Identification of Variables for Site Calibration and Power Curve Assessment in Complex Terrain

SiteParIden

JOR3-CT98-0257

Relative Power Curve Measurements in Complex Terrain
Task 7

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Abstract

Within the framework of the EC co-funded project “Identification of Variables for the Site Calibration and Power Curve Assessment in Complex Terrain; SiteParIden”; JOR3-CT98-0257, tasks 6 & 7 have been carried out by ECN and DEWI. Both tasks concern the “Relative Power Curve Measurements in Flat (task 6) and Complex Terrain (task 7).
The objective of the tasks 6 and 7 is: To verify whether the cup anemometers in natural conditions perform comparable or differently in the presence of different turbulence intensities and inclined flow, in flat and complex terrain. For this purpose similar experiments have been performed by ECN and DEWI to compare cup anemometer output in the free atmosphere.
This comparison showed unexpected big differences in cup anemometer output. A reason for these differences lies in the way specific type of cup anemometers respond to turbulent wind, especially the sensitivity to vertical turbulence intensity. The activities both at ECN and DEWI came up with consistent results. It is recommended to work out correction possibilities for cup anemometers to this effect to establish that power performance measurement results from different locations are really comparable in the future.

Keywords:
Cup anemometer, performance measurements, power curve, turbulence intensity.

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1. INTRODUCTION

Within the framework of the EC co-funded project "Identification of Variables for the Site Calibration and Power Curve Assessment in Complex Terrain; SiteParIden"; JOR3-CT98-0257, tasks 6 & 7 have been carried out by ECN and DEWI. Both tasks concern the "Relative Power Curve Measurements in Flat (task 6) and Complex Terrain (task 7).
The general objective of the SiteParIden project is to define a set of parameters important for site calibration and power curve identification in complex terrain in comparison with flat terrain circumstances.

Power curve determination in flat and complex terrain results or may result in different measured performance characteristics despite being exposed to the same wind conditions. In this respect the wind speed is an important parameter. It is expected that observed performance differences probably are due to terrain; i.e. turbulence conditions like: inclined flow, turbulence intensities, wind shear etc.
The objective of the tasks 6 and 7 is: To verify whether the cup anemometers in natural conditions perform comparable or differently in the presence of different turbulence intensities and inclined flow, in flat and complex terrain. For this purpose similar experiments have been performed by ECN and DEWI to compare cup anemometer output in the free atmosphere.

In the present report the results are presented obtained by ECN in task 7.
The measurement sites, applied equipment, measurement results and analyses results are presented in this report.

2. APPLIED METHODOLOGY

The verification of anemometer performance in free wind circumstances or natural conditions has been carried out through comparison of the output of different types of cup anemometers as used in the power performance measurements carried out within the whole SiteParIden project.
The purpose of the comparison measurements was to investigate whether different types of cup anemometers, under natural conditions, perform comparable in presence of different turbulence intensities and inclined flow.

At DEWI (Wilhelmshaven), (flat terrain) and at ECN Petten (complex terrain) similar measurements, with similar equipment (test rigs), have been carried out.
At ECN a relative low (6 m) mast was installed in the dunes of the ECN wind turbine test station to simulate the complex terrain situation.
On both test rigs reference anemometers where installed:

1. A Thies anemometer, type 4.3303.22.0000 at DEWI;
2. A Miery anemometer, type 018, at ECN Petten.

These reference anemometers are not applied in the site calibration and power performance measurements as specified in the tasks 2-5.

The other cup anemometers to be compared were:

1. A Vector, type A 100 instrument made available by CRES;
2. A Friedrichs, type 4033.1100x instrument made available by WINDTEST;
3. A Risø, type P2445b instrument made available by RISØ.

These instruments were compared with their reference by both ECN and DEWI.
Moreover, within the project, a Thies anemometer was measured at ECN Petten and a Miery instrument was measured at DEWI.
Before the different cup anemometer types were compared, two identical Miery 018 at ECN and two Thies instruments were compared on the test rig to identify possible differences on both cup anemometer positions.

The instruments were installed side by side on the test rigs. In between a Gill 3D sonic vector anemometer was placed to get the additional measurements of local turbulence intensities and the vertical wind speed component.

The comparison measurements were carried out with instrumentation typically used in power performance measurements. The reference anemometers remained on the rig while the other anemometers were interchanged one after the other in successive measurement campaigns.

Originally, the cup anemometers were calibrated at the home institutes of the project partners. During the project it was decided to calibrate all cup anemometers, used in the tasks 6 & 7, at one tunnel to eliminate possible differences due to tunnel effects. All calibrations were carried out according to the Measnet procedure by DEWI in the wind tunnel of the University of Oldenburg.

The data measured and stored were 10-minute averages, standard deviation and minimum and maximum values during the 10 minutes. The horizontal (2d) and vector wind speed (3d) were calculated online after each sample and treated as separate signals.
Raw data are finally stored on CD.

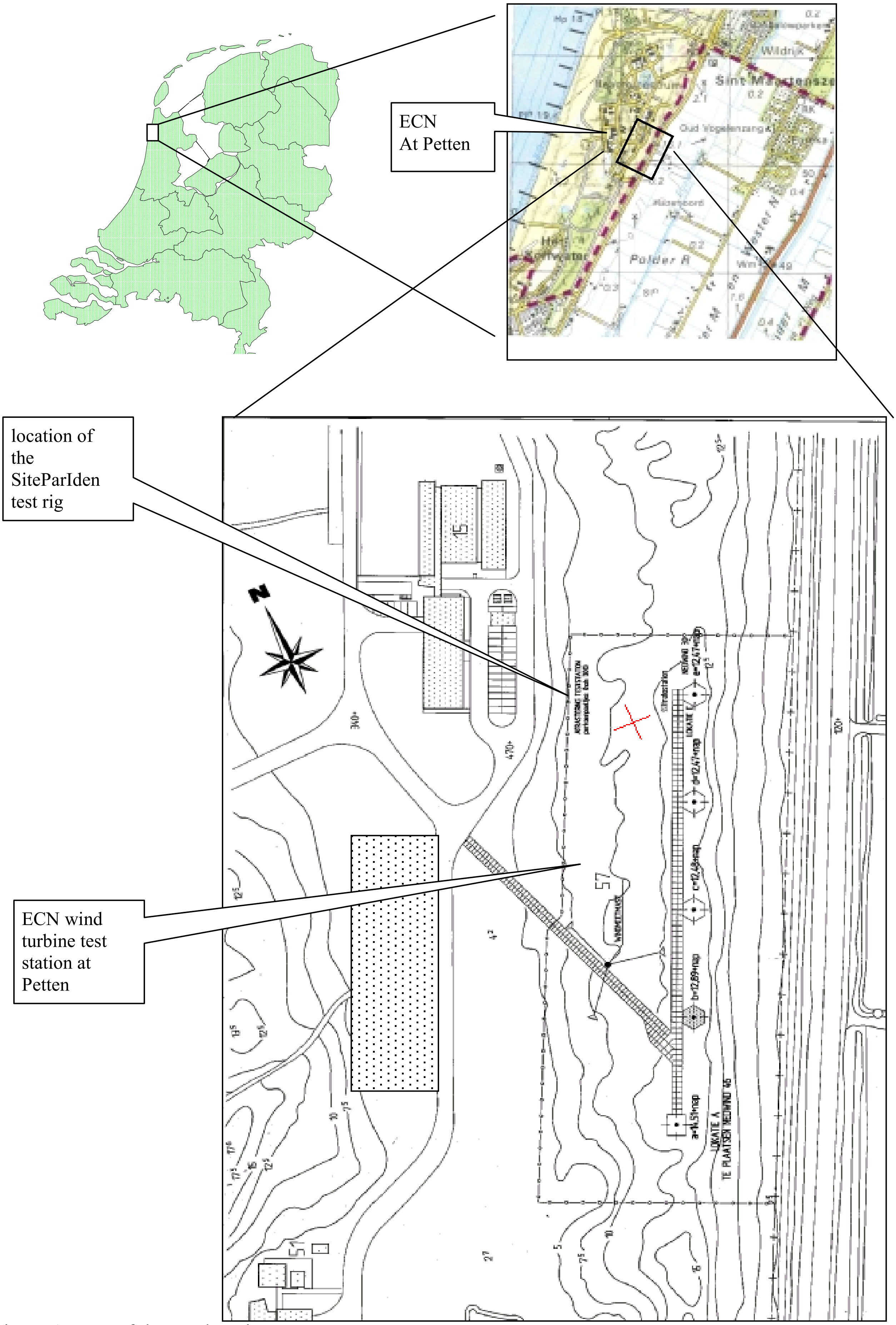

Figure 1. Map of the test location

3. ECN TEST LOCATION AND FACILITY

3.1 Location

ECN is located at the west coast of The Netherlands, close to the North Sea, see figure 1. The wind turbine test station is located at the east side of ECN and a 6m high SiteParIden test facility is installed at that test station, in the dunes, to represent a kind of complex terrain; see figure 2. The location itself is at about 10m above sea level. Looking to the east of the mast first a 10 - 15 m (above sea level) high dune and then open flat farmland (1m below sea level) appears. In the west the wind is coming from the sea over the dunes (local width about 1 km) and ECN buildings. From the North and South wind is coming primarily over the dunes.

