Fulcrum 3D Pty Ltd

Performance Assessment of Fulcrum 3D Sodar in Simple and Complex Terrain

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PARSONS BRINCKERHOFF

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Author, Reviewer and Approver details

Prepared by:	B. Inkster	Date: 14/02/2014	Signature:
Reviewed by:	W. Chua	Date: 14/02/2014	Signature:
Approved by:	A. Kerley	Date: 14/02/2014	Signature:

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Parsons Brinckerhoff Australia Pty Limited

ABN 80 078 004 798

Level 15 28 Freshwater Place
Southbank VIC 3006
Tel: +61 3 9861 1111
Fax: +61 3 9861 1144
Email: melbourne@pb.com.au
www.pbworld.com

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Abbreviations

AEST	Australian Eastern Standard Time
Deg.	Degrees from north (may be indicated as true north)
IEC	International Electrotechnical Commission
km	Kilometres
mAGL	Metres above ground level
mASL	Metres above mean sea level
MEASNET	Measuring Network of Wind Energy Institutes
m/s	Metres per second
Sodar	Sonic Detection and Ranging device
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator
WGS84	World Geodetic System established in 1984, revised in 2004

Executive summary

Fulcrum 3D Pty Limited (Fulcrum 3D) has engaged Parsons Brinckerhoff to evaluate the performance of three Fulcrum 3D Sodars in simple and complex terrains. Evaluation of these Sodars has been conducted through detailed comparison with nearby reference measurement sources at three separate locations in Australia. The analysis has been performed on Sodar data pre-processed by Fulcrum 3D using software version 3.3.

Sodars were installed and commissioned at various sites by Fulcrum 3D and each were located in proximity to reference wind masts with reliably calibrated cup anemometers. Concurrent wind data have been measured at both the reference masts and the Sodars and a detailed analysis of the concurrent datasets has been performed to measure equivalency in linearity and bias. Parsons Brinckerhoff has not verified the wind data supplied, but has cleaned and modified data in situations where erroneous samples were detected or tower sheltering was present. All steps undertaken to clean or modify data have been described within this report. Statistical analysis has been performed on data after cleaning and minor modification.

To evaluate terrain complexity, each site has been evaluated using the classification system described in the standard IEC 61400-12-2, in which sites have been quantified in metrics of Ruggedness Index (RIX) and the slope of terrain. Correlations have been performed for 30 degree direction sectors and the corresponding terrain complexity has been determined.

Based on the findings of the statistical analyses, Parsons Brinckerhoff concludes that the Fulcrum 3D Sodars using software version 3.3 have measured comparative data to reference masts in simple and complex terrains for IEC 61400-12-2 terrain class from 1 to 5, for nominal measurement heights of 60, 70 and 80 mAGL. For each site, direction sectors affected by flow disturbance of some source (such as obstacles including nearby vegetation) were identified.

Although linear deviations and bias were minimal, it is expected that improvements in correlation results and reduced bias in data would be achieved if flow disturbances from site obstacles were not present in the data.



1. Introduction

Fulcrum 3D Pty Limited (Fulcrum 3D) has engaged Parsons Brinckerhoff to undertake an assessment of the Fulcrum 3D Sodar performance in simple and complex terrains by detailed comparison with reliable and known measurement sources at three separate locations in Australia.

Cup anemometers are considered industry standard for wind measurement, whereas Sodar is a relatively new technology which can be validated through a considered approach of comparisons with appropriately mounted cup anemometers. Parsons Brinckerhoff has used guidelines and standards applicable to the measurement of wind data to undertake a detailed comparison of Sodars with cup anemometer reference sources. Many of these standards do not explicitly apply to Sodar wind measurements and hence, each has been used as a guideline for analyses where considered appropriate. The standards adopted by Parsons Brinkerhoff for guidance on the validation of Sodars include:

- IEA Recommended Practices for the Use of Sodar in Wind Energy Resource Assessments, 2011 [1]
- IEC 61400-12-1 2005, Power performance measurements of electricity producing wind turbines [2]
- IEC 61400-12-2 2013, Power performance measurements of electricity producing wind turbines based on nacelle anemometry [3].

Sodars were installed and commissioned at various sites by Fulcrum 3D and each were located in proximity to reference wind masts with cup anemometers. Parsons Brinckerhoff has not conducted site inspections of the Sodars or reference masts. Concurrent wind data have been measured at both the reference masts and the Sodars and a detailed analysis of the concurrent datasets has been performed to measure equivalency. Initially, Sodar data for several sites was supplied using software version 3.21, before updated Sodar data was provided using software version 3.3. It was observed that data produced using software version 3.3 achieved higher availability and improvements such as reduced bias and higher correlations. Therefore, the data measured by each Sodar has been pre-processed from raw data using Fulcrum 3D's data processing software version 3.3, and the results presented in this report are specific to this software version.

This report summarises the steps undertaken and the results of the comparisons, to validate the measurements taken by the Sodars at each site. In this assessment, a regression analysis has been performed to quantify linearity and bias, and subsets of data have been investigated to identify systematic bias in direction and data recovery, and wind shear profiles have also been compared.

1.1 Background

Wind climate measurement has traditionally been performed using cup anemometers and wind direction vanes. This method of measurement has formed the foundation of standardisation in the wind industry for the prediction of wind energy yield for wind farms and the power performance measurement of wind turbines. In recent years, remote sensing technologies, such as Sodar, have achieved an increased presence in the industry due to the benefits of using a transportable measuring apparatus that is capable of measuring relevant wind climate parameters at various heights.

The principles of measurement between these two methods are fundamentally different and each has its own benefits and drawbacks. A cup anemometer converts highly localised wind velocity into mechanical rotation, which is then translated to wind speed. This method is well understood and the behaviour of this method has been tried and tested over many years of research and field use. Cup anemometers offer high data recovery rates over annual time scales, however they are susceptible to damage, wear and tear, degradation and sheltering effects by their mounting arrangements. Cup anemometer accuracy can also be sensitive to inclined flow, turbulence, rain and ambient temperature. These issues can be difficult to detect and lead to skewed results. Additionally, these devices are required to be installed at heights close to the expected hub height of wind turbines, and often in combination with other anemometers to form an array of measurement heights to profile the wind. These requirements often result in fixed or semi-permanent locations of measurement masts without the flexibility to easily probe surrounding locations of interest.

In contrast, Sodar devices emit a focussed acoustic pulse through a volume of atmosphere which is scattered by turbulent fluctuations in the wind. Some scattering will cause reflections of the acoustic pulse which can be received by the Sodar, and interpreted as vectors using Doppler Shift analysis. This process can be used to measure wind vectors and turbulence at various heights through the volume of atmosphere, which can then be interpreted as wind speed and direction data. Sodars offer several key advantages over cup anemometers, some of which are: the ability to measure multiple heights with a single device (often covering the height range of the rotor diameter), Sodars are compact and portable and allow for multiple locations to be measured with minimal effort.

An important consideration in the context of this report is that Sodar measures a wind speed vector for a volume of air, whereas a cup anemometer measures a scalar for a localised point and are combined with wind direction to achieve a scalar average wind vector [4]. This is of particular relevance in complex terrain, where variations in flow in the measured volume of a Sodar may result in different vector measurements to a cup anemometer and wind vane. It is therefore important that evaluation is undertaken to establish the equivalency of Sodar to cup anemometers in complex terrain. Such evaluation allows users of the Sodar data to undertake wind modelling with confidence in that data.

1.2 Scope of work

Parsons Brinckerhoff has performed the following scope of work as agreed with Fulcrum 3D in accordance with the proposal *201304676-PWR-PPO-001 Rev C* [5] and further email discussions between Ben Inkster (Parsons Brinckerhoff) and Hugh Sangster (Fulcrum 3D) [6]:

For three sites, Parsons Brinckerhoff has performed analysis including:

- Comparison of average wind speeds, time series graphs
- Linear correlation
- Directional binned wind speed distribution
- Wind speed difference distribution
- Diurnal analysis
- Wind shear analysis
- Terrain assessment in accordance with the relevant standards

1.3 Data received

Parsons Brinckerhoff has received the following data from Fulcrum 3D for each site.

- Fulcrum 3D Sodar data from three locations – pre-processed by Fulcrum 3D using software version 3.3 [7] [8] [9]
- Processed reference mast data – Parsons Brinckerhoff has not verified reference data but has undertaken minor modifications to clean erroneous samples, apply time offsets and resolve tower sheltering effects where necessary [10] [11] [12]
- Installation reports of reference masts and Sodars [13] [14] [15]
- Digital elevation contour data [16] [17] [18] [19]
- Other miscellaneous site documentation and data processing notes

2. Methodology

2.1 Terrain classification

Terrain has been classified using the definitions in the IEC 61400-12-2 standard. The Ruggedness Index (RIX) and average slope are calculated for each 30 degree sector, and the corresponding final terrain class is determined. The IEC 61400-12-2 standard uses predefined variables for hub height (H) and rotor diameter (D), and for the purposes of this report it has been assumed that D and H both equal 80 m.

The average slope is calculated from a radius of 5 times the hub height to the tower base for each 30 degree sector, and the IEC classification is shown in the table below.

Table 2.1 IEC 61400-12-2 terrain slope classification [3]

Absolute slope (%)	Slope terrain class
Compliant to IEC 61400-12-1:2005 Annex B (use L = 2,5D)	1
0° ≤ slope < 10°, but not class 1	2
10° ≤ slope < 15°	3
15° ≤ slope < 20°	4
20° ≤ slope	5

The absolute difference between adjacent elevation points is calculated for each 30 degree sector. The RIX index for each sector is calculated as a percentage of the absolute elevation difference that exceed a range of defined distances, as shown in the table below.

Table 2.2 IEC 61400-12-2 RIX terrain classification [3]

RIX (%)	RIX terrain class
Compliant to IEC 61400-12-1:2005 Annex B (use L = 2,5D)	0
$RIX_{0,04}$ < 16 AND $RIX_{0,06}$ < 8 AND $RIX_{0,08}$ < 4 but not class 0	1
$RIX_{0,04}$ < 32 AND $RIX_{0,06}$ < 16 AND $RIX_{0,08}$ < 8 but not class 1	2
$RIX_{0,04}$ < 48 AND $RIX_{0,06}$ < 32 AND $RIX_{0,08}$ < 16 but not class 2	3
$RIX_{0,04}$ ≥ 48 OR $RIX_{0,06}$ ≥ 32 OR $RIX_{0,08}$ ≥ 16	4

The terrain class is evaluated by considering the average slope and the three RIX indices for each 30 degree sector. The terrain class is the sum of the slope terrain class and the RIX terrain class with the understanding that the maximum terrain class is 5 i.e. if the sum of slope and RIX terrain class is higher than 5, then the terrain class is 5, as shown in the Table 2.3.

Table 2.3 IEC 61400-12-2 final terrain classification [3]

Slope terrain class	RIX terrain class				
	0	1	2	3	4
1	1	2	3	4	5
2	2	3	4	5	5
3	3	4	5	5	5
4	4	5	5	5	5
5	5	5	5	5	5

Terrain complexity can often be described in subjective terminology. To provide a quantitative judgement of terrain complexity in this assessment, locations with an IEC 61400-12-2 terrain class of 3 or greater are classified as complex and locations with a terrain class of 2 or less are classified as simple.

2.2 Measured data

Sodar data has been supplied by Fulcrum 3D in a clean and filtered condition. Measured reference mast data has also been supplied by Fulcrum 3D as a pre-calibrated data file. Parsons Brinckerhoff has not performed verification of the reference mast data or Sodar data and has assumed that all data provided by Fulcrum 3D has appropriately applied calibrations to instrumentation measurements.

Some minor conditioning of data has been performed, including removal of erroneous samples, applying time offsets for local time and resolving tower sheltering where necessary. These operations have been documented where applicable in the following sections.

2.3 Correlation analysis

2.3.1 Wind speed linear correlation

Wind speed data from both measurement sources have been correlated and a linear relationship between datasets has been established. The two datasets have been assessed using a least squares linear regression model that fits the data to linear function in the form of:

$$ws_{sodar} = (m \times ws_{reference}) + c \ ,$$

where the parameters of *m*, c and the coefficient of determination (R^2) are calculated for each regression analysis.

2.3.2 Bias

Wind speed bias has been calculated by comparing the average wind speeds between the reference mast and Sodar datasets according to the following equation:

$$Bias[\%] = \frac{\sum_{i=1}^{n}(ws_{sodar,i} - ws_{reference,i})}{\sum_{i=1}^{n}(ws_{reference,i})} \times 100$$

Where *n* is the number of concurrent samples included in the analysis.

In this method, negative bias is representative of the Sodar measuring lower wind speed values, on average, compared to the reference mast and positive bias is representative of the Sodar measuring higher wind speed values, on average, compared to the reference mast.

2.3.3 Directionally binned correlation

The relationship between the Sodar and the reference mast wind speeds may be affected by different wind directions. To evaluate this possibility, datasets have been binned by 30˚ wind direction sectors and a linear correlation has been performed on each bin. Each sector is compared to the terrain class at the Sodar and reference mast locations.

2.3.4 Diurnal analysis

It is a common feature that Sodar data quality, availability and consistency may fluctuate with varying levels of atmospheric stability and that this feature may introduce bias on a diurnal time scale [1]. To assess if any diurnal bias exists in the Sodar measurements, linear correlations and bias assessments have been performed on the concurrent datasets after dividing data into periods of 'Day' and 'Night'. These periods have been defined after analysis of the diurnal recovery rates includes data between the hours of 6 am to 8 pm and the 'Night' period includes data from the remaining hours of the day.

2.3.5 Wind direction linear correlation

Wind direction data from both measurement sources have been correlated and a linear relationship between datasets has been established. The two datasets have been assessed using a least squares linear regression model that fits the data to linear function in the form of:

$$Dir_{sodar} = (m \times Dir_{reference}) + c \ ,$$

where the parameters of *m*, c and the coefficient of determination (R^2) are calculated for each regression analysis.

2.4 Wind shear analysis

Wind shear is the term used to describe the change in wind speed with height above ground level. Wind shear is accurately modelled at most sites using the power law wind shear model, and the wind shear profile can be estimated using wind speed measurements from multiple heights.

The magnitude of wind shear (rate of change of wind speed against height) is known to vary in differing wind speeds, wind directions and time of day. It is therefore important to evaluate wind shear measured by the Sodar and reference mast using equivalent datasets without introducing bias from unique conditions experienced in either dataset. To achieve equivalency in data, only timestamps that have valid data for all wind speeds from the Sodar and reference mast are included in the wind shear assessment. Any timestamp that has one or more missing or invalid wind speed has been excluded. Average wind speeds are then taken from the remaining dataset to estimate the power law wind shear profile.

After reducing to concurrent datasets, equivalency in the measured conditions is achieved, and this is considered preferable to maintaining the highest possible level of data availability.

Reference mast measurements and Sodar heights with low availability have been excluded from the wind shear analysis to avoid excessive reduction in concurrent data quantity. For this reason, Sodar data above 110 m has been excluded from the wind shear analysis to achieve a balance between evaluating the wind shear profile with height and acceptable data availability.

3. Site A

The first location provided by Fulcrum 3D for evaluation is known as Site A; located near the town of Gundagai in New South Wales. Fulcrum 3D has measured concurrent data between a Sodar unit (FS1M_1011) and data from a permanent 70 m tubular mast. The Sodar has been located 144 m south east of the permanent reference mast. The site is considered complex and the measurement locations are situated on top of a hill with steep inclines to the southwest and north of the reference mast and Sodar locations.

Table 3.1 shows the details of the mast, and Figure 3.1 and Figure 3.2 show the terrain and location of the mast with respect to the Sodar.

Table 3.1 Site A reference mast and Sodar elevations and duration of measurements

	Elevation
Reference mast	519 mASL
Sodar	515 mASL
Period of concurrent measurement	
Start Date	27 May 2012
End Date	15 July 2012
Duration	49 days

Figure 3.1 Location of Site A reference mast and Sodar (far)

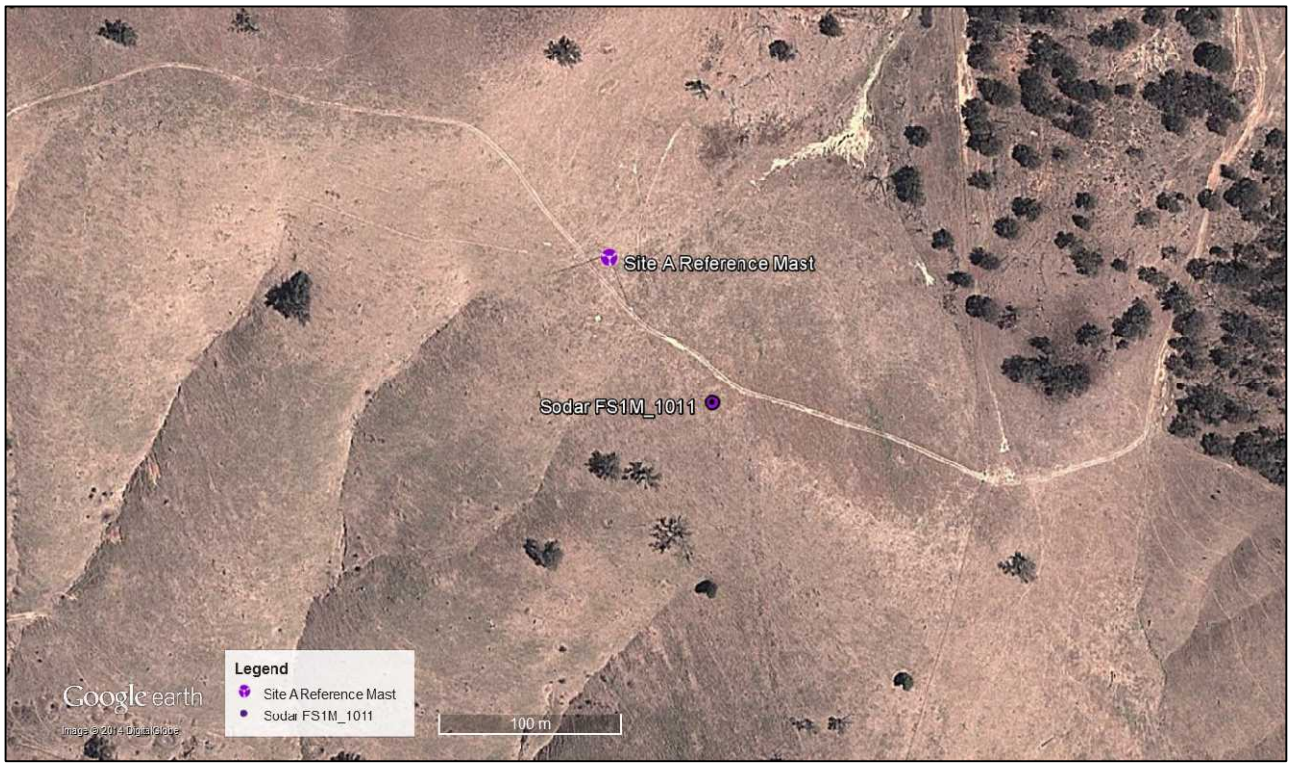

Figure 3.2 Location of Site A reference mast and Sodar (near)

3.1 Terrain analysis

The surrounding terrain to the reference mast and Sodar consists of low lying grassland and pasture with sparse trees approximately 5 mAGL in height. The surrounding terrain is estimated to have a roughness class of approximately 2 (roughness height, z_o of 0.1 m). There is small cluster of sparsely-spaced medium density trees to the east of the site and three trees are located in proximity to the southwest of the Sodar location. Terrain undulations and surrounding vegetation can be seen in Figure 3.3.

