A Comparison of Remote Sensing Device Performance at Rotsea

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Approved: Jeremy Bass Signed Electronically: 09-Feb-2011

Revision History

Issue	Date	Author	Nature And Location Of Change
01	30 Sep 2010	Iain Campbell	First Created
02	01 Dec 2010	Iain Campbell	Various small revisions
03	31 Jan 2011	Iain Campbell	Final small revisions
04	08 Feb 2011	Iain Campbell	Final small revisions

CONTENTS

1 INTRODUCTION

Remote sensing devices have the potential to provide reliable wind data at numerous heights and locations to an extent which would be prohibitively expensive using conventional tubular or lattice meteorological masts.

There is, however, some uncertainty as to how well data captured by remote sensing devices correlate with fixed mast instrumentation. Therefore, it is important to first understand and quantify the accuracy, uncertainty and limitations associated with these devices.

In June 2010 RES had the opportunity to locate both a LiDAR and SoDAR remote sensing device at its Rotsea site. This opportunity provided a four week window where data were simultaneously available from each of the M345 - fixed mast, the M808 - Triton (SoDAR device by SecondWind) and the M809 - WINDCUBE (LiDAR device by LEOSPHERE).

This report sets out what data were available, how these data were used and to what extent the devices were in agreement with the fixed mast and with each other.

1.1 Site Description

Rotsea was used for this comparison due to its terrain. There are some clusters of trees surrounding the site at varying distances. The Rotsea site, however, is flat and generally uncomplicated. The following drawing [1] shows the site and its surroundings including the positions of the fixed mast and the remote sensing devices.

1.2 Device Locations

For the comparison, the remote sensing devices were co-located. The devices were located at the following positions:

1. Site assessment fixed mast (505812, 451512)

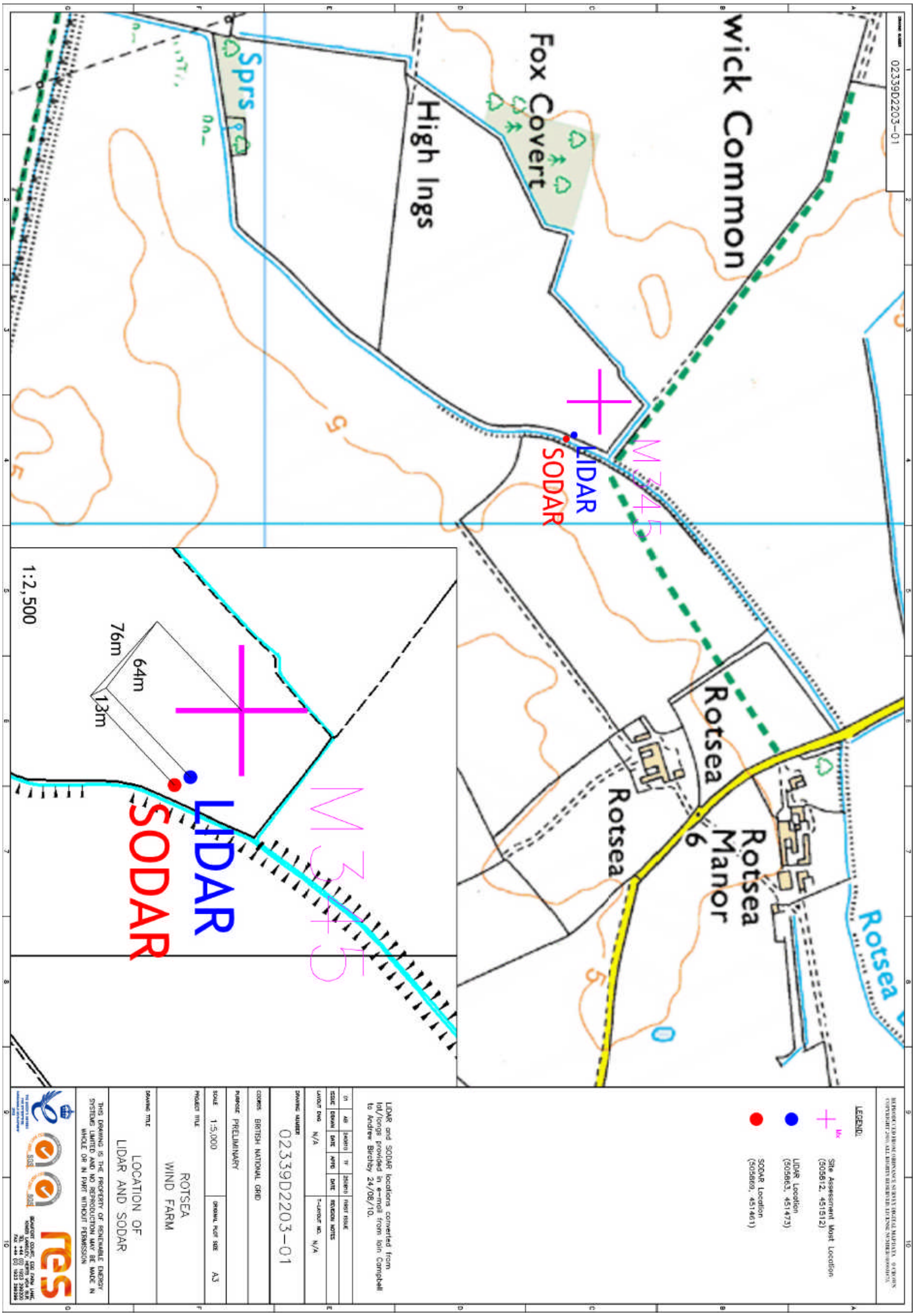
2. Triton SoDAR device (505869, 451461)

3. WINDCUBE LiDAR device (505863, 451473)

The WINDCUBE and Triton were separated by 13m from each other and 64m and 76m[1] respectively from the fixed mast.

While the two remote sensing devices are not at the exact same location as the fixed mast, the R^2 values achieved will suggest that there is no significant variation of the wind flow between these locations. The devices themselves are only separated by 13m and should therefore be observing almost identical wind flow.

[1] “The minimum distance between the tower and Triton should be approximately 1 times the height of the tower” [2]. At Rotsea, the Triton was located ~4m within the 1 mast height distance.



Wick Common
Fox Covert
High Ings
Sprs
Rotsea
Rotsea Manor
LIDAR
SODAR
M345
1:2,500
76m
64m
13m
LEGEND:
Site Assessment Mast Location (505612, 451512)
LIDAR Location (505663, 451473)
SODAR Location (505669, 451461)
LIDAR and SODAR locations converted from lat/longs provided in e-mail from Iain Campbell to Andrew Birchby 24/08/10.
02339D2203-01
BRITISH NATIONAL GRID
PRELIMINARY
1:5,000
A3
ROTSEA WIND FARM
LOCATION OF LIDAR AND SODAR

1.3 Device Descriptions and Setup Diagnostics

All 3 devices provide 10 minute data, averaged over the preceding 10 minutes (i.e. the timestamps are all at the end of each 10 minute averaging period.

1.3.1 M345ENGskn

The fixed mast at Rotsea, M345ENGskn, has a variety of instruments with anemometers at 4 heights and wind vanes at two heights. The instruments used in the analysis are the 80.2m and 62m anemometers and the two wind vanes.

Site ID	Mast Number	Type	Sub Type	Deployed On	Height (m)	Units	Boom Length	Boom Orientation
ENGskn	345	Anemometer	A100L2	05/03/2007	10.01	m/s	0.72	226
ENGskn	345	Anemometer	A100L2	05/03/2007	61.98	m/s	1.76	226
ENGskn	345	Anemometer	A100L2	05/03/2007	75.37	m/s	1.76	226
ENGskn	345	Anemometer	A100L2	05/03/2007	80.16	m/s	1.69	312
ENGskn	345	Barometric Pressure	PTB101B	05/03/2007	2	mBar	-	-
ENGskn	345	Solar Panel	SOP18X	05/03/2007	-	Volts	-	-
ENGskn	345	Temperature Sensor	Thermistor Probe	05/03/2007	2	deg C	-	-
ENGskn	345	Voltage Regulator	PS-CHG-E	05/03/2007	-	Volts	-	-
ENGskn	345	Wind vane	W200P	05/03/2007	73.97	deg N	1.76	224
ENGskn	345	Wind vane	W200P	05/03/2007	80.23	deg N	1.69	132

1.3.2 M808ENGskn

The Triton device has 10 measurement heights for which it returns data for a variety of parameters, some of which are shown below. The firmware revision currently in use for this Triton device is revision 1.10.

Measurement heights (m)	Measurement parameters	
40	Wind Direction	Spectra
50	Wind Speed	Suppressed Echoes
60	Vertical Wind Speed	Temperature
80	Data Quality	Pressure
100	Wind Turbulence	Humidity
120	Turbulence Quality	
140	Confidence	
160	SNR	
180	Signal	
200	Number of Shots Valid	

The Triton also provides the relevant set up information:

True Azimuth	0^{o}
Tilt X (around Y axis)	-0.2^{o}
Tilt Y (around X axis)	0.5^{o}

The Triton does not provide values for maximum and minimum horizontal wind speed or values of standard deviation of wind speed.

1.3.3 M809ENGskn

The WINDCUBE also has 10 measurement heights for which it returns data for a variety of parameters.

Measurement heights (m)	Measurement parameters	
40	Temperature	Ave Data Availability (of good data)
60	Mean Wind Speed	Standard Deviation of Wind Speed
80	Max Wind Speed	Min Wind Speed
90	Wind Direction	
100	x-axis Wind Vector	Std Dev of x-axis Wind Vector
120	y-axis Wind Vector	Std Dev of y-axis Wind Vector
140	z-axis Wind Vector (vertical wind speed)	Std Dev of z-axis Wind Vector
160	Ave Carrier to Noise Ratio	Std Dev of CNR
180	Max CNR	Min CNR
200	Spectral Broadening	Std Dev Spectral Broadening

In addition, the WINDCUBE provides various set up information including:

Scan Angle	27.82°
Roll Angle	0.00°
Heading Angle	-0.50°
Pitch Angle	0.20°
Angle Between Two Positions	90°
Direction Offset	35.200°

1.4 Data Availability

In this analysis the concurrent period is from 26/06/2010 at 10:30 until 23/07/2010 at 00:00. This is the period for when data are available from all devices (the fixed mast, the Triton and the WINDCUBE) and is ~10 hours less than four weeks of data.

Defining operational availability as the time during which the devices were sampling the wind and recording data, over the concurrent period all devices had an operational availability of 100%.

Qualified data capture is the percentage of periods for which usable data, filtered according to the requirements of this analysis, was acquired by each remote sensor.

The qualified data capture of the WINDCUBE is based on ‘Availability’. A value of ‘Availability’ is returned for each ten minute time period. In WINDCUBE terminology, the ‘Availability’ is the percentage of valid wind speed samples obtained over the ten minute averaging period. By way of example, a ten minute time period with 90% ‘Availability’ means that 540 valid values of wind speed were used to compute the ten minute mean value of wind speed. Likewise, an ‘Availability’ of 75% equates to 450 valid values of wind speed being used to compute the ten minute mean value of wind speed. See Figure A-1 in appendix A for a graph showing data capture rates when filtering by ‘Availability’ values of 50%, 90%, 95% and 100%.

The qualified data capture of the Triton is based on ‘Quality Factor’. A value of ‘Quality Factor’ is returned for each ten minute time period. ‘Quality Factor’ is a function of the signal-to-noise ratio (SNR) and the number of valid samples collected over the ten minute interval. See Figure A-2 in appendix A for a graph showing data capture rates when filtering by ‘Quality Factor’ values of 50%, 90% and 95%.

Note that **the values of 'Availability' (WINDCUBE) and 'Quality Factor' (Triton) are not directly comparable**, and characterise the performance of the respective devices specifically at Rotsea. The performance of these devices will naturally vary from site to site due to varying site conditions such as the level of particulate matter present or the presence (or otherwise) of turbulence or vertical temperature gradients at a site.

2 METHODOLOGY

2.1 *Data Filtering*

In all, six different data filtering scenarios were considered during the analysis to better understand the effect different filters have on the data and to help minimise data loss while still ensuring robust results.

The following filters were recommended by SecondWind in its report, 'Guidelines for Triton Data Analysis and Comparison to Nearby Met Tower Measurements' [3], and applied as general filters:

- Triton wind speed quality factor: ≥ 90%
- Triton vertical wind speed: < ±1.5 $m.s^{-1}$
- Fixed mast mean wind speed: > 0.5 $m.s^{-1}$

In the same report, SecondWind also recommended the exclusion of data that may be affected by tower shadow. It was felt that this recommendation involved the removal of too much data and therefore the following - more inclusive - tower shadow filter was applied as a further scenario:

- Fixed mast mean wind direction: ≠ boom inverse ± 15°

Deutsche WindGuard in its report [4] recommended, when calculating turbulence intensity, the use of time periods where the WINDCUBE availability (of good data) is 100%. This recommendation was considered as a further scenario.

Where bad data values were returned by the instruments these too were filtered and considered as an additional filtering scenario.

More details on the losses [5] arising from the various filtering scenarios can be found in Appendix B.

2.1.1 Filtering Scenarios

The six filter scenarios considered were:

1. No data filters [6]
2. Bad data filter [7]
3. Bad data filter, general data filters applied [8]
   (Filter for tower shadow and LiDAR availability excluded)
4. Bad data filter, general data filters applied, LiDAR availability filter applied [9]
   (Filter for tower shadow excluded)
5. Bad data filter, general data filters applied, tower shadow filter applied [10]
   (Filter for LiDAR availability excluded)
6. All data filters applied [11]

Using the results summary [12] for each filtering scenario provides an indicator of the value of each scenario. On comparing the average R^2 values, as shown in the table below, scenario 3 gives very good R^2 values while minimising data losses due to filtering.

	Average R^2 values							
	FM Comparison				RS Comparison			
Filtering Scenario	Correlation of wind speed		Correlation of direction		Correlation of wind speed	Correlation of direction		
	Triton	WINDCUBE	Triton	WINDCUBE			Averages	% diff
1	0.9767	0.9950	0.9724	0.9774	0.7812	0.8773	**0.9300**	5.26%
2	0.9767	0.9950	0.9764	0.9739	0.8485	0.9120	**0.9471**	3.53%
3	0.9827	0.9950	0.9838	0.9809	0.9623	0.9854	**0.9817**	0.00%
4	0.9827	0.9953	0.9838	0.9853	0.9722	0.9872	**0.9844**	-0.28%
5	0.9833	0.9952	0.9822	0.9789	0.9623	0.9854	**0.9812**	0.05%
6	0.9833	0.9954	0.9822	0.9843	0.9707	0.9872	**0.9838**	-0.22%

From this brief analysis, it is therefore best to apply scenario 3, where only the bad data filter and the general filters are applied and neither the filter for tower shadow nor the filter for LiDAR availability (of good data) is applied. Moreover, the table of average R^2 values shows that filtering for the effects of tower shadow (scenario 5) is of no additional benefit when compared to applying only the bad data filter and general data filters (scenario 3)[2].

The following analysis section (Section 3) will, therefore, only consider data filtered under **scenario 3** (bad data filter and general data filters applied). To remove any uncertainty, **the data from the WINDCUBE is only filtered for time periods where the WINDCUBE returns 'NaN' (Not a Number) values**. As illustrated above, there is no need to apply any further filter to the WINDCUBE data as clearly this does not have more than a marginal effect on the R^2 value[3].

2.2 *Analysis*

A variety of correlations and comparisons have been undertaken to assess the performance of the remote sensing devices. These come under 2 headings:

1. Comparison of Remote Sensing devices against Fixed Mast (60m and 80m)
2. Comparison of Triton and WINDCUBE (from 60m to 200m)

The correlations and comparisons conducted include:

- Correlations of wind speed
- Correlations of wind direction
- Comparison of wind speed ratios
- Correlation of extreme wind speeds (WINDCUBE only)
- Correlation of standard deviation of wind speed (WINDCUBE only)

[2] It is accepted practice to remove data from sectors affected by tower shadow. However, at Rotsea the removal of these data did not aid the verification process, as shown by the very small variation in R^2 values. In this instance, therefore, and in order to preserve as much of the original data as possible, the decision was made to retain the data from these sectors.

[3] Filtering the WINDCUBE data on data quality levels ('availability') had only a very marginal effect on the R^2 values. The two filters considered were 100% and 0% (no filter). The resulting differences in the values of R^2 were only variations to the 3rd or 4th decimal place.

- Comparison of Ratios of component wind speed (WINDCUBE only)

Where relevant, the coefficients of determination (R^2 values) were obtained from the graphed trend lines (least squares regression) and provide a statistical measure of how well the trend line fits to the data and how well the devices correlate with each other.

The root mean square deviation (RMSD) was used to provide a good measure of the scatter of the devices compared to the predicted values (as calculated from the equation of the least squares regression trend lines).

An orthogonal regression (York method) was also used, allowing a comparison with the least squares regression method. From the data (see appendices) it is clear that the least squares regressions are in very good agreement with the orthogonal regressions. A comparison of the two regression techniques is possible using the data presented in the appendices. For comparison, the trend lines obtained from both the least squares and orthogonal regressions are presented on the graphs. In the analysis section (section 3), the data presented for gradient, intercept and R^2 is obtained using the York method. Given that the difference between the two regression techniques is in most cases almost negligible, the RMSD values (least squares regression) are also presented.

Uncertainties were also calculated for both the slope and intercept of the orthogonal regression trend lines. These are presented in the following section.

In the main body of the report, graphs are presented for 80m only. Graphs for all heights considered in this analysis can be found in the relevant sections of the appendices.

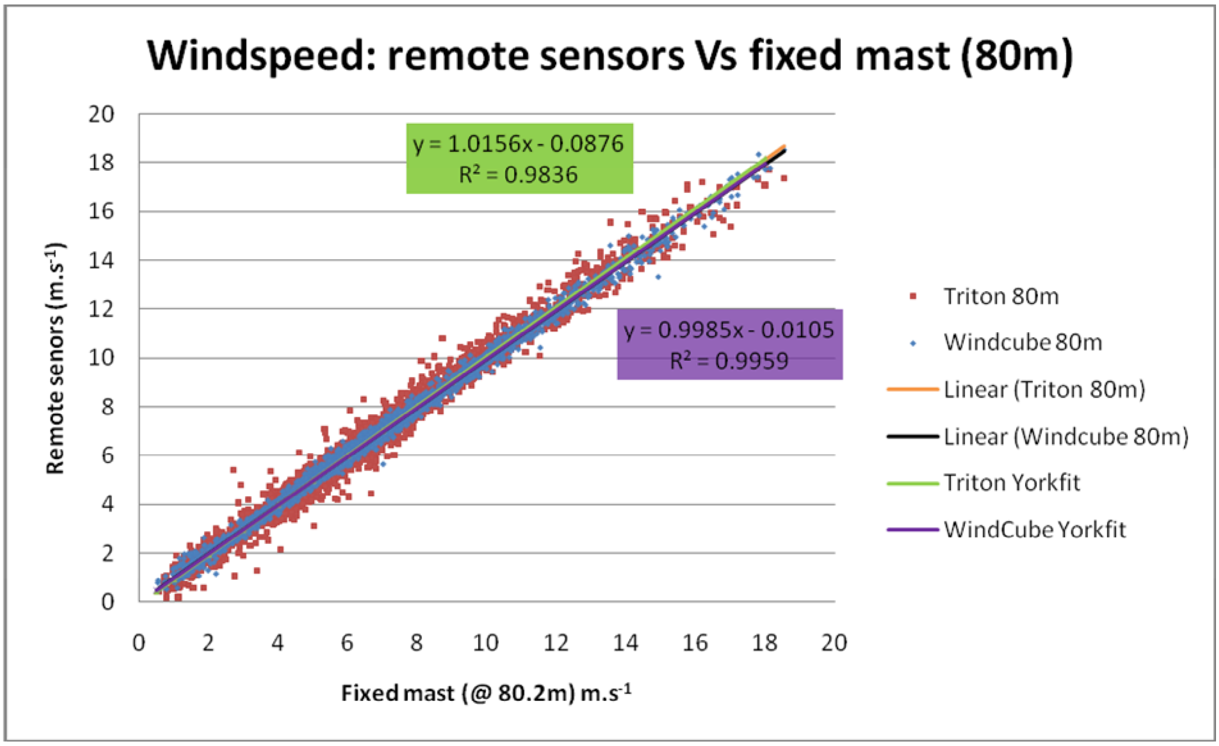
3 ANALYSIS

3.1 Comparison of Remote Sensing devices against Fixed Mast (60m and 80m)

3.1.1 Correlation of Wind Speed

By comparing the wind speed measurements of the remote sensing devices with the fixed mast, it is possible to see how well correlated the devices are and this can give confidence that the devices are 'seeing' the same wind speed as the fixed mast. It is possible therefore, in terms of wind speed measurements at least, to confirm that the devices are operating well.

For the correlations with the fixed mast, the wind speed data from the remote sensors at 60m and 80m was correlated with the fixed mast data from 62m and 80.2m, respectively.



Correlation of wind speed							
	Triton						
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	RMSD	Valid data
60	1.0339	0.0023	-0.1452	0.0149	0.9817	0.00632	96.31%
80	1.0156	0.0021	-0.0876	0.0152	0.9836	0.00616	94.65%
	WINDCUBE						
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	RMSD	Valid data
60	1.0100	0.0012	0.0096	0.0081	0.9941	0.00348	99.52%
80	0.9985	0.0010	-0.0105	0.0071	0.9959	0.00297	99.92%

Both the Triton and WINDCUBE correlate very well with the fixed mast at both 60m and 80m, however, the WINDCUBE correlates marginally better (~1%) than the Triton at both heights.

It is interesting to note the gradients of each correlation as this is a key parameter when conducting acceptance tests for remote sensing devices[4]. At both 60m and 80m, the WINDCUBE is within 1% of a gradient of 1, whereas the Triton is 3.4% and 1.6% from a gradient of 1, respectively.

There is a slight improvement in correlation (and overall) from 60m to 80m. This is due to the height of the fixed mast anemometers which are at 62m and 80.2m.

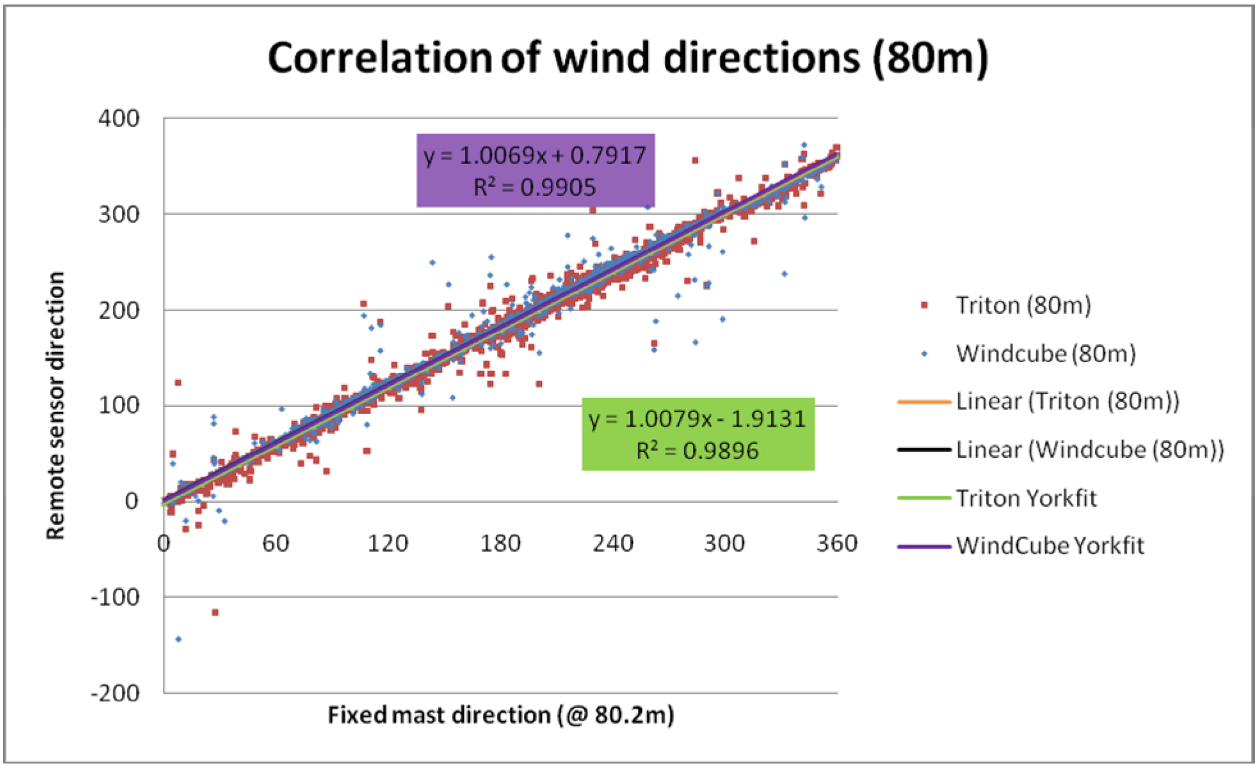
The RMSD values clearly show that the WINDCUBE produces half as much scatter compared to the Triton at both 60m and 80m.

After filtering, there is an excellent level of valid data for both the Triton and the WINDCUBE comparisons. For the comparison with the WINDCUBE, there is between 3% and 4% more valid data than for the Triton comparison. It should be emphasised that the filter for WINDCUBE ‘Availability’ in this analysis is set at 0. Given the excellent R^2 value obtained, this indicates that the data returned by the WINDCUBE, even with a low percentage of valid samples, provide a remarkably accurate profile of the wind at the Rotsea site.

3.1.2 Correlation of Wind Direction

By comparing the wind direction measurements of the remote sensing devices with the fixed mast, it is possible to see how well correlated the devices are and this can give confidence that the devices are ‘seeing’ the same wind direction as the fixed mast. It is possible therefore, in terms of wind direction measurements at least, to confirm that the devices are operating well and do not show signs of systematic bias.

For the correlations with the fixed mast, the wind direction data from the remote sensors at 60m and 80m was correlated with the fixed mast data from 74m and 80.2m, respectively.



[4] It is important to note that the data used in this analysis has not been filtered to the standard that would normally be required for acceptance tests. Nevertheless under the filtering regime used in this analysis and considering the gradient of the wind speed correlations, the WINDCUBE would pass such acceptance tests.

Correlation of direction[5]							
	Triton						
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	RMSD	Valid data
60	1.0175	0.0024	-4.6421	0.5204	0.9778	0.17931	96.61%
80	1.0079	0.0017	-1.9131	0.3563	0.9896	0.12206	94.65%
	WINDCUBE						
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	RMSD	Valid data
60	1.0144	0.0027	-0.9208	0.5857	0.9709	0.20422	99.92%
80	1.0069	0.0016	0.7917	0.3302	0.9905	0.11539	99.92%

Both the Triton and WINDCUBE correlate very well with the fixed mast at both 60m and 80m, with the trend line gradients very close to 1. However at 60m the Triton correlates marginally better than the WINDCUBE and at 80m the WINDCUBE correlates marginally better than the Triton.

The intercept offsets indicate that there is a slight misalignment on one or more of the fixed mast or the remote sensors. This error is small, however, and still within the instrument uncertainty.

There is a small improvement in correlation (and in gradient, intercept and RMSD) from 60m to 80m. This is due to the height of the fixed mast wind vanes which are at 74m and 80.2m.

The RMSD values show that the amount of scatter from the WINDCUBE for directional data is approximately the same as that from the Triton at both 60m and 80m.