Figure 2. The SiteParIden test facility at the ECN wind turbine test station.

A schematic view of the location where the test facility is installed is given in figure 1 and on the photo of fig. 2. Figure 3.1 to 3.8 show eight photographs of the test surrounding (from the North every 45° a picture is shown.

Figure 3. 1 Orientation North =(0°)

Figure 3. 2 Orientation Northeast =(45°)

Figure 3. 3   Orientation East=(90°)

Figure 3. 4   Orientation Southeast =(135°)


Figure 3. 5 Orientation South = (180°)


Figure 3. 6   Orientation Southwest = (225°)


Figure 3. 7 Orientation West = (270°)


Figure 3. 8   Orientation Northwest = (315°)

3.2 Test facility

The SiteParIden test facility for cup anemometer comparison exists of a 6 m high lattice tower on top of which a horizontal boom has been placed. This boom can be oriented perpendicular to the present wind direction by hand. For that purpose discrete eight positions are defined. Downwind of the boom an additional boom has been fixed on which a wind direction sensor is placed to measure the wind direction relative to the anemometer boom.
At both ends of the mean boom the reference anemometer and 'other' anemometer is placed; in between a 3D Gill anemometer sensor is fixed.
The relevant dimensions of the test rig are shown in figure 4.

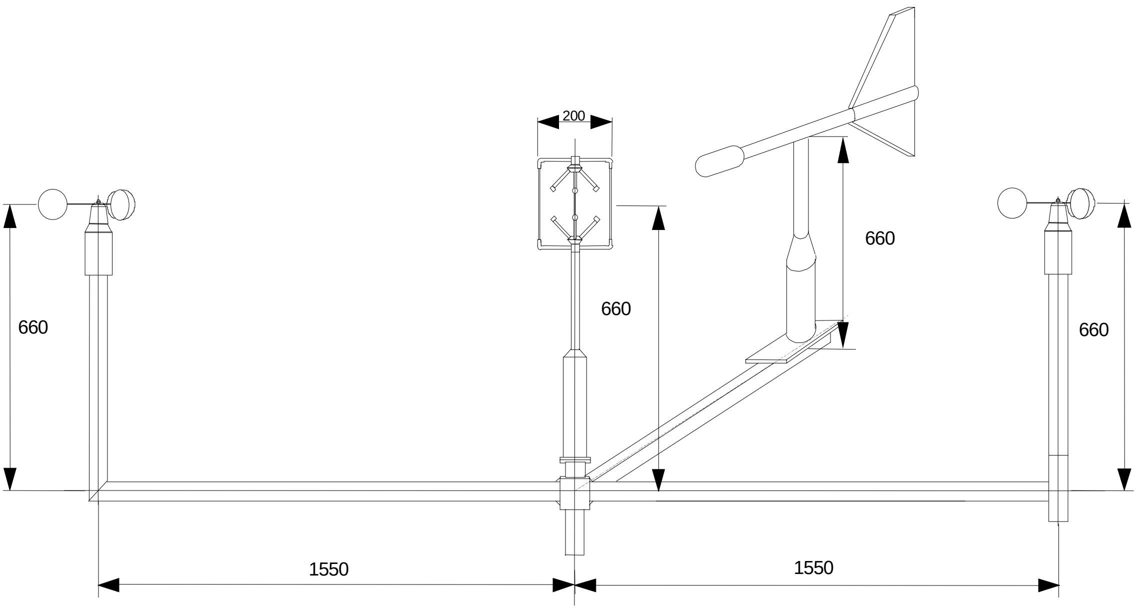

Figure 4. The SiteParIden test Rig, its dimensions and mounted instrumentation.

4. INSTRUMENTATION AND MEASUREMENT SYSTEM

This chapter describes the applied instrumentation, signal conditioning and data acquisition system.

4.1 Instrumentation

Table 1. Instrumentation table, including sensors and additional items.

Item Nr.	sensor or item	Manufacturer / supplier	Type of sensor	ECN ID no	Serial no
1	Ref. wind speed	Miery	018	DEWS0354	012.0042
2	wind speed 2	Miery	018	DEWS0418	012.0031
3	air pressure	Druck	PDCR 901	DELD0452	956795
4	wind direction	Miery		DEWR0435	
5	rain detection	Miery			
6	temperature	Miery			
7	wind speed (partner)	Vector	A100K		1824 - cup 1HA
		Thies	4.3303.22.000		123
		Friedrichs	Friedrichs		WT 0107696
		Risø	Risø		0656
8	wind speed u	Gill	Windmaster 1086M	DEWS0507	D251
9	wind speed v	Gill			
10	wind speed w	Gill			
11	control gill	Gill			
12	v (gill) 2d (horizontal)	calculated channel	V hor = sqrt (u^2+v^2)		
13	v (gill) 3d (vector)	calculated channel	V tot = sqrt ($u^2+v^2+w^2$)		
14	I/U converter	Resistor	250 ohm		
15	F/I converter	Jaquet	FTW 1613 AC 230	DEFR0538	
16	Signal amplifier	The amplitude of the pulses from anemometer must be above the detection level of the frequency converter.			
17	Gill PCI	Converts serial data from the Gill into analogue voltage and status signals.			
18	**Miery signal conditioning equipment** The applied components have the following identifications:				
18.1	circuit board	Miery	050	DEWS0304	050.0013
	filter	Miery	079	DEFR0454	079.0018
18.2	circuit board	Miery	050	DEWS0305	050.0014
	filter	Miery	079	DEFR0455	079.0017
18.3	circuit board	Miery	078	DELD0453	078.0010
19	ADC	Keithly	570		
20	PC + DAQ software	WIMPSPI	Special version of ECN DAQ program Wimpro with respect to the calculation of items 12 + 13.		

In this project a standard ECN measurement system has been used for the channels (items 1 – 13) and other items as indicated in table 1. The mutual connection of the items are schematically shown in fig 5. Apart from the air pressure sensor all the sensors are mounted on the six-meter SiteParIden mast as showed in figure 2. The rest of the instrumentation is placed in a cabin near the mast on the test station.

