

Instrumentation report for the BeNeWakes scanning lidar measurement campaign

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Author(s)	M.F. van Dooren, H. Links, G. Bergman
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Abstract	In the scope of the BeNeWakes project, RVO aims at the measurement and analysis of the wake propagation downstream of the Belgian-Dutch wind farm cluster – including Borssele – with a range of different measurement instruments (platform-based lidars, floating lidars, a single scanning lidar). TNO was contracted to commission and execute a scanning lidar measurement campaign for near wake wind field measurements. This report describes the instrumentation and configuration of this measurement campaign.

Task	Name	Role	Signature
Main author	M.F. van Dooren	Project Manager	
Expert review	H. Links	Engineer	
Generic review	G. Bergman	Lead Engineer	
Approval	S. Mancini	Deputy Research Manager	
Authorization	E.D. Nennie	Research Manager	

1 Introduction

The Netherlands has set clear ambitions to accelerate the energy transition. By 2050 all energy used in the country shall come from sustainable sources and offshore wind energy plays a vital role in the transition to a carbon-free energy supply. The government has defined a roadmap for the Dutch offshore wind portfolio aiming to expand to 21 GW by 2032.

To support these goals, TNO has been performing offshore wind measurement campaigns at various strategic locations in the North Sea since 2011. Currently TNO is performing platform-based lidar measurements in the scope of the Wind op Zee project on Lichteiland Goeree (LEG), Europlatform (EPL), K13-A, L2-FA-1 and F2-A-Hanze.

In the scope of the BeNeWakes project, RVO aims at the measurement and analysis of the wake propagation downstream of the Belgian-Dutch wind farm cluster – including Borssele – with a range of different measurement instruments (platform-based lidars, floating lidars, a single scanning lidar). The already freely accessible data from the LEG and EPL measurement locations will be a part of the dataset for the project. In addition, three floating lidars have been deployed roughly on the connecting line between Borssele and LEG by Aqua Vision.

In addition to the platform-based and floating lidars, TNO was contracted to commission and execute a scanning lidar measurement campaign for near wake wind field measurements. It has been decided to use a Galion G6000 lidar from Mecal for this measurement. It was installed on the transition piece of wind turbine BF5 in the Borssele 1&2 wind farm partition operated by Ørsted on 19 December 2025. This report describes the instrumentation of this measurement campaign.

2 Scanning lidar installation and commissioning

This chapter documents the procedures followed for the installation and commissioning of the scanning lidar in the Borssele 1&2 wind farm. Specifications of the Galion G6000 scanning lidar are provided in section 2.1. The site layout and wind turbine selection within Borssele 1&2 are described in section 2.2. The two aspects of the lidar installation, namely the mounting and the connection, are detailed in sections 2.3 and 2.4, respectively. Finally, section 2.5 summarises the steps undertaken for the commissioning and the site acceptance test.

2.1 Scanning lidar specifications

The Galion G6000 (see [Figure 2-1](#)) is a type of scanning lidar originally developed by consulting & engineering company Wood and currently further developed and manufactured by Mecal through a bilateral partnership. It has an operational measurement range of 6 km.

The dimensions of the lidar are 820 mm × 500 mm × 900 mm (L x W x H). The weight of the lidar itself is 90 kg, whereas the additional power supply unit (PSU) weighs 20 kg. The total weight of the system's packed flight case is 195 ± 5 kg. The flight case dimensions are 1200 mm × 800 mm × 1200 mm (L x W x H). The lidar operates under 24 V DC power. The nominal power usage of the lidar is 150 ± 10 W, but with maximum heating/cooling this can increase up to 400 ± 10 W. The lidar's laser beam is eye-safe corresponding to Laser Class 1M. Consult Appendix A for a complete table of hardware specifications.



Figure 2-1: The Galion G6000 lidar.

The lidar was accepted by TNO as suitable for the BeNeWakes project on the basis of calibration and verification reports provided by Mecal¹.

¹ Confirmation of suitability of the Galion G6000 scanning lidar for the BeNeWakes project, M.F. van Dooren, TNO 2026 M10614, 16 March 2026.