Figure 3.3 Surrounding terrain and vegetation to the Site A reference mast (image source: Fulcrum 3D)

3.1.1 Sector based terrain classification

The terrain complexity surrounding the Site A reference mast and Sodar has been evaluated using the procedure described in Section 2.1. The results of the terrain analysis are shown below for 30 degree direction sectors surrounding both the mast and Sodar locations. Both locations are complex and IEC 61400-12-2 terrain classes range between 3 and 5 (when assuming a nominal rotor and hub height of 80 m).

Table 3.2 IEC61400-12-2 terrain classification of Sodar and Reference mast locations for Site A (Assuming D+H = 160 m)

Direction Sector [deg.]	Sodar Location			Reference Mast Location		
	RIX Class	Slope Class	IEC Terrain Class	RIX Class	Slope Class	IEC Terrain Class
0	1	2	**3**	1	2	**3**
30	1	2	**3**	1	2	**3**
60	1	2	**3**	1	2	**3**
90	1	2	**3**	1	2	**3**
120	1	2	**3**	1	2	**3**
150	2	2	**4**	2	2	**4**
180	2	3	**5**	2	3	**5**
210	2	3	**5**	2	3	**5**
240	2	3	**5**	1	3	**4**
270	2	2	**4**	2	2	**4**
300	3	1	**4**	3	2	**5**
330	2	1	**3**	2	2	**4**

3.2 Reference mast data

The Site A mast is a 70 m tubular tower and consists of five measurements levels at approximately 71 m, 70 m, 60 m, 52 m and 29 m. Parsons Brinckerhoff has not undertaken a site visit of this mast, but has obtained an understanding of the mast configuration from the *Site A Installation Report* supplied by Fulcrum 3D [13]. Based on this report, the instrument mounting configurations appear to be broadly consistent with the guidelines of IEC 61400-12-1 Annex G [2]. Wind speeds have been measured using Vector A100LM anemometers, calibrated in a MEASNET accredited facility and the primary upper level anemometer has been mounted using a vertical boom from the top of the tower. This instrument has been used as the primary reference wind speed due to the minimal flow distortion effects from the tower.

Fulcrum 3D has provided the reference mast data in a processed form with instrumentation calibrations applied, supplied as three .csv files [10]. Parsons Brinkerhoff has not verified that the supplied data has appropriate calibrations applied to the raw data, however the data has been cleaned and adjusted as described in Table 3.3. Parsons Brinckerhoff has, at the request of Fulcrum 3D, applied a time offset of 10 hours and 10 minutes to the reference mast data to convert time stamps to Australia Eastern Standard Time (AEST or +10 UTC) [20].

Table 3.3 Data quality checking procedures for reference mast data

Step	Quality check	Outcome/Result	Actions taken
1	Time offset observed	Poor correlation	Adjusted reference data timestamp by 10 hours 10 minutes to achieve AEST, as advised by Fulcrum3D [20].

Step	Quality check	Outcome/Result	Actions taken
2	Excessive outlier	Erroneous wind speed standard deviation (140) detected on 70 mAGL wind speed 19/06/2012 17:30	Data removed from S1 for 19/06/2012 17:30
3	Erroneous data check	Erroneous sample identified with -999 code	Erroneous S1 samples omitted
4	Sheltering analysis of S2 using S1 as reference	Tower sheltering observed on S2 between the directions of 5 to 18 degrees	S2 wind speeds removed for wind directions between 5 and 18 degrees (200 samples)
5	Sheltering analysis of S3 using S1 as reference	Tower sheltering observed on S3 between the directions of 355 to 18 degrees	S3 wind speeds removed for wind directions between 355 and 18 degrees (300 samples)
6	Sheltering analysis of S4 using S1 as reference	Tower sheltering observed on S4 between the directions of 355 to 18 degrees	S4 wind speeds removed for wind directions between 355 and 18 degrees (300 samples)
7	Sheltering analysis of S5 using S1 as reference	Tower sheltering observed on S5 between the directions of 355 to 18 degrees	S5 wind speeds removed for wind directions between 355 and 18 degrees (300 samples)

Table 3.4 Site A Reference mast data summary after cleaning

Recording period	Date			Time	
Start	01 May 2012			13:50	
Finish	31 July 2012			13:40	
Wind statistics					
Instrument	S1	S2	S3	S4	S5
Height above ground level [m]	71.3	70.4	60.4	51.9	28.7
Recovery rate [%]	100	55.5	95.8	95.8	95.8
Average wind speed [m/s]	5.7	6.4	5.6	5.5	5.1
Maximum mean wind speed [m/s]	17.8	16.0	17.5	17.3	16.7

Given the low availability of data from the second level anemometer (S2 70.4 m), this instrument has been discounted from the analysis.

3.3 Sodar data

Fulcrum 3D has provided pre-processed Sodar data .csv format [7]. Data has been pre-processed using Fulcrum 3D's software Version 3.3 and data is supplied with status flags for signal quality, processing quality and consistency checking. Parsons Brinkerhoff has removed any data that has an associated signal flag of zero (0) for Signal Quality (F1_v01), Processing Quality (F2_v01) or Consistency Check (F3_v01), and any missing data flags (-999) as recommended by Fulcrum 3D in the document *Sodar Performance Verification Note – Version 3.3* [21] .

A consistent wind direction offset was observed between the Sodar and mast data provided following an initial comparison. It is expected that this offset may be due to setup and configuration error from factors such as magnetic declination and vane orientation which may not have been accurately documented. Parsons Brinckerhoff has adjusted the Sodar wind direction by applying a consistent offset of +9.7 degrees to remove the mean offset of wind direction data. Table 3.5 summarises the Site A Sodar data analysed after filtering and adjustment.

Table 3.5 Sodar cleaned data summary

Recording period	Date						Time			
Start	27 May 2012						0:00			
Finish	15 July 2012						8:50			
Wind statistics										
Height above ground level [m]	60	70	80	90	100	110	120	130	140	150
Recovery rate [%]	86.9	87.2	86.5	87.0	86.2	83.7	80.5	77.1	71.4	62.2
Average wind speed [m/s]	5.7	5.9	6.1	6.0	6.1	6.4	6.6	6.6	6.7	6.3
Maximum mean wind speed [m/s]	16.2	17.2	16.7	16.7	16.8	18.3	18.1	19.1	19.0	19.5

3.4 Time series comparison

As a first stage evaluation, the times series of these concurrent datasets has been analysed to identify any anomalies and to verify the appropriateness of the previous data manipulation steps. For Site A, the primary data analysis has been performed at the nominal height of 70 mAGL since the primary wind speed measured by the reference mast is at 71.3 mAGL. For wind parameters, such as wind shear, additional heights have been compared between the two data sets. The following figures show that the wind speed, direction and standard deviation datasets are in general agreement and that obvious data anomalies are not present.

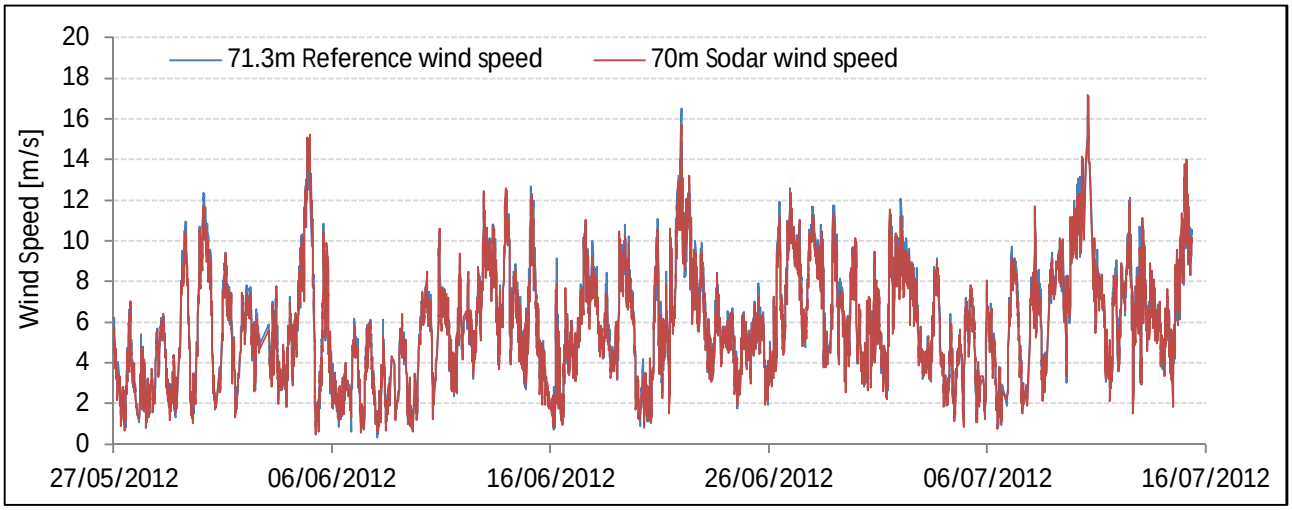

Figure 3.4 Comparison of time series wind speed at 70 m

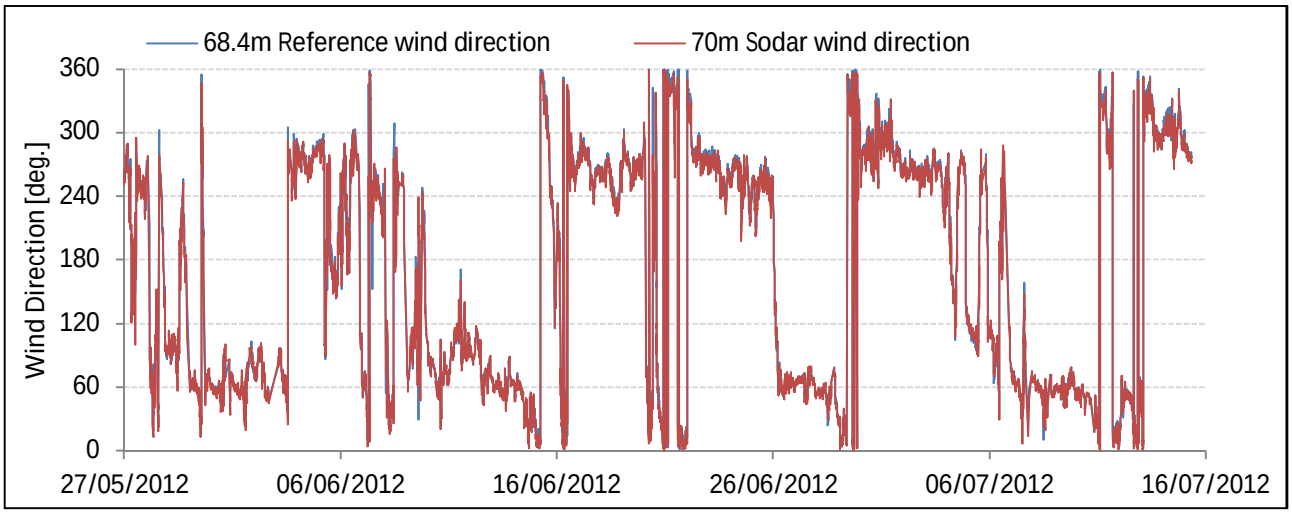

Figure 3.5 Comparison of time series wind direction at 70 m

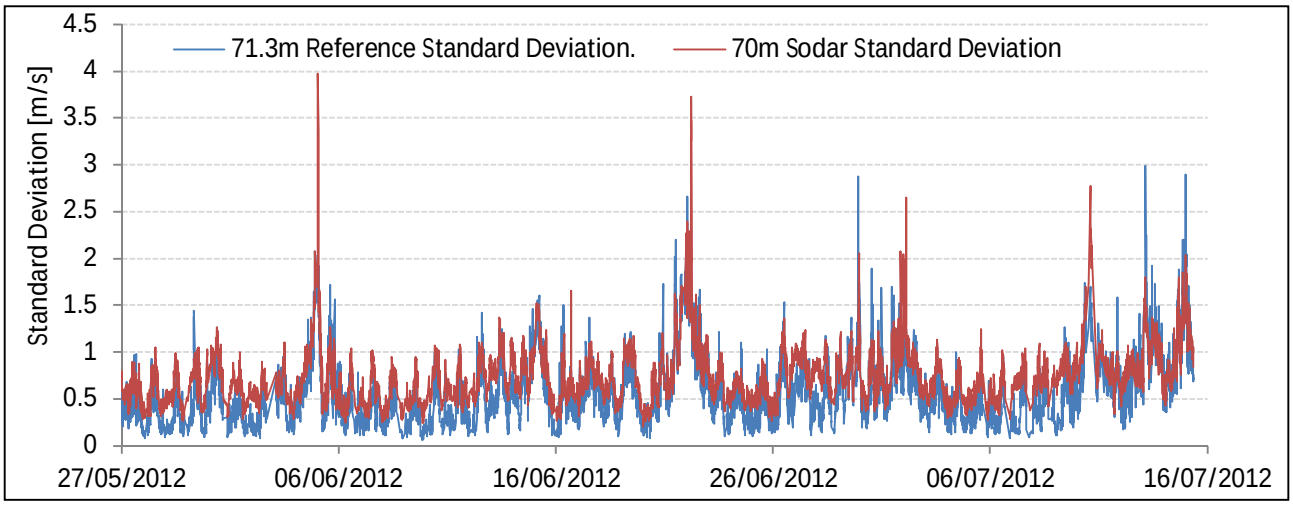

Figure 3.6 Comparison of time series wind speed deviation at 70 m

3.5 Correlations

The results of the linear correlation between the two datasets at the nominal measurement height are shown below for the nominal measurement height of 70 m.

Table 3.6 Correlation results of reference mast wind speed with Sodar wind speed at 70 m

Item		Result
Line of Best fit	Scale (m)	0.960
	Offset (c)	0.08
Coefficient of determination (R^2)		0.975
Bias (Sodar minus Reference) (%)		-2.6

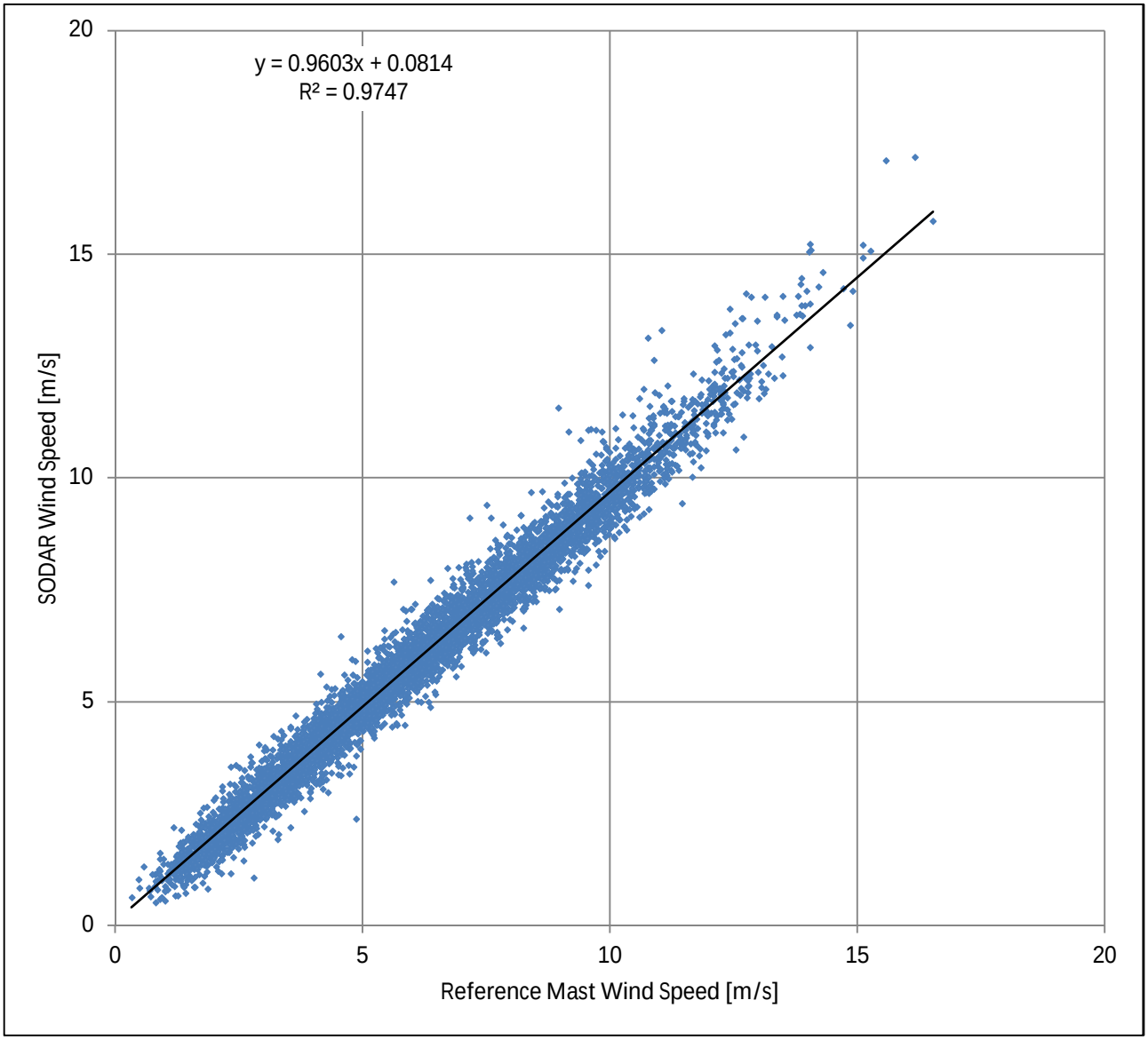

Figure 3.7 Correlation of wind speeds between 71.3 m anemometer at reference mast and 70 m Sodar level.

