OWA GLOBE PROJECT WEBINAR 1

Measuring the Global Blockage Effect

Carbon Trust and RWE

6th August 2024

OWA GloBE Project Webinars

RWE CARBON TRUST

Welcome, and thanks for joining!

Webinar 1: Measuring the Global Blockage Effect (today)

- Background & motivation for the project
- Objectives
- Project participants and structure
- Measurement campaign design
- Validation & verification
- Blockage measurements
- Q&A

Webinar 2: Modelling and Accounting for Wake and Blockage Effects (Thursday)

- Recap of objectives
- Modelling approaches
- Validation against measurements
- Conclusions
- Joint Statement
- Q&A

Introductions

Neil Adams, Carbon Trust
Programme manager for Offshore Wind Accelerator
Carbon Trust project manager for GloBE

Christopher Rodaway, RWE
Lead Scientist – Advanced Numerics
Technical lead for GloBE

Offshore Wind Accelerator

Joint industry Programme currently involving 9 developers + Carbon Trust

- Industry-led initiative

Set up 2008 in response to the need to **bring down the cost of Offshore Wind**

The largest and most established innovation programme

- New **lower-cost technologies**, ready to use
- Simple governance model

Over **£120m total programme spend** to date

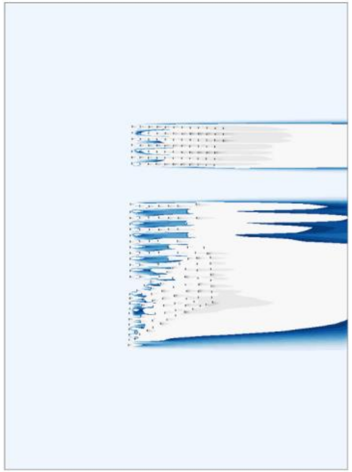
- Industry has funded >60%

Involved in over ¾ of all operating EU wind farms

Objective of OWA Stage IV

*The OWA programme aims to **continue the cost reduction of offshore wind** to make it cost competitive with other sources of energy generation, overcome **market barriers**, develop industry **best practice**, trigger the development of new **industry standards** and support the **international expansion** of offshore wind*

Potted History of GloBE



Historical approach to turbine interaction losses:

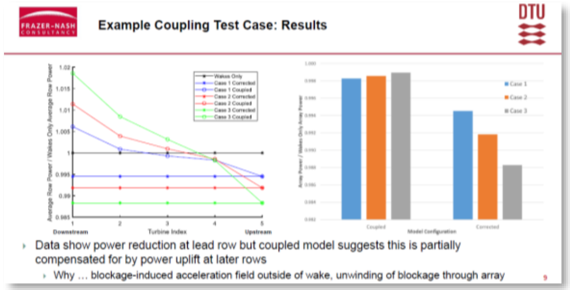
- Upwind turbines see free-stream wind speed
- Wake effects impact downstream turbines
- Turbine interaction losses = wake losses

‘Blockage-effect insight shows science of wind still evolving’
Ørsted's production forecast revision put the issue in the spotlight, but better understanding of such phenomena can only help the industry long-term

28 Nov. 2019
Recharge

Blockage becomes a hot topic in the industry:

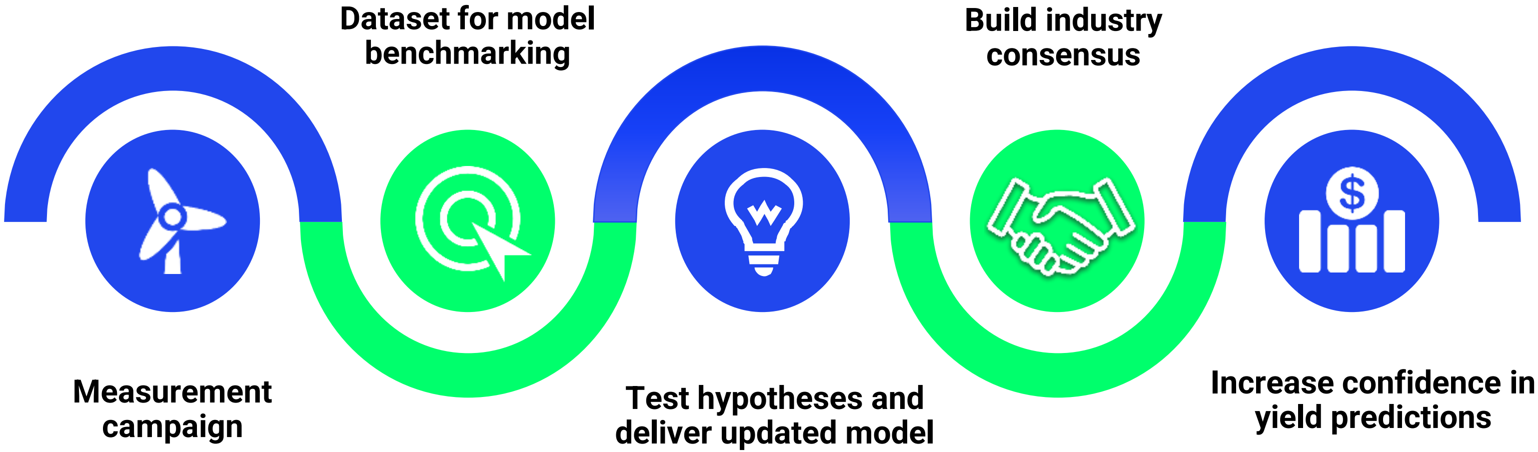
- Increased understanding that the wind slows down as it approaches a wind farm
- Turbine interaction losses = complex, two-way interaction between turbines and atmosphere



OWA Common R&D project improved Partners’ understanding:

- The reduction in power at lead row is partially compensated by increases elsewhere
- A comprehensive measurement campaign is required to achieve certainty and consensus

Objectives of GloBE



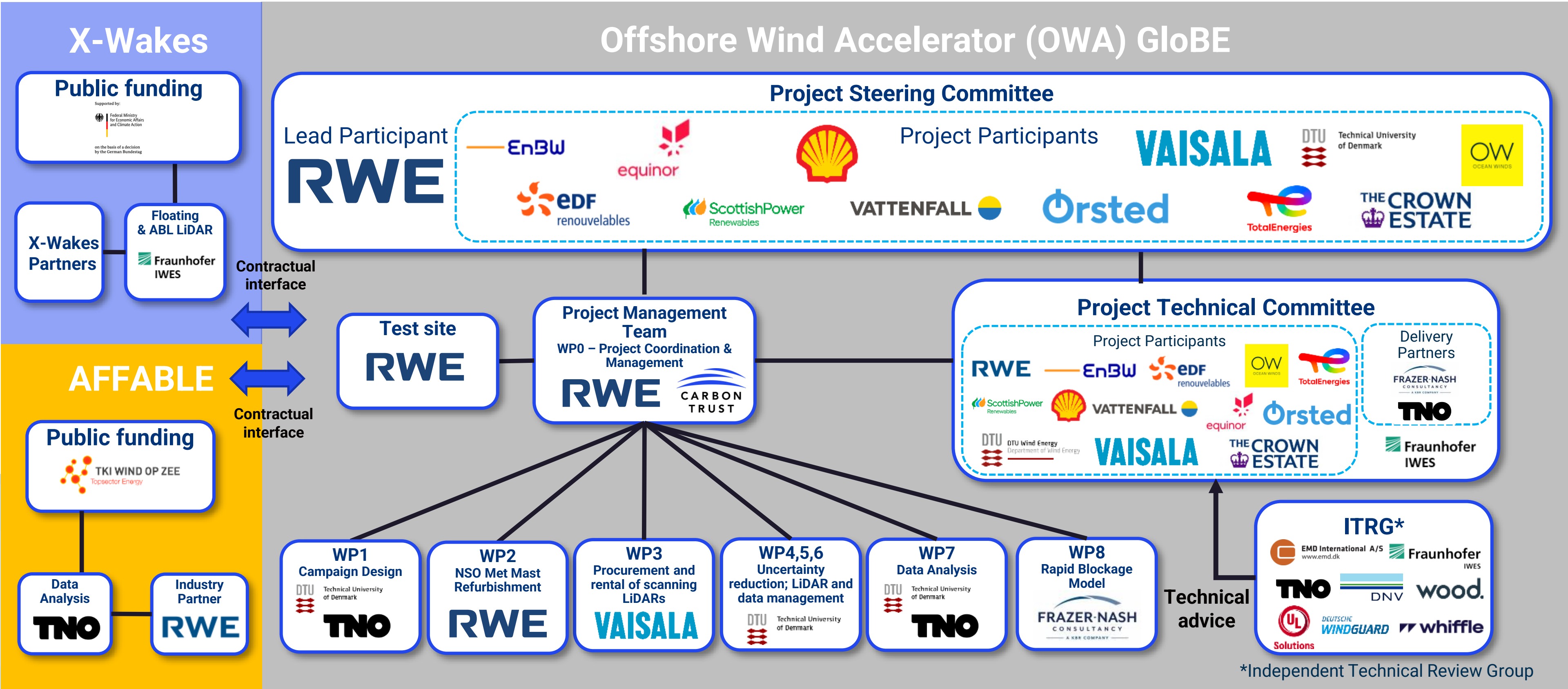
Objectives of GloBE

Measurement campaign

Requirements:
- Agnostic to the various hypotheses on the blockage effect
- Capable of discerning a small signal amidst measurement noise and uncertainty
- Realisable on an existing wind farm or cluster

Solution: RWE campaign at the Heligoland cluster

GloBE Project Structure



RWE | GLOBE Global Blockage Effect

Measuring the Global Blockage Effect

Carbon Trust Webinar Session 1

6th August 2024

Christopher Rodaway[1], Kester Gunn[1], Sam Williams[1], Alessandro Sebastiani[1], Elliot Simon[2], Michael Courtney[2], Gunhild Rolighed Thorsen[2], Emilie Clausen[2], Marco Turrini[3], Dennis Wouters[3], Yichao Liu[3], Julia Gottschall[4], Martin Dörenkämper[4], Erik Patschke[4], Lin-Ya Hung[4], Neil Adams[5]

[1]RWE Renewables, [2]DTU Wind Energy, [3]TNO, [4]Fraunhofer-IWES, [5]Carbon Trust

CARBON TRUST

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on the basis of a decision by the German Bundestag

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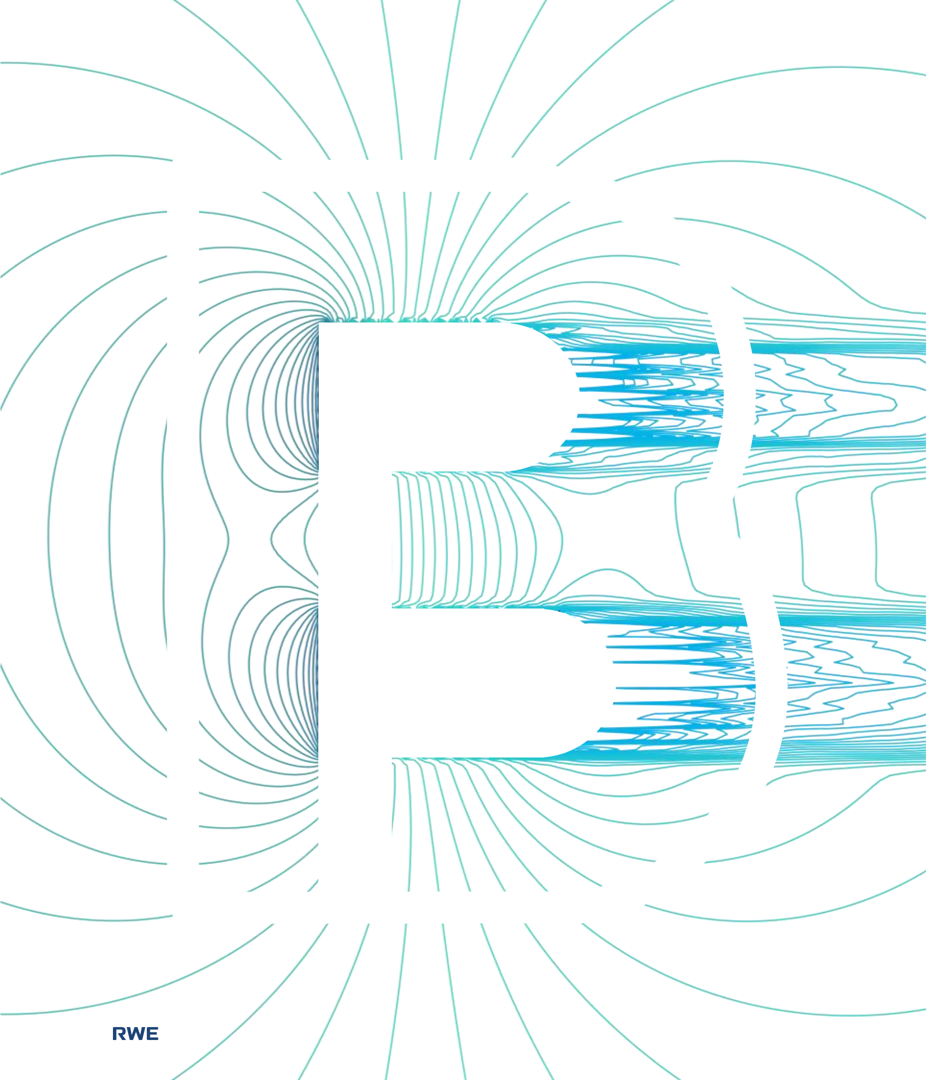
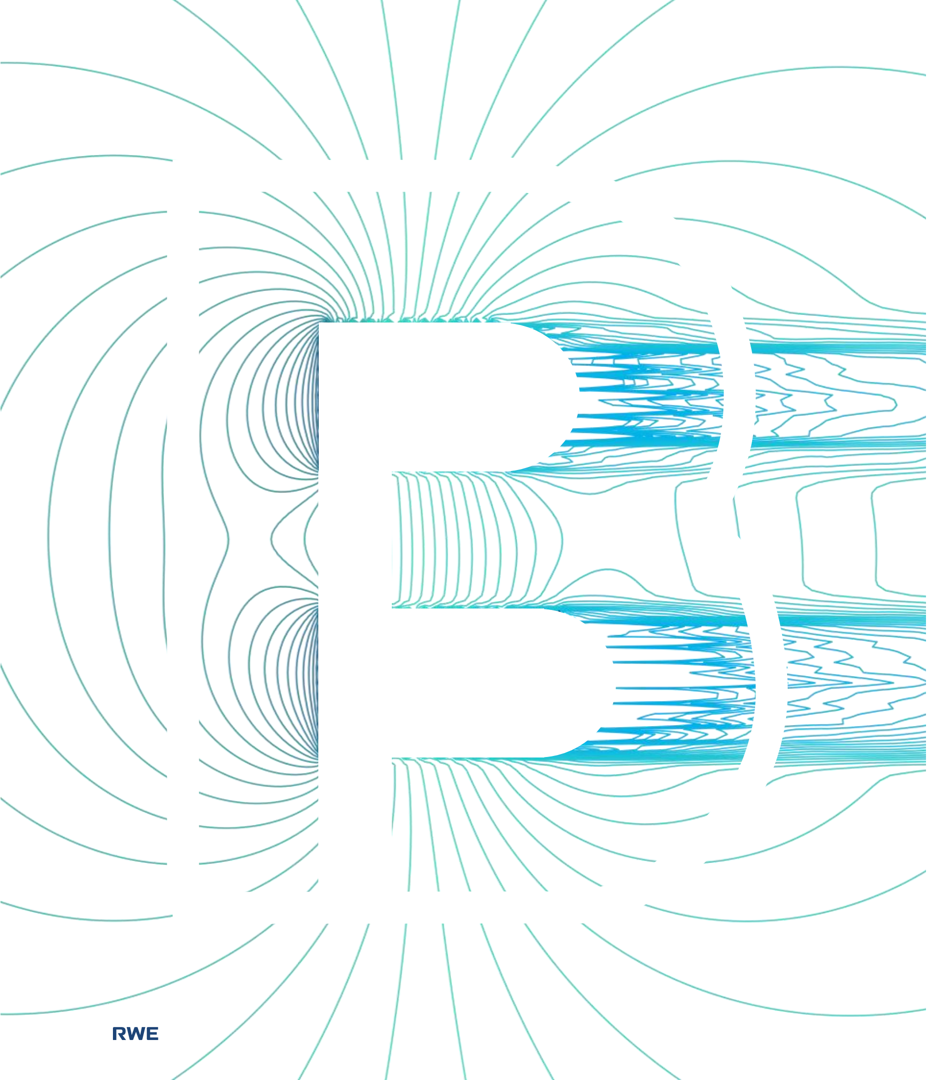
HLRN

Ministerie van Economische Zaken en Klimaat



RWE | GLOBE
Global Blockage Effect

- Introduction & Motivation
- Experimental Design
- Results
- Conclusions
- Questions



RWE | GLOBE
Global Blockage Effect

- **Introduction & Motivation**
- Experimental Design
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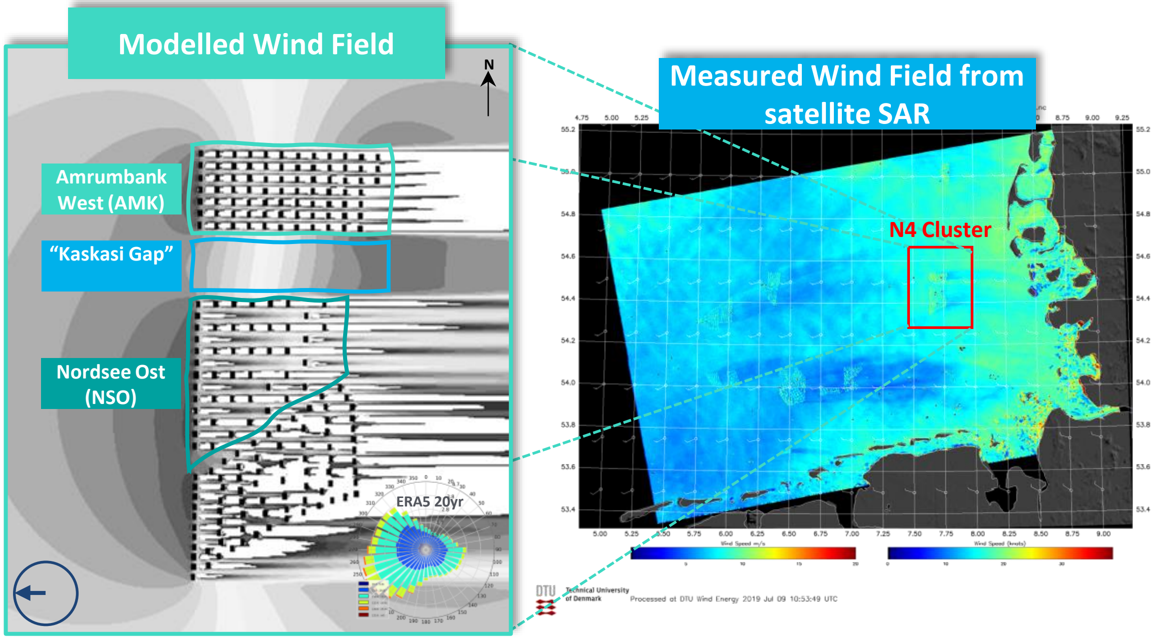
Why N4 (Helogoland)?

