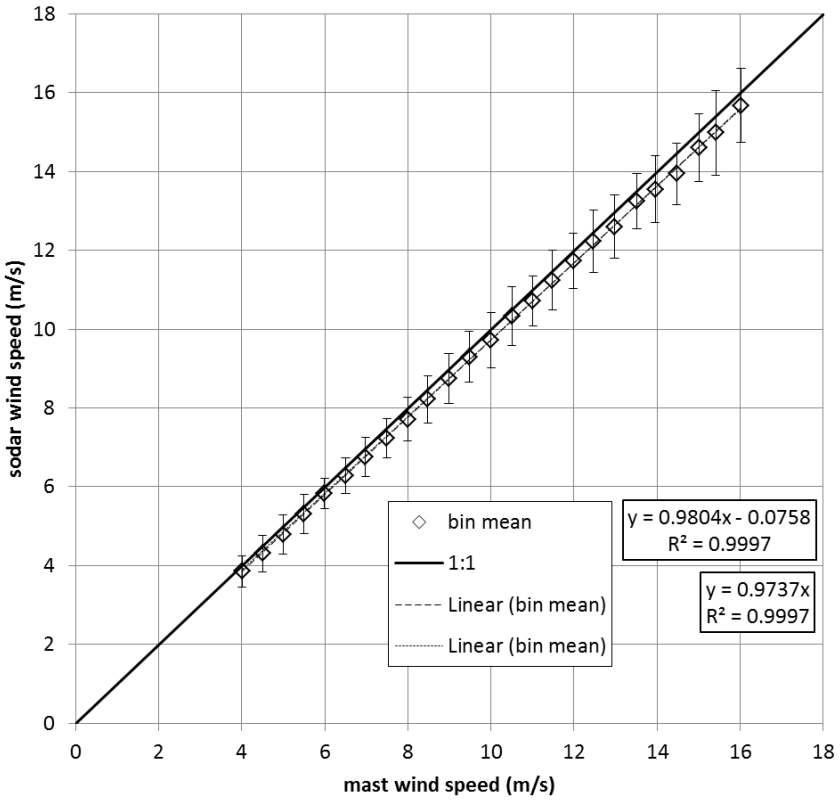

Figure B.7: Sodar 60 m wind speed vs. Mast 60.3 m wind speed, binned correlation

Table B.7: Wind speed correlation results

Level	linear best fit			forced through origin	
	Slope	Offset	R2	Slope	R2
90	1.0041	0.0158	0.9996	1.0055	0.9996
80	0.9805	-0.0271	0.9994	0.9781	0.9994
60	0.9804	-0.0758	0.9997	0.9737	0.9997

B.7 Wind speed differences

Absolute and relative differences between the mast and sodar wind speeds at the 80 m level are presented in the following figures, which also display the median and standard deviation for each wind speed bin.

Figures for the 60 m height are not shown, but Entura notes these provide similar results.

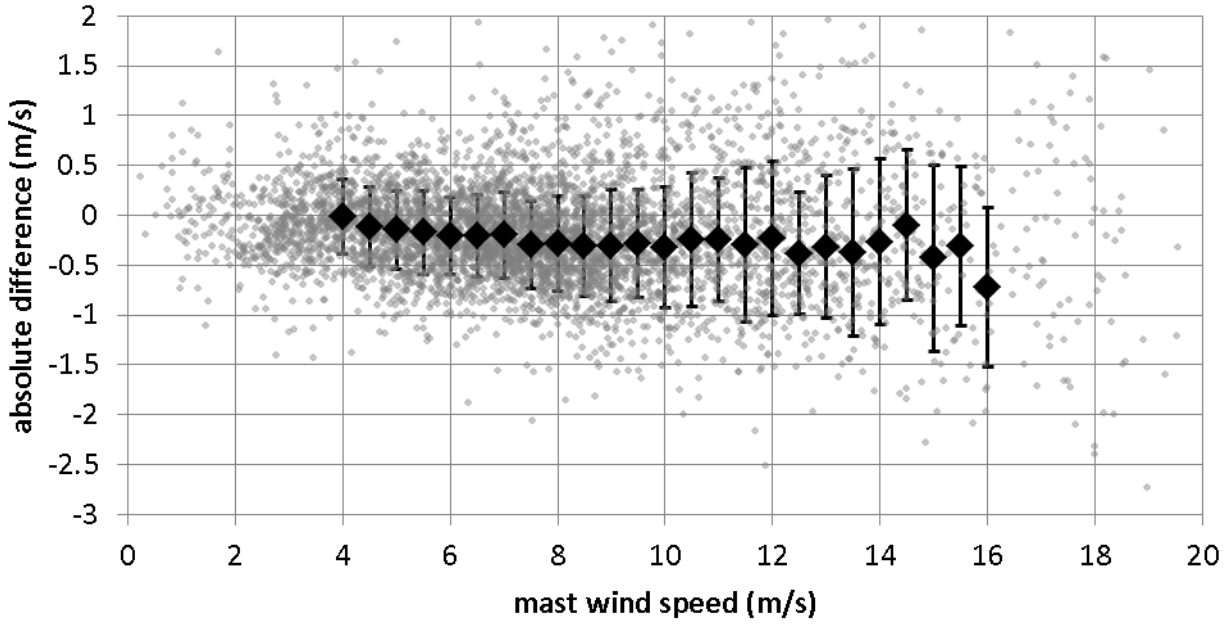

Figure B.8: Sodar 80 m - Mast 84.5 m absolute wind speed difference vs. mast wind speed

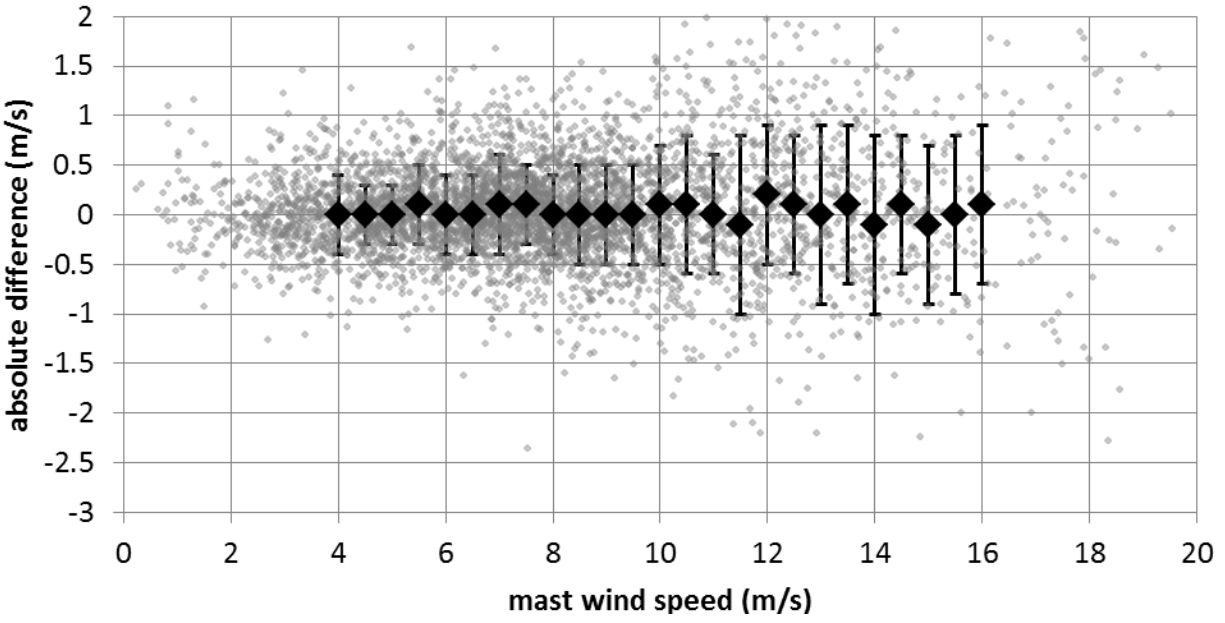

Figure B.9: Sodar 90 m - Mast 84.5 m absolute wind speed difference vs. mast wind speed

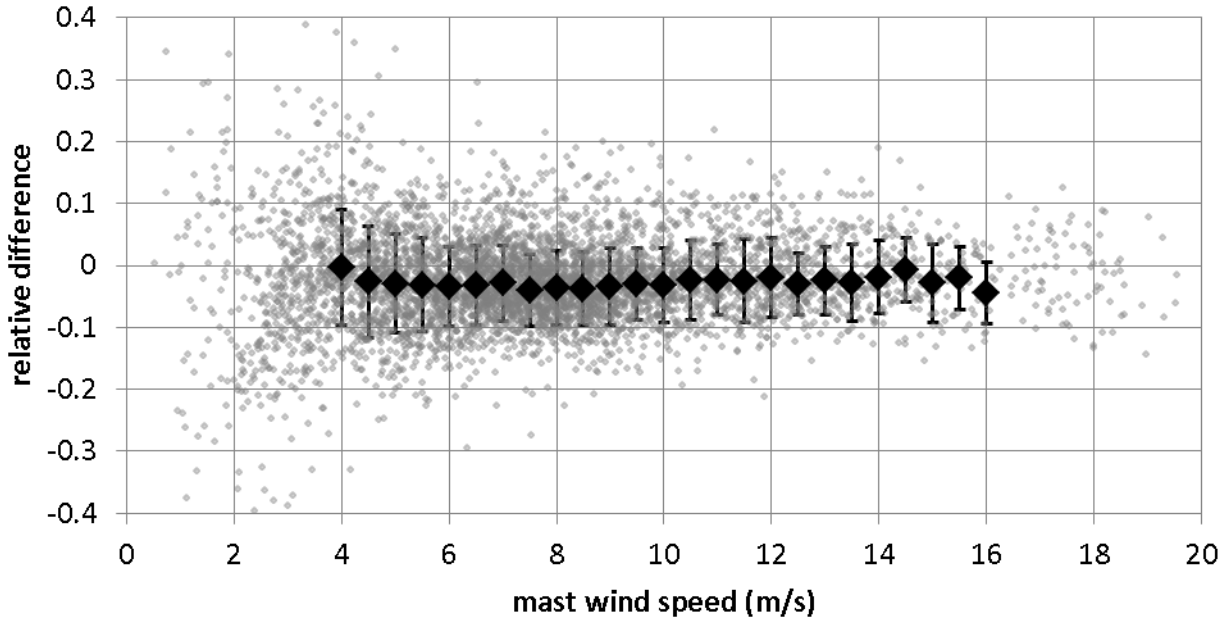

Figure B.10: Sodar 80 m - Mast 84.5 m relative wind speed difference vs. mast wind speed