2.2 Site layout and wind turbine selection

The Borssele Wind Farm Zone consists of five wind farm sites, of which the site Borssele 1&2 is owned and operated by Ørsted. They agreed to host and support a scanning lidar on one of the transition pieces of their wind turbines.

The specific wind turbine within Borssele 1&2 was selected based on the following criteria:

- The lidar should not obstruct any operational activities of personnel of Ørsted or their subcontractors of the wind turbine.
- The lidar should have a free line of sight in horizontal direction in the prevailing wind direction $\pm 30^\circ$ and under elevation angles up to 45° , not obstructed by e.g. neighbouring wind turbines or the railing of the wind turbine transition piece.
- There should be an unobstructed overlap possible between the scanning lidar scans and the closest floating lidar system FL-West.
- There should be an uninterrupted power supply and stable internet connection for the lidar.

A best compromise therefore needed to be found where the scanning lidar is allowed to be installed without being in the way and has an as large as possible opening angle in the horizontal plane. Placing the lidar on a wind turbine on the outer rows of the wind farm allows the best field of view in the downstream direction, taking into account the most common south-western wind direction. The ideal installation location for the scanning lidar was found to be the north-eastern part of Borssele 1&2. The wind turbine BF5 on the easternmost wind turbine row was finally selected for the measurement, fulfilling all of the above criteria. This wind turbine position is indicated in [Figure 2-2](#).



Figure 2-2: Selected scanning lidar location at the easternmost wind turbine BF5 of Borssele 1&2, indicated by a red circle (source: 4C Offshore).

2.3 Mounting of the scanning lidar

The scanning lidar is mounted on a custom support frame that rests on the concrete transition piece flooring. The support frame is constructed by Mecal. The height of the transition piece is 18.29 m AMSL (above mean sea level) and the height of the lidar scanning head is 1.55 m above the transition piece floor, or 19.84 m AMSL. It is not possible to secure the lidar support frame to the concrete flooring. Therefore, the lidar is attached to the transition piece railing by means of two clamps that are tightened around the railing, to reduce vibrations due to wind load.

A CAD drawing of the Galion G6000 on the transition piece of wind turbine BF5 that was made during the preparation phase of the project. This drawing can be seen in [Figure 2-3](#). The positioning of the Galion G6000 after installation can be seen in [Figure 2-4](#).

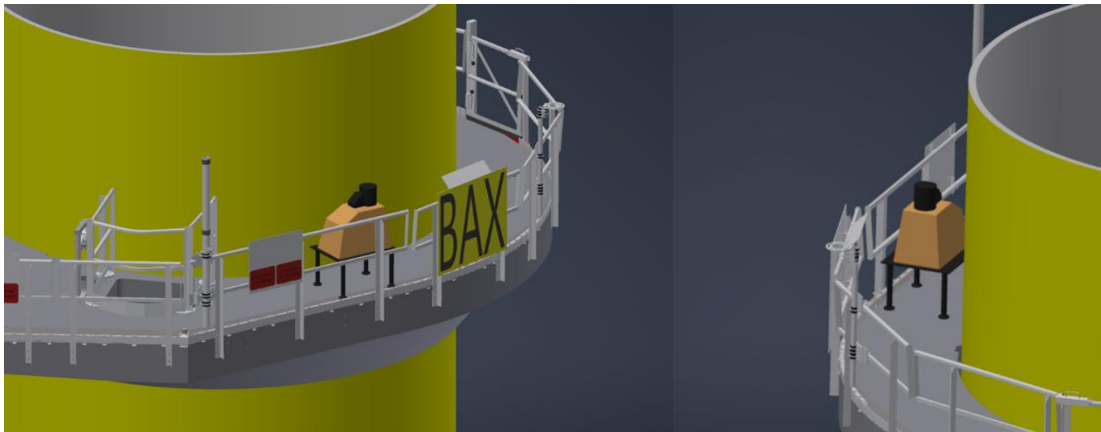


Figure 2-3: CAD drawing of the Galion G6000 on the transition piece of wind turbine BF5.

