ECN-NORCOWE wake LiDAR measurement campaign at ECN test site

Overview report

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Acknowledgement

This report is written within the LiDAR Applications for WINd farm Efficiency (LAWINE) project, partially funded by Dutch government in the framework of TKI Wind op Zee. The LAWINE project is coordinated by ECN and the project partners are Technical University of Delft, XEMC Darwind and Avent LiDAR Technology. Within the project a collaboration was initiated with the NORwegian Centre for Offshore Wind Energy (NORCOWE).

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Abstract

In this report an overview of the ECN and NORCOWE wake LiDAR campaign at the ECN Wind turbine Test site Wieringermeer in the period 2012-2014 is given. In this campaign in parallel to meteorological masts, several ground based and nacelle based LiDARs were used to measure the wind regime and wind turbine wake behaviour. In particular the test set-up is described, the used equipment, sensors and signals and the duration of the campaigns. This document is aimed to be a public reference document for future publications describing the measurement campaign overview.

Contents

1 Introduction

1.1 LAWINE

ECN has initiated the project named “Efficiency improvements by LiDAR assistance” or “LAWINE: Lidar Application for WINd farmEfficiency” together with Delft University of Technology, Avent Lidar Technology and XEMC Darwind in the framework of TKI Wind op Zee [1]. The project is built around testing, evaluating and developing LiDAR technology to reduce the Cost of Energy for offshore wind farms.

Work package B “WindScanner”of the Lawine project is focused around scanning LiDAR technology. Here, it is aimed to test this technology in the multi-MW research turbines at ECNs test site, where 5 large meteorological masts are accurately measuring the wind field at multiple heights. Based on these tests the WindScanner research infrastructure [2] is further developed.

1.2 NORCOWE

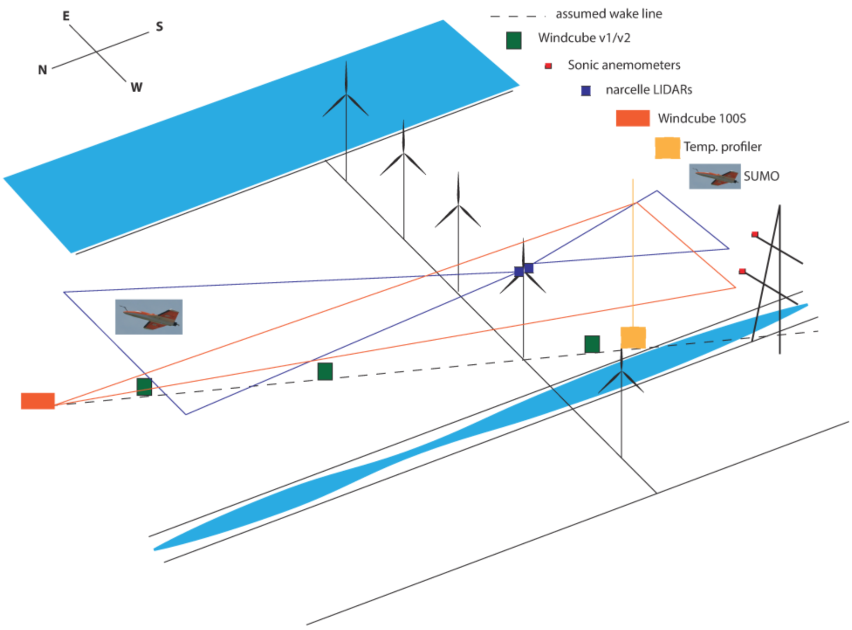
The NORwegian Centre for Offshore Wind Energy (NORCOWE) [3] is an interdisciplinary resource centre for exploitation of offshore wind energy as a natural sustainable energy source. The vision of NORCOWE is to combine Norwegian offshore technology and leading international communities on wind energy in order to provide innovative and cost efficient solutions and technology for large water depths and harsh offshore environments. It is a goal that NORCOWE will help building strong clusters on offshore wind energy in Norway by developing new knowledge and by providing skilled persons for the industry.

Work package 1 “Wind and Ocean conditions” of NORCOWE aims to improve the knowledge of the offshore wind and ocean conditions – with focus on climatology and the marine (sea-air) boundary layer (MBL). This is done with modelling and observations. The models and new measurement techniques are being developed and are taken into use in order to improve our understanding of the marine boundary layer.

1.3 Joint LiDAR campaign

The Wind Turbine Wake Experiment - Wieringermeer (WINTWEX-W) is a cooperative wake measurement campaign conducted by the ECN and NORCOWE. A scanning LiDAR, four static Windcubes as well as a downstream looking nacelle LiDAR are placed for half a year downstream of and on one of the five research wind turbines in the ECN Wind turbine Test site Wieringermeer (EWTW) to measure single wind turbine wakes. The aim of the campaign is a qualitative and quantitative description of single wind turbine wake propagation and persistency, as well as to improve CFD wake models by delivering a detailed data set of several real atmospheric conditions.

Figure 1: Proposed set-up and layout of the joint ECN-NORCOWE campaign



1.4 Purpose of this document

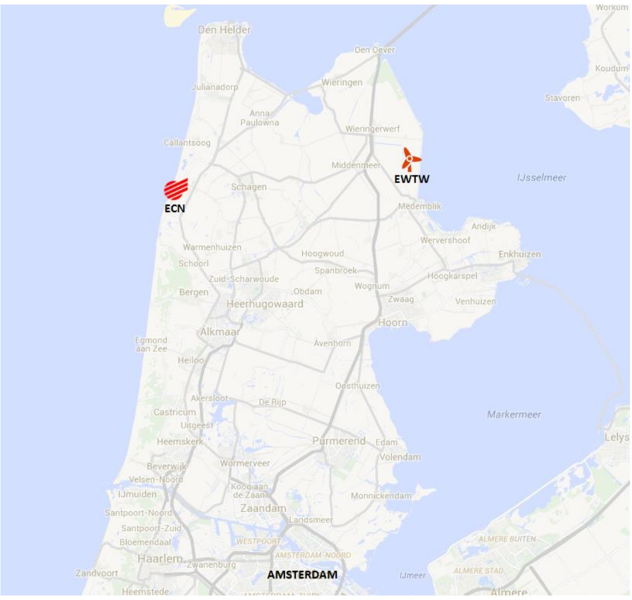
The indicated campaign has resulted in the creation of a huge database. Of course such a campaign needs to be properly documented. Now, several document have been issued in this respect [4], however, because they all contain at least some confidential information, none of them is available in the public domain. One of the goals of this joint campaign is to generate publicly available foreground knowledge in the form of papers, reports, conference contributions, etc. In these documents reference needs to be made to the campaign available to the reader and hence the purpose of this document is explained.

2

ECN Test Site EWTW

In the end of 2002 ECN commenced a wind turbine test site in Wieringermeer located on the North east of the province North Holland, about 60 km North of Amsterdam and 35 km east of the ECN headquarters in Petten. The test site, named EWTW, is shown in **Figure 2** and is located in the vicinity of the artificial lake of IJsselmeer.

Figure 2: Location of the EWTW [Google]

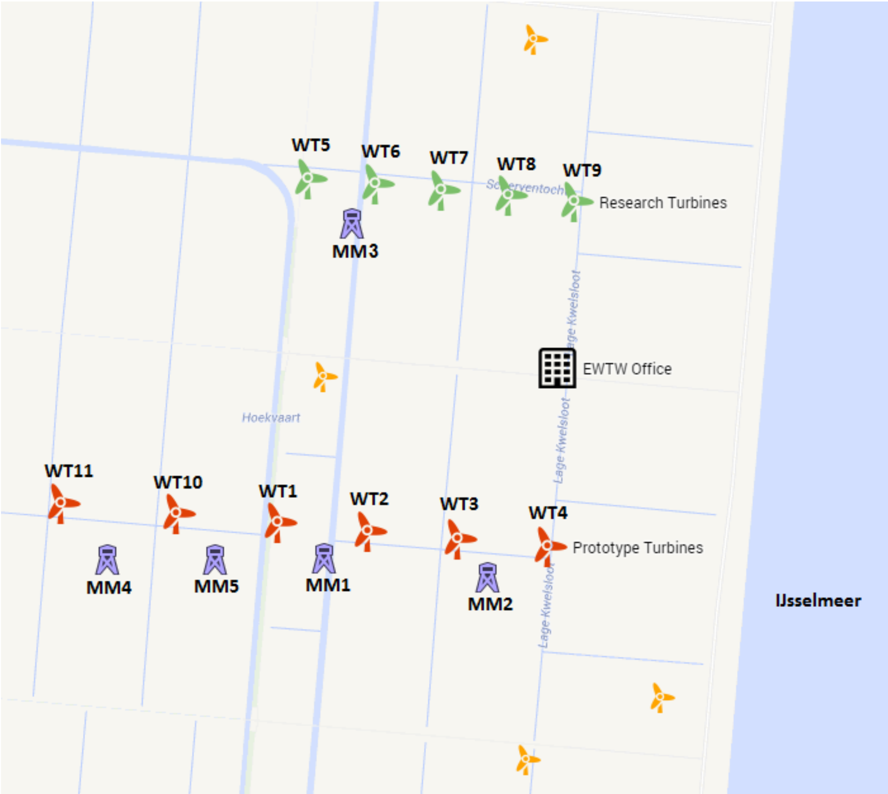


The test site is equipped with a state of the art infrastructure for site assessment and wind turbine testing and certification. Currently, the test site consists of:

- Five research turbines in locations Wt5 to Wt9 (**Figure 3**). The research turbines are used for experimental research conducted by ECN wind unit and other European research institutes.

- Six prototype locations in locations Wt11, Wt10 and Wt1 to Wt4 (**Figure 3**). The wind turbine manufactures use prototype locations for tests and certification of their new wind turbines.
- Five meteorological masts (hereafter referred to as met mast or MM) MM1 to MM5 (**Figure 3**).
- 10kV cables to connect turbines to a 50/100 kV transformer station and then, direct connection to a high voltage substation.
- Glass fibre network to transmit the measurement data.
- Measurement pavilion of the site.

Figure 3: The EWTW infrastructure: research turbines in green, prototype locations in red, neighbour turbines in orange and meteorological masts in purple [Google]



In **Table 1** general specifications of the EWTW meteorological masts including their coordinates and erection date are given.

Table 1: General description of the EWTW met masts

Met Mast	Latitude	Longitude	Lattice Height (m)	Erected for	Erected on	In Operation Since
MM1	52.81443	5.07977	108	Wt 1-2	Mar/Apr 2003	30 Jun 2003
MM2	52.81365	5.09055	96.2	Wt 3-4	Jul 2005	10 Oct 2005
MM3	52.82814	5.08164	108	Wt 5-9	Jul 2004	10 Dec 2004
MM4	52.81625	5.06649	96.2	Wt 10-11	Feb/Apr 2011	10 May 2011
MM5	52.81627	5.07383	88.8	Wt 1	Aug/Sept 2011	04 Oct 2011

Similarly, in **Table 2** general specifications of the research turbines are given.

Table 2: General description of the EWTW turbine locations

Location	Turbine Type	Latitude	Longitude	Erected on	Rated Power	Rotor Diameter	Hub Height
					(kW)	(m)	(m)
Wt5	Nordex N80/2500	52.831788	5.080083	2004	2500	80.0	80.0
Wt6	Nordex N80/2500	52.831552	5.084593	2004	2500	80.0	80.0
Wt7	Nordex N80/2500	52.831313	5.089106	2004	2500	80.0	80.0
Wt8	Nordex N80/2500	52.831083	5.093613	2004	2500	80.0	80.0
Wt9	Nordex N80/2500	52.830852	5.098120	2004	2500	80.0	80.0

A photograph of the test is provided in **Figure 4**, where the research turbines located on the north side of the measurement pavilion are shown in **Figure 5** and the prototype locations located on the south side of the measurement pavilion in **Figure 6**.

Figure 4: Turbine locations of the EWTW test site [taken Jan. 2015]

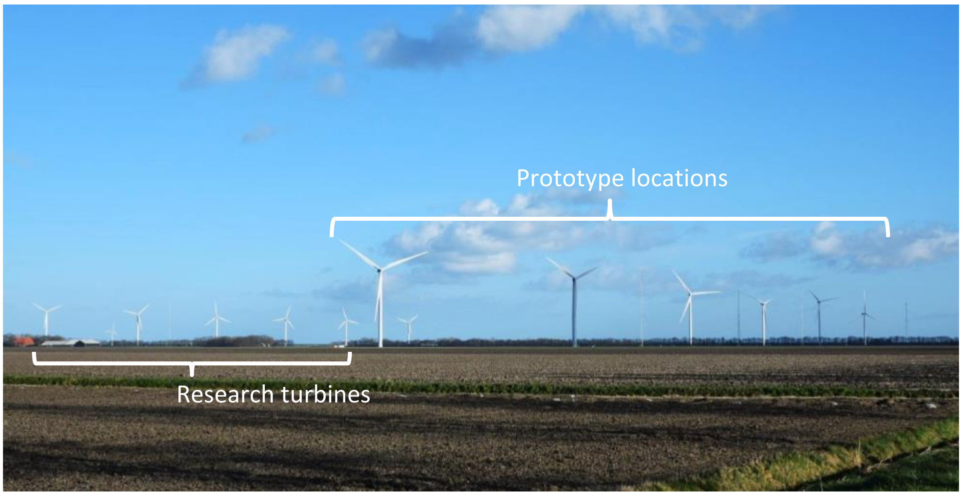


Figure 5: The research turbines and MM3 of the EWTW test site [taken Jan. 2015]

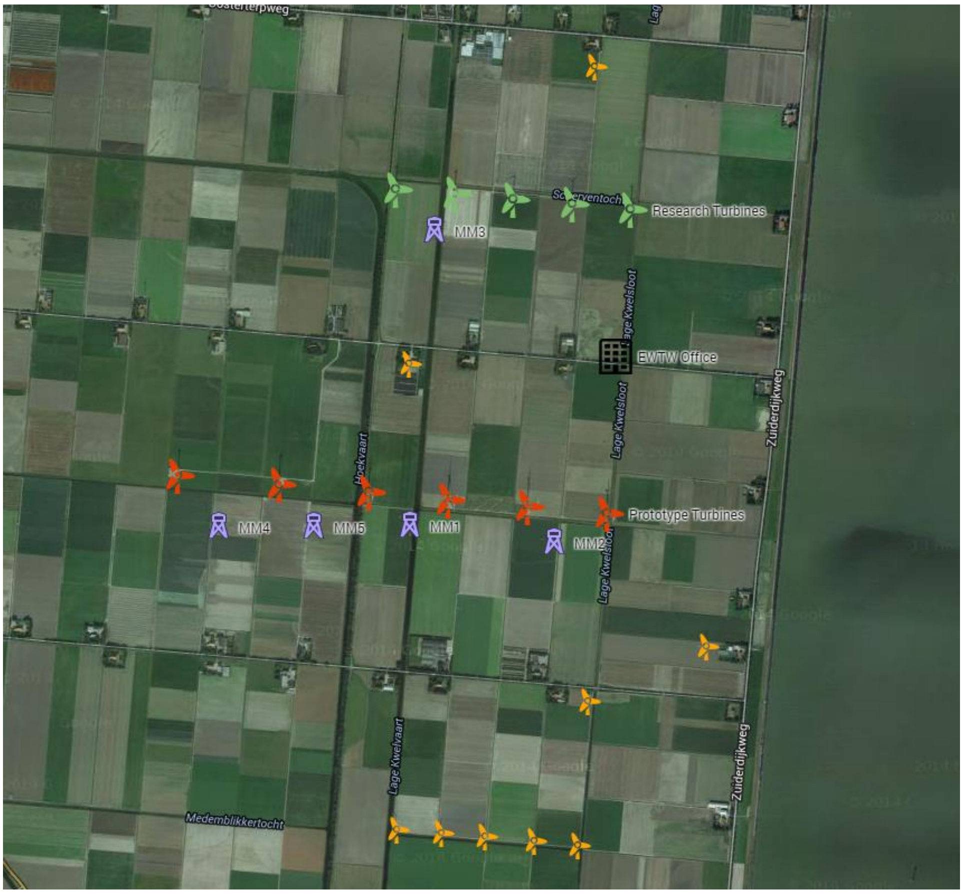
Figure 6: Prototype locations, MM1, MM2, MM4 and MM5 of the EWTW test site [taken Jan. 2015]

The LiDARs in this campaign are mainly located around WT6 and MM3. Therefore, only WT6 and MM3 and their instrumentation are discussed further. In chapter 3 and 4 of this report the WT6 and MM3 is discussed in detail.