4.2 Diagram of the signal conditioning

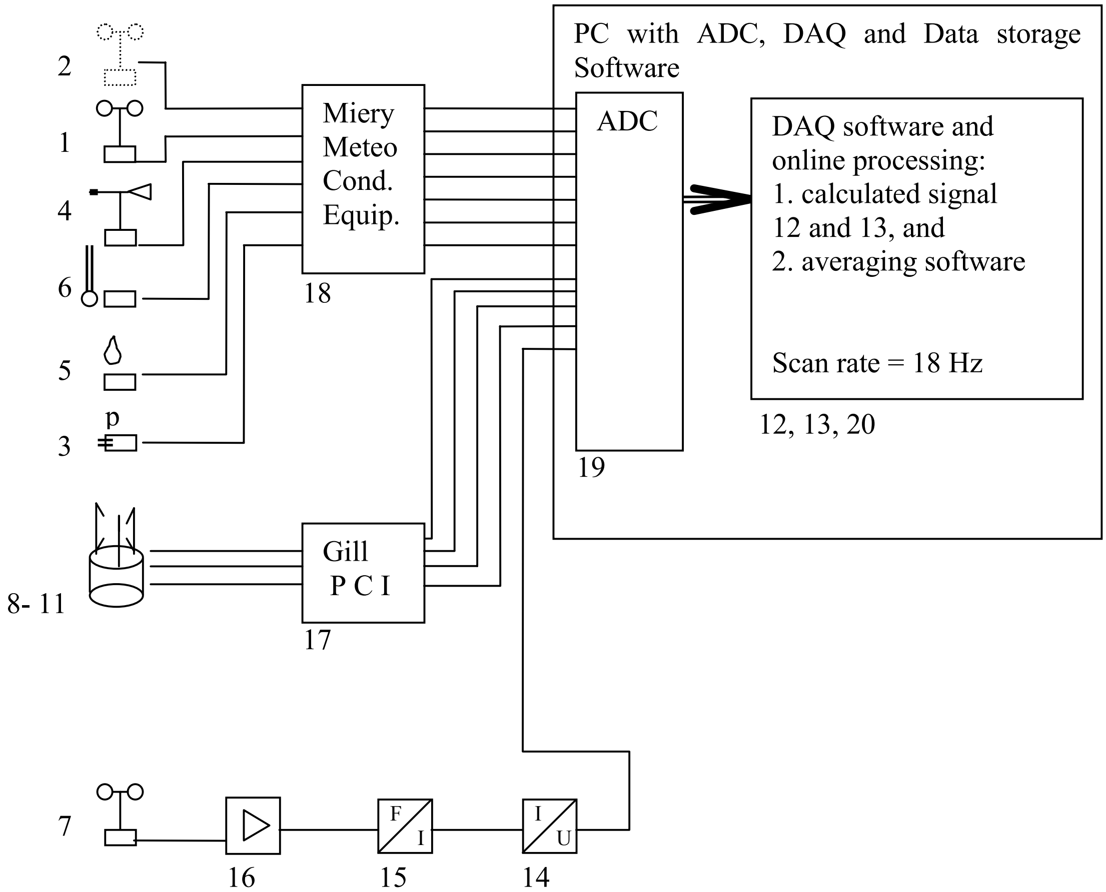

Figure 5. Schematic overview of the applied measurement system. (Numbers refer to table 1)

Item 7 represents the cup anemometer to be compared. The signal conditioning is done through a Jaquet F/I converter. Table 2 shows the applied Jaquet settings for the different anemometers.

Table 2 Diagram of measurement system

Instrument	Full Scale Setting of the Jaquet F/I converter
Vector	400Hz -> 20mA -> 5V
Friedrichs	400Hz-> 20mA -> 5V
Thies	800Hz -> 20mA -> 5V
Risø	50Hz -> 20mA -> 5V

5. MEASUREMENTS AT ECN

5.1 Database

The measurements have been carried out during 1999 and 2000. The resulting database with which the final analyses have been performed is summarised in table 3. Starting points to select the data were:
- the relevant wind speed range is 3.75 m/s and higher;
- a wind direction relative to the boom position of ± 45 degrees;
- measurements during periods of rain were excluded.

Table 3. Database SiteParIden measurements as applied in the final analyses.

Number of valid measurements per anemometer and boom setting
Selection Conditions:
Measurement Period: 12-3-1999 until 23-10-2000
Wind speed : > 3.75 m/s
Wind Direction : >-45 ° and < 45 ° relative to test rig
Rain detection : No-rain; max value in 10 minutes < 20%

Count of measurements	Direction setting of the boom												
Campaign	0	45	50	90	110	135	180	225	250	270	315	330	Grand Total
Miery					197					2550	303		3050
Vector			471	2801				1704			699		5675
Friedrich								4745					4745
Thies	1322	184						2258	2653			419	6836
Risø	466					234	1385	1956		784	145		4970
Grand Total	1788	184	471	2801	197	234	1385	10663	2653	3334	1147	419	25276

5.2 measurement periods and calibration

Table 4. Overview measurement periods and DEWI anemometer calibration results.

Type	**Miery 018**	**Miery 018**	**Vector A100**	**Friedrichs 4033**	**Thies 4.3303**	**Riso P2445b**
Start	3-12-1999	3-12-1999	16-6-1999	7-12-1999	21-2-2000	19-7-2000
Stop	23-10-2000	15-6-1999	7-12-1999	21-2-2000	13-7-2000	23-10-2000
Calibration date at DEWI	19-1-2001	22-3-2000	22-3-2000	22-3-2000	19-1-2001	19-1-2001
gain [m]	0.0614	0.06136	0.04914	0.09565	0.04828	0.62004
offset [m/s]	0.111	0.101	0.289	0.304	0.368	0.272

The rig is mounted on top of the mast in such a way that the boom can be positioned perpendicular to the wind direction in eight discrete positions. During the measurement periods the boom was adjusted by hand according the wind direction taken from the weather forecast to realise the perpendicular situation as much as possible. During the overall measurement period the wind came mainly from the south west, which is the prevailing wind direction at the ECN test station. The database in table 3 shows that most results came from south west direction.

In table 4 the anemometer specific measurement periods are mentioned, plus the final wind tunnel calibration results as established by DEWI, according to Measnet, and as used in the analyses.

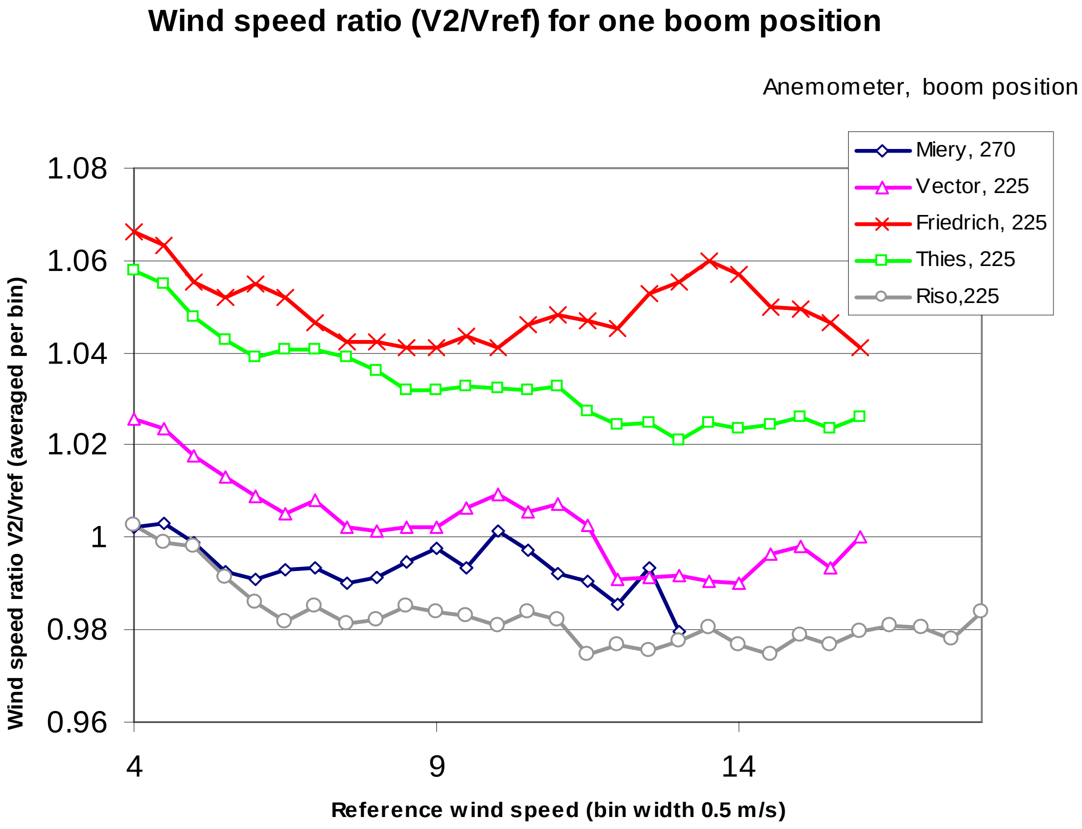

Figure 6. Measured wind speed ratios versus reference wind speed for 5 different cup anemometers.