The ideal experimental location!

1. High installed capacity (~1GW) and energy density
2. Flat leading edge
3. Regular grid (AMK) and perimeter-based (NSO)
4. Far downstream of neighbouring wake & minimal coastal effect
5. Highly westerly winds
6. “Kaskasi gap” for DD* to test lateral effects (GloBE)
7. <u>AMK & NSO 100% owned / operated by RWE</u>



Reaching Consensus

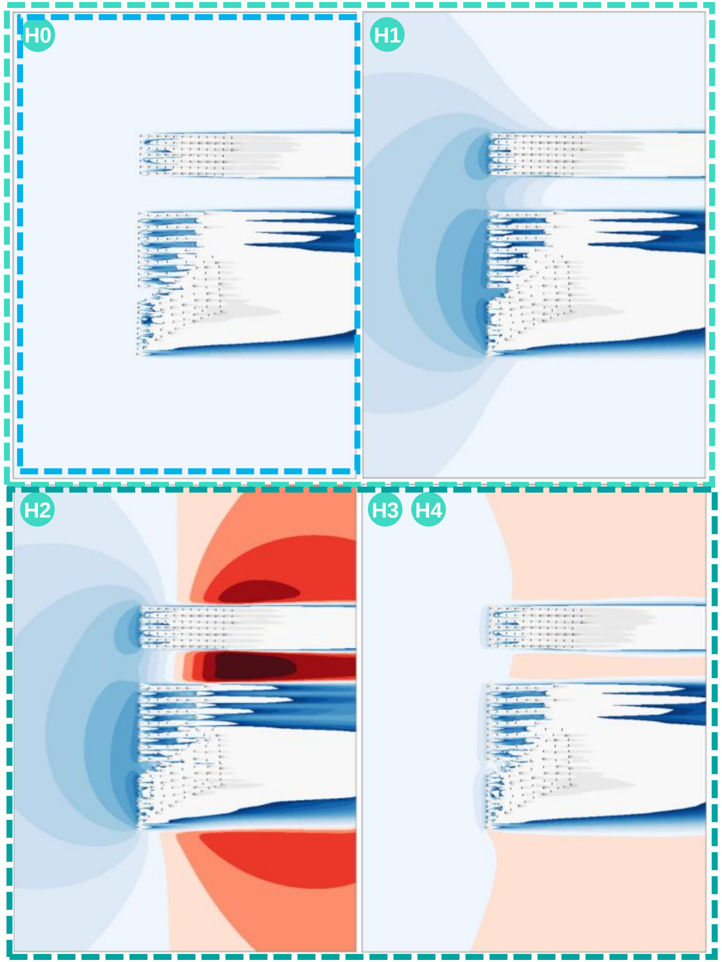
Hypothesis testing approach

- H0 There is no GBE
- H1 GBE results only in a downwards bias in AEP
- H2 GBE results in a downwards or upwards bias in AEP
- H3 Geostrophic height (ABL) has little impact on GBE
- H4 Geostrophic height (ABL) has large impact on GBE

No GBE

Decoupled approach

Tightly- / fully-coupled approach

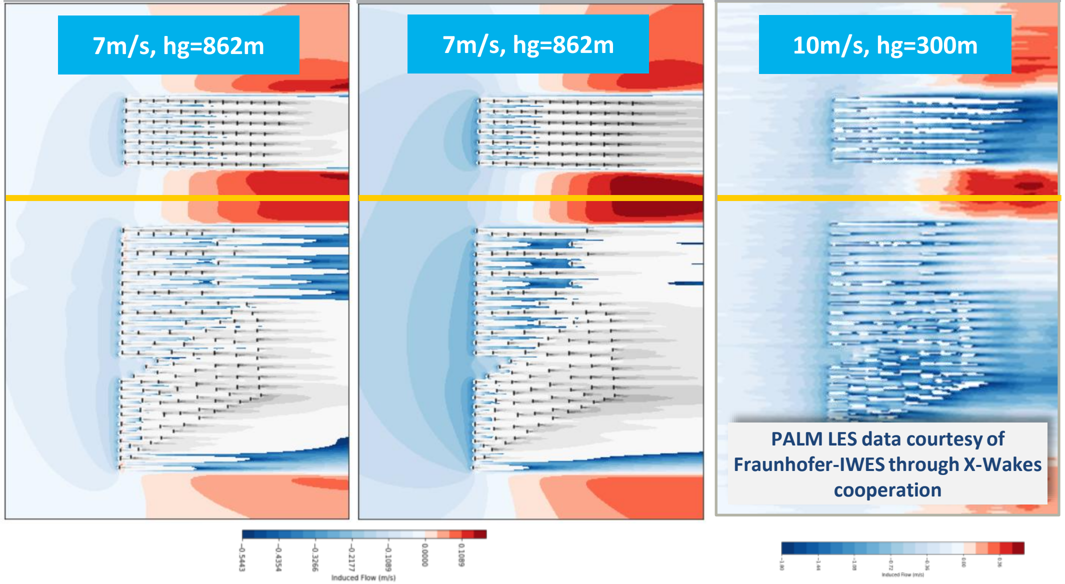


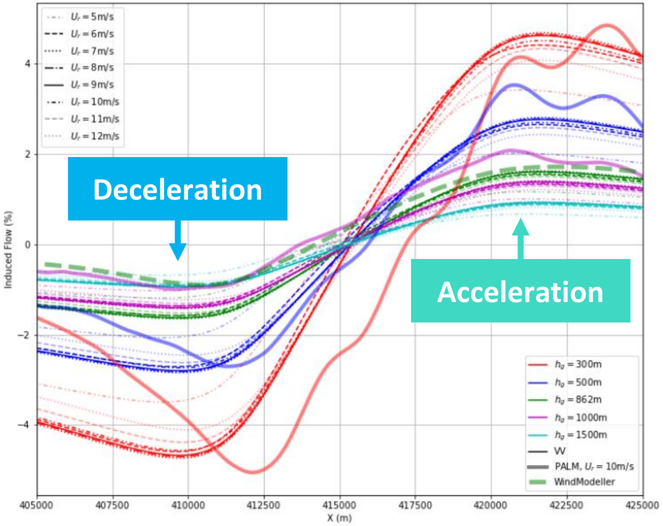
Why N4 (Heligoland)?

Unique “Kaskasi gap” feature

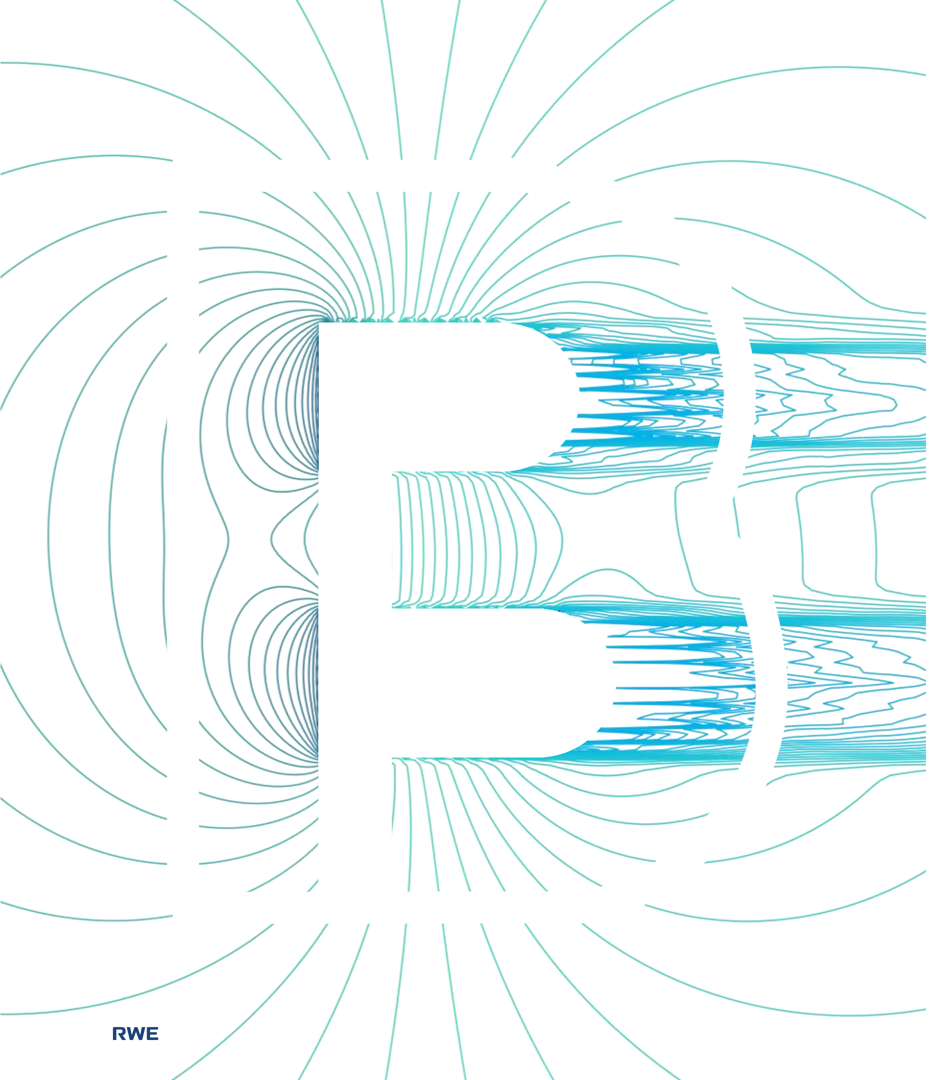
Comparison of models and flow variations

WindModeller [RANS CFD]	RWE’s VV [Reduced Order]	PALM [LES CFD]*	Direct Comparison





*Very strong inversion and low ABL height



RWE | GLOBE
Global Blockage Effect

Introduction & Motivation

Experimental Design

Results

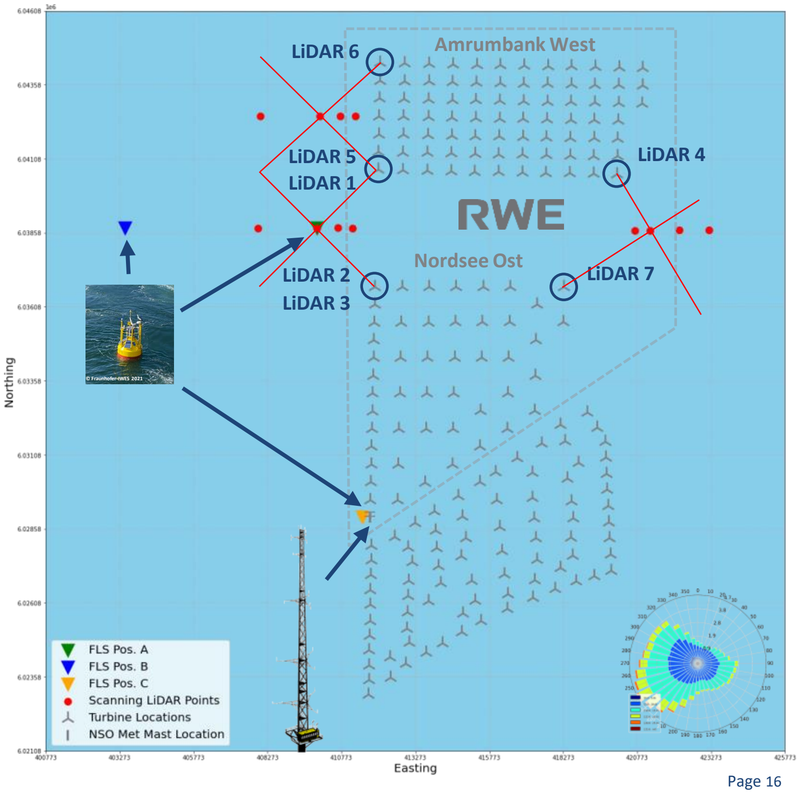
Conclusions

Questions

Experiment design

Summary of GloBE measurement campaign

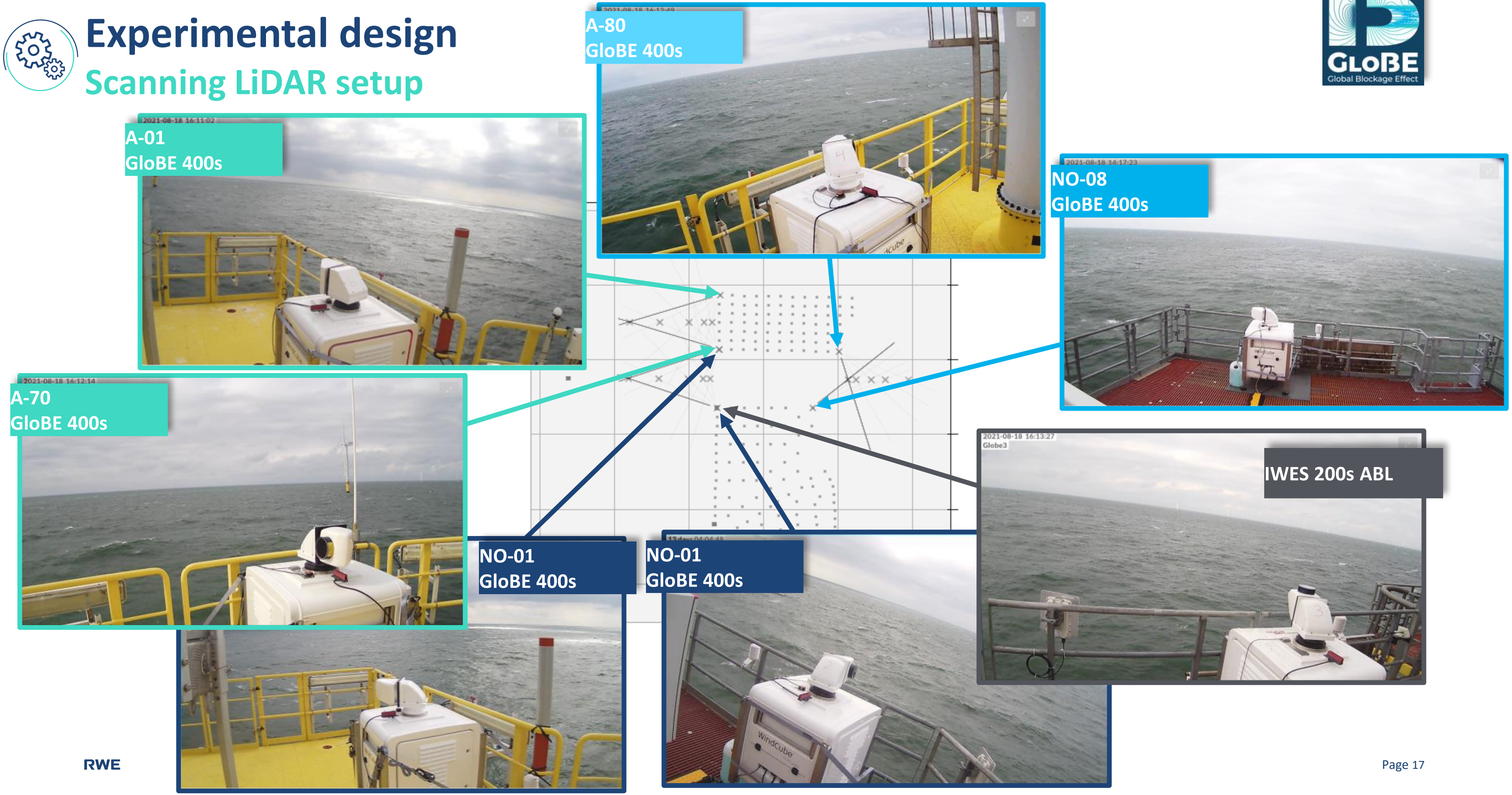
1. **6x WindCube 400s scanning in 3x dual Doppler pairs to conduct dual Doppler reconstruction (DDR) of wind speed from LoS:**
   - Operating in step-stare scanning patterns
   - Motion corrected, de-biased, levelled, time synchronised
2. **Dedicated WindCube 200s for ABL:**
   - Boundary layer height
   - VAD tall profiles
3. **Floating LiDAR System (FLS)**
   - Measuring in 3 locations, 2x co-located with scanning LiDAR and mast as trusted reference
4. **Met mast**
   - Refurbished with high-frequency sampling inc. ultrasonics for atmospheric stability and SST