2.1 Site Topography

The polder Wieringermeer consists of flat agricultural land at an altitude of 5 meters below sea level. The East border of the polder is a dike (or sea wall) about 8 meters height, seen from the land site, and 3 meters height seen from the IJsselmeer.

Figure 7: The EWTW infrastructure from satellite view: research turbines in green, prototype locations in red, neighbour turbines in orange and meteorological masts in purple [Google]



Since the LiDAR campaign is mainly carried out around the MM3, only site topography around this meteorological mast is discussed here. As seen from MM3, the relevant obstacles are a row of trees, farmhouses plus barn, and surrounding wind turbines. The small village of Kreileroord is in the vicinity. In chapter 3 of this report 360° photos taken from the MM3 location are given. Following points are noticeable around MM3:

- Along the road (Zuiderkwelweg), 250 meters west of the MM3, a row of trees stretches from the North to the South. It ranges from the village Kreileroord to 3 kilometres South of the prototype turbines. The height of the trees is approximately 15 meters.
- North of the MM3, five EWTW research turbines are located.
- South of the MM3, a single wind turbine (NEG Micon NM52) is located.
- South of the MM3, the EWTW prototype turbines are located.

2.2 Site Climate

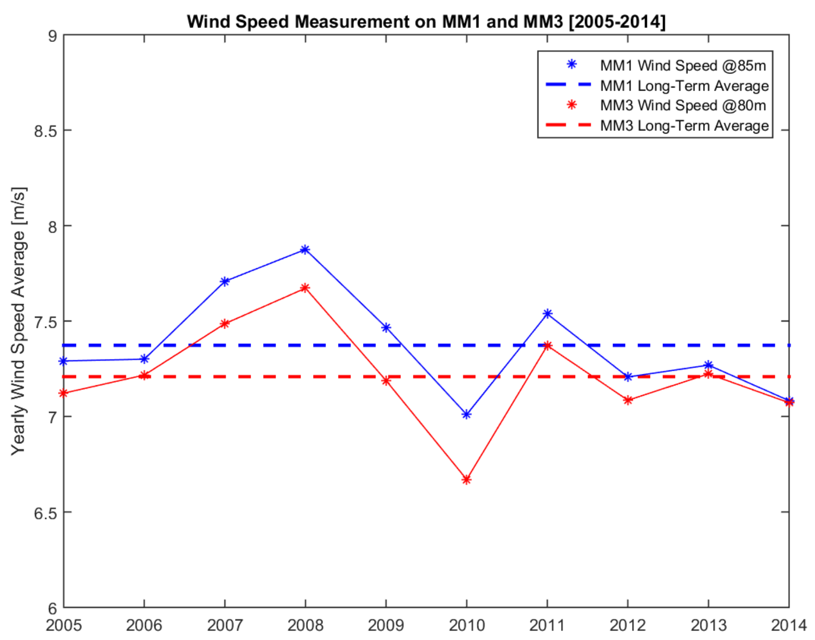
In **Table 3**, overall statistics (yearly maximum, minimum, average and standard deviation) of 10 years (2005 to 2014) climate condition at the EWTW for MM1 at 85 meters height and MM3 at 80 meters height are given. See also [5] for more information.

Table 3: Overall statistics of climate condition at the EWTW for the period 2005 to 2014 (including wakes)

Measurement Signal	Unit	Min		Max		Mean		STD	
		MM1	MM3	MM1	MM3	MM1	MM3	MM1	MM3
Wind Speed	[m/s]	0.08	0.25	32.02	32.69	7.37	7.21	3.53	3.48
Turbulence Intensity	[%]	0.00	0.00	59.88	59.98	10.95	11.63	6.18	6.16
Flow Inclination	[deg]	0.00	0.00	20.00	19.98	2.61	2.23	1.97	1.59
Air Temperature	[°C]	-12.6	-12.8	31.35	31.34	10.31	10.30	6.16	6.12
Atmospheric Pressure	[hPa]	953.3	954.1	1037.5	1038.2	1005.1	1005.9	10.11	10.09
Relative Humidity	[%]	0.09	0.07	100.00	100.00	79.24	78.51	12.94	12.74

In **Figure 8**, yearly average of wind speed measurement on MM1 and MM3 for the period of 2005 to 2014 are depicted.

Figure 8: Wind speed measurement of MM1 and MM3 for the period 2005 to 2014 (including wakes)



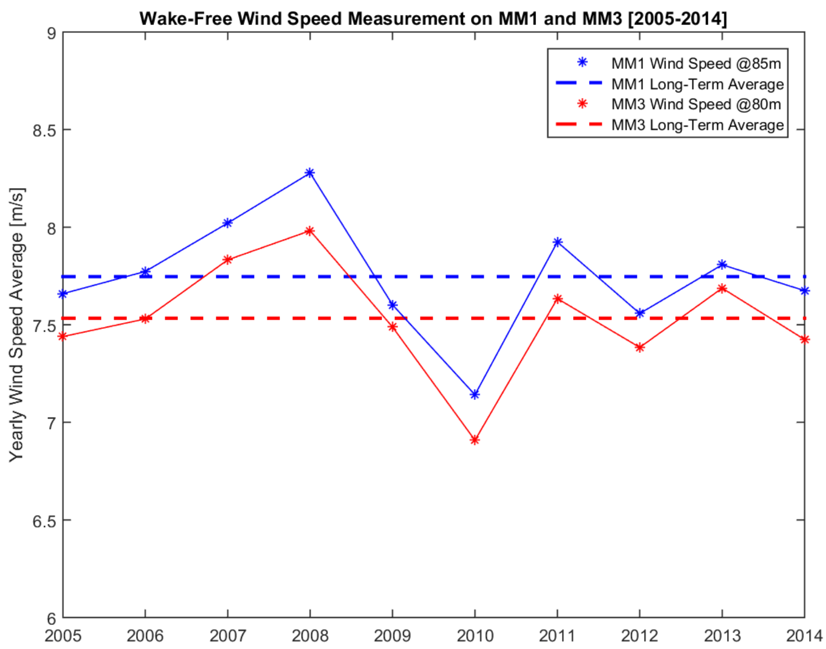
In **Table 4**, wake-free statistics (yearly maximum, minimum, average and standard deviation) of 10 years (2005 to 2014) climate condition at the EWTW for MM1 at 85 m height and MM3 at 80 m height are given.

Table 4: Wake-free statistics of climate condition at the EWTW for the period 2005 to 2014

Measurement Signal	Unit	Min		Max		Mean		STD	
		MM1	MM3	MM1	MM3	MM1	MM3	MM1	MM3
Wind Speed	[m/s]	0.078	0.247	32.018	32.688	7.746	7.533	3.519	3.510
Turbulence Intensity	[%]	0.000	0.000	59.881	59.978	9.633	10.298	4.568	5.038
Flow Inclination	[deg]	0.000	0.000	19.998	19.977	2.565	2.188	1.632	1.510

In **Figure 9** yearly average of wake-free wind speed measurement on MM1 and MM3 for the period of 2005 to 2014 are depicted.

Figure 9: Wake-free wind speed measurement on MM1 and MM3 for the period 2005 to 2014



3

Research Turbine

The ECN research turbines are 5 Nordex N80 turbines. They are pitch regulated machines with a rated power of 2.5MW. The hub height and the rotor diameter is 80m. They are numbered Wt05 to Wt09 from West to East. The turbine under test is Wt06, i.e. the second turbine as seen from East.

The main reason for considering turbine Wt06 (sometimes referred to as N6 or Nordex 6) is that the meteorological mast MM3 is at a distance of 2.5D, i.e. the optimal distance according to the IEC 61400-12-1 [6] standard. Another reason is that the main wind direction at the site is South-West. With winds from this direction the mast directly is in front of the turbine measuring the inflow conditions. Below the signals as measured from the indicated turbine are discussed, separately.

Active power Wt06
Signal: Wt06_Mb_Epow_Q1
Dimension: kW

The active power is measured at the low voltage side of the transformer by means of current transformers and a power transducer. The output signal of the power transducer is measured with an analogue Dante module data acquisition system.