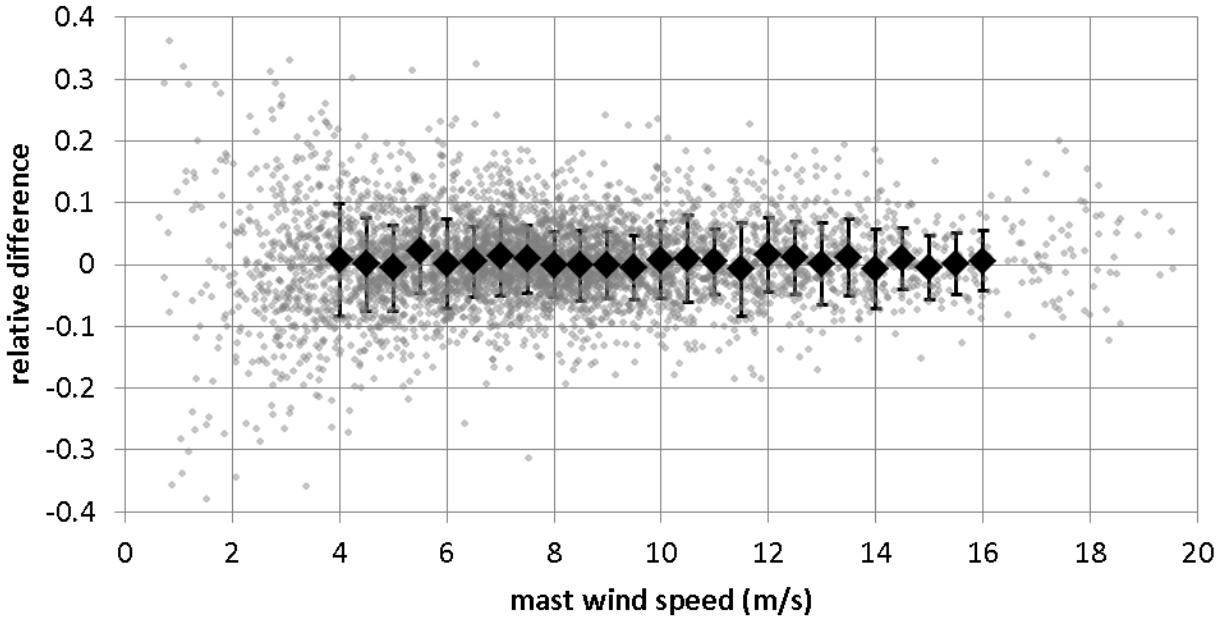

Figure B.11: Sodar 90 m - Mast 84.5 m relative wind speed difference vs. mast wind speed

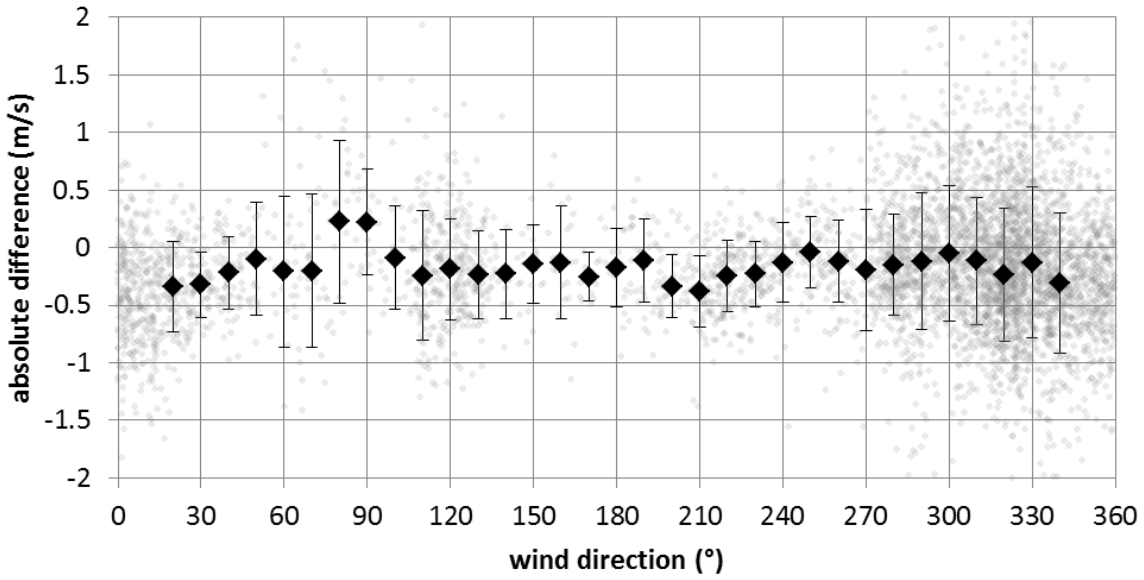

Figure B.12: Sodar 80 m - Mast 84.5 m absolute wind speed difference vs. mast wind direction

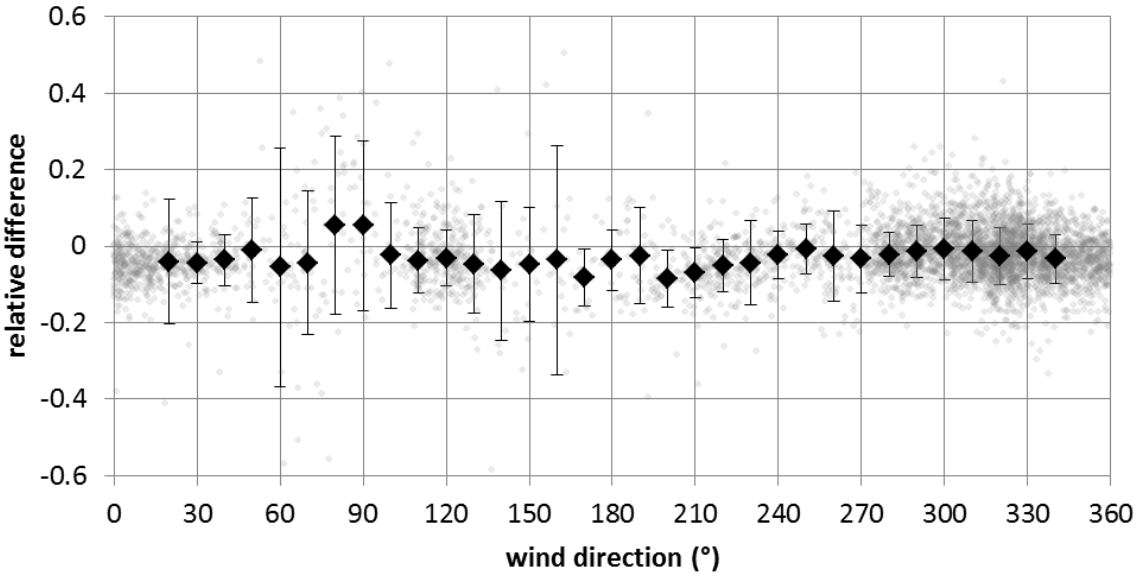

Figure B.13: Sodar 80 m - Mast 84.5 m relative wind speed difference vs. mast wind direction

B.8 Wind speed uncertainty

Table B.8 displays the inputs and the calculated relative uncertainty as a percentage of the bin-mean mast wind speed for the 80 m level. It is assumed that all sources of uncertainty are uncorrelated, and the total uncertainty is the square-root of the sum of the square of the uncertainties.

Estimating the mast anemometer uncertainty includes consideration of the following factors (listed in order of importance):

- Tower, boom and instrument mounting effects – an uncertainty of 2.0% is estimated.
- Complex wind flow and environmental conditions during field measurements, including increases and decreases in wind speed (dynamic overspeeding), turbulence, angled inflows, and rain – an uncertainty of 1.0% is estimated considering the relatively benign terrain at site #1b, and the characteristics of the Risø anemometer [8].
- Anemometer calibration – an uncertainty of 1.0% is estimated based on the anemometer specifications and the calibration undertaken of the 80 m anemometer [11].
- Anemometer degradation – an uncertainty of 0.2 % is estimated (a nominal amount, given the recent calibration and the good quality instrument).
- Data processing accuracy – an uncertainty of 0.2% is estimated (a nominal amount).

These individual uncertainties are combined using the root-sum-square technique. The combined uncertainty of the wind speed measurements is 2.5%.