Experimental design

Scanning LiDAR setup

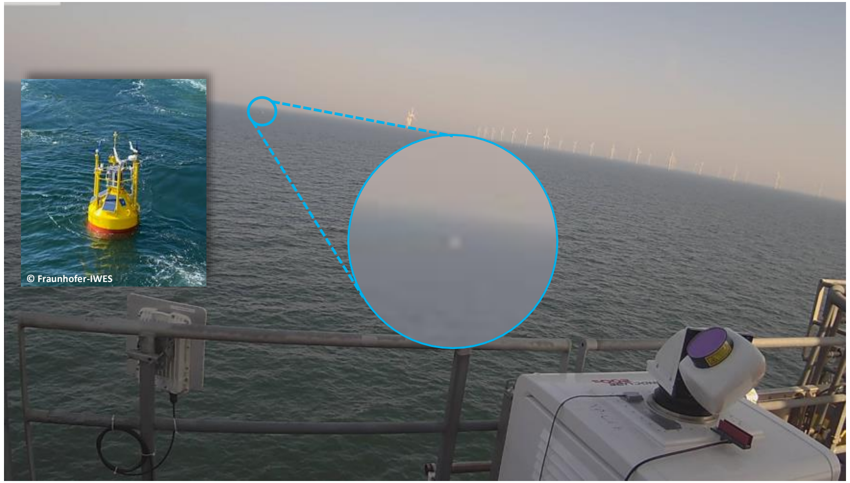
GLoBE
Global Blockage Effect



Experimental design
Floating LiDAR system setup

Locations of the FLS Over Time

Position A	Position C

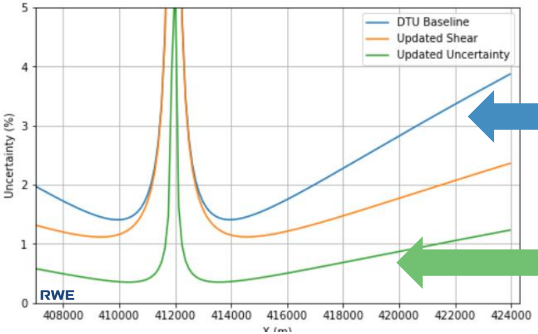


Uncertainty & bias

Why is this so important for measuring blockage?

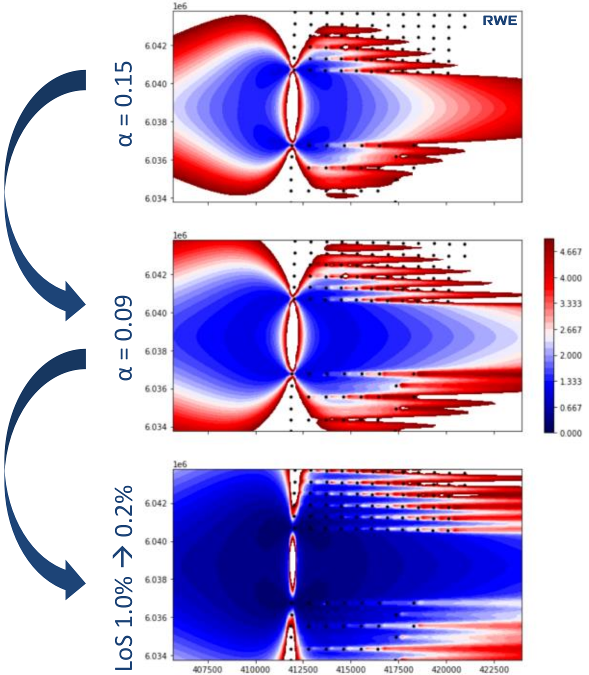
A small signal in a lot of noise

- If blockage is within 1-4% of wind speed[1], uncertainty and bias needs to be controlled and minimised.
- Else, we either can't see blockage or mis-attribute measurement bias to blockage effects…
- Example showing impact of wind shear and LiDAR line of sight (LoS) on overall uncertainty with range:



Meaningless blockage measurement

Meaningful blockage measurement

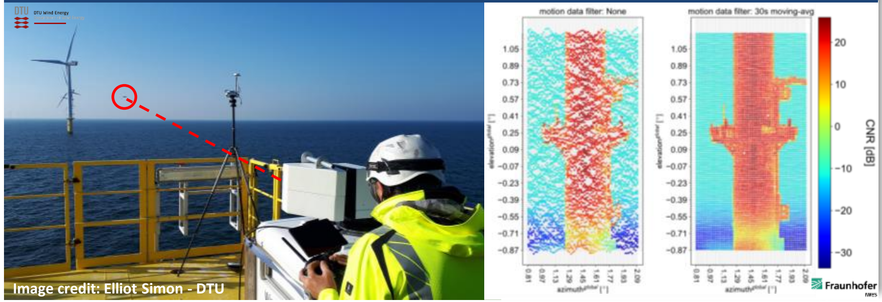


RWE [1]Bleeg, J.; Purcell, M.; Ruisi, R.; Traiger, E. Wind Farm Blockage and the Consequences of Neglecting Its Impact on Energy Production. Energies 2018, 11, 1609. https://doi.org/10.3390/en11061609

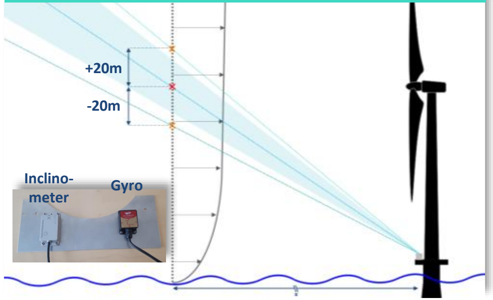
Uncertainty & bias

Controlling & correcting known sources

Pointing: Drone / turbine hard-targeting & Earth curvature

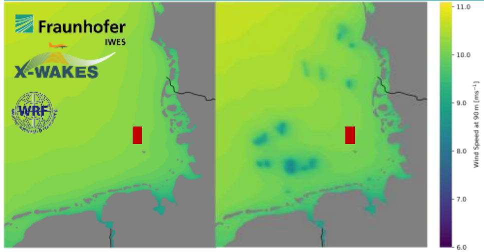


Motion: Dynamic tilt correction



Line of sight: Inter-device calibration

Spatial: WRF ambient + wake



Wind data processing & bias removal

Summary of corrections

Comprehensive correction of systematic known sources of biases to isolate blockage

Final processing of LiDAR data includes:

- Removal of earth curvature and eddy correlation at measurement level.
- Identification & correction of inter-device LoS wind speed offsets.
- Identification & correction of time-wise LoS wind speed offsets.
- Motion compensation using additional high frequency inclinometer measurements.
- Adjustment for pitch/roll & static elevation offset using drone and applied in motion correction step.
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- Time syncronised

Scanning LiDAR setup

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Wind data processing & bias removal

Earth curvature correction

Correction and finalization steps

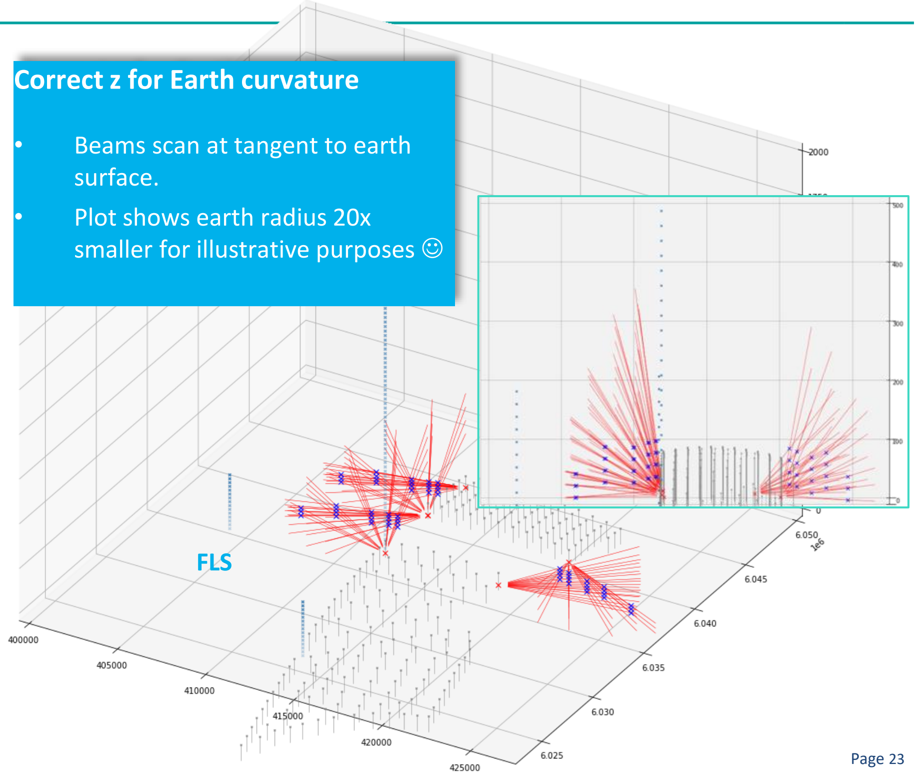
- Points adjusted in z (and therefore elevation) to account for Earth curvature at measurement source.

- Post-processing pipelines presented with data that has already been corrected for Earth curvature.

- No further processing needed.

Correct z for Earth curvature

- Beams scan at tangent to earth surface.
- Plot shows earth radius 20x smaller for illustrative purposes ☺



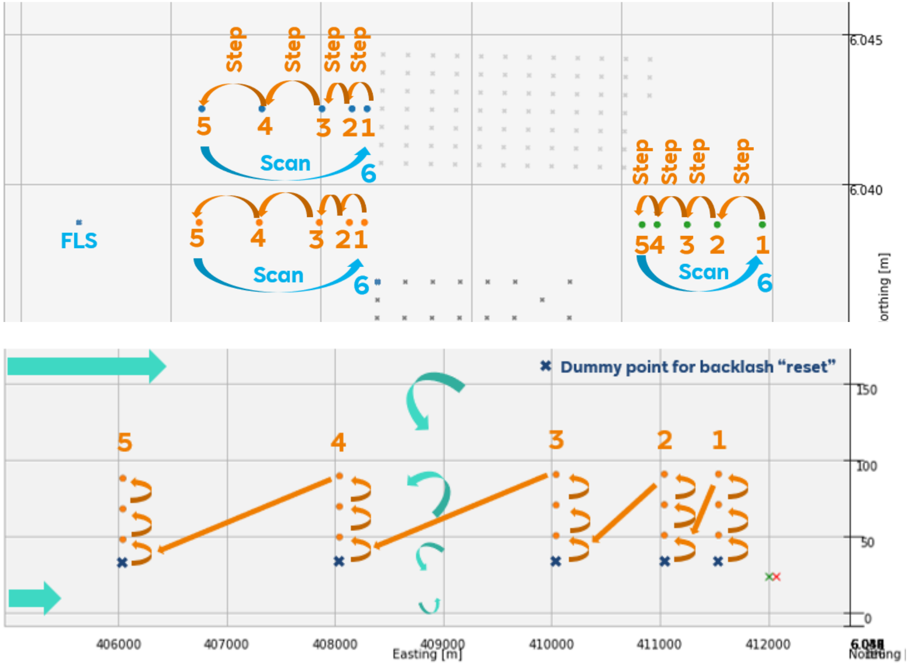
Wind data processing & bias removal
Turbulence advection decorrelation

Horizontal & Vertical Correlation Considerations

1. Scanning order in x,y done upstream to decorrelate eddy advection for predominant westerly directions.

2. Scanning in order in z always the same i.e. from bottom to top with an additional dummy start point to reduce backlash impact.

3. A 30min averaging period permits turbulence advection through the gap (applied in post-processing).



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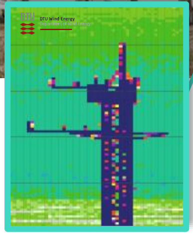
Wind data processing & bias removal

Inter-device biases

Comprehensive correction of systematic known sources of biases to isolate blockage

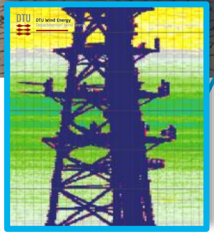
- LiDARs deployed in a pre- and post-campaign inter-calibration to check and control for initial and developing radial WS biases **between LiDAR devices**.

Pre-Campaign @Riso



Tested at 1.0, 1.5, 2.0, 3.0 & 5.0km ranges

Post-Campaign @Heligoland



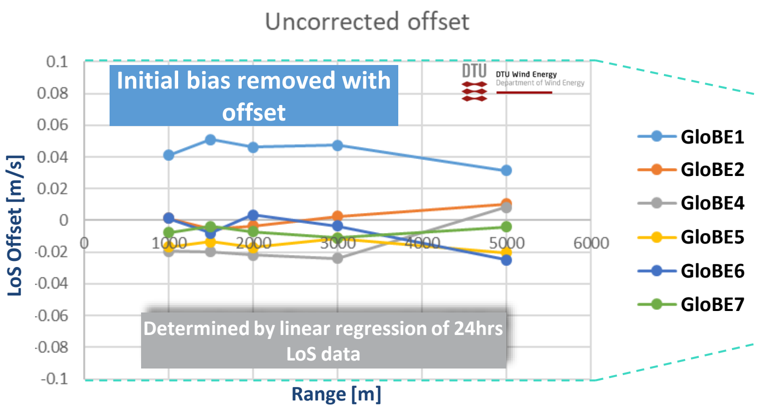
Elevations the same in both cases, LiDAR beams parallel

Wind data processing & bias removal

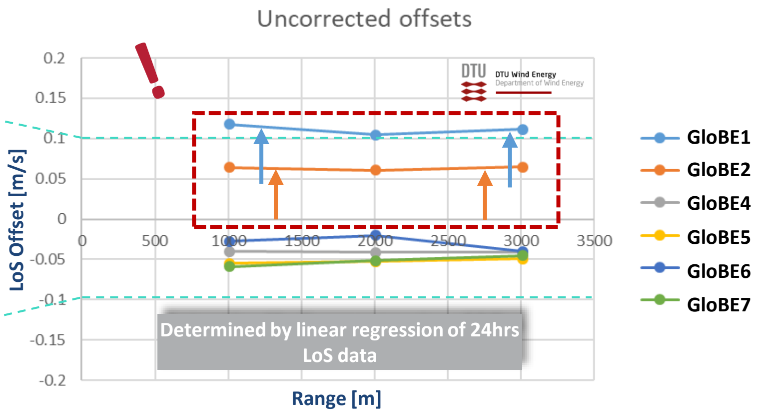
Inter-device biases

Emergence of offsets with LiDARs 1&2

Pre-campaign @Riso



Post-campaign Heligoland



GloBE 1&2 have produced an offset / bias before and/or during the campaign!

Note that offset is relatively constant with range – no beam misalignment

Wind data processing & bias removal

Inter-device biases

Resolving Inter-Device Biases

Process for correcting the data:

1. Consult with Vaisala to determine what key identifier we should be seeking in the data.
2. Identify when in time the offsets occurred, looking for sudden changes in CNR.
3. Conduct a test (period after event occurred) against a control (period before event occurred) to confirm findings.
4. Implement offsets in dataset from time event occurred of the measured value.
5. Separate initial factory offset for GloBE 1 from event.
6. Apply timewise offset in LoS wind speed from the point of each event through the entire dataset.

