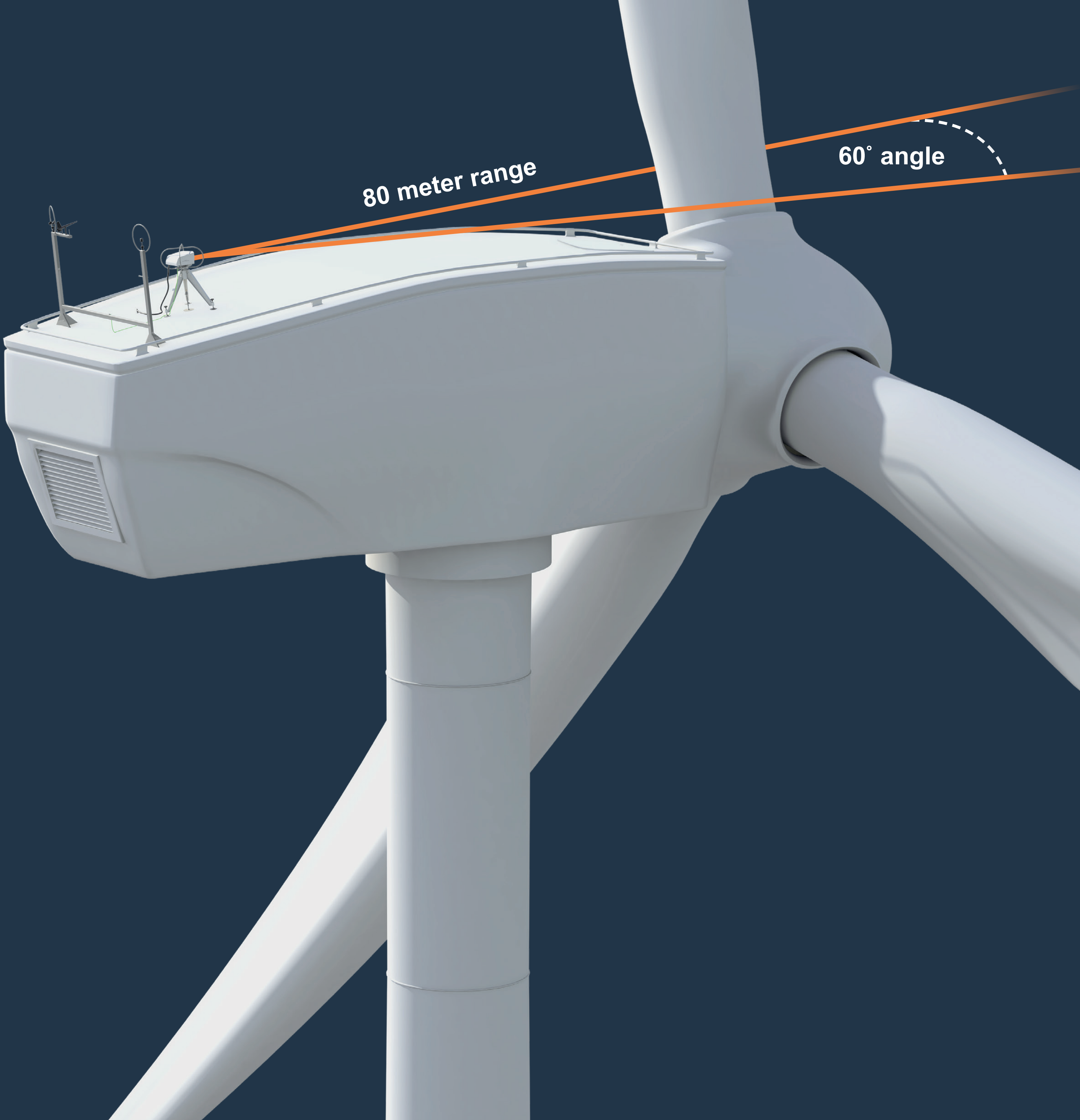
WINDAR PHOTONICS

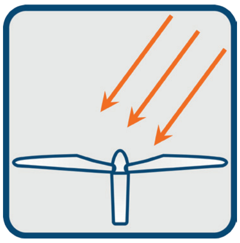
WindEYE™ nacelle LiDAR



AEP increases of 1-4%

The WindEYE™ LiDAR

Yaw misalignment correction

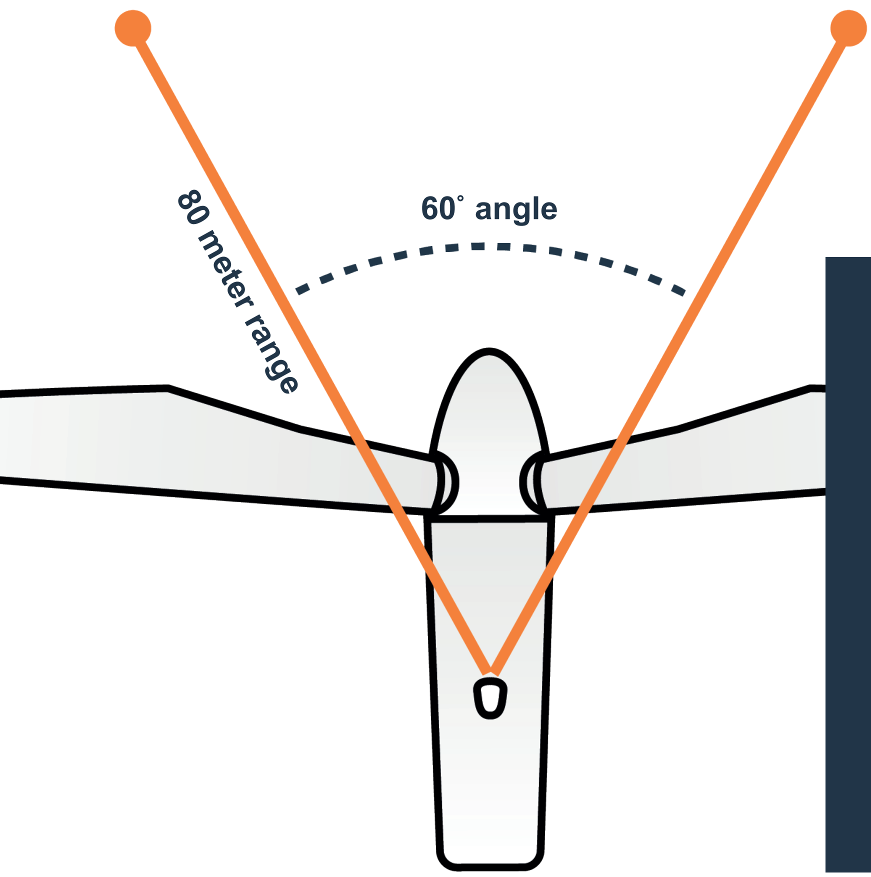


Yaw misalignment occurs when the turbine is not aligned with the incoming wind, causing increased loads and reduced power production

WINDEYE™

The WindEYE™ is a nacelle-mounted LiDAR that measures wind direction and wind speed 80m in front of the turbine. The WindEYE™ is a cost efficient optimisation solution that can yield an AEP increase of 1-4%, while having a payback time of only 1-4 years.

The WindEYE™ integrates with the wind turbine's control system, enabling the LiDAR to give information to the turbine about the wind, well-before it reaches the turbine. Knowing the correct wind direction enables the turbine to yaw accordingly with the incoming wind, which will increase the energy production and reduce loads on vital parts of the turbine.



Features

- **Control integration**
- **Remote upgrading and monitoring**
- **Only requires a minimum of maintenance**
- **No moving mechanical parts**
- **Easy handling and installation**
- **A light-weight, compact, and durable system**

LIGHTNING BRACKET:

The LiDAR is equipped with a grounded lightning cage.

Lightning protection Zone 0B

OPTICAL UNIT:

The optical unit is mounted on the roof of the nacelle. The optical unit emits the laser beams used for measuring the wind.