6. ANEMOMETER COMPARISON RESULTS

6.1 General.

Two identical Miery 018 anemometers have been compared from December 1999 until June 2000. Subsequently the Vector, Thies, Friedrichs and Risø sensors were measured. This means that the successive anemometers were compared during different periods and seasons and therefor did not 'see the same kind of wind'.
Before the Risø sensor was installed the test rig including measurement equipment was maintained.

From the database it is clear that one boom position (225°) gave measurement results for all sensors. The analyses showed that the measurements with wind coming from the east were very problematic with respect to comparison of both anemometers due to close obstacles (wind turbine, several small compartments) on top of the dune (see figure 3.3). It was decided that the anemometer comparison should be based on the (south-west) results. In that way the comparison with respect to turbulence, vertical wind speed etc, is based on more equal conditions and circumstances. The results are more comparable in that way.

Dependency of the ratio of cup anemometer wind speeds with respect to reference wind speed, wind direction, air temperature and turbulence has been investigated, but did not show a relevant dependency. Analyses results are presented in intermediate reports [2]. Only a slight dependency of the wind speed ratio with wind direction was observed. This could indicate that topography or obstacles effect the measurements. However measurements with the boom in other positions resulted in the same kind of dependency. After maintaining the test rig and equipment the effect disappeared. Indications about errors in the measurement system or equipment were not found.

Because different signal conditioning equipment was applied for the reference anemometer (Miery) and the partner's anemometers, it was checked whether these conditioners would introduce additional differences in cup anemometer output. A slight difference due to this effect has been found. Details are reported in the appendix to this report. In the further analyses the measurement results are corrected for this small difference to be able to focus on the anemometer output only.

From several intermediate results, both obtained at DEWI and at ECN it appeared very clear that the differences in measured wind speed between the cup anemometer types was much larger than expected. For that reason the project activities, of task 6 and 7, focussed more on the comparison as such.

6.2 Comparison of cup anemometer output

First, two Miery type anemometers were compared. The result of this comparison is shown in figure 6, where the ratio of both ten minute average wind speeds is plotted as a function of the reference wind speed. The presented lines are bin wise averages, using bins of 0.5 m/s. Different from other measurement periods the wind came mainly from the west direction. The difference in average wind speed of two Miery anemometers is less than 1% over the range of 4 – 12 m/s.
Comparing different anemometer types in free atmospheric circumstances show however large differences. All final comparison results are summarised in fig 6. The Miery, Vector and Risø anemometers are relatively comparable. These three cup anemometers have conical cups.

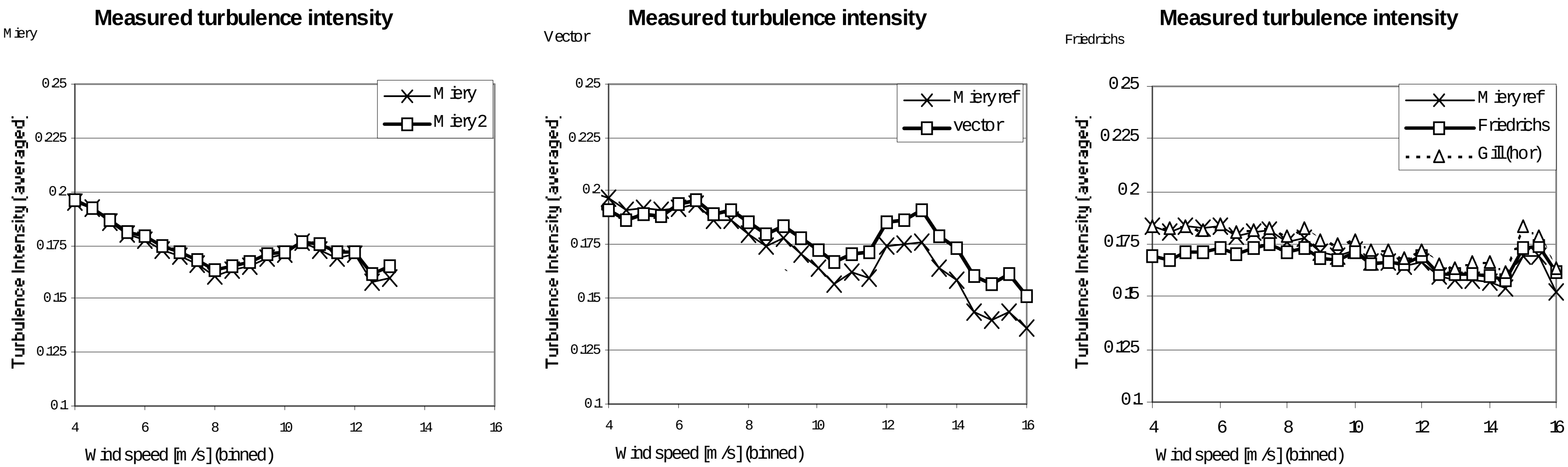

Figure 7.1 - 7.3

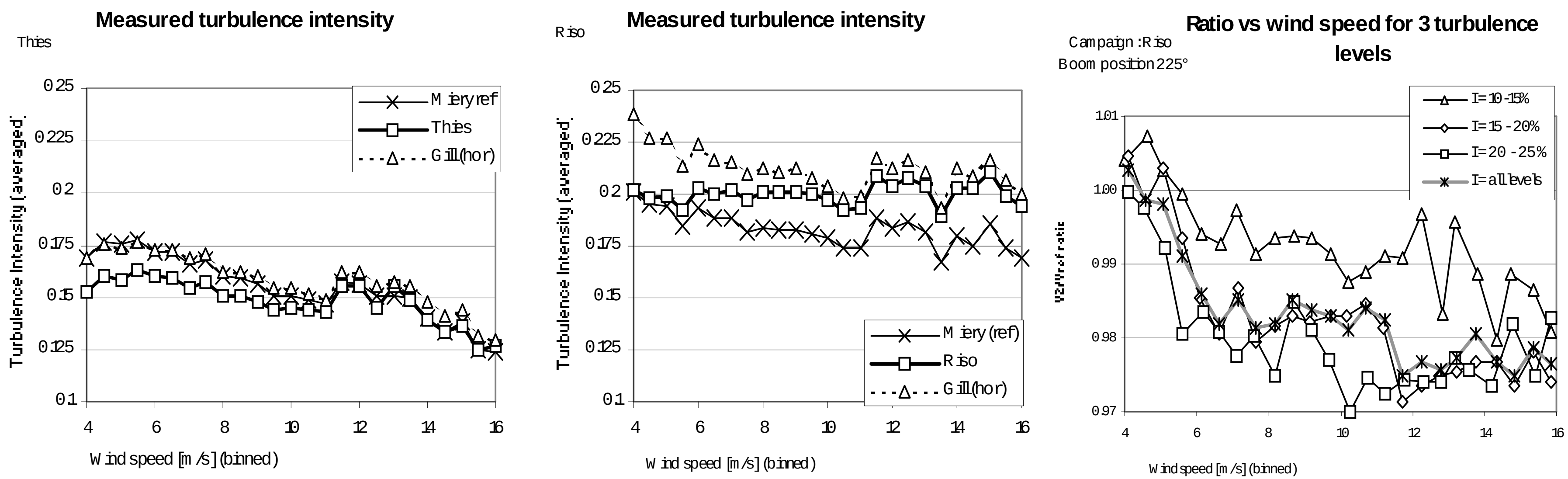

Figure 7.4 - 7.6

Friedrichs and Thies, both having spherical cups, are close to each other but have a few percent higher output.
The extreme differences as measured in this campaign, are between 5 – 7% points in wind speed, which for example roughly means that 10 m/s wind speed measured with a Miery sensor is roughly 9.8 m/s with a Risø sensor and 10.5 m/s with a Friedrichs anemometer.
The anemometer comparison by DEWI [3] showed the same results. Not in absolute figures but trendwise. The individual results, as obtained by ECN and DEWI measurements are consistent with each other. The extreme values observed by DEWI in flat terrain are slightly less; up to 5% points.

The reasons for the observed differences in cup anemometer output in the free atmosphere are not trivial. Known phenomena that influence the anemometer output are:

- the sensitivity to flow inclination which is anemometer type dependent [5];
- sensitivity to turbulence, resulting in over-speeding, which is type dependent as well.