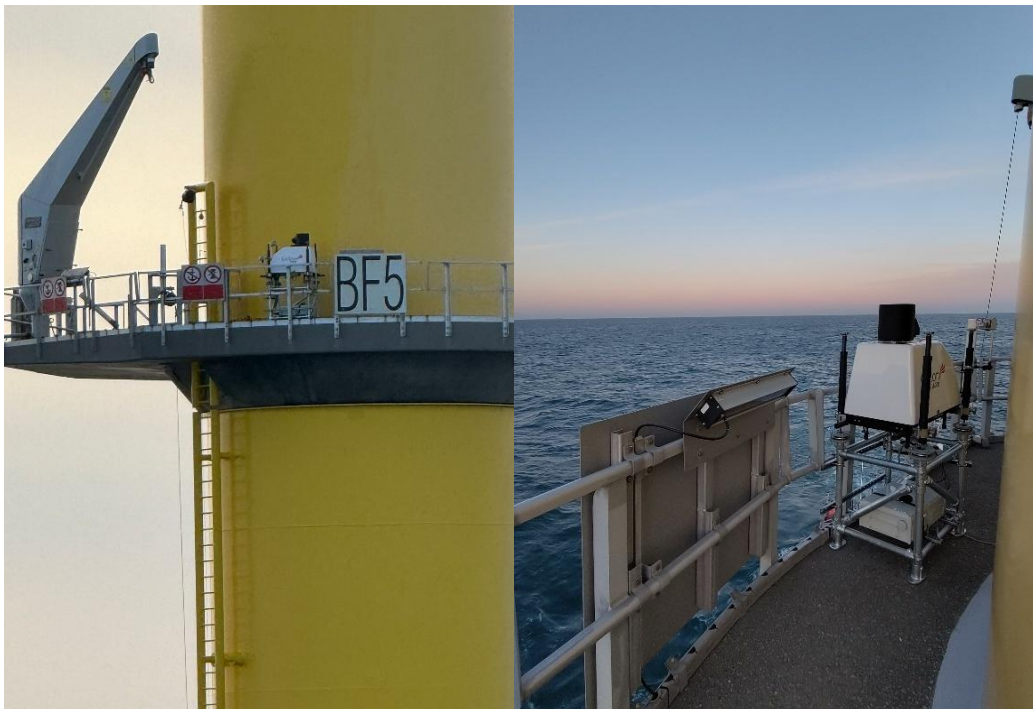


Figure 2-4: Actual positioning of the Galion G6000 on the transition piece of wind turbine BF5.

2.4 Connection of the scanning lidar

The lidar needs two connections, i.e. a 230 V AC power and network connection. A power cable is routed from the lidar to the service socket inside the tower base, as can be seen in **Figure 2-5**. The lidar power cable is connected to the 230 V service socket with an adapter cable that was specifically prepared for this project. This adapter cable connects the 230 V AC appliance connector male, 2-pin with side earth contacts on the side of the lidar, with the 230 V AC 1-phase industrial connector female, type 2P+E 16A-6h inside the tower base.

For network connection, a cellular modem is placed in the lidar cabinet, and two 4G antennas are mounted on the lidar frame. The 4G connection allows for monitoring the lidar, changing the scanning configuration if necessary, and retrieving measurement data. The measurement data is also locally stored on the hard disk of the lidar.



Figure 2-5: Cable routing indicated with orange arrows. Top left: 4G antennas on the lidar frame. Top right: power cable routed along the tower with magnets. Bottom left: power cable is routed along the tower entrance and entering the tower through the existing cable glands on top of the entrance. Bottom right: the power cable is connected to the 230 V service socket inside the tower base.

2.5 Commissioning and site acceptance test

After fixating the lidar on the frame the lidar was levelled horizontally. With the service screen connected to the lidar computer, the lidar was levelled in both pitch and roll by adjusting the lidar feet in vertical direction. The aim was to get pitch and roll angles as close as possible to 0 degrees. During installation, both pitch and roll angles were varying with about 0.2 degrees due to tower movement.

During the site visit, the heading of the floating lidar system FL-West was confirmed by personnel on board of the CTV (Crew Transfer Vessel) by means of their on board GPS compass. The CTV sailed behind the floating lidar system FL-West and the heading towards turbine BF5 was found to be 216.9 degrees ([Figure 2-6](#)). This matches up to 0.1 degree with the (opposite direction) heading that was calculated by TNO based on the coordinates provided by Aqua Vision.