Wind data processing & bias removal

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Wind data processing & bias removal

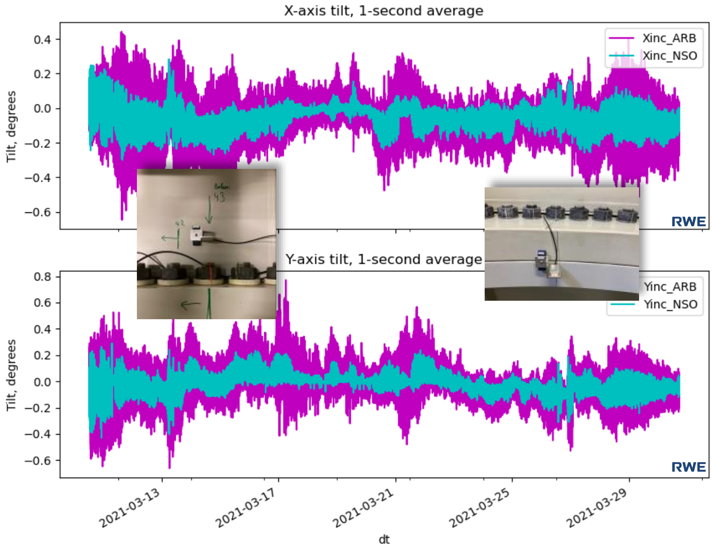
Motion compensation

Pre-campaign 3month measurements for tilt

- A pre-LiDAR campaign to measure tilt conducted as part of the feasibility and go/no-go decision.

- The following questions needed answering:
  - What is the peak tilt we can expect?
  - Are there significant differences in the dynamic response of each foundation type?
  - Can we use the dataset to test a motion compensation method for use in GloBE?

- Inclinometers installed at tower – transition piece interface and measured for 3months.



Wind data processing & bias removal

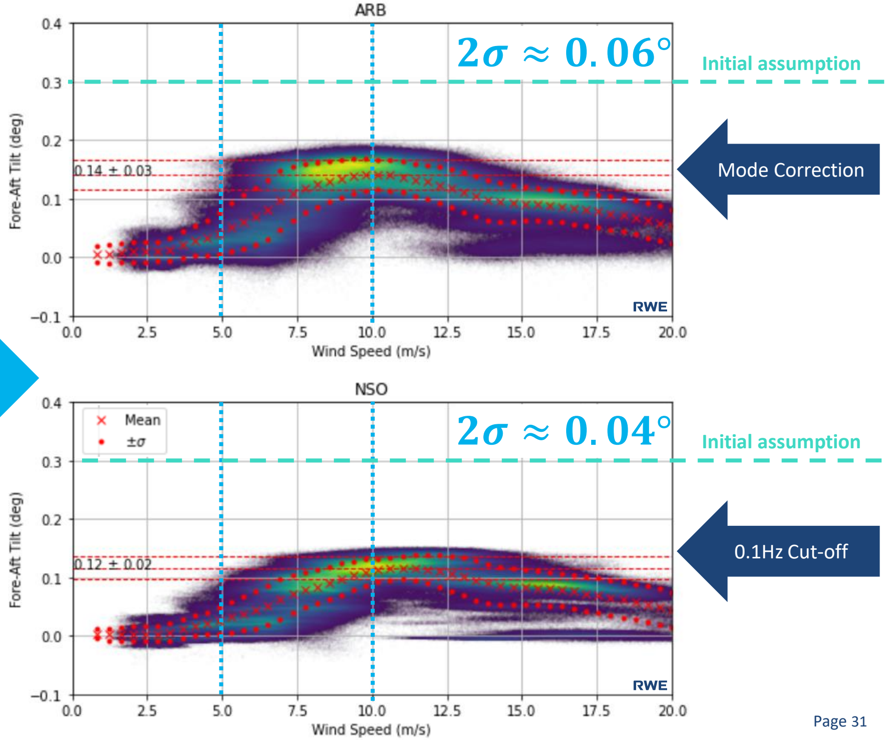
Motion compensation

Removing the high-frequency artifacts

Lower than expected tilt magnitudes:

- We can now see the wind-induced tilt.
- Max (mean) tilt for ARB and NSO are about 0.14 and 0.12 respectively (about the same)

After mode correction / filter to remove oscillations



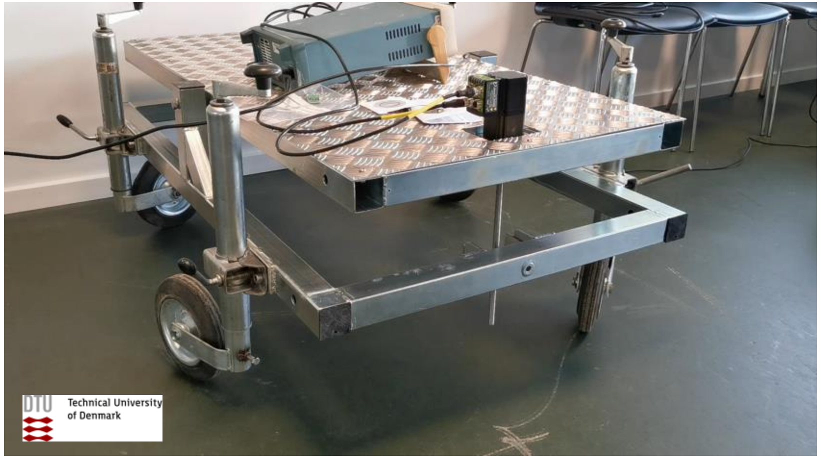
- Peak tilts similar between foundation types as an indication of design stiffness, however dynamics responses are different.
- Peak tilts lower than expected, good for GloBE!

Wind data processing & bias removal

Motion compensation

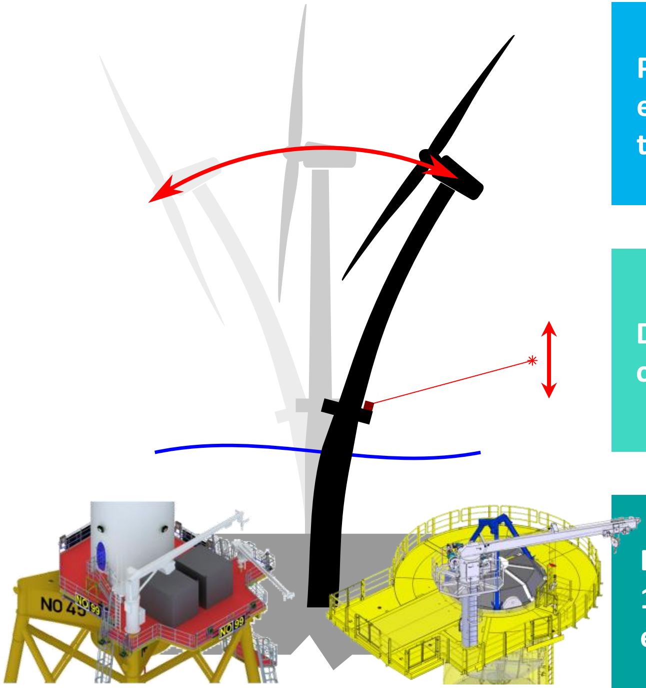
Bench test for tilting impact assessment

- Dynamic test bench fabricated by DTU to test a LiDAR in motion against a static LiDAR and met mast to develop shear-based correction method to be used offshore that is more robust than more simple approaches (e.g. assuming a shear level for vertical extrapolation).

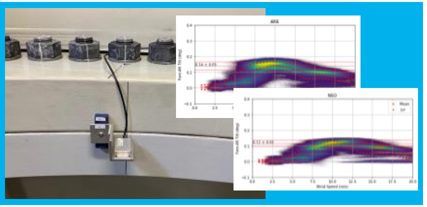


Wind data processing & bias removal

Motion compensation



Pre-campaign 3month tilting measure-ments at each wind farm as proof of concept to generate tilt time-series



Development of correction method tested pre-campaign at DTU using acquired real tilt time-series

Image credit: Elliot Simon - DTU

Deployment of real-time motion monitoring at 16hz using inclinometer and gyro array fixed to each WindCube for correction in post-processing

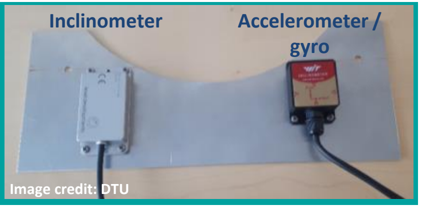


Image credit: DTU

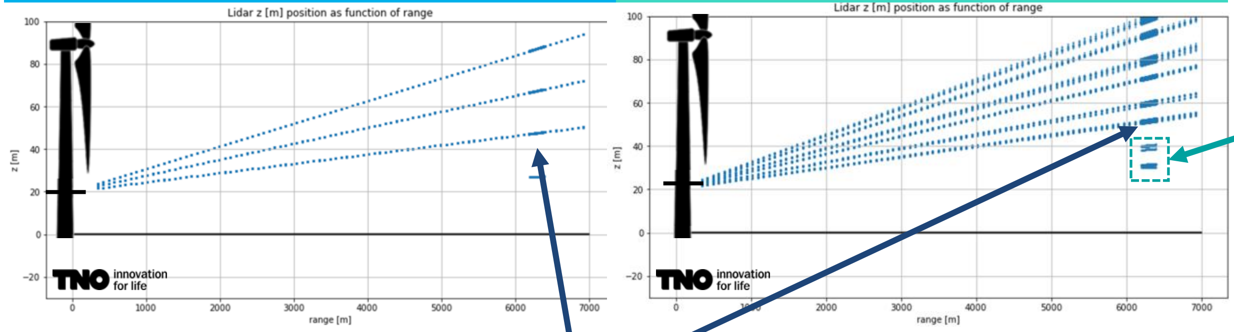
Wind data processing & bias removal

Motion compensation

Motion compensation in post-processing

- Take a **moving average of 30s from inclinometer data to filter out high-frequency vibrations** and leave true inclinations.
- Collect points in net around measurement height using highly concentrated points to get as many samples as possible as a 10min average for LoS WS prior to dual Doppler reconstruction.
- Interpolate / extrapolate between heights in z back to 90m as final data point.

Desired points in z @6.5km	Inc. Tilt Motions @6.5km



Ignore these, backlash reset point in each loop

Non-uniform distribution of sample points around region of interest

Wind data processing & bias removal

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Wind data processing & bias removal

Beam pointing accuracy

Initial setup onshore

Initial setup of the LiDARs done onshore at DTU as follows

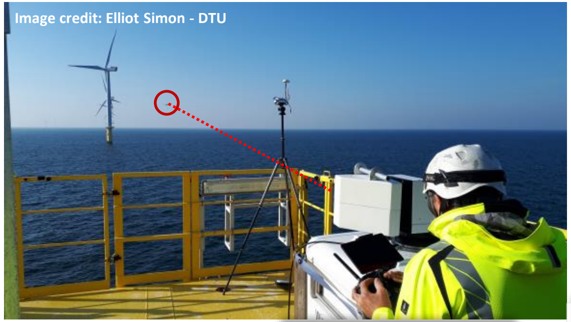
- Levelling on compacted surface:
  - Hard targeting using small objects for azimuth.
  - Hard targeting for static elevation offset.
- We **assume that this remains true when going offshore** but ultimately checked by:
  - Drone hard targeting for pitch, roll and elevation offsets.
  - Subsequent assessment of weekly turbine hard targets to test drone-based hard-targeting and capture any temporal changes in offsets.

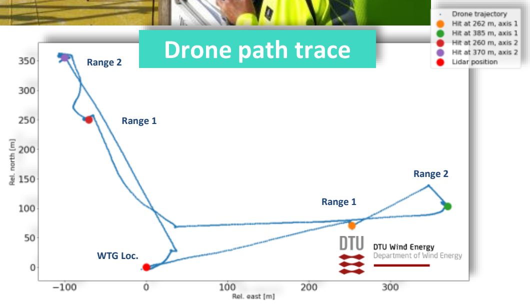
Wind data processing & bias removal

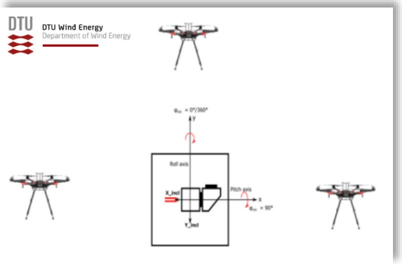
Drone-based hard targeting

New & novel methods for ensuring beam pointing accuracy

- Drone deployed for pitch, roll and motor offset calibrations using RTK absolute & relative GPS positioning in combination with turbine geometric information to calculate beam position compared to the commanded head position.





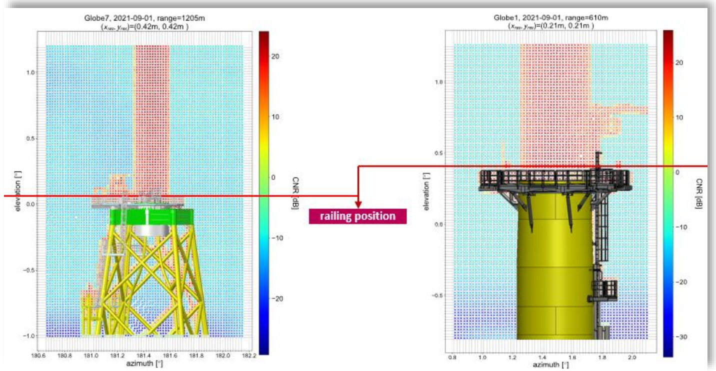


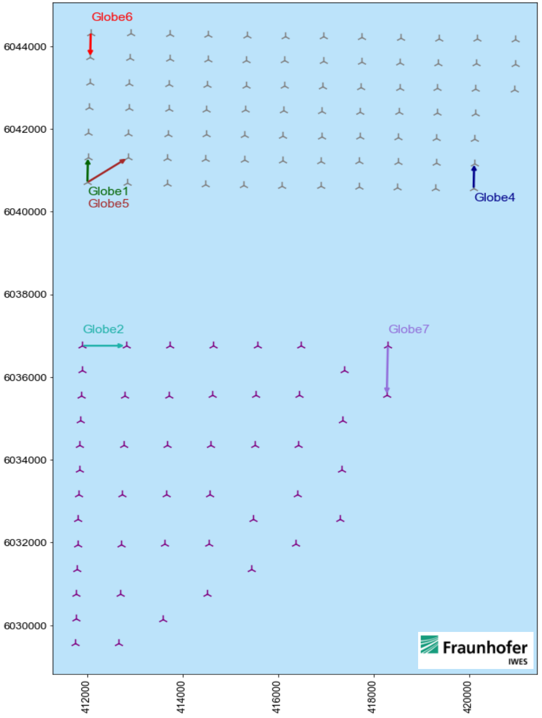
Wind data processing & bias removal

LiDAR pointing accuracy

Turbine Hard Targeting Method

- Scan reference turbines regularly (plan was weekly) through the campaign.
- Apply motion compensation turbine hard target data and same 30s avg filter.
- Track reference point over (railing) time to see if there are time-wise changes.