The specifications about the power transducer are listed below:
Brand: Muller-Ziegler
Type: Pdr-Mu with additional second order low pass filter with cut-off frequency of 400 Hz
Range: -2500…4000 kW

Table 5: Nordex 6 power signal

Signal name	unit
Wt06_Mb_Epow_Q1	kW

PLC signals

The following PLC signals are measured in the Nordex turbines.

Table 6: Nordex PLC signals

Signal name	unit
Wt0x_Ct_PEpow_Q5	kW
Wt0x_Ct_Pgspd_Q5	Rpm
Wt0x_Ct_Pwsnac_Q5	m/s
Wt0x_Ct_Pwdnac_Q5	Deg
Wt0x_Ct_Pnacdrtn_Q5	Deg
Wt0x_Ct_Ppitch1_Q5	Deg
Wt0x_Ct_Ppitch2_Q5	Deg
Wt0x_Ct_Ppitch3_Q5	Deg
Wt0x_Ct_Popmode_Q5	-
Wt06_Ct_Pred_pow_Q5	1/0

Apart from the Wt06_Ct_Pred_pow_Q5 signal, all PLC signals are measured in the turbines Nordex 5- 9.

Short description of the signals:

Wt0x_Ct_PEpow_Q5:	electrical power
Wt0x_Ct_Pgspd_Q5:	generator speed
Wt0x_Ct_Pwsnac_Q5:	nacelle wind speed Default, this is the wind speed measured with 2D sonic wind sensor mounted on top of the nacelle. In case of a failure of the sonic wind sensor, the turbine switches to the cup anemometer.
Wt0x_Ct_Pwdnac_Q5:	wind direction nacelle When the turbine is in upwind position, this signal equals the T6_Pnacdrtn signal. Default, this is the wind direction measured with 2D sonic wind sensor mounted on top of the nacelle. In case of a failure of the sonic wind sensor, the turbine switches to the wind vane.
Wt0x_Ct_Pnacdrtn_Q5:	nacelle direction relative to North.
Wt0x_Ct_Ppitch1_Q5:	pitch angle blade 1
Wt0x_Ct_Ppitch2_Q5:	pitch angle blade 2
Wt0x_Ct_Ppitch3_Q5:	pitch angle blade 3
Wt0x_Ct_Popmode_Q5:	operational mode
Wt0x_Ct_Pred_pow_Q5:	reduced power.

All this signals come from the so called “Messbox”, a Nordex device where the digital PLC signals are converted into mA signals picked-up by the ECN Dante Frontend. The signal Wt0x_Ct_Pnacdrtn_Q5 is calibrated by measuring the nacelle position with respect to the magnetic North using a compass. Most of these signals are measured using analogue Dante modules, some of these signals are measured using a LON-ADC telemetry unit.

For more information about the signals and the instrumentation reference is made to [4].

4
Meteorological Mast

The MM3 is the second met mast installed at the EWTW site and erected in July 2004. The MM3 is designed in such a way to support the experimental research on the turbines in locations WT5 to WT9. The distance of the MM3 to the research turbines is given in **Figure** 10.

Figure 10: The distance of the MM3 to research turbines.

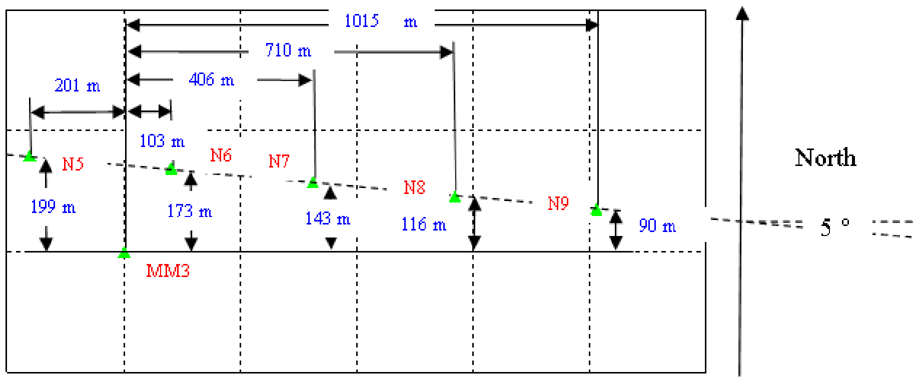


Table 7 gives an overview of the undisturbed wind sectors of MM3 and WT6 as determined according to [6].

Table 7: Undisturbed wind sectors MM3 & Nordex turbines

	Min angle (deg)	Max angle (deg)
WT6	305.14	32.67
	125.76	138.4
	239.85	244.63
MM3	345.92	353.75
	102.35	132.52
	241.84	283.22
WT6 & MM3	345.92	353.75
	125.76	132.52
	241.84	244.63

4.1 Mast Structure

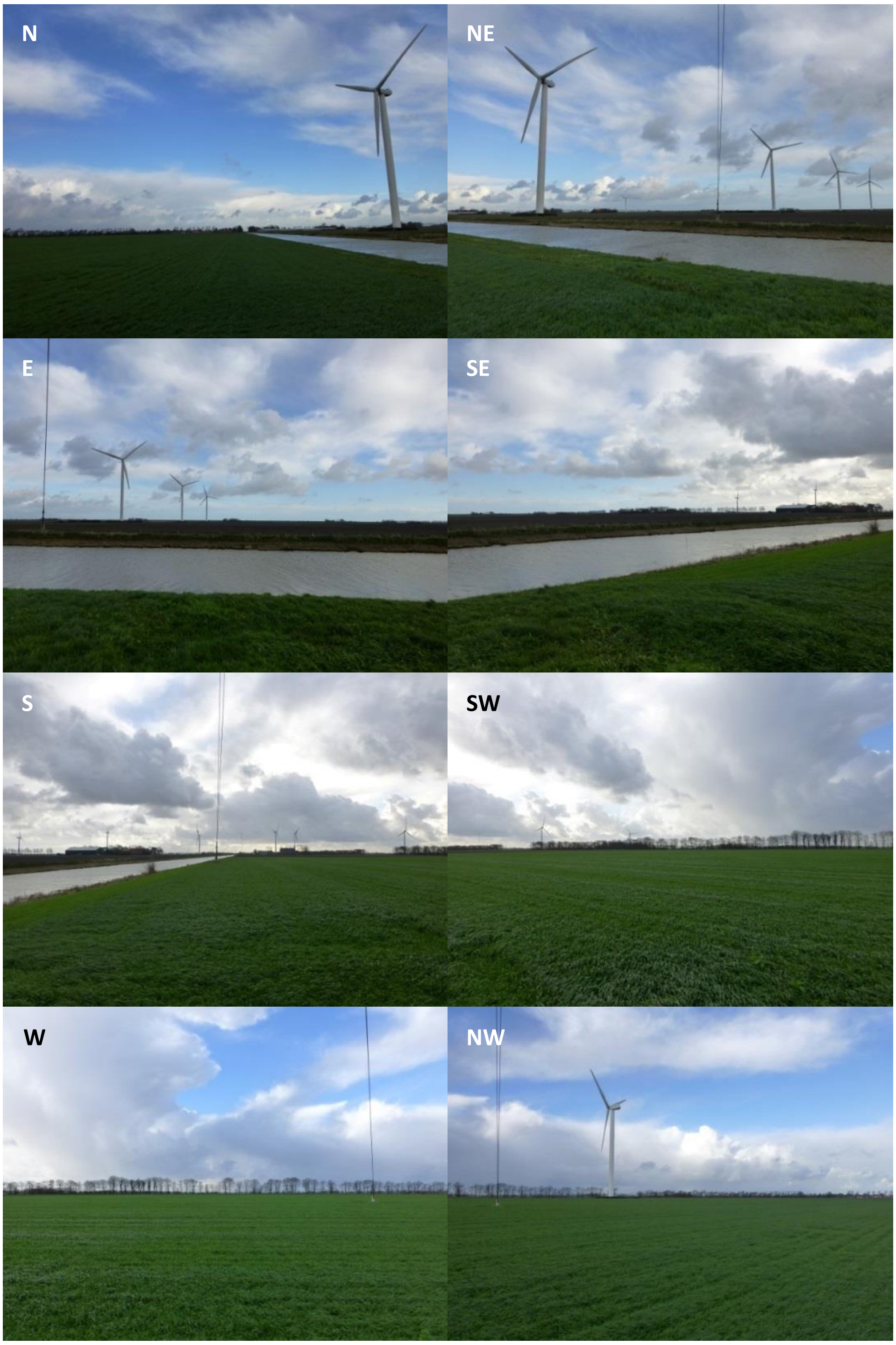
The overall structure of the MM3 is similar to MM1, which is 108 m lattice tower. In MM3, booms are installed at two different heights, 50.4 and 78.4 m. In MM3 the instrumentation are installed on the booms and on top of the mast at 108 m. The structure of the MM3 is shown in **Figure 11**.