Figure 2-6: Confirmation of the heading of floating lidar system FL-West. Left: looking over the Galion scanning head towards FL-West and the CTV in the background. Right: zoomed in on FL-West and CTV.

A hard target test was performed to derive an accurate offset for the scanning lidar with respect to north. The heading of the neighbouring turbine towers was calculated upfront as a preparation for the hard target test, using the coordinates as given in [Table 2-1](#).

Table 2-1: Heading and distance of neighbouring turbines BF2, BF4 and floating lidar FL-West to BF5, calculated from UTM (Zone 31U) coordinates.

Object	X (m)	Y (m)	Heading as seen from BF5 (deg)	Distance to BF5 (m)
FL-West	509946.011	5730071.007	36.8	2209.0
BF2	506997.136	5729640.611	309.5	2106.2
BF4	508444.855	5729286.152	349.7	1000.3
BF5	508623.123	5728301.844	--	--

An initial offset of 90 degrees from North was programmed into the lidar. This was a first rough estimate to be fine-tuned with the hard target test.

A first hard target test was performed by aiming the scanning lidar at turbine BF4, located at 1000.3 m from turbine BF5, with a heading of 349.70 degrees. A PPI scan was programmed aiming at 340 to 360 degrees azimuth. The scan was adjusted a few times to narrow down the azimuth range and the centre of turbine tower BF4 was found at 354.85 degrees. Extracting the actual heading of turbine tower BF4, 349.70 degrees, gives a correction of 5.15 degrees on the initial offset. Resulting in **84.85 degrees offset** which is programmed into the scanning lidar. A second hard target test was performed on turbine BF4. Resulting in a deviation of 0.06 degrees with respect to the true heading.

A third hard target test was performed to confirm the lidar offset on a different target. The lidar was aimed at turbine tower BF2, and a PPI scan was programmed with a narrow azimuth range around the expected heading. The centre of the tower was found at 309.40 degrees, in the 2100 m range gate. This matches with the actual heading and distance given in [Table 2-1](#) up to 0.1 degrees, and matches with the scanner pointing accuracy of ±0.05 to ±0.1 degrees (see Appendix A). [Table 2-2](#) summarizes the results of the hard target tests.

Table 2-2: Hard target tests used to find the scanning lidar offset with respect to North.

Test	Offset to North (deg)	Target	Azimuth range (deg)	Deviation from true heading (deg)	Galion scan file
1	90.00	BF4	354 - 356	354.58 - 349.70 = 5.15	PPI_01_1844_455051_19122512_203.scn
2	84.85	BF4	340 - 355	349.76 - 349.70 = 0.06	PPI_01_1846_455054_19122512_203.scn
3	84.85	BF2	308 - 310	309.50 - 309.40 = 0.1	PPI_01_1848_455056_19122513_203.scn

3 Scanning lidar measurement configuration

The implemented measurement setup for the BeNeWakes project is indicated in an overview map from RVO, see **Figure 3-1**. The map shows the three floating lidars, i.e. FL-West, FL-Center and FL-East, as well as a scanning lidar scan at the preferred location within the wind farm with an indicated nominal range of 6 km. The actual maximum range depends on the atmospheric conditions and the measurement configuration settings of the lidar. From the transition piece of the easternmost wind turbine BF5 of Borssele 1&2, the lidar will be able to measure part of the near wake of the Borssele Wind Farm Zone in line with the three floating lidars.