500 mm x 340 mm x 140 mm (L x W x H)

Optical Unit & Hybrid Cable: 22.4 kg

IP Class: IP67

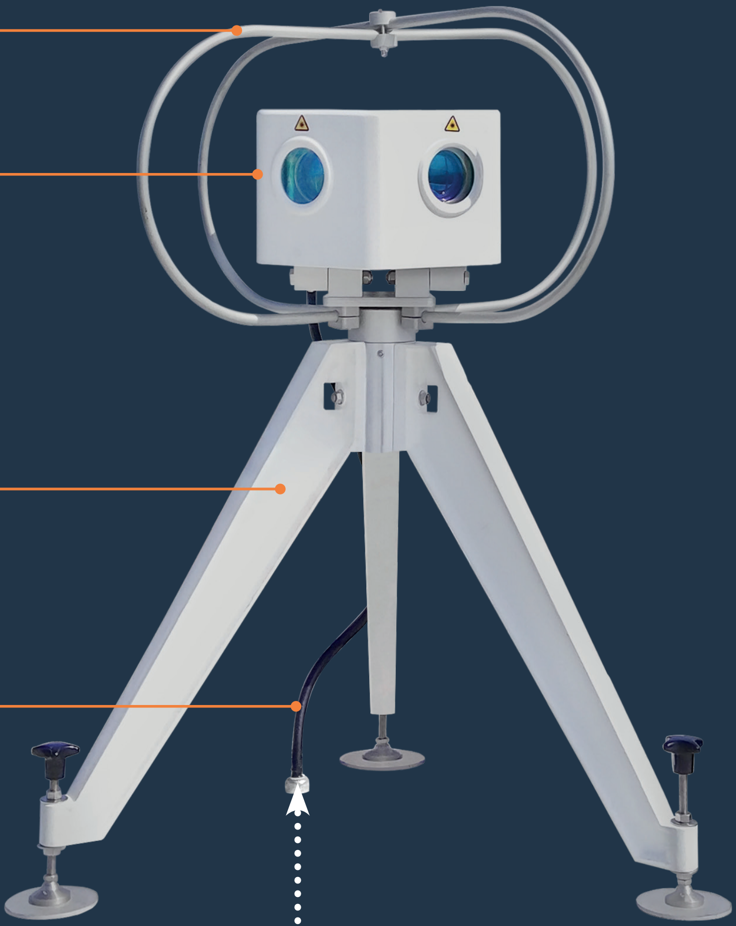
TRIPOD:

The tripod is the standard mounting option for the LiDAR, which is placed on the back of the nacelle, parallel with the rotor axis.

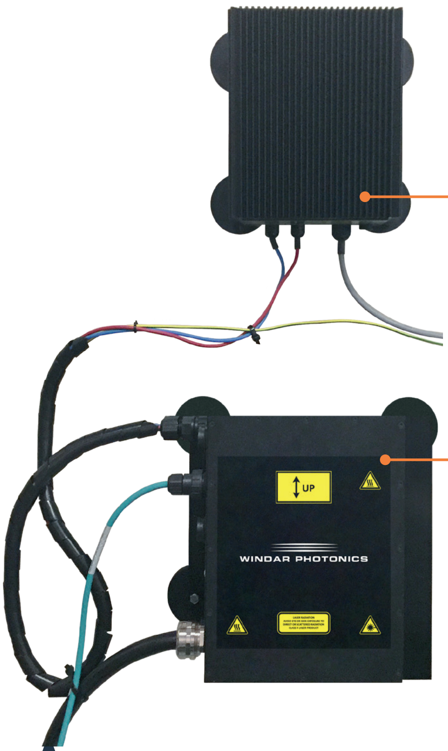
Optional Tripod: 9.8 kg

HYBRID CABLE:

The hybrid cable transmits the light from the Laser System Unit to the control unit, and facilitates the communication between the Optical Unit and the Laser System Unit.



WINDEYE™



PSU:

The PSU is an industry standard PSU, which is mounted inside the nacelle.

110 VAC / 230 VAC

LASER SYSTEM UNIT:

The Laser system unit is mounted inside the nacelle. The Laser System Unit contains the system's light source.

250 mm x 248 mm x 140 mm (L x W x H)

Laser System Unit: 6.5 kg

IP Class: IP67

HYBRID CABLE

GSM MODEM & ANTENNA:

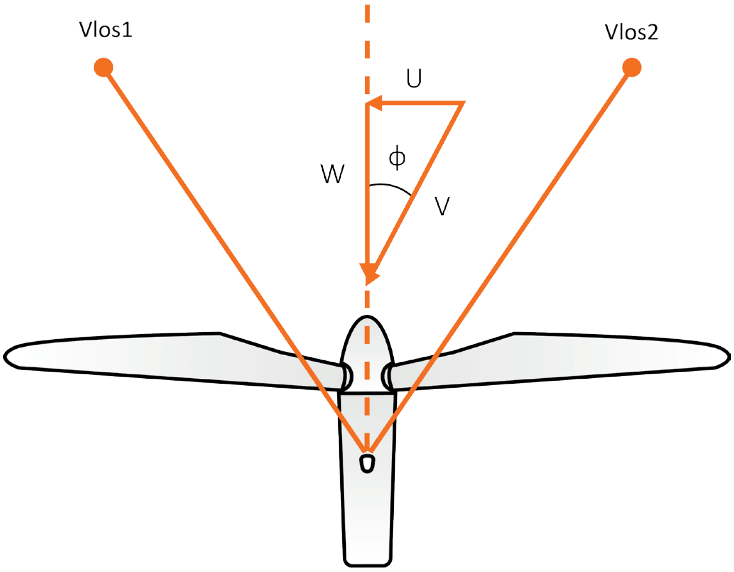
The GSM modem and antenna ensures that the LiDAR can be connected to the internet via the GSM-network, without relying on an available internet connection for the LiDAR in the wind turbine.

Technical Data

Laser Source	Continuous Wave Laser, Laser Source, Eye safety class 4M LiDAR system Eye safety class 1M
Wind Speed Range	2m/s - 75m/s
Data Output Rate	1Hz (2Hz optional)
Operating Temperature	-40°C to +55°C
Physical Interfaces	RS485, Ethernet
Dimensions	**Optical Unit:** 500mm x 340mm x 140mm (L x W x H) **Laser System Unit:** 250mm x 248mm x 140mm (L x W x H)
Weight	**Laser System Unit:** 6.5kg **Optical Unit & Hybrid Cable:** 22.4kg **Optional Tripod:** 9.8kg
Cable	Length 10m. Diameter 16.5mm
IP Class, Laser System Unit	IP67
IP Class, Optical Head	IP67
Power Supply	110 VAC / 230 VAC
Data Storage	12 Months

Protocol & data

The general concept behind the WindEYE™ LiDAR's measurements is displayed in the below diagram:



The measurements and calculations will be collected and stored in an accessible ASCII format in accordance with the below protocol list:

Protocol list from RS485		
Protocol	Specification	Unit
Timestamp		YYYY/MM/DD HH:MM:SS
Vlos1	Measured Wind speed along beam 1	Cm/s
Vlos2	Measured Wind speed along beam 2	Cm/s
U	Calculated Lateral Wind speed	Cm/s
W	Calculated Axial Wind speed	Cm/s
V	Calculated Incoming Wind speed	Cm/s
Phi (Φ)	Calculated Misalignment angle	°x100
Status	1 second measurement Status	0/1 – Bad/ Good

An example of measurement data from the data log.

Timestamp	Vlos 1	Vlos 2	U	W	V	Phi	Status
23-03-2017 00:00	525	568	44	631	633	395	1
23-03-2017 00:10	488	518	29	581	582	289	1
23-03-2017 00:20	482	544	62	593	596	596	1
23-03-2017 00:30	494	576	82	618	623	755	1
23-03-2017 00:40	509	516	6	592	592	63	1
23-03-2017 00:50	52	536	16	61	61	152	1
23-03-2017 01:00	515	539	24	609	609	23	1
23-03-2017 01:10	53	469	-6	577	58	-597	1
23-03-2017 01:20	522	572	5	632	634	456	1
23-03-2017 01:30	451	507	57	553	556	586	1
23-03-2017 01:40	46	523	63	568	571	63	1

The below diagrams list the various interfaces for accessing and interacting with the LiDAR.