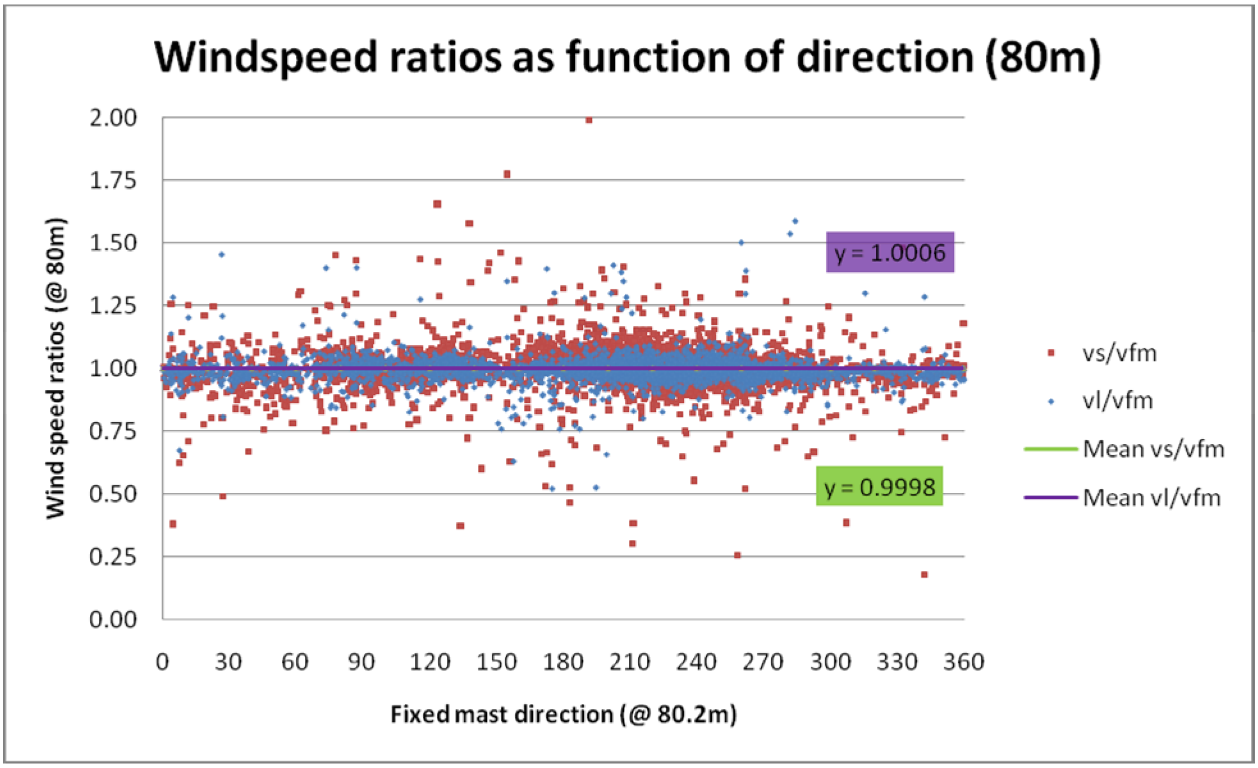
Again, there is an excellent level of valid data for both the Triton and the WINDCUBE comparisons. For the comparison with the WINDCUBE, there is again between 3% and 4% more valid data than for the Triton comparison.

3.1.3 Ratios of Wind Speed

Another method of ensuring that the remote sensing devices are operating as expected is by considering the wind speed ratios (remote sensing device / fixed mast) against direction. It would be expected that such ratios would be close to unity.

For the comparisons with the fixed mast, the wind speed data from the remote sensors at 60m and 80m was compared with the fixed mast data from 62m and 80.2m, respectively.

[5] Note that the correlation of direction graphs may show data beyond the normal 0°-360° limits. This is necessary to allow an accurate trend line to be shown. To achieve this some data have had an offset of ± 360° applied.



Ratio of wind speed as function of fm direction						
	Triton			WINDCUBE		
	Intercept	RMSD	Valid data	Intercept	RMSD	Valid data
60	1.0096	0.00169	96.31%	1.0174	0.00097	99.52%
80	0.9998	0.00142	94.65%	1.0006	0.00077	99.92%

The intercept for the wind speed ratios was calculated using the arithmetic mean of the filtered data. Both the Triton and WINDCUBE are in good agreement with the fixed mast at both 60m and 80m, as indicated by the intercepts being very close (within 2%) to 1.

There is a small improvement in the RMSD from 60m to 80m. This is again likely due to the height of the fixed mast anemometers which are at 62m and 80.2m.

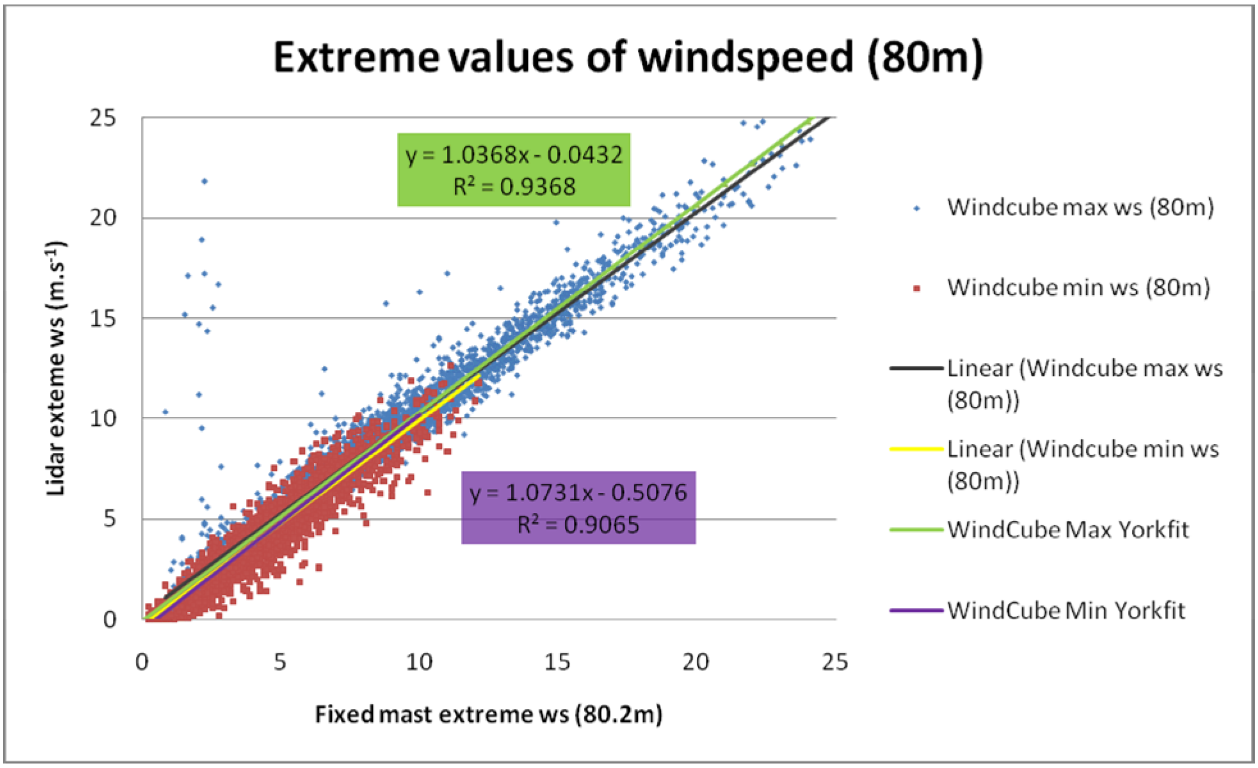
The RMSD values show that, at both 60m and 80m, the WINDCUBE produces half as much scatter compared to the Triton.

Once more, there is an excellent level of valid data for both the Triton and the WINDCUBE comparisons. For the comparison with the WINDCUBE, there is again between 3% and 4% more valid data than for the Triton comparison.

3.1.4 Correlation of Extremes of Wind Speed (WINDCUBE only)

By considering extreme wind speed (maxima and minima) measurements it is possible to gain further confidence as to the proper operation of the remote sensing devices. These correlations would be expected to be worse than the correlations with average wind speed but nevertheless good correlations can still be obtained and are good indicators of excellent device operation.

Given that the data available from the Triton was only the basic data, this meant it was only possible to conduct extreme wind speed correlations between the WINDCUBE and the fixed mast. For the correlations with the fixed mast, the wind speed data from the WINDCUBE at 60m and 80m was correlated with the fixed mast data from 62m and 80.2m, respectively.



Extreme values of Wind speed						
	WINDCUBE Maximum					
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	Valid data
60	1.0391	0.0030	-0.0310	0.0267	0.9663	99.52%
80	1.0368	0.0041	-0.0432	0.0379	0.9368	99.92%
	WINDCUBE Minimum					
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	Valid data
60	1.0782	0.0058	-0.3812	0.0248	0.8850	99.52%
80	1.0731	0.0052	-0.5076	0.0250	0.9065	99.92%

Given that this is a correlation for extreme wind speed rather than average wind speed, the data above are quite remarkable. For both maximum and minimum values of wind speed, the WINDCUBE correlates very well with the fixed mast at both 60m and 80m. The trend line gradients are close to 1, with the minima within 8% of unity and the maxima within 4%.

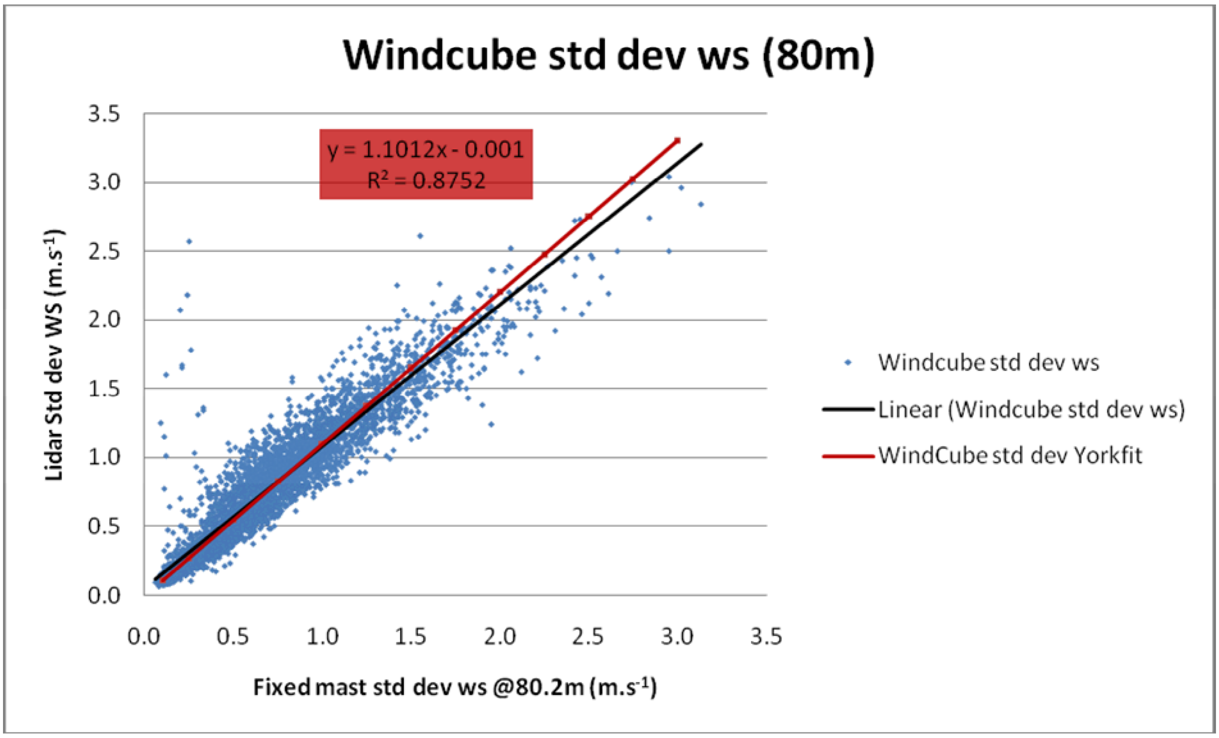
At 60m and more so at 80m there are a reasonable number of data points where the maximum wind speed observed by the WINDCUBE is significantly above the maximum wind speed value returned by the fixed mast. At both 60m and 80m these deviations occur at various fixed mast wind speeds below 10m.s^{-1}. At 80m, however, there is a slight trend of deviations at a fixed mast maximum wind speed of ~ 2m.s^{-1}. This probably corresponds with the anemometer cut in speed.

Again there is an excellent level of valid data available for the extreme wind speed correlations.

3.1.5 Correlation of Standard Deviation of Wind Speed (WINDCUBE only)

By considering the measurements of standard deviation of wind speed, it is possible to gain more confidence as to the proper operation of the remote sensing devices. Again, these correlations would be expected to be worse than the correlations with average wind speed (and worse than extreme wind speed correlations) but nevertheless good correlations can still be obtained and are good indicators of excellent device operation.

As stated earlier, only basic data was available from the Triton. Therefore it was only possible to conduct standard deviation of wind speed correlations between the WINDCUBE and the fixed mast. For the correlations with the fixed mast, the wind speed data from the WINDCUBE at 60m and 80m was correlated with the fixed mast data from 62m and 80.2m, respectively.



Correlation of standard deviation of wind speed						
	WINDCUBE					
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	Valid data
60	1.0772	0.0053	-0.0025	0.0046	0.9045	99.52%
80	1.1012	0.0061	-0.0010	0.0052	0.8752	99.92%

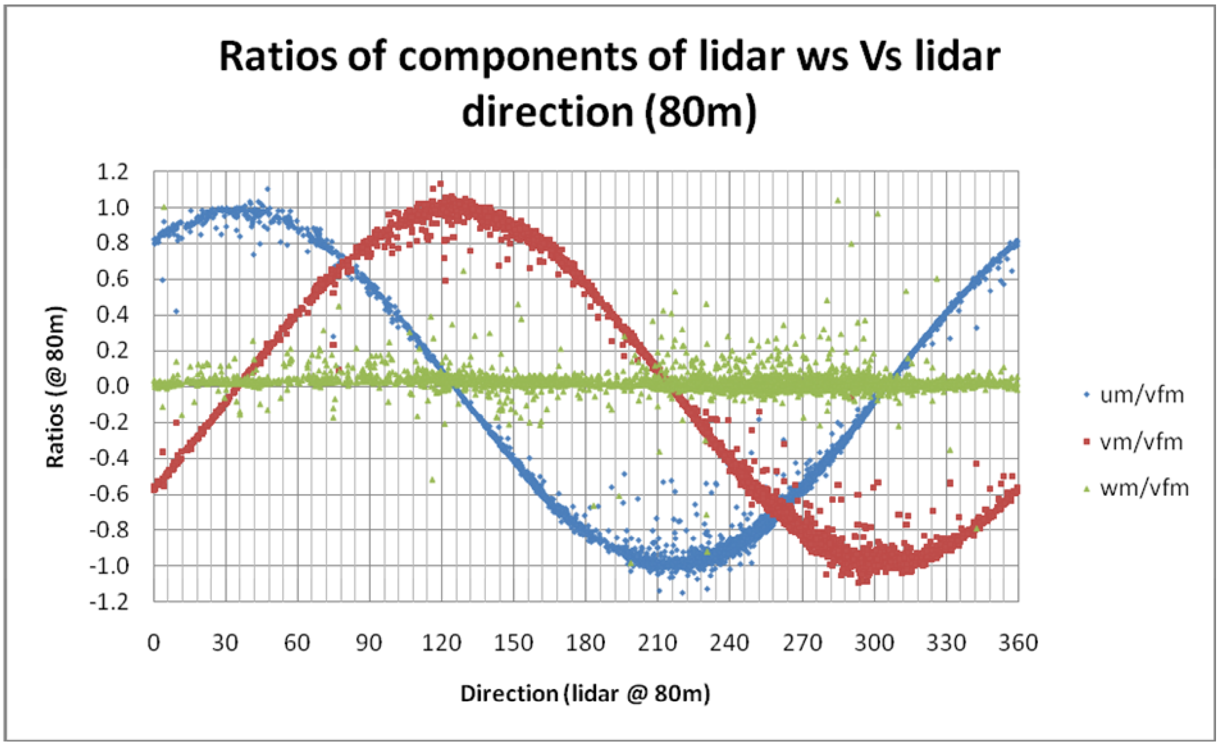
For the standard deviation of wind speed, the WINDCUBE correlates very well with the fixed mast at both 60m and 80m, with the trend line gradients close (within ~10%) to 1.

As with maximum wind speed values, at 80m, there is a slight trend of data points deviating from the trend at a low values (0.2) of fixed mast standard deviation of wind speed.

Again it should be reiterated that the above correlations are really very good and actually quite profoundly useful. Indeed, it is clear that, for this site at least, the WINDCUBE is returning a very meaningful standard deviation of wind speed, with a gradient close to 1 and an intercept very close to zero. The important implication of this is that, it may be possible to use the WINDCUBE to obtain reliable turbulence intensity information, specific to individual turbine locations.

3.1.6 WINDCUBE Device Geometry

By plotting the ratios of the components of WINDCUBE wind speed (dividing by fixed mast wind speed) against WINDCUBE direction, it is possible the confirm the geometry of the WINDCUBE and ensure that any orientation offset has been recorded correctly. The peaks and troughs of the non-vertical component ratios correspond to the measurement beam orientation plus the offset angle. At Rotsea the WINDCUBE was installed with an offset to avoid some local obstacles. The value of the offset was 35.2°. Additionally, the vertical component ratio would be expected to approximate to 0.



Plotting the ratio of the components of WINDCUBE wind speed with the fixed mast wind speed allows the orientation of the WINDCUBE to be confirmed. As indicated in section 1.3.3 and above, the WINDCUBE has been set up with an orientation offset of 35.2°. In the above graphs the peaks and troughs of the u_m/v_{fm} and v_m/v_{fm} series should coincide with the 4 measurement positions of the WINDCUBE. The WINDCUBE measures at 0°, 90°, 270° and 360°, therefore, when considering the orientation offset the peaks and troughs of the above graphs should coincide with the measurement angles plus the 35.2° offset. As can be seen in the graphs, the peaks and troughs agree very well with the offset measurement angles. Moreover, there is very little scatter and both the u_m/v_{fm} and v_m/v_{fm} series describe offset cosines extremely well, as expected.

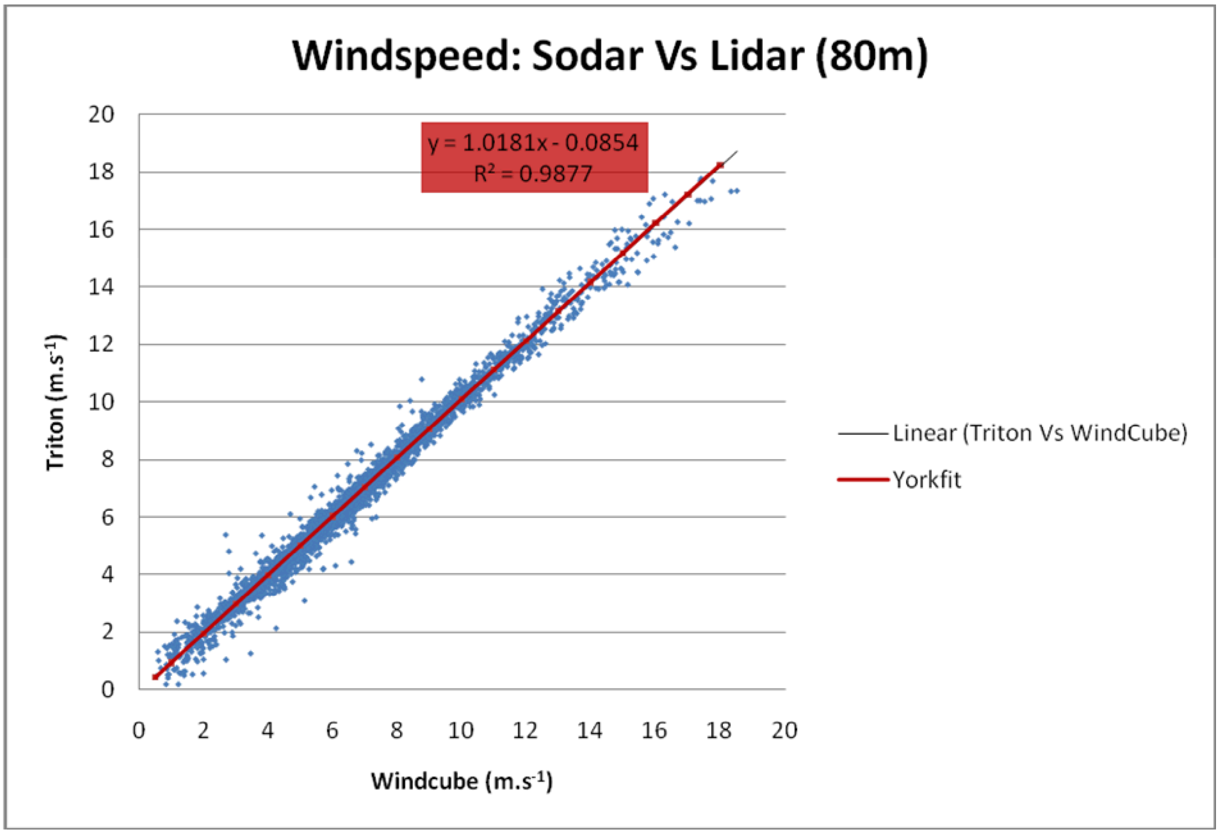
Additionally, the component of wind speed which represents the vertical wind speed, w_m, has a ratio, w_m/v_{fm}, which is very close to 0.

3.2 *Comparison of Triton and WINDCUBE (from 60m to 200m)*

3.2.1 Correlation of Wind Speed

By comparing the wind speed measurements of the remote sensing devices with each other, it is possible to see how well correlated the devices are and this can give confidence that the devices are 'seeing' the same wind speed as each other. It is possible therefore, in terms of wind speed measurements at least, to confirm that the devices are operating well at heights above the fixed mast (100m – 200m).

Correlations between the devices were conducted at 60m, 80m, 100m, 120m, 140m, 160m, 180m, and 200m.



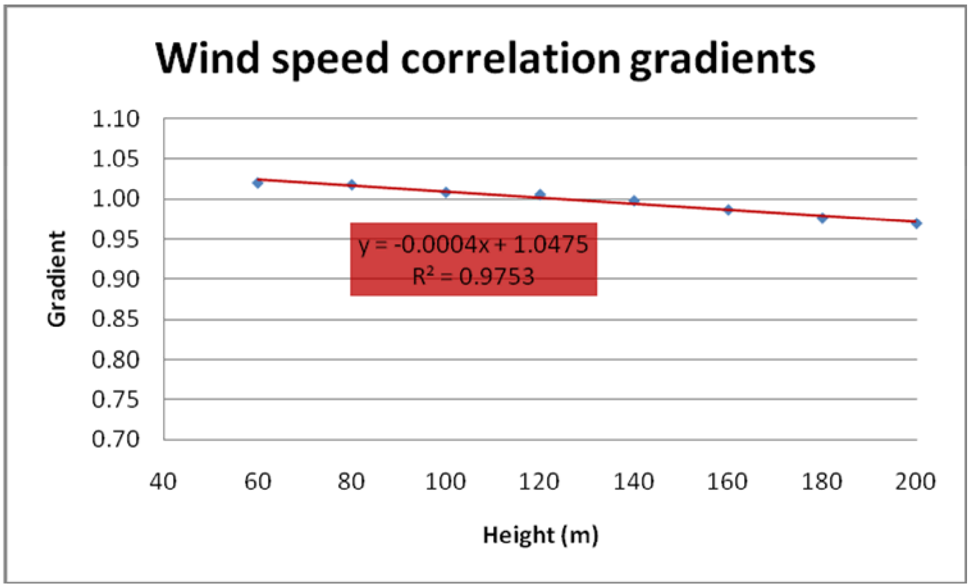
Correlation of wind speed							
	Triton Vs WINDCUBE						
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	RMSD	Valid data
60	1.0204	0.0018	-0.1306	0.0117	0.9887	0.00499	96.54%
80	1.0181	0.0018	-0.0854	0.0131	0.9877	0.00534	94.58%
100	1.0087	0.0025	-0.1632	0.0186	0.9788	0.00837	91.27%
120	1.0058	0.0024	-0.0756	0.0187	0.9810	0.00723	86.65%
140	0.9980	0.0030	-0.0942	0.0248	0.9719	0.01012	79.74%
160	0.9867	0.0042	-0.0943	0.0351	0.9529	0.01493	71.34%
180	0.9762	0.0060	-0.0662	0.0518	0.9204	0.02132	57.71%
200	0.9694	0.0075	-0.0410	0.0652	0.9158	0.02772	40.24%

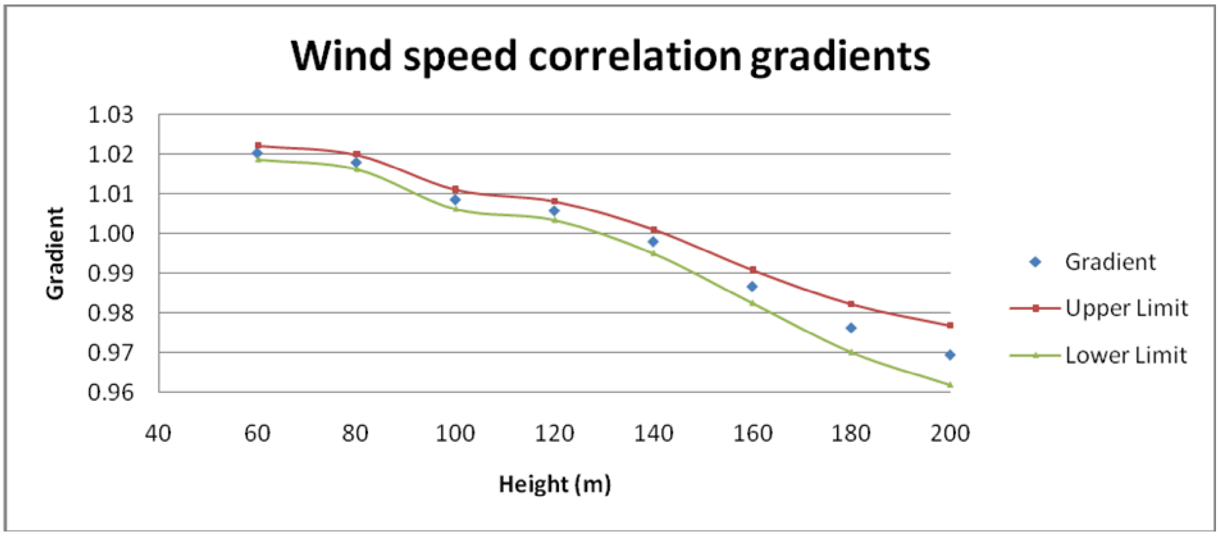
The Triton and WINDCUBE correlate very well with each other at all heights, with the trend line gradients very close (within ~3%) to 1 and the intercepts close to 0. However, as expected, there is a decrease in the correlation and an increase in RMSD with increasing height. This is due to increased beam scatter as a result of measuring over larger volumes.

At 180m and 200m, there is a noticeable worsening of both the correlation and the RMSD, perhaps due to increased data loss following filtering at these heights. This can be seen in the percentage of valid data available at these heights dropping below 60% for 180m and then to just above 40% for 200m.

The decreasing gradient with increasing height is shown in the following graphs and indicates a systematic under-reading (Triton) or over-reading (WINDCUBE) of wind speed with increasing height. This suggests that, with increasing height and for the same time period, the Triton observes lower wind speeds than the WINDCUBE. Though small, this systematic trend is a key result of this analysis and suggests that one of these remote sensing devices is not operating as it ought.

Without data from the fixed mast, it is impossible to determine which device is not operating as expected but it is clear that the operation of the two devices is diverging above the height of the fixed mast. Nevertheless, the second graph shows that the variation between 60m and 160m is ~3% which is within the uncertainty of a fixed mast anemometer.

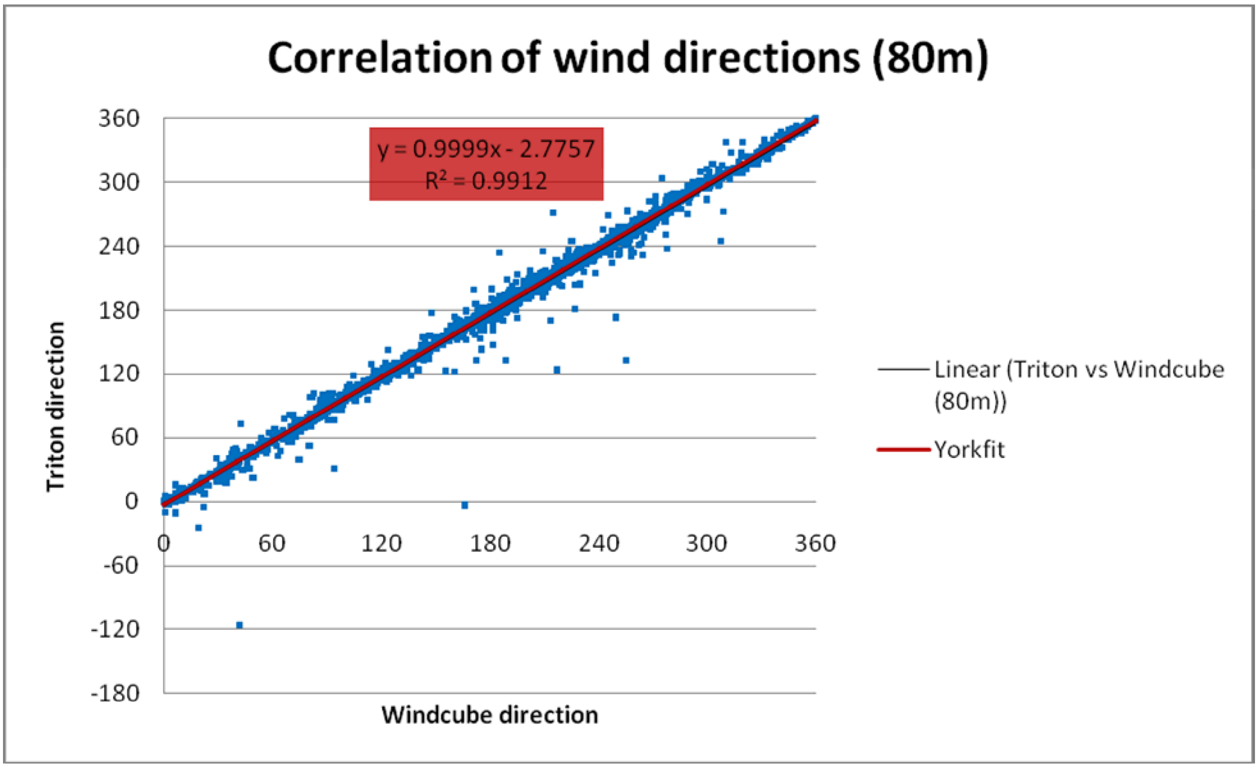




3.2.2 Correlation of Wind Direction

By comparing the wind direction measurements of the remote sensing devices with other, it is possible to see how well correlated the devices are and this can give confidence that the devices are 'seeing' the same wind direction as each other. It is possible therefore, in terms of wind direction measurements at least, to confirm that the devices are operating well at heights above the fixed mast (100m – 200m).