Figure 11: Lattice structure of the MM3 with attached booms positioned by guy wires [taken Jan. 2015]

4.2 360° Photographs

The complete 360° sector photographs taken from the MM3 position is given **Figure 12**.

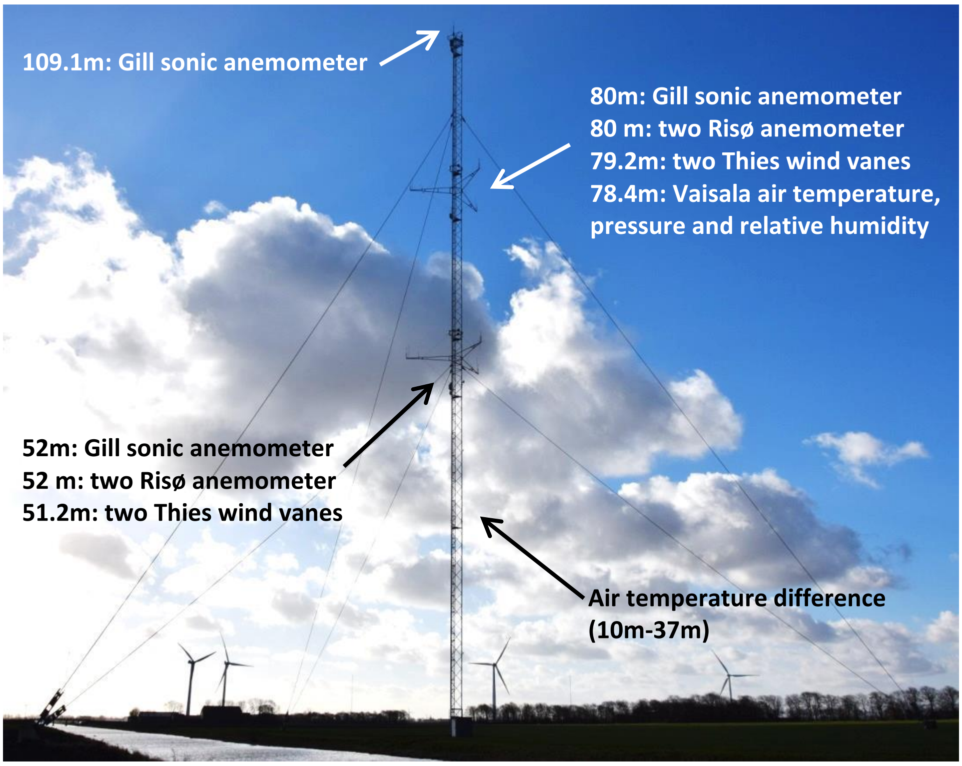
Figure 12: 360° sector photographs taken from the MM3 position [taken Dec. 2014]



4.3 Sensor Arrangement

In the MM3 meteorological instrumentations are installed on booms at two heights and on the top of the mast. In **Figure 13** an overview of the MM3 instrumentation is illustrated.

Figure 13: Overview of the MM3 instrumentations.



The complete list of sensors installed on the MM3 is given in **Table 8**. The sensors mounted at different height level are separated with a black line.

Table 8: Sensor list of the MM3.

Signal	Signal Name	Unit	Height	Brand	Sensor Type
			(m)		
Wind speed 108 m	MM3_S108	m/s	109.1	Gill	1086 M
Wind direction 108 m	MM3_S108_VDIR	deg	109.1	Gill	1086 M
Wind speed 80 m	MM3_S80N	m/s	80	Gill	1086 M
Wind direction 80 m	MM3_S80N_VDIR	deg	80	Gill	1086 M
Wind speed SE 80 m	MM3_WS80_120	m/s	80	Risø	P2456A
Wind speed SW 80 m	MM3_WS80_240	m/s	80	Risø	P2456A
Wind direction SE 80 m	MM3_WD80_120	deg	79.2	Thies	4.3150
Wind direction SW 80 m	MM3_WD80_240	deg	79.2	Thies	4.3150
Air temperature 80 m	MM3_Tair80	°C	78.4	Vaisala	HMP 155
Air humidity 80 m	MM3_RH80	%	78.4	Vaisala	HMP45A
Air pressure 80 m	MM3_Pair80	hPa	78.4	Vaisala	PTB 210
Wind speed 52 m	MM3_S52N	m/s	52	Gill	1086 M
Wind direction 52 m	MM3_S52N_VDIR	deg	52	Gill	1086 M
Wind speed SE 52 m	MM3_WS52_120	m/s	52	Risø	P2456A
Wind speed SW 52 m	MM3_WS52_240	m/s	52	Risø	P2456A
Wind direction SE 52 m	MM3_WD52_120	deg	51.2	Thies	4.3150
Wind direction SW 52 m	MM3_WD52_240	deg	51.2	Thies	4.3150
Temperature difference	MM3_dT_37min10	°C	--	Rense	--

In the following sections each sensor of the MM3 is described in detail.

Wind Speed Instruments

3D sonic anemometer at 109.1m

Signals: MM3_S108_U, MM3_S108_V, MM3_S108_W, MM3_S108_VHOR
Dimension: (m/s)
Signal: MM3_S108_VDIR
Dimension: (deg)
Signal: MM3_S108_St (status)
Dimension: (-)

The Gill anemometer is located on top of the meteorological mast. It is mounted on top of the East mast pillar. The sensor itself is 1.15 m above the mast top at 109.1 m height. On the South pillar a 5 m long lightning conductor is fixed. The wind, coming from the South-West (around 240° direction), will be influenced by this rod. On the West pillar an air-traffic warning light is positioned.

3D sonic anemometer at 80 m

Signals: MM3_S80N_U, MM3_S80N_V, MM3_S80N_W, MM3_S80N_VHOR
Dimension: (m/s)
Signal: MM3_S80N_VDIR
Dimension: (m)
Signal: MM3_S80N_St (status)
Dimension: (-)

The Gill sonic anemometer is located at the tip end of the tri-angular boom directed to North. The distance between mast and sensor is 6.5 m. The sensor is identified with the direction of the boom, which is North. The distance, in a straight line at the horizontal level, between the anemometer and cup anemometers is 12.4 m. The sonic anemometer measures 1.61 m above the boom end, which is 21 times the boom thickness (Ø76 mm). Next to the sonic anemometer a lightning conductor (Ø22 mm) is located. The distance between sensor and conductor is 263 mm. The sonic anemometers in the North of the mast is required to measure wake conditions with sonic anemometers.

3D sonic anemometer at 52m

Signals: MM3_S52N_U, MM3_S52N_V, MM3_S52N_W, MM3_S52N_VHOR
Dimension: (m/s)
Signal: MM3_S52N_VDIR
Dimension: (m)
Signal: MM3_S52N_St (status)
Dimension: (-)

The Gill sonic anemometer is located at the tip end of the tri-angular boom directed to North. The distance between mast and sensor is 6.5 m. The sensor is identified with the direction of the boom, which is North. The distance, in a straight line at the horizontal level, between the anemometer and cup anemometers is 12.4 m. The sonic anemometer measures 1.61 m above the boom end, which is 21 times the boom thickness (Ø76 mm). Next to the sonic anemometer a lightning conductor (Ø22 mm) is located. The distance between sensor and conductor is 263 mm. The choice of the sonic anemometers in the North of the mast is driven by the desire to measure wake conditions with sonic anemometers.

Cup anemometers at 80 m

Signals: MM3_WS80_120, MM3_WS80_240
Dimension: (m/s)

Risø-type cup-anemometers are located at the tip ends of the tri-angular booms. The distance between mast and sensor is 6.5 m. The signals from the cup-anemometers are identified with the directions the booms are pointed at: 120 and 240 degrees. The distance, in a straight line at the horizontal level, between the anemometers is 12.4 m.

The cup rotors of the anemometers are mounted 1.61 m above the boom end, which is 21 times the boom thickness (Ø76mm). Beside the cup-anemometers a lightning conductor (Ø22 mm) is located. The distance between sensor and conductor is 263 mm.