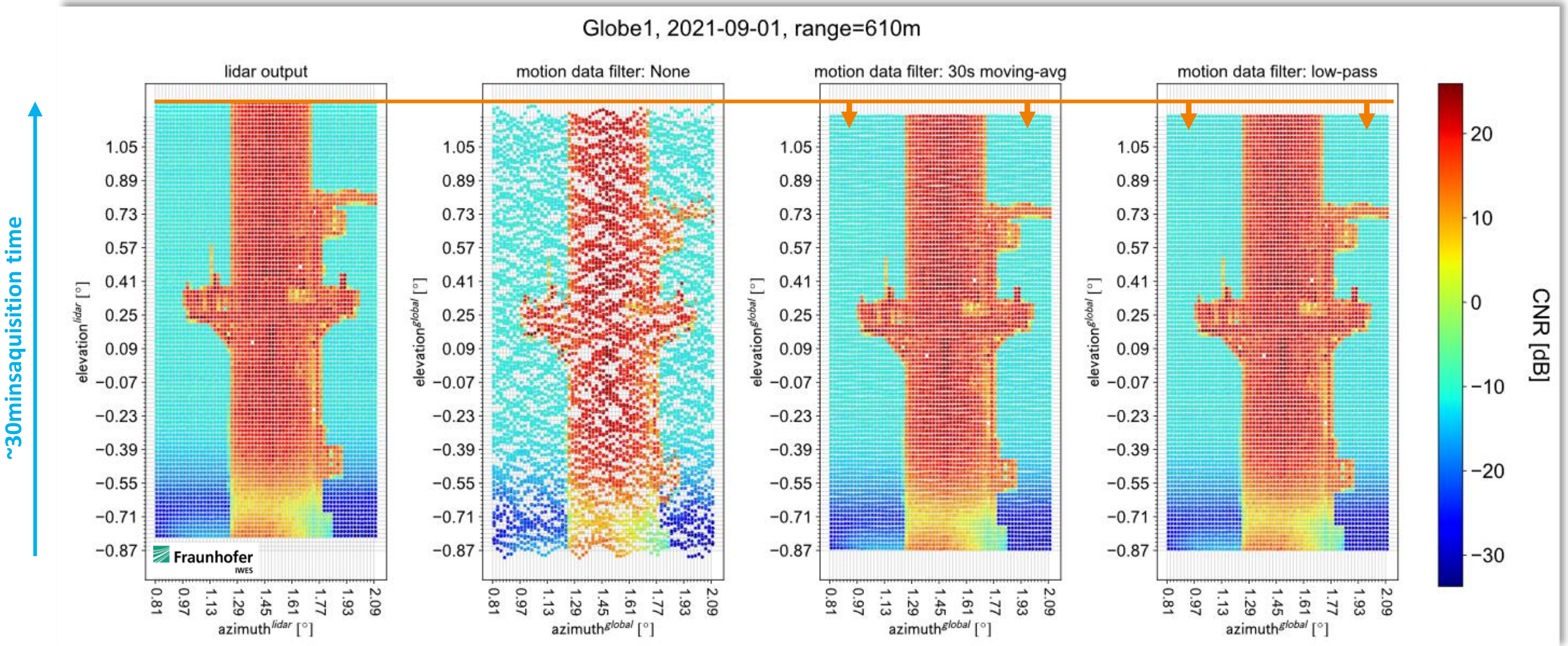




Wind data processing & bias removal

LiDAR pointing accuracy

Turbine Hard Targeting Method

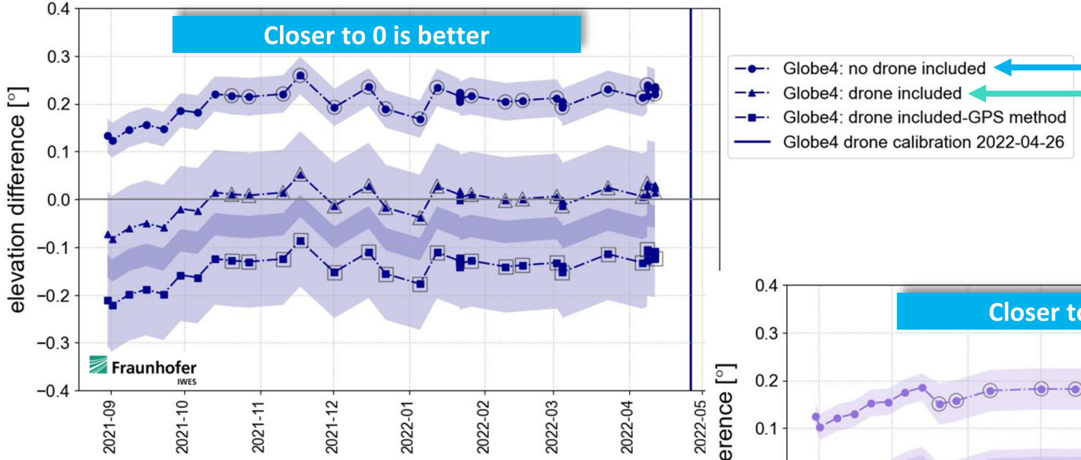


Wind data processing & bias removal

LiDAR pointing accuracy

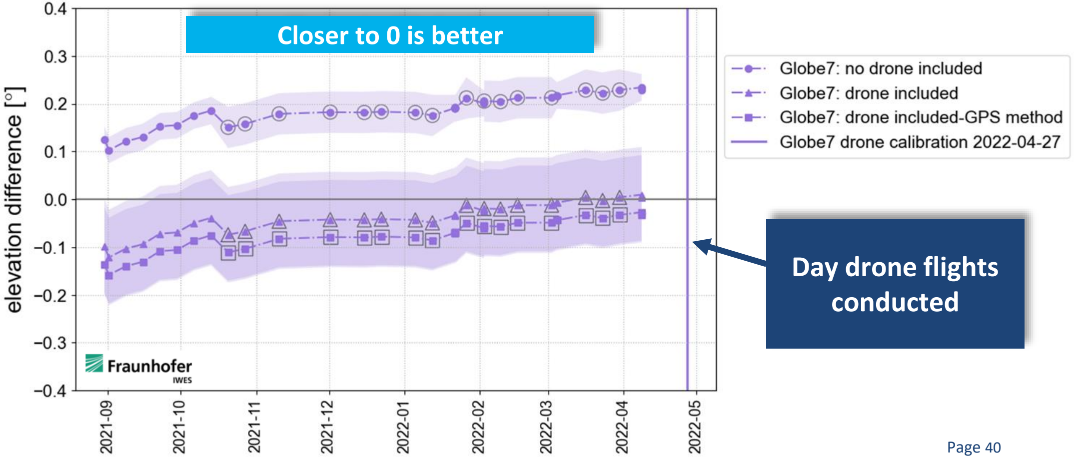
GLOBE
Global Blockage Effect

Turbine Hard Targeting Outcome Example for LiDAR Pair 4|7



Independent test of drone-based offsets verifies positive impact and time-varying nature

Subtle changes over time



Day drone flights conducted

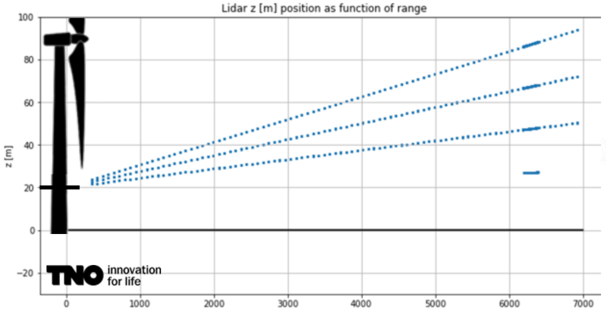
Note: Serves as check only, only single turbine observable for each LiDAR due to structures, need two for pitch and roll calculation.

Wind data processing & bias removal

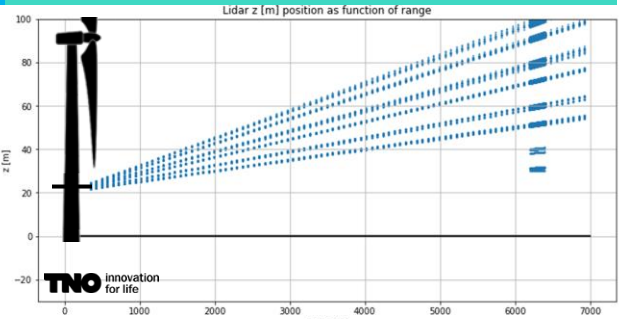
Beam pointing accuracy

Example beam deflection from data pipelines from pitch, roll and elevation offsets

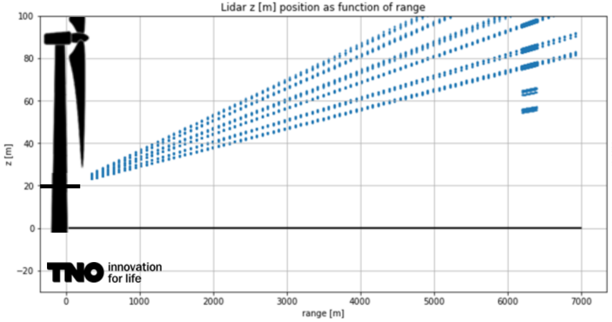
Desired points in z @6.5km



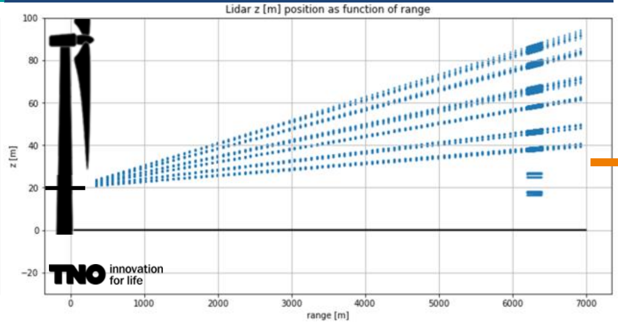
Inc. Tilt Motions @6.5km



Inc. Drone Inc Offsets (Pitch/Roll) @6.5km



Inc. Drone Motor Offsets @6.5km



Makes a huge difference!!

Wind data processing & bias removal

Summary of corrections

Comprehensive correction of systematic known sources of biases to isolate blockage

Final processing of LiDAR data includes:

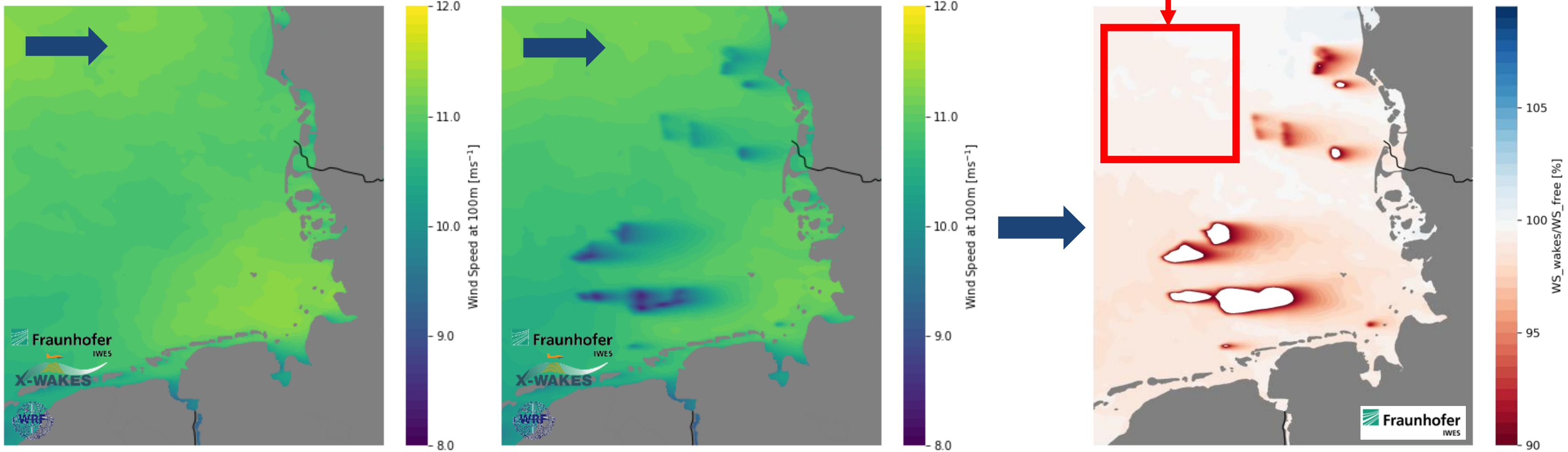
- Removal of earth curvature and eddy correlation at measurement level.
- Identification & correction of inter-device LoS wind speed offsets.
- Identification & correction of time-wise LoS wind speed offsets.
- Motion compensation using additional high frequency inclinometer measurements.
- Adjustment for pitch/roll & static elevation offset using drone and applied in motion correction step.
- Spatial correction using WRF to determine speedups to common point statistically using wind speed filters (3-12m/s) with and without wake.
- Time synchronisation.

Wind data processing & bias removal

Spatial variations and neighboring wind farms

Spatial Correction Method

- WRF contains internal numerical variability resulting from seeding and randomisation.
- Any correction using WRF to the DDR wind speeds done statistically and not temporally to avoid phase errors, only when larger than numerical variability.



Wind data processing & bias removal

Summary of corrections

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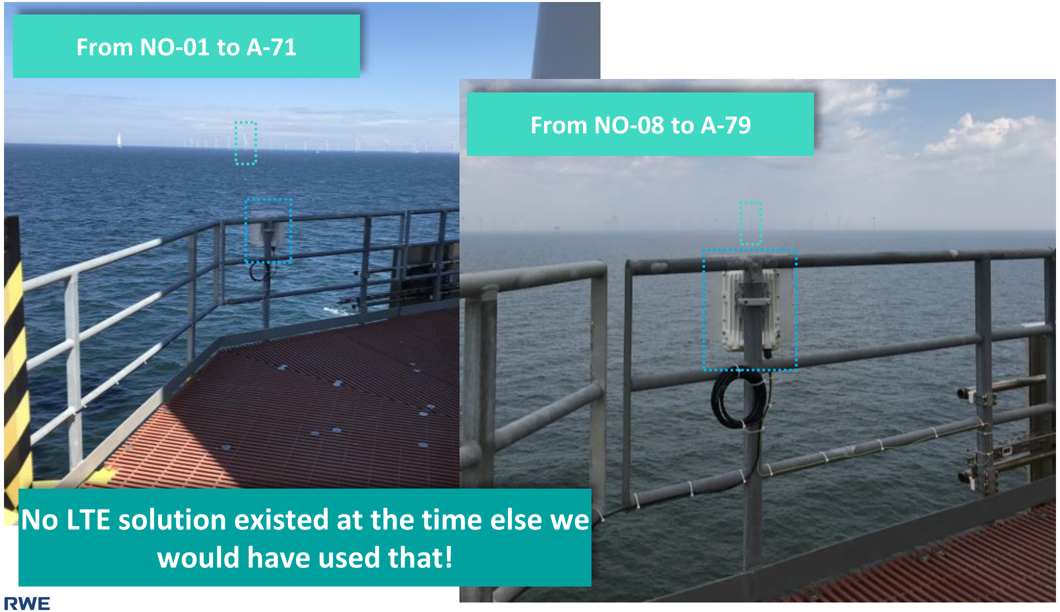
- Time synchronisation.

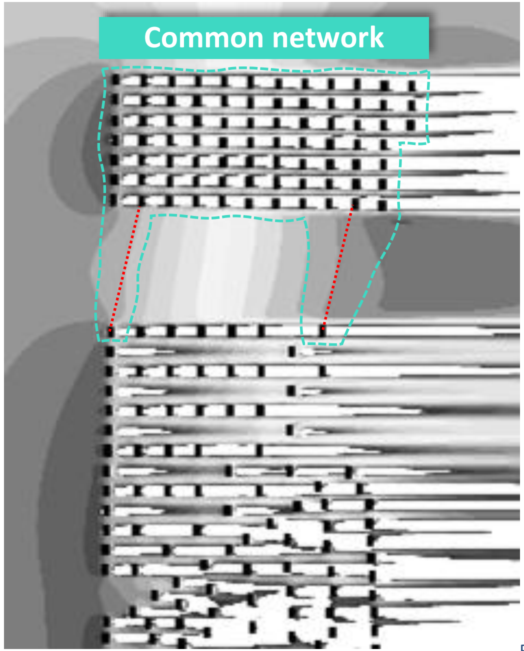
Wind data processing & bias removal

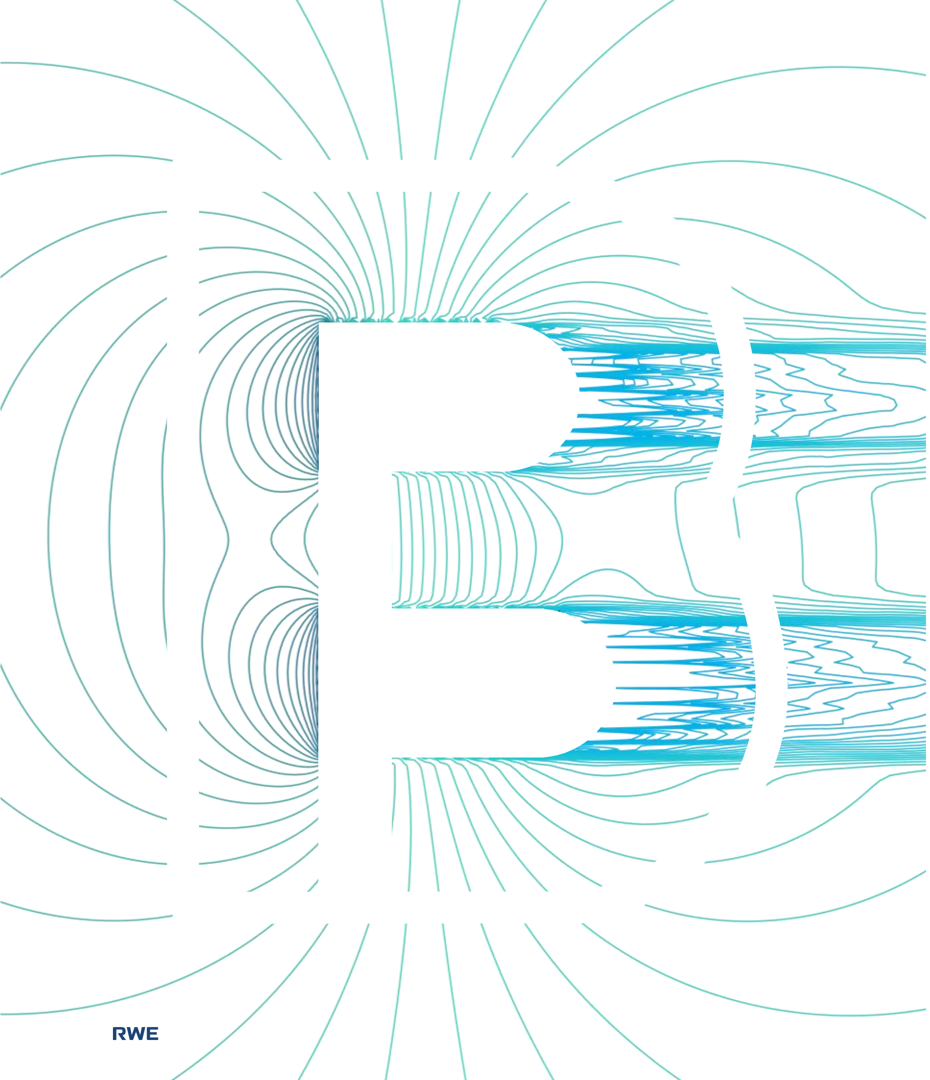
Scanning LiDAR time synchronisation

Provision of bespoke IT infrastructure

- All measurement devices placed on common network and wind farm NTP server for consistent logging, monitoring and time synchronisation.