Correlations between the devices were conducted at 60m, 80m, 100m, 120m, 140m, 160m, 180m, and 200m.



Correlation of direction							
	Triton Vs WINDCUBE						
	Gradient	Uncertainty	Intercept	Uncertainty	R^2	RMSD	Valid data
60	1.0028	0.0015	-3.6871	0.3272	0.9911	0.15531	96.54%
80	0.9999	0.0015	-2.7757	0.3298	0.9912	0.11216	94.58%
100	0.9940	0.0019	-1.6886	0.4015	0.9876	0.12763	88.65%
120	0.9927	0.0015	-1.0123	0.3301	0.9921	0.10307	84.14%
140	0.9923	0.0017	-0.9389	0.3634	0.9908	0.11789	79.74%
160	0.9933	0.0024	-0.9295	0.5143	0.9834	0.16504	71.34%
180	0.9904	0.0033	-0.5658	0.6802	0.9758	0.21916	57.71%
200	0.9910	0.0044	-0.3598	0.9075	0.9697	0.29628	40.24%

The Triton and WINDCUBE correlate very well with each other at all heights, with the trend line gradients very close (within ~1%) to unity. As expected the R^2 values for wind speed direction are better than the R^2 values for wind speed. This is due to the greater natural fluctuation in wind speeds compared with wind direction.

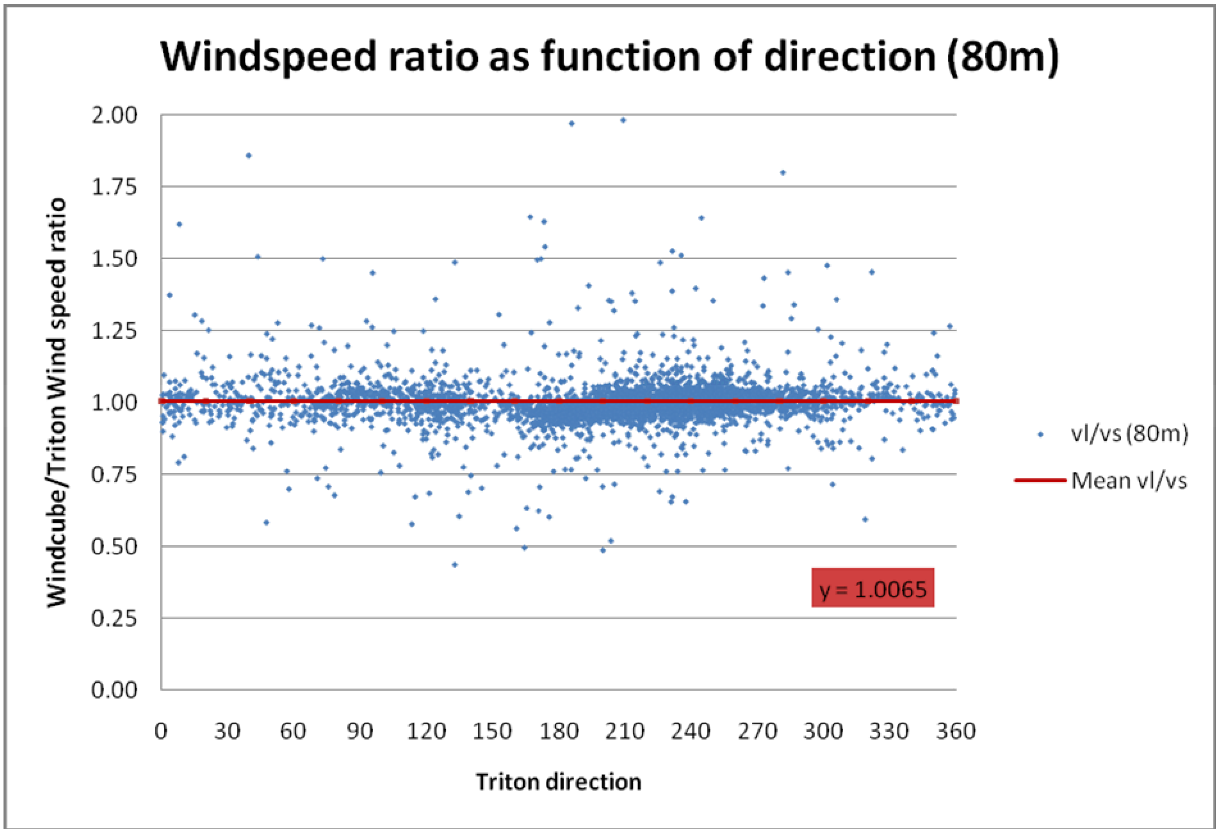
The intercept offset (from 0) perhaps suggests that the Triton and WINDCUBE are not exactly aligned. However, the offset decreases from 60m to 200m which suggests something other than a simple device misalignment. The discrepancy is still within the boom alignment uncertainty allowed for fixed masts and within the allowed fixed mast instrument uncertainty.

Once more, at 180m and 200m, there is a noticeable worsening of both the correlation and the RMSD, perhaps due to increased data loss following filtering at these heights. Again, this can be seen in the percentage of valid data available at these heights dropping below 60% for 180m and then to just above 40% for 200m.

3.2.3 Ratios of Wind Speed

Another method of ensuring that the remote sensing devices are operating as expected is by considering the wind speed ratios (LiDAR / SoDAR) against direction. It would be expected that such ratios would be close to unity.

Comparisons between the devices were conducted at 60m, 80m, 100m, 120m, 140m, 160m, 180m, and 200m.



Ratio of wind speed as function of SoDAR direction			
	WINDCUBE / Triton		
	Intercept	RMSD	Valid data
60	1.0128	0.00212	96.54%
80	1.0065	0.00244	94.58%
100	1.0377	0.00327	91.27%
120	1.0242	0.00397	86.65%
140	1.0337	0.00263	79.74%

160	1.0858	0.03436	71.34%
180	1.0639	0.00447	57.71%
200	1.0651	0.00487	33.53%

Both the Triton and WINDCUBE are in very good agreement with each other at all heights (slight disagreement at 160m), as indicated by the intercepts being close (generally within 7%) to unity.

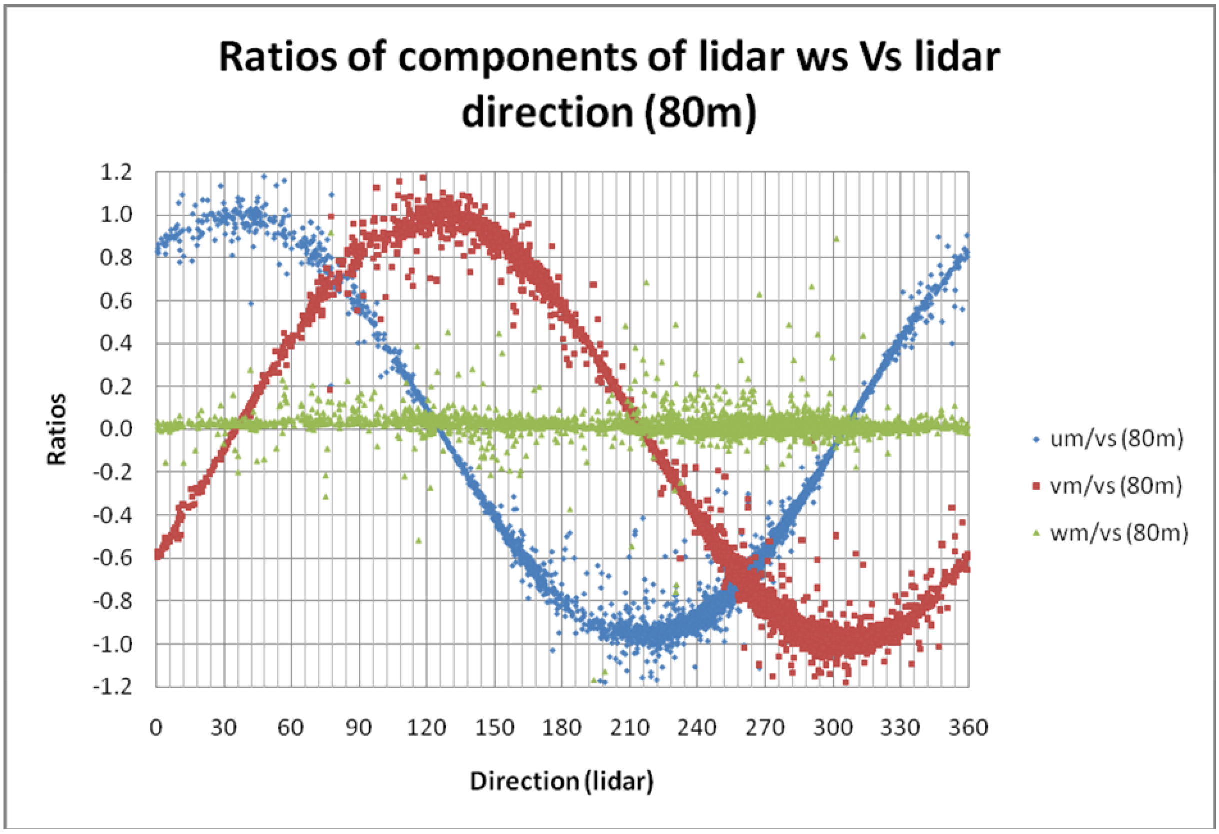
Generally the RMSD values indicate low scatter. The observed deviation from the general trend at 160m is perhaps artificial and due to a few significant outliers in the data series.

Again, at 180m and 200m, there is a noticeable worsening of both the intercept and the RMSD from the general trends. As stated previously, this is perhaps due to increased data loss following filtering at these heights.

3.2.4 WINDCUBE Device Geometry

As previously stated, by plotting the ratios of the components of WINDCUBE wind speed (here dividing by Triton wind speed) against WINDCUBE direction, it is possible the confirm the geometry of the WINDCUBE and ensure that any orientation offset has been recorded correctly.

These geometry checks were conducted at 60m, 80m, 100m, 120m, 140m, 160m, 180m, and 200m.



As can be seen in the graphs (also see Appendix F), for all heights, the peaks and troughs agree very well with the offset measurement angles and both the u_m/v_s and v_m/v_s series describe offset cosines extremely well, as expected. There is, however, more scatter than for the comparison with fixed mast wind speed, v_{fm}.

Moreover, with increasing height there is more scatter. In particular from 140m to 200m there are very few data points in the 336°-36° sector. This worsens with increasing height with the data loss sector at 140m approximately only 360°-6°.

The component of wind speed which represents the vertical wind speed, w_m, has a ratio, w_m/v_s, which is very close to 0 across all heights.

4 CONCLUSIONS

In conclusion, the analysis of the data shows that, at all heights, there is excellent agreement between the fixed mast, the Triton and the WINDCUBE. There is excellent linearity, correlation and very low scatter. In particular and even with a relaxed filtering regime, the values of gradient obtained in wind speed correlations between the WINDCUBE and the fixed mast are within 1% of unity (Triton: 3.4% and 1.6% at 60m and 80m, respectively). As such the WINDCUBE would meet the acceptance test criteria (for wind speed correlation gradient) for remote sensing devices.

For the comparisons with the fixed mast, the correlation results for extreme wind speeds and standard deviation of wind speed with the WINDCUBE are really very good. These results indicate that the WINDCUBE is in very good agreement with the fixed mast. In particular, the excellent correlations obtained for the standard deviation of wind speed imply that, it may be possible to use the WINDCUBE to obtain reliable turbulence intensity information, specific to individual turbine locations.

The Remote sensing devices both operate very well, with no evidence of directional bias and, in general, both show excellent linearity. With the exception of wind speed direction, the Triton shows twice as much scatter as the WINDCUBE and generally increased scatter is observed (for both devices) with increasing height.

It should be emphasised that the filter for WINDCUBE 'Availability' in this analysis is set at 0. Given the excellent R^2 value obtained, this indicates that the data returned by the WINDCUBE, even with a low percentage of valid samples, provide a remarkably accurate profile of the wind at the Rotsea site.

Generally, there is a decrease in the correlation and an increase in RMSD with increasing height. This is due to increased beam scatter as a result of measuring over larger volumes. For all comparisons between the Triton and WINDCUBE, at 180m and 200m, there is a slight but noticeable worsening of correlation and RMSD, perhaps due to increased data loss following filtering at these heights.

The intercept offset observed in the wind direction correlations perhaps suggests that the Triton and WINDCUBE are not exactly aligned. Nevertheless, the discrepancy is still within the boom alignment uncertainty allowed for fixed masts and within the allowed fixed mast instrument uncertainty.

The implications of the systematic trend seen in the wind speed correlations need to be understood. The decreasing gradient with increasing height indicates that the Triton observes lower wind speeds than the WINDCUBE. Though small, this systematic trend is a key result of this analysis and suggests that one of these remote sensing devices is not operating as it ought.

While it is interesting to be able to compare both the Triton and WINDCUBE devices up to 200m it is perhaps of more worth to ensure an accurate understanding of shear from mast height to turbine hub height and possibly also across the swept area of the turbine blades. To this end and given that the possibility exists to alter the sampling heights, it would be expedient to agree standard measurement heights for the WINDCUBE. Common measurement heights would still exist between the Triton and WINDCUBE but the increased measurement heights up to turbine hub height would allow for a more accurate understanding of the varying nature of the wind distribution at a (turbine) location.

REFERENCES

1. BIRCHBY, A (2010), 'Location of LiDAR and SoDAR', RES Drawing 02339D2203 Issue 01, dated 25 August 2010
2. SecondWind (2009), 'Guidelines for Siting a Triton by Met Towers, Trees and in Complex Terrain', SecondWind Report, dated 5th October 2009
3. WALLS, E (2009), 'Guidelines for Triton Data Analysis and Comparison to Nearby Met Tower Measurements', SecondWind Report, prepared 23rd October 2008, revised 25th September 2009
4. ALBERS, A JANSSEN, AW (2008), 'Evaluation of WINDCUBE', Deutsche WindGuard Consulting GmbH Report PP 08007, dated 16 March 2008.
5. CAMPBELL, RI (2010), 'ENGskn_Availability', RES Spreadsheet, 01485-000091, dated 08 February 2011
6. CAMPBELL, RI (2010), 'ENGskn_V4.0.0 (no data filters)', RES Spreadsheet, 01485-000082, dated 30 August 2010
7. CAMPBELL, RI (2010), 'ENGskn_V4.0.1 (bad data filter only)', RES Spreadsheet, 01485-000083, dated 30 August 2010
8. CAMPBELL, RI (2010), 'ENGskn_V4.1.0 (data filters applied excl TS and LiDAR avail)', RES Spreadsheet, 01485-000084, dated 28 September 2010
9. CAMPBELL, RI (2010), 'ENGskn_V4.1.1 (data filters applied excl TS)', RES Spreadsheet, 01485-000085, dated 31 August 2010
10. CAMPBELL, RI (2010), 'ENGskn_V4.2.0 (data filters applied excl LiDAR avail)', RES Spreadsheet, 01485-000076, dated 30 August 2010
11. CAMPBELL, RI (2010), 'ENGskn_V4.2.1 (data filters applied)', RES Spreadsheet, 01485-000077, dated 30 August 2010
12. CAMPBELL, RI (2010), 'ENGskn_Summary', RES Spreadsheet, 01485-000078, dated 28 September 2010

APPENDICES

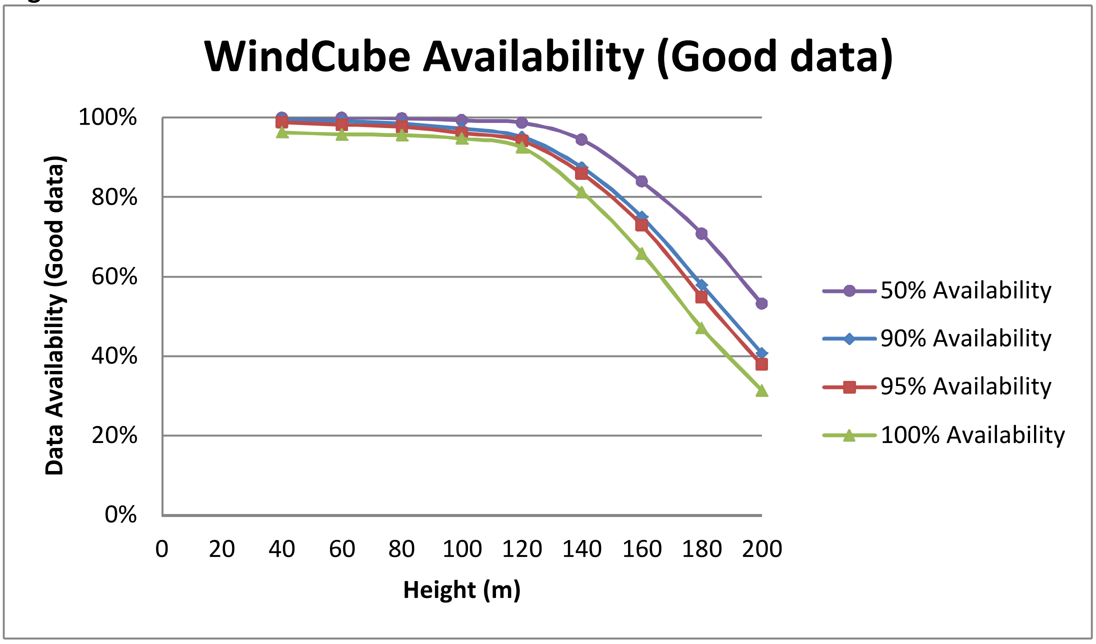
APPENDIX A QUALIFIED DATA CAPTURE

The following graph and accompanying table present the percentage of data remaining when filtering according to the WINDCUBE measure of data quality, "Availability". Four scenarios are presented.

1. "Availability" ≥ 50%
2. "Availability" ≥ 90%
3. "Availability" ≥ 95%
4. "Availability" = 100%

For each scenario, the graph and table show (for each measurement height) the percentage of time periods for which the value of "Availability" is at least equal to the selected filter value (50, 90%, 95%, 100%).

Figure A-1



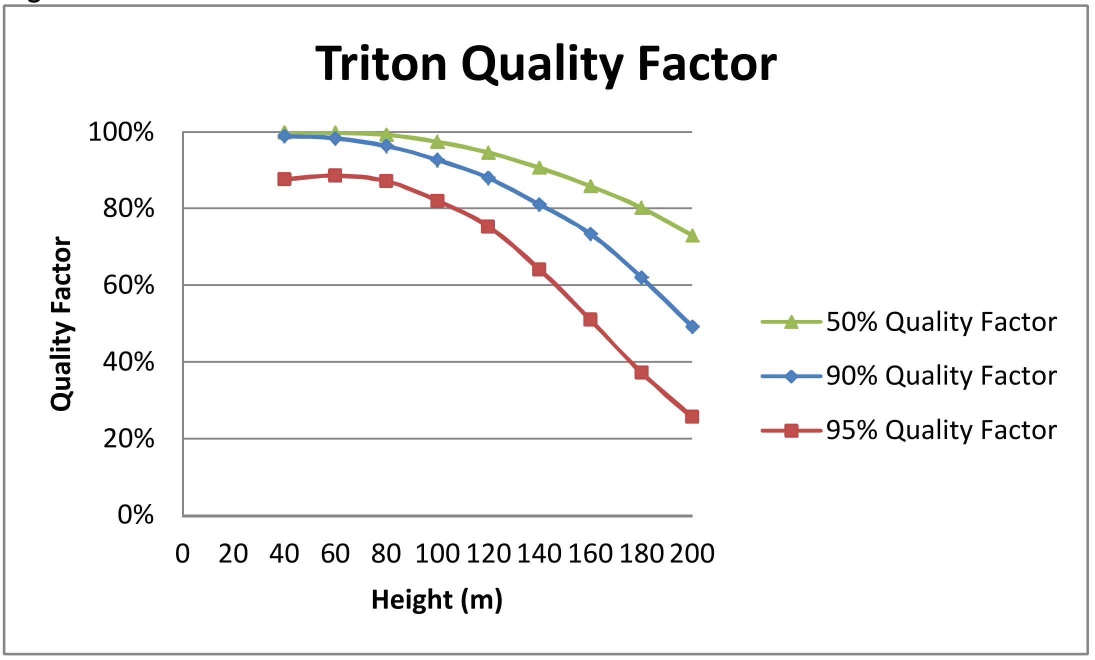
	WINDCUBE Qualified Data Capture			
Height (m)	50% Availability	90% Availability	95% Availability	100% Availability
40	99.92%	99.57%	98.77%	96.29%
60	99.92%	99.12%	98.19%	95.76%
80	99.80%	98.47%	97.72%	95.58%
100	99.27%	97.16%	96.08%	94.70%
120	98.67%	95.11%	94.13%	92.47%
140	94.40%	87.40%	85.89%	81.20%
160	83.86%	74.97%	72.89%	65.79%
180	70.73%	57.83%	54.79%	47.01%
200	53.09%	40.69%	37.83%	31.38%

The following graph and accompanying table present the percentage of data remaining when filtering according to the Triton measure of data quality, “Quality Factor”. Three scenarios are presented.

1. “Quality Factor” ≥ 50%
2. “Quality Factor” ≥ 90%
3. “Quality Factor” ≥ 95%

For each scenario, the graph and table show (for each measurement height) the percentage of time periods for which the value of “Quality Factor” is at least equal to the selected filter value (50%, 90%, 95%).

Figure A-2



	Triton Qualified Data Capture		
Height (m)	50% Quality Factor	90% Quality Factor	95% Quality Factor
40	99.82%	98.90%	87.65%
60	99.80%	98.34%	88.58%
80	99.25%	96.31%	87.15%
100	97.36%	92.70%	82.00%
120	94.58%	87.98%	75.23%
140	90.59%	81.05%	64.13%
160	85.84%	73.39%	50.90%
180	80.22%	62.05%	37.20%
200	72.94%	49.15%	25.55%

Clearly WINDCUBE 'Availability' and Triton 'Quality Factor' are not the same and are not directly comparable. Nevertheless, both indices provide an indication of the quality of the data being returned by the respective devices.

APPENDIX B DATA FILTERS

Bad Data Filter

This involved filtering those time periods where either no data or 'bad data' values were returned. The data capture losses are shown in the following table.

Data Capture								
Height (m)	60	80	100	120	140	160	180	200
WINDCUBE	0.08%	0.08%	0.20%	0.53%	0.73%	2.13%	7.45%	16.92%
Triton	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%

General Data Filter

This involved filtering those data as recommended in the SecondWind report [3] and as listed above. The data losses as a result of these filters are shown in the tables below.

	Triton (>90%)	Triton vertical wind speed: $< \pm 1.5$ m.s^{-1}
Height (m)	Data Losses	Data Losses
60	1.53%	1.71%
80	3.56%	1.76%
100	7.18%	1.96%
120	11.90%	2.59%
140	18.83%	3.41%
160	26.48%	5.05%
180	37.83%	7.30%
200	50.73%	10.57%

	Fixed mast mean wind speed: > 0.5 m.s^{-1}	
	Height (m)	Data Losses
Anemometer	62	0.40%
Anemometer	80.2	0.00%

WINDCUBE Availability Filter

This filter was applied, removing time periods for which the availability of WINDCUBE data was less than 100%. It is noted in the Deutsche WindGuard report [4] that **this filter is only necessary when considering turbulence**. However, in this analysis this filter did slightly improve the R^2 value of the correlations between the WINDCUBE and both the fixed mast and the Triton remote sensor. The data losses as a result of the LiDAR availability filter are shown in the table below.

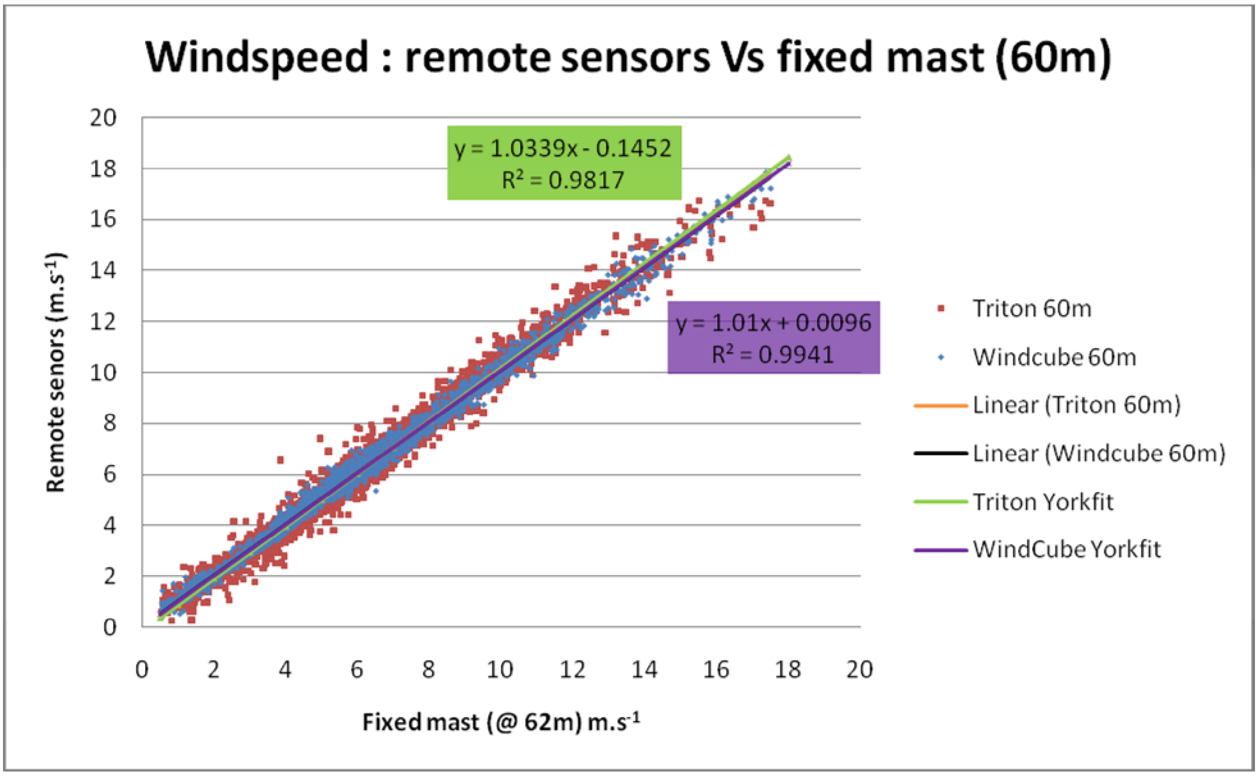
	WINDCUBE (=100%)
Height (m)	Data Losses
60	4.17%
80	4.34%
100	5.10%
120	7.00%
140	18.07%
160	32.08%
180	45.53%
200	51.71%

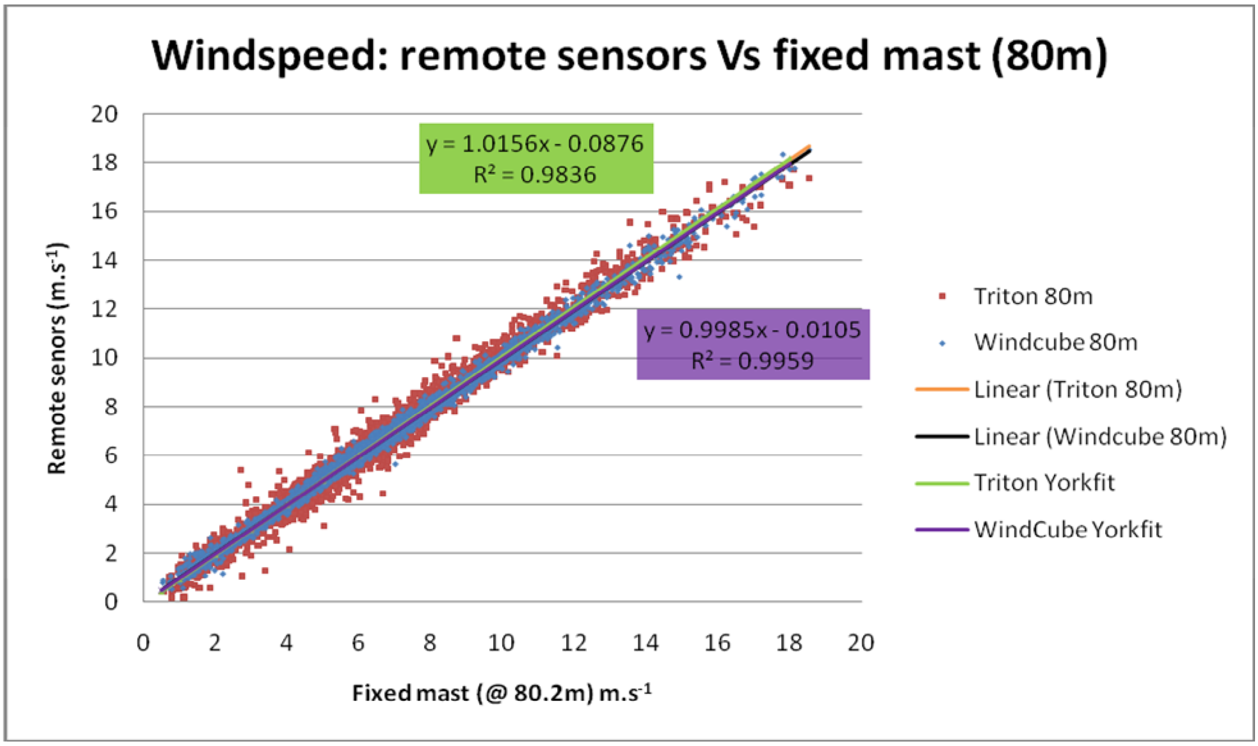
Tower Shadow Filter

A tower shadow filter was applied to the data from the fixed mast. This removed data for when the wind direction was within a 30° arc of the instruments' boom inverses. This filter made a negligible impact on the quality of the correlations obtained. The data losses from this filter are shown in the table below.