Cup anemometers at 52m

Signals: MM3_WS52_120, MM3_WS52_240
Dimension: (m/s)

Risø-type cup-anemometers are located at the tip ends of the tri-angular booms. The distance between mast and sensor is 6.5 m. The signals from the cup-anemometers are identified with the directions the booms are pointed at: 120 and 240 degrees. The distance, in a straight line at the horizontal level, between the anemometers is 12.4 m. The cup rotors of the anemometers are mounted 1.61 m above the boom end, which is 21 times the boom thickness (Ø76 mm). Beside the cup-anemometers a lightning conductor (Ø22 mm) is located. The distance between sensor and conductor is 263 mm.

Wind Direction Instruments

Wind vanes at 79.2 m

Signals: MM3_WD80_120, MM3_WD80_240
Dimensions (deg)

At 78.4 m, three booms are mounted pointing at 0, 120 and 240 degrees. The Thies wind vanes are installed on the 120° and 240° booms. They are attached to the boom at a distance of 4.7 m from the mast and 1.8 m from the boom tip end (cup anemometer). The top of the vane is 0.83 m above the boom. The heights of the wind vanes are 79.2 m above ground level. The type of wind vane differs from the MM1, the locations on the booms are identical.

Wind vanes at 51.2 m

Signals: MM3_WD52_120, MM3_WD52_240
Dimension: (deg)

At 50.4 m, three booms are mounted pointing at 0, 120 and 240 degrees. The Thies wind vanes are installed on the 120° and 240° booms. They are attached to the boom at a distance of 4.7 m from the mast and 1.8m from the boom tip end (cup anemometer). The top of the vane is 0.83 m above the boom. The heights of the wind vanes are 51.2 m above ground level.

Air Temperature Instruments

Temperature sensor at 78.4m

Signal: MM3_Tair80
Dimension: (°C)

One temperature sensor is mounted in the MM3. It is located at 78.4 m, and is mounted on a boom. The temperature sensor is a Vaisala HMP45A instrument equipped with a radiation shield.

Temperature difference sensor

Signals: MM3_dT
Dimensions (°C)

The temperature difference between 37 m height and 10 m height is measured.

Relative Humidity Instruments

Humidity sensor at 78.4m

Signal: MM3_RH80
Dimension: (%)

The relative humidity is measured with a Vaisala HMP45A instrument mounted on a boom at 78.4 m. Note that the temperature and relative humidity sensor are combined in a single Vaisala sensor.

Air Pressure Instruments

Air pressure sensor at 78.4m

Signal: MM3_Pair80
Dimension: (hPa)

One air pressure sensor is mounted on one of the booms at 78.4 m height. The air pressure is measured with silicon capacitive absolute pressure sensors of Vaisala.

4.4 Pseudo Signals

Pseudo signals are signals that are derived from measured signals on sample basis. In the following several pseudo signals are defined.

4.4.1 Wind speed and wind direction sonic anemometer

Signals:	MM3_H52_WsHorSon_Q5, MM3_H80_WsHorSon_Q5, MM3_H108_WsHorSon_Q5 [m/s]
	MM3_H52_WdHorSon_Q5, MM3_H80_WdHorSon_Q5, MM3_H108_WdHorSon_Q5 [deg]

At a height of 52m and 108m sonic anemometers are installed measuring the wind speed components u, v and w. These components are used to calculate the horizontal wind speed and wind direction in accordance with the following relationships:

(1)
$$V_{\mathrm{hor}} = \sqrt{u_{\mathrm{son}}^2 + v_{\mathrm{son}}^2}$$

(2)
$$V_{\mathrm{dir}} = 240 + \frac{180}{\pi}\,\mathrm{atan2}\left(\frac{-v_{\mathrm{son}}}{-u_{\mathrm{son}}}\right)$$

Where 240 is the offset correction for wind direction. These equations are elaborated in terms of the signal names below.

Table 9: Sonic horizontal Ws and Wd equations

name	label	equation
Horizontal Sonic Ws at 52 m	MM3_H52_WsHorSon_Q5	$(\mathrm{MM3\_H52\_WsUSon}^2 + \mathrm{MM3\_H52\_WsVSon}^2)^{0.5}$
Horizontal Sonic Wd at 52 m	MM3_H52_WdHorSon_Q5	240+(180/π*atan2(-MM3_H52_WsUSon /-MM3_H52_WsVSon))[1]
Horizontal Sonic Ws at 80 m	MM3_H80_WsHorSon_Q5	$(\mathrm{MM3\_H80\_WsUSon}^2 + \mathrm{MM3\_H80\_WsVSon}^2)^{0.5}$
Horizontal Sonic Wd at 80 m	MM3_H80_WdHorSon_Q5	240+(180/π*atan2(-MM3_H80_WsUSon /-MM3_H80_WsVSon))
Horizontal Sonic Ws at 108 m	MM3_H108_WsHorSon_Q5	$(\mathrm{MM3\_H108\_WsUSon}^2 + \mathrm{MM3\_H108\_WsVSon}^2)^{0.5}$
Horizontal Sonic Wd at 108 m	MM3_H108_WdHorSon_Q5	240+(180/π*atan2(-MM3_H108_WsUSon /- MM3_H108_WsVSon))

[1] atan2(y,x)=$\tan^{-1}(y/x)$

4.4.2 Temperature differences

Signals: MM3_H37-10_dT_Q5 [°C]

The temperature difference is an indicator for atmospheric stability. MM3_dT_37min10 is the temperature difference in meteorological mast 3, between the levels 37 and 10 meters. The temperature difference is the temperature at 37 m minus the temperature at 10 m. It is calculated in accordance with the following relationships:

$$\Delta T = -2 + \frac{4*(V_{dT} - 0.039 \;*T + 1.1436\,)}{(12.6253 - 0.1005*T)} \qquad (3)$$

Where:
$V_{d\,t}$= the measured temperature difference (dT) signal in volts (V): MM3_H37-10_dT_V_Q5
T = the air temperature at 80 meters: MM3_H80_Temp_Q1

This formula is derived by the supplier of the measurement equipment. A series of calibration measurements at stable temperatures are the basis for this formula.

4.4.3 Wind direction and wind speed at 52 and 80 m

Signals: MM3_H52_WD_Q1, MM3_H80_WD_Q1 [deg]
MM3_H52_WS_Q1, MM3_H80_Ws_Q1 [m/s]

At 52m and 80m cups and vanes are mounted on booms. The measurements on these booms are combined to minimize mast effects. The wind direction at 52m and at 80m (MM3_Hxx_Wd_Q1) is measured with 2 wind vanes (MM3_WDxx_120_Wd, MM3_WDxx_240_Wd). The combined wind direction MM3_Hxx_Wd_Q1 is equal to:

- MM3_WDxx_120 when MM3_WDxx_120 is in the sector between 0° and 105 ° or in the sector between 180 ° and 255 °
- MM3_WDxx_240 in all other cases.

The wind speed (MM3_Hxx_Ws_Q1) is a selection of one of the two cups, MM3_WSxx_120 and MM3_WSxx_240. The wind speed is equal to:

- MM3_WSxx_120 when MM3_Hxx_Wd_Q1 is >= 20 deg and < 160 deg.
- MM3_WSxx_240 when MM3_Hxx_Wd_Q1 is >= 200 deg and < 340 deg.
- (MM3_WSxx_120+ MM3_WSxx_240)/2 in all other cases.

These equations are elaborated in terms of the signal names in **Table 10**.