The error bias between the two sites has been measured and a distribution of error bias is shown in Figure 3.8.

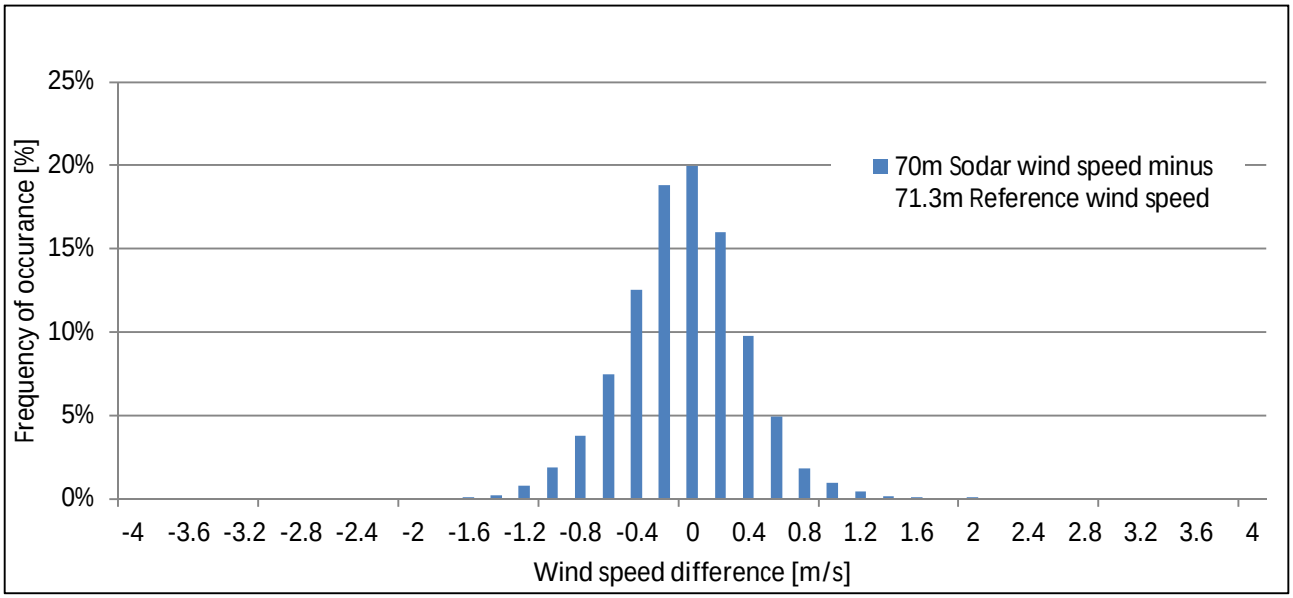

Figure 3.8 Frequency histogram for wind speed differences (Sodar minus Reference mast)

The overall linear comparison shows that the two sites have a strong linear correlation (R^2 of 0.975) and the Sodar has a lower wind speed measurement bias of -2.6%. A likely cause of this bias is the relative difference in measurement height of 1.3 m; where the reference mast measures at a higher elevation compared to the Sodar.

3.5.1 Directionally binned correlation

Wind speed comparisons have been undertaken for each 30 degree direction sector. Table 3.7 shows the results of this analysis in comparison to the terrain classification for corresponding direction sector.

Table 3.7 Directionally binned correlation results and IEC 61400-12-2 Terrain Class (obstacle affected sectors highlighted)

Direction Sector [Deg.]	Scale	Offset	Coefficient of Determination (R^2)	Bias [%]	Frequency of Sector [%]	Terrain Class - Referenc e mast	Terrain Class - Sodar
0	0.918	0.224	0.976	-5.05	4.51	3	3
30	0.943	0.073	0.973	-4.57	7.04	3	3
60	0.965	-0.026	0.972	-3.84	26.15	3	3
90	0.984	0.050	0.959	-0.60	8.04	3	3
120	1.009	0.038	0.973	1.70	3.25	3	3
150	0.988	0.036	0.983	-0.22	1.81	4	4
180	1.007	-0.025	0.975	-0.14	1.88	5	5
210	0.962	0.009	0.911	-3.44	2.40	5	5
240	0.917	0.148	0.972	-4.79	8.63	4	5
270	0.951	0.118	0.977	-2.98	23.58	4	4
300	1.056	-0.128	0.973	3.42	8.27	5	4
330	0.998	-0.002	0.965	-0.22	4.43	4	3

It can be seen that all direction sectors show a high level of correlation with R^2 values above 0.959, with the exception of the 210 degree direction sector. These high correlations are achieved in direction sectors with terrain classes ranging from 3 to 5, which are defined as complex in this report.

An analysis of nearby vegetation and terrain from satellite imagery shows that three trees are located approximately 50 m from the Sodar location in the 210 degree direction sector, and similar conditions are not present for the reference mast. It is likely that the Sodar is affected by flow disturbances from these trees which may have caused the relative reduction in wind speed correlation for this direction sector.

3.5.2 Diurnal analysis

Linear correlations and bias assessments have been performed on the concurrent datasets after dividing data into periods of 'Day' and 'Night'. The 'Day' period includes data between the hours of 6 am to 8 pm and the 'Night' period includes data from the remaining hours of the day. The results of this diurnal assessment are shown below.

Table 3.8 Correlation results for 'Day' and 'Night' periods

Item		Day	Night
Line of Best fit	Scale (m)	0.957	0.962
	Offset (c)	0.088	0.087
Coefficient of determination (R^2)		0.970	0.978
Bias (Sodar minus Reference) (%)		-2.8	-2.5

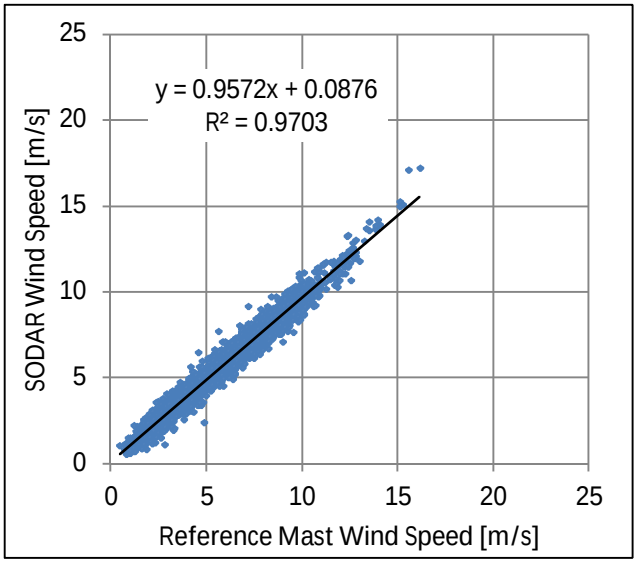

Figure 3.9 Correlation of wind speeds between 71.3 m anemometer at reference mast and 70 m Sodar level for Day time periods.

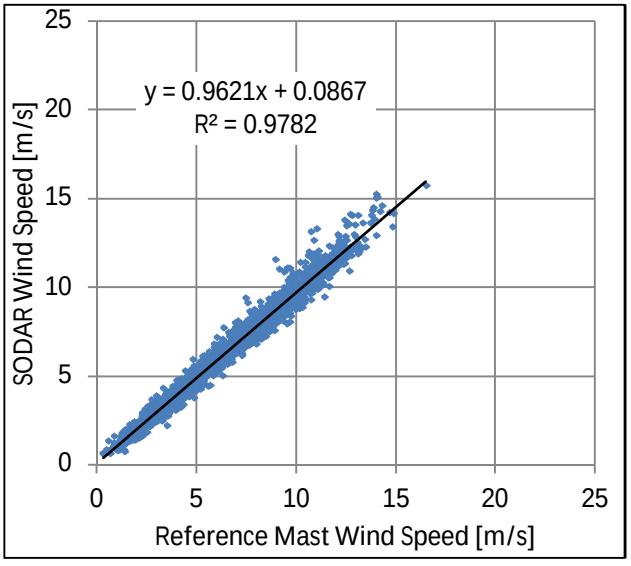

Figure 3.10 Correlation of wind speeds between 71.3 m anemometer at reference mast and 70 m Sodar level for Night time periods

The diurnal analysis shows limited variation between 'Day' and 'Night' periods of measurement. The R^2 values and bias of the two periods are in general agreement and no significant diurnal variation is observable. A histogram of wind speed difference for 'Day' and 'Night' is shown in Figure 3.11.

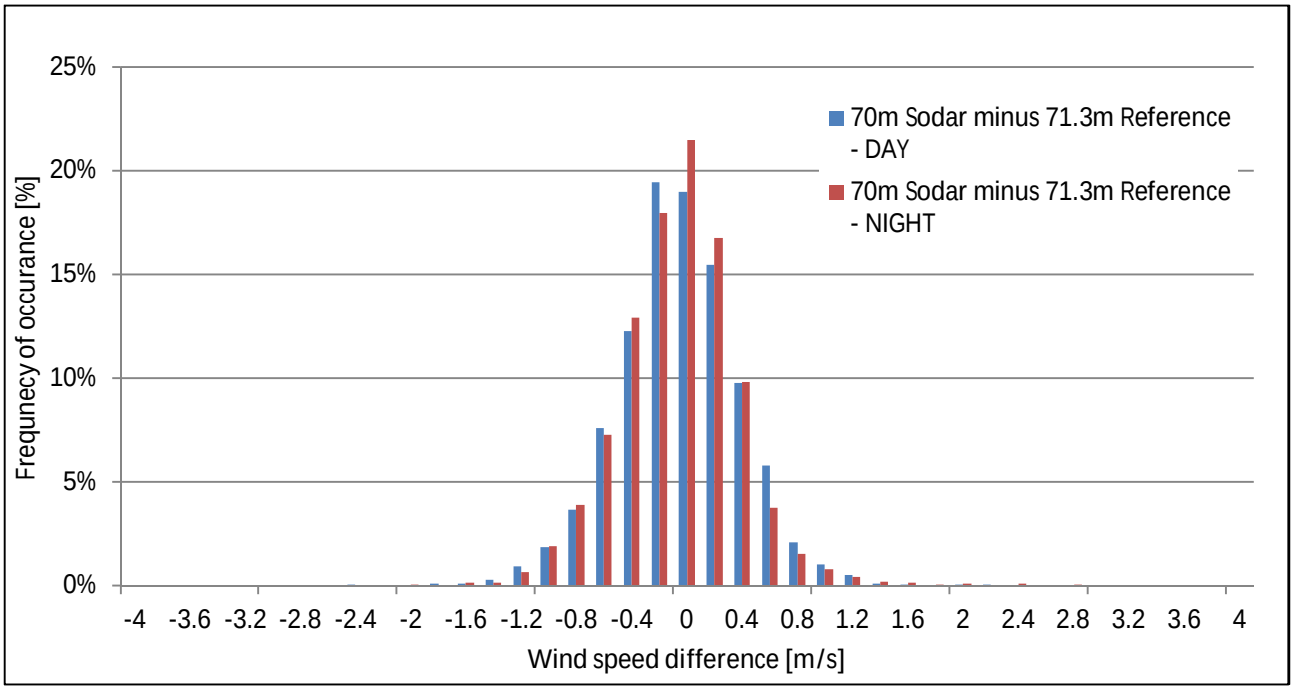

Figure 3.11 Frequency histogram for wind speed differences (Sodar minus Reference) for Day and Night periods at 70 m

3.5.3 Wind direction

A comparison of wind directions between the reference mast and Sodar is shown in Figure 3.12. This figure shows that the comparative wind directions experience a strong correlation with an R^2 value of 0.996.

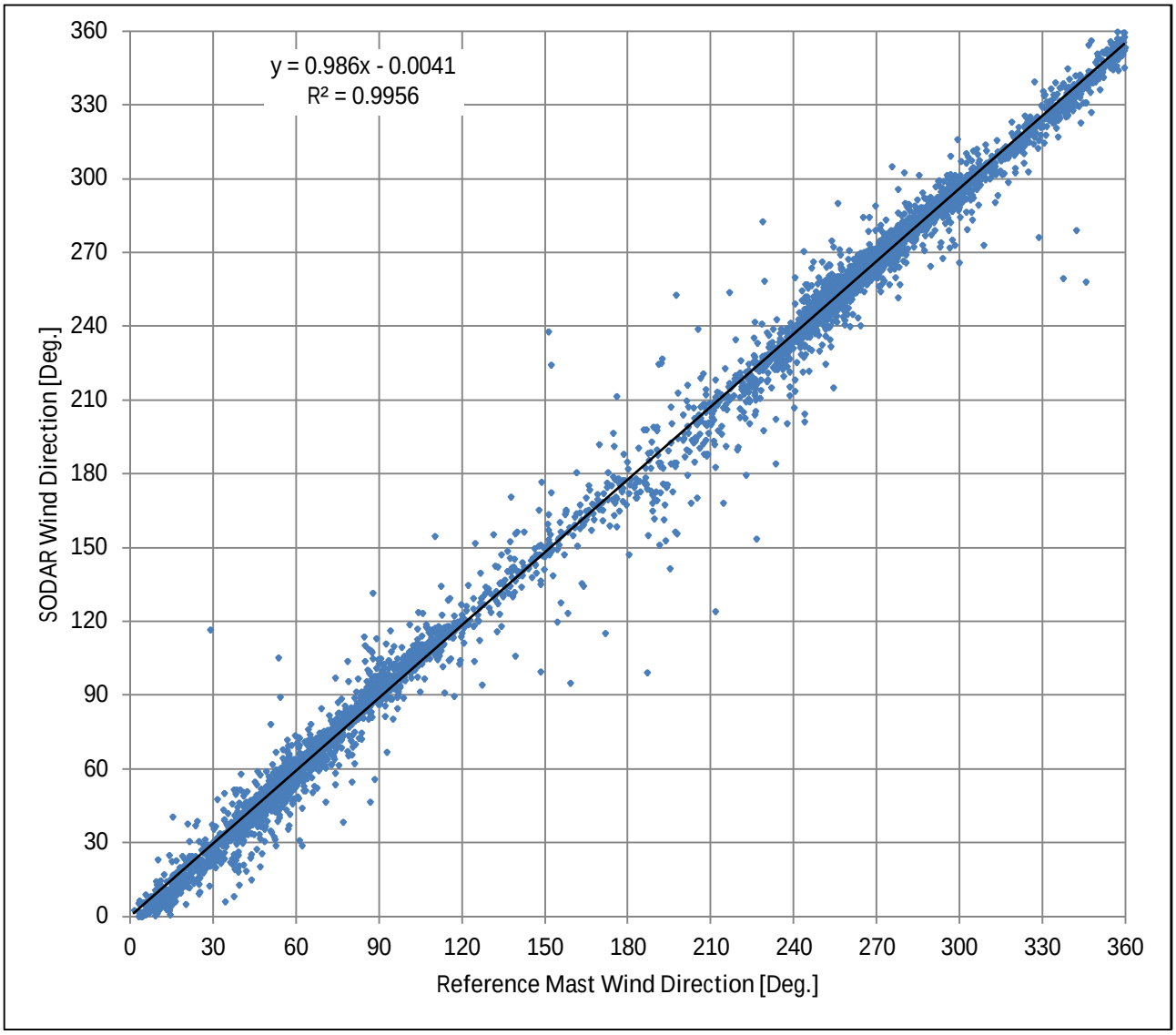

Figure 3.12 Correlation of wind directions between the 68.4 m reference mast direction vane and the 70 m Sodar level.

3.6 Wind shear

Parsons Brinckerhoff has performed an analysis of wind shear using concurrent data sets of all wind speeds and directions at multiple heights for each data source. By using concurrent datasets between all instruments, the total availability of data is reduced, which is mainly due to Sodar levels with below average data availability. However, after reducing to concurrent datasets, equivalency in the measured conditions is achieved. This concurrent dataset includes Sodar wind speeds measured between 60 m and 110 m to achieve a balance between evaluating the wind shear profile with height and achieving acceptable data availability; all other levels were deemed to have recorded insufficient data for concurrent analysis. A summary of the data used in the shear analysis is described Table 3.9, and Figure 3.13 shows the wind shear profiles of concurrent data.

Table 3.9 Site A wind shear analysis data summary

Reference Mast			Sodar			Total recovery rate of concurrent data
Anemometer Height [m]	Average of concurrent wind speed [m/s]	Average concurrent shear exponent (α)	Measurement Height [m]	Average of concurrent wind speed [m/s]	Average concurrent shear exponent (α)	
28.7	5.4	0.16	60	5.9	0.20	75.3%
51.9	5.8		70	6.0		
60.4	5.9		80	6.2		
71.3	6.2		90	6.3		
			100	6.5		
			110	6.6		

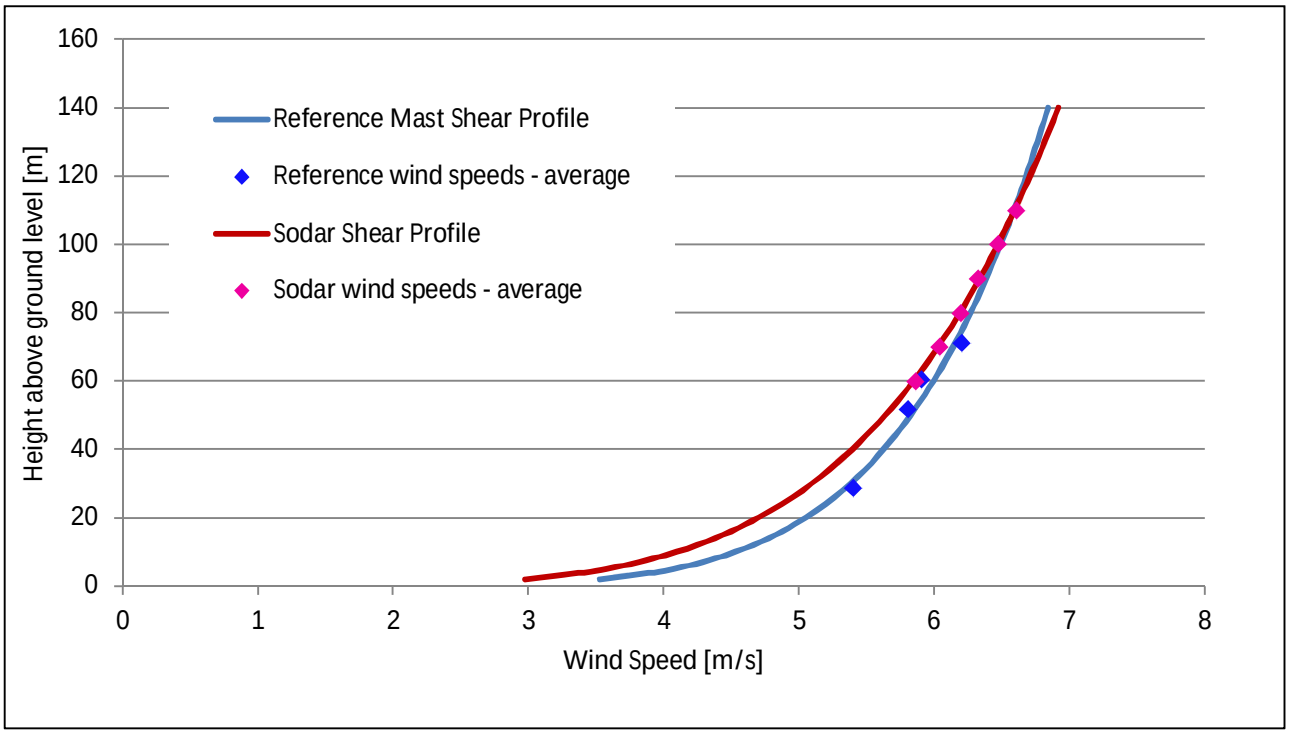

Figure 3.13 Comparison of wind shear profiles and average wind speeds for concurrent periods of measurement.