Estimating the sodar mounting uncertainty includes consideration of the following factors (listed in order of importance):

- Instrument uncertainty – an uncertainty of 0.5% is estimated.
- Complex wind flow and environmental conditions during field measurements, fixed echoes, turbulence, angled inflows, and rain – uncertainty of 1.0% is estimated considering the relatively benign terrain and absence of obstacles visible at site #1b

The uncertainty caused by the flow variability across the site is estimated to be quite low given the close proximity between the masts and the sodar unit, 140 m. Therefore an uncertainty of 0.5% is estimated.

The uncertainty table for the 60 m height is not shown, but Entura notes this provide similar results.

Table B.8: Wind speed uncertainty, 80 m

				bin uncertainty (% of mast wind speed)					
mast wind speed	**Sodar wind speed**	**# data points**	**std. dev.**	**sodar precision**	**mean deviation**	**Mast**	**Sodar mounting**	**Site effects**	**Total**
U_{mast}	U_{sodar}	n	$\sigma(U_{sodar})$	$\sigma(U_{sodar})/\sqrt{n}$	$U_{sodar}-U_{mast}$				
4.00	4.03	212	0.40	0.69	0.70	2.5	1.1	0.5	2.9
4.51	4.42	269	0.43	0.58	1.99	2.5	1.1	0.5	3.4
5.01	4.84	317	0.43	0.48	3.27	2.5	1.1	0.5	4.3
5.48	5.33	290	0.43	0.46	2.67	2.5	1.1	0.5	3.9
5.98	5.78	266	0.42	0.43	3.33	2.5	1.1	0.5	4.3
6.51	6.33	319	0.45	0.39	2.78	2.5	1.1	0.5	3.9
7.01	6.86	370	0.46	0.34	2.14	2.5	1.1	0.5	3.5
7.50	7.25	362	0.45	0.31	3.33	2.5	1.1	0.5	4.3
7.98	7.74	335	0.49	0.34	3.07	2.5	1.1	0.5	4.1
8.49	8.23	309	0.52	0.35	3.11	2.5	1.1	0.5	4.2
9.00	8.73	267	0.59	0.40	2.93	2.5	1.1	0.5	4.0
9.48	9.23	187	0.55	0.43	2.68	2.5	1.1	0.5	3.9
10.00	9.78	190	0.61	0.44	2.25	2.5	1.1	0.5	3.6
10.49	10.29	130	0.69	0.58	1.95	2.5	1.1	0.5	3.4
10.98	10.82	122	0.64	0.53	1.49	2.5	1.1	0.5	3.2
11.51	11.31	104	0.80	0.68	1.69	2.5	1.1	0.5	3.3
11.98	11.78	124	0.82	0.62	1.70	2.5	1.1	0.5	3.3
12.50	12.25	104	0.63	0.49	2.02	2.5	1.1	0.5	3.5
13.01	12.76	74	0.72	0.64	1.92	2.5	1.1	0.5	3.4
13.49	13.31	77	0.85	0.71	1.33	2.5	1.1	0.5	3.1
13.99	13.80	61	0.85	0.78	1.34	2.5	1.1	0.5	3.2
14.48	14.37	59	0.74	0.67	0.79	2.5	1.1	0.5	2.9
14.99	14.56	41	0.94	0.98	2.86	2.5	1.1	0.5	4.1
15.47	15.03	25	0.75	0.97	2.83	2.5	1.1	0.5	4.1
15.94	15.42	25	0.77	0.97	3.26	2.5	1.1	0.5	4.4

Table B.9: Wind speed uncertainty, 90 m

				bin uncertainty (% of mast wind speed)					
mast wind speed	**Sodar wind speed**	**# data points**	**std. dev.**	**sodar precision**	**mean deviation**	**Mast**	**Sodar mounting**	**Site effects**	**Total**
U_{mast}	U_{sodar}	n	$\sigma(U_{sodar})$	$\sigma(U_{sodar})/\sqrt{n}$	$U_{sodar}-U_{mast}$				
4.01	4.02	149	0.38	0.79	0.40	2.5	1.1	0.5	2.9
4.52	4.51	203	0.36	0.56	0.15	2.5	1.1	0.5	2.8
5.00	4.98	219	0.38	0.52	0.36	2.5	1.1	0.5	2.8
5.49	5.56	210	0.40	0.50	1.42	2.5	1.1	0.5	3.1
5.98	6.03	230	0.47	0.51	0.85	2.5	1.1	0.5	2.9
6.52	6.57	288	0.41	0.37	0.78	2.5	1.1	0.5	2.9
7.01	7.11	335	0.48	0.38	1.41	2.5	1.1	0.5	3.1
7.50	7.55	328	0.43	0.32	0.72	2.5	1.1	0.5	2.9
7.98	8.02	313	0.45	0.32	0.44	2.5	1.1	0.5	2.8
8.49	8.49	293	0.49	0.34	0.02	2.5	1.1	0.5	2.8
9.00	9.03	255	0.53	0.37	0.32	2.5	1.1	0.5	2.8
9.49	9.47	180	0.50	0.39	0.12	2.5	1.1	0.5	2.8
10.00	10.10	184	0.62	0.46	0.95	2.5	1.1	0.5	2.9
10.49	10.56	126	0.76	0.64	0.69	2.5	1.1	0.5	2.9
10.98	11.06	121	0.59	0.49	0.73	2.5	1.1	0.5	2.9
11.50	11.51	102	0.88	0.75	0.07	2.5	1.1	0.5	2.9
11.98	12.12	122	0.76	0.58	1.18	2.5	1.1	0.5	3.0
12.50	12.67	104	0.74	0.58	1.34	2.5	1.1	0.5	3.1
13.00	13.11	72	0.87	0.79	0.83	2.5	1.1	0.5	3.0
13.48	13.65	71	0.82	0.72	1.26	2.5	1.1	0.5	3.1
13.99	14.14	57	0.93	0.88	1.07	2.5	1.1	0.5	3.1
14.48	14.67	56	0.71	0.66	1.29	2.5	1.1	0.5	3.1
14.99	14.88	40	0.82	0.86	0.70	2.5	1.1	0.5	3.0
15.47	15.43	23	0.73	0.98	0.29	2.5	1.1	0.5	2.9
15.94	15.96	25	0.81	1.01	0.15	2.5	1.1	0.5	2.9

B.9 Wind direction comparison

Correlations between mast and sodar wind speeds are presented in the following figures.

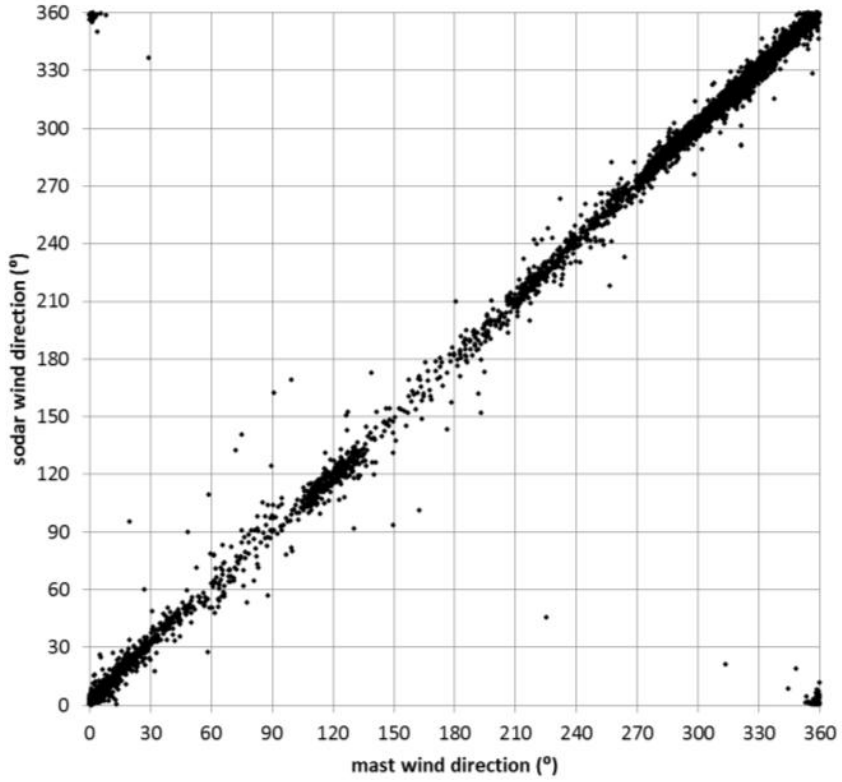

Figure B.14: Sodar 60 m wind direction vs. Mast 60.3 m wind direction, 10-min data