Clear observations are:

- the variability of the wind speed, contrary to the wind tunnel wind speed during calibration, results in different anemometer outputs;
- anemometers with spherical cups show higher output results relative to conical cup anemometers.

In section 6.5 parameters responsible for the differences are analysed using multivariate regression analyses.

6.3 Turbulence intensities

The turbulence intensities have been measured with all cup anemometers. The results are presented in the figures 7. From these figures a tendency can be observed that cup anemometers, giving lower wind speed outputs, like Risø and Vector, measure slightly higher turbulence intensities, relative to the reference. Thies and Friedrichs measure a slightly lower turbulence intensity, with a higher wind speed output relative to the reference. In the figures 7.3 – 7.5 the turbulence, of the horizontal wind speed, measured by the 3D Gill anemometer has been included as well. The lines in figure 7 are not mutually comparable, because the measurements are carried out in different periods. But generally it can be concluded that the measured mean turbulence intensity are comparable even with the 3D Gill Turbulence.

To investigate whether the level of turbulence itself influences the result as shown in figure 6, the 'Risø' measurements are processed again but the ratios have been established for different turbulence intensity intervals. The result is in figure 7.6 showing wind speed ratios tending to unity with decreasing turbulence intensities. This result is also consistent with the 'flat terrain' results measured by DEWI [3].

6.4 Terrain effects

It was investigated whether terrain could have an effect on the cup anemometer output. For that purpose data measured in two different sectors are compared with respect to turbulence, vertical wind speed component and ratio of measured wind speed. The selected sectors for the analyses are:

- south west sector (position 225 deg), and
- south sector (position 180 deg), where the wind is coming over a dune of 15 m height.

The results are in figures 8.1 - 8.4 and 9.

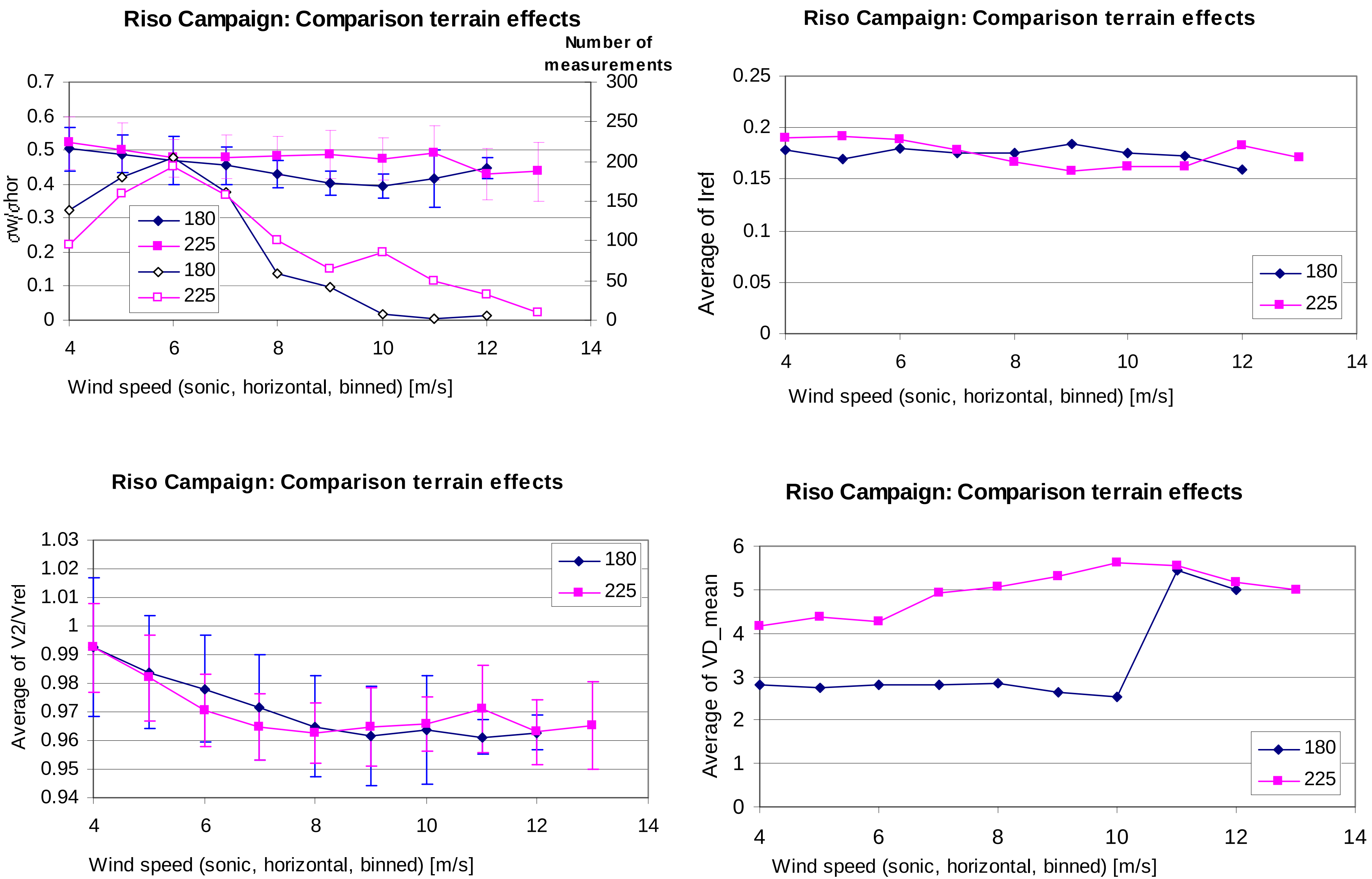

Figure 8.1 - 8.4 Effect of landscape (wind direction 180 and 225) on wind speed ratios and turbulence and vertical wind speed during the Riso campaign

In figure 8.1 the σ_w / σ_{hor} is shown for both sectors, indicating that there is not much difference. Wind coming over the dune (180° sector) even shows a slightly lower turbulence ratio. The measured values are in average between 0.4 and 0.5 which means that the location probably is not really a complex terrain. According to EWTS 2 [4], complex terrain should result in 0.7 as a ratio of standard deviations of vertical and horizontal wind speed. Figure 8.2 gives the Gill measured turbulence intensities of the two different sectors.
In figure 8.3 the wind speed ratio of the Risø sensor relative to the reference is shown for the two different sectors, indicating that the anemometer output is about the same in those two sectors. So the anemometer output seems not depending on specific terrain effects.
Figure 8.4 compares the vertical wind speed for the two sectors with different approach of the test rig.
In figure 9. the measured value of the vertical component in the wind speed is given. This is represented as inclined flow or the angle of the wind speed vector relative to the horizontal, resulting in: between 5 and 8 degrees for the given location with the boom in the south west position.

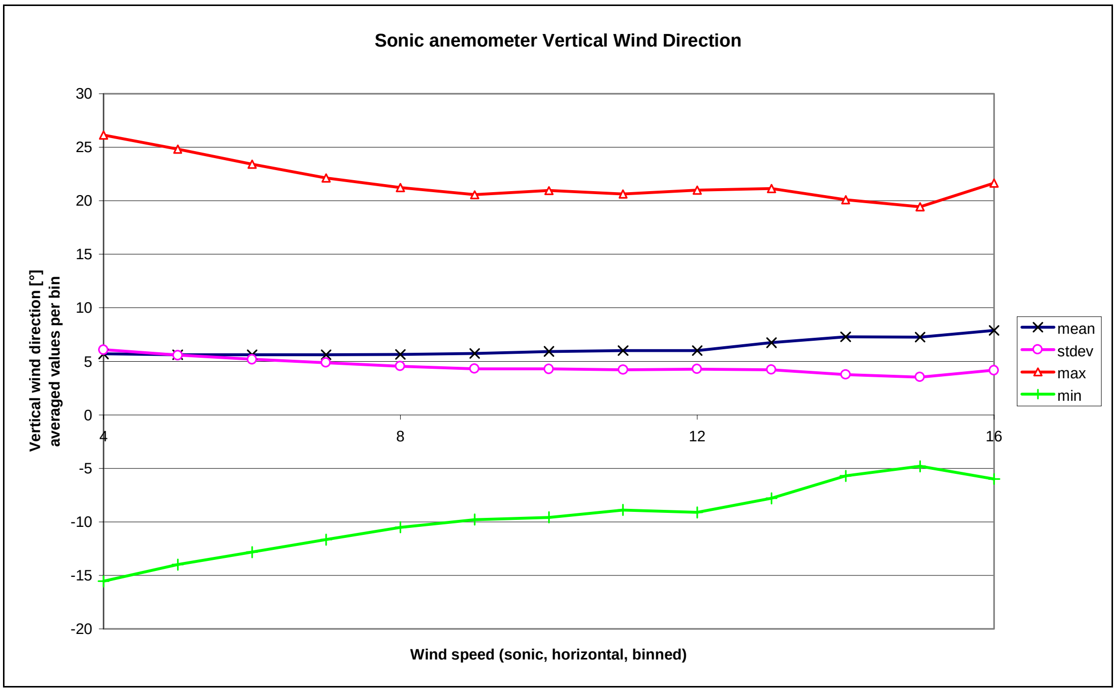

Figure 9. Vertical component of the wind speed with reference to the horizontal wind speed, measured with a 3d sonic anemometer on the SiteParIden location.