	Fixed mast mean wind direction: ≠ boom inverse ± 15°	
	Height (m)	Data Losses
Anemometer	62	2.64%
Anemometer	80.2	9.39%
Wind vane	74	2.91%
Wind vane	80.2	9.39%

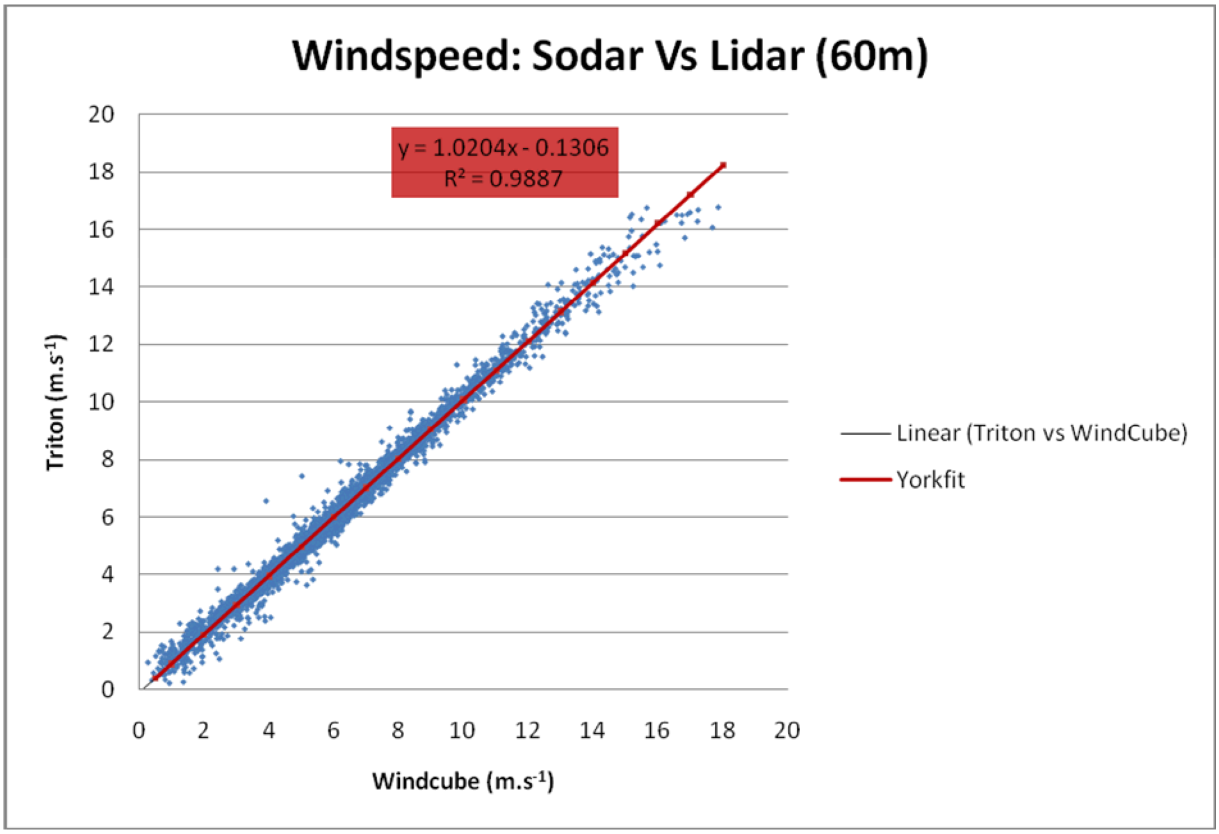
APPENDIX C WIND SPEED

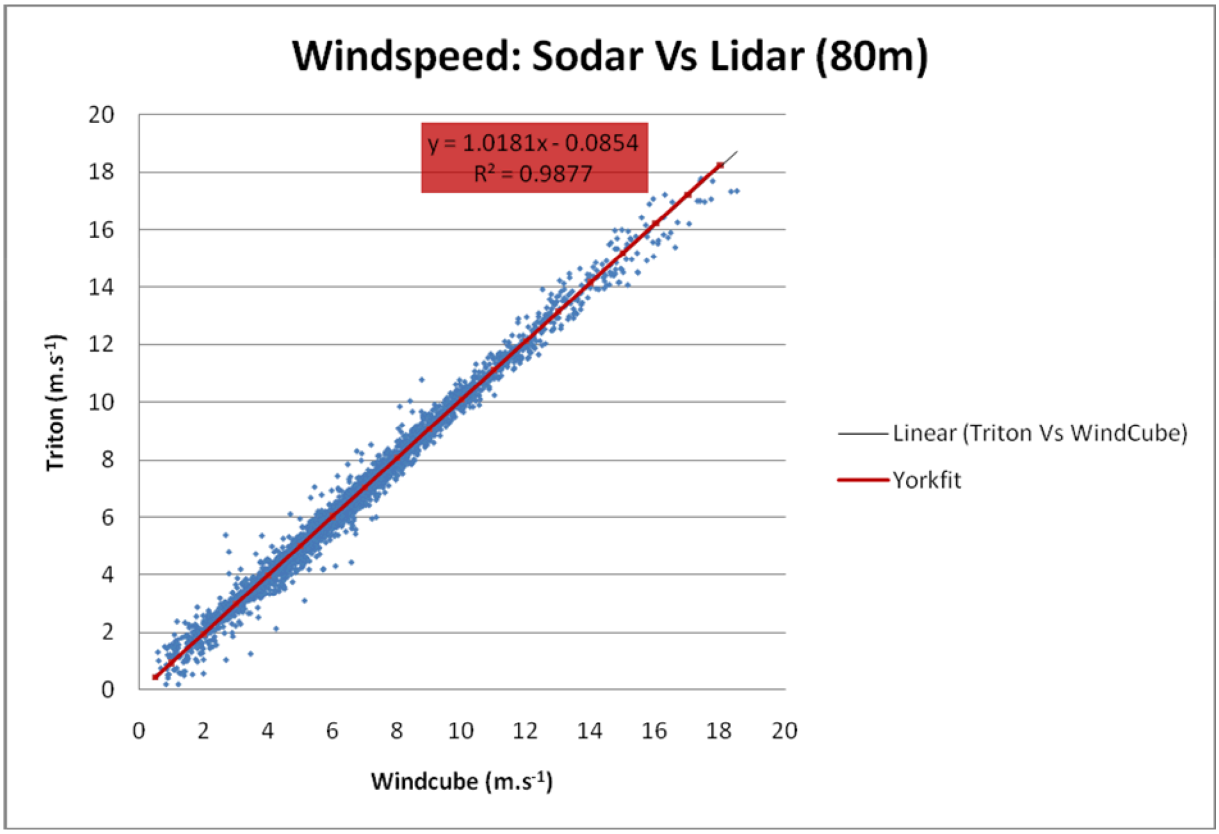


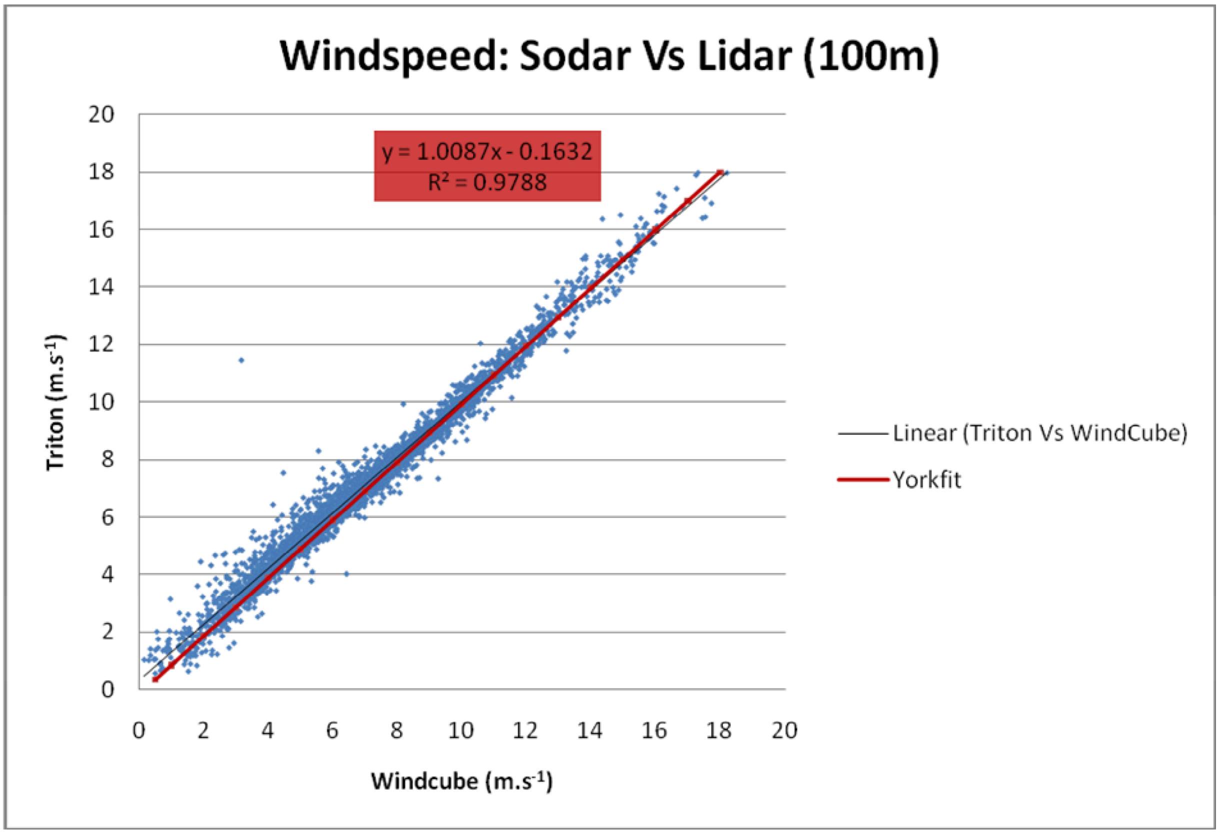


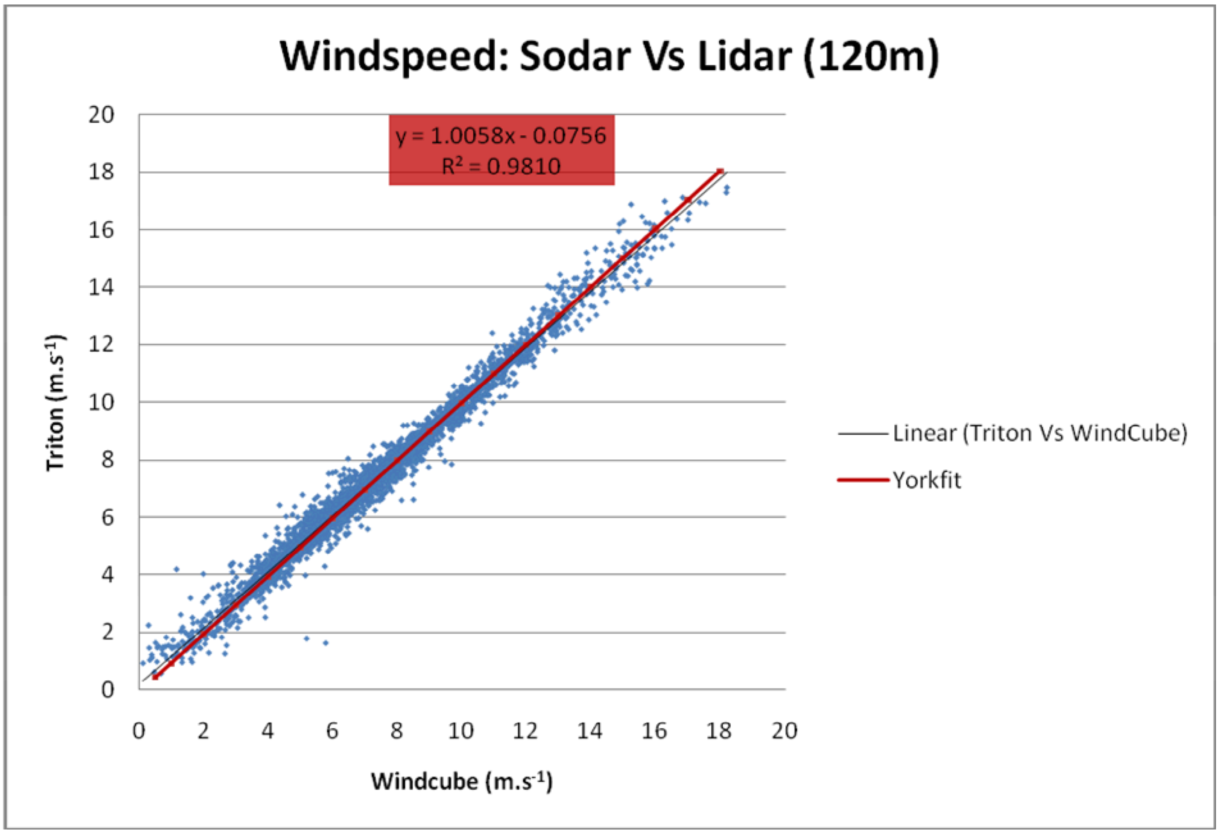
Correlation of wind speed (Least Squares Regression)						
	Triton			WINDCUBE		
	Gradient	Intercept	R^2	Gradient	Intercept	R^2
60	1.0243	-0.0876	0.9818	1.0070	0.0274	0.9941
80	1.0106	-0.0596	0.9836	0.9965	0.0025	0.9959

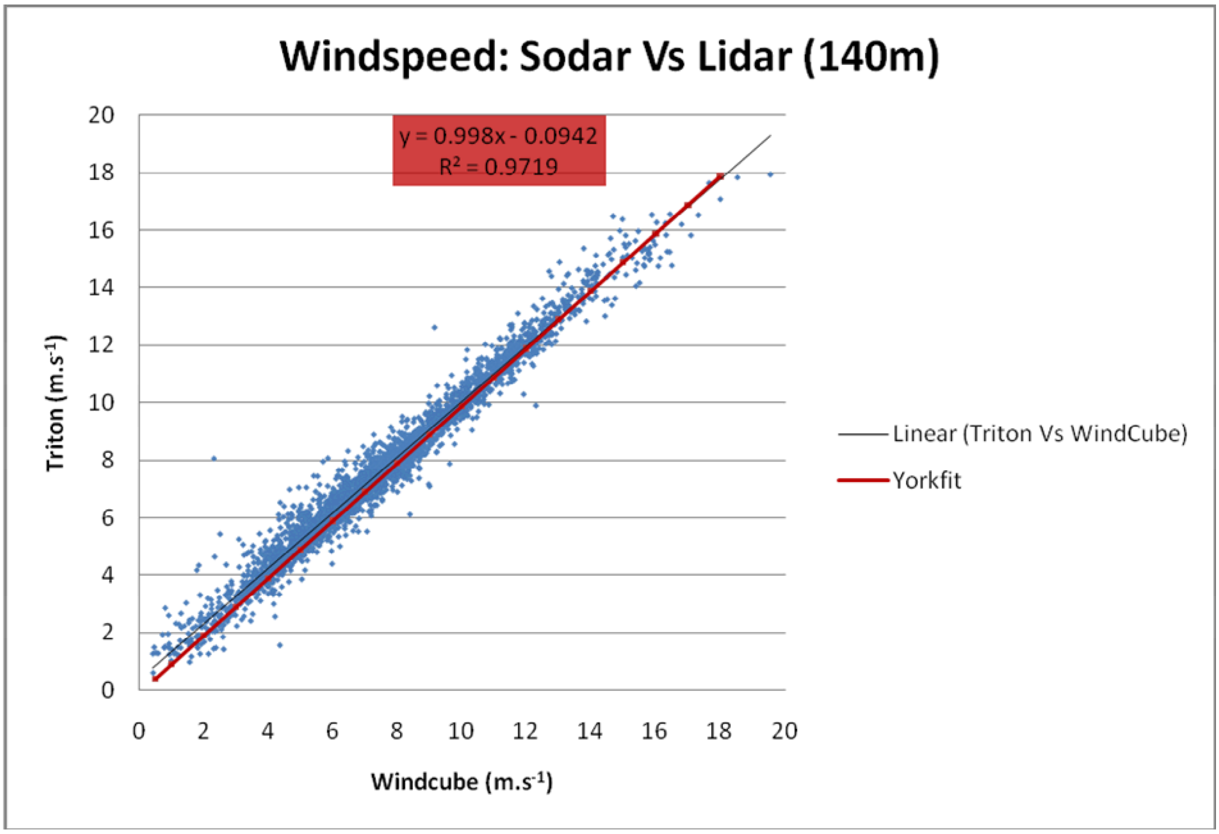
Correlation of wind speed (Orthogonal Regression)						
	Triton			WINDCUBE		
	Gradient	Intercept	R^2	Gradient	Intercept	R^2
60	1.0339	-0.1452	0.9817	1.0100	0.0096	0.9941
80	1.0156	-0.0876	0.9836	0.9985	-0.0105	0.9959

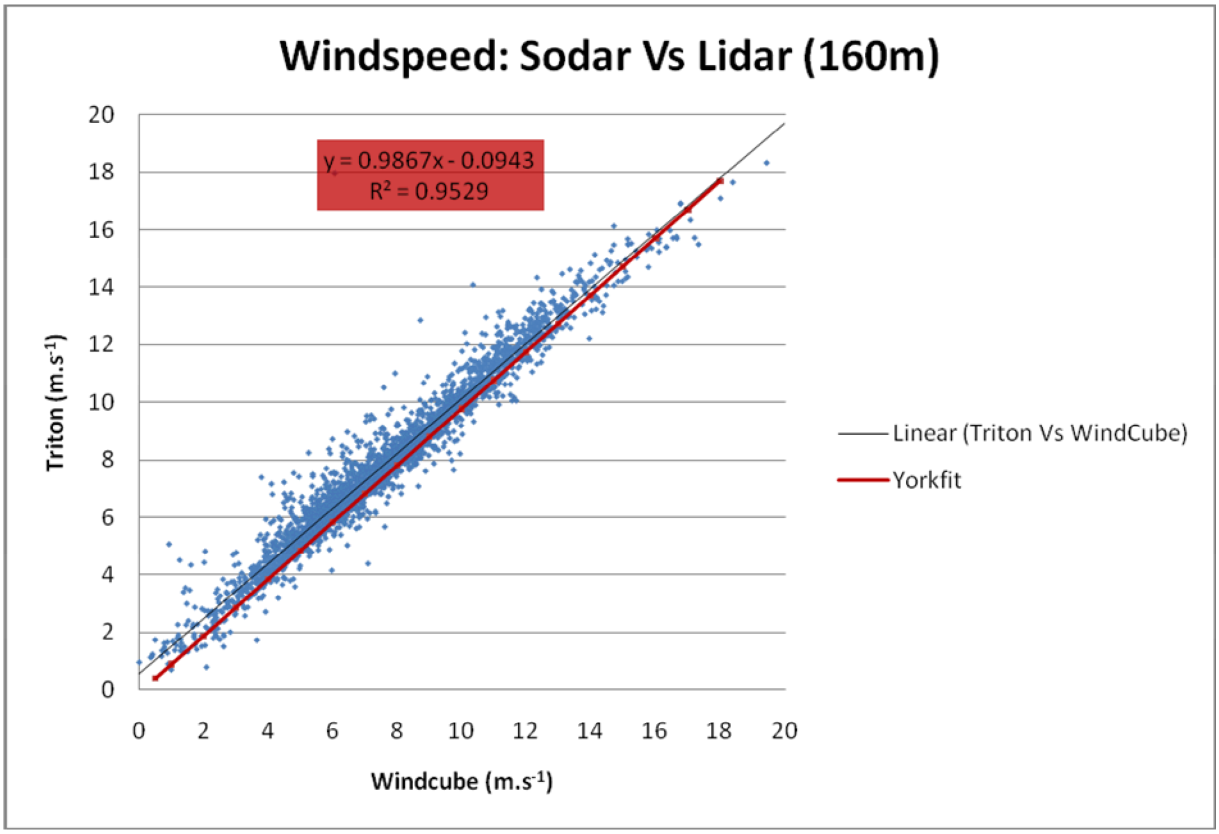


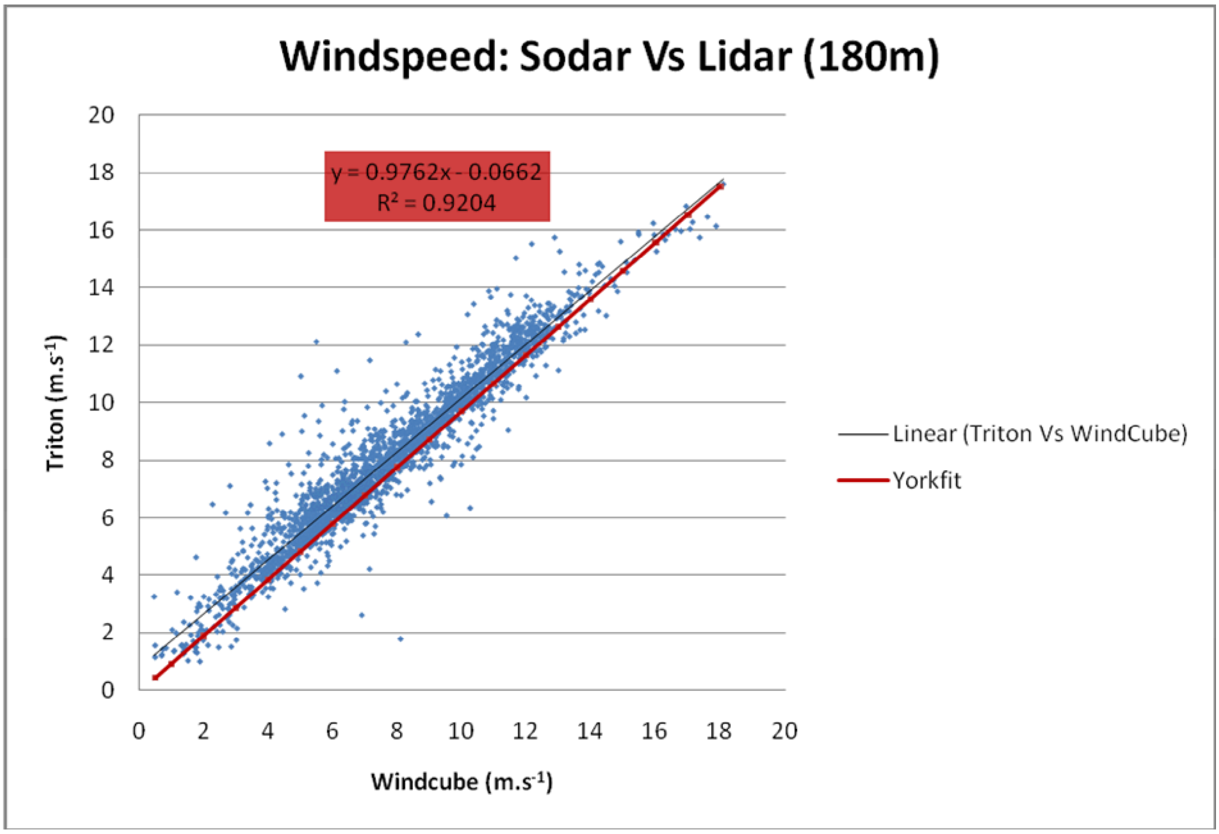

Windspeed: Sodar Vs Lidar (80m)
y = 1.0181x - 0.0854
R² = 0.9877
Triton (m.s-1)
Windcube (m.s-1)
0
2
4
6
8
10
12
14
16
18
20
Linear (Triton Vs WindCube)
Yorkfit

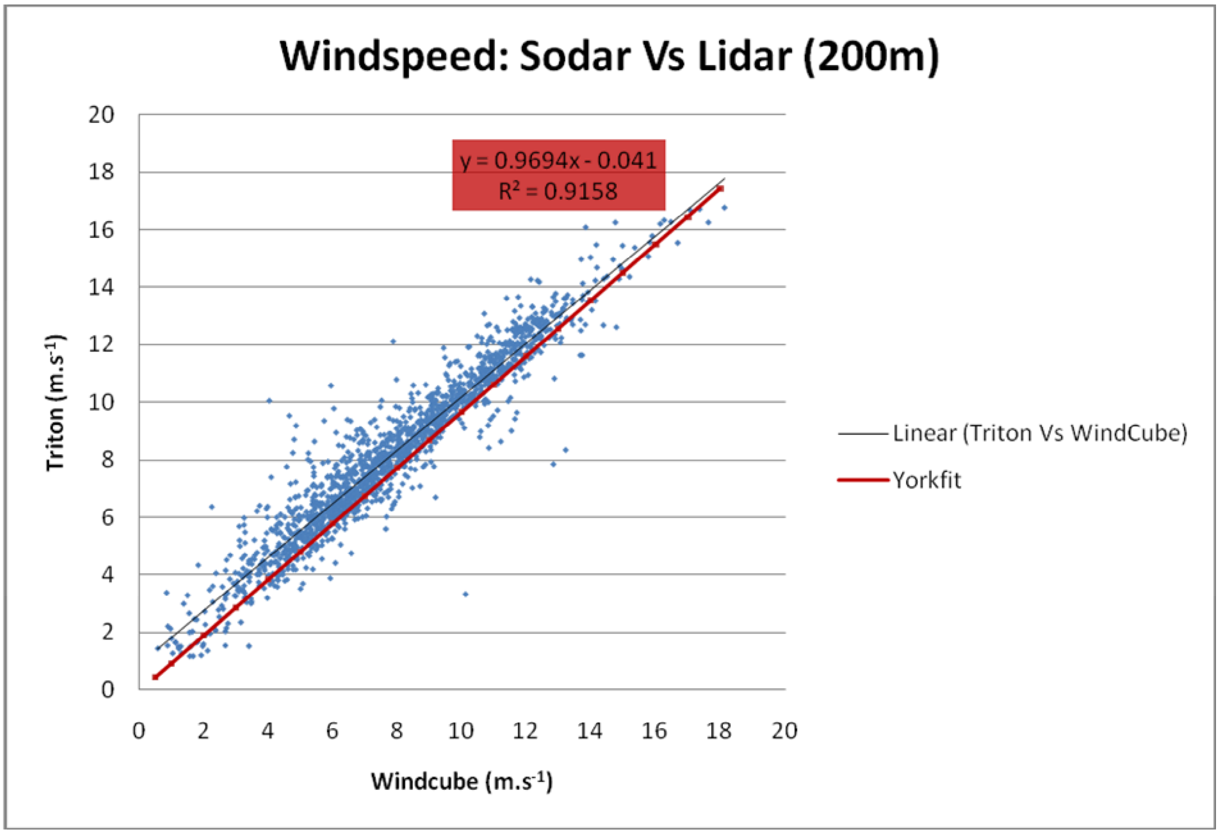

Windspeed: Sodar Vs Lidar (100m)
y = 1.0087x - 0.1632
R² = 0.9788
Triton (m.s-1)
Windcube (m.s-1)
0
2
4
6
8
10
12
14
16
18
20
Linear (Triton Vs WindCube)
Yorkfit