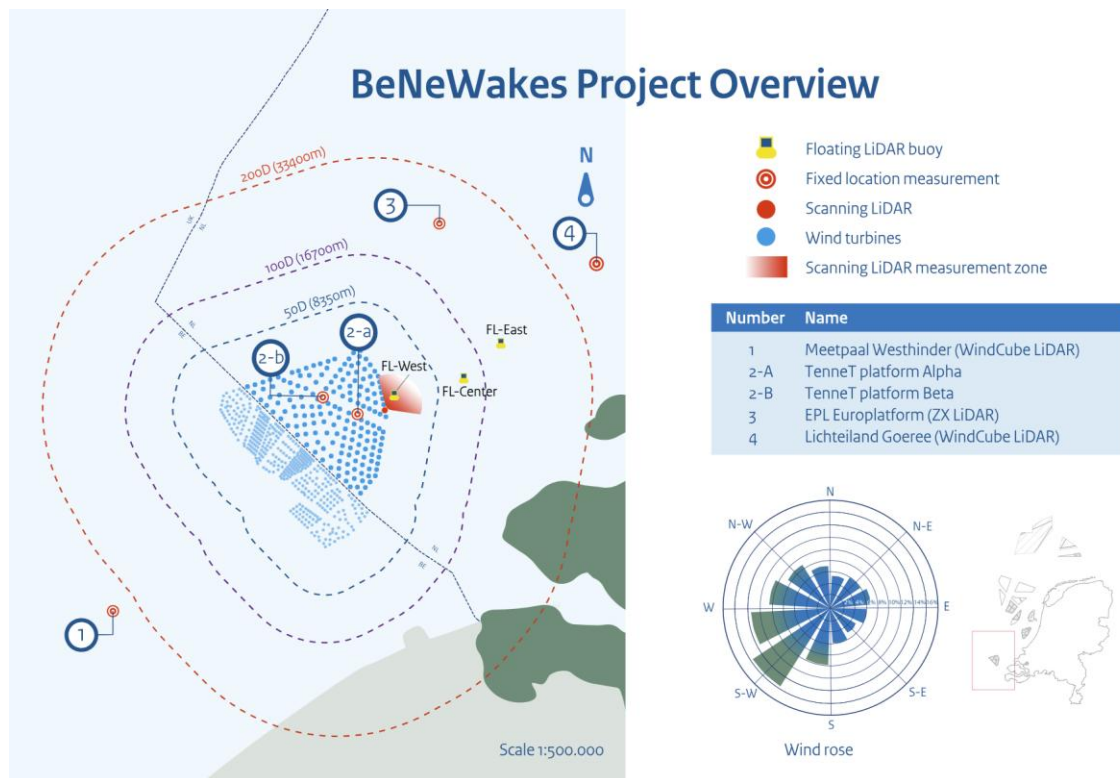


Figure 3-1: BeNeWakes project measurement setup (source: RVO).

The following scenarios were envisioned:

1. Horizontal sector scans (in technical terms; Plan Position Indicator or PPI scans) of the wind farm cluster wake, enabling wind field reconstruction either derived from the scans themselves or based on the wind direction of the measurement of FL-West.
2. A vertical sector scan (in technical terms; Range Height Indicator or RHI scan) of the wind farm cluster wake to measure the atmospheric boundary layer (ABL) at higher altitudes and investigate the interaction between the ABL and the wind farm.

Scenario 1 can provide valuable data for the further development and verification of wake models. Scenario 2 can enable a meteorological analysis of the interaction between wind farms and the ABL. Scenarios 1 and 2 provide data, respectively, of horizontal and vertical wind fields of 2D wind vectors. The resolution is in the order of minutes.

In order to calculate the optimal scanning lidar measurement configuration, it is important to first define the relevant heights and distances;

- $h_h = 116.4$ m wind turbine hub height (AMSL)
- $D = 167$ m wind turbine rotor diameter

- $h_{TP} = 18.29$ m wind turbine transition piece height (AMSL)
- $h_{SL} = 1.55$ m scanning lidar height
- $h_{SL_{total}} = h_{TP} + h_{SL} = 19.84$ m scanning lidar height (AMSL)
- $h_{FL-West} = 1.91$ m floating lidar height (AMSL)

- $h = [50, 150, 250, 350, 450]$ m selected heights AMSL at FL-West

The relevant quantities are also indicated in the sketch in **Figure 3-2** below (not to scale).