The wind shear profiles of the two data sources are in general agreement, with a minor difference within the expected ranges of uncertainty for the measured wind shear profile. The Sodar is therefore considered to adequately characterise the wind shear profile for Site A.

4. Site B

The second location provided by Fulcrum 3D for evaluation is known as Site B, located near Coolah in New South Wales. Fulcrum 3D has installed and measured concurrent data between a Sodar unit (FS1M_1002) and a 80 m lattice mast and data has been provided to Parsons Brinckerhoff for analysis of equivalency. The Sodar has been located 163 m south of the permanent reference mast. The site is considered complex and the measurement locations are situated on top of a hill range with steep inclines to the east, west and south of the mast and Sodar locations.

The locations of the reference mast and Sodar are detailed in Table 4.1, and satellite imagery is shown in Figure 4.1 and Figure 4.2 showing location and surrounding vegetation to the mast and Sodar.

Table 4.1 Site B mast and Sodar elevation and duration of measurements

	Elevation
Reference mast	665 mAGL
Sodar	666 mAGL
Period of concurrent measurement	
Start Date	3 May 2013
End Date	8 July 2013
Duration	67 days

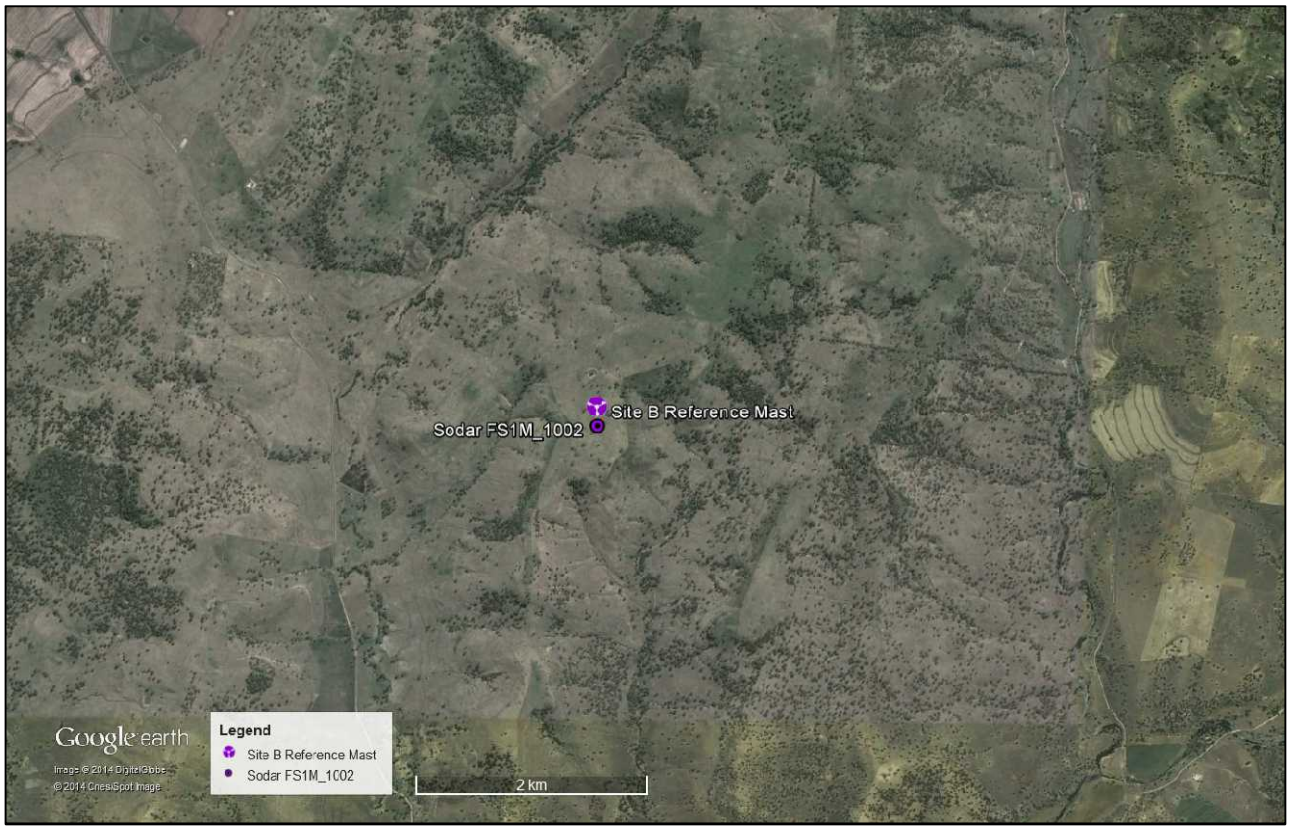

Figure 4.1 Location of the Site B reference mast and Sodar (far)

Figure 4.2 Location of the Site B reference mast and SODAR (near)

4.1 Terrain analysis

The surrounding terrain to the reference mast and Sodar consists of low lying grassland and pasture with sparse trees approximately 5 mAGL in height. The surrounding terrain is estimated to have a roughness class of approximately 2 (roughness height, z_o of 0.1 m). There is small cluster of sparsely-spaced medium density trees approximately 50 m north of the reference mast and a cluster of trees approximately 100 m north east of the Sodar location.

4.1.1 Sector based terrain classification

The terrain complexity surrounding the Site B reference mast and Sodar has been evaluated using the procedure described in Section 2.1. The results of the terrain analysis are shown below for 30 degree direction sectors surrounding both the mast and Sodar locations. Both locations are complex and IEC 61400-12-2 terrain classes range between 1 and 4 (when assuming a nominal rotor and hub height of 80 m).

Table 4.2 IEC61400-12-2 terrain classification of Sodar and Reference mast locations for Site B (Assuming D+H = 160 m)

Direction Sector [deg.]	Sodar Location			Reference Mast Location		
	RIX Class	Slope Class	IEC Terrain Class	RIX Class	Slope Class	IEC Terrain Class
0	1	2	**3**	1	2	**3**
30	1	0	**1**	1	2	**3**
60	1	2	**3**	1	2	**3**
90	2	2	**4**	2	2	**4**
120	1	2	**3**	1	2	**3**
150	1	2	**3**	1	2	**3**
180	1	2	**3**	1	2	**3**
210	1	2	**3**	1	2	**3**
240	1	2	**3**	1	2	**3**
270	2	2	**4**	1	2	**3**
300	2	1	**3**	1	2	**3**
330	1	1	**2**	1	2	**3**

4.2 Reference mast data

The Site B mast is an 80 m lattice tower and consists of four measurements levels at approximately 81 m, 66 m, 51 m and 36 m. Parsons Brinckerhoff has not undertaken a site visit of this mast, but has obtained an understanding of its configuration from the *Site B Installation Report* supplied by Fulcrum3D [14]. Based on this report, the instrument mounting configurations appear to be broadly consistent with the guidelines of IEC 61400-12-1 Annex G [2]. Wind speeds have been measured using Vector A100LK anemometers, calibrated in a MEASNET accredited facility and the upper level anemometers have been mounted on a cross-arm boom with an alignment of 39 / 219 degrees (specific instrument orientations has not been provided).

Fulcrum 3D has provided the reference mast data in a processed form with instrumentation calibrations applied, supplied as a .csv file [11]. Parsons Brinkerhoff has not verified that the supplied data has appropriate calibrations applied to the raw data, however the data has been cleaned and adjusted as described in Table 4.3. Parsons Brinckerhoff has, at the request of Fulcrum 3D, applied a time offset of 10 minutes to the reference mast data to account for logger time drift [22].

Table 4.3 Site B data quality checking procedures for reference mast data

Step	Quality check	Outcome/Result	Actions taken
1	Time offset observed	-	Adjusted reference data timestamp by 10 minutes, as advised by Fulcrum3D.
2	Erroneous sample check	Single row of erroneous data detected 05/06/2013 01:40	Erroneous data removed
3	S1 & S2 consistency check	Instruments record similar results with the exception of S2 sheltering from a direction of 200 to 251 degrees	Averaged composite dataset created from S1 and S2. Only S1 data used for directions between 200 and 251 degrees
4	Sheltering analysis of S3, S4 and S5 using composite S1/S2	Sheltering observed in directions between 208 to 240 degrees	S3, S4 and S5 wind speeds removed for wind directions between 208 and 240 degrees (580 samples)

Table 4.4 Site B reference mast cleaned data summary

Recording period	Date			Time		
Start	1 May 2013			0:10		
Finish	16 October 2013			0:00		
Wind statistics						
Instrument	S1/S2 composite	S1	S2	S3	S4	S5
Height above ground level [mAGL]	80.76	80.76	80.76	66.03	50.76	36.03
Recovery rate [%]	99.9	99.9	98.6	97.6	97.6	97.6
Average wind speed [m/s]	6.3	6.2	6.3	6.1	5.8	5.5
Maximum 10 min mean wind speed [m/s]	23.6	23.6	20.0	23.0	21.8	20.4

4.3 Sodar data

Fulcrum 3D has provided pre-processed Sodar data in .csv format [8]. Data has been pre-processed using Fulcrum 3D's software Version 3.3 and data is supplied with signal quality flags for signal quality, processing quality and consistency checking. Parsons Brinkerhoff has removed any data that has an associated signal flag of zero (0) for Signal Quality (F1_v01), Processing Quality (F2_v01) or Consistency Check (F3_v01), and any missing data flags (-999) as recommended by Fulcrum 3D in the document *Sodar Performance Verification Note – V3.3* [21] .

A consistent wind direction offset was observed between the Sodar and mast data provided following an initial comparison. It is expected that this offset may be due to setup and configuration error from factors such as magnetic declination and vane orientation which may not have been accurately documented. Parsons Brinckerhoff has adjusted the Sodar wind direction by applying a consistent offset of -3.0 degrees to remove the mean offset of wind direction data. Table 4.5 summarises the Site B Sodar data analysed.

Table 4.5 Sodar cleaned data summary

Recording period	Date			Time						
Start	3 May 2013			0:00						
Finish	10 October 2013			0:00						
Wind statistics										
Height above ground level [m]	60	70	80	90	100	110	120	130	140	150
Recovery rate [%]	77.4	82.7	81.5	71.1	68.2	58.8	78.6	69.3	73.5	70.2
Average wind speed [m/s]	5.7	6.0	5.3	5.7	4.6	5.4	6.1	6.5	6.7	6.9
Maximum mean wind speed [m/s]	19.5	27.0	32.3	19.4	20.9	21.1	25.5	27.1	26.9	45.6

4.4 Time series comparison

As a first stage evaluation, the times series of these concurrent datasets has been analysed to identify any anomalies. For Site B, the primary wind speed data analysis has been performed at the nominal height of 80 mAGL and 50 mAGL for direction since the highest level measured by the reference mast is 80.8 mAGL. For wind parameters, such as wind shear, additional heights have been compared between the two data sets.

The following figures show that the wind speed and direction datasets are in general agreement and that erroneous samples are not evident.

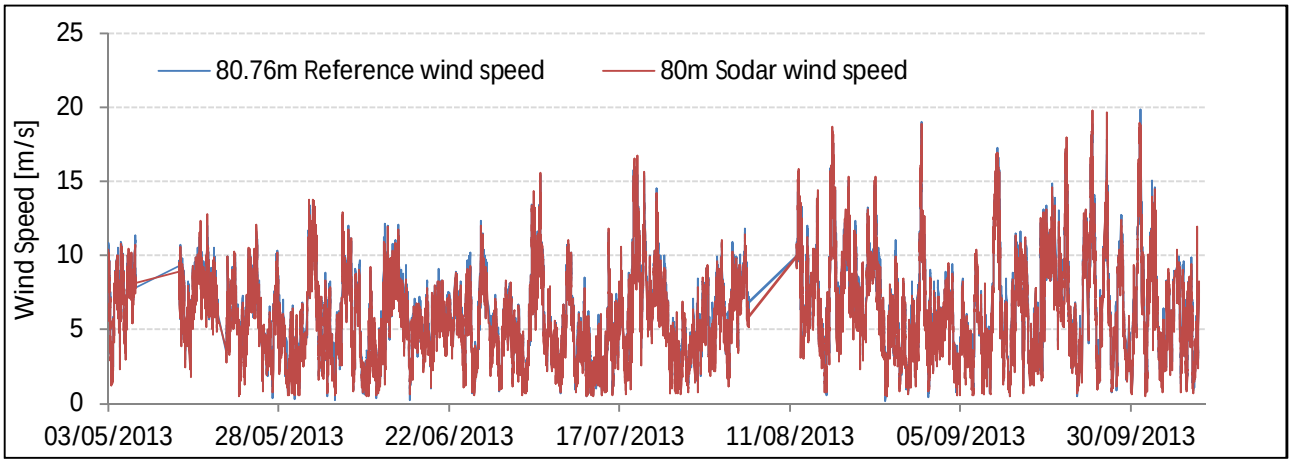

Figure 4.3 Comparison of time series wind speed at 80 m

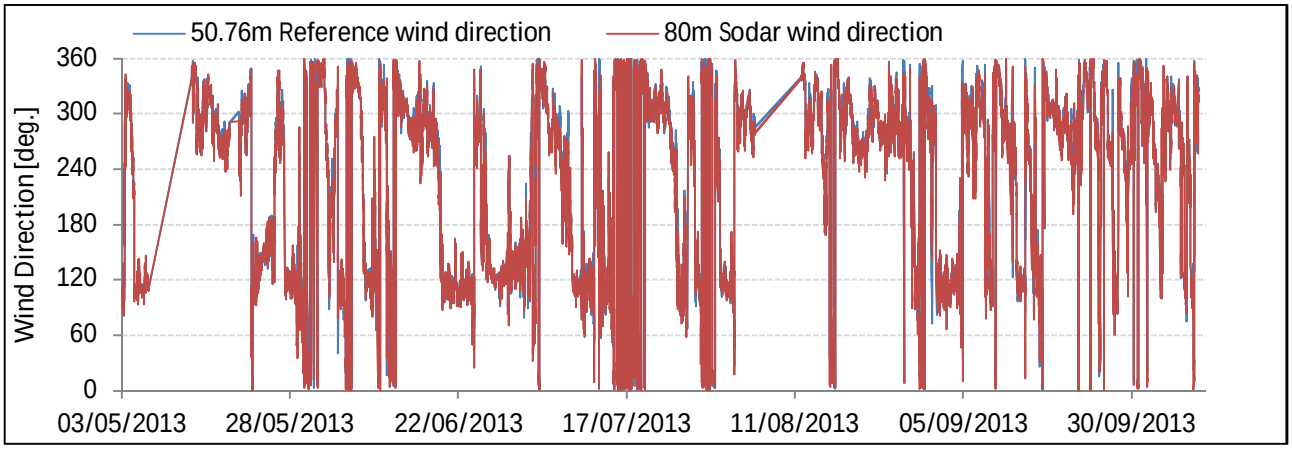

Figure 4.4 Comparison of time series wind direction at 50.8 m for the reference mast and 80 m for the Sodar

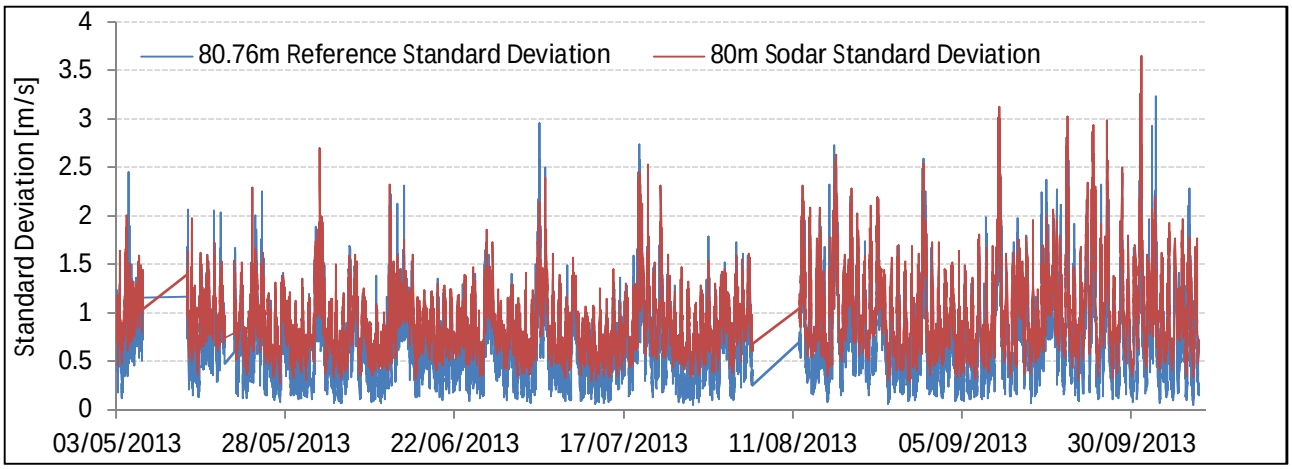

Figure 4.5 Comparison of time series wind speed standard deviation at 80 m

4.5 Correlations

The results of the straight line correlation between the two datasets at the nominal measurement height are shown below for the nominal measurement height of 80 m.