Windspeed: Sodar Vs Lidar (120m)
y = 1.0058x - 0.0756
R² = 0.9810
Triton (m.s-1)
Windcube (m.s-1)
Linear (Triton Vs WindCube)
Yorkfit


Windspeed: Sodar Vs Lidar (140m)
y = 0.998x - 0.0942
R² = 0.9719
Triton (m.s-1)
Windcube (m.s-1)
Linear (Triton Vs WindCube)
Yorkfit

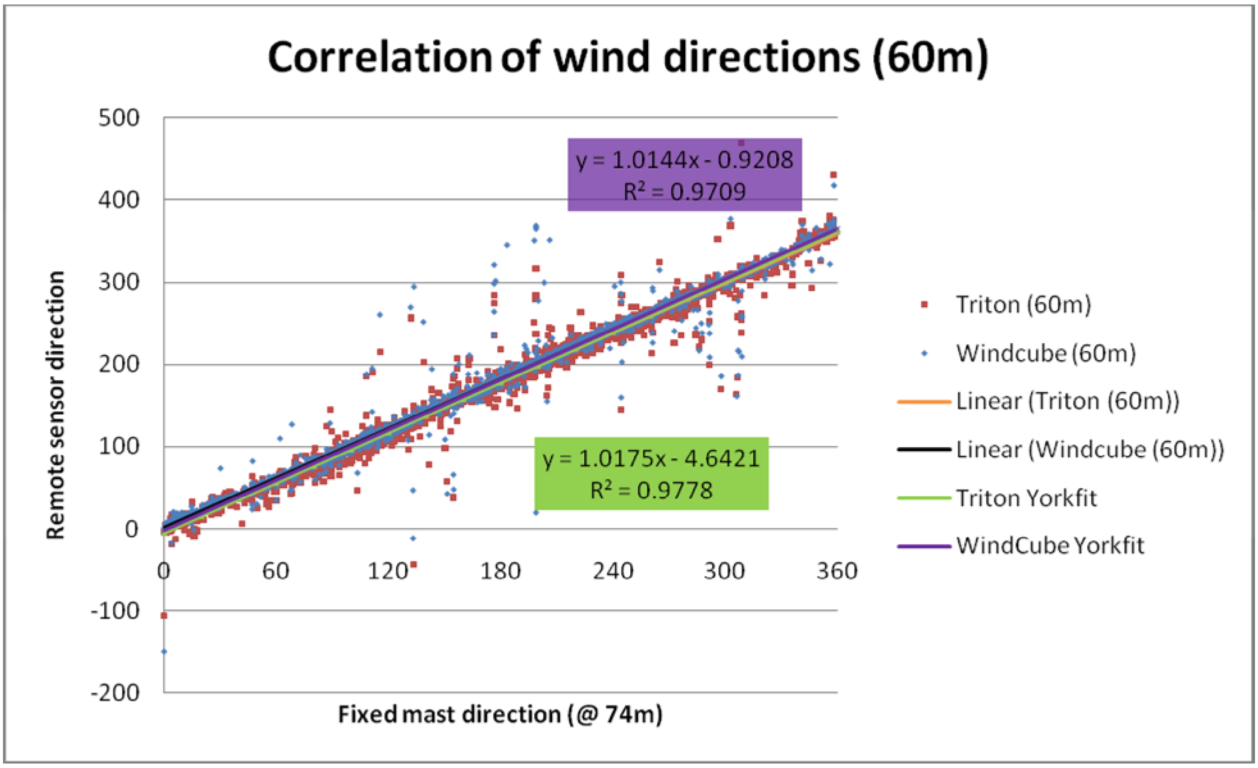

Windspeed: Sodar Vs Lidar (160m)
y = 0.9867x - 0.0943
R² = 0.9529
Triton (m.s-1)
Windcube (m.s-1)
0
2
4
6
8
10
12
14
16
18
20
Linear (Triton Vs WindCube)
Yorkfit

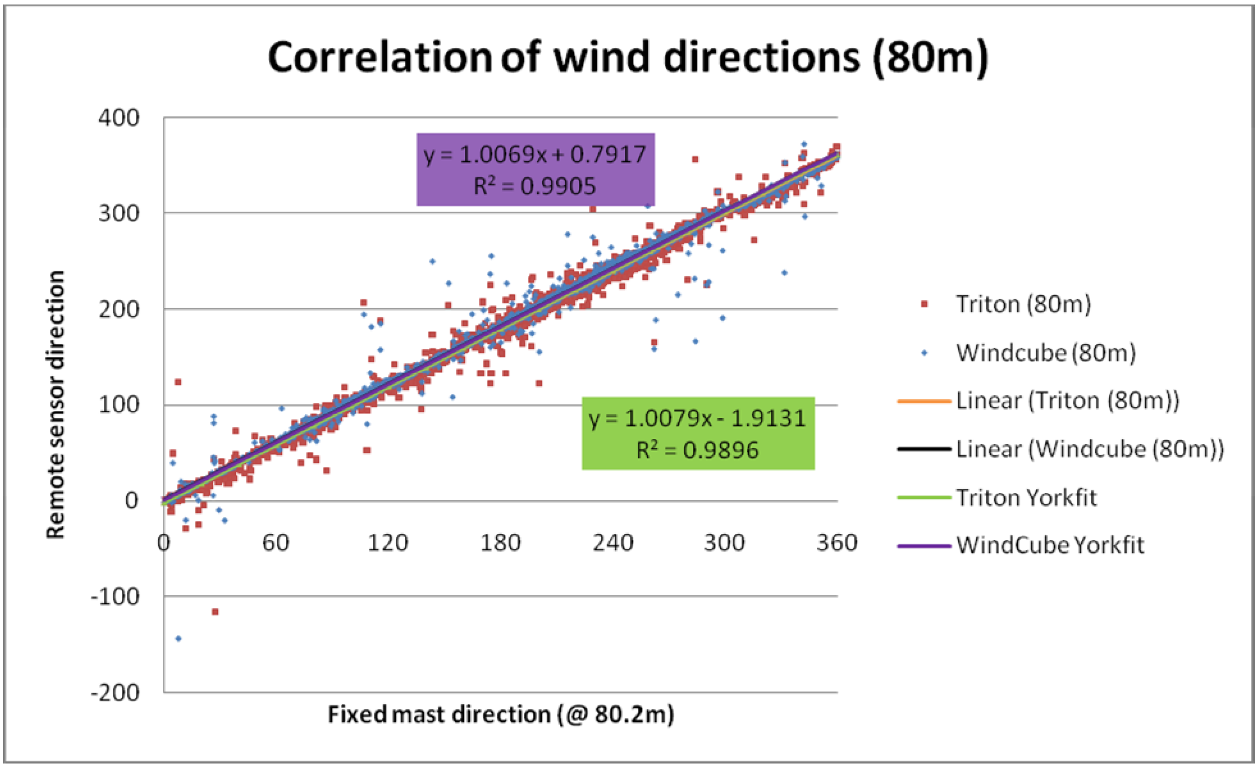

Windspeed: Sodar Vs Lidar (180m)
y = 0.9762x - 0.0662
R² = 0.9204
Triton (m.s-1)
Windcube (m.s-1)
0
2
4
6
8
10
12
14
16
18
20
Linear (Triton Vs WindCube)
Yorkfit



Correlation of wind speed (Least Squares Regression)			
	Triton Vs WINDCUBE		
	Gradient	Intercept	R^2
60	1.0176	-0.1173	0.9887
80	1.0152	-0.0709	0.9877
100	0.9695	0.3259	0.9788
120	0.9754	0.2228	0.9810
140	0.9677	0.3757	0.9720
160	0.9555	0.5802	0.9532
180	0.9378	0.7925	0.9207
200	0.9318	0.8925	0.9164
Correlation of wind speed (Orthogonal Regression)			
	Triton Vs WINDCUBE		
	Gradient	Intercept	R^2
60	1.0204	-0.1306	0.9887
80	1.0181	-0.0854	0.9877
100	1.0087	-0.1632	0.9788
120	1.0058	-0.0756	0.9810
140	0.9980	-0.0942	0.9719
160	0.9867	-0.0943	0.9529
180	0.9762	-0.0662	0.9204
200	0.9694	-0.0410	0.9158

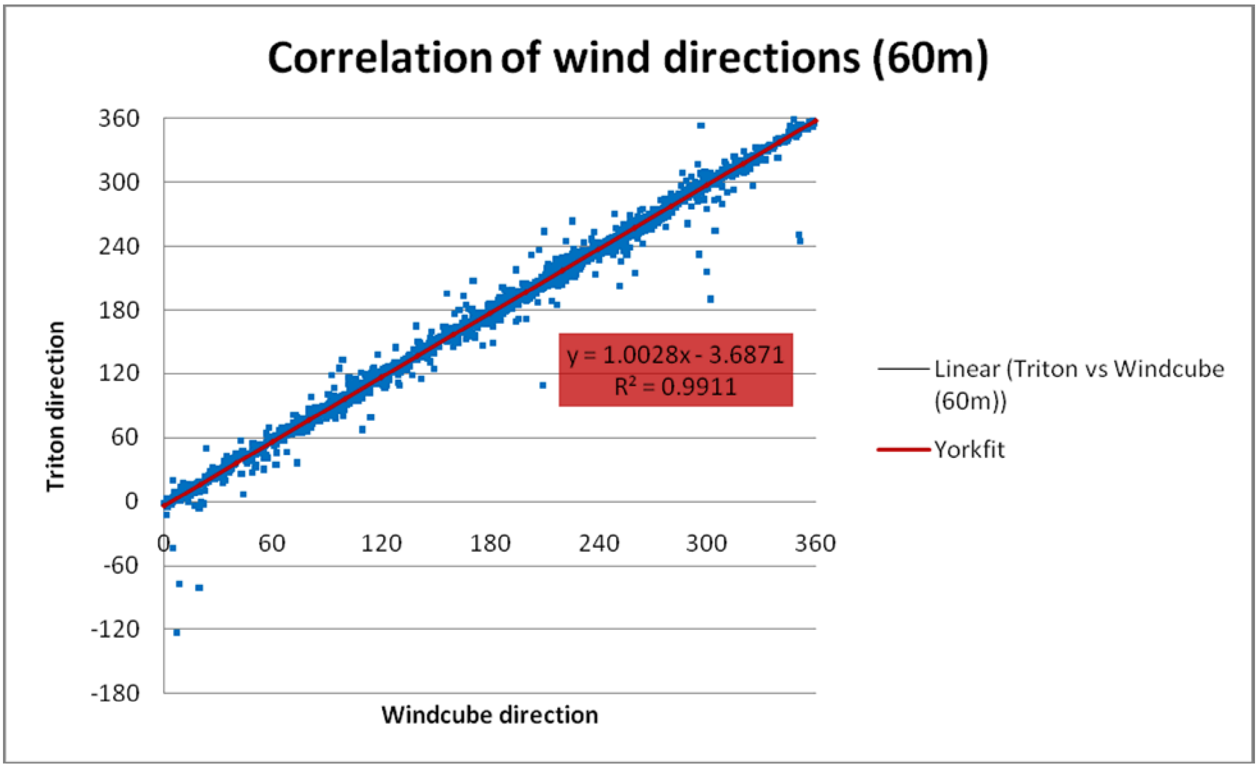
APPENDIX D WIND DIRECTION

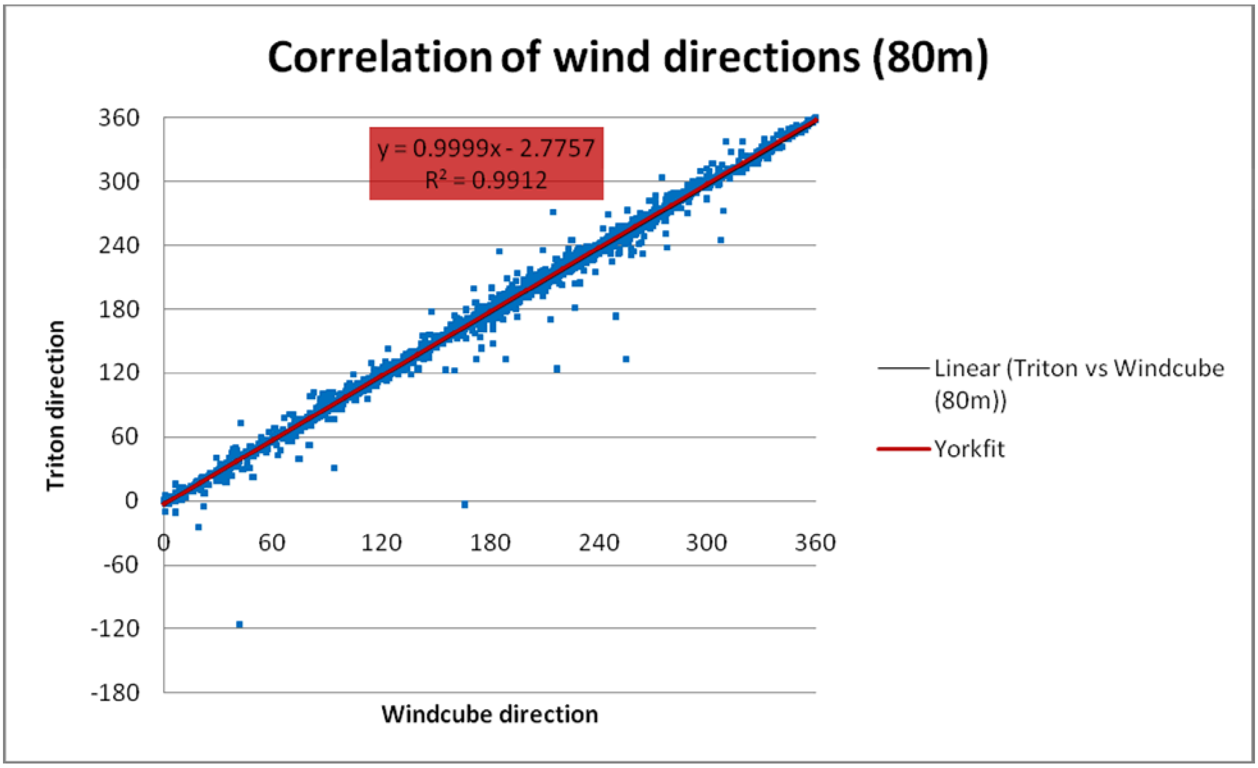


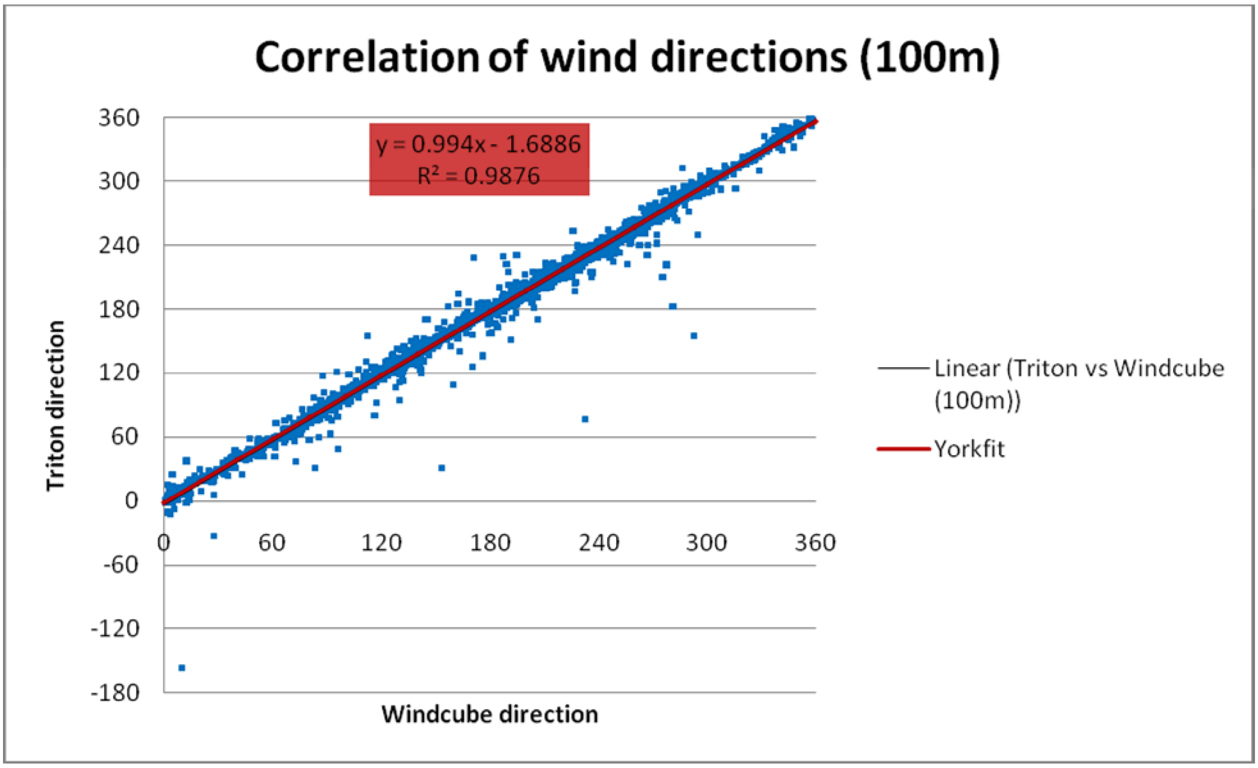


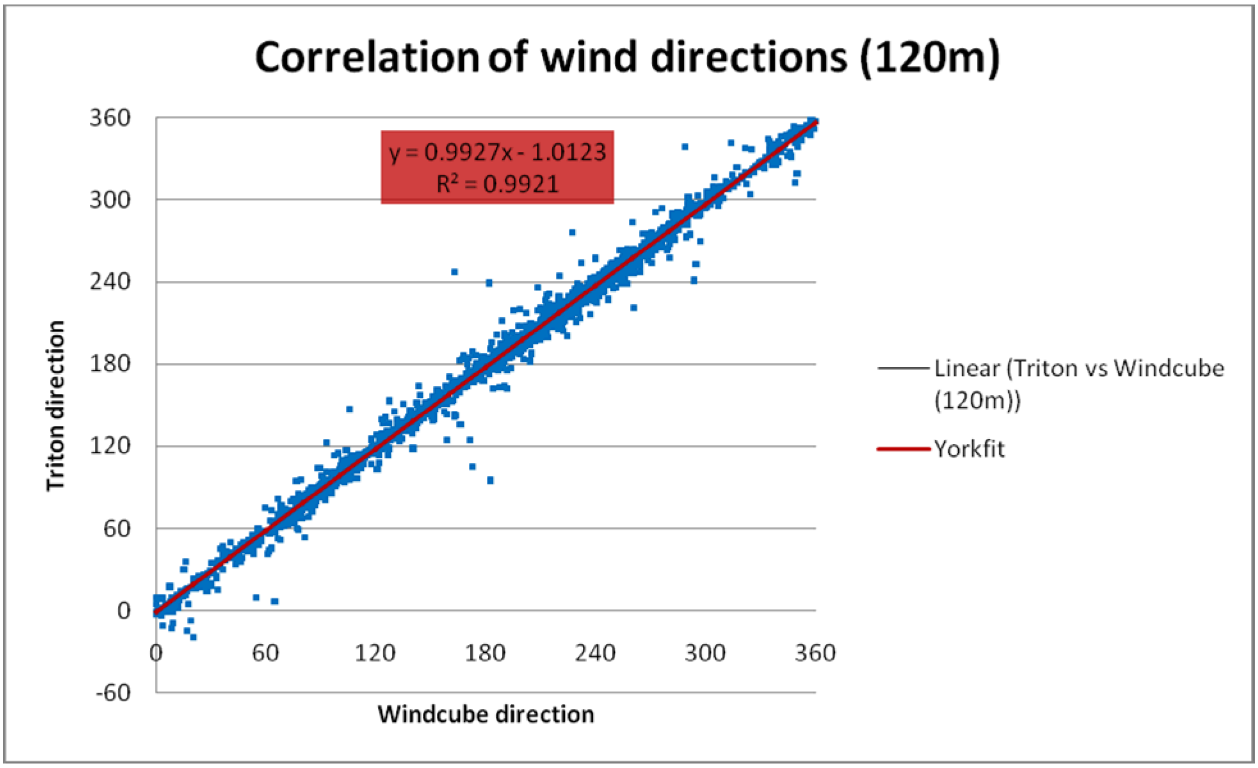
Correlation of direction (Least Squares Regression)						
	Triton			WINDCUBE		
	Gradient	Intercept	R^2	Gradient	Intercept	R^2
60	1.0061	-2.3681	0.9780	0.9995	2.0543	0.9711
80	1.0062	-1.6893	0.9896	1.0021	1.7440	0.9906

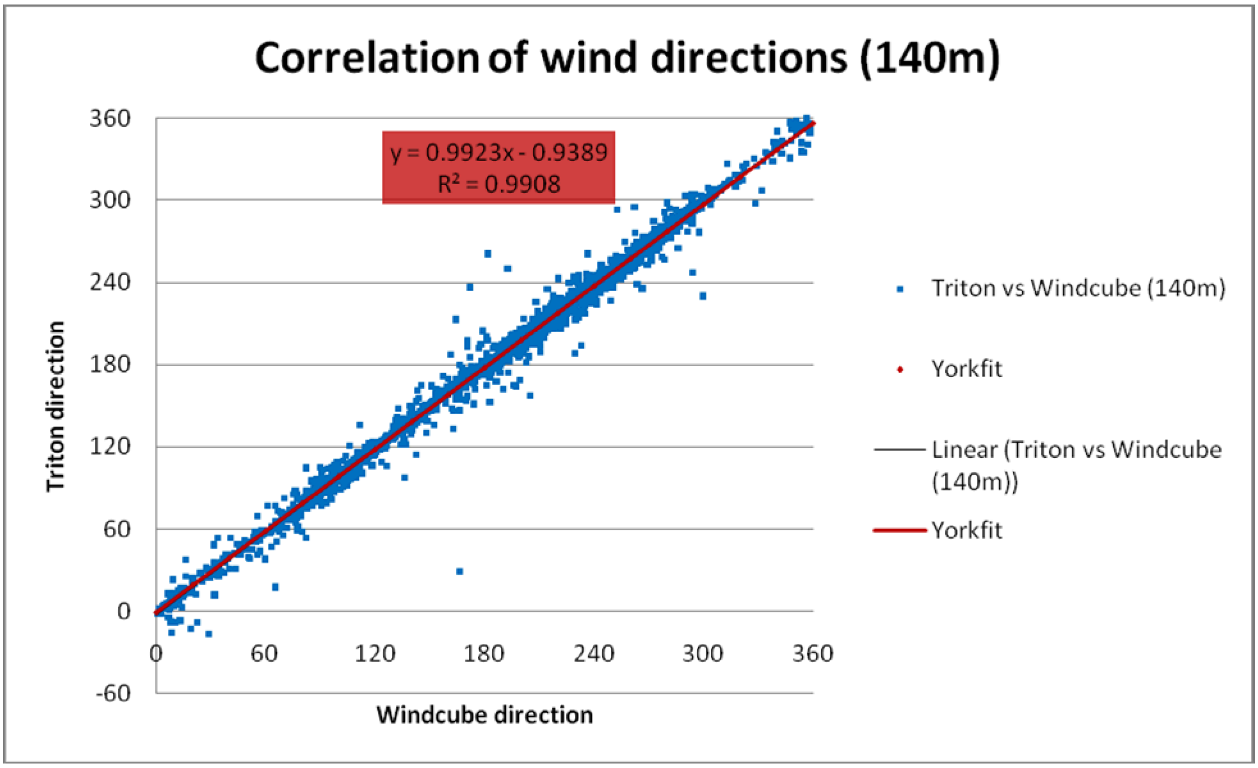
Correlation of direction (Orthogonal Regression)						
	Triton			WINDCUBE		
	Gradient	Intercept	R^2	Gradient	Intercept	R^2
60	1.0175	-4.6421	0.9778	1.0144	-0.9208	0.9709
80	1.0079	-1.9131	0.9896	1.0069	0.7917	0.9905

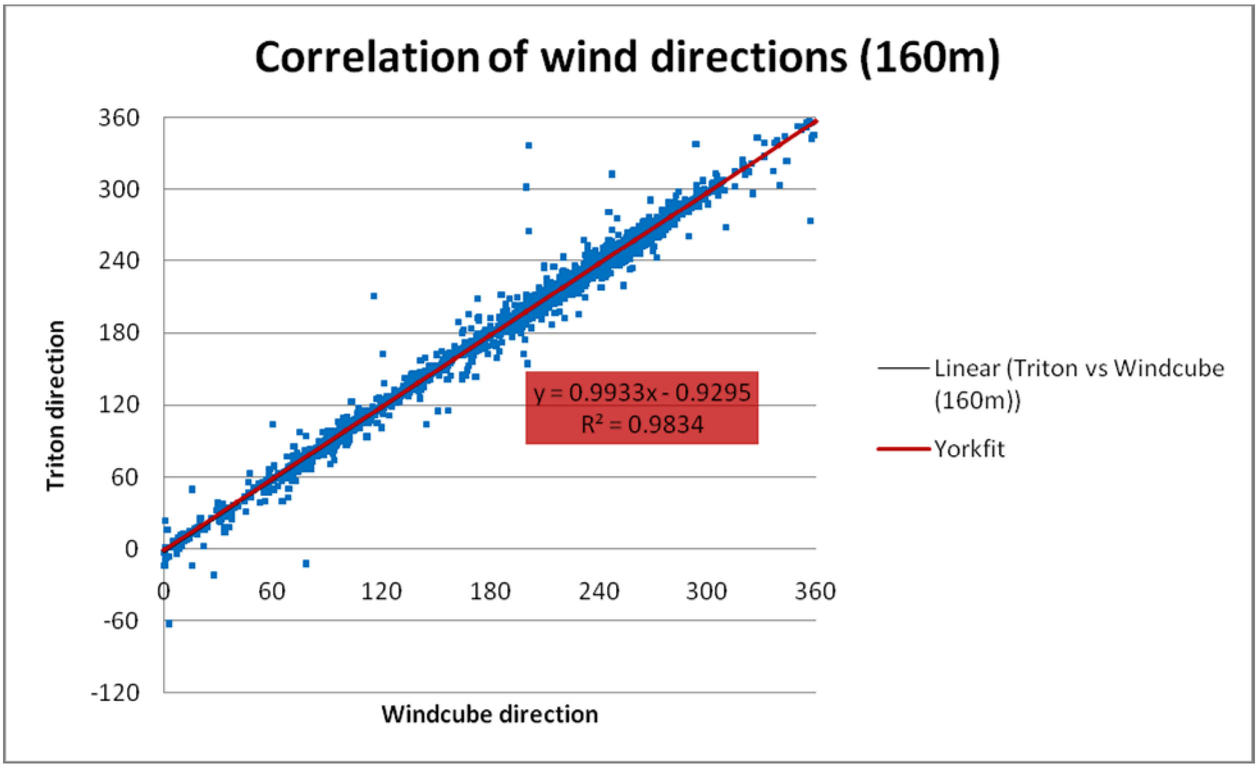



Correlation of wind directions (80m)
y = 0.9999x - 2.7757
R² = 0.9912
360
300
240
180
120
60
0
-60
-120
-180
Triton direction
0
60
120
180
240
300
360
Windcube direction
Linear (Triton vs Windcube (80m))
Yorkfit