6.5 Multi Variate Regression Analyses MVRA

In all tasks of the SPI project in which measurements are carried out a Multi Variate Regression Analyses is carried out to identify parameters significantly influencing the deviations between the cup anemometer outputs.
The following set of relevant parameters is chosen for the MVRA.

Data selected from the SiteParIden database **data_all_meters.mdb**
The data in this data base is converted with the results of the Tunnel Calibration at DEWI's
The selection parameters were (**MVRA_query1**)

Signals to produce:	**Selected range**	**Remark**
Vref	> 3.75 m/s	Wind speed of the Miery reference anemometer
Boom position	180° to 270°.	Select the wind coming from south to west.
Relative wind direction	>-45° And < 45°	Select only undisturbed measurements
V2/Vref		The **de**pendent variable for the MVRA
Air density ρ		**In**dependent variable for the MVRA
Vertical turbulence (vert_turb)		**In**dependent variable for the MVRA (st dev of the vertical wind speed divided by the mean of the horizontal wind speed)
V –vector (V3D_mean)		**In**dependent variable for the MVRA
Hor. turbulence (I hor)		**In**dependent variable for the MVRA (st dev of the horizontal wind speed divided by the mean of the horizontal wind speed)

During the Vector campaign the online calculation of the horizontal and vector (3D) wind speed was not yet implemented in the data acquisition system. As a substitute for the mean value of horizontal wind speed an approximate was calculated according to the following formula:

$$V_{horizontal} = \sqrt{\bar{u}^2 + \bar{v}^2} + \tfrac{1}{2}\frac{\bar{v}^2\sigma_u^2 + \bar{u}^2\sigma_v^2}{(\bar{u}^2 + \bar{v}^2)^{3/2}}$$

Where :

$\bar{u}, \bar{v}$ = mean value of the wind speed in u, v direction

σ_u, σ_v = standard deviation of the wind speed in u, v direction

By using the $V_{horizontal}$ the vertical turbulence intensity (σ_w/V_{hor}) could be calculated. The horizontal turbulence and the vector wind speed could not.

With the data of each campaign (Vector, Friedrich, Thies and Risø) a MVRA analyse was carried out using the Function: “LinEst” of Microsoft Excel. As dependent variable the ratio V2/Vref is chosen. The independent variables in case of the Vector campaign are air density and vertical turbulence. The independent variables in case of the Thies, Friedrich and Risø campaigns are air density, vector wind speed, vertical and horizontal turbulence. The MVRA results are given in table 5.

Table 5. MVRA results with the dependent variable V2/ Vref

Vector campaign					
	Ak	**Se**	**t =(Ak/se)**	**stdev**	**ske**
Air density	0.4340	0.0627	6.9188	0.007	0.0030
Vertical turbulence	0.1863	0.0147	12.6383	0.030	0.0056
Const	0.4681	0.0760	6.1573		
T crit	**R^2**	**F obs**	**f crit**	**average**	
1.961366252	0.094304175	88.24462462	3.001034088	1.0077141	

Friedrich Campaign					
	Ak	**Se**	**t =(Ak/se)**	**stdev**	**ske**
Air density	-0.0293	0.0150	-1.9536	0.019	-0.0005
Vertical turbulence	1.1838	0.0167	70.9471	0.019	0.0220
V3D_mean	0.0027	0.0001	20.8347	2.473	0.0064
I hor	-0.2803	0.0095	-29.6228	0.030	-0.0081
Const	1.0135	0.0198	*51.2694*		
T crit	**R^2**	**F obs**	**f crit**	**average v2/vref**	
1.960465852	0.536424372	1363.985054	2.373816699	1.04743886	

Thies campaign					
	Ak	**Se**	**t =(Ak/se)**	**stdev**	**ske**
Air density	0.1255	0.0115	10.8826	0.019	0.0023
Vertical turbulence	1.1313	0.0146	77.4286	0.019	0.0209
V3D_mean	-0.0001	0.0001	-1.1283	2.311	-0.0003
I hor	-0.2948	0.0080	-37.0333	0.032	-0.0091
Const	0.8456	0.0149	*56.7540*		
T crit	**R^2**	**F obs**	**f crit**	**average**	
1.960452209	0.61751873	1965.258784	2.373759855	1.0402562	

Riso campaign					
	Ak	**Se**	**t =(Ak/se)**	**stdev**	**ske**
Air density	0.1420	0.0349	4.0706	0.012	0.0017
Vertical turbulence	0.2348	0.0171	13.7435	0.022	0.0052
V3D_mean	-0.0010	0.0001	-7.5033	3.072	-0.0032
I hor	-0.1900	0.0085	-22.2269	0.041	-0.0080
Const	0.8358	0.0437	*19.1296*		
T crit	**R^2**	**F obs**	**f crit**	**average**	
1.9612	0.2870	195.0922	2.3765	0.9840	

Ak = regression coefficient
se = statistical uncertainty
t = t-value (= Ak/se)
stdev = st. dev. of the independent variable
ske = dependence coefficient

T crit = critical t-value
R^2 = regression coefficient
F obs = F-value observed
f crit = F-value critical
Average v2/vref
= average of the dep. variable V2/Vref

The dependence coefficients (ske) are calculated as follows, ske = regression coefficient (Ak in table 5) multiplied with the standard deviation of the independent variable divided by the average of the dependent variable.

In figure 10 the ske values of the independent variables for the four campaigns are shown.

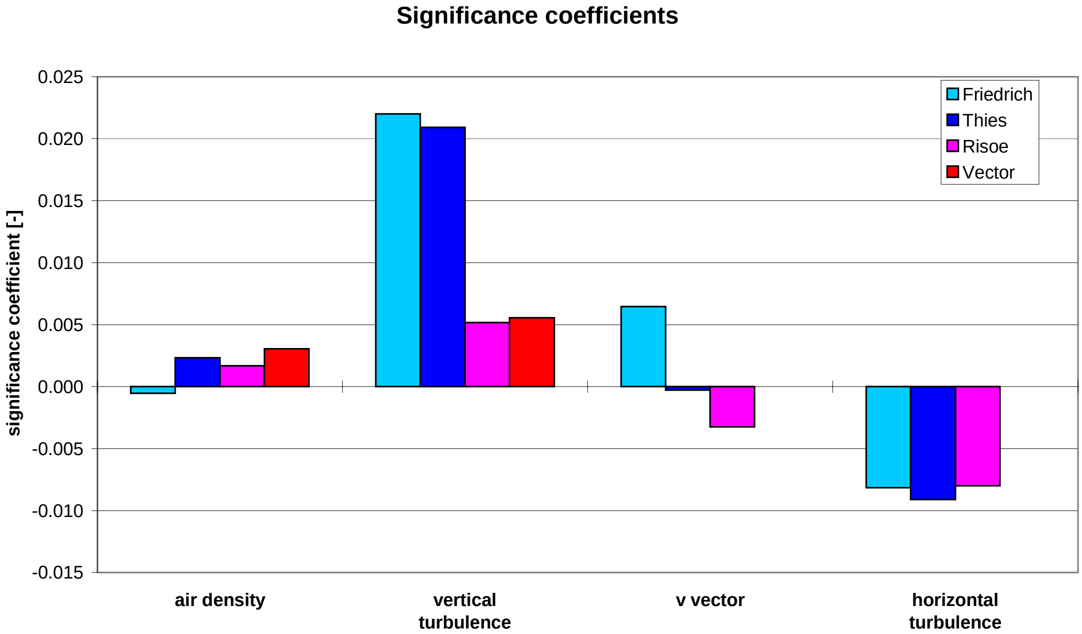

Fig 10. Significance Coefficients ske with V2/Vref as dependent variable.