User Access

Features	Description
Terminal	Terminal controls for low-level supervision and control using SSH2 - protected by both a OpenVPN certificate and a password
WindInterface GUI	Graphical User Interface for supervising and controlling the LiDAR
FTP client	Data and file transfer
WinterGUI	Local point to point RS485 connection only
Multi user access	Unlimited user access on the same unit

User Handling

Features	Description
Remote upgrade	Manually handled from terminal via SSH2 access
LiDAR Status	General and advanced status provided through terminal and WindInterface GUI
LiDAR Configurations	Setups performed through the terminal
FTP server	Data and files transfer
Tracking	General overview of the LiDAR's setups through terminal or WindInterface GUI

Security and Crash Handling

Features	Description
VPN	OpenVPN secure tunnel to the server
SSH2 connection	SSH2 is protected by certificate and password
Triple firmware boot	Two running/upgrade firmware and one safe image
Multiple watchdogs	Software and hardware watchdogs available on different levels to protect against faults
Flash disk supervision	Logging protection. Will remove oldest logging files, when reaching 90% full

Data Handling

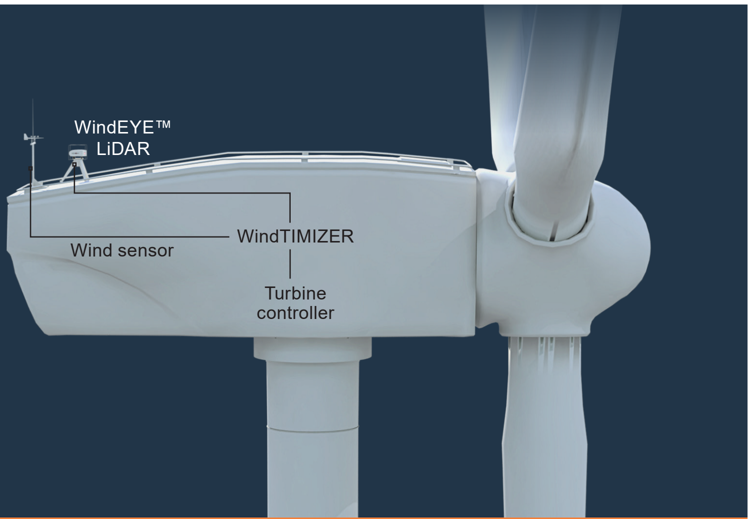
Features	Description
Files transfers	VSFTP server and terminal using Secure copy
Protocol logging	Streamed protocol logging on the flash disk – 32GB/1 year (default)
Measurement logging	All sensor data are stored on the flash disk for analysis

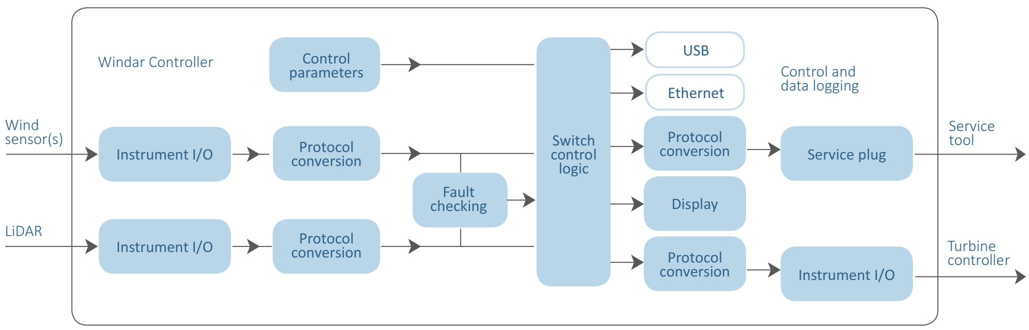
WindTIMIZER integration

For compatibility with the WindTIMIZER integration, it is a requirement that GE 1.5MW and the NM82 wind turbines are equipped with digital FT ultra-sonic wind sensors, or that the anemometry is changed to FT ultra-sonic sensors in conjunction with the LiDAR integration.

Control integration with the WindTIMIZER for dynamic yaw misalignment correction

To enable the dynamic yaw correction feature of the WindEYE™, the LiDAR needs to be integrated with the wind turbine control system. The Wind-TIMIZER is a mediator that allows the LiDAR to integrate with the wind turbine control system and the legacy anemometry as part of a retrofit solution. As such, the WindTIMIZER functions as a mediator between the controller and the WindEYE™ system without the necessity of actually altering anything in the wind turbine controller at all.



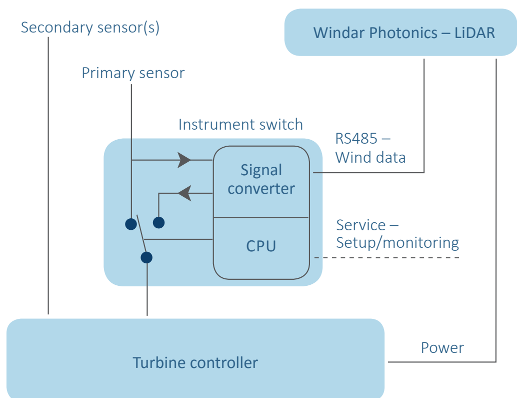


Safety chain

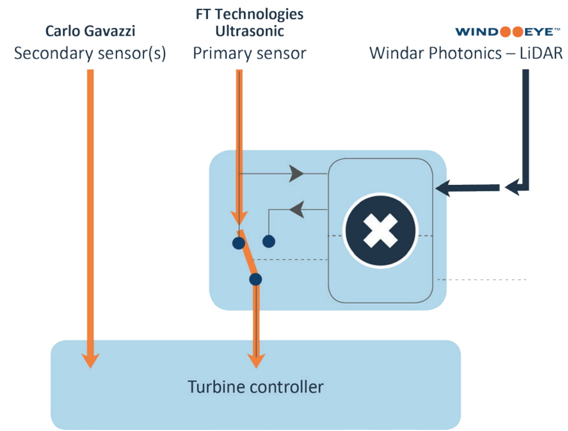
Maintaining the wind turbine safety chain is of the greatest importance, hence it is imperative that any technical or metereological problems involving the WindEYE™ system and the WindTIMIZER do not jeopardize the integrity of the safety chain. In case of a force majeure emergency, like a lightning strike that harms the WindTIMIZER, a failsafe switch will still transmit the legacy anemometry signal to the controller.

Integration and signal conversion

The WindTIMIZER receives the signals from both the legacy wind-sensors and the WindEYE™ system, converts the signal from the WindEYE™ system to the protocol of the legacy wind-sensor signals, and sends the signal of the WindEYE™ system into the wind turbine controller, as long as the WindEYE™ system signal is available. This makes the WindEYE™ instrument “appear” as the legacy anemometry to the wind turbine control system, which makes it possible to integrate the WindEYE™ without any changes to the wind turbine control system. Furthermore, the WindTIMIZER will compare the converted measurements from both the WindEYE™ system and the legacy anemometry to check for any faults. In case the Wind-EYE™ system gets an unusable datum (e.g. if a blade passes in front of one of the WindEYE™'s beams), then the WindTIMIZER will be able to use the datum from the legacy sensor instead. A diagram showing the software system of the WindTIMIZER and the conversion process can be seen in the signal conversion diagram.



WindTIMIZER Modes



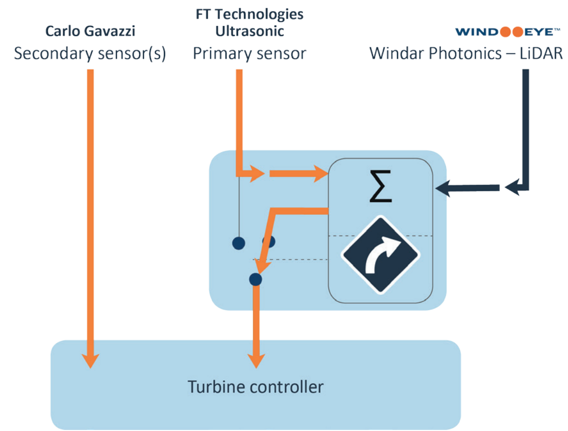
1

Safe Mode

In the safe mode, the WindTIMIZER is bypassed completely. The wind turbine will in essence function as if no WindTIMIZER or LiDAR is installed on the turbine.