Table 4.6 Correlation results of reference mast wind speed with Sodar wind speed at 80 m

Item		Result
Line of Best fit	Scale (m)	0.991
	Offset (c)	-0.239
Coefficient of determination (R^2)		0.966
Bias (Sodar minus Reference) (%)		-4.6

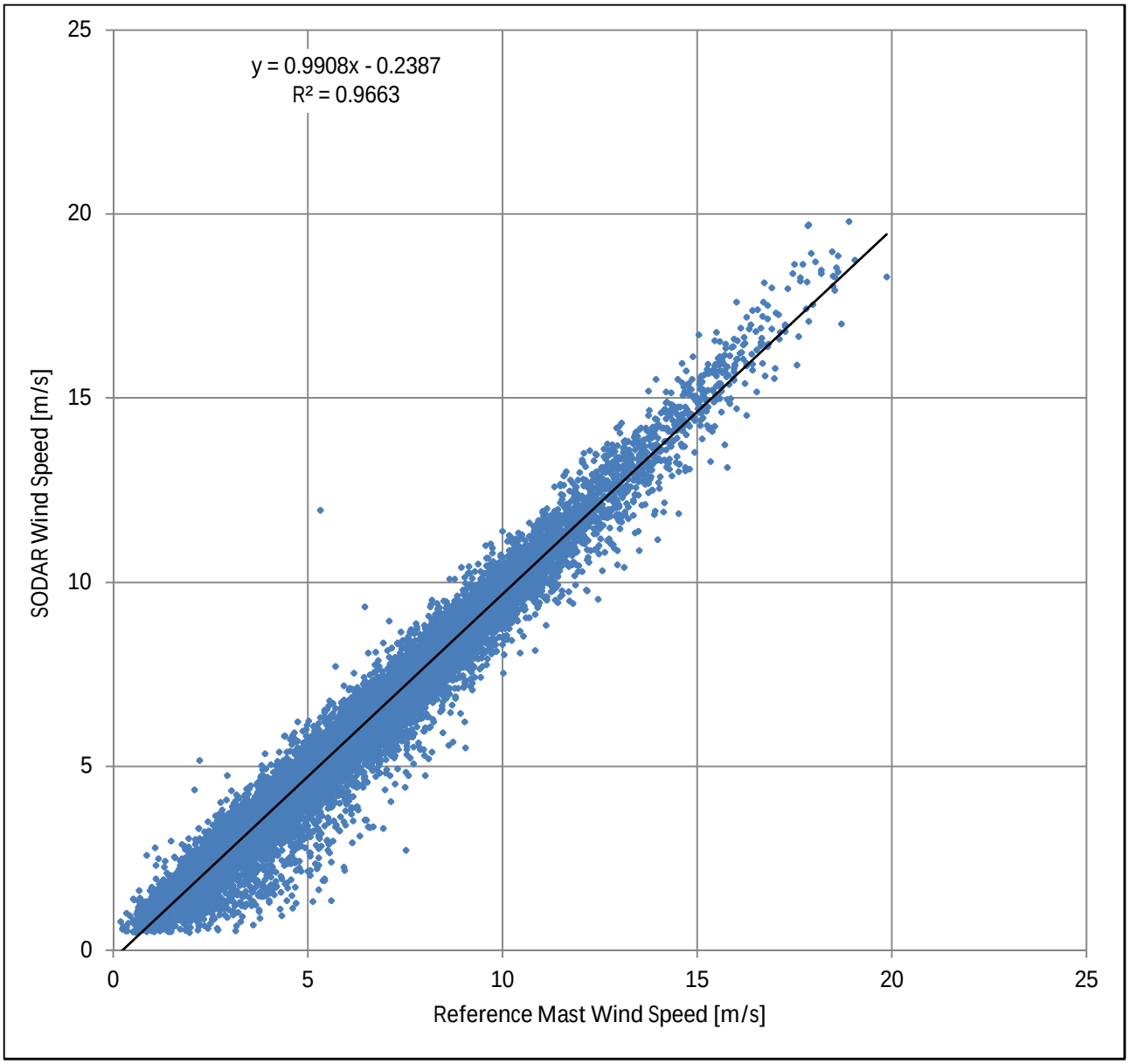

Figure 4.6 Correlation of wind speeds between 80.76 m anemometer at reference mast and 80 m Sodar level.

The error bias between the two sites has been measured and a distribution of error bias is shown in Figure 4.7.

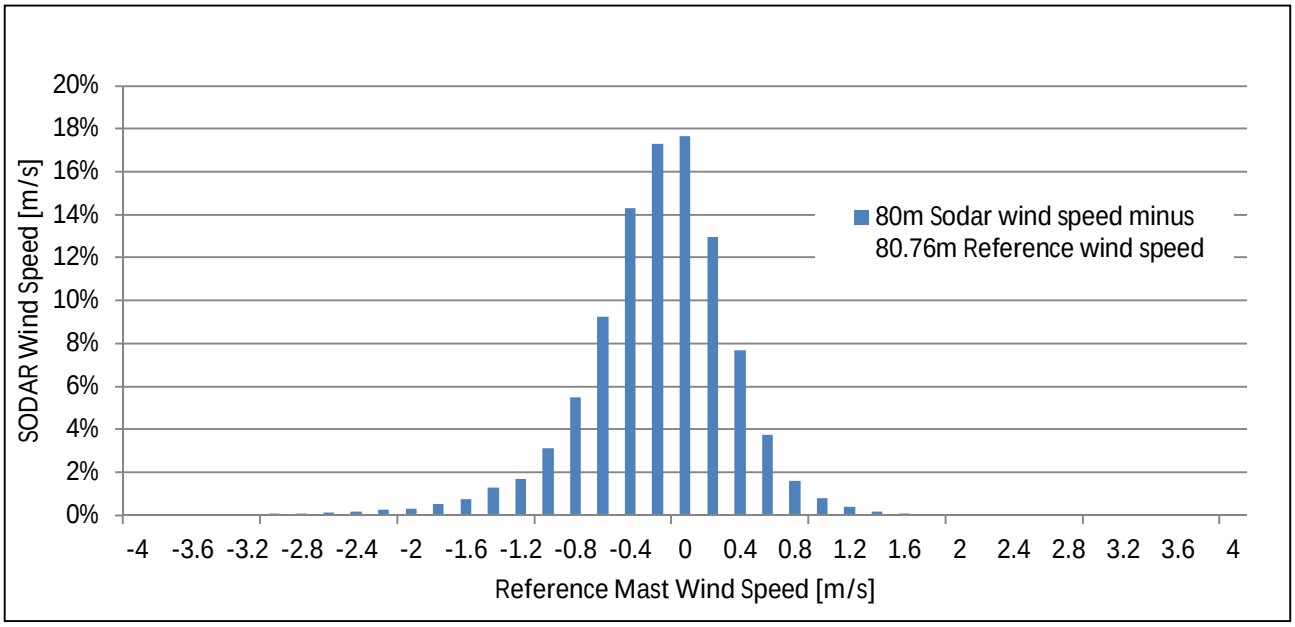

Figure 4.7 Frequency histogram for wind speed differences at 80 m (Sodar minus Reference mast)

The overall linear comparison shows that the two sites have a strong linear correlation (R^2 of 0.966) and the Sodar has a wind speed measurement bias of -4.6% (Sodar measures a lower wind speed). Further directional analysis described in Section 4.5.1 identifies that a significant flow disturbance is a possible cause or contributor to the high negative wind speed bias.

4.5.1 Directionally binned correlation

Wind speed comparisons have been undertaken for each 30 degree direction sector. Table 4.7 shows the results of this analysis in comparison to the terrain classification for corresponding direction sector.

Table 4.7 Directionally binned correlation results and IEC 61400-12-2 Terrain Class (obstacle affected sectors highlighted)

Direction Sector [Deg.]	Scale	Offset	Coefficient of Determination (R^2)	Bias [%]	Frequency of Sector [%]	Terrain Class - Reference mast	Terrain Class - Sodar
0	1.012	-0.176	0.990	-0.88	7.29	3	3
30	1.035	-0.469	0.961	-5.76	1.48	3	1
60	1.045	-0.819	0.818	-19.14	1.35	3	3
90	0.978	-0.546	0.883	-13.46	5.96	4	4
120	0.976	-0.114	0.954	-4.26	18.38	3	3
150	0.971	0.056	0.965	-1.64	5.26	3	3
180	0.981	-0.049	0.944	-3.28	2.63	3	3
210	0.977	-0.049	0.943	-3.48	2.21	3	3
240	0.992	-0.351	0.922	-7.12	4.61	3	3
270	0.962	-0.251	0.945	-7.35	16.35	3	4
300	0.984	-0.205	0.972	-4.47	19.48	3	3
330	0.979	0.017	0.982	-1.85	15.00	3	2

All direction sectors show a high level of correlation with R^2 values above 0.943, with the exception of three direction sectors from 60 to 90, and 240 degrees (highlighted in Table 4.7). An analysis of satellite imagery shows that sectors from 60 to 90 and 240 degrees have significant vegetation obstacles (trees) surrounding

the Sodar which are not present at the reference mast location. It is possible that these obstacles may be causing flow differences between the two sites and causing a reduced correlation and a higher degree of bias between the datasets.

4.5.2 Diurnal analysis

Linear correlations and bias assessments have been performed on the concurrent datasets after dividing data into periods of 'Day' and 'Night'. The 'Day' period includes data between the hours of 6 am to 8 pm and the 'Night' period includes data from the remaining hours of the day. The results of this diurnal assessment are shown below.

Table 4.8 Correlation results for 'Day' and 'Night' periods

Item		Day	Night
Line of Best fit	Scale (m)	0.985	1.001
	Offset (c)	-0.190	-0.317
Coefficient of determination (R^2)		0.965	0.969
Bias (Sodar minus Reference) (%)		-4.4	-4.9

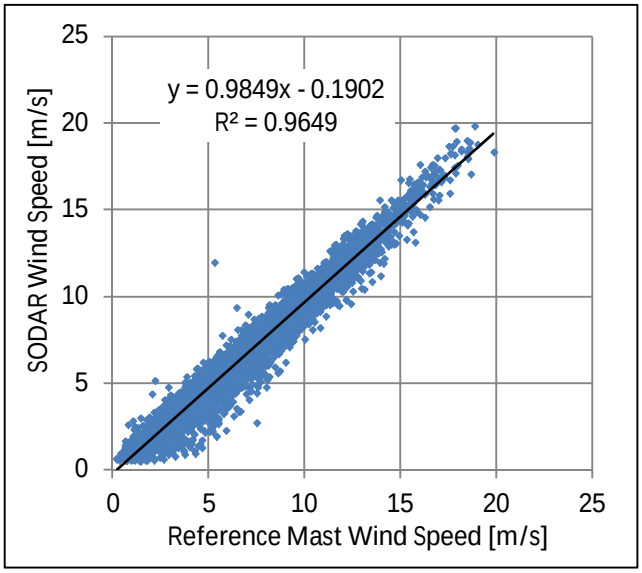

Figure 4.8 Correlation of wind speeds between 80.76 m anemometer at reference mast and 80 m Sodar level for Day time periods.

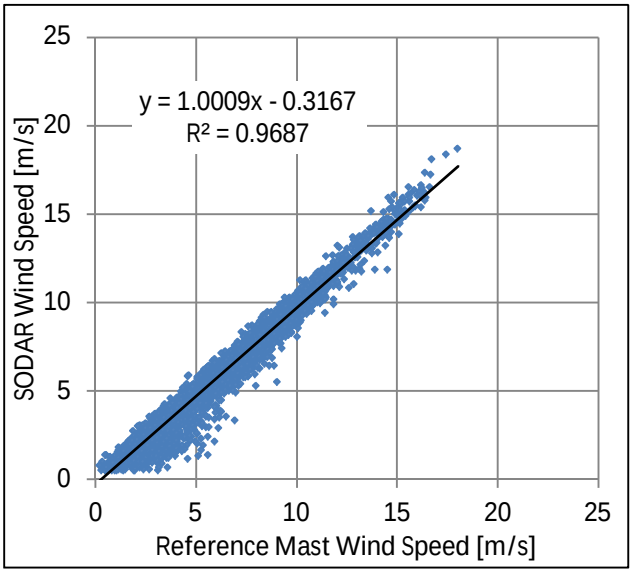

Figure 4.9 Correlation of wind speeds between 80.76 m anemometer at reference mast and 80 m Sodar level for Night time periods

The diurnal analysis shows limited variation between 'Day' and 'Night' periods of measurement. The R^2 values and bias of the two periods are in general agreement and no significant diurnal variation is observable. A histogram of wind speed difference for 'Day' and 'Night' periods is shown in Figure 4.10.

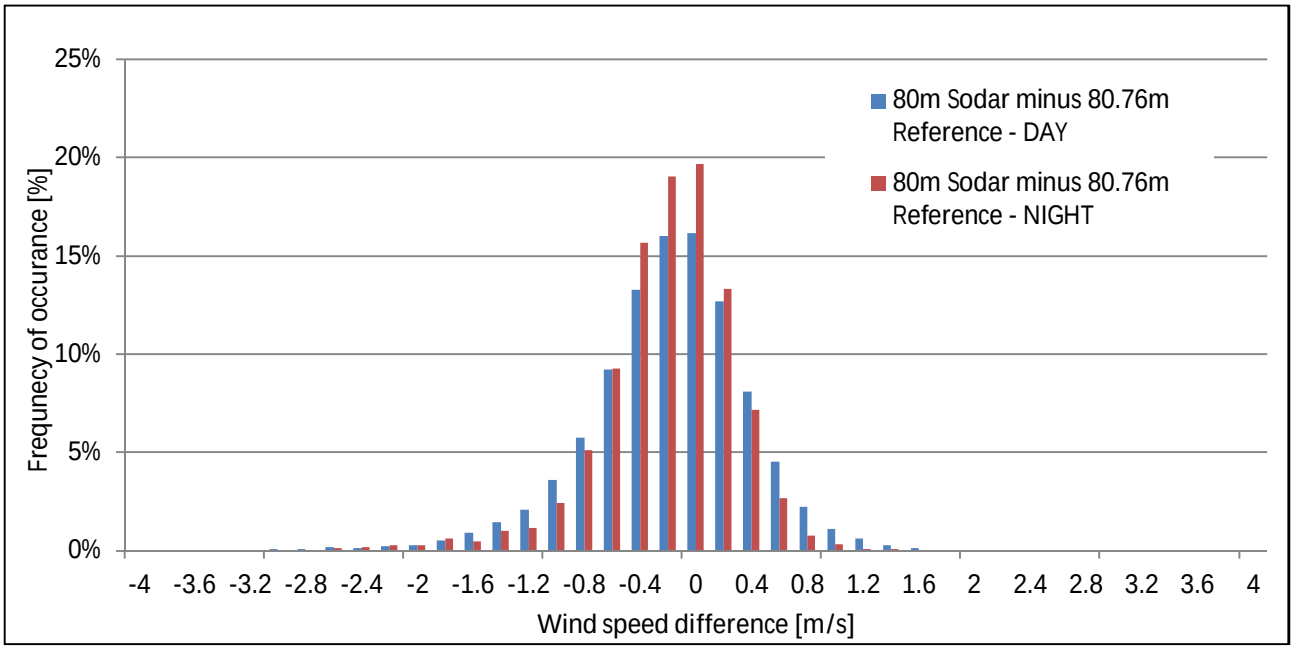

Figure 4.10 Frequency histogram for wind speed differences (Sodar minus Reference) for Day and Night periods

4.5.3 Wind direction

A comparison of wind directions between the reference mast and Sodar is shown in Figure 4.11. This figure shows that the comparative wind directions experience a strong correlation with an R^2 value of 0.988.

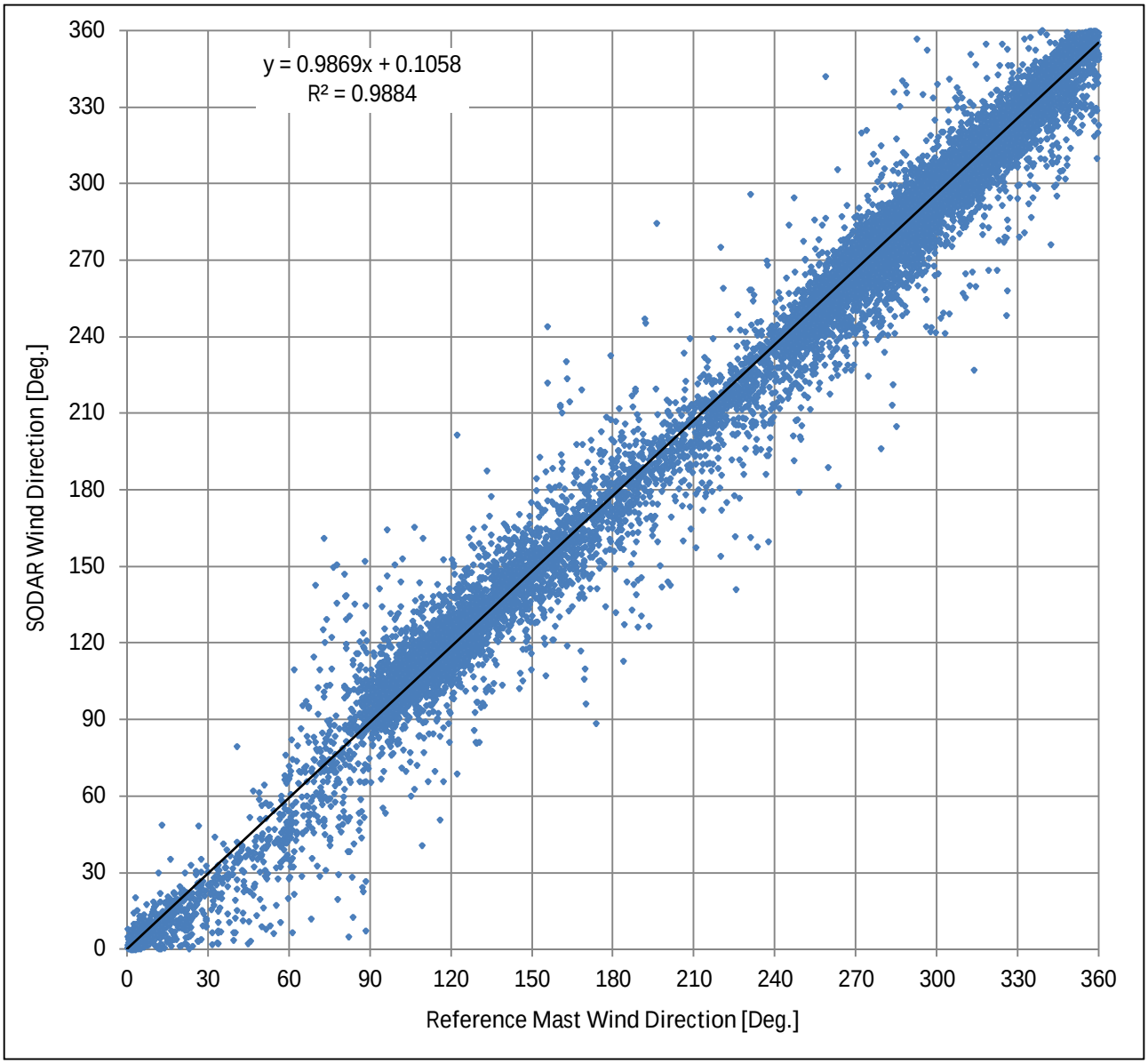

Figure 4.11 Correlation of wind directions between the 50.76 m reference mast direction vane and the 80 m Sodar level.