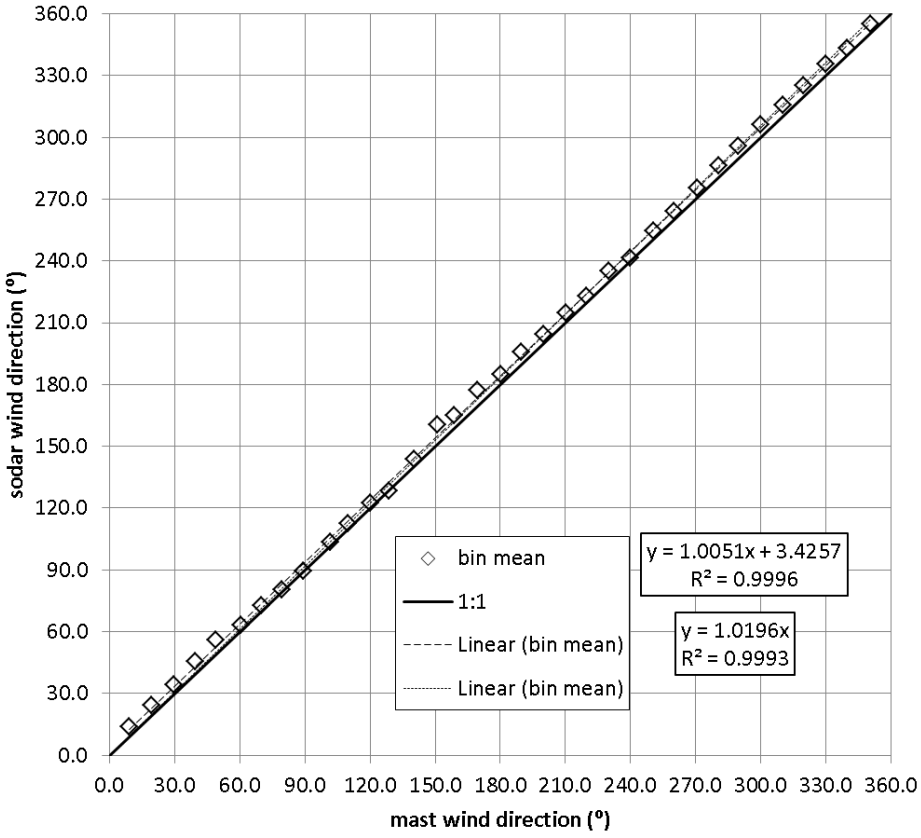

Figure B.15: Sodar 60 m wind direction vs. Mast 60.3 m wind direction, binned correlation

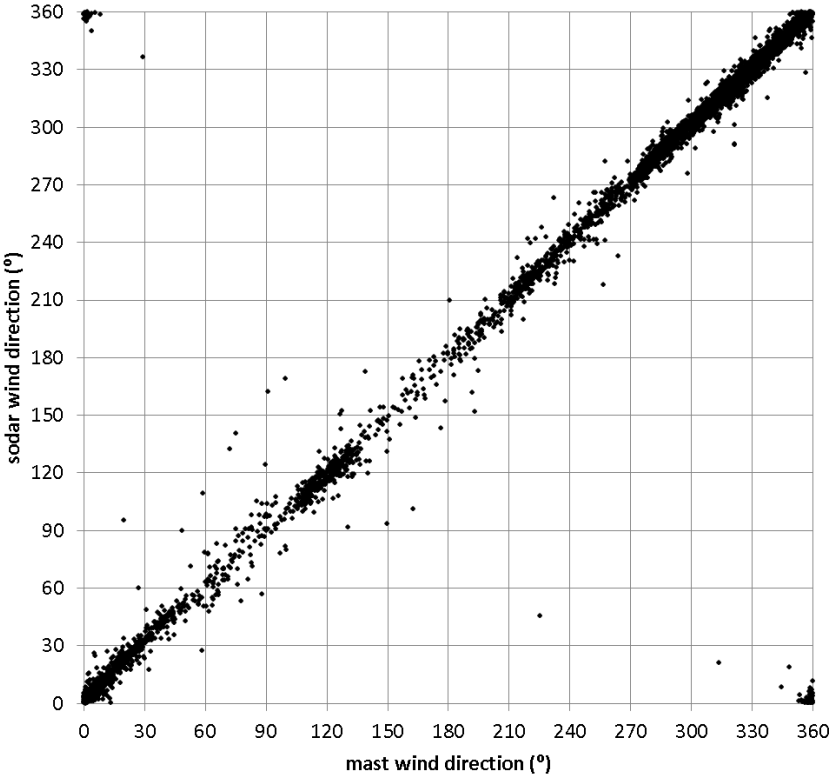

Figure B.16: Sodar 80 m wind direction vs. Mast 82.5 m wind direction, 10-min data

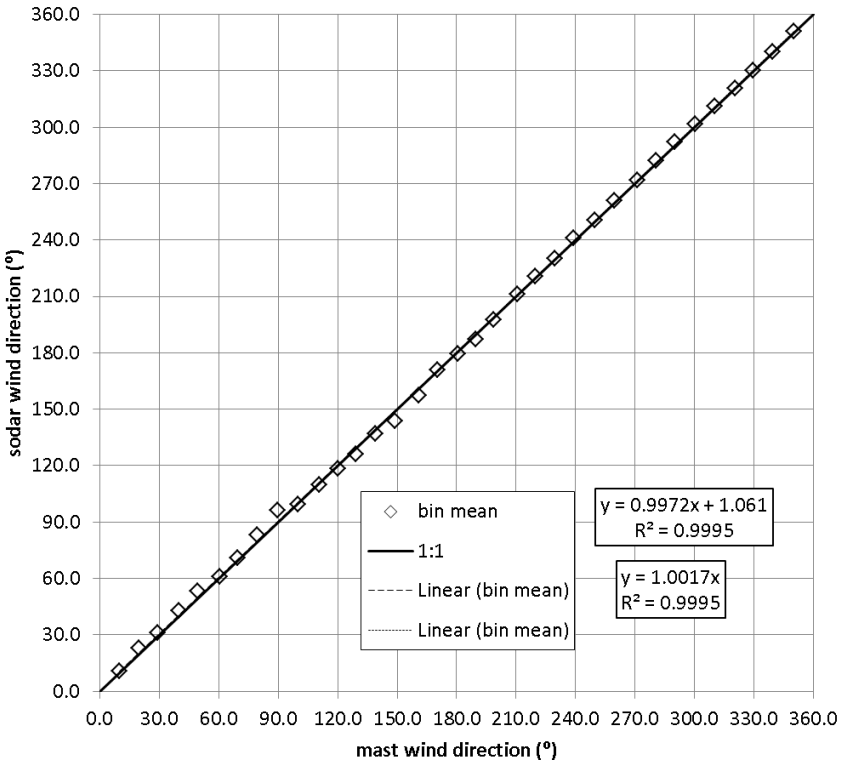

Figure B.17: Sodar 80 m wind direction vs. Mast 82.5 m wind direction, binned correlation

The previous figures suggest some non-linearity in the relationship between sodar and mast wind direction, which may be due to instrument error (mast or sodar) or differences between the two locations. Generally the difference is relatively small, particularly at the 80 m level where it is no greater than 12° for any direction.

Comparisons of wind energy roses, based on 10 minute data at 80 m indicate a close relationship as shown in Figure B.18.

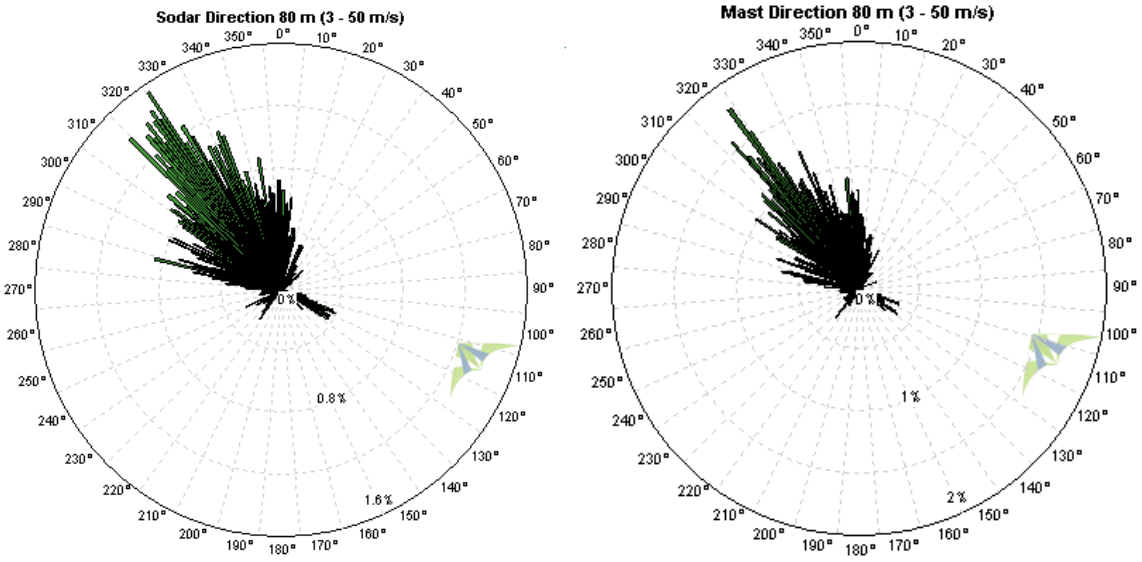

Figure B.18: Wind direction frequency rose, left sodar 80 m, right mast 82.5 m, and 360 sectors

B.10 Wind shear analysis

Vertical wind shear exponent (power law) was compared between the 60 m and 80 m heights of the sodar and mast, for concurrent wind speeds greater than 3.0 m/s, and the results are displayed in Table A.10.

Table B.10: Shear comparison

	Shear exponent mast (all data points)		Shear exponent		
Time	**Mast (60.3–84.5 m)**	**# data points**	**Sodar (60–80 m)**	**Mast (60.3–84.5 m)**	**# data points**
All	0.23	4,822	0.31	0.24	4,131
Day (06:00 – 18:00)	0.19	2,637	0.27	0.19	1,820
Night (18:00 – 06:00)	0.28	2,185	0.36	0.29	2,311

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C Site #2 1011

At Site #2 (1011), a Fulcrum 3D sodar unit was installed adjacent to a 71 m wind monitoring mast, located in complex terrain. This Appendix addresses the following issues:

- The wind monitoring mast setup
- The sodar unit setup
- The comparison of the data sets

C.1 Wind monitoring mast setup

A single wind monitoring mast is installed, and details of the mast setup provided by [6]. From a brief review of this information, Entura has summarised the setup in Table C.1 and Table C.2 and notes the following:

- The physical mast setup may be generally compliant with IEC 61400-12-1 [3] standard, however photographs are poor quality and Entura has not verified the site, so independent verification is not possible. Mast data is suggestive of some flow distortion upwind of the mast, which suggests boom lengths may be less than ideal.
- Throughout the period, corrections were made to logger directional data.
- The 70.4 m anemometer exhibited poor performance and has been excluded from analysis.