The safe mode furthermore acts as a fall back function (in the same way a normal closed relay functions) in case that The WindTIMIZER is not operational.

When the WindTIMIZER is initially turned on, it will always start in the safe mode. For the WindTIMIZER to be fully operational, it will have to be activated manually, either by a technician on site or via remote access.

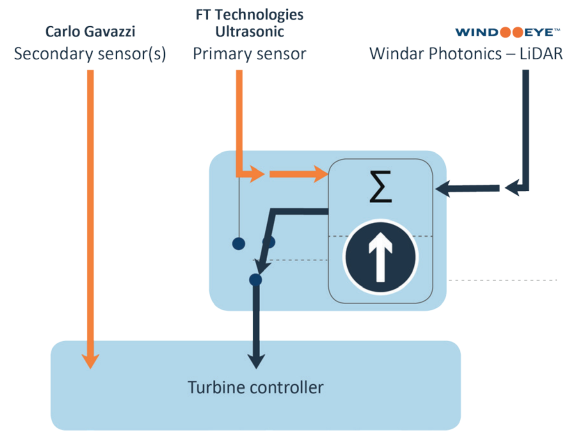


2

Passive Mode

In the Passive Mode, the WindTIMIZER is operational, but waiting for valid data from the LiDAR.

In the Passive Mode, the WindTIMIZER performs a quality assessment of every packet of data sent from the LiDAR. In case the data from the LiDAR is assessed as being inadequate (e.g. the measurement was blocked by a blade), then the unaltered signal from the standard anemometry will bypass the WindTIMIZER.



3

Active Mode

In the Active Mode, the WindTIMIZER is operational and actively analyses the signal from the wind turbine's FT-sensor, and amends the wind direction measurements based on the LiDARs measurements.

The signal coming from the FT-sensor consists of two individual parts: a wind speed measurement [m/s], and a wind direction measurement relative to the nacelle position [°].

Wind Speed: In the Active Mode, the wind speed measurement is passed through the WindTIMIZER without any further actions.

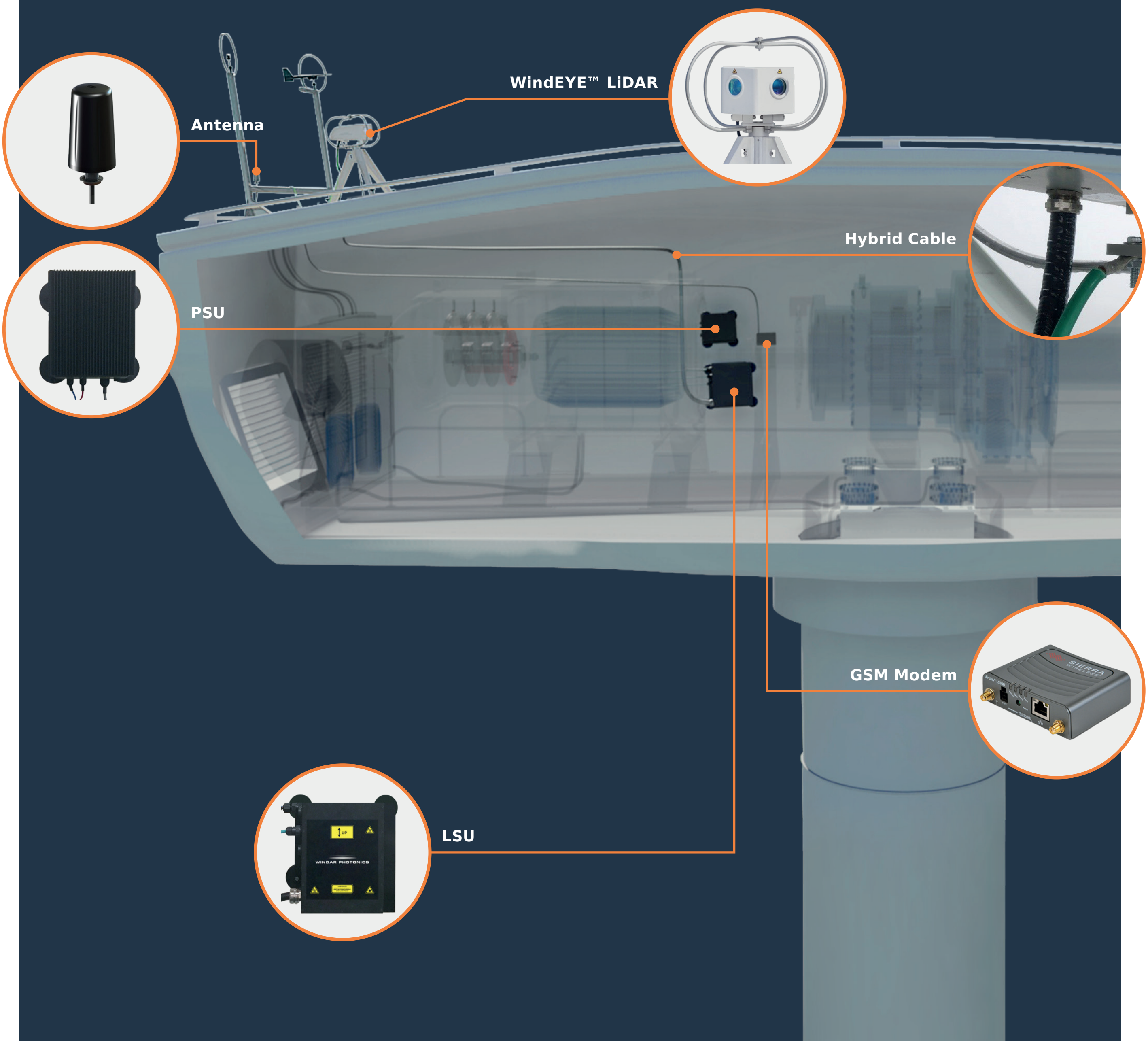
Wind Direction: In the Active Mode, the WindTIMIZER compares the wind direction measurements from the LiDAR and the standard anemometry. If there is a difference between the two measurements, then the WindTIMIZER will add a correction to the data from the FT-sensor, before the wind direction measurement is sent ahead to the turbine control system.

Installation

The WindEYE™ is exceptionally easy to install, requires no special cranes or hoisting solutions, and the complete installation procedure can be performed in less than a day by a single experienced wind turbine technician.

The most rugged components of the WindEYE™ system are installed on the roof of the wind turbine, whereas the more sensitive parts are mounted inside the nacelle.

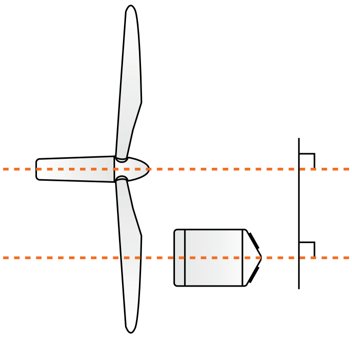
Configuration of the LiDAR components installed on a wind turbine



Alignment of the windEYE™

In order for the LiDAR to function as intended, the Optical Unit will have to be aligned with the rotor-axis of the wind turbine, which is performed during the installation process.

The initial alignment during installation is the only alignment or calibration that will have to be performed during the LiDAR's lifetime.



Alignment of the LiDAR unit during installation

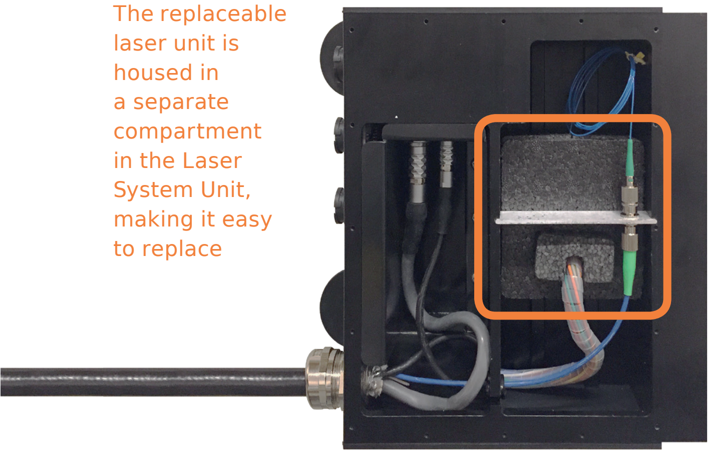
Maintenance & system lifetime

Maintenance

The WindEYE™ and WindVISION™ systems have very minimal maintenance requirements:

- The windows on the Optical Unit must be cleaned with a soft rag during normal turbine maintenance.
- The light source must be replaced every 4th year.