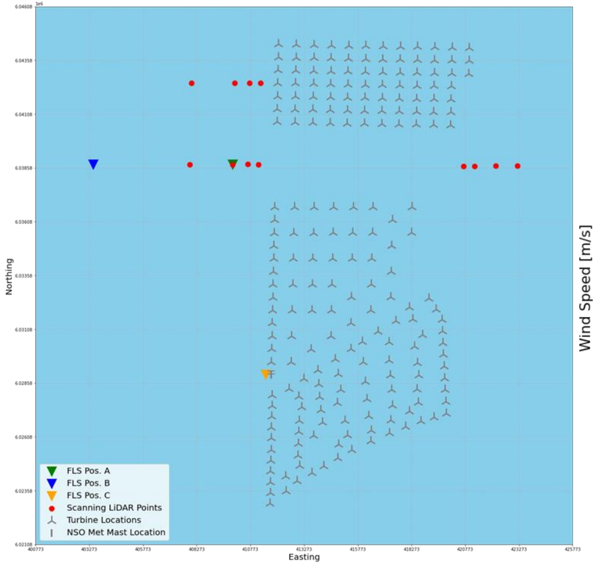


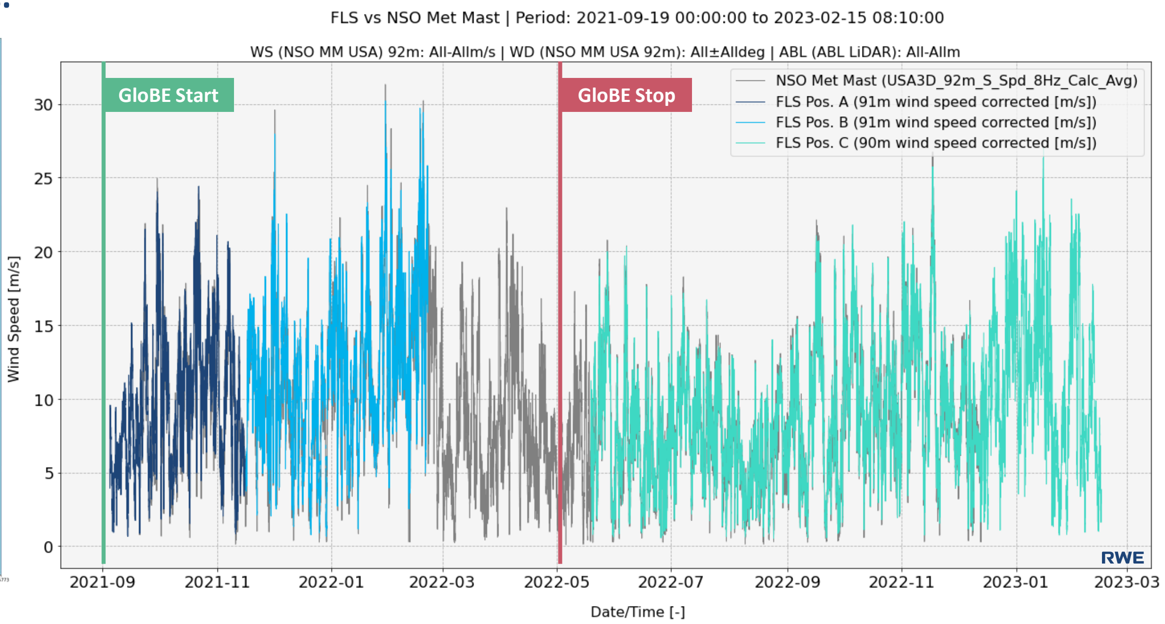


RWE | GLOBE
Global Blockage Effect

Measurement location takin into final analysis

FLS located in 3 positions A, B & C:

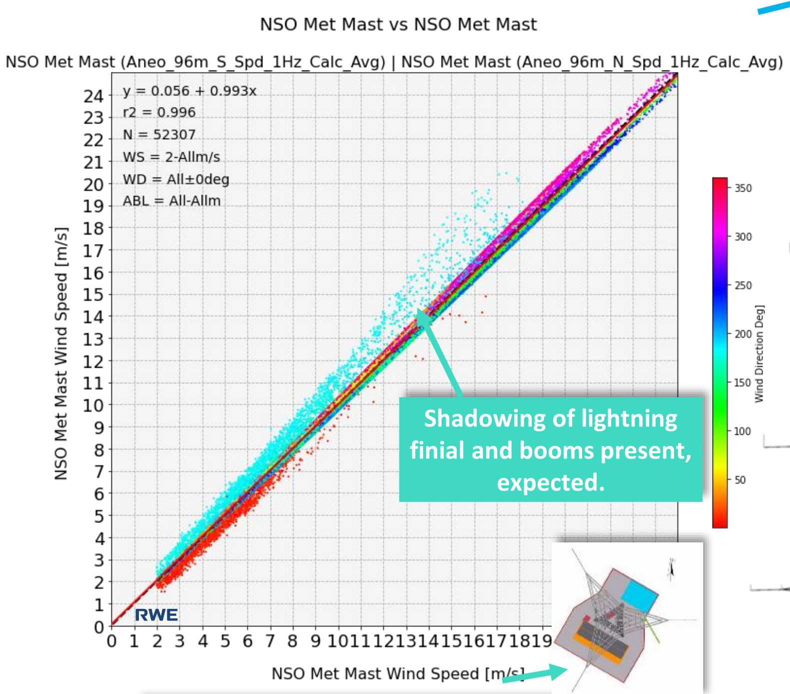


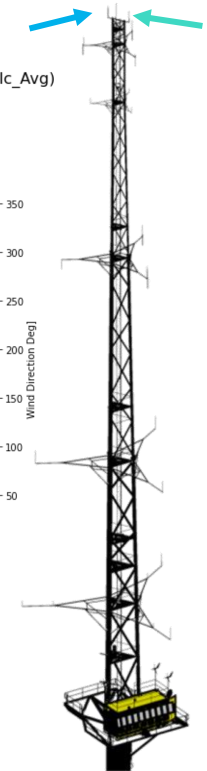


Results & observations

Met mast comparisons

NSO Met Mast Aneo 96m N vs NSO Met Mast Aneo 96m S





Shadowing of lightning finial and booms present, expected.

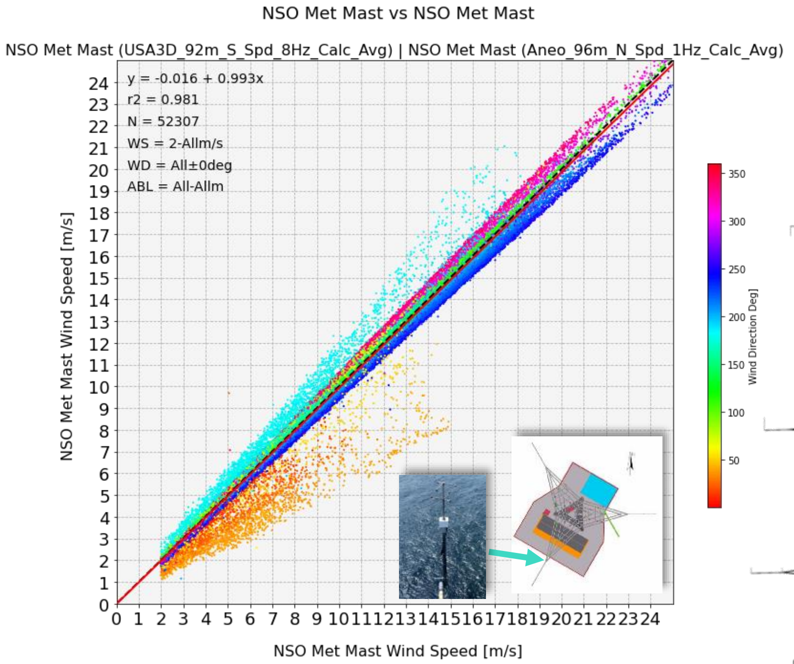
No data cleaning done, completely raw

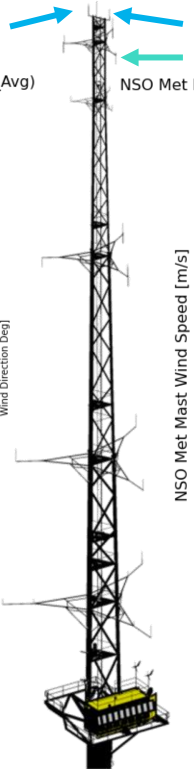
Important note: Met mast data presented is completely raw and un-cleaned. It is used to illustrate regressions and statistical performance of other measurement instrument technologies for context!

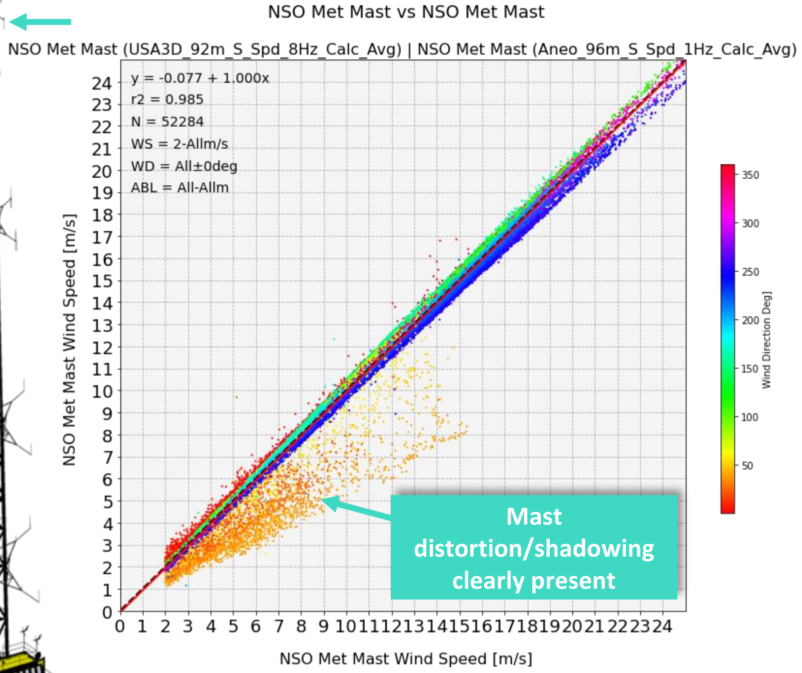
Results & observations

Met mast comparisons

NSO Met Mast Aneo 96m N/S vs NSO Met Mast USA @92m





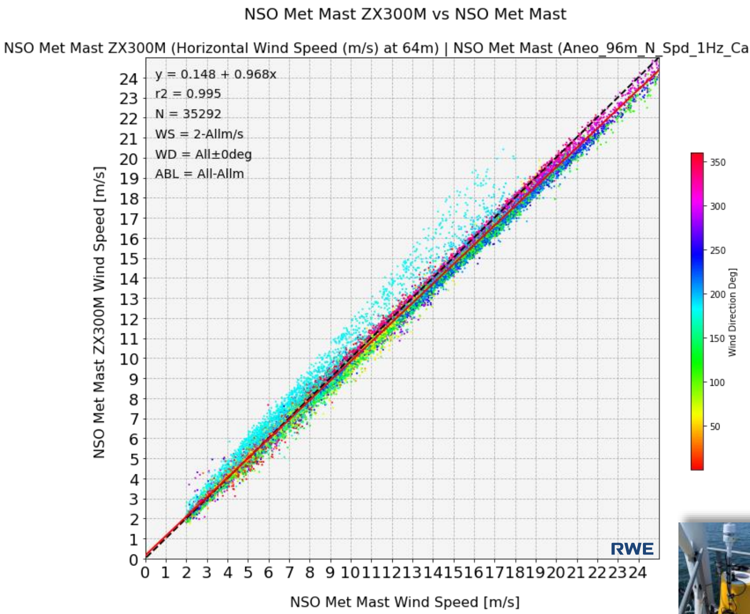


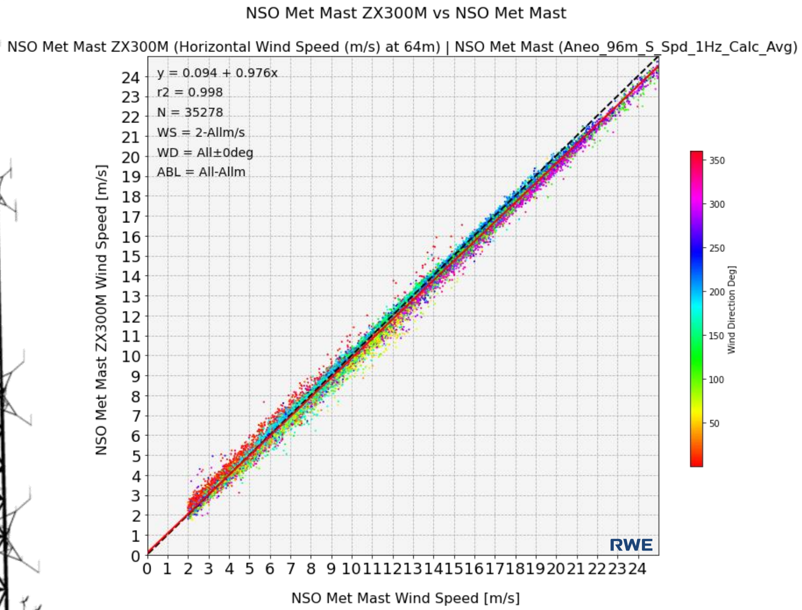
No data cleaning done, completely raw!

Results & observations

Met mast comparisons

NSO Met Mast ZX300M @91m vs NSO Met Mast Aneo 96m N/S



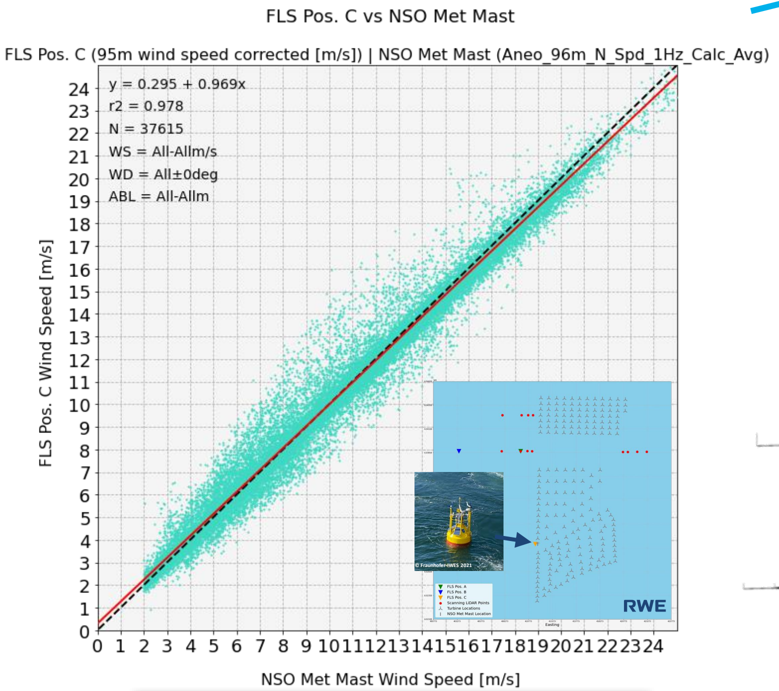


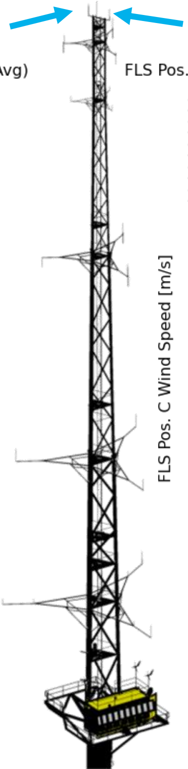
No data cleaning done, completely raw!