The wind data is considered to be of reasonable quality and suitable for verification of the sodar data.

The 71.3 m anemometer is installed on a boom straight up from the mast in line with IEC standards and is therefore not shaded by the mast. Details of the lighting finial placement are not confirmed, however it is assumed to have negligible effect on the data. The 60.4 m anemometer is installed in the direction 180^{o} and there are indications of shading impact from approximately 10^{o}. Data from the directions 350^{o} to 30^{o} has been removed to account for mast shading.

Data from the lower levels (51.9 m and 28.7 m) is not used in this assessment.

Table C.1: Site #2 mast setup

Mast Name	Site #2		
Coordinates and Datum	Confidential		
Altitude	519 m above sea level		
Mast Type	Nexgen 70m HiMast		
Face Width	219 mm up to 42 m, then 152 mm to 70 m		
Boom Clamping Method	Unconfirmed		
IEC Compliant?	Unconfirmed		
Mast Operating Period	Start: 10/09/2009	End: present	
Surrounding Terrain Description	Complex		
Visible Obstructions/Terrain Features Affecting Data	There is a hill northwest of the tower which is roughly 25 m higher		

	according to the GPS.
Logger Type	NOMAD 2 – SecondWind
Logger ID	5423
Data Time Step / Offset	10 minutes
Service History	21/3/2012, a full systems check was carried out at ground level. All instruments were seen to be fully operational. Remote communications were unavailable, and this was fixed.
Event Log	None
Other Comments	Magnetic declination approx. 11 deg East of North Anchors are orientated to 0º, 90º, 180º and 270º magnetic. There is known to be some drift with time in the mast logger and aligning data sets takes this into consideration when synchronizing the 2 data sets. The mast affects instruments on the mast between approximately 0 and 20 and 350 and 360

Table C.2: Site #2 mast instrument setup

Height AGL (m)	Type	S/N	Calibration Date	Boom (*approx.*) (m)			Logged Parameters			
				Length	Up stand	Orient.	Ave	SD	Max	Min
Wind Speed										
71.3	Vector A100LM	6058/VAB	10/03/2009	NA	0.95	n/a	✓	✓	✓	✓
70.4	Vector A100LM	6057/VAA	10/03/2009	1.52	0.40	180°	✓	✓	✓	✓
60.4	Vector A100LM	6056/UZZ	10/03/2009	1.52	0.40	180°	✓	✓	✓	✓
51.9	Vector A100LM	6055/UZY	10/03/2009	1.51	0.40	180°	✓	✓	✓	✓
28.7	Vector A100LM	6054/UZX	10/03/2009	2.02	0.69	180°	✓	✓	✓	✓
Wind Direction										
68.4	Vector W200P	53405	NA	1.47	0.40	180°	✓	✓		
44.4	Vector W200P	53404	NA	1.47	0.40	180°	✓	✓		
26.7	Vector W200P	53403	NA	1.99	0.69	180°	✓	✓		
Temperature										
3.3	SW1 10k						✓			
Pressure										
2.0	Setra	3849601					✓			

C.2 Fulcrum 3D sodar setup

Based on reference [7], Table C.3 summarises the Fulcrum 3D sodar setup.

Table C.3: Site #2 Fulcrum 3D sodar configuration

Device manufacturer	Fulcrum 3D
Serial number	FS1M_1011
Software version	v3.30
Software date	N/A
Measured heights	60, 70,80, 90,100, 110, 120, 130, 140, 150 m
Raw data time zone	UTC +00:00
Time zone for site	UTC +10:00
Tilt X, absolute maximum during period, (within +/- 3°)	N/A
Tilt Y, absolute maximum during period, (within +/- 3°)	N/A
Location: Easting, Northing, Zone	Confidential
Elevation	515 m
Elevation relative to mast base	~5 m
Orientation	Magnetic north
Description of site:	Complex terrain, grassland, active cattle grazing. Initially drops gradually to the north, east and south, and remains fairly level up to the adjacent mast which is to the north west of the SODAR unit. Further to the west the ground slopes upwards.
Obstacles:	Wind monitoring mast: Height 70 m Bearing ~315^{o} Distance 96 m
Notes:	A fence was installed around the sodar unit from 21 March 2012

The following has been considered in siting the sodar:

- A minimum separation distance of 1.25x mast height, in this case, 96 m.
- Sodar beam orientation not directly at the mast.

The placement of the sodar unit is located 98 m to the south east of the existing mast location and within 5 m elevation, with uniform, though sloping terrain and surface roughness in the immediate vicinity. No changes to the sodar firmware or setup occurred during the reporting period.

Photographs of the sodar unit are provided in Figure C.1.

Due to the complexity of the terrain, Entura does not believe that Fulcrum 3D sodar accuracy against mast data can be reliably verified at this site. This is an inherent difficulty with measurements in complex terrain. Nonetheless, a comparison can be made, and aspects of the data acquired can be discussed.

Figure C.1: Site #2 surrounding terrain and vegetation, Clockwise; North, East, South and West

C.3 Data recovery

Details of the test period are displayed in Table C.4

Table C.4: Site #2 data period

Data begin	27/05/2012 00:00, UTC +10:00
Data end	15/07/2012 08:50, UTC +10:00
Number of days	49
Number of 10 minute periods	7,110

As a test of the sufficiency of the data period, Entura has confirmed the recommendations of [1] as listed in Section 4.1 have generally been fulfilled at this test site. However, insufficient data has been acquired in wind speed bins > 14 m/s, and therefore the subsequent correlation analysis cannot be undertaken over the full recommended range of 0 to 16 m/s. For the purposes of this report, this is not a significant limitation.

The data recovery rates for the mast and sodar are displayed in Table C.5. For the purpose of reporting data recovery, Entura does not distinguish between data lost through operational downtime, and data lost through filtering. The sodar data has only had the standard filtering applied as discussed in Section 3.

Aside from problems with the 70.4 m anemometer on the mast, sodar recovery rates are comparably lower, as is typical with remote sensing devices.

Table C.5: Site #2 data recovery by height

Mast			Fulcrum 3D sodar	
Height AGL (m)	**Data Recovery (%)**		**Height AGL (m)**	**Data recovery (%)**
28.7	100#		60	87
51.9	100#		70	87
60.4	93*		80	86
70.4	65		90	87
71.3	100		100	86
68.4 DIR	100		110	84
44.4 DIR	100		120	80
26.7 DIR	100		130	77
			140	71
			150	62

mast shading not removed from these levels, which are not used in this analysis

*data recovery with data affected by mast shading filtered out

C.4 Time series observations

From a comparison against the mast data it appeared that the sodar direction data was not offset to correct for the magnetic declination. Therefore Entura has offset the sodar direction data by 11° east.

The wind speeds at 70 m and 60 m heights from the sodar and mast track each other reasonably well throughout the period, provided the sodar data is appropriately filtered.

Some individual outliers in the dataset are apparent in the comparative measured 10 minute time series.

C.5 Average wind speed

Table C.6 displays a comparison of the average wind speeds measured at the mast and sodar over the period.

'All wind speed data' refers to whatever data is available for the specified time period. 'Concurrent wind speed data' has been filtered so that only time-steps where both mast and sodar data are available for the given level, are considered.

Sodar data has been compared with the nearest mast level, with no corrections for the small height discrepancy.

Table C.6: Site #2 comparison of average wind speeds

Height AGL (m)	All wind speed data (m/s)		Concurrent wind speed data (m/s)	
	Mast	Sodar	Mast	Sodar
(60.4) 60	5.59	5.75	5.79	5.69
(71.3) 70	5.88	5.93	6.09	5.93
80	-	6.07	-	-
90	-	6.16	-	-
100	-	6.28	-	-
110	-	6.42	-	-
120	-	6.55	-	-
130	-	6.60	-	-
140	-	6.69	-	-
150	-	6.80	-	-

C.6 Wind speed correlation

Correlations between mast and sodar wind speeds are presented in the following figures.