MVRA results:

- The vertical turbulence intensity (in this case σ_w/V_{hor}) is clearly the most significant independent variable. This result is at least valid for spherical cup anemometers (Thies and Friedrichs). This means that there is a difference in response relative to the Miery ref anemometer. In case of the conical cup anemometers (Risø and Vector) the significance is lower, probably due to the fact that the response is similar for these type of instruments.
- Another independent variable that showed up is the turbulence, but the significance is much smaller.
- Both the density and vector wind speed show a relative low significance coefficient.

These results are consistent with an extensive multi variate regression analyses carried out by DEWI [7] within the framework of this SiteParIden project. It was decided during the project that DEWI would perform additional measurements and analyses especially with regard to the unexpected results obtained in the anemometer comparison.

Figure 11 gives the relation between the independent variable V2/Vref as a function of the measured vertical turbulence intensity. This figure confirms the MVRA result with respect to this item.
For one case a correction method had been applied by DEWI [7] successfully so comparable outputs from two different types of anemometers showed up.

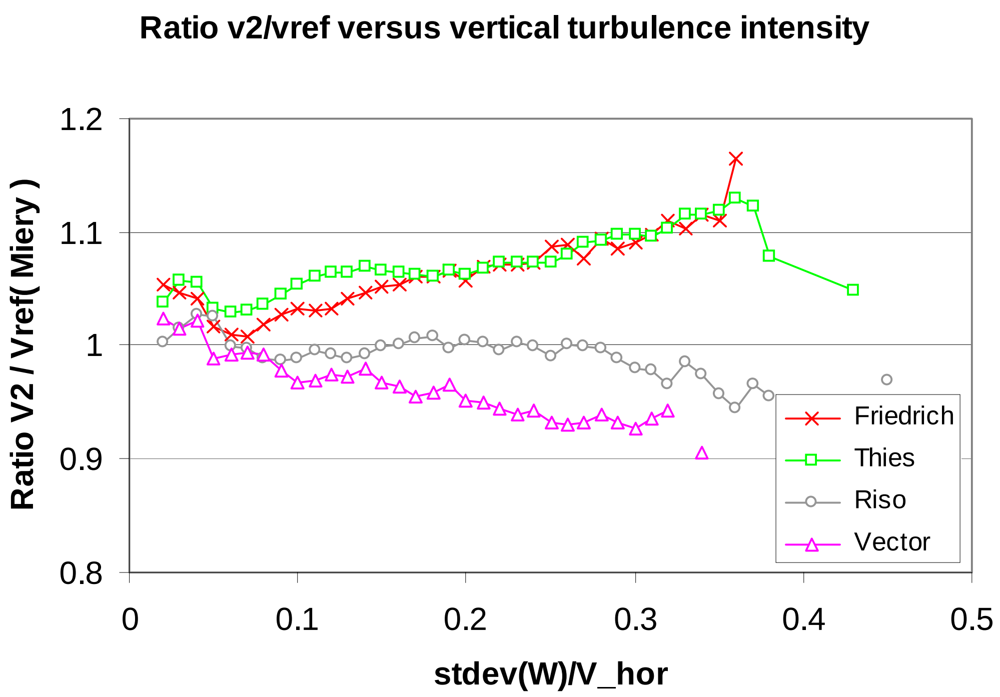

Figure 11. ratio independent variable V2/Vref as function of vertical turbulence intensity

6.6 Influence of wind speed deviation on power production estimation

The anemometer comparison results have a big impact on power performance testing and related wind energy production estimation. It means that the same test can result in higher or lower energy output estimation depending on the type of cup anemometer that has been used. In principle, this is difficult to accept because of the following reason.

The impact on AEP (Annual Energy Production) of a Power performance characteristic has been estimated. For that purpose we used the power curve as given in the Power Performance Testing standard document IEC 61400-12 [6]. The power curve has been adjusted simulating measurement results obtained with different anemometers. The wind speed was varied from +3.5 % up to –3.5% representing the 7% points difference as results of the cup anemometer comparison. The results are shown in Figure 12.
This difference in wind speed results is over 20% in energy output deviation for a low (5 m/s) wind regime and almost 10% in a high (9m/s) wind regime. This difference is more than the measurement uncertainty that is claimed up to now in power performance testing.

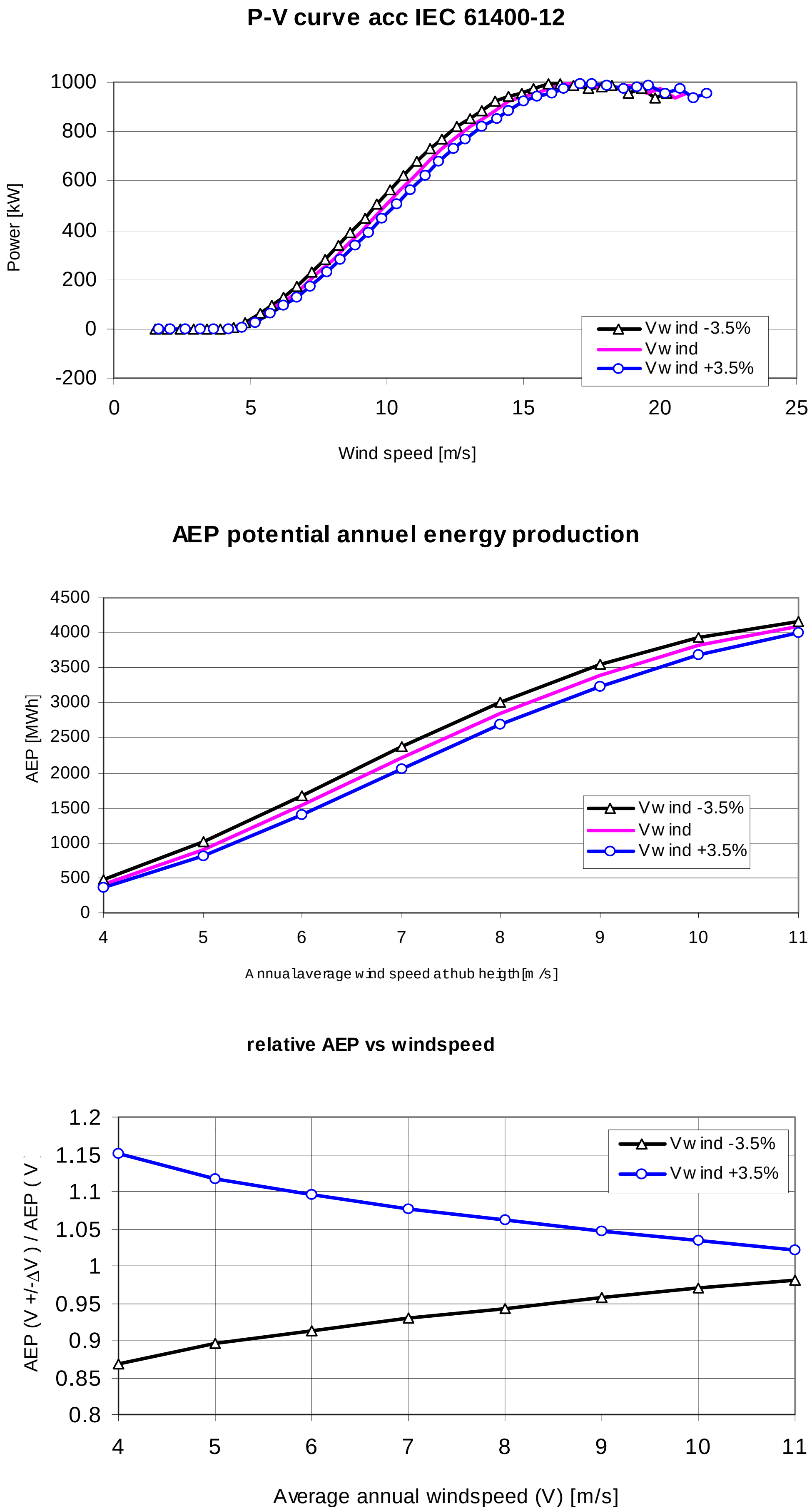

Figure 12. Influence of the wind speed deviations on the estimated wind energy production