Table 10: MM3 true WD and WS equations

name	label	Equation
True wind direction at 52m	MM3_H52_Wd_Q1	IF ((0< MM3_WD52_120 <105) OR (180< MM3_WD52_120 <255)) MM3_H52_Wd_Q1 = MM3_WD52_120 ELSE MM3_H52_Wd_Q1 = MM3_WD52_240
True wind speed at 52m	MM3_H52_Ws_Q1	IF ((MM3_H52_Wd_Q1 >= 20) && (MM3_H52_Wd_Q1 < 160)) MM3_H52_Ws_Q1 = MM3_WS52_120 ELSE IF ((MM3_H52_Wd_Q1 >= 200) && (MM3_H52_Wd_Q1 < 340)) MM3_H52_Ws_Q1 = MM3_WS52_240 ELSE MM3_H52_Ws_Q1 = (MM3_WS52_120+ MM3_WS52_120)/2

True wind direction at 80m	MM3_H80_Wd_Q1	IF ((0< MM3_WD80_120 <105) OR
		(180< MM3_WD80_120 <255))
		MM3_H80_Wd_Q1 = MM3_WD80_120
		ELSE
		MM3_H80_Wd_Q1 = MM3_WD80_240

True wind speed at 80m	MM3_H80_Ws_Q1	IF ((MM3_H80_Wd_Q1 >= 20) && (MM3_H80_Wd_Q1 < 160))
		MM3_H80_Ws_Q1 = MM3_WS80_120
		ELSE IF
		((MM3_H80_Wd_Q1 >= 200) && (MM3_H80_Wd_Q1 < 340))
		MM3_H80_Ws_Q1 = MM3_WS80_240
		ELSE
		MM3_H80_Ws_Q1 =
		(MM3_WS80_120+ MM3_WS80_120)/2

4.4.4 Air density

The air density ρ is calculated according to the equation:

(4) $$\rho = \frac{P}{(R_{specific} \times T)}$$

Here, $R_{specific}$ = specific gas constant (287.06 for dry air), P is the air pressure and T is the air temperature. These equations are elaborated in terms of the signal names in **Table 11**.

Table 11: Air density equation

Name	label	Equation
Air density	MM3_H80_Airdens_Q5	MM3_H80_Airdens_Q5 = MM3_H80_Pair_Q1 / (287.06 x MM3_H80_Temp_Q1+273.15)

5

LiDARs

5.1 Ground based LiDARs ECN

5.1.1 Windcube V2 LiDARs

Two WindCube V2 LiDAR systems have been measuring for a period of time located at the foot of one of the guy wires of MM3 (180° with respect to North), see **Figure 10**.

The LiDAR principle is based on Doppler shift of the backscattered light to determine the wind speed in the LOS (Line Of Sight) direction. The time of the pulsed light used to travel to the target and back is used to determine the measurement distance. The WindCube V2 is equipped with a fifth beam looking vertically to measure directly the vertical component of the wind to increase the accuracy of the vertical wind speed and to improve the turbulence intensity measurement. The other 4 LOS make an angle of 28 degrees to the vertical with an orientation of 0 deg, 90 deg, 180 deg and 270 deg to the North.

The LiDARs are accurately positioned to the North by using a compass. From a distance (>15 meters) person 1 is positioned exactly north by aiming the compass to the LiDAR at 180 deg. Then person 2 is aiming the LiDAR exactly to person 1 (the north) by instructions of person 1.

Figure 14: LOS angle to the vertical

WLS7-127 data:

GPS coordinates:	52°49'45.96"N 5° 4'59.31"E
Start:	17-03-2013
Stop:	15-09-2013
Height configuration:	40, 52, 60, 80, 100, 108, 140, 160, 200

WLS7-258 data:

GPS coordinates:	52°49'45.93"N 5° 4'59.31"E
Start:	20-11-2012
Stop:	30-01-2014
Height configuration altered:	15-08-2013
Height configuration:	40, 52, 80, 100, 108, 140, 160, 180, 200
Altered height configuration:	40, 52, 60, 80, 100, 108, 140, 160, 200

Both are WindCube V2 LiDAR systems but the WLS7-258 is an upgraded version with the FCR (Flow Complexity Recognition) software. The FCR is a smart flow analysis using the unbiased LOS measurements and the vertical component measured by the 5^{th} beam of the V2. The standard V2 measurement assumes a homogenous wind flow, the FCR analyses the homogeneity of the wind flow which results in more accurate wind speed measurements in complex wind flows. The WLS7-258 provides corrected data as well as the standard measured data.

Table 12 gives an overview of the different undisturbed wind sectors for the LiDAR (located at MM3), MM3 and the Nordex 6 turbine.

Table 12: Undisturbed wind sectors LiDAR (located at MM3), MM3 & Nordex 6

	Min angle (deg)	Max angle (deg)
LiDAR	230.63 98.66	292.13 131.55
LiDAR & MM3	230.63 102.35	283.22 131.55
LiDAR & Nordex 6	230.63 125.76	244.63 131.55
LiDAR & MM3 & Nordex 6	230.63 125.76	244.63 131.55

5.1.2 ZephIR 300 near MM4

The ground based LiDAR ZephIR 300 with ID 308 has measured from 12-09-2013 until 11-11-2013 near MM4, located a few meters east from the base of MM4.

The ZephIR is a continuous wave LiDAR which means it has a continuous laser beam which rotates using a mirror instead of fixed line of sights with an angle of 30 degrees to the vertical. It measures one height at a time but can measure up to 10 heights by adapting its focus point up to 300m from ground level.

The LiDAR is accurately positioned to the north by using a compass and two persons in the same way as described before.

ZPH308 data:

GPS coordinates:	52°48'58.43"N 5° 3'59.76"E
Start:	12-09-2013
Height configuration altered:	04-10-2013
Stop:	11-11-2013
Height configuration:	10, 20, 45, 70, 91,120
Altered height configuration:	10, 27, 43, 71, 99, 127, 155, 199, 299

Table 13 gives an overview of the undisturbed wind sector for which the ZephIR location at MM4 and the XEMC Darwind turbine (XD115), also present at the test site. Note that the ZephIR experiences the same undisturbed wind sector as MM4.

Table 13: Undisturbed wind sectors Zephir, MM4 & XD115

	Min angle (deg)	Max angle (deg)
Zephir (same as MM4)	104.60	24.65
XD115	125.12	32.20
Zephir & XD115	125.12	24.65

5.2 Ground based LiDARs NORCOWE

5.2.1 Windcube scanning LiDAR

The Windcube WLS100s-2 is a scanning LiDAR of Leosphere. At the start of the measurement in October 2013, the LiDAR was located near the Oosterterpweg in Kreileroord. After a couple of weeks the LiDAR is relocated to a more sheltered place at the foundation of a turbine near a farm in Kreileroord. See **Figure 15**.

The configuration of the scanning pattern before and after relocation can be found in **Table 14** and **Table 15**. Here, PPI and RHI refer to horizontal and vertical scans, respectively. An RHI scan starts at azimuth angle azi1 and ends at azimuth angle azi2. Acctime is the accumulation time.

The LiDAR is accurately positioned to the north by using a compass and two persons. From a distance (>15 meters) person 1 is positioning oneself exactly north by aiming the compass to the LiDAR at 0deg. Then person 2 is aiming the LiDAR exactly to person 1 (the south) by instructions of person 1.

WLS100s-2 data:

GPS coordinates:	52°50'20.36"N 05°05'31.38"E
GPS relocated:	52°50’14.78”N 05°05’42.96”E
Start:	31-10-2013
Scan rate changed from 6 to 2 Hz:	10-12-2013 (due to new configuration)
Restart after relocation:	10-12-2013 (available in database from 12-12-2013
Stop:	11-05-2014
Distance configuration:	50 to 3000 meters in steps of 25 meters

Figure 15: Left: Photo of scanning LiDAR at Kreileroord. Right: Old (yellow) and new (red) location of scanning LiDAR

Table 14: Configuration scanning LiDAR at the start of the measurement

iteration	mode	azi1	azi2	elev1	elev2	acctime	speed
1	PPI	180	240	2.4	-	0.17	6
1	PPI	240	180	4.8	-	0.17	-6
1	PPI	180	240	7.2	-	0.17	6
1	RHI	210	-	63	0	0.17	-6
1	RHI	210	-	0	63	0.17	6
1	PPI	180	240	7.2	-	0.17	6
1	PPI	240	180	4.8	-	0.17	-6
1	PPI	180	240	2.4	-	0.17	6

Table 15: Configuration scanning LiDAR after relocation

iteration	mode	azi1	azi2	elev1	elev2	acctime	speed
1	PPI	198	258	2.4	-	0.5	6
1	PPI	258	198	4.7	-	0.5	-6
1	PPI	198	258	7.2	-	0.5	6
1	RHI	228	-	60	0	0.5	-6
1	RHI	228	-	0	60	0.5	6
1	RHI	228	-	60	0	0.5	-6

5.2.2 Windcube V1 WLS7-067

The WindCube V1 WLS7-067 was located near the base of the 180 degrees guy wire of MM3, see **Figure 16**.