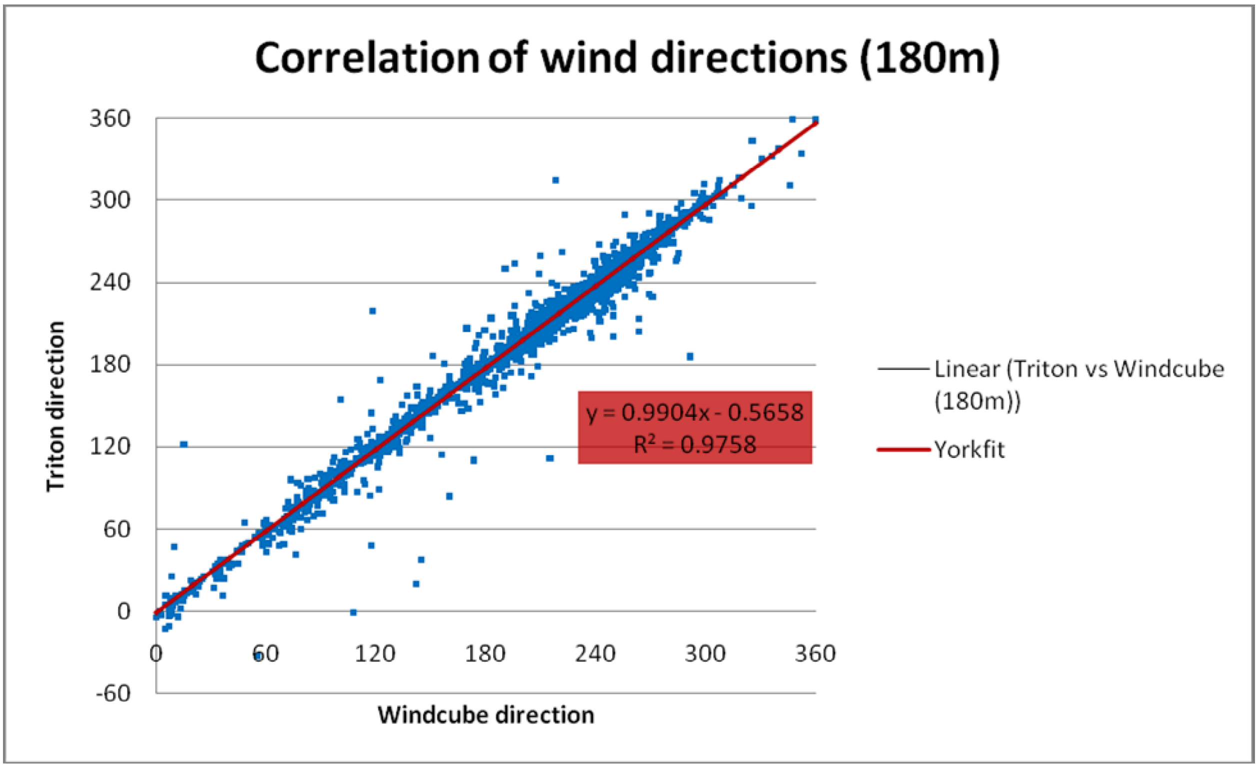

Correlation of wind directions (100m)
y = 0.994x - 1.6886
R² = 0.9876
360
300
240
180
120
60
0
-60
-120
-180
Triton direction
0
60
120
180
240
300
360
Windcube direction
Linear (Triton vs Windcube (100m))
Yorkfit


Correlation of wind directions (120m)
y = 0.9927x - 1.0123
R² = 0.9921
360
300
240
180
120
60
0
-60
Triton direction
0
60
120
180
240
300
360
Windcube direction
Linear (Triton vs Windcube (120m))
Yorkfit

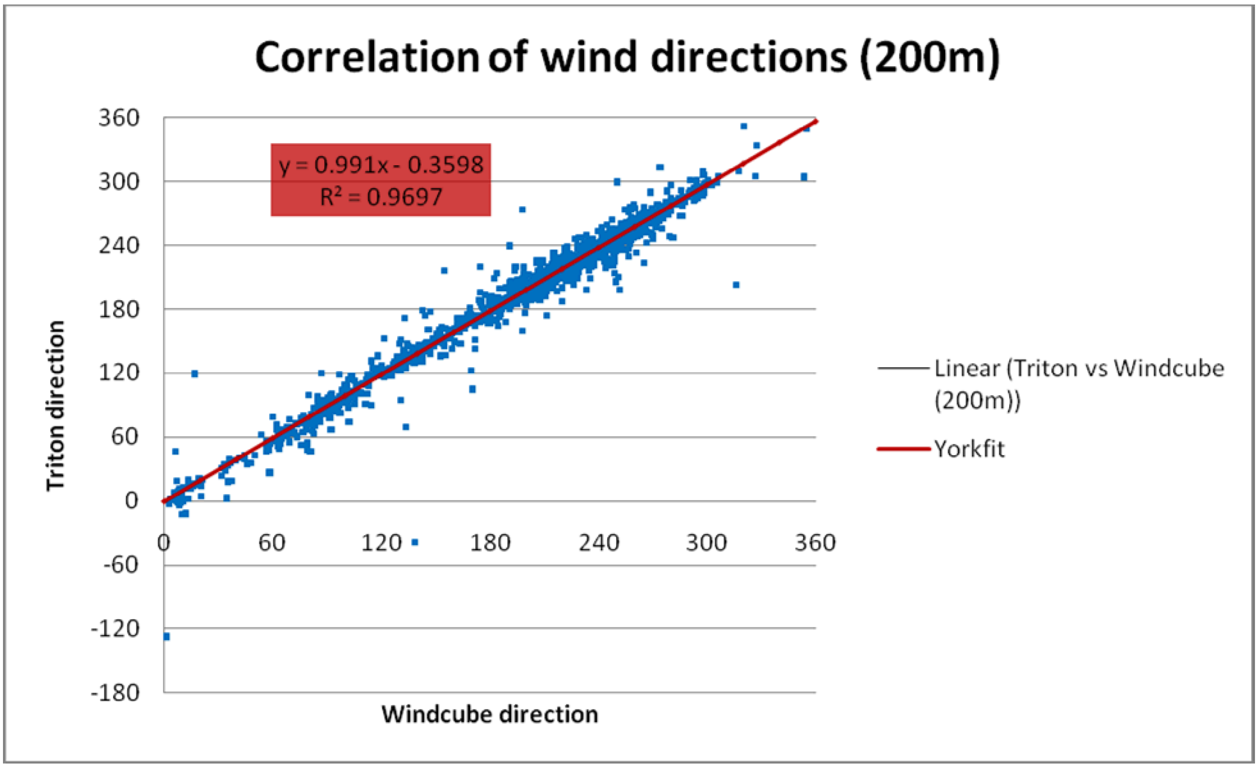

Correlation of wind directions (140m)
y = 0.9923x - 0.9389
R² = 0.9908
360
300
240
180
120
60
0
-60
Triton direction
0
60
120
180
240
300
360
Windcube direction
Triton vs Windcube (140m)
Yorkfit
Linear (Triton vs Windcube (140m))
Yorkfit



Correlation of wind directions (160m)
360
300
240
180
120
60
0
-60
-120
Triton direction
0
60
120
180
240
300
360
Windcube direction
y = 0.9933x - 0.9295
R² = 0.9834
Linear (Triton vs Windcube (160m))
Yorkfit

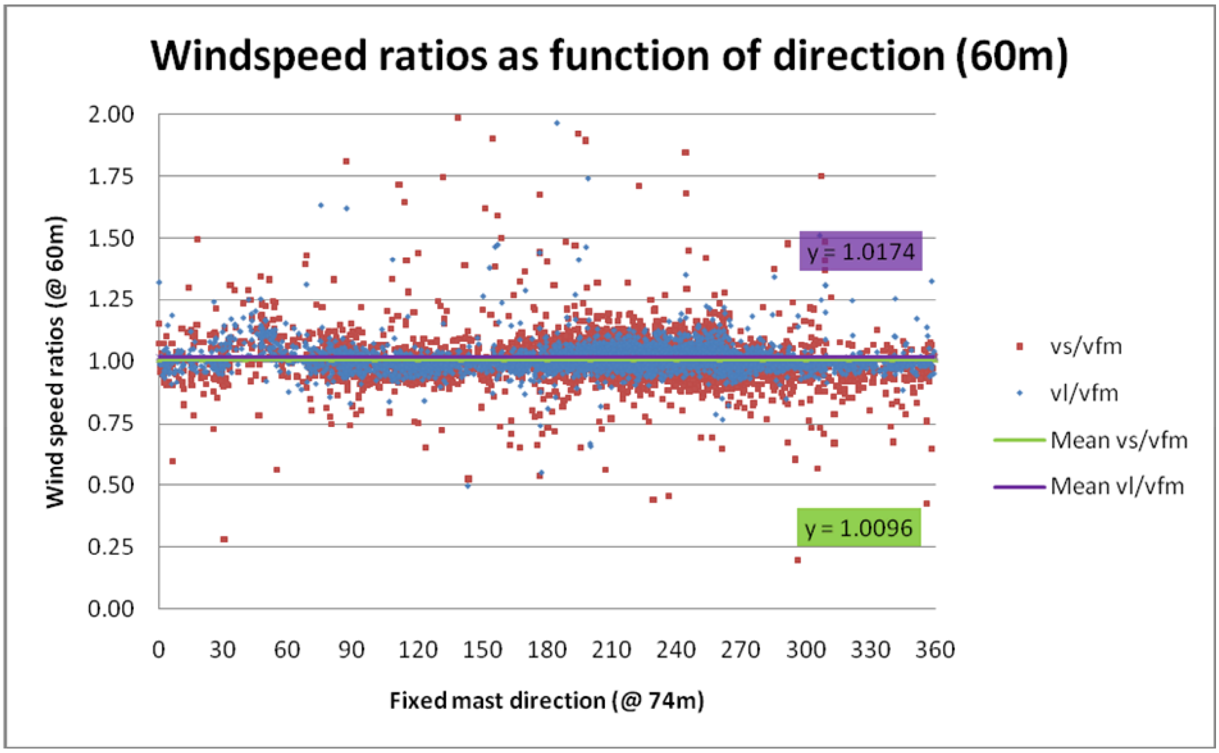


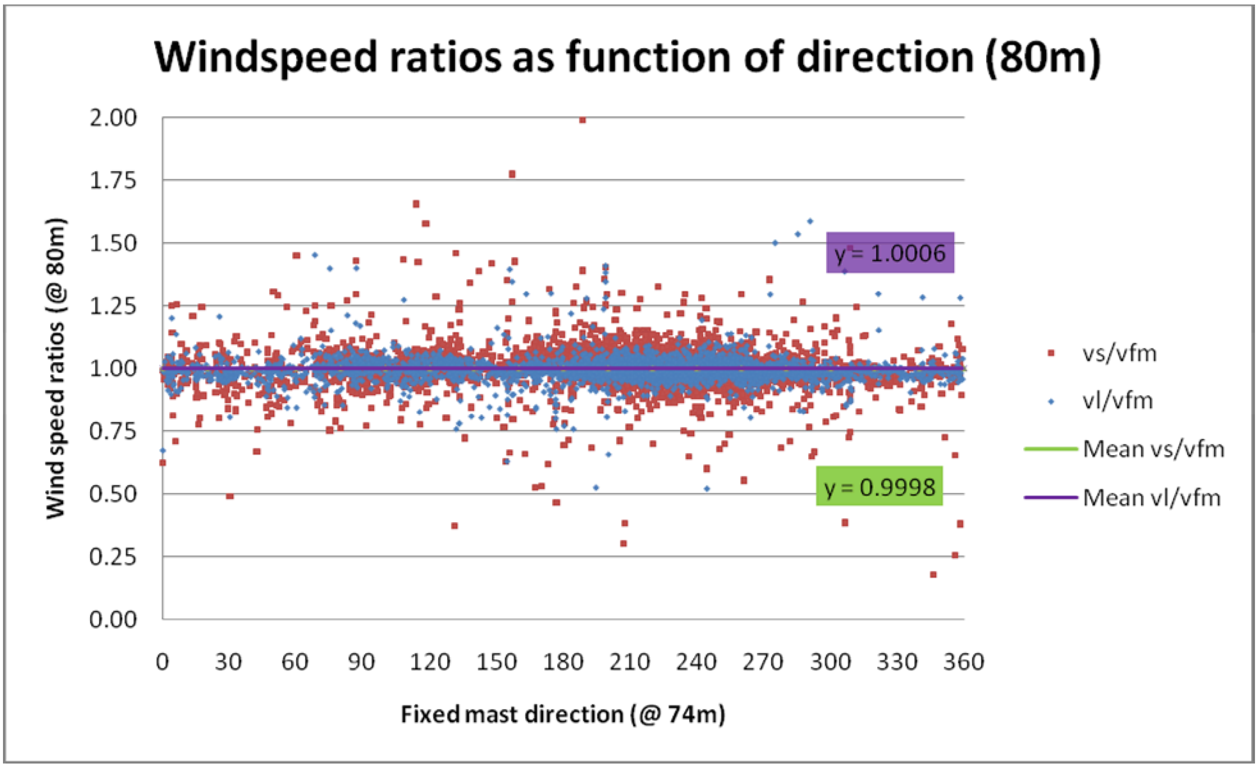
Correlation of wind directions (180m)
360
300
240
180
120
60
0
-60
Triton direction
0
60
120
180
240
300
360
Windcube direction
y = 0.9904x - 0.5658
R² = 0.9758
Linear (Triton vs Windcube (180m))
Yorkfit



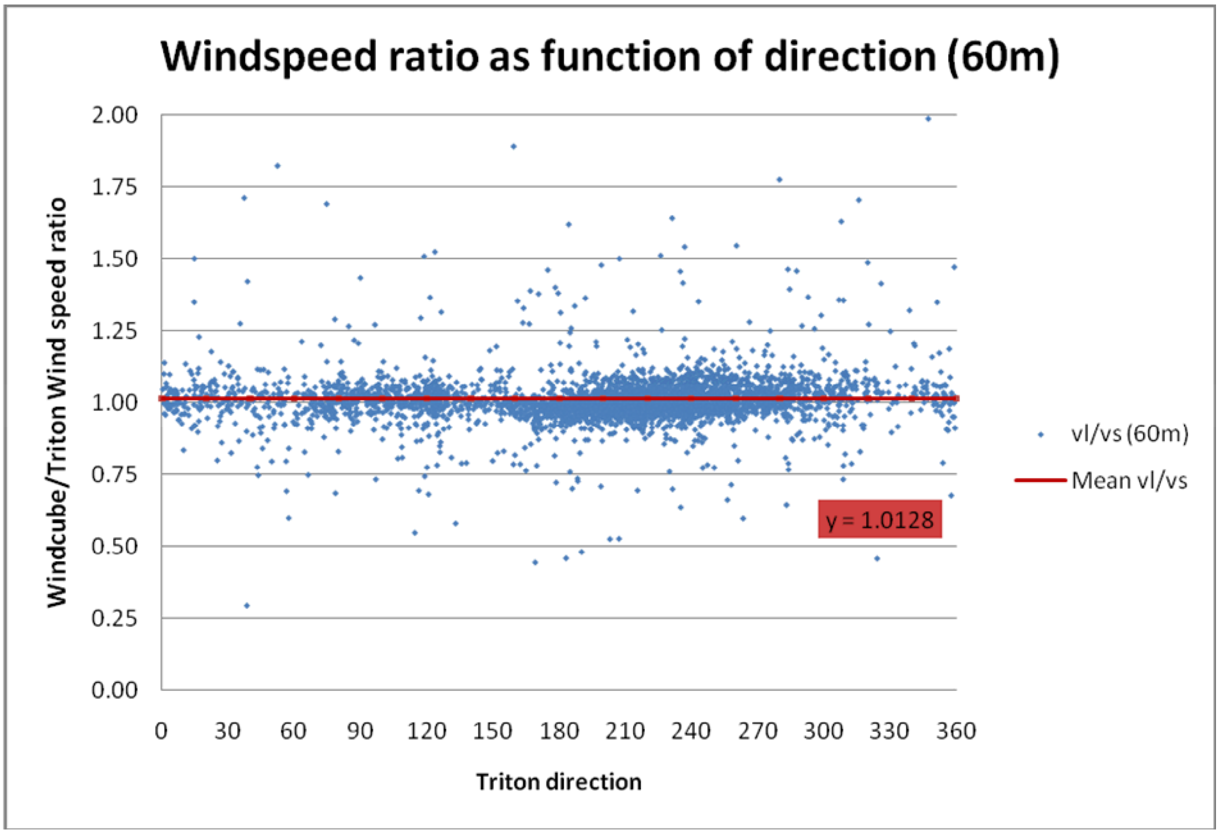
Correlation of direction (Least Squares Regression)			
	Triton Vs WINDCUBE		
	Gradient	Intercept	R^2
60	0.9888	5.4518	0.9911
80	1.0009	-3.1223	0.9912
100	0.9969	-2.4674	0.9885
120	0.9972	-2.0995	0.9927
140	0.9974	-2.2034	0.9908
160	1.0008	-2.7771	0.9835
180	0.9959	-2.064	0.9759
200	0.9987	-2.2683	0.9698
Correlation of direction (Orthogonal Regression)			
	Triton Vs WINDCUBE		
	Gradient	Intercept	R^2
60	1.0028	-3.6871	0.9911
80	0.9999	-2.7757	0.9912
100	0.9940	-1.6886	0.9876
120	0.9927	-1.0123	0.9921
140	0.9923	-0.9389	0.9908
160	0.9933	-0.9295	0.9834
180	0.9904	-0.5658	0.9758
200	0.9910	-0.3598	0.9697

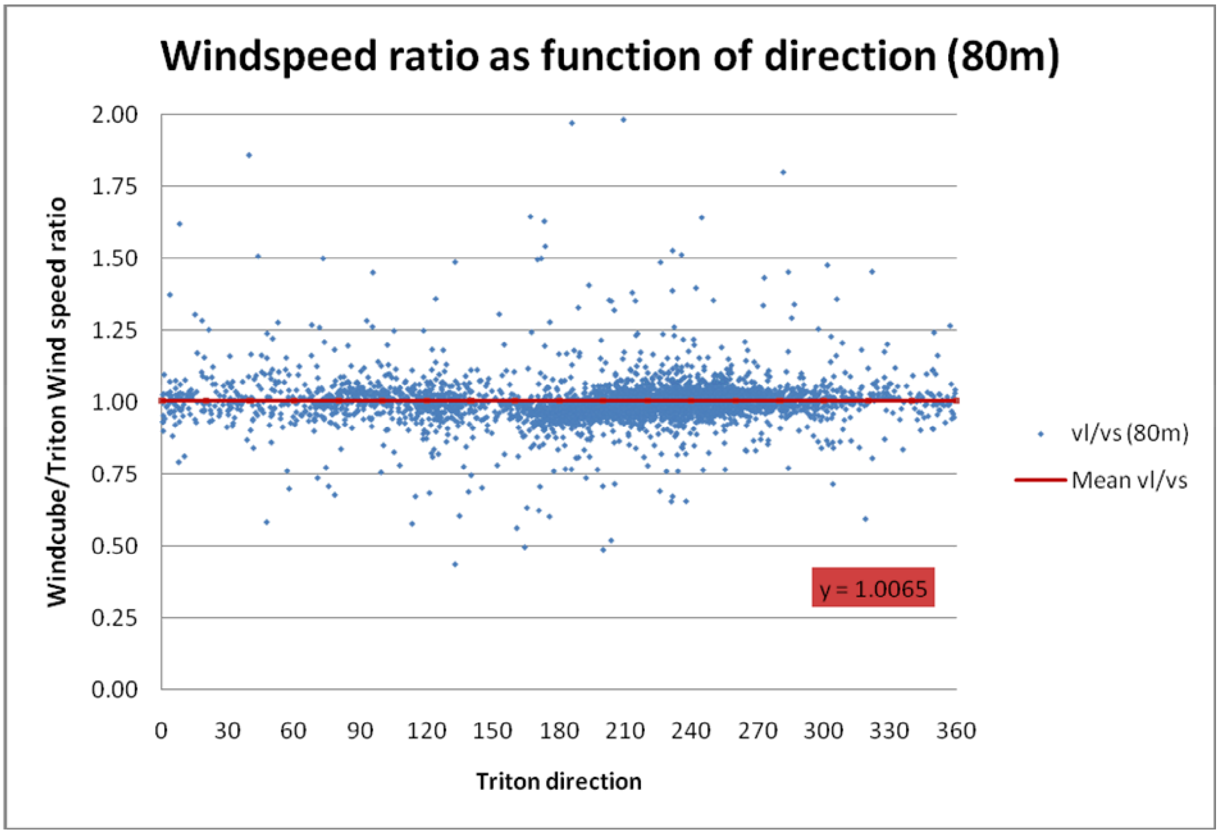
APPENDIX E WIND SPEED RATIOS



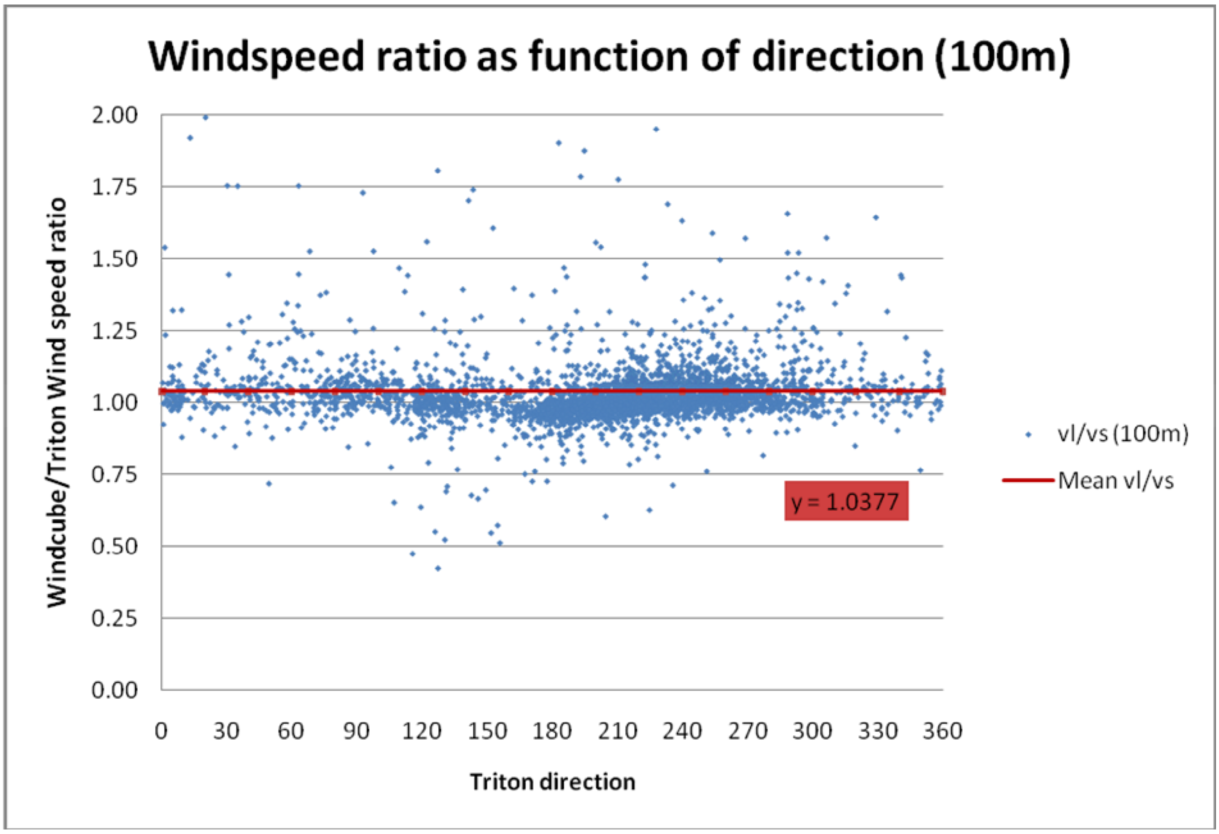


Ratio of wind speed as function of fm direction		
	Triton	WINDCUBE
	Intercept	Intercept
60	1.0096	1.0174
80	0.9998	1.0006

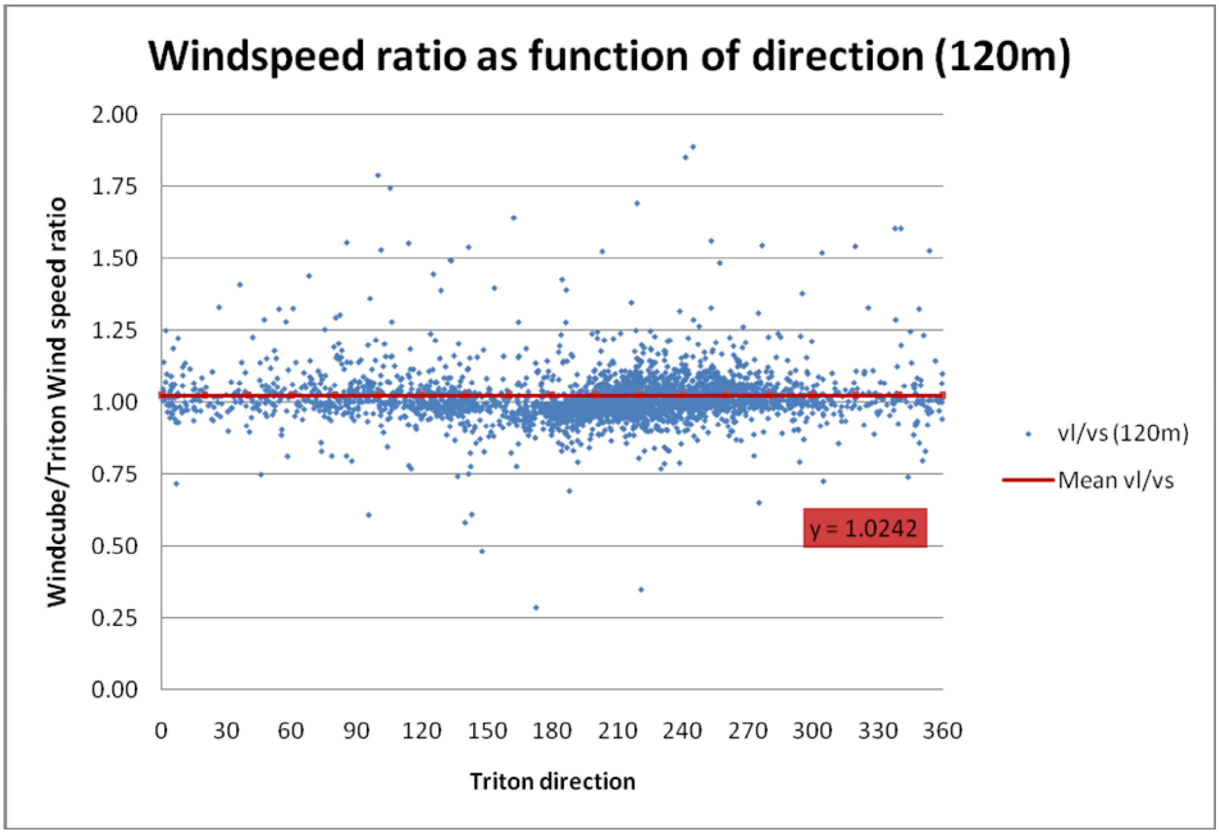


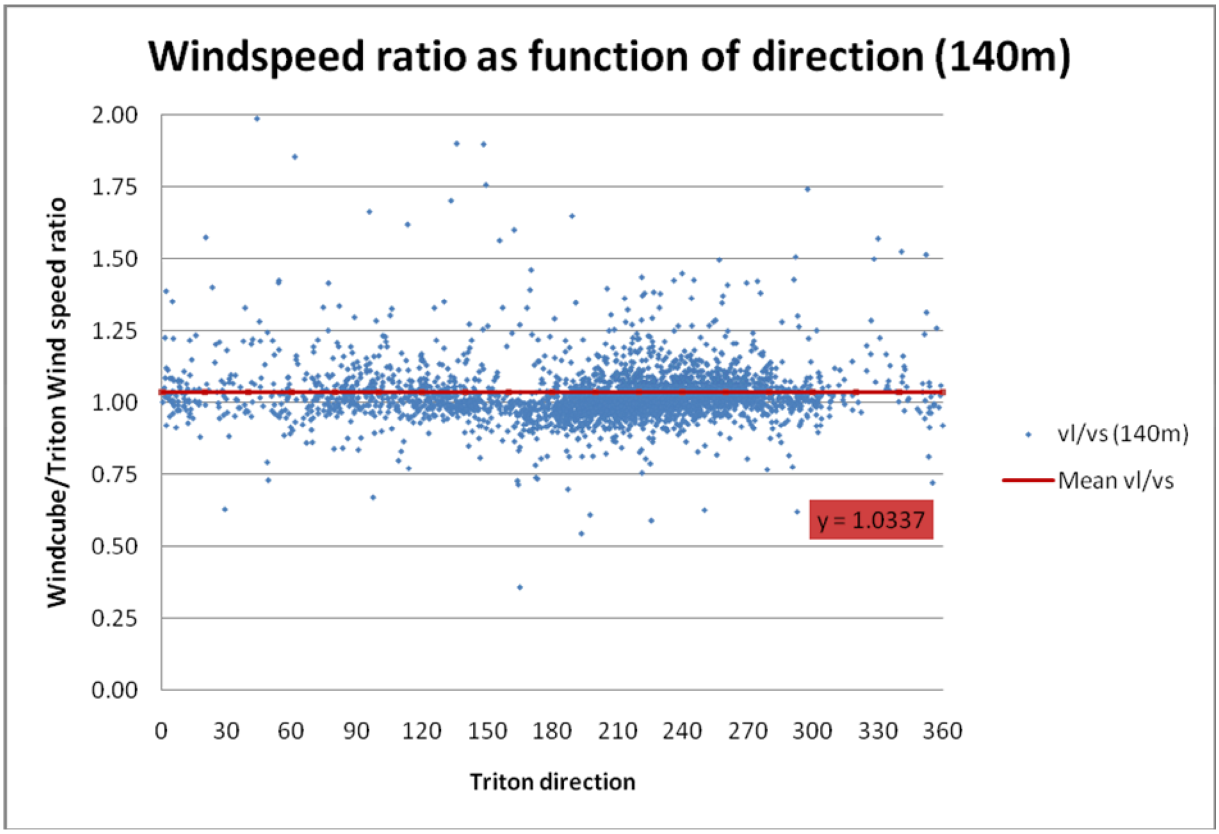


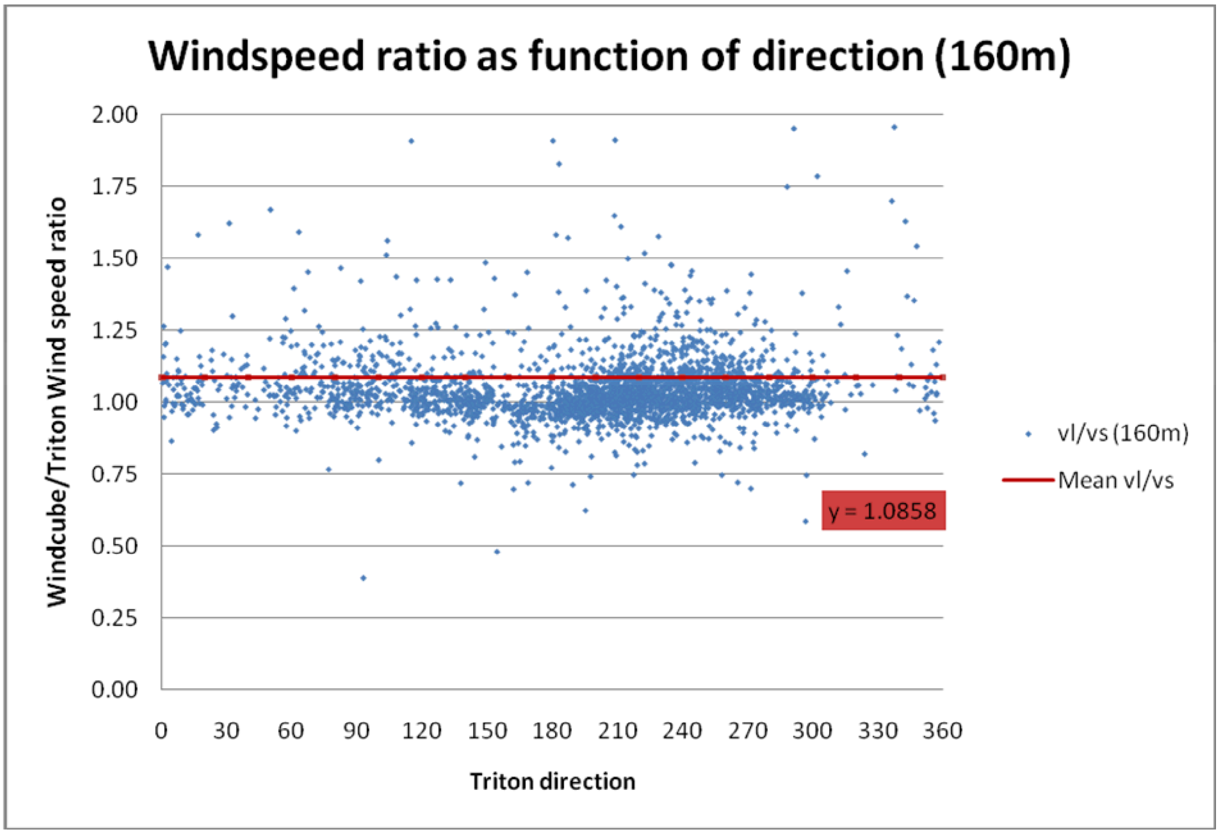
Windspeed ratio as function of direction (80m)
Windcube/Triton Wind speed ratio
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
30
60
90
120
150
180
210
240
270
300
330
360
Triton direction
vl/vs (80m)
Mean vl/vs
y = 1.0065