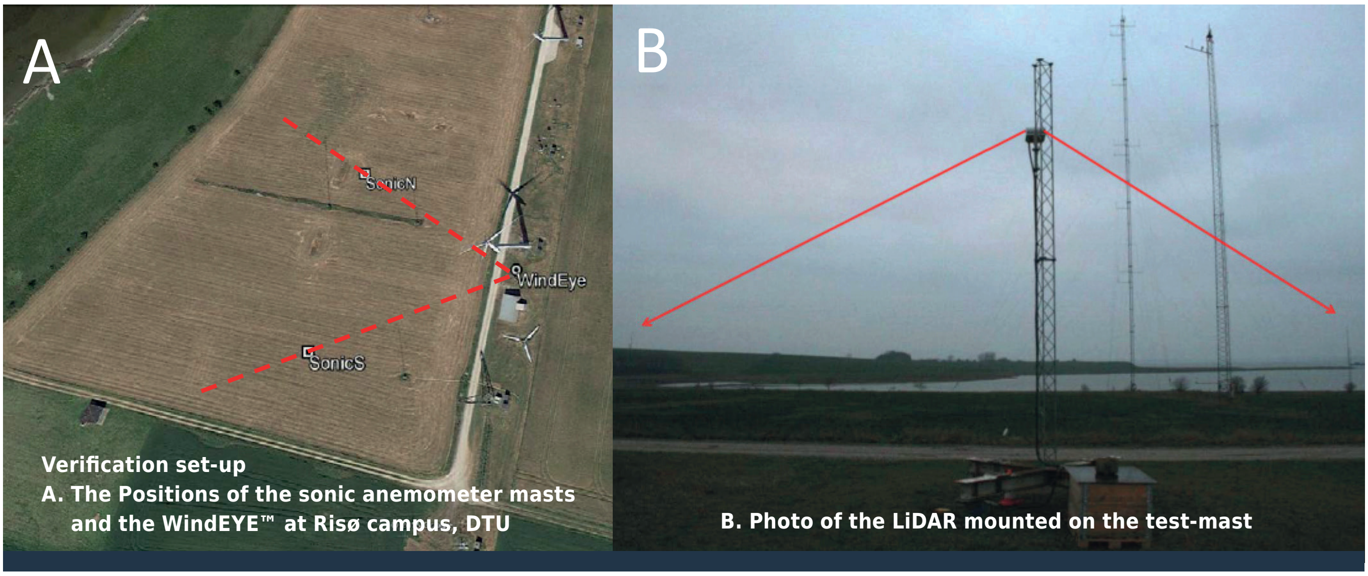
The replaceable laser unit is housed in a separate compartment in the Laser System Unit, making it easy to replace



Laser Lifetime

The light source (the laser) must be replaced every 4th year. The light source is located in the Laser System Unit that is located inside the nacelle. The replaceable light-source has its own individual compartment in the laser system unit, which makes it both very fast and uncomplicated to change the light source – competent service personnel is able to replace the light source in about 20 minutes per system.

WindEYE™ Verification DTU 2015



Verification set-up
A. The Positions of the sonic anemometer masts and the WindEYE™ at Risø campus, DTU

B. Photo of the LiDAR mounted on the test-mast

The WindEYE™ has been tested against sonic anemometers concerning the precision of the measurements. The below paragraph is from the test report from DTU Risø (Dellwik et al, Feb. 2015):

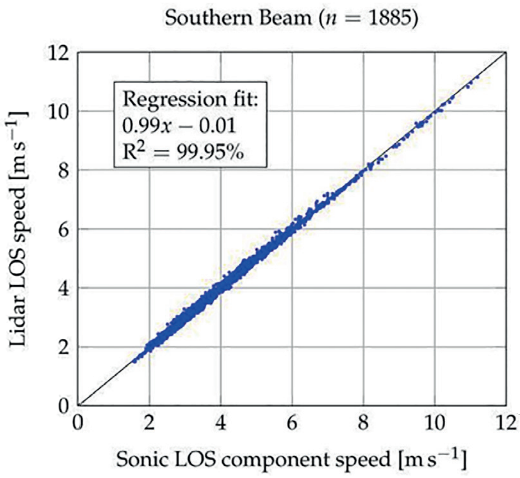
"The functionality of a WindEYE™ LiDAR developed by Windar Photonics A/S for the wind energy market was tested in a two months long field experiment. The WindEYE™ sensor measures the wind speed along two beams to determine the wind direction of the incoming wind field.

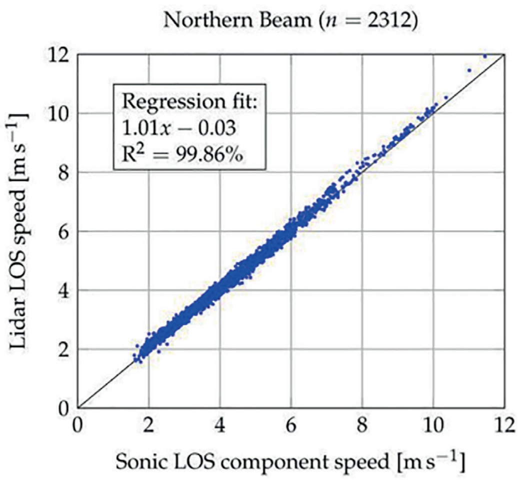
The field experiment utilised two sonic anemometers, which were located in the two centers of the measurement volumes of the WindEYE™, as reference instruments.

The wind vectors measured by the sonic anemometers were projected onto the line-of-sight directions of the WindEYE™ and the wind direction was calculated based on the WindEYE™ algorithm.

It was found that the WindEYE™ measured the wind direction with a high accuracy during the whole campaign."

The following two diagrams displays the correlation concerning wind speed between the measurements of the Windar Photonics LiDAR and the sonic anemometers from the test at DTU Risø, 2015

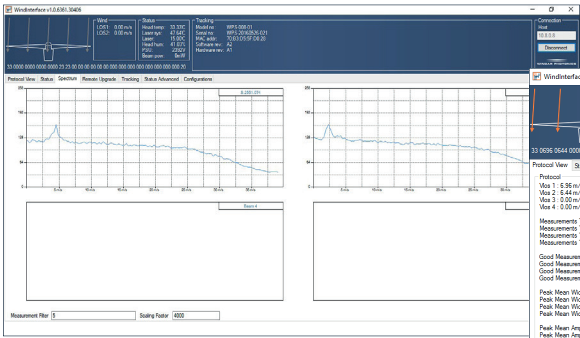


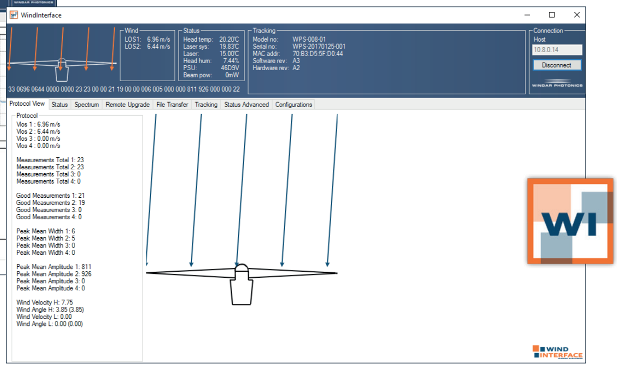


Remote monitoring and data collection

The WindEYE™ is connected to the internet, which enables the end-user to monitor the system remotely. The LiDAR's graphical interface, the WindINTERFACE GUI, can be accessed by connecting to the LiDAR via a secure connection, providing the user both a wealth of information concerning the operation of the LiDAR and real-time wind measurement data.

The data collected by the LiDAR can likewise be collected remotely through a secure connection.