4.6 Wind shear

Parsons Brinckerhoff has performed an analysis of wind shear using concurrent data sets of all wind speeds and directions at multiple heights for each data source. By using concurrent datasets between all instruments, the total availability of data is reduced, which is mainly due to the Sodar measurement levels with below average data availability. However, after reducing to concurrent datasets, equivalency in the measured conditions is achieved at both the reference mast and the Sodar and wind shear profiles can be compared. This concurrent dataset includes Sodar wind speeds measured between 60 m and 110 m to achieve a balance between evaluating the wind shear profile with height and achieving acceptable data availability; all other levels were deemed to have recorded insufficient data for concurrent analysis. A summary of the data used in the shear analysis is described Table 4.9.

Table 4.9 Site B wind shear analysis data summary

Reference Mast			Sodar			Total recovery rate of concurrent data
Anemometer Height [m]	Average of concurrent wind speed [m/s]	Average concurrent shear exponent (α)	Measurement Height [m]	Average of concurrent wind speed [m/s]	Average concurrent shear exponent (α)	
36.0	5.5	0.18	60	5.6	0.12	52.6%
50.8	5.7		70	6.0		
66.0	6.0		80	6.1		
80.8 (composite)	6.3		90	6.1		
			100	6.0		
			110	6.2		

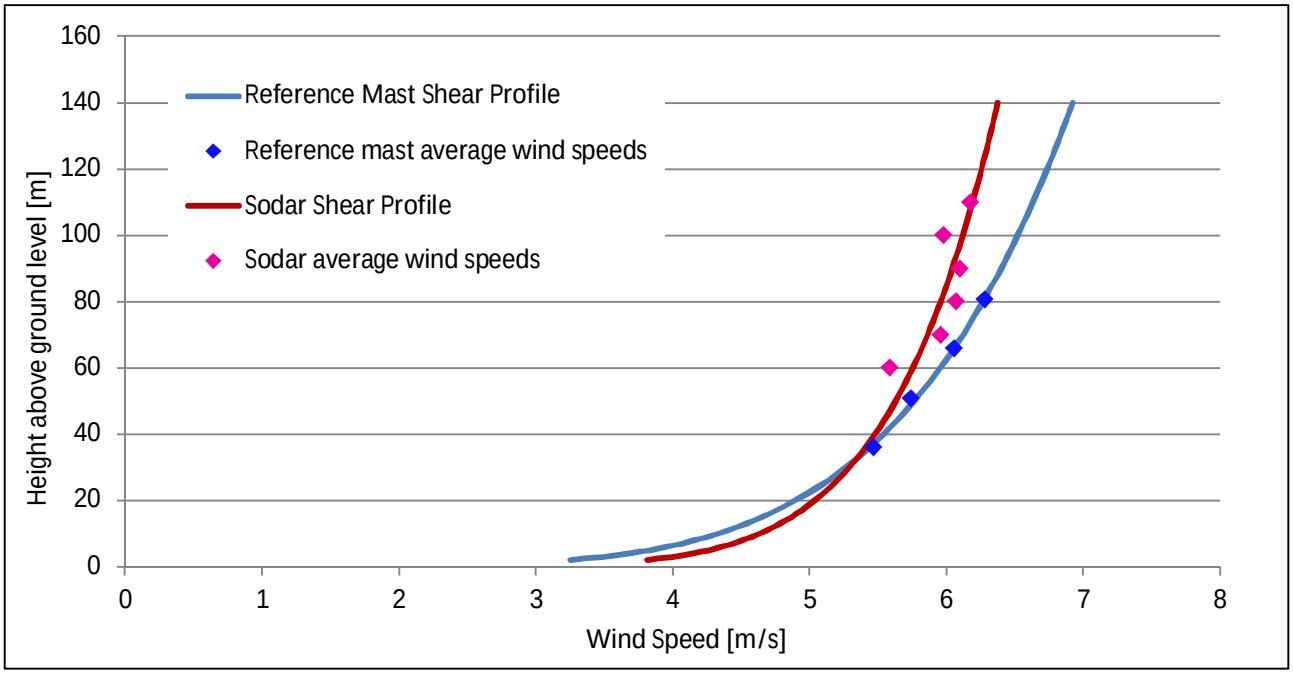

Figure 4.12 Comparison of Site B wind shear profiles and average wind speeds for concurrent periods of measurement.

The wind shear profiles of the two data sources are noticeably different. Additionally, the Sodar shows a significant deviation from a power law shear profile. The difference in wind shear may be caused by many factors including localised site variations between the Sodar location and the reference mast location, the poor availability of concurrent data across all measurement levels, or it may be the result of measurement variability and accuracy from one or both data sources. Further assessment of the validity of the datasets, or the wind shear profile, is not within Parsons Brinckerhoff's scope of work.

5. Site C

The third location provided by Fulcrum 3D for evaluation is known as Site C, located near Adelaide in South Australia. Fulcrum 3D has measured concurrent data between a Sodar unit (FS1M_1019) and a permanent 80 m lattice mast, and data has been provided to Parsons Brinckerhoff for analysis of equivalency. The Sodar has been located 144 m south of the permanent reference mast. The site is considered simple and the surrounding terrain and vegetation is very flat with minimal disturbances.

Table 5.1 shows the details of the mast, and Figure 5.1 and Figure 5.2 show the terrain and location of the mast with respect to the Sodar.

Table 5.1 Reference mast and Sodar elevations and duration of measurements

	Elevation
Reference mast	10 mASL
Sodar	10 mASL
Period of concurrent measurement	
Start Date	26 September 2013
End Date	14 November 2013
Duration	49 days

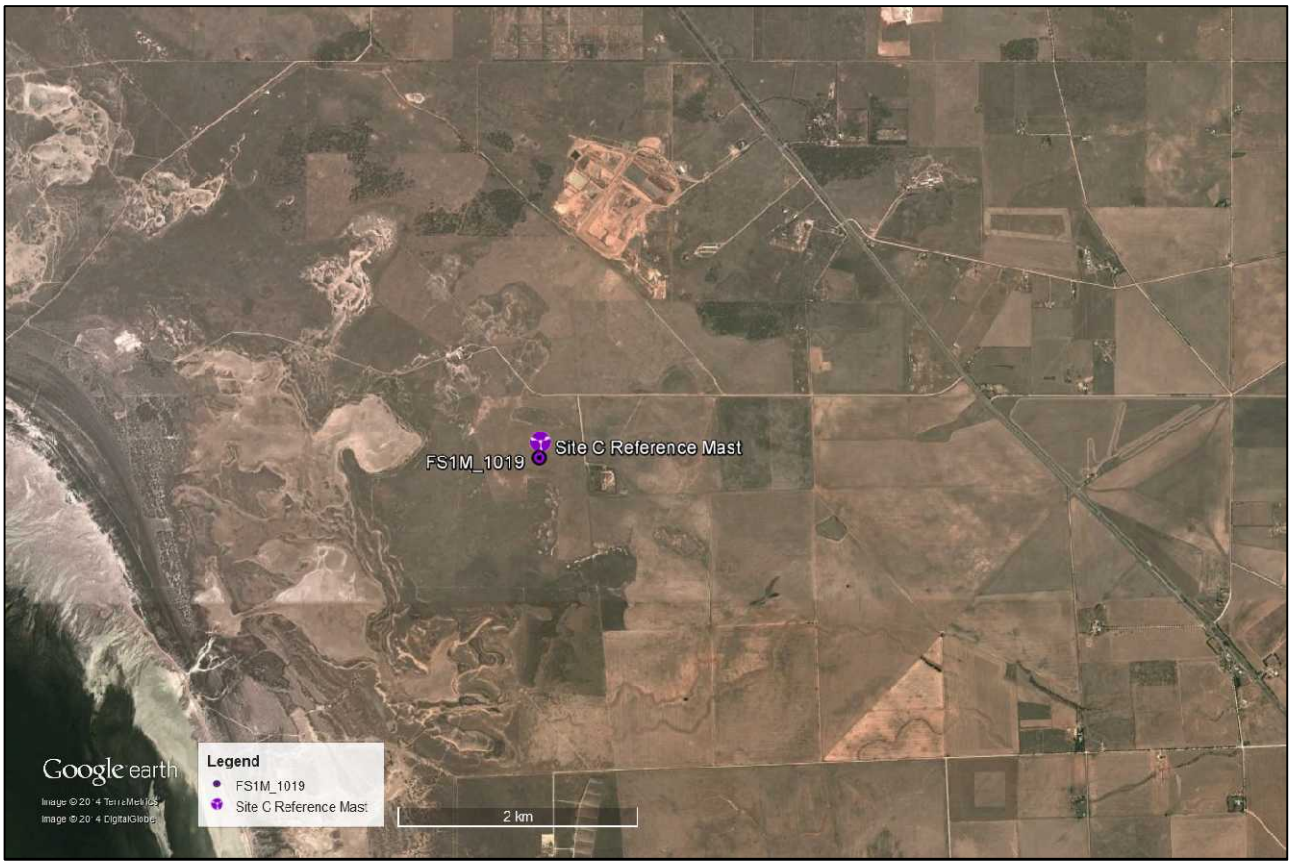

Figure 5.1 Location of reference mast and SODAR (far)

Figure 5.2 Location of reference mast and SODAR (near)

5.1 Terrain analysis

The surrounding terrain to the reference mast and Sodar consists of very low lying grassland and exposed soil (seasonal) with little to no vegetation or obstacles present. The surrounding terrain is estimated to have a roughness class of approximately 1 (roughness height, z_o of 0.03 m). In areas approximately 150 m north of the reference mast and 170 m south of the Sodar, there are pockets of vegetation plantation, consisting of low lying shrubs, estimated to be 1 mAGL in height.

5.1.1 Sector based terrain classification

The terrain complexity surrounding Site C reference mast and Sodar has been evaluated using the procedure described in Section 2.1. The results of the terrain analysis are shown below for 30 degree direction sectors surrounding both the mast and Sodar locations. Both locations consist of simple terrain and IEC 61400-12-2 terrain classes are limited to 1 (when assuming a nominal rotor and hub height of 80 m).

Table 5.2 IEC61400-12-2 terrain classification of Sodar and Reference mast locations for Site C (Assuming D+H = 160 m)

Direction Sector [deg.]	Sodar Location			Reference Mast Location		
	RIX Class	Slope Class	IEC Terrain Class	RIX Class	Slope Class	IEC Terrain Class
0	1	0	**1**	1	0	**1**
30	1	0	**1**	1	0	**1**
60	1	0	**1**	1	0	**1**
90	1	0	**1**	1	0	**1**
120	1	0	**1**	1	0	**1**
150	1	0	**1**	1	0	**1**
180	1	0	**1**	1	0	**1**
210	1	0	**1**	1	0	**1**
240	1	0	**1**	1	0	**1**
270	1	0	**1**	1	0	**1**
300	1	0	**1**	1	0	**1**
330	1	0	**1**	1	0	**1**

5.2 Reference mast data

The Site C reference mast is an 80 m lattice tower and consists of five wind speed measurements levels at approximately 82 m, 80 m, 60 m, 40 m and 10 m. Parsons Brinckerhoff has not undertaken a site visit of this mast, but has obtained an understanding of the mast configuration from the *Site C Installation Report* supplied by Fulcrum 3D [15]. Based on this report, the instrument mounting configurations appear to be broadly consistent with the guidelines of IEC 61400-12-1 Annex G [2]. Wind speeds have been measured using WindSensor P2546A anemometers, with the exception of the 80 m level which was measured using a Vector A100L2 anemometer. All anemometers were calibrated in a MEASNET accredited facility. The top level anemometer is vertically mounted and has been chosen as the primary instrument for analysis due to the minimal flow disturbance of this mounting arrangement. Subsequent analysis has shown that the lightning finial near to this instrument has affected measurements from a single direction sector (see section 5.5.1) and data modification has been performed to rectify this disturbance (as described in Table 5.3). The location of this reference mast was not documented in the installation and commissioning report; however, Parsons Brinckerhoff has been provided a map *Mast_Sodar_Locations_point* [16] which contains the coordinates of the mast and Sodar.

Fulcrum 3D has provided the reference mast data in a processed form with instrumentation calibrations applied. Parsons Brinkerhoff has not verified that the supplied data has appropriate calibrations applied to the raw data, however the data has been cleaned and adjusted as described in Table 5.3. As directed by Fulcrum 3D, Parsons Brinckerhoff has applied a time offset of 10 minutes to the reference data to account for logger clock drift.

Table 5.3 Data quality checking procedures for reference mast data

Step	Quality check	Outcome/Result	Actions taken
1	10 minute time offset observed	Poor correlation	Adjusted reference data timestamp by +10 minutes
2	Erroneous sample check	Two rows of data found to be erroneous for all wind speeds	Wind speed samples removed 24/08/2013 5:00 – 5:10
3	Erroneous sample check	S4 wind speed recording 0 reading for entire measurement period	S4 wind speed omitted from analysis

Step	Quality check	Outcome/Result	Actions taken
4	S1/S2 Sheltering analysis	S1 sheltered by lightning finial between 44 and 75 degrees	S2 data substituted for S1 data for wind directions between 44 and 75 degrees
5	S2, S3 and S5 Sheltering analysis	All lower level wind speeds found to be significantly sheltered for wind directions between 85 and 111 degrees	S2, S3 and S5 wind speeds removed for wind directions between 85 and 111 degrees (428 samples)

Table 5.4 Reference mast cleaned data summary

Recording period	Date		Time		
Start	15/08/2013		13:10		
Finish	15/11/2013		13:10		
Wind statistics					
Instrument	S1	S2	S3	S4	S5
Height above ground level [mAGL]	82.0	80.3	60.0	40.0	10.0
Recovery rate [%]	100	96.7	96.8	0	96.8
Average wind speed [m/s]	8.5	8.5	8.2	-	5.7
Maximum 10 minute average wind speed [m/s]	26.9	26.8	26.3	-	21.7

No data has been provided for the 40 mAGL anemometer and this instrument was not considered further.

5.3 Sodar data

Fulcrum 3D has provided pre-processed Sodar data .csv format [9]. Data has been pre-processed using Fulcrum 3D's software Version 3.3 and data is supplied with status flags for signal quality, processing quality and consistency checking. Parsons Brinkerhoff has removed any data that has an associated signal flag of zero (0) for Signal Quality (F1_v01), Processing Quality (F2_v01) or Consistency Check (F3_v01), and any missing data flags (-999) as recommended by Fulcrum 3D in the document *Sodar Performance Verification Note – Version 3.3* [21].

A consistent wind direction offset was observed between the Sodar and mast data provided following an initial comparison. It is expected that this offset may be due to setup and configuration error from factors such as magnetic declination and vane orientation which may not have been accurately documented. Parsons Brinckerhoff has adjusted the Sodar wind direction by applying a consistent offset of -13.5 degrees to remove the mean offset of wind direction data. Table 5.5 summarises the Site C Sodar data analysed.

Table 5.5 Sodar cleaned data summary

Recording period	Date					Time				
Start	26/09/2013					12:10				
Finish	15/11/2013					0:00				
Wind statistics										
Height above ground level [m]	60	70	80	90	100	110	120	130	140	150
Recovery rate [%]	90.2	89.2	88.1	86.7	85.2	81.9	77.0	65.2	58.3	54.2
Average wind speed [m/s]	8.7	9.0	9.1	9.0	9.2	9.2	9.3	9.1	7.6	8.2
Maximum mean wind speed [m/s]	27.5	27.0	29.4	28.5	24.2	25.9	23.7	24.3	23.4	24.8

5.4 Time series comparison

As a first stage evaluation, the times series of the concurrent datasets have been analysed to identify any unusual anomalies and to verify the appropriateness of the previous data manipulation steps. For Site C, the primary data analysis has been performed using a Sodar measurement height of 80 m and the 82 m wind speed measurement level of the reference mast; since the top level anemometer has the least tower induced flow disturbance. For wind parameters such as wind shear, additional heights have been compared between the two data sets.

The following figures show that the wind speed, direction and standard deviation datasets are in general agreement and that obvious data anomalies are not present.