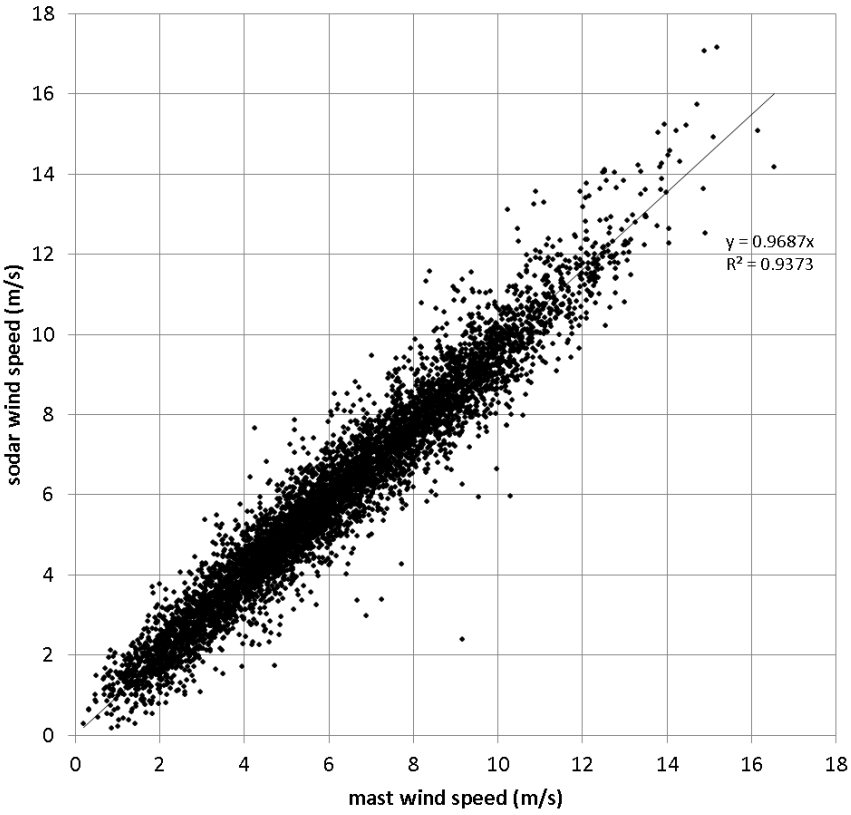

Figure C.2: Sodar 70 m wind speed vs. Mast 71.3 m wind speed, 10-min data

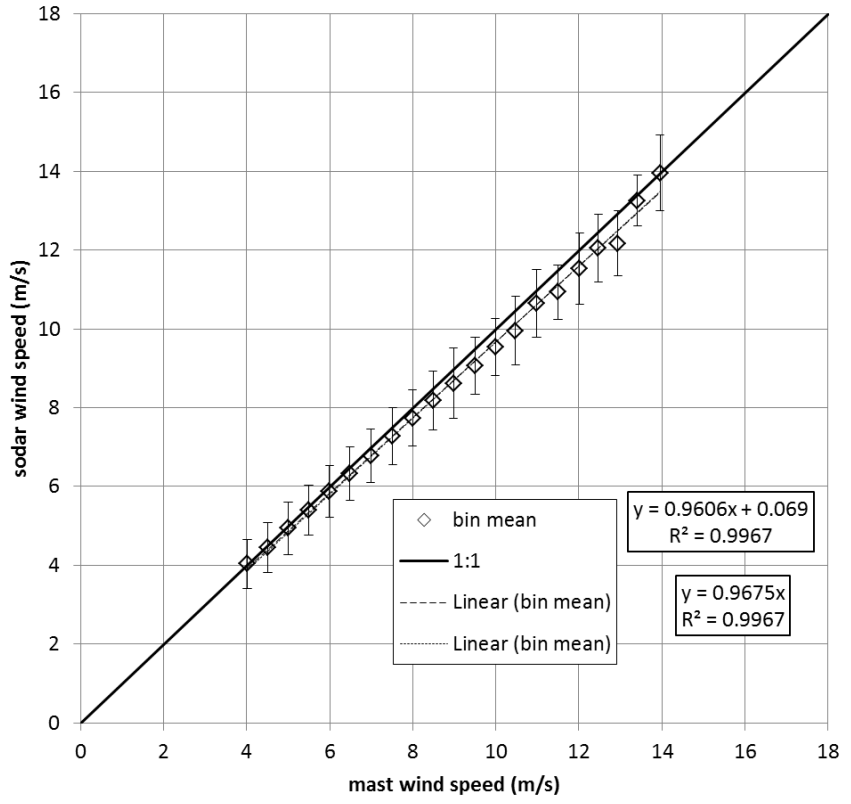

Figure C.3: Sodar 70 m wind speed vs. Mast 71.3 m wind speed, binned correlation

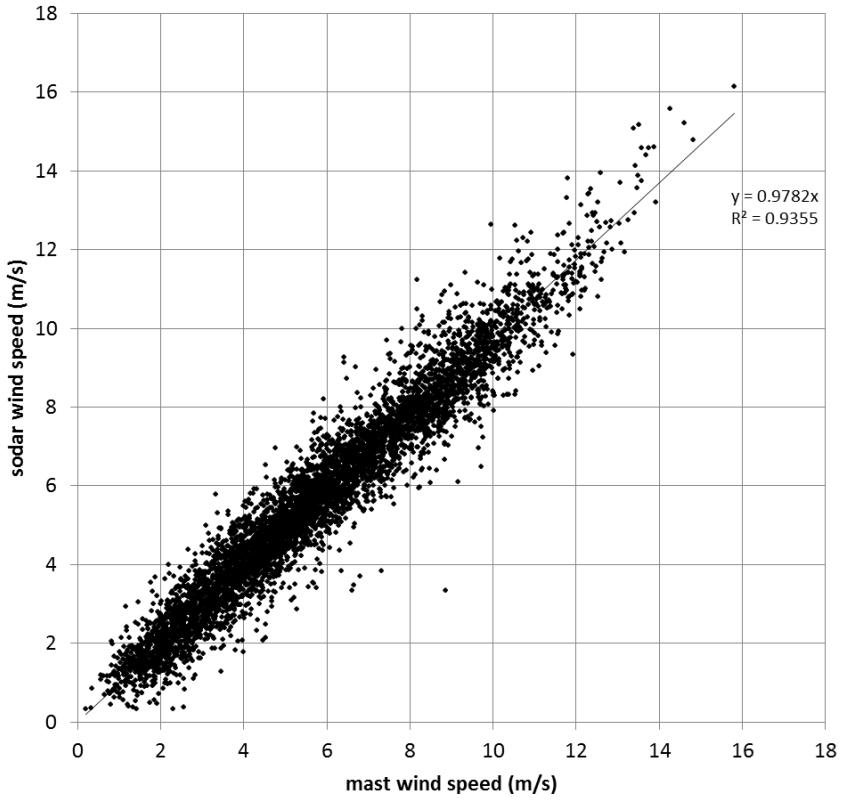

Figure C.4: Sodar 60 m wind speed vs. Mast 60.4 m wind speed, 10-min data

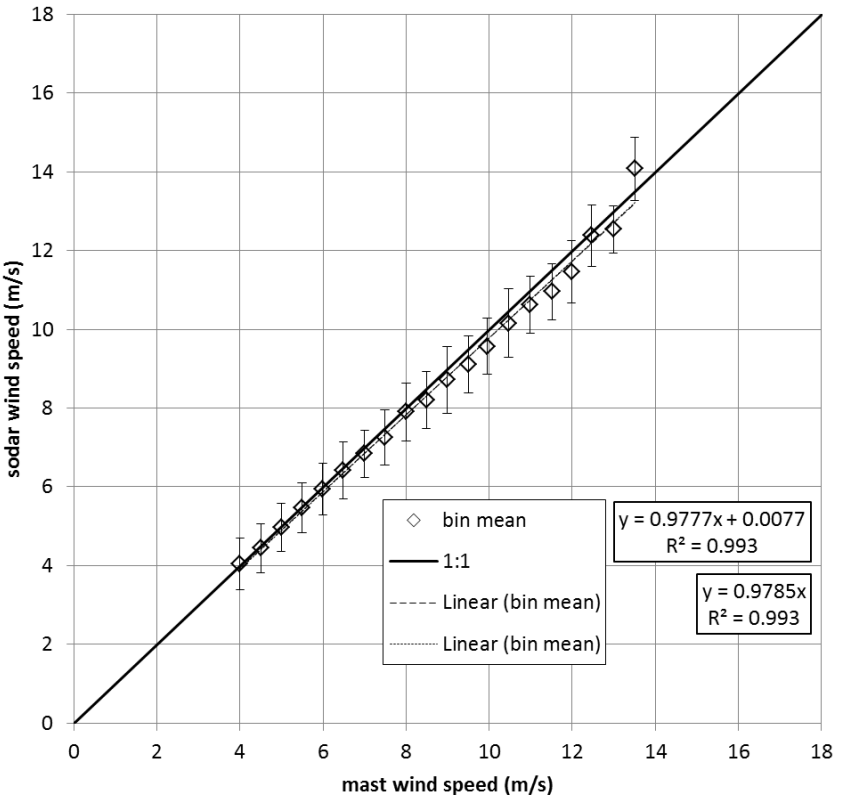

Figure C.5: Sodar 60 m wind speed vs. Mast 60.4 m wind speed, binned correlation

Table C.7: Wind speed correlation results

Level	linear best fit			forced through origin	
	Slope	Offset	R2	Slope	R2
70	0.9606	0.069	0.9967	0.9675	0.9967
60	0.9777	0.0077	0.9930	0.9785	0.9930

C.7 Wind speed differences

Absolute and relative differences between the mast and sodar wind speeds at the 70 m level are presented in the following figures, which also display the median and standard deviation for each wind speed bin.

Figures for the 60 m height is are not shown, but Entura notes these provide similar results.