The WindINTERFACE GUI is a powerful tool that enables the end user to monitor the LiDAR system in real-time

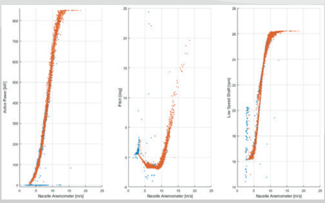
Interfaces for connection with the LiDAR

On-site Access	Remote Access

Monitoring

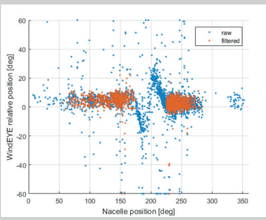
On-site Access

1 **RS485 Cable connection**

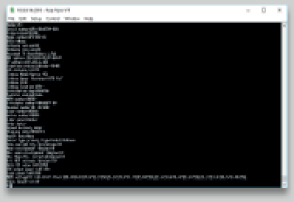


WinterGUI (GUI)

2 **Ethernet Cable connection**



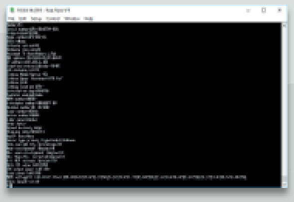
WindINTERFACE (GUI)



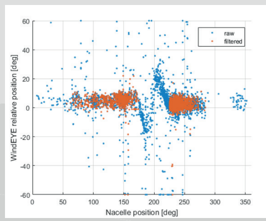
Terminal

Remote Access

1 **Ethernet Remote connection**



Terminal

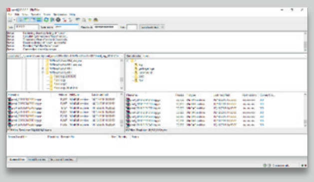


WindINTERFACE (GUI)

Download of Data

On-site Access

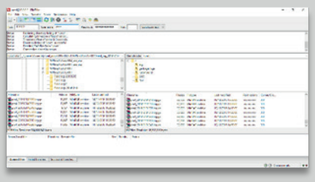
1 **Local cabled Ethernet connection**



FTP Client

Remote Access

1 **Ethernet remote connection Downloading via FTP**



FTP Client

Data Handling

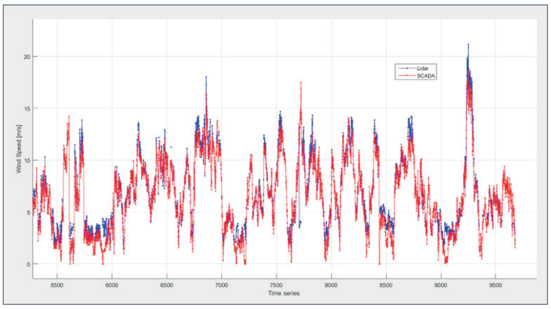
Data handling procedure

Before the raw measurements from the WindEYE™ LiDAR can be utilised for optimising the wind turbine, the raw data need to be processed into applicable data.

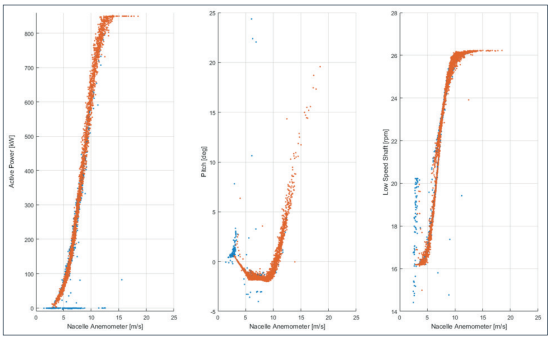
The data handing procedure consists of several steps: First the LiDAR data is synchronized with the SCADA data from the turbine, then the collective total amount of data is filtered and a data availability analysis is performed. Afterwards, the misalignment per wind speed bin is calculated, which forms the base for the final AEP gains estimation.

Data analysis and reporting - The data analysis process for the final report

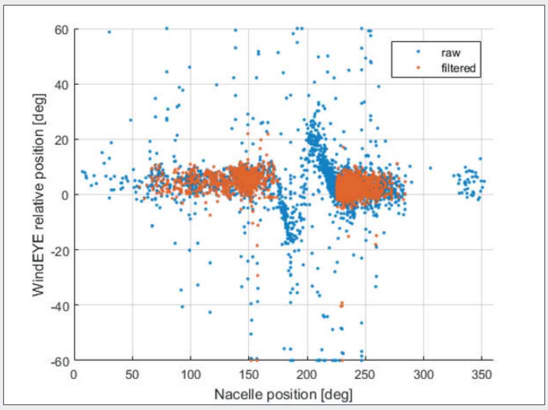
1 Synchronizing the LiDAR data with the SCADA data



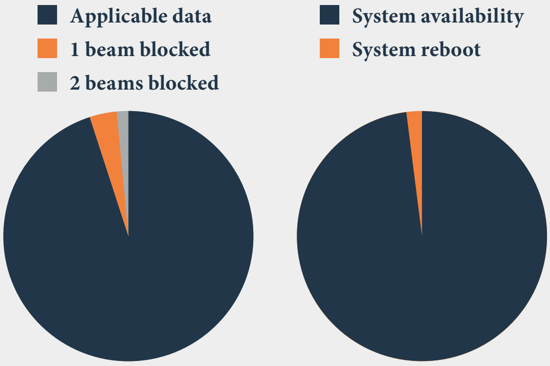
2 Filtering the data for the time that the turbine was operative



3 Filtering wake



4 Data availability analysis

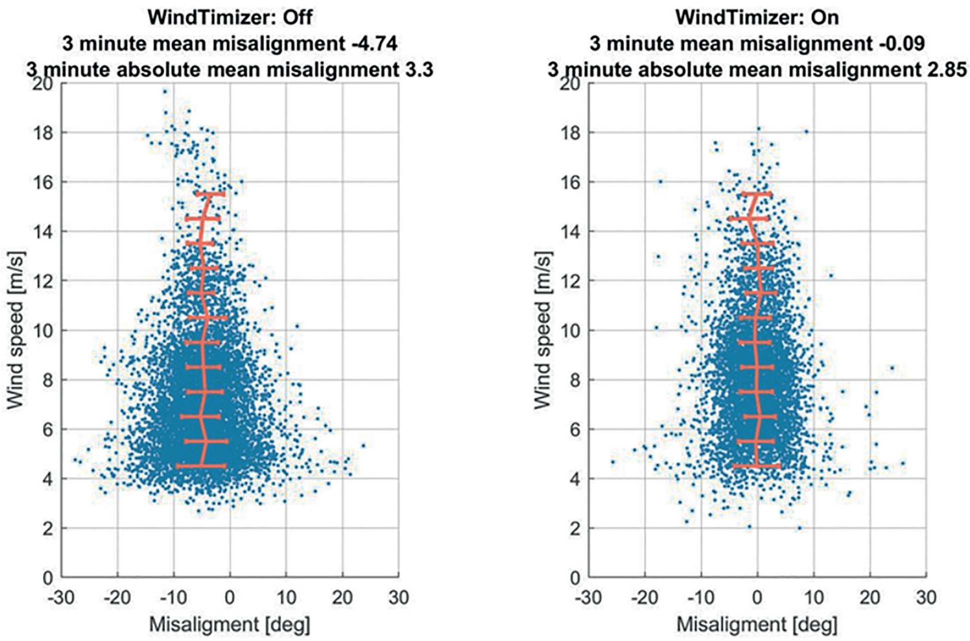


Data Availability	
Applicable data [%]	95%
1 beam blocked [%]	3.6%
2 beams blocked [%]	1.4%

System Availability	
System available [%]	98.1%
System reboot [%]	1.9%

5

Yaw Misalignment before and after



6

AEP calculation

AEP-gains calculation methodology

The AEP calculations are comprised of calculations based on both an empirical method (utilising cos^2) and a theoretical method (utilising cos^3). The final AEP-increase estimate is an average between the two methods, which we have found to be the most precise methodology for providing an adequate and realiable AEP-gains estimation.