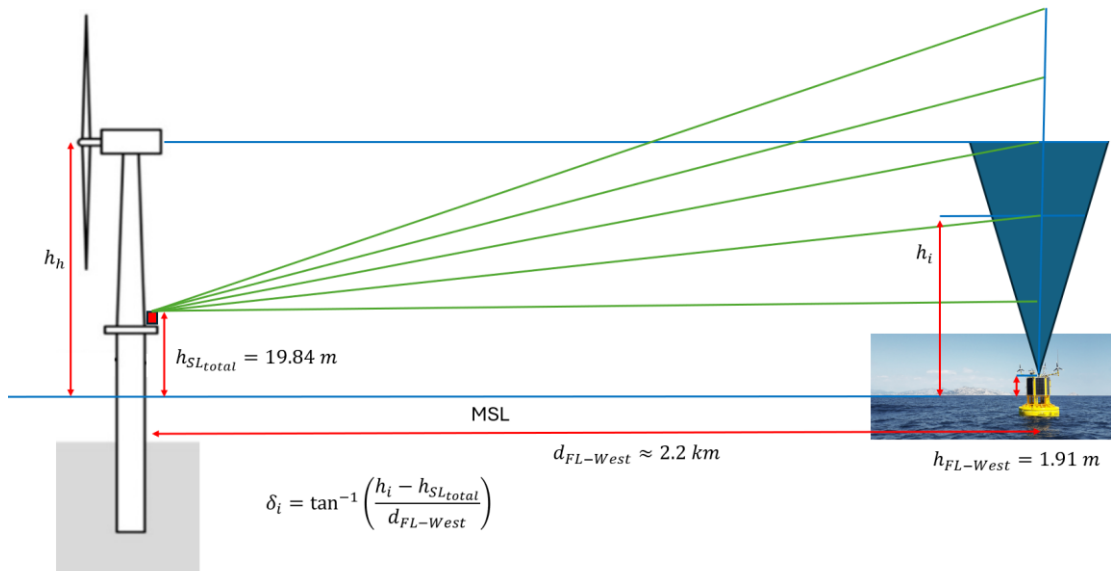


Figure 3-2: Sketch of the scanning lidar position with respect to FL-West and the calculation of PPI elevation angles (not to scale).

During the project duration, there have been different measurement configurations implemented. One can distinguish between the following periods:

Period 1: 19 December 2025 – 24 February 2026

Period 2: 24 February 2026 – Present

The scanning configuration for Period 1 was heavily focused on the measurement of wind fields at hub height with high spatial coverage, enabled by a series of PPI scans with different elevation angles. After collecting roughly two months of data, it was collectively decided to shift the focus on RHI scans covering the vertical plane between the scanning lidar and FL-West with an increased temporal resolution.

3.1 Configuration for Period 1

The initial configuration of the scanning lidar consisted of a repeated sequence of five PPIs and one RHI.

For the definition of the elevation angles for the PPI scans, two main criteria were considered relevant:

- To ensure the quality of the data, a comparison with FL-West at different heights is beneficial.
- When measuring wind turbine wakes, it is relevant to have a good coverage of heights close to the hub height over a significant area.

Based on these criteria, the following scanning parameters were defined:

Table 3-1: Scanning lidar configuration parameters for Period 1.

Scan	Azimuth angle (deg)	Elevation angle (deg)	Range gates	Beams	Scan duration (s)
PPI 1	-60 to +60 w.r.t. the connecting line between scanning lidar and FL-West (heading 36.8 deg)	0.84	72 range gates of 90 m length from 949.6 to 7339.6 m ensuring that range gate 15 has its center directly above the average position of FL-West at 2209.6 m distance	28 (one per 4.3 deg)	80
PPI 2		3.43			80
PPI 3		6.00			80
PPI 4		8.55			80
PPI 5		11.07			80
RHI 1	36.8	0 – 75	72 range gates of 90 m length from 949.6 to 7339.6 m	35 (one per 2.1 deg)	102

The PPI scans allow the measurements to coincide with the following heights above MSL at FL-West (m):

Table 3-2: Scanning lidar target heights and respective elevation angles for Period 1.

Height above MSL at FL-West (m)	50	150	250	350	450
Elevation angle (deg)	0.84	3.43	6.00	8.55	11.07

The RHI scan is on the connecting line between scanning lidar and FL-West (heading 36.8 deg) at 2209.6 m distance.

The 5 PPI scans and 1 RHI scan are measured in an alternating pattern taking 8:22 minutes per cycle.

Figure 3-3 and **Figure 3-4** show example reconstructed horizontal and vertical wind fields, based on the PPI and RHI scans respectively, resulting from this configuration.