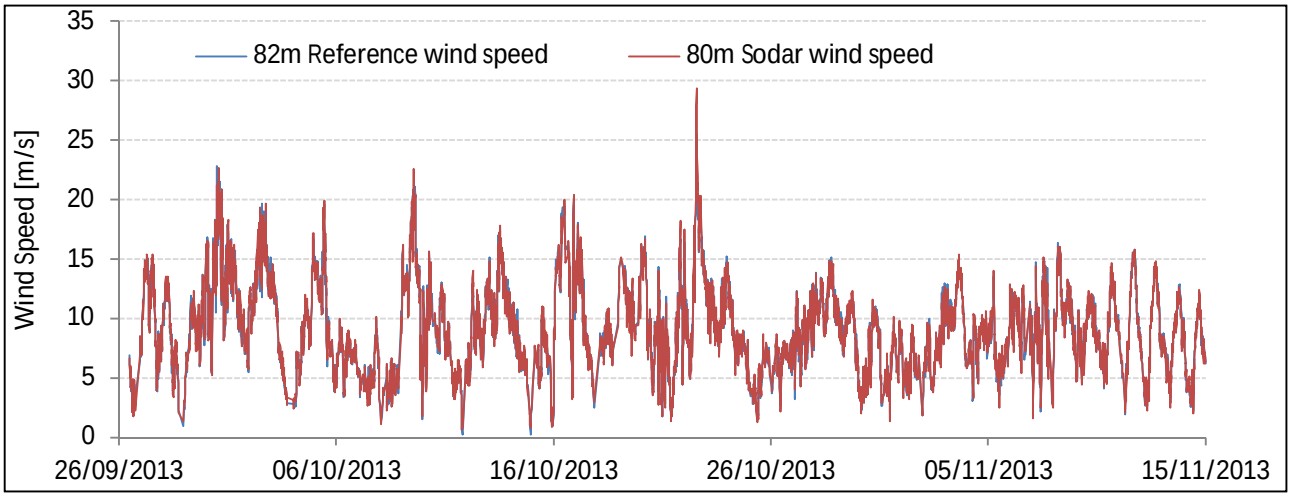

Figure 5.3 Comparison of time series wind speed at 80 m

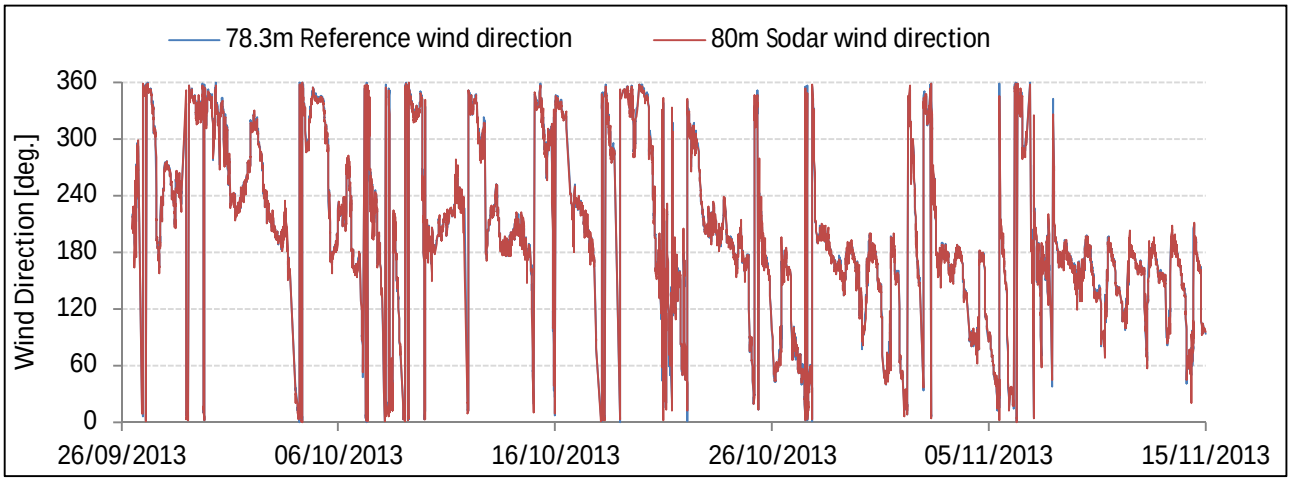

Figure 5.4 Comparison of time series wind direction at 80 m

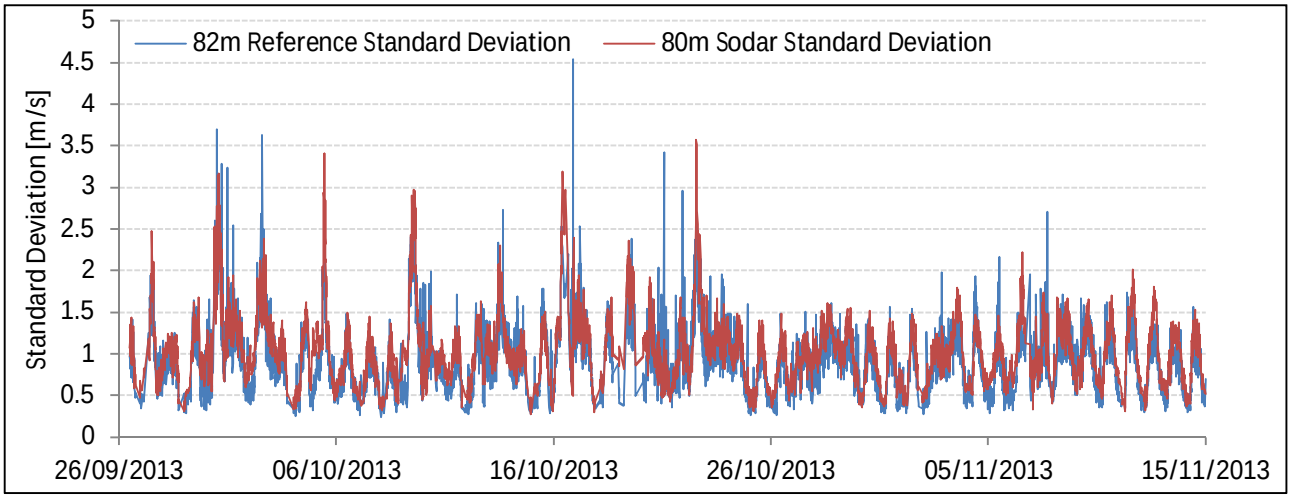

Figure 5.5 Comparison of time series wind speed standard deviation at 80 m

5.5 Correlations

The results of the straight line correlation between the two datasets at the nominal measurement height are shown below for the nominal measurement height of 80 m. At Fulcrum 3D's request, an additional correlation

has been performed for a secondary height of 60 m since the reference mast at Site C offers additional data that can be compared against the equivalent Sodar measurement height. The correlation analyses results are described in Table 5.6.

Table 5.6 Correlation results of reference mast wind speed with Sodar wind speed at 80 m and 60 m

Item		80 m Result	60 m Result
Line of Best fit	Scale (m)	0.984	0.994
	Offset (c)	0.147	0.032
Coefficient of determination (R^2)		0.975	0.971
Bias (Sodar minus Reference) (%)		0.0	-0.2

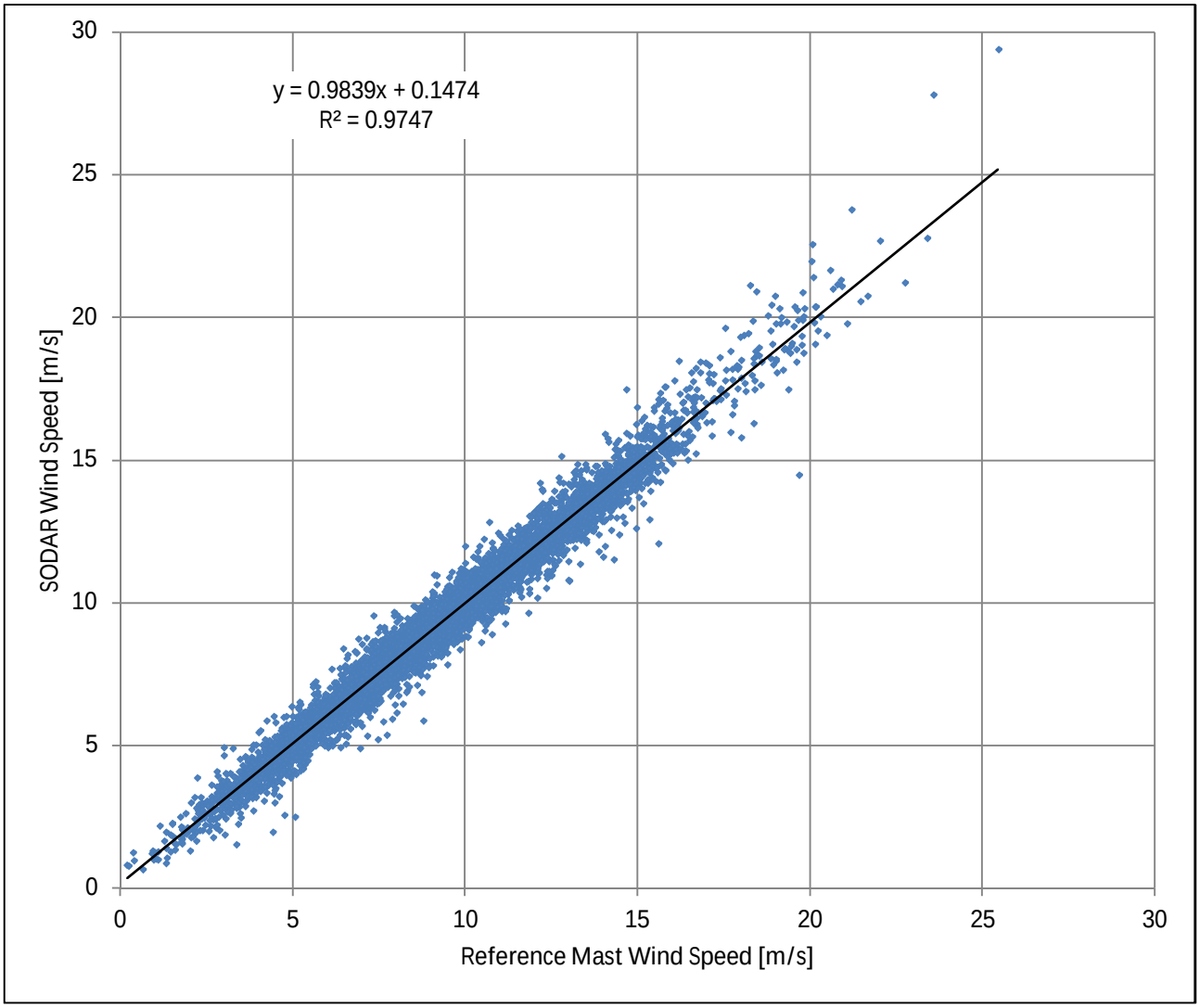

Figure 5.6 Correlation of wind speeds between 82 m anemometer at reference mast and 80 m Sodar level.

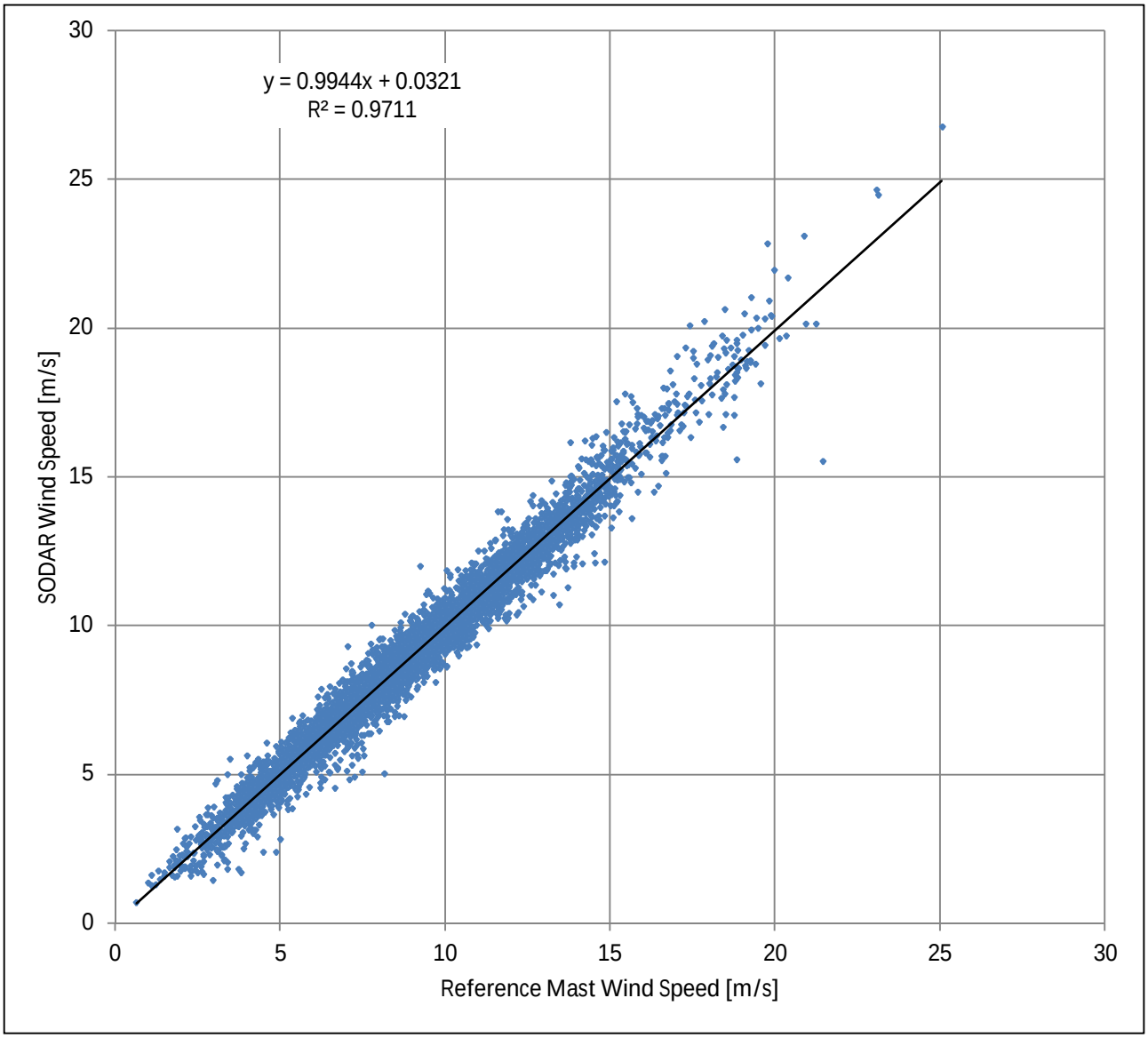

Figure 5.7 Correlation of wind speeds between 60 m anemometer at reference mast and 60 m Sodar level.

The error bias between the two sites, at the two heights have been measured and a distribution of error bias is shown in Figure 5.8 and

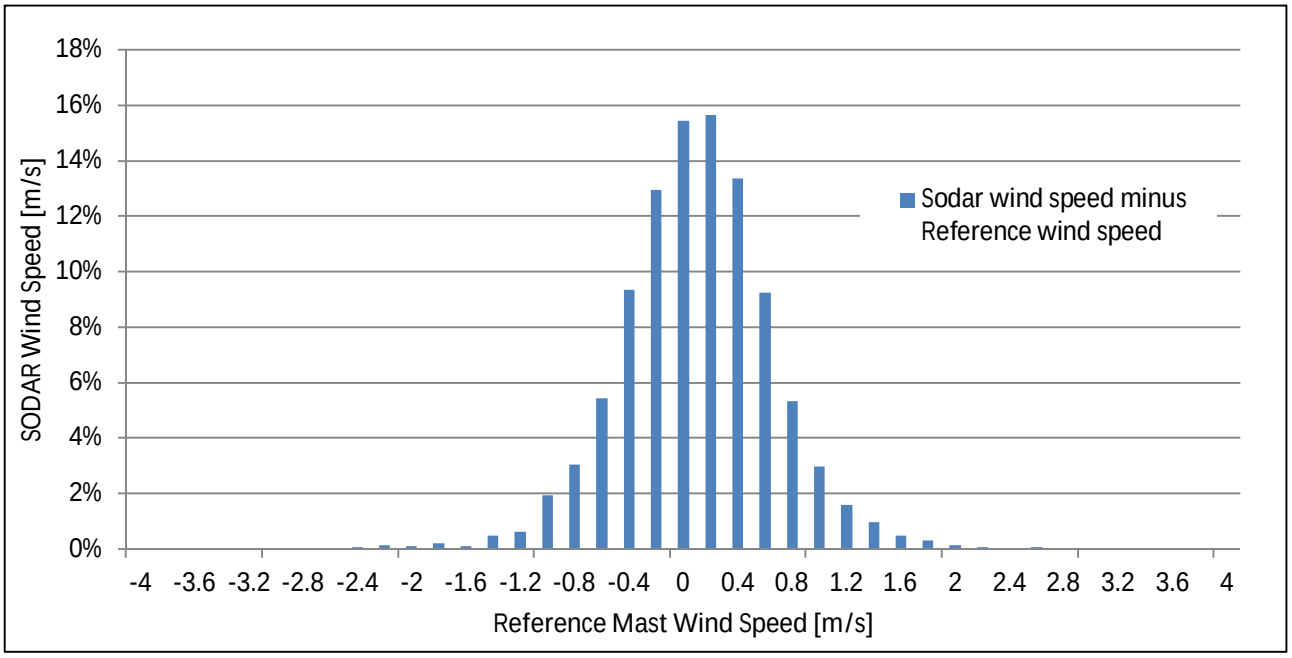

Figure 5.8 Frequency histogram for wind speed differences at 80 m (Sodar minus Reference mast)

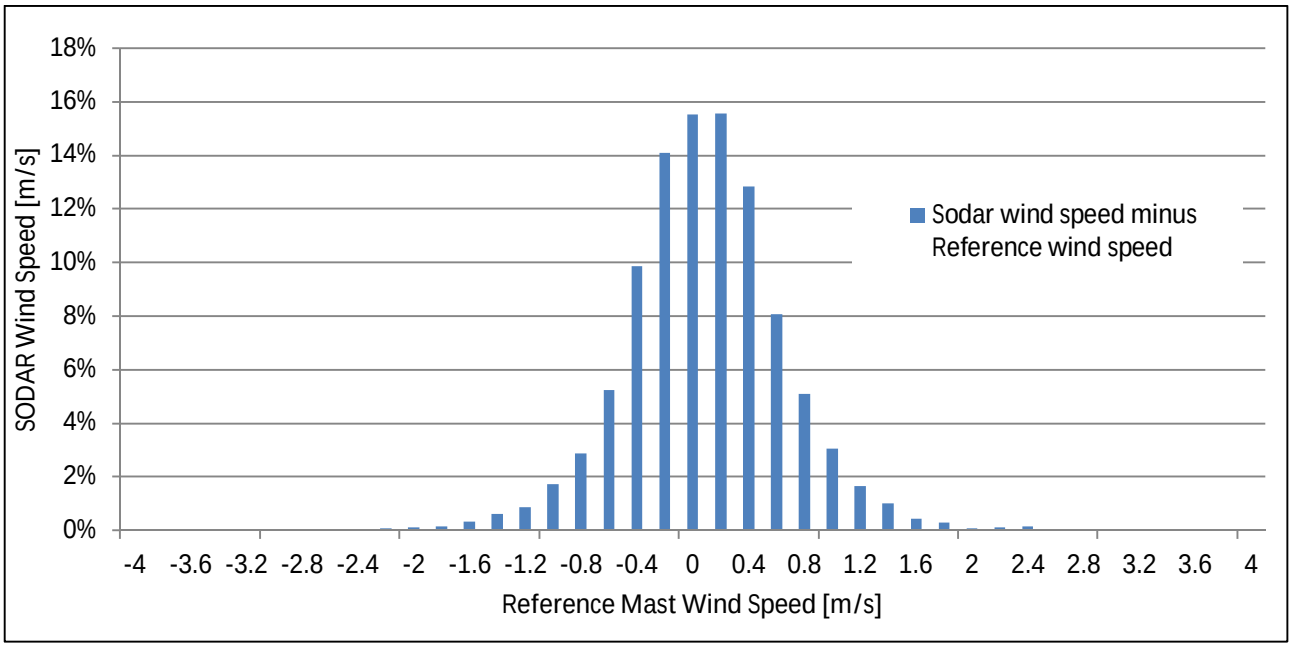

Figure 5.9 Frequency histogram for wind speed differences at 60 m (Sodar minus Reference mast)

The overall linear comparison shows that the two sites have a strong linear correlation (R^2 of 0.975 at 80 m and 0.971 at 60 m) and the Sodar has a negligible wind speed bias of 0.0% at 80 m and -0.2% at 60 m.

5.5.1 Directionally binned correlation

Wind speed comparisons have been undertaken for each 30 degree direction sector. Table 5.7 shows the results of this analysis in comparison to the terrain classification for corresponding direction sector.