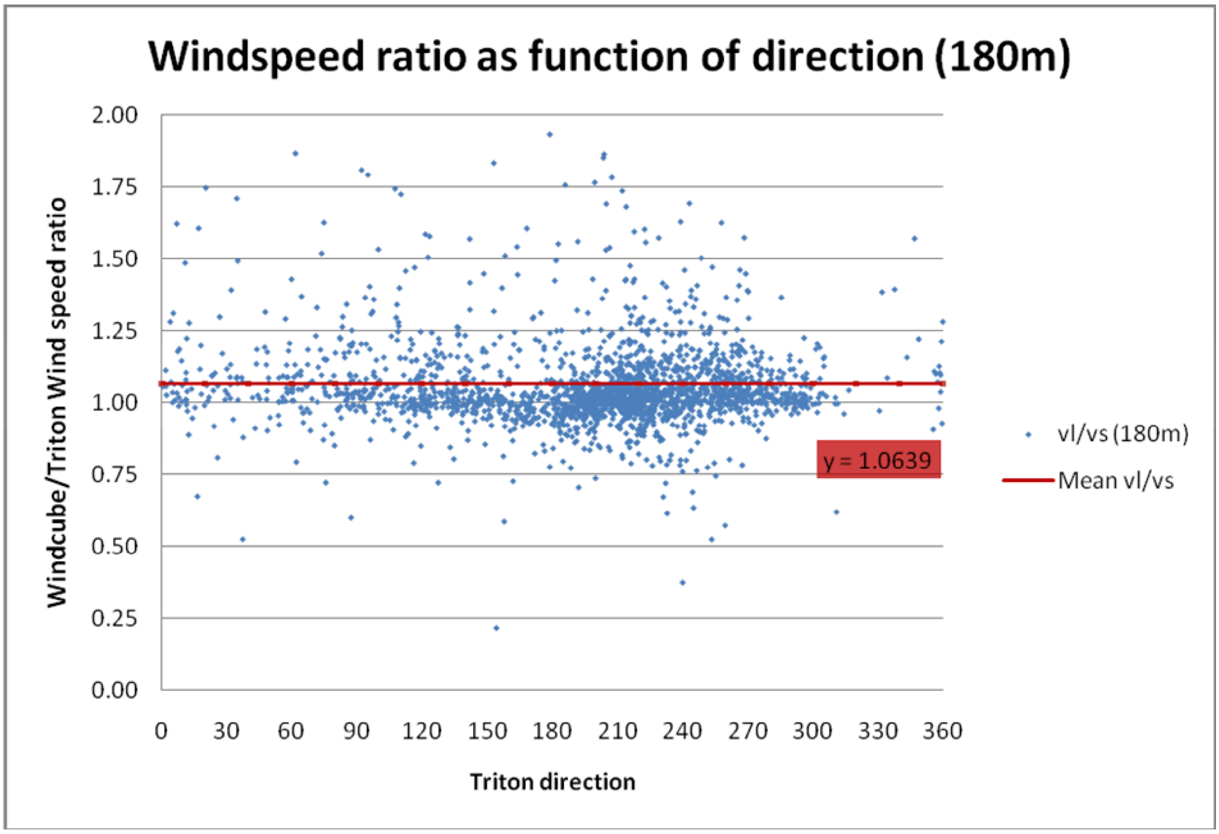


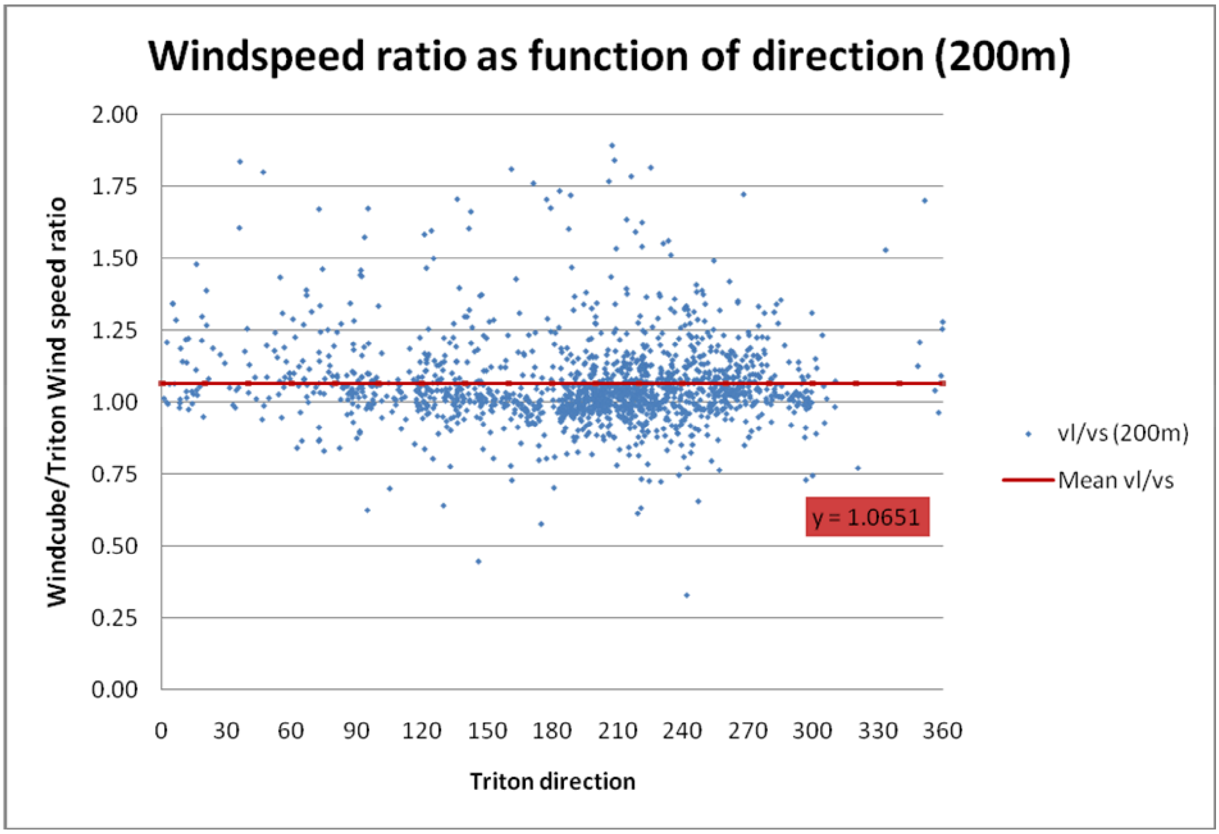
Windspeed ratio as function of direction (100m)
Windcube/Triton Wind speed ratio
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
30
60
90
120
150
180
210
240
270
300
330
360
Triton direction
vl/vs (100m)
Mean vl/vs
y = 1.0377


Windspeed ratio as function of direction (120m)
Windcube/Triton Wind speed ratio
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
30
60
90
120
150
180
210
240
270
300
330
360
Triton direction
vl/vs (120m)
Mean vl/vs
y = 1.0242

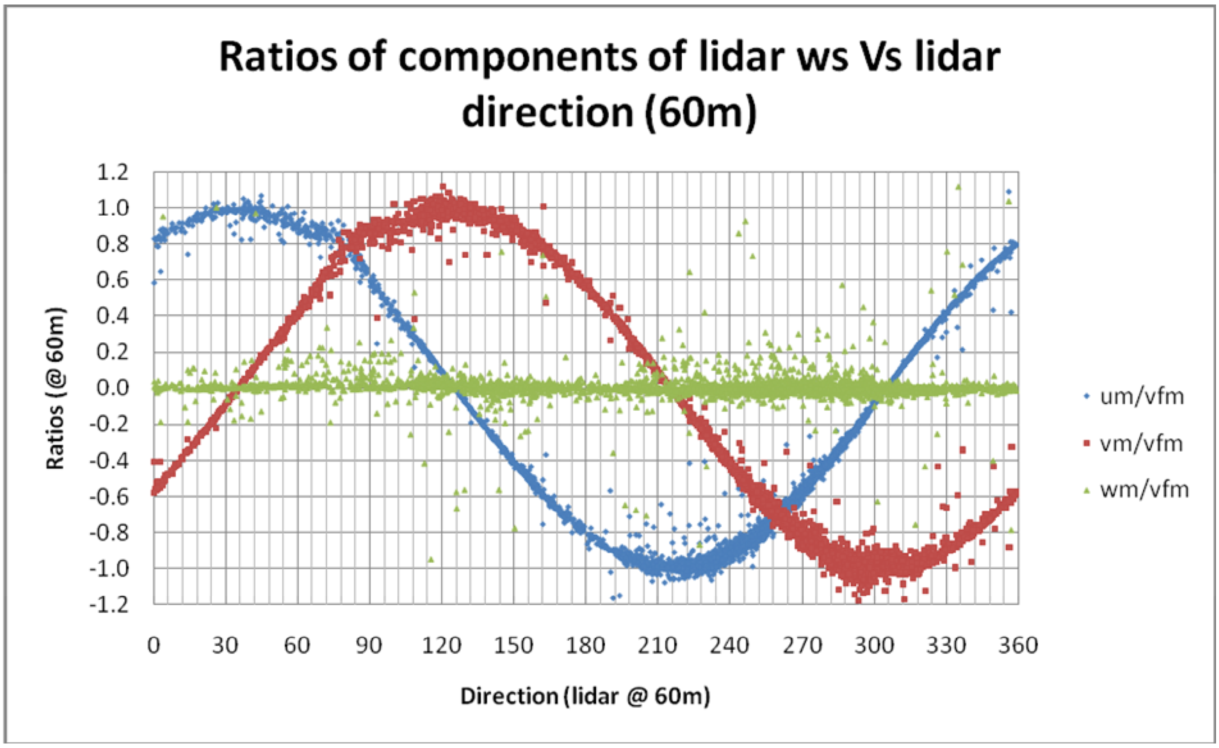

Windspeed ratio as function of direction (140m)
Windcube/Triton Wind speed ratio
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
30
60
90
120
150
180
210
240
270
300
330
360
Triton direction
vl/vs (140m)
Mean vl/vs
y = 1.0337

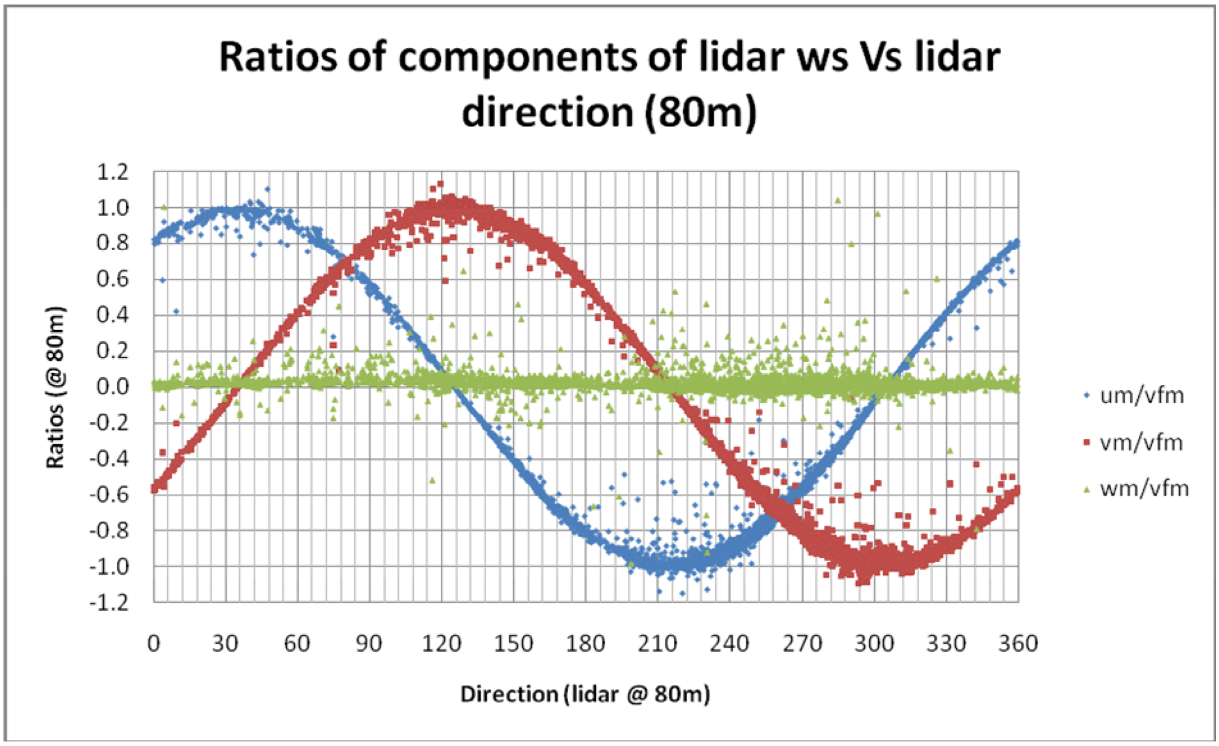

Windspeed ratio as function of direction (160m)
Windcube/Triton Wind speed ratio
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
30
60
90
120
150
180
210
240
270
300
330
360
Triton direction
vl/vs (160m)
Mean vl/vs
y = 1.0858

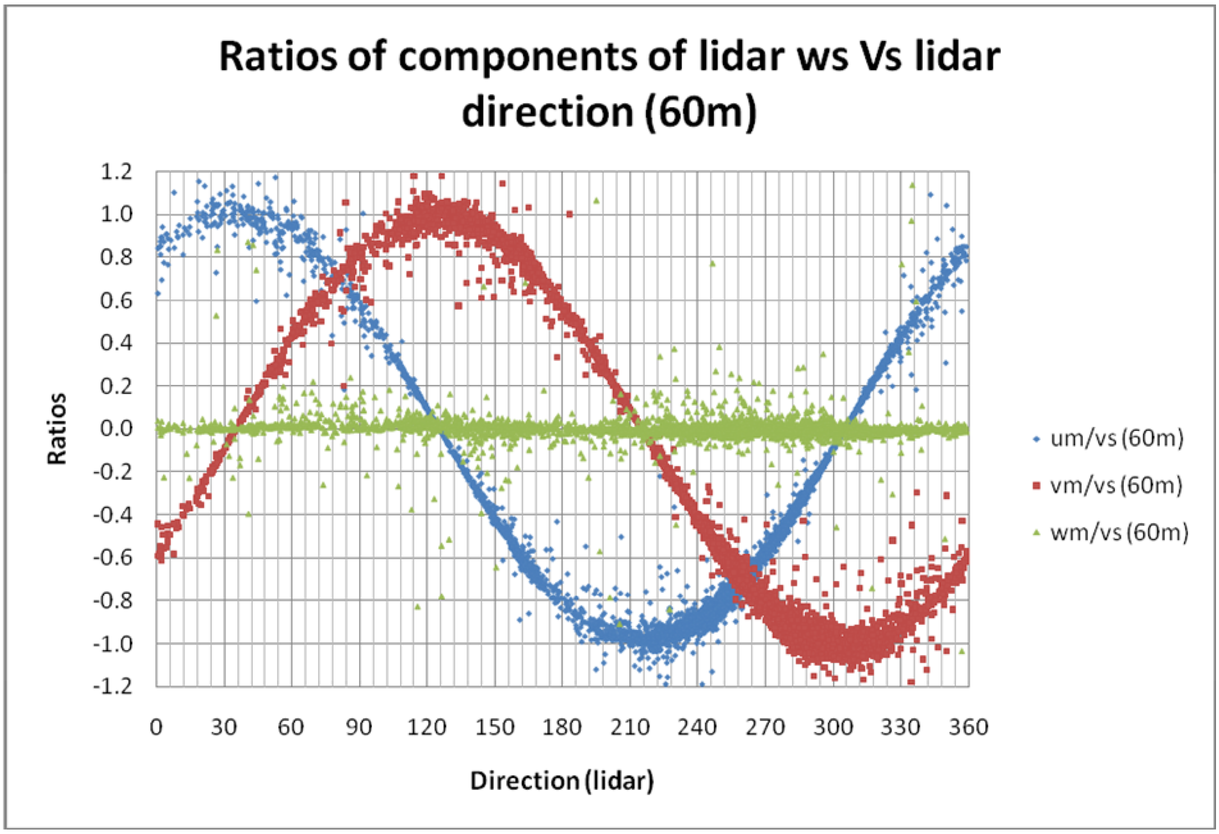

Windspeed ratio as function of direction (180m)
Windcube/Triton Wind speed ratio
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
30
60
90
120
150
180
210
240
270
300
330
360
Triton direction
vl/vs (180m)
Mean vl/vs
y = 1.0639



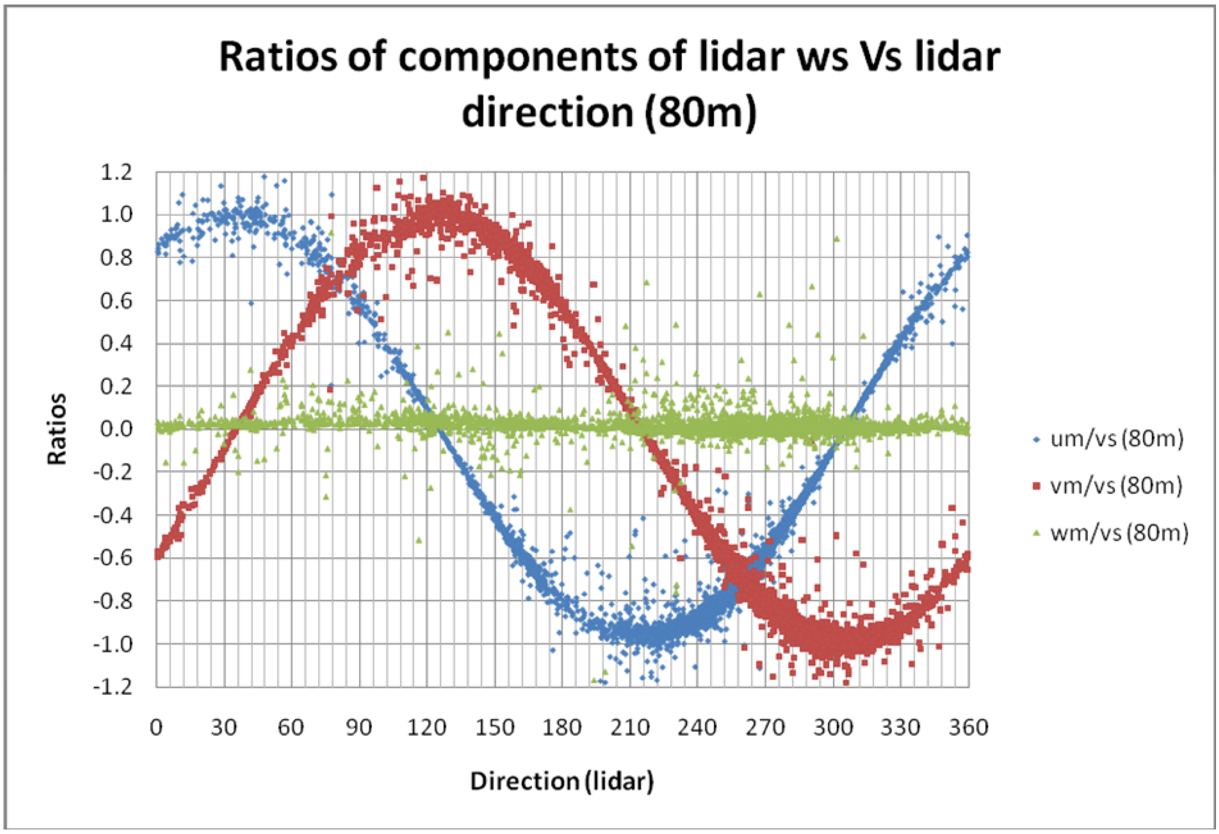
Ratio of wind speed as function of SoDAR direction	
	WINDCUBE / Triton
	Intercept
60	1.0128
80	1.0065
100	1.0377
120	1.0242
140	1.0337
160	1.0858
180	1.0639
200	1.0651


Ratios of components of lidar ws Vs lidar direction (60m)
Ratios (@ 60m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar @ 60m)
um/vfm
vm/vfm
wm/vfm

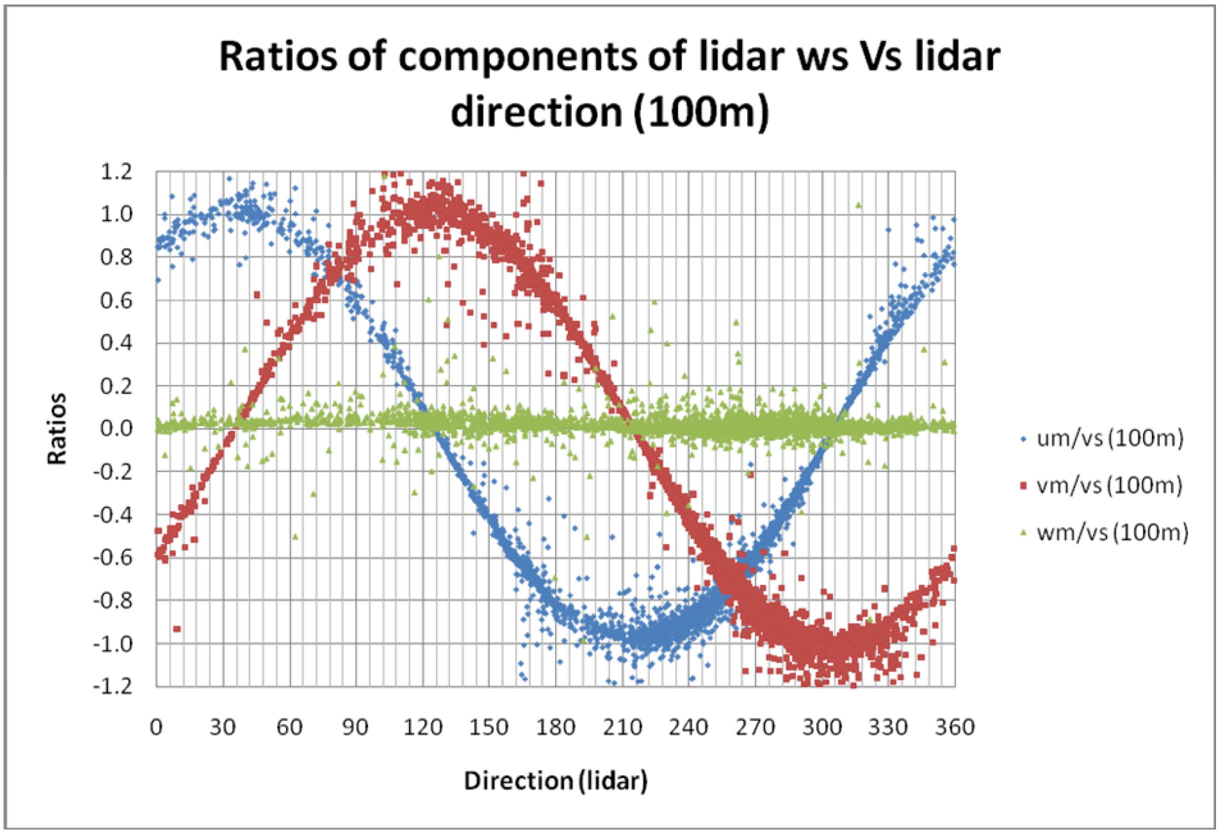

Ratios of components of lidar ws Vs lidar direction (80m)
Ratios (@ 80m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar @ 80m)
um/vfm
vm/vfm
wm/vfm