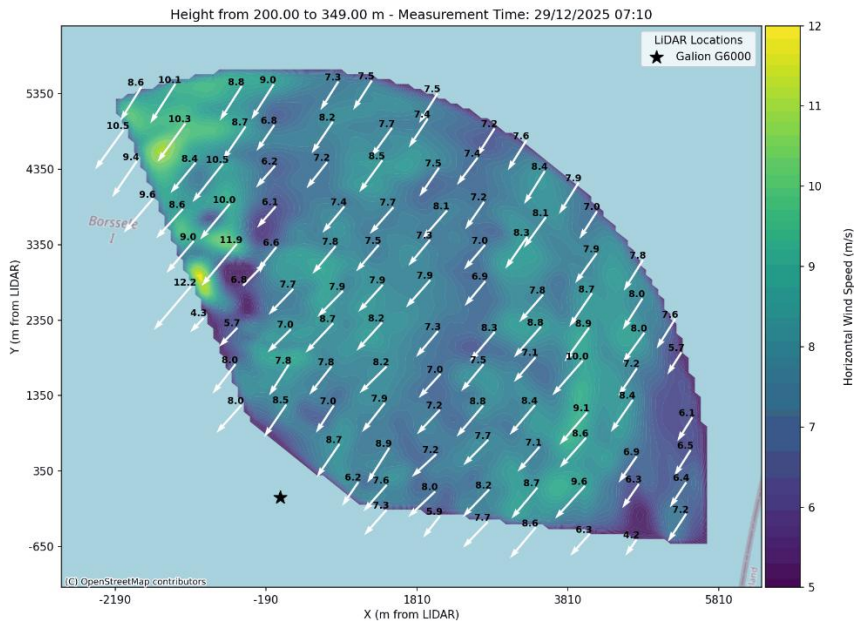


Figure 3-3: Example of a reconstructed horizontal wind field (based on the PPI scans) northeast of the Borssele Wind Farm Zone (source: Mecal).

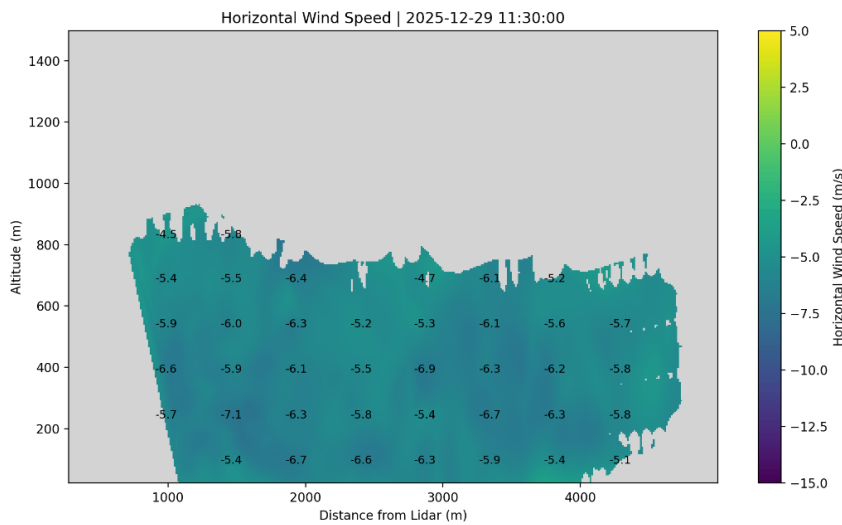


Figure 3-4: Example of a reconstructed vertical wind field (based on the RHI scans) northeast of the Borssele Wind Farm Zone (source: Mecal).

3.2 Configuration for Period 2

An initial analysis of the data from the first measurement period highlighted a low temporal resolution of the measurement points that have an overlap between the scanning lidar and FL-West. This is the direct trade-off of choosing a scanning configuration that focuses on spatial coverage by means of multiple PPIs. Although the data gathered in Period 1 remains valuable, it was agreed upon by all project partners to alter the scanning configuration to focus more on temporal resolution alongside the data of FL-West.

Based on this priority shift, the following scanning parameters were defined:

Table 3-3: Scanning lidar configuration parameters for Period 2.