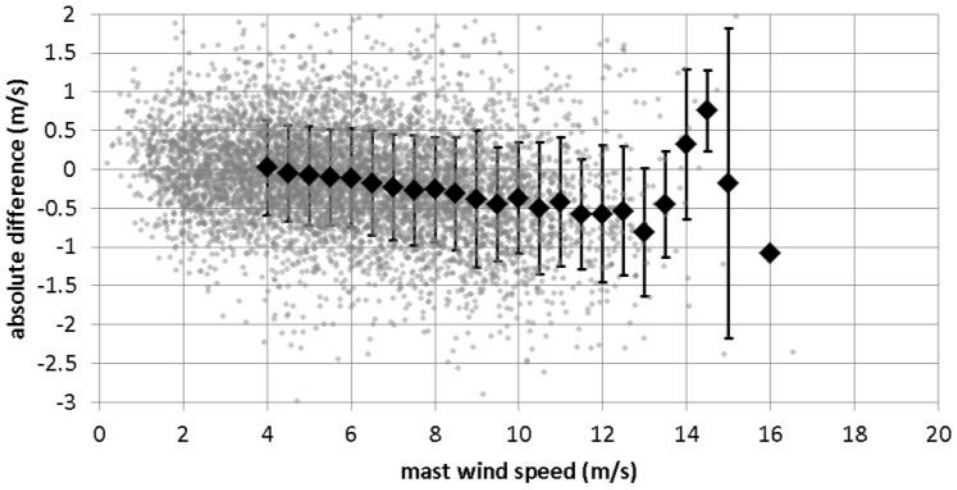

Figure C.6: Sodar 70 m - Mast 71.3 m absolute wind speed difference vs. mast wind speed

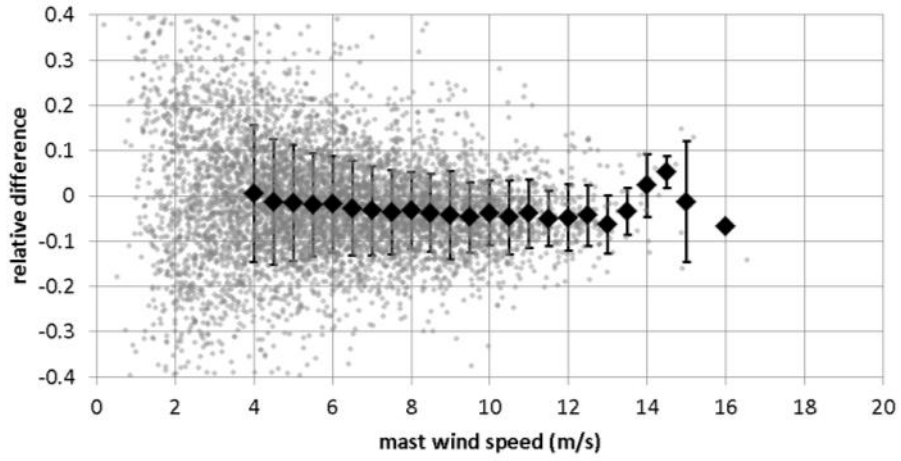

Figure C.7: Sodar 70 m - Mast 71.3 m relative wind speed difference vs. mast wind speed

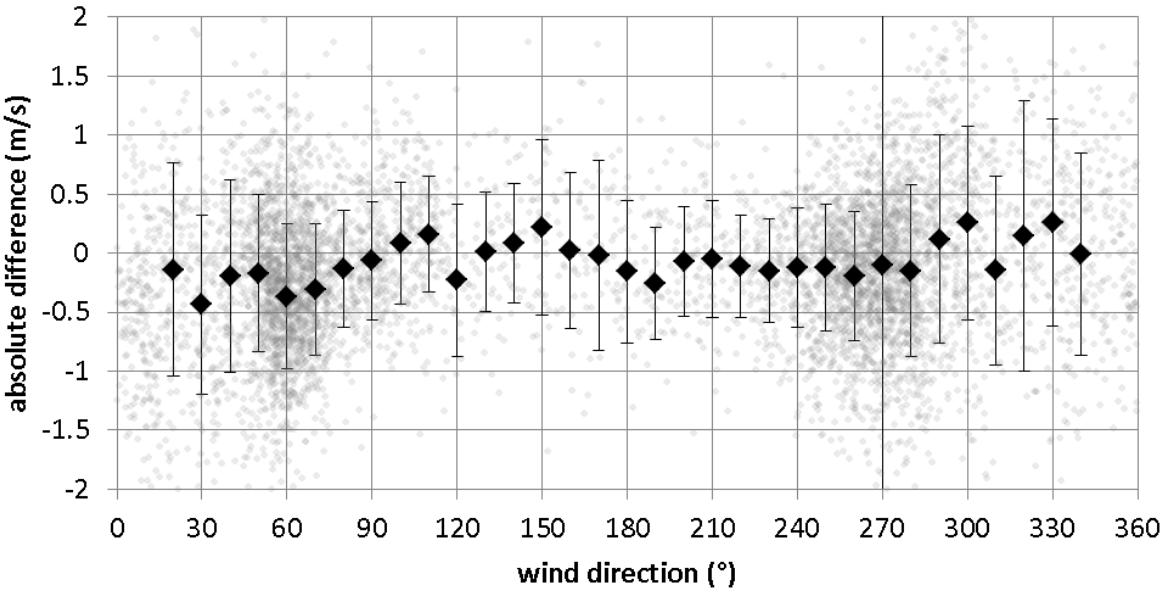

Figure C.8: Sodar 70 m - Mast 71.3 m absolute wind speed difference vs. mast wind direction

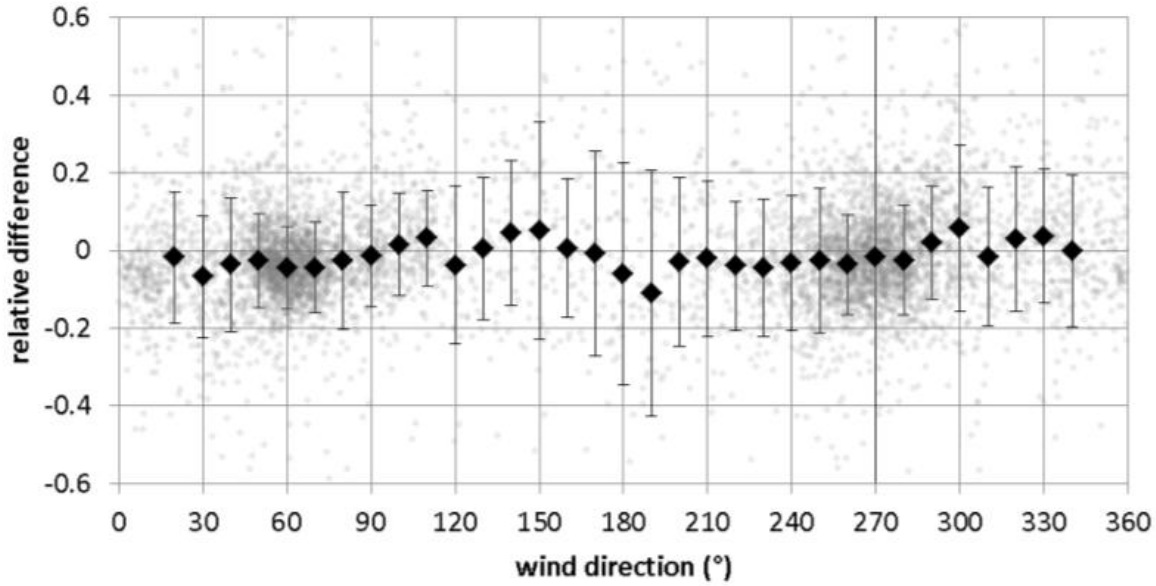

Figure C.9: Sodar 70 m - Mast 71.3 m relative wind speed difference vs. mast wind direction

C.8 Wind speed uncertainty

Table C.8 displays the inputs and the calculated relative uncertainty as a percentage of the bin-mean mast wind speed for the 70 m level. It is assumed that all sources of uncertainty are uncorrelated, and the total uncertainty is the square-root of the sum of the square of the uncertainties.

Estimating the mast anemometer uncertainty includes consideration of the following factors (listed in order of importance):

- Tower, boom and instrument mounting effects – an uncertainty of 2.0% is estimated.

- Complex wind flow and environmental conditions during field measurements, including increases and decreases in wind speed (dynamic overspeeding), turbulence, angled inflows, and rain – an uncertainty of 2.0% is estimated considering the relatively complex terrain at site #2, and the characteristics of the Vector Instruments anemometer [6].
- Anemometer calibration – an uncertainty of 1.0% is estimated based on the anemometer specifications and the calibrations undertaken for the 70 m anemometer [13].
- Anemometer degradation – an uncertainty of 1.0 % is estimated given that the instruments have been in place for over 3 years without recalibration.
- Data processing accuracy – an uncertainty of 0.2% is estimated (a nominal amount).

These individual uncertainties are combined using the root-sum-square technique. The combined uncertainty of the wind speed measurements is 3.2%.

Estimating the sodar mounting uncertainty includes consideration of the following factors (listed in order of importance):

- Instrument uncertainty – an uncertainty of 0.5% is estimated.
- Complex wind flow and environmental conditions during field measurements, fixed echoes, turbulence, angled inflows, and rain – an uncertainty of 2.0% is estimated considering the relatively more complex terrain at site #2.

The uncertainty caused by the flow variability across the site is estimated to be quite low given the close proximity between the masts and the sodar unit, 96 m although it would be higher than a non-complex site. Therefore an uncertainty of 0.8% is estimated.

The uncertainty table for the 60 m height is not shown, but Entura notes these provide similar results.