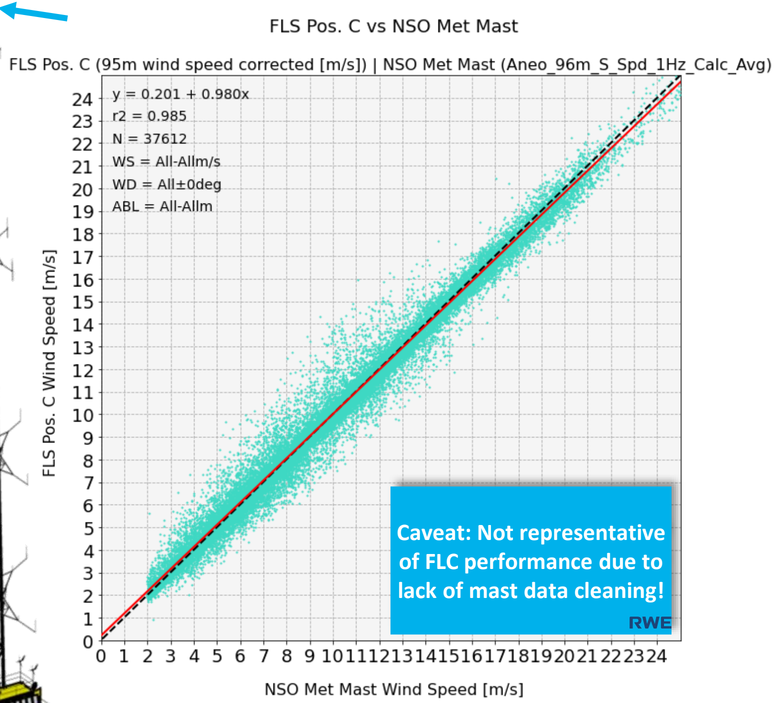
Results & observations

Met mast comparisons

FLS @95m vs NSO Met Mast Aneo N/S @96m





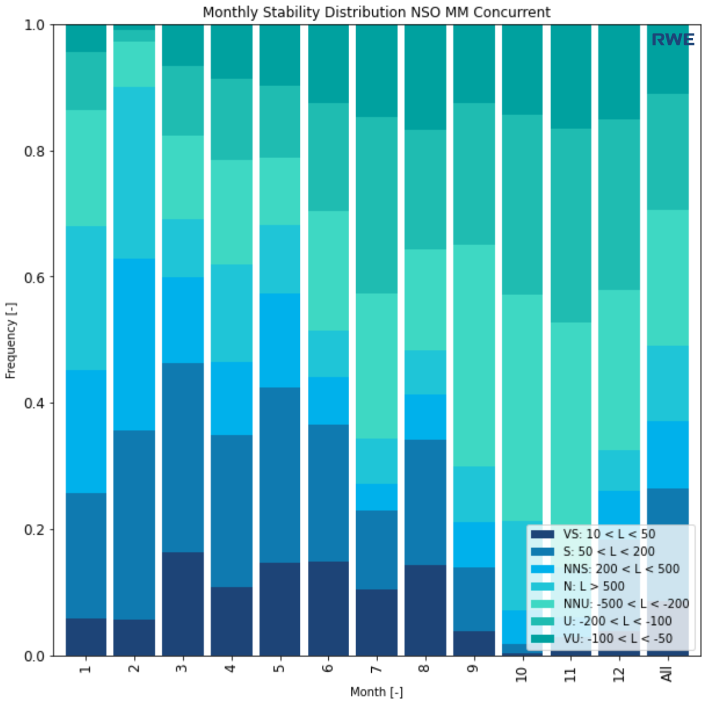


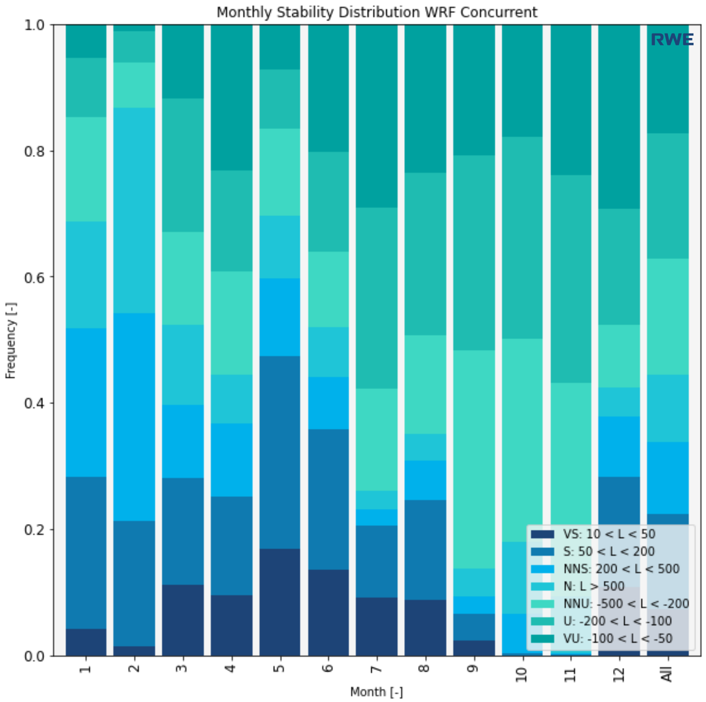
No data cleaning done, completely raw!

Results & observations

Atmospheric stability distributions

Monin-Obukhov Length (MOL) from Different Sources – Measured vs Modelled





Note: MOL dataset calculated & provided by Fraunhofer-IWES through GloBE – X-Wakes cooperation

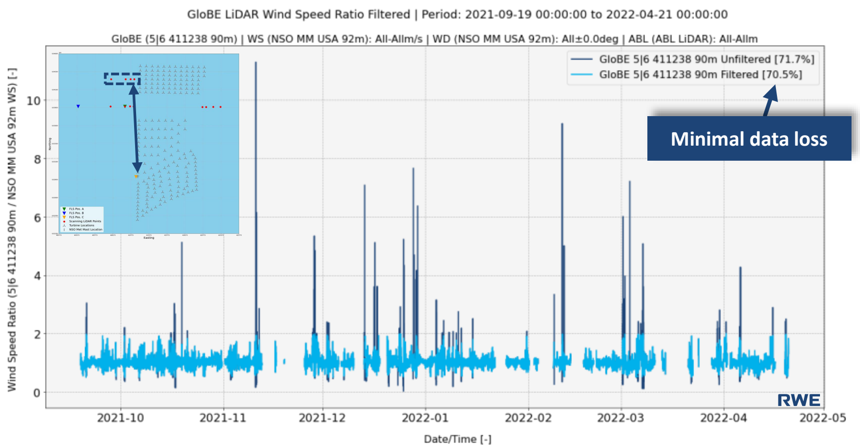
Results & observations

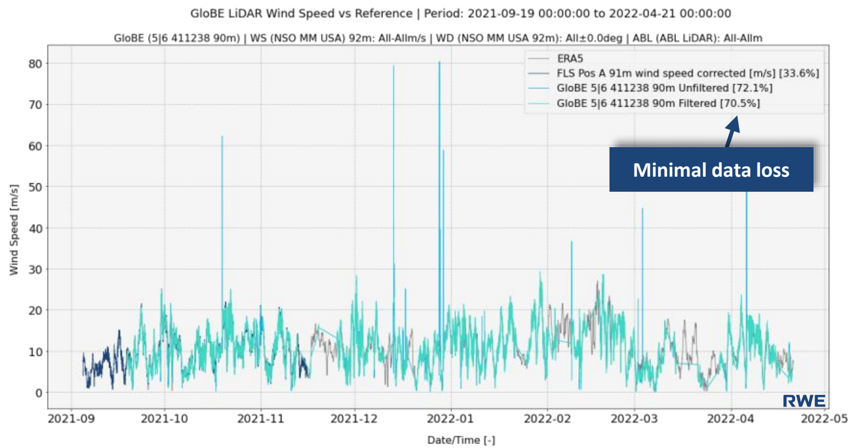
Scanning LiDAR data post-processing

Filtering of Extreme Points / Outliers

Calculate wind speed ratio between DDR point and NSO USA every 10min

Exclude DDR point if ratio is greater than a factor of 2 either direction

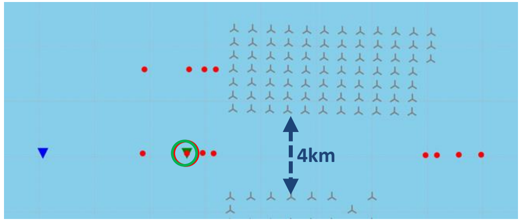




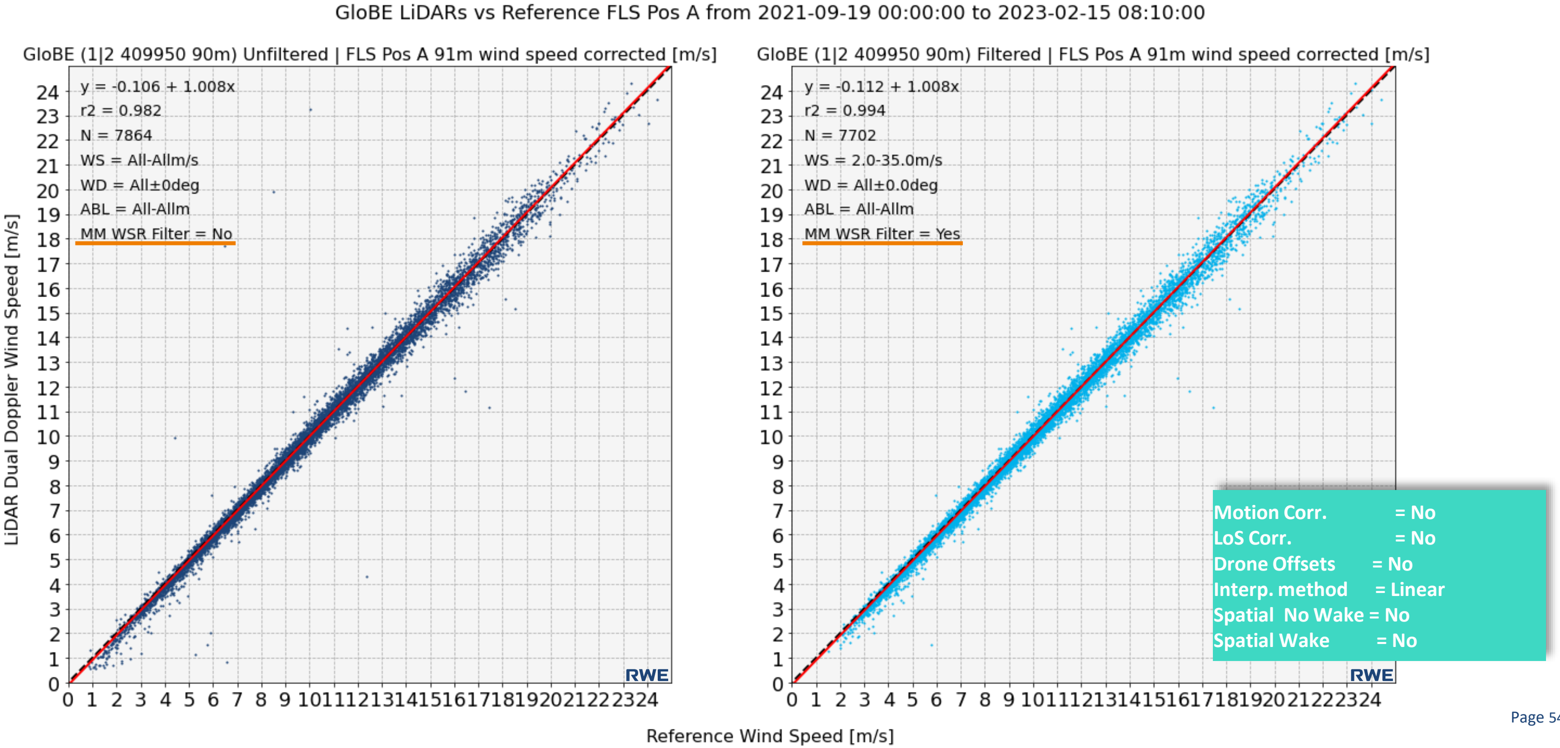
Nearly all upwards ratios, suggesting this is resulting from the motion correction

Results & observations

Impact of correction steps on LiDAR data

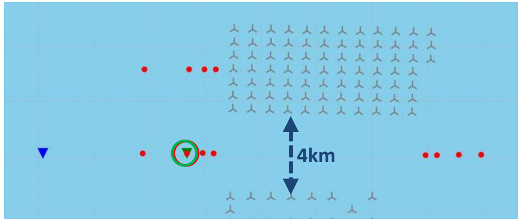


Scanning LiDAR Pair 1|2 Loc. 3 vs FLS Pos A – Wind Speed

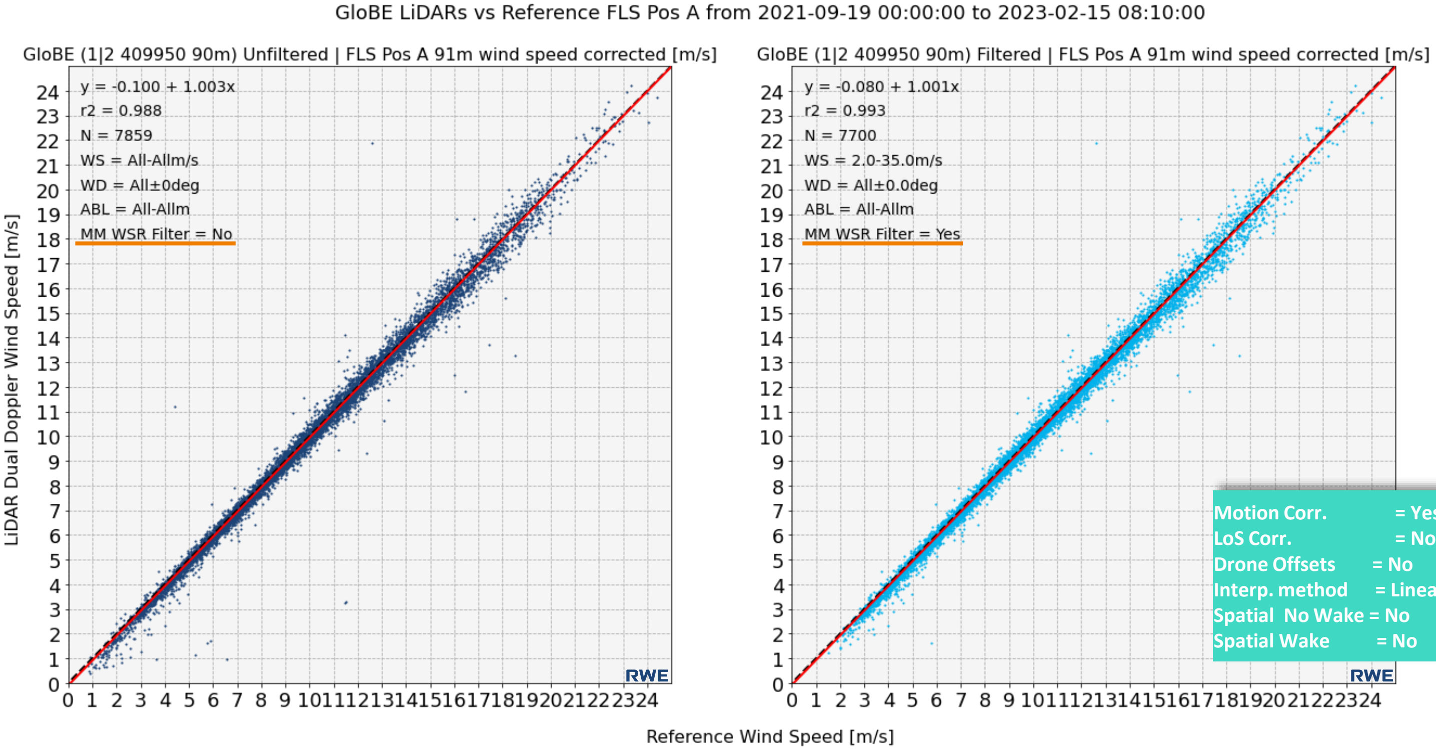


Results & observations

Impact of correction steps on LiDAR data



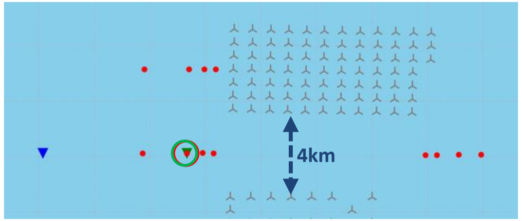
Scanning LiDAR Pair 1|2 Loc. 3 vs FLS Pos A – Wind Speed