Scan	Azimuth angle (deg)	Elevation angle (deg)	Range gates	Beams	Scan duration (s)
RHI	36.8	0 to 21.80	72 range gates of 90 m length from 949.6 to 7339.6 m ensuring that range gate 15 has its center directly above the average position of FL-West at 2209.6 m distance	20	54
PPI 1	-30 to +30 w.r.t. the connecting line between scanning lidar and FL-West (heading 36.8 deg)	2.50		13	35
RHI	36.8	0 to 21.80		20	54
PPI 2	-30 to +30 w.r.t. the connecting line between scanning lidar and FL-West (heading 36.8 deg)	14.71		7	19
RHI	36.8	0 to 21.80		20	54
PPI 1	-30 to +30 w.r.t. the connecting line between scanning lidar and FL-West (heading 36.8 deg)	2.50		13	35
RHI	36.8	0 to 21.80		20	54
PPI 1	-30 to +30 w.r.t. the connecting line between scanning lidar and FL-West (heading 36.8 deg)	2.50		13	35
RHI	36.8	0 to 21.80		20	54
RHI	36.8	0 to 21.80		20	54

The elevations of the RHI scans allow the measurements to coincide with the following heights above sea level at the location of FL-West (m):

Table 3-4: Scanning lidar target heights and respective elevation angles for Period 2.

Height above MSL at FL-West (m)	19.84	40	60	80	100	110	120	140	160	180
Elevation angle (deg)	0.00	0.52	1.04	1.56	2.08	2.34	2.60	3.11	3.63	4.15
Height above MSL at FL-West (m)	200	220	260	300	400	500	600	700	800	900
Elevation angle (deg)	4.66	5.18	6.20	7.23	9.76	12.26	14.71	17.11	19.45	21.72

The elevation angles of PPI 1 and PPI 2 are 2.50 deg and 14.71 deg, and intersect with 116.4 m (hub height) and 600 m above MSL at the location of FL-West, respectively.

Similar to the configuration for Period 1, the sequence of alternating PPI and RHI scans is continuously repeated, taking 6:34 minutes per cycle.

Appendix A

Galion G6000 hardware specifications

Category	Specification
Physical Specification	
Galion dimensions (L x W x H)	820 mm × 500 mm × 900 mm
Weight (Galion only)	90 kg
Weight (PSU only)	20 kg
Weight (packed flight case)	195 ± 5 kg
Flight case dimensions (L x W x H)	1200 mm × 800 mm × 1200 mm
Operational Characteristics	
Max acquisition range (RMaxA)	7,470 m (with a 30 m range gate length)
Max operational range (RMaxO)	6,000 m
Range gate length	30 m to 120 m (in 1 m increments)
Accumulation time	0.1 s to 3.0 s (2,000 to 60,000 pulses)
Doppler accuracy	± <0.1 m/s
Operating ambient temperature range	-30 to +40 °C
Inclinometer accuracy	± 0.03 °
Scanner pointing accuracy	± 0.05 to 0.1 °
Azimuth rotation range	360 °
Elevation rotation range	-15 to +195 °
Scanner rotation speed	45 °/s
Power Specification	
DC Voltage	24 ± 1.0 V
DC Current	PSU fuse rating: 20 A, Max draw: 17 A
Power draw	Nominal: 150 ± 10 W Maximum (full heating/cooling): 400 ± 10 W
Laser Specification	
Laser safety class	Class 1M
Wavelength	1550 nm ± 0.1%
Pulse width (FWHM)	200 ns (± 10%) or 30 m
Pulse repetition frequency	20 kHz
Pulse power	250 mW (± 10%)
Laser-case temperature range	+10 to +50 °C
Sample frequency (spatial resolution)	180 MHz or 0.83 metres
Max LOS velocity	69.75 m/s
Data Storage	
OS Drive (C:\)	512 GB M.2 NVME SSD
Data drive (D:\)	2 TB 2.5" SATA HDD 2
Backup drive (E:\)	2 TB 2.5" SATA HDD

Source: Mecal Galion G6000 Product Guide

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Westerduinweg 3
1755 LE Petten
www.tno.nl

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