Table C.8: Wind speed uncertainty, 70 m

				bin uncertainty (% of mast wind speed)					
mast wind speed	**Sodar wind speed**	**# data points**	**std. dev.**	**sodar precision**	**mean deviation**	**Mast**	**Sodar mounting**	**Site effects**	**Total**
U_{mast}	U_{sodar}	n	$\sigma(U_{sodar})$	$\sigma(U_{sodar})/\sqrt{n}$	$U_{sodar}-U_{mast}$				
4.016	4.033	439	0.615	0.73	0.42	3.2	2.1	0.8	4.0
4.505	4.447	494	0.626	0.63	1.29	3.2	2.1	0.8	4.1
5.005	4.941	500	0.665	0.59	1.28	3.2	2.1	0.8	4.1
5.496	5.403	438	0.638	0.55	1.69	3.2	2.1	0.8	4.3
5.998	5.882	455	0.656	0.51	1.93	3.2	2.1	0.8	4.4
6.489	6.325	406	0.675	0.52	2.53	3.2	2.1	0.8	4.6
6.988	6.776	344	0.683	0.53	3.03	3.2	2.1	0.8	4.9
7.516	7.277	343	0.728	0.52	3.18	3.2	2.1	0.8	5.0
7.995	7.738	300	0.716	0.52	3.21	3.2	2.1	0.8	5.1
8.489	8.19	313	0.747	0.50	3.52	3.2	2.1	0.8	5.3
8.986	8.617	266	0.895	0.61	4.11	3.2	2.1	0.8	5.7
9.502	9.072	247	0.728	0.49	4.53	3.2	2.1	0.8	6.0
9.989	9.533	199	0.721	0.51	4.57	3.2	2.1	0.8	6.0
10.479	9.958	145	0.878	0.70	4.97	3.2	2.1	0.8	6.3
10.986	10.65	108	0.862	0.76	3.06	3.2	2.1	0.8	5.0
11.5	10.933	68	0.691	0.73	4.93	3.2	2.1	0.8	6.3
12.021	11.539	68	0.906	0.91	4.01	3.2	2.1	0.8	5.6
12.468	12.051	55	0.867	0.94	3.34	3.2	2.1	0.8	5.2
12.945	12.173	29	0.832	1.19	5.96	3.2	2.1	0.8	7.2
13.417	13.254	17	0.645	1.17	1.21	3.2	2.1	0.8	4.2
13.955	13.963	16	0.97	1.74	0.06	3.2	2.1	0.8	4.2

C.9 Wind direction comparison

Correlations between mast and sodar wind directions are presented in the following figures.

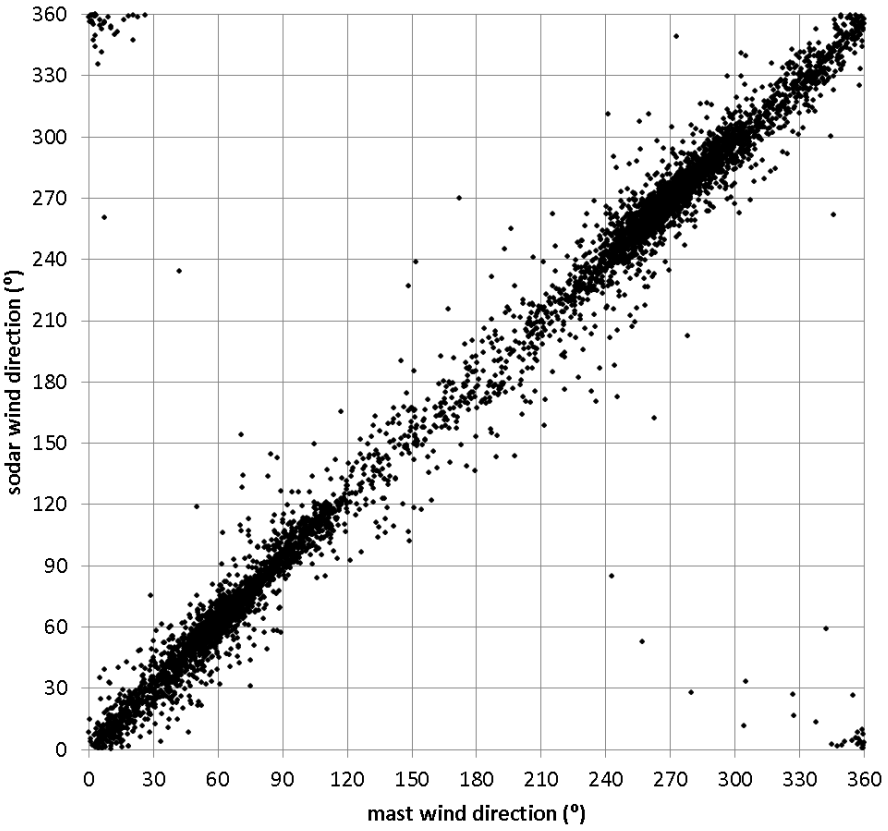

Figure C.10: Sodar 70 m wind direction vs. Mast 68.4 m wind direction, 10-min data

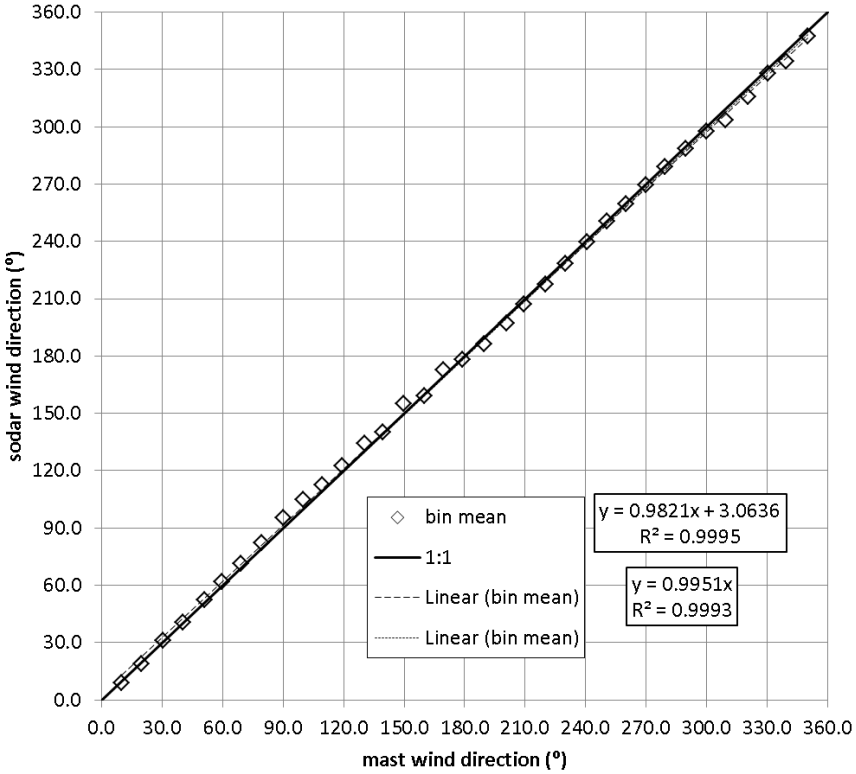

Figure C.11: Sodar 70 m wind direction vs. Mast 68.4 m wind direction, binned correlation

The previous figures suggest some non-linearity in the relationship between sodar and mast wind direction, which may be due to instrument error (mast or sodar) or differences between the two locations. However the difference is relatively small, and no greater than 10° for any direction except for between 305° – 25° where the difference is up to 29°.

Comparisons of wind frequency roses, based on 10 minute data at 70 m indicate a close relationship as shown in Figure C.12.

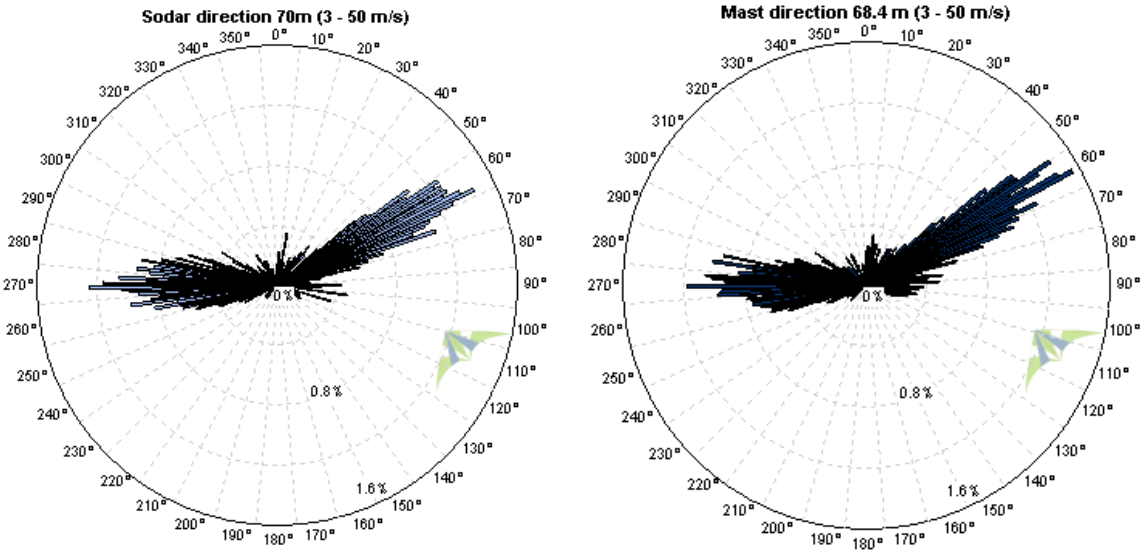

Figure C.12: Wind direction frequency rose, left sodar 70 m, right mast 68.4 m, and 360 sectors

C.10 Wind shear analysis

Vertical wind shear exponents (power law) between the 60 m and 70 m heights of the sodar and mast, for concurrent wind speeds greater than 3.0 m/s, are displayed in Table C.9.

Table C.9: Shear comparison

	Shear exponent mast (all data points)		Shear exponent		
Time	**Mast (60.4–71.3 m)**	**# data points**	**Sodar (60–70 m)**	**Mast (60.4–71.3 m)**	**# data points**
All	0.23	5,482	0.22	0.24	4,591
Day (06:00 – 18:00)	0.19	2,941	0.18	0.19	2,502
Night (18:00 – 06:00)	0.28	2,542	0.26	0.29	2,089