Motion Corr. = Yes
LoS Corr. = No
Drone Offsets = No
Interp. method = Linear
Spatial No Wake = No
Spatial Wake = No

Results & observations

Impact of correction steps on LiDAR data



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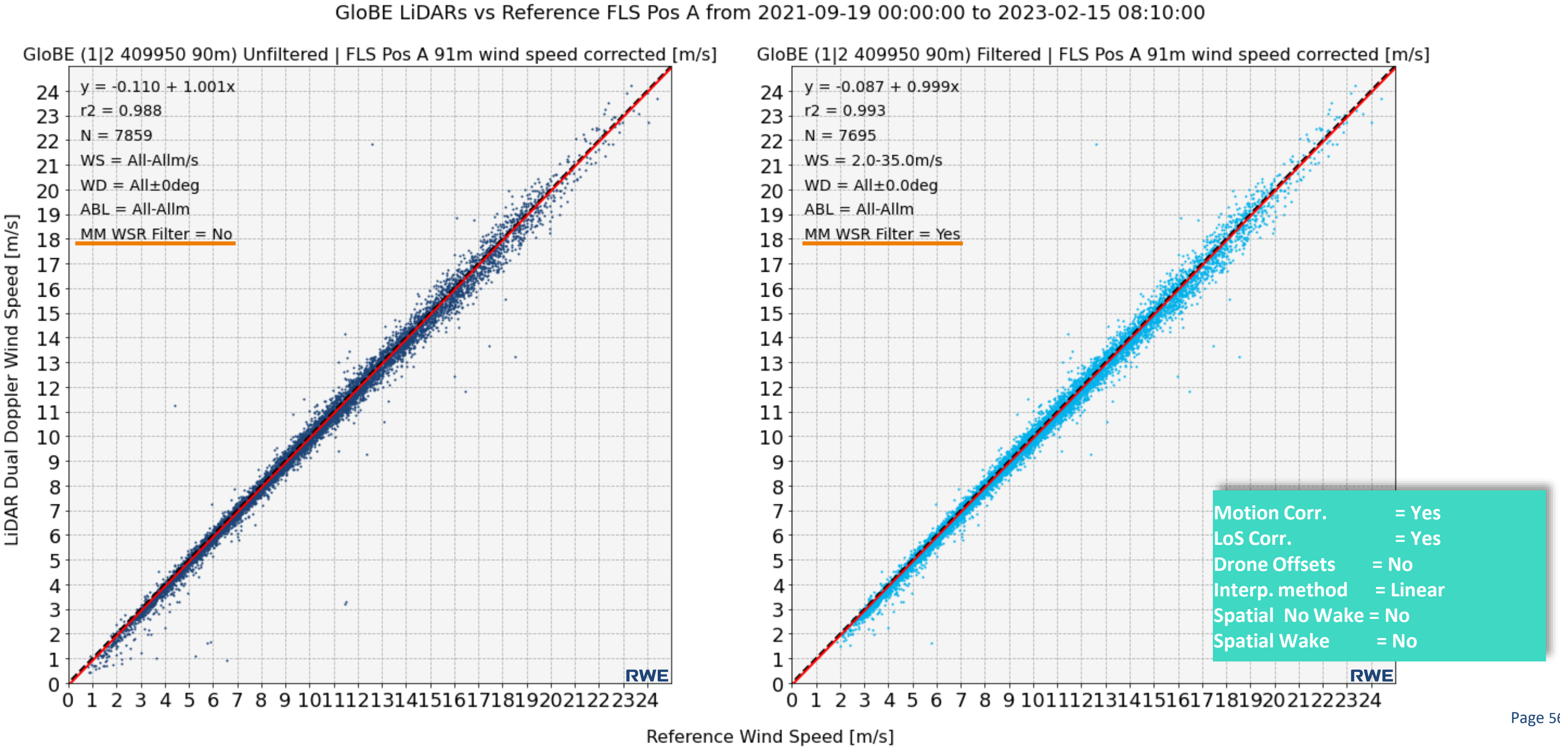
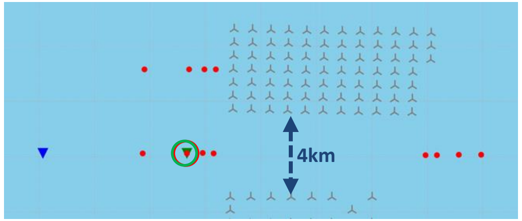


Results & observations

Impact of correction steps on LiDAR data



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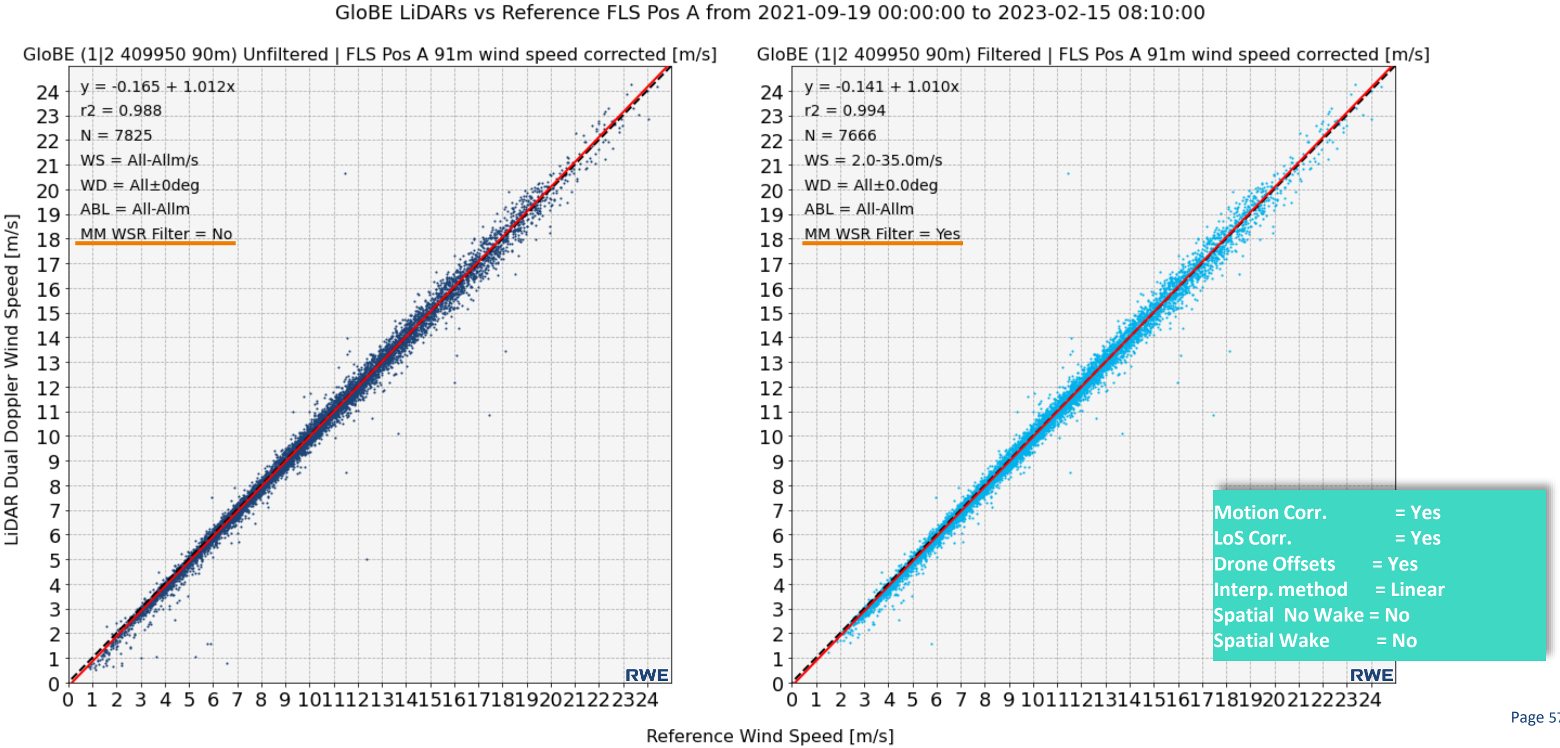
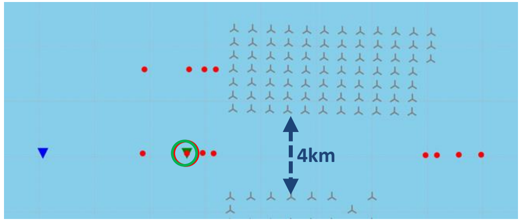
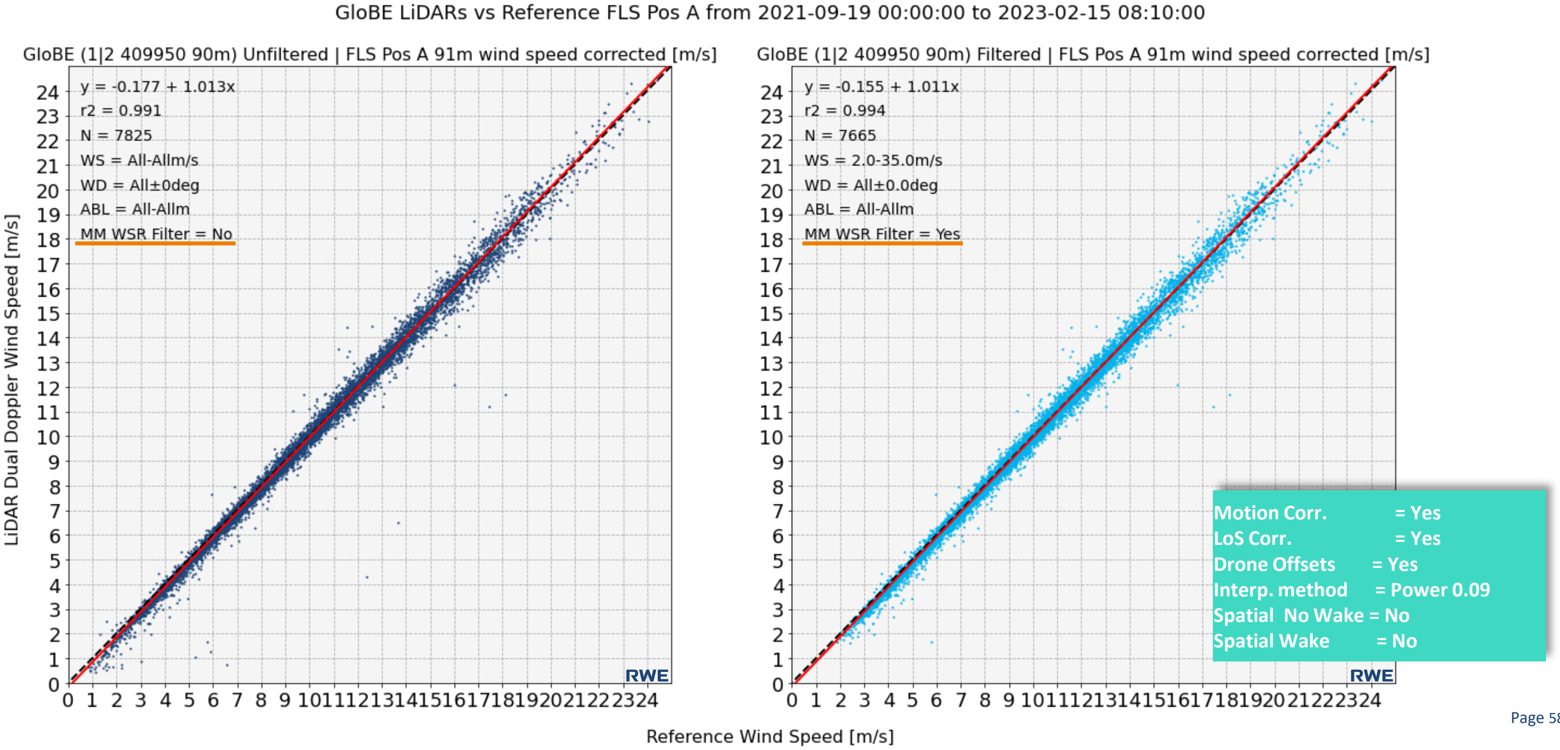


Results & observations

Impact of correction steps on LiDAR data

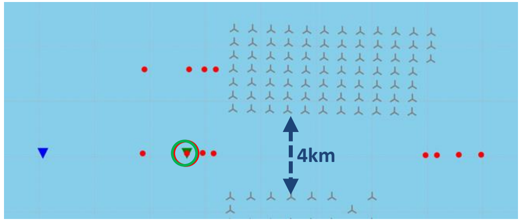


Scanning LiDAR Pair 1|2 Loc. 3 vs FLS Pos A – Wind Speed

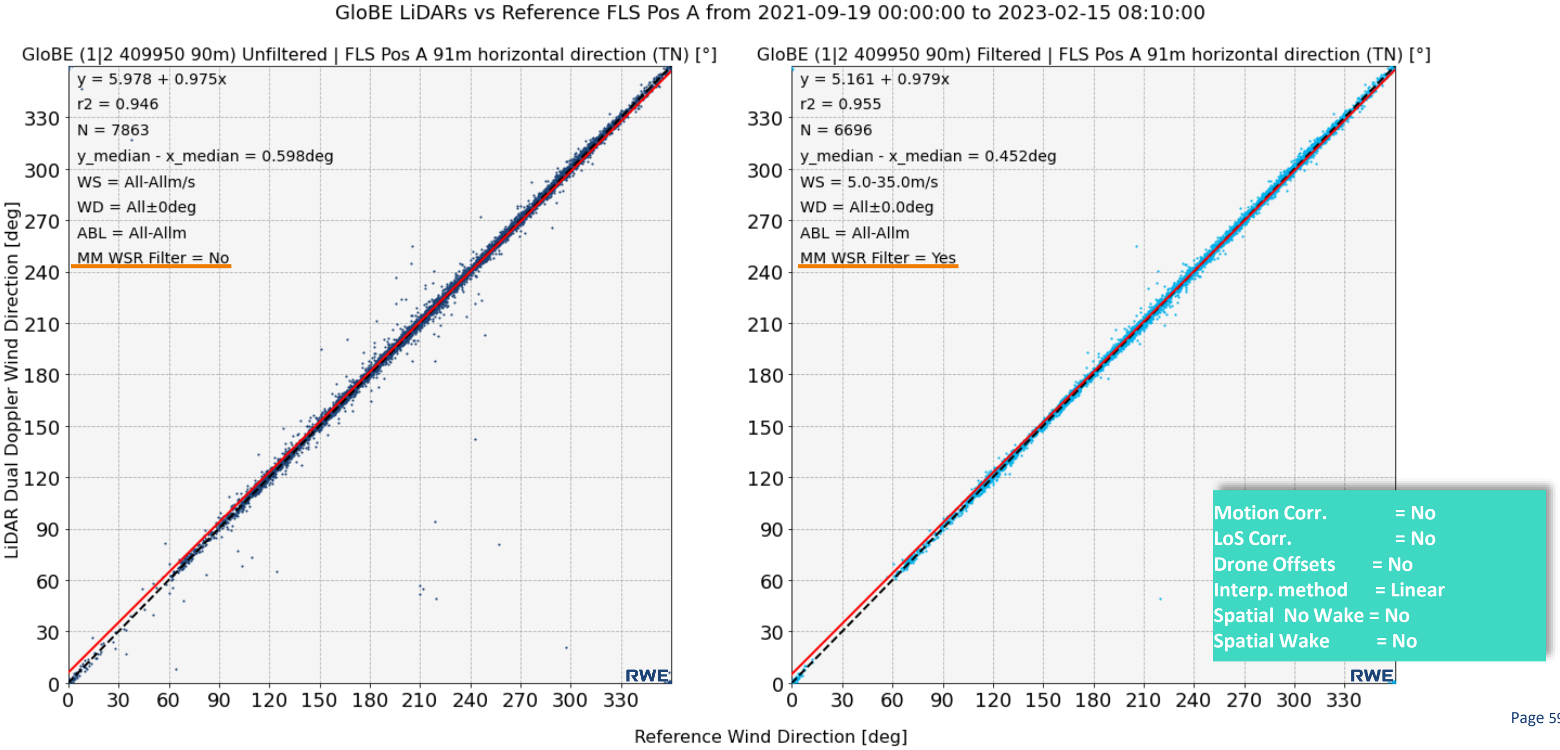


Results & observations

Impact of correction steps on LiDAR data

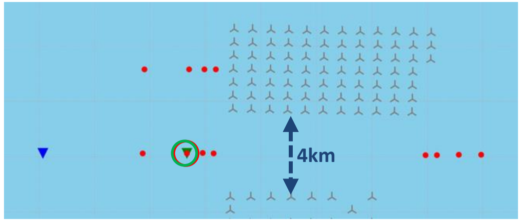


Scanning LiDAR Pair 1|2 Loc. 3 vs FLS Pos A – Wind Direction