Table 5.7 Directionally binned correlation results and IEC 61400-12-2 Terrain Class (highlight cells are assumed to be affected by lightning finial sheltering)

Direction Sector [Deg.]	Scale	Offset	Coefficient of Determination (R^2)	Bias [%]	Frequency of Sector [%]	Terrain Class - Reference mast	Terrain Class - Sodar
0	0.969	0.146	0.984	-1.65	7.61	1	1
30	0.960	0.346	0.972	1.35	2.70	1	1
60	1.028	0.031	0.979	3.22	4.20	1	1
90	0.967	0.288	0.950	1.39	4.57	1	1
120	0.967	0.228	0.956	0.66	3.10	1	1
150	0.963	0.255	0.961	-0.51	11.55	1	1
180	0.976	0.177	0.968	-0.62	24.74	1	1
210	0.979	0.102	0.970	-1.04	13.70	1	1
240	0.989	0.209	0.979	1.09	7.93	1	1
270	1.046	-0.121	0.974	3.34	3.59	1	1
300	1.023	0.052	0.959	2.83	5.85	1	1
330	0.981	0.140	0.980	-0.64	10.46	1	1

It can be seen that all direction sectors show a high level of correlation with R^2 values above 0.95 and minimal variation in bias for each 30 degree sector.

5.5.2 Diurnal analysis

Linear correlations and bias assessments have been performed on the concurrent datasets after dividing data into periods of 'Day' and 'Night'. The 'Day' period includes data between the hours of 6 am to 8 pm and the 'Night' period includes data from the remaining hours of the day. The results of this diurnal assessment are shown below.

Table 5.8 Correlation results for 'Day' and 'Night' periods

Item		Day	Night
Line of Best fit	Scale (m)	0.993	0.969
	Offset (c)	0.099	0.243
Coefficient of determination (R^2)		0.973	0.979
Bias (Sodar minus Reference) (%)		0.3	-0.5

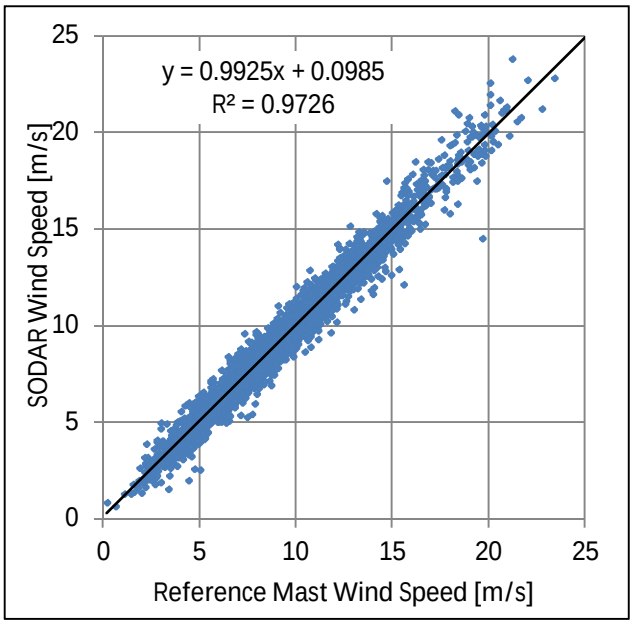

Figure 5.10 Correlation of wind speeds between 82 m anemometer at reference mast and 80 m Sodar level for Day time periods.

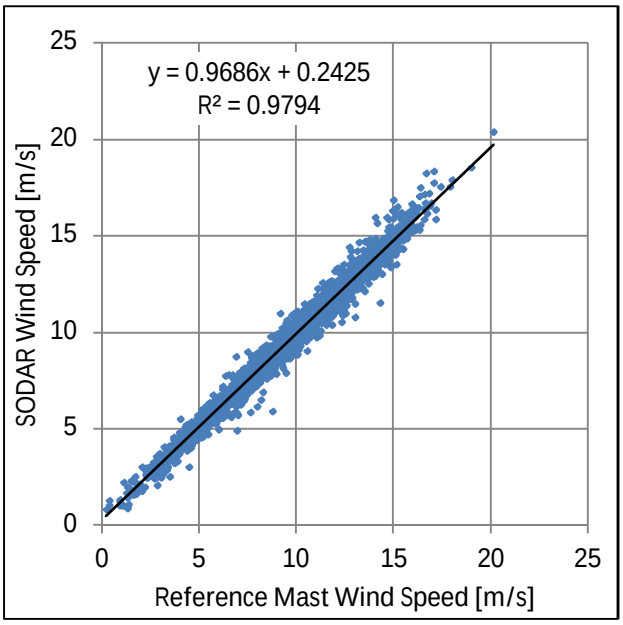

Figure 5.11 Correlation of wind speeds between 82 m anemometer at reference mast and 80 m Sodar level for Night time periods.

The diurnal analysis shows limited variation between 'Day' and 'Night' periods of measurement. The R^2 values and bias of the two periods are in general agreement and no significant diurnal variation is observable. A histogram of wind speed difference for 'Day' and 'Night' is shown in Figure 5.12.

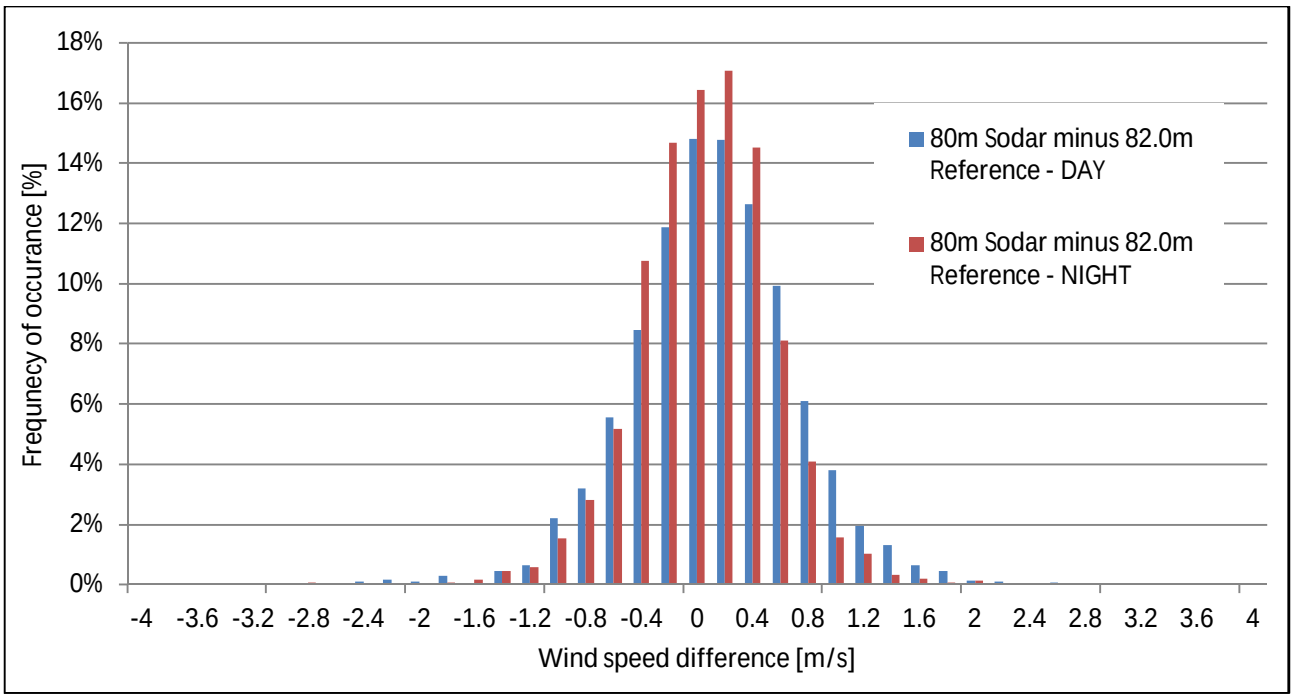

Figure 5.12 Correlation of wind speeds between 82.0 m anemometer at reference mast and 80 m Sodar level for Day and Night time periods

5.5.3 Wind direction

A comparison of wind directions between the reference mast and Sodar is shown in Figure 5.13. This figure shows that the comparative wind directions experience a strong correlation with an R^2 value of 0.995.

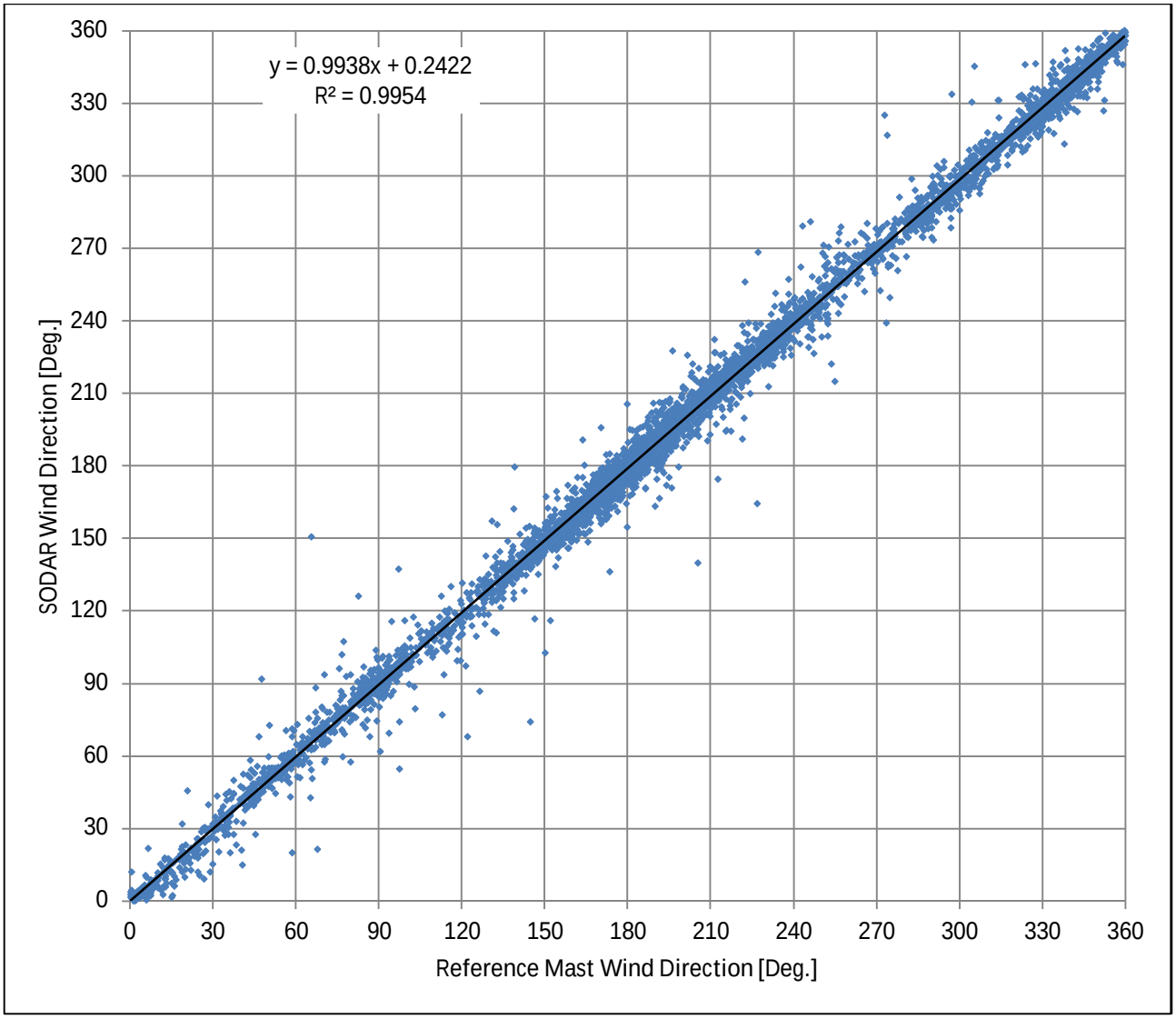

Figure 5.13 Correlation of wind directions between the 78.3 m reference mast direction vane and the 80 m Sodar level.

5.6 Wind shear

Parsons Brinckerhoff has performed an analysis of wind shear using concurrent data sets of all wind speeds and directions at multiple heights for each data source. By using concurrent datasets between all instruments, the total availability of data is reduced, which is mainly due to the Sodar measurement levels with below average data availability. However, after reducing to concurrent datasets, equivalency in the measured conditions is achieved at both the reference mast and the Sodar and wind shear profiles can be compared. This concurrent dataset includes Sodar wind speeds measured between 60 m and 110 m to achieve a balance between evaluating the wind shear profile with height and achieving acceptable data availability; all other levels were deemed to have recorded insufficient data for concurrent analysis. A summary of the data used in the shear analysis is described Table 5.9.

Table 5.9 Site C wind shear analysis data summary

Reference Mast			Sodar			Total recovery rate of concurrent data
Anemometer Height [m]	Average of concurrent wind speed [m/s]	Average concurrent shear exponent (α)	Measurement Height [m]	Average of concurrent wind speed [m/s]	Average concurrent shear exponent (α)	
10	6.6	0.14	60	8.7	0.14	87.7%
40	-		70	8.9		
60	8.8		80	9.1		
80.3	9.1		90	9.2		
82	9.1		100	9.3		
			110	9.5		

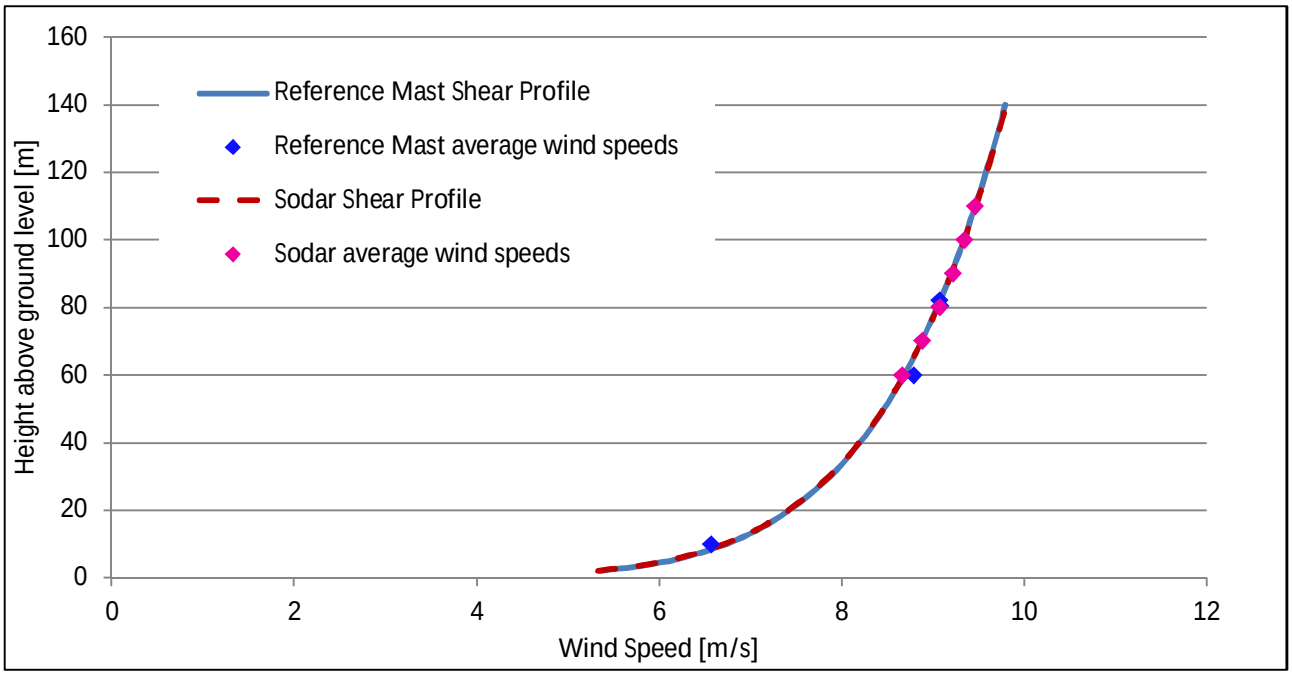

Figure 5.14 Comparison of wind shear profiles and average wind speeds for concurrent periods of measurement.

The power law wind shear profiles of the two data sources are near identical and show high agreement for the concurrent period of measurement.

6. Conclusions

Statistical analyses of concurrent wind data between three Fulcrum 3D Sodars and nearby reference masts have been undertaken for complex and simple terrains. The Sodar data analysed has been pre-processed using the Fulcrum 3D software version 3.3. The results of the analyses have been documented in this report and the following conclusions are made:

1. Comparison of the three disparate sites found that the Fulcrum 3D Sodars and the respective reference masts achieved linear Coefficients of Determination, R^2 values ranging from 0.966 to 0.975.
2. The average wind speed bias for Site A and Site C varies from -2.6% to 0.0%.
3. Site B achieved an average wind speed bias of -4.6%. It is likely that Site B experienced significant flow distortion contributing to the higher negative bias.
4. Site A and Site B have IEC 61400-12-2 terrain classes ranging from 2 to 5 (complex terrain) and direction sectors were found to achieve R^2 values ranging between 0.943 and 0.990 when excluding direction sectors that are likely affected by flow disturbance.
5. Site C has an IEC 61400-12-2 terrain class of 1 (simple terrain) for all direction sectors and direction sectors were found to achieve R^2 values ranging between 0.950 and 0.984.
6. Diurnal analysis of the three sites showed no significant bias in 'Day' or 'Night' periods.
7. Comparison of wind directions shows that the Sodars and the respective reference masts achieved R^2 values ranging from 0.988 to 0.996 and all three sites had some amount of wind direction offset, which is likely the result of human error in misalignment of wind vanes, documentation of magnetic declination or the orientation of the Sodars. This is not necessarily an indication of underperformance by the Sodars.
8. Site A shows general agreement in wind shear profiles and the minor difference is expected to be within the uncertainty bounds of the reference mast.
9. Site B shows noticeably different wind shear profiles between the Sodar and the reference mast. The cause of this difference is not immediately obvious and may be due to localised site conditions, measurement error and inaccuracy, or poor availability of concurrent data across all relevant heights. It is not within Parsons Brinckerhoff's scope to investigate the cause of this discrepancy.
10. The Site C wind shear profiles from the Sodar and reference mast are near identical and show strong agreement.

Based on the findings of these analyses, Parsons Brinckerhoff concludes that the Fulcrum 3D Sodars using software version 3.3, have measured comparative data to reference masts in simple and complex terrains at the nominal heights of 60, 70 and 80 mAGL.

Although linear deviations and bias were minimal, it is expected that improvements in correlation results and reduced bias in data would be achieved if flow disturbances from site obstacles were not present in the data.

7. References

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