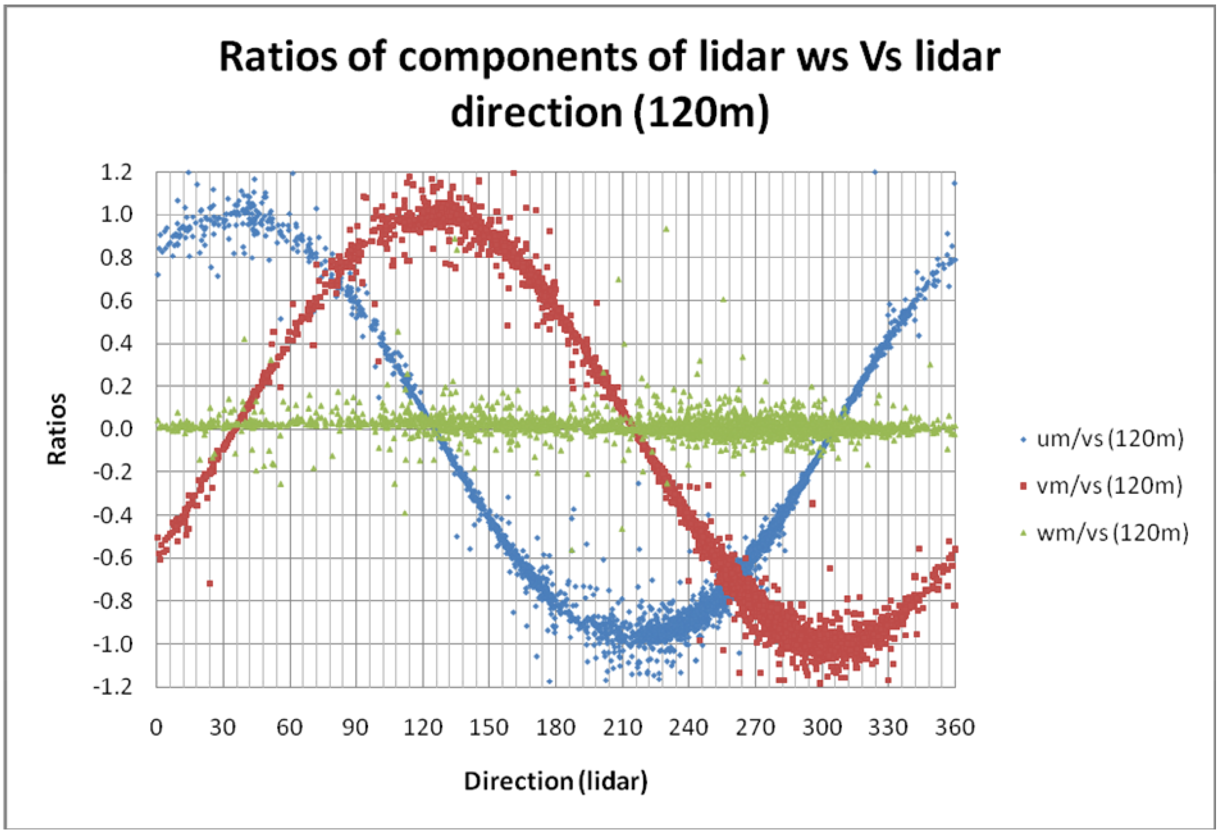


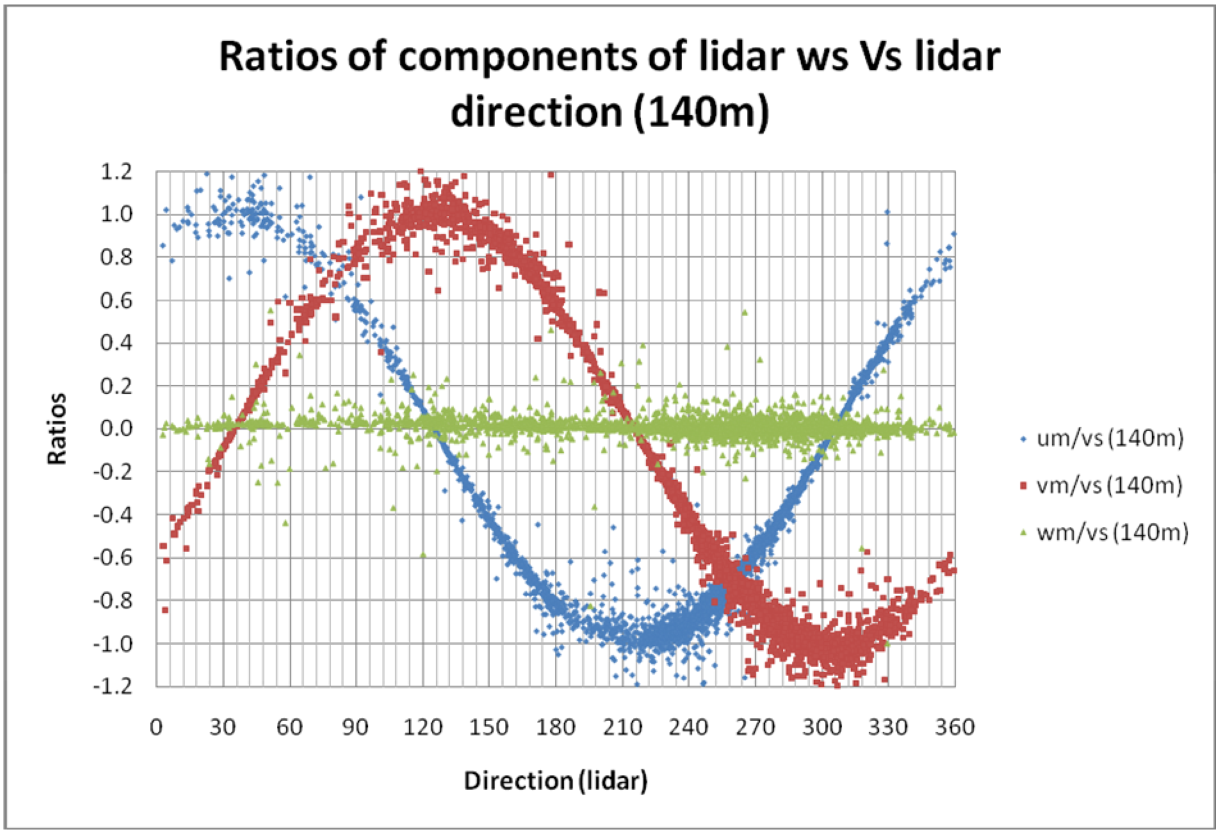
Ratios of components of lidar ws Vs lidar direction (60m)
Ratios
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar)
um/vs (60m)
vm/vs (60m)
wm/vs (60m)



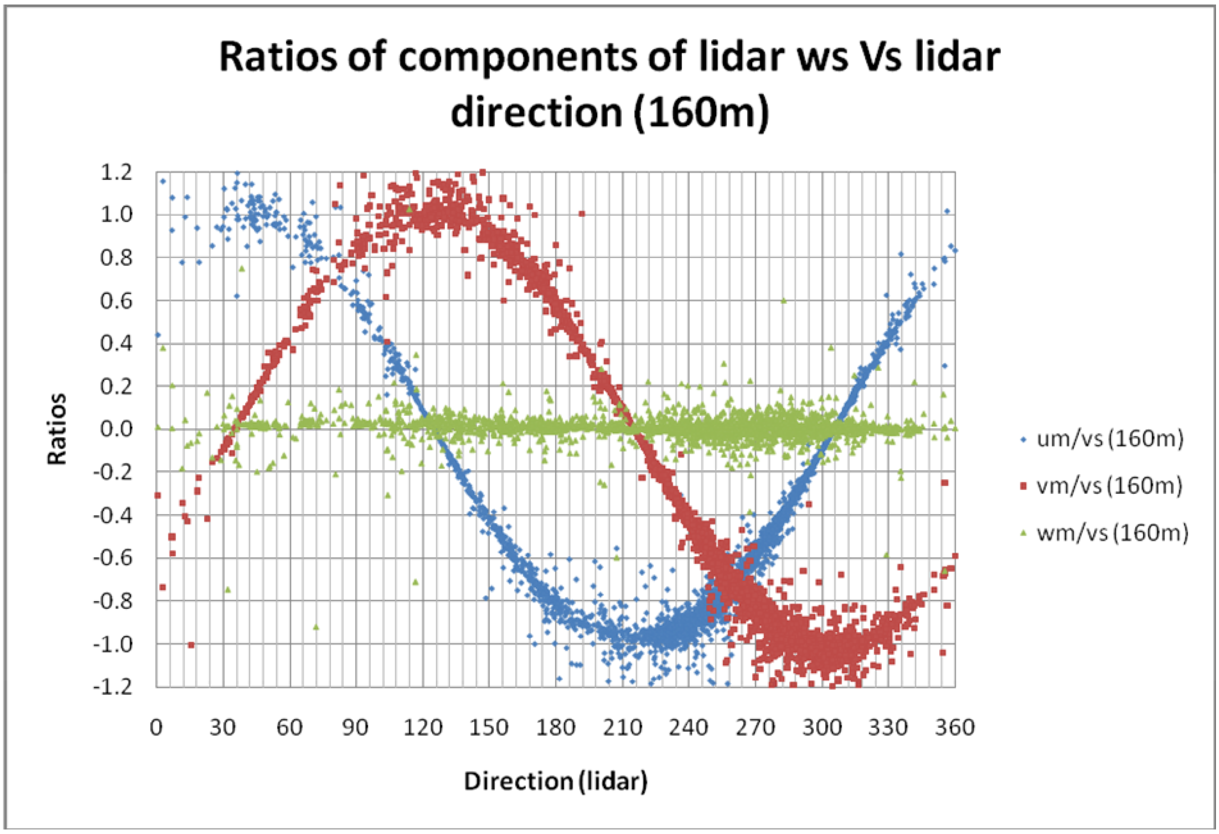
Ratios of components of lidar ws Vs lidar direction (80m)
Ratios
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar)
um/vs (80m)
vm/vs (80m)
wm/vs (80m)


Ratios of components of lidar ws Vs lidar direction (100m)
Ratios
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar)
um/vs (100m)
vm/vs (100m)
wm/vs (100m)

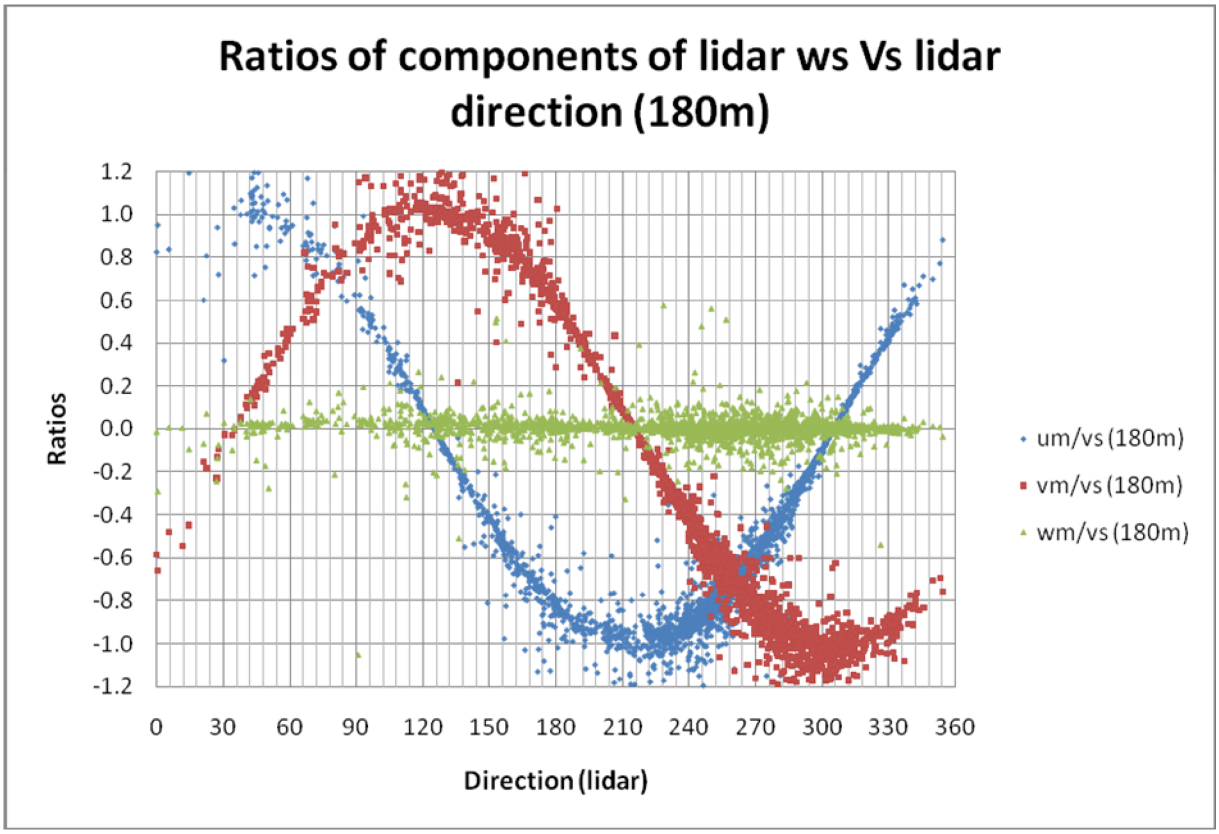

Ratios of components of lidar ws Vs lidar direction (120m)
Ratios
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar)
um/vs (120m)
vm/vs (120m)
wm/vs (120m)



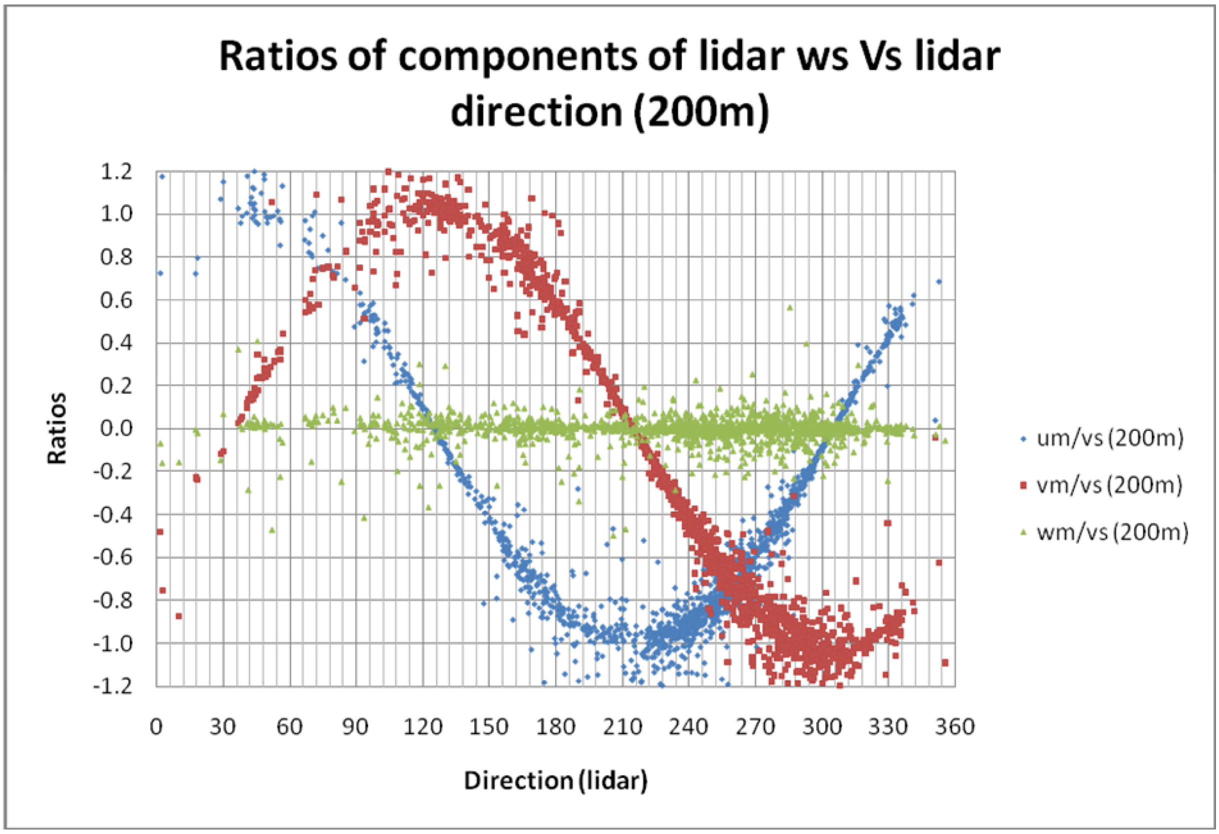
Ratios of components of lidar ws Vs lidar direction (140m)
Ratios
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar)
um/vs (140m)
vm/vs (140m)
wm/vs (140m)



Ratios of components of lidar ws Vs lidar direction (160m)
Ratios
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar)
um/vs (160m)
vm/vs (160m)
wm/vs (160m)

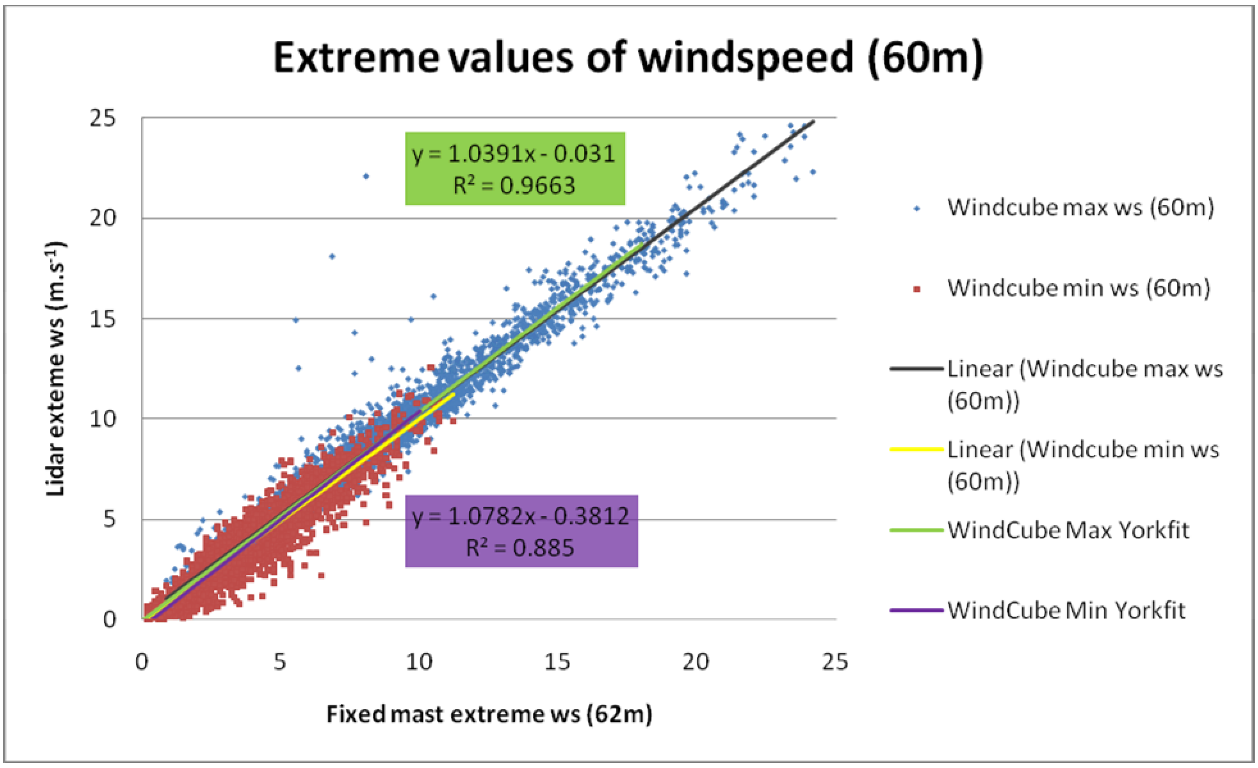


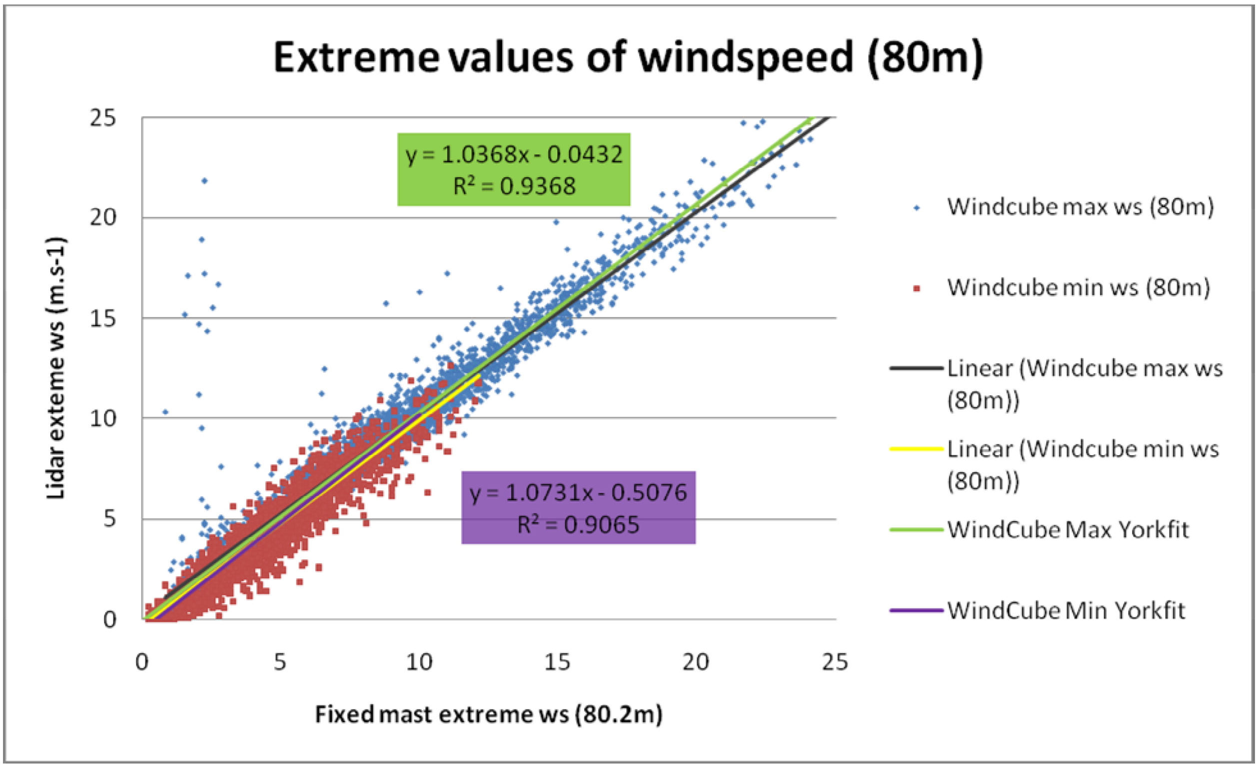
Ratios of components of lidar ws Vs lidar direction (180m)
Ratios
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar)
um/vs (180m)
vm/vs (180m)
wm/vs (180m)



Ratios of components of lidar ws Vs lidar direction (200m)
Ratios
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
210
240
270
300
330
360
Direction (lidar)
um/vs (200m)
vm/vs (200m)
wm/vs (200m)

APPENDIX G EXTREME VALUES OF WIND SPEED

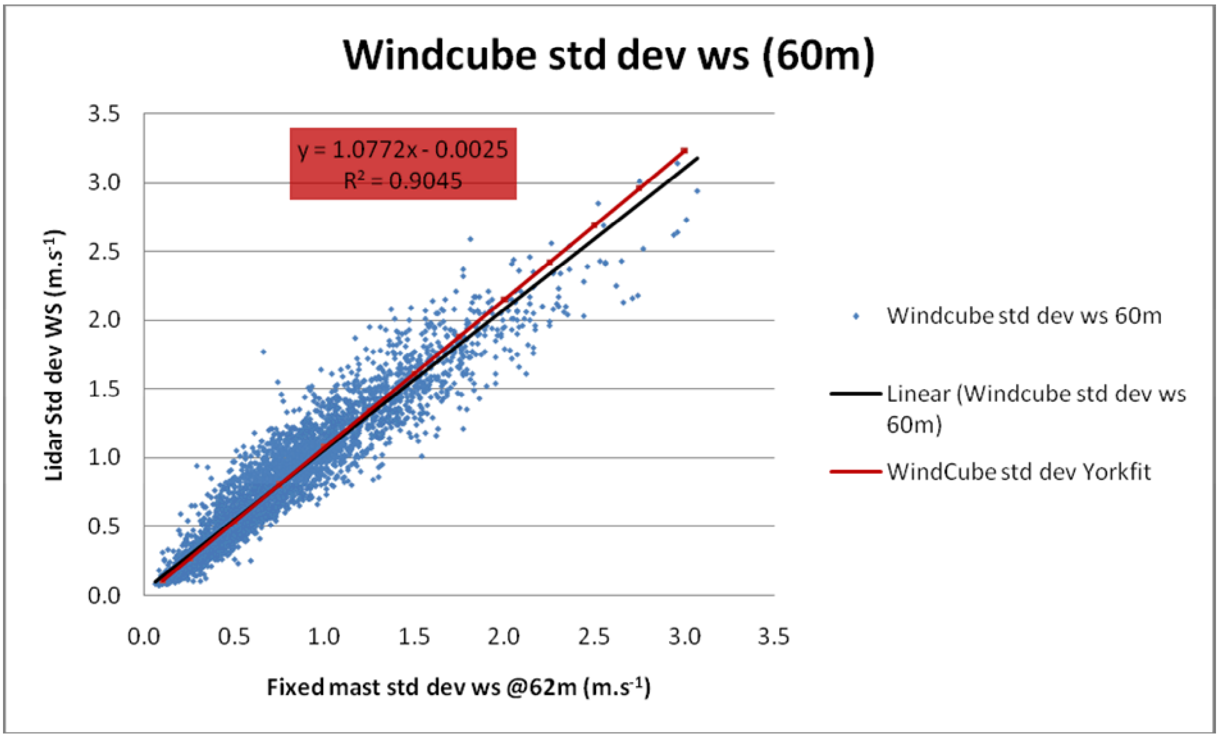


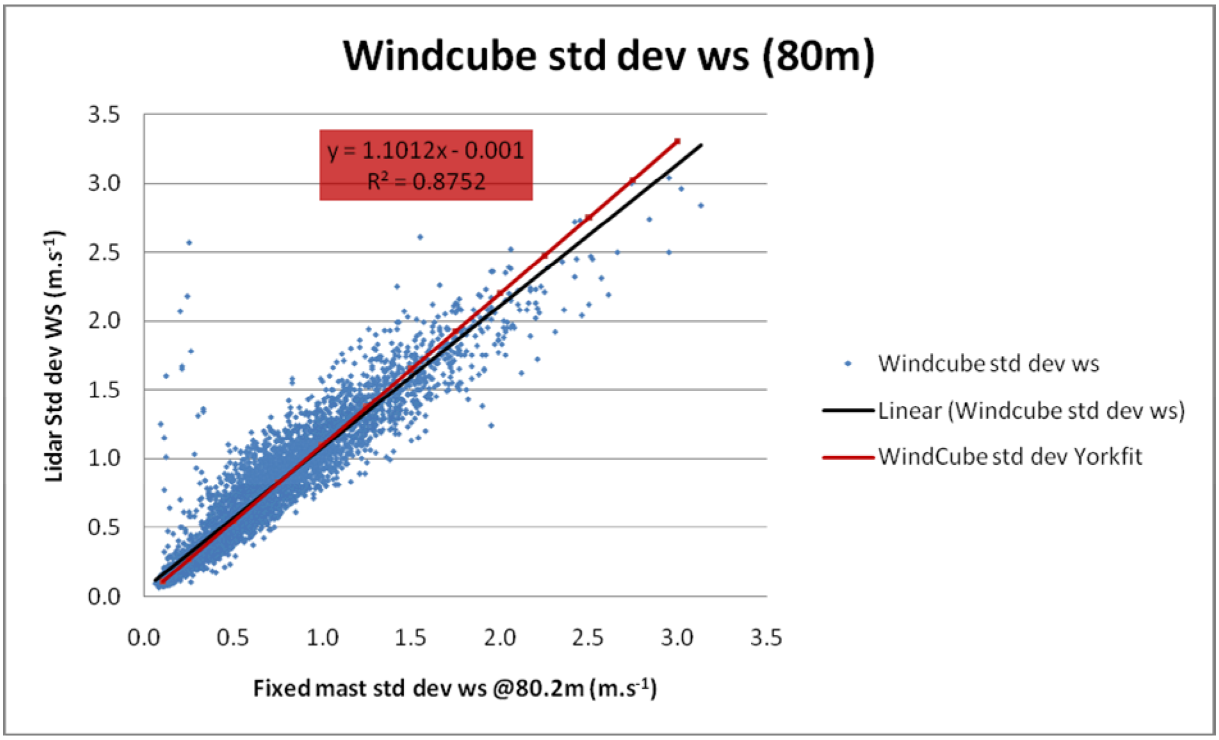


Extreme values of wind speed (Least Squares Regression)						
	WINDCUBE Max			WINDCUBE Min		
	Gradient	Intercept	R^2	Gradient	Intercept	R^2
60	1.0212	0.1101	0.9666	1.0141	-0.1324	0.8885
80	1.0034	0.2335	0.9378	1.0214	-0.2801	0.9089

Extreme values of wind speed (Orthogonal Regression)						
	WINDCUBE Max			WINDCUBE Min		
	Gradient	Intercept	R^2	Gradient	Intercept	R^2
60	1.0391	-0.0310	0.9663	1.0782	-0.3812	0.8850
80	1.0368	-0.0432	0.9368	1.0731	-0.5076	0.9065

APPENDIX H STANDARD DEVIATION OF WIND SPEED





Correlation of standard deviation of wind speed (Least Squares Regression)			
	WINDCUBE		
	Gradient	Intercept	R^2
60	1.0241	0.0367	0.9070
80	1.0296	0.0500	0.8795

Correlation of standard deviation of wind speed (Orthogonal Regression)			
	WINDCUBE		
	Gradient	Intercept	R^2
60	1.0772	-0.0025	0.9045
80	1.1012	-0.0010	0.8752