COS^2

The AEP gain is calculated from the following equation for both the mean and the absolute mean realignment utilising cos^2:

$$AEP_{gain} = \Sigma_{i=cut_{in}}^{i=Rated}\left(\left(\frac{\cos\phi'^2}{\cos\phi^2}\right)-1\right)+\left(\left(\frac{\cos|\phi'|^2}{\cos|\phi|^2}\right)-1\right) * PDF(i) * 100$$

COS^3

The AEP gain is then calculated from the following equation for both the mean and the absolute mean realignment utilising cos^3:

$$AEP_{gain} = \Sigma_{i=cut_{in}}^{i=Rated}\left(\left(\frac{\cos\phi'^3}{\cos\phi^3}\right)-1\right)+\left(\left(\frac{\cos|\phi'|^3}{\cos|\phi|^3}\right)-1\right) * PDF(i) * 100$$

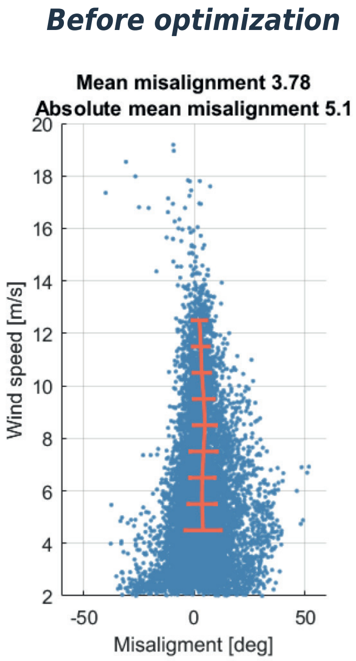
Final AEP-gain estimation

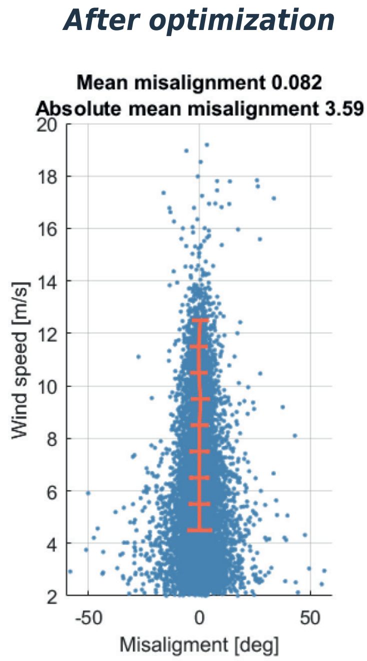
Lastly, the two AEP gain calculations are averaged to produce the final AEP gain estimate, which is presented in the final project report.

Optimisation results

Optimisation results from a Gamesa G87 wind turbine

AEP gain: 1.01%

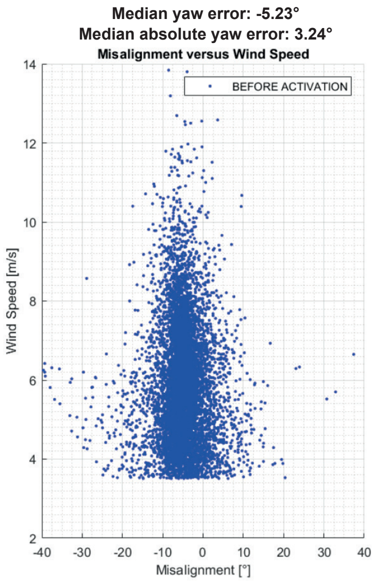




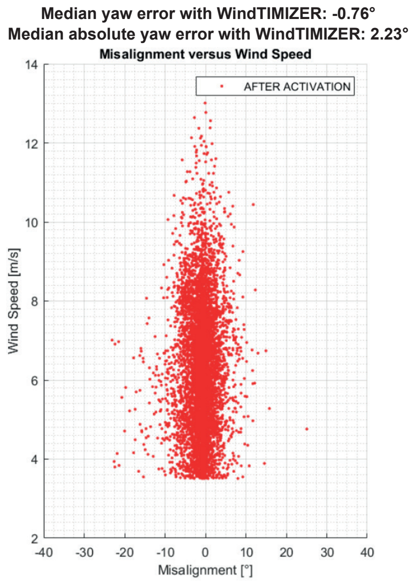
Optimisation results from a GE 1.5MW wind turbine

AEP gain: 1.7%

Before optimization



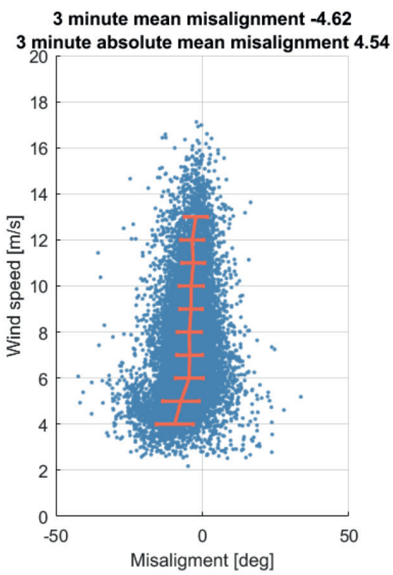
After optimization



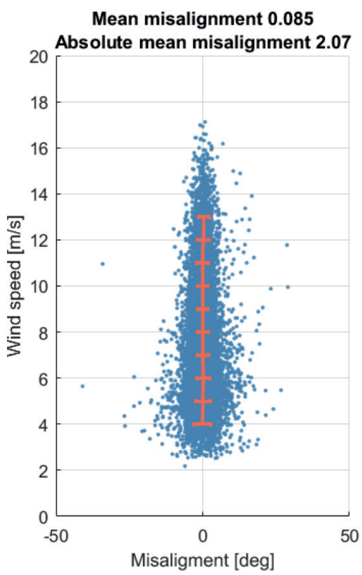
Optimisation results from a Neg Micon NM82 wind turbine

AEP gain: 1.45%

Before optimization



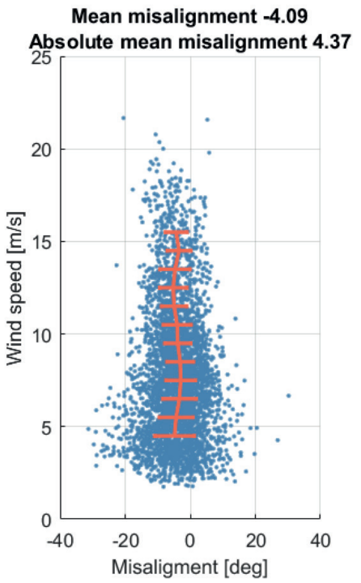
After optimization



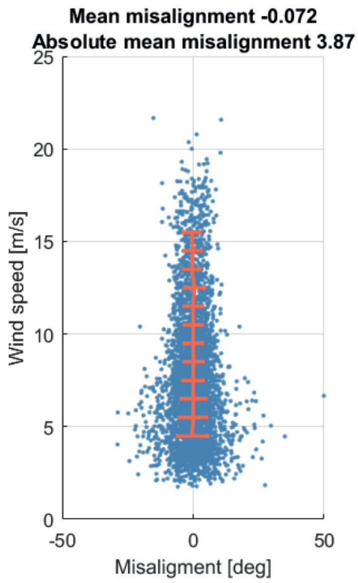
Optimisation results from a Vestas V66 wind turbine

AEP gain: 2.5%

Before optimization



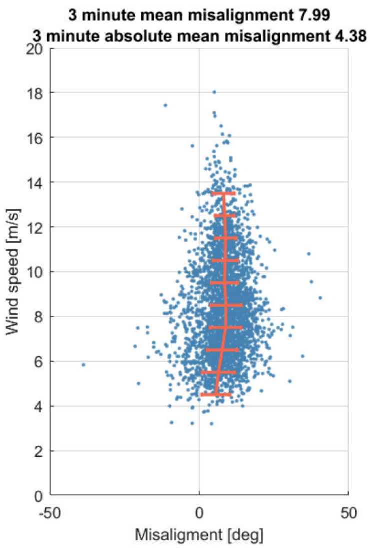
After optimization



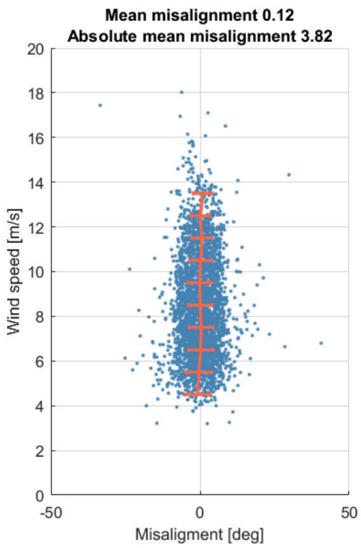
Optimisation results from a Vestas V80 wind turbine

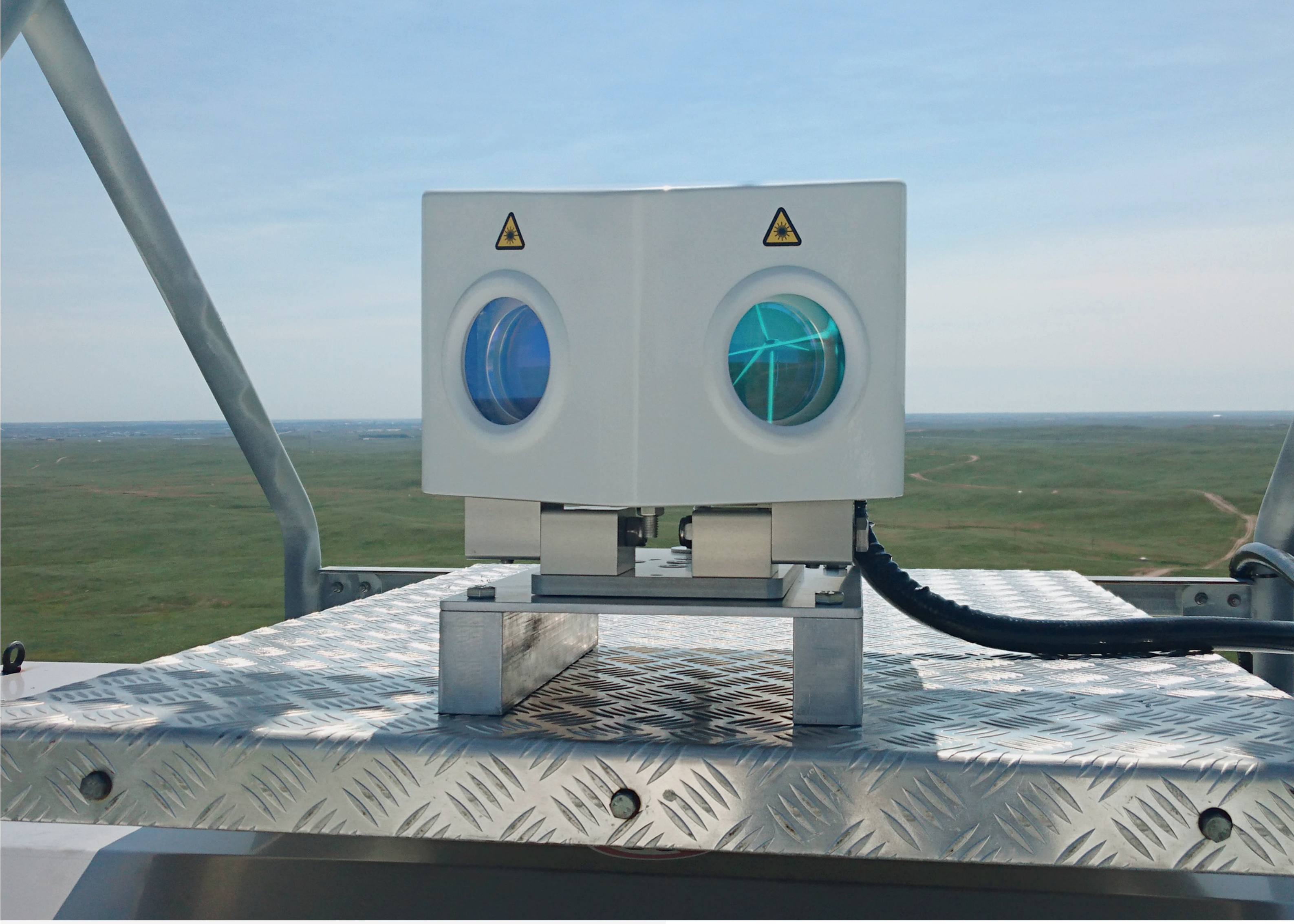
AEP gain: 2.18%

Before optimization



After optimization

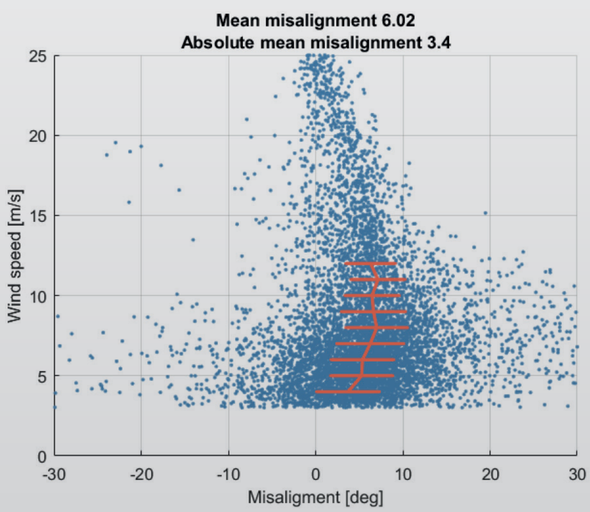




Optimisation results from Suzlon S88 wind turbines

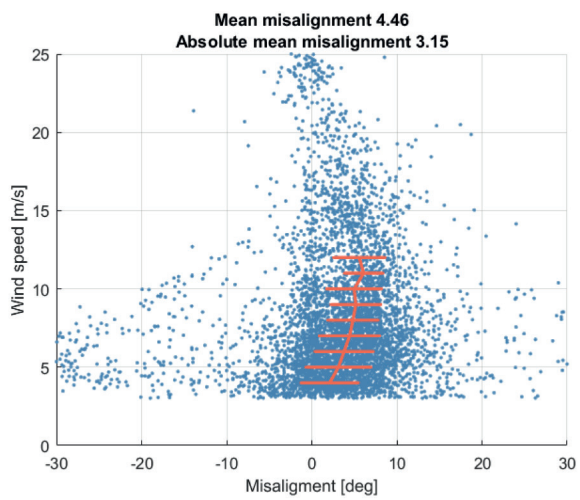
Result 1

AEP gain: 1.8%



Result 2

AEP gain: 1.5%




VESTAS V66


GE 1.5MW


NEG MICON NM82

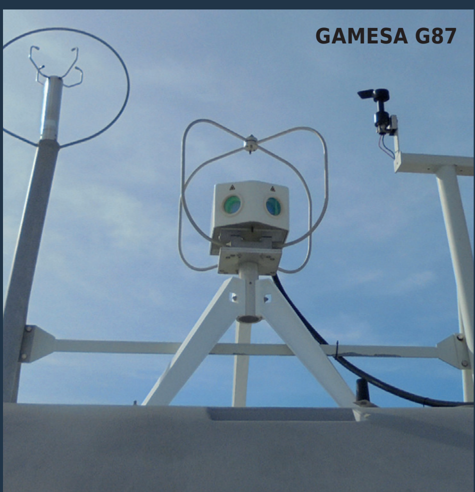

SUZLON S88


VESTAS V80


NEG MICON NM82


GE 1.5MW


VESTAS V66


GAMESA G87


VESTAS V80


GE 1.5MW

Plan for implementation

Our optimisation projects usually follow the below procedure, but a measurement campaign is never concluded before sufficient wind data has been gathered for all wind speeds.

Suggested timeframe for the project

Total project time estimation: 11 weeks

1. First measurement period: 4 weeks. First measurement period is initiated

2. Initial report: 1 week. Initial report will be handed over to the customer

3. Integration: 1 week. The LiDAR will be integrated with the wind turbine

4. Final measurement period: 4 weeks. Final measurement period is initiated

5. Final report: 1 week. Final report handed over to the customer

WINDAR PHOTONICS