WLS7-067 data:

GPS coordinates: 52°49'46.07"N 5° 4'59.32"E
Start: 01-11-2013
Height configuration altered: 10-12-2013
Stop: 16-06-2014 (because of moisture inside LiDAR)
Height configuration (m): 40, 52, 60, 80, 100, 108, 140, 160, 200
Altered height configuration: 40, 52, 60, 80, 100, 108, 120, 140, 160, 200

Table 16 shows the undisturbed wind sectors for the LiDAR location and MM3

Figure 16: Windcube V1 LiDAR near the base of the 180deg guy-wire of MM3

Table 16: Undisturbed wind sector LiDAR location MM3 & MM3

	Min angle (deg)	Max angle (deg)
LiDAR location MM3	230.63 98.66	292.13 131.55
LiDAR location MM3 & MM3	230.63 102.35	283.22 131.55

5.2.3 Windcube V1 WLS7-037

The WindCube V1 WLS7-037 (**Figure 17**) was located between Nordex 6 and the scanning LiDAR at approximately 2D distance of Nordex 6.

WLS7-037 data:

GPS coordinates: 52°49’58.01”N 05°05’08.47”E
GPS relocated: 52°49'56.79"N 05°05'10.21"E
Start: 16-11-2013
Restart after relocation: 29-11-2013
Height configuration altered: 10-12-2013
Stop: 21-07-2014
Height configuration: 40, 60, 76, 80, 100, 116, 160, 200, 250, 300
Altered configuration: 40, 52, 60, 80, 100, 108, 120, 140, 160, 200

Figure 17: Windcube V1 behind N6

The WC037 has a pseudo signal to correct the wind direction signal. WC037 automatic corrected the wind direction based on an old specified offset. Therefor the correction applied by the LiDAR is undone using the pseudo signal.

5.2.4 Windcube V1 WLS7-065

The WindCube V1 WLS7-065 (**Figure 18**) was located between Nordex 6 and the scanning LiDAR at approximately 4D distance of Nordex 6.

WLS7-065

GPS coordinates:	52°50'02.50"N 05°05'12.69"E
GPS relocated:	52°49’59.74”N 05°05’15.42”E
Start:	16-11-2013
Relocated:	29-11-2013
Height configuration altered:	10-12-2013
Stop:	21-07-2014
Height configuration (m):	40, 60, 80, 100, 120, 140, 160, 180, 200, 300
Altered configuration (m):	40, 52, 60, 80, 100, 108, 120, 140, 160, 200

Figure 18: Second Windcube V1 behind N6

5.3 Nacelle mounted LiDARs

5.3.1 Avent Wind Iris

A Wind Iris LiDAR is mounted on the nacelle of turbine N6. More specifically it is mounted on the cooler with a tripod also part of the system. The optical head on top of the tripod is connected via a cable to the processing unit in the back of the nacelle. This processing unit is connected to a CompactRIO measurement system using CANBus protocol.

The Wind Iris is a two beam LiDAR with a beam angle of 15 deg horizontal to the center line. The Wind Iris LiDAR is based on the same principle as the Windcube LiDARs which is based on Doppler shift of the backscattered light to determine the wind speed in the LOS direction. The time of the pulsed light used to travel to the target and back is used to determine the measurement distance.

The directional alignment is done by aiming the nacelle towards MM3 and then hard targeting both LOS's to MM3. Using the positioning laser of the Wind Iris for both directions two markers are set at the nacelle. The middle of both markers is used for the Wind Iris direction, in line with the nacelle.

Wind Iris

Start:	01-06-2013
Distance configuration altered:	05-06-2013
Distance configuration altered (2nd):	17-06-2013
Scan rate altered 128 to 4 Hz:	25-06-2013 10:10u
Stop:	26-06-2014
Distance configuration (m):	80, 120, 160

Changed configuration (m):	80, 120, 160, 200, 240, 280, 320, 360, 400
Changed (2nd) configuration (m):	80, 120, 160, 200, 240, 280, 320, 360, 400, 440

Figure 19: Wind Iris at the back of the nacelle of Nordex 6

For some time the Wind Iris LiDAR was installed in a special set-up, namely facing backwards with one beam pointing along the nacelle axis. The installation was on the 26th of June 2014 and the system was removed on the 27th of November 2014. The configuration was exactly the same as before.

5.3.2 ZephIR nacelle LiDAR NORCOWE

A ZephIR 300 with ID 328 was installed on the back of the nacelle of Nordex 6 behind the cooling fan, looking horizontal in the wake of the turbine.

ZPH328 data:

Start:	14-12 2013
Stop:	26-11-2014
Distance configuration (m):	19, 29, 39, 49, 64, 79, 99, 119, 129

The frame of the Zephir LiDAR is directly installed on the cooler frame of the turbine which is exactly at 90 deg to the nacelle center line. Therefore, the LiDAR is directly measuring behind the turbine in line with the nacelle.

Figure 20: photograph of the Zephir located on the back of the nacelle of Nordex 6

6

Measurement Campaign Timeline

The following measurement activities have taken place grouped on subject or participant:

- Meteorological measurements;
- Turbine measurements;
- ECN ground based LiDAR measurements;
- Avent nacelle LiDAR measurements;
- NORCOWE LiDAR measurements.

Based on this division the timeline is build up providing the availability of the measurements in **Figure 21** and **Figure 22**. From November 2012 onwards, data is available in the LAWINE database. The LAWINE project started at the 1th of January 2013 but as useful LiDAR measurements already started in November 2012 the measurement data is integrated into the LAWINE database. The last LiDAR campaigns ended in November 2014. The meteorological measurement and Nordex measurements continued in the LAWINE database until end of December 2014.

It is noted that also measurements have been taken from the XEMC Darwind turbine (XEMC Darwind is one of the partners in the Lawine project). These measurements are outside the scope of this report. Nevertheless they are part of **Figure 21** and **Figure 22**.

Figure 21: Timeline table LAWINE measurement campaigns 2012/2013

2012/2013	2012-11	2012-12	2013-01	2013-02	2013-03	2013-04	2013-05	2013-06	2013-07	2013-08	2013-09	2013-10	2013-11	2013-12
mm3[1]	20-nov													
MM4											13-sep			
Nordex[2]							3-mei							
XEMC Darwind											12-sep			
WLS7-127					17-mrt						15-sep			
WLS7-258[4]	20-nov													
Zephir 308[5]											12-sep		10-nov	
WindIris (nac)[6]								1-jun						
WindIris REV (nac)														
5-beam demonstrator[7]											12-sep			
WLS100s-2[8]												31-okt		
WLS7-037[9]													16-nov	
WLS7-065[9]													16-nov	
WLS7-067[9]													1-nov	
Zephir 328 (nac)														14-dec

Figure 22: Timeline table LAWINE measurement campaigns 2014

2014	2014-01	2014-02	2014-03	2014-04	2014-05	2014-06	2014-07	2014-08	2014-09	2014-10	2014-11	2014-12
MM3[1,3]												
MM4[3]												
Nordex[2]												
XEMC Darwind					31-mei							
WLS7-127												
WLS7-258	30-jan											
Zephir 308												
WindIris (nac)				25-apr								
WindIris REV (nac)						26-jun					27-nov	
5-beam demonstrator					31-mei							
WLS100s-2					11-mei							
WLS7-037							21-jul					
WLS7-065							21-jul					
WLS7-067						16-jun						
Zephir 328 (nac)											26-nov	

[1] additional precipitation signals of other meteorological masts at the EWTW are added from 03-05-2013

[2] from 25-02-2014 the main shaft measurement has been removed because of replacement of the main bearings of the turbine and not reinstalled because of low priority

[3] the Nordex measurements continued in 2014 but with lower priority, validated and data acquisition in calibration, but no calibration checks on the loads signals.

[4] height configuration changed at 15-08-2013

[5] height configuration changed at 04-10-2013

[6] Distance configuration changed at 05-06-2013 & 17-06-2013, scan rate changed at 25-06-2013

[7] height configuration changed at 26-09-2013

[8] relocated at 10-12-2013, after relocation the settings changed and as result the scan rate changed as well

[9] relocated at 29-11-2013 and height configuration changed at 10-12-2013

Meteorological measurements
Turbine measurements
ECN ground based LiDAR measurements
ECN ground based LiDAR measurements, before change of configuration
Avent nacelle LiDAR measurements
Avent nacelle LiDAR measurements before change of configuration
NORCOWE LiDAR measurements
NORCOWE LiDAR measurements before change of configuration

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