7. CONCLUSIONS AND RECOMMENDATIONS

The activities of Task 7 can be finalised with the following conclusions and recommendations:

1. Average wind speeds measured with different cup anemometer sensor types, at the ECN test station, deviate up to 7% points relative to each other. This means that power characteristics measured with different types of anemometers give significant different results in estimated wind energy production potentials.
2. The effect of the observed differences on the estimated wind energy production is about 10% for good (9m/s) wind regimes and 20% for lower (5 m/s) wind regime sites.
3. The turbulence intensities measured with the different sensors show deviations between the applied sensors of 2-5% points. Although the measured turbulence intensities indicate complex terrain circumstances, this is not found for the location at ECN Petten, on the basis of measured standard deviations of the different wind vector components.
4. The reason for the unexpected big deviations between the anemometers is not trivial. The variability of the natural wind, with respect to magnitude and direction of the wind speed vector plus the design of the anemometer, in terms of housing, shape of cups and arm length of the cups contribute to the observed differences.
5. A limited multivariate regression analysis showed that the vertical turbulence intensity is the most significant variable causing the differences of anemometer output under natural turbulent conditions.
6. Cup anemometers perform comparable at sites with very low turbulence intensities. The comparability of the anemometer output deviates more with increasing turbulence at the site; i.e. complexity of the terrain. So differences of anemometer output will be due to site specific turbulence or flow.
7. Further research is needed to identify correction methods, which will be anemometer type dependent. Applying correction methods will lead to more comparable measured power characteristics.
8. It is necessary that cup anemometer sensors will be classified on the basis of their output characteristics; i.e. inclined flow, turbulence, etc. The results of the EC project ClassCup are important input for specific classification of cup anemometers.

8. REFERENCE

[1] A. Albers; Identification of Variables for Site Calibration and Power Curve Assessment in Complex Terrain (JOR3-CT98-0257), Project Task 6, Relative Power Curve Measurements in Flat Terrain, 6th Month Interim Note, 1999

[2] I. Antoniou; e.a., Identification of Variables for Site Calibration and Power Curve Assessment in Complex Terrain (JOR3-CT98-0257), Second periodic progress report; August 1999 – July 2000.

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[4] EWTS II, Complex Terrain and Fatigue Loading, pp.1 sub B.27 of ECN-C—99-073.

[5] IEA Recommended Practices, 11. Wind Speed Measurement and Use off Cup Anemetry, 1. Edition 1999.

[6] International Standard, IEC 61400-12; Wind Turbine Power Performance, First Edition 1998-02.

[7] A. Albers; Identification of Variables for Site Calibration and Power Curve Assessment in Complex Terrain (JOR3-CT98-0257), Project Task 6, Relative Power Curve Measurements in Flat Terrain, Final Report.
Report-No.: JOR3-CT98-0257-0601-DEWI07, 13 June 2001

APPENDIX

Comparison of behaviour of the Jaquet and Miery Frequency converter.

The reference wind speed signal is conditioned with the Miery F/I converter, which is part of the standard ECN wind measurement equipment. The signals from the anemometers under comparison (Vector, Thies, Friedrichs , Risø) are converted with a Jaquet F/I converter. This converter is used because it can easily be adapted to the specific frequency range of the different instrument. In order to obtain only the possible differences of the cup anemometer sensors itself both applied frequency converters were tested in a comparative measurement. The Jaquet and Miery converter were connected parallel to the Miery cup anemometer. So both converters are connected to the same signal source. Prior to the measurement the two signal chains were calibrated end to end. In theory both converters should give the same output. In practise a small difference has been measured. From the measured data 10-minute average values are determined. In figure 13 the results of the measurements are given.

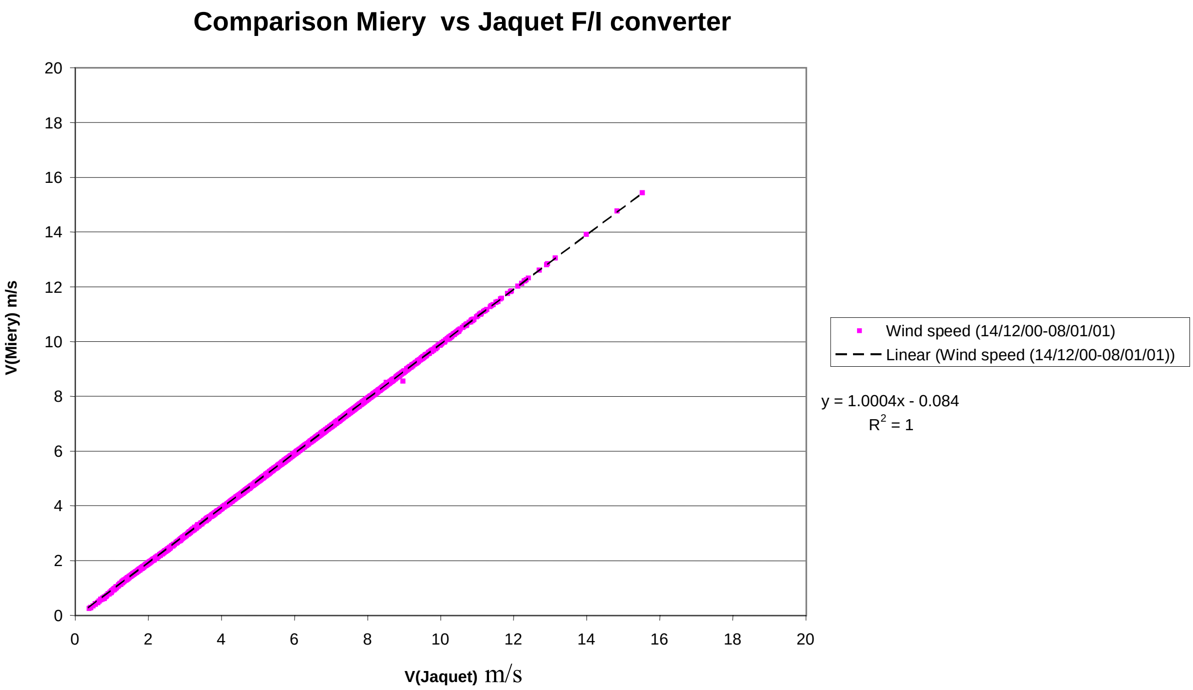

Figure 13. Effect of the frequency converter on the measured wind speed

By means of a line fit algorithm the relation between the measured two wind speeds is determined. The result is at the right side of the picture above. As shown the differences are very small.

In the project is chosen to compensate the Miery reference wind speed signal according to the following relation:

Vwind = VMiery * 0.9996 + 0.0839664 (the inverse function of the function found by the line fit).

The differences in measured wind speed as a function of wind speed is shown in figure 14.

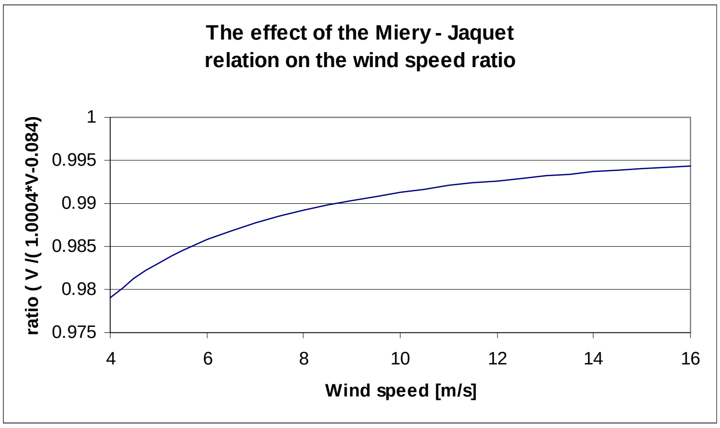

Figure 14. Relative effect of the two frequency converters on the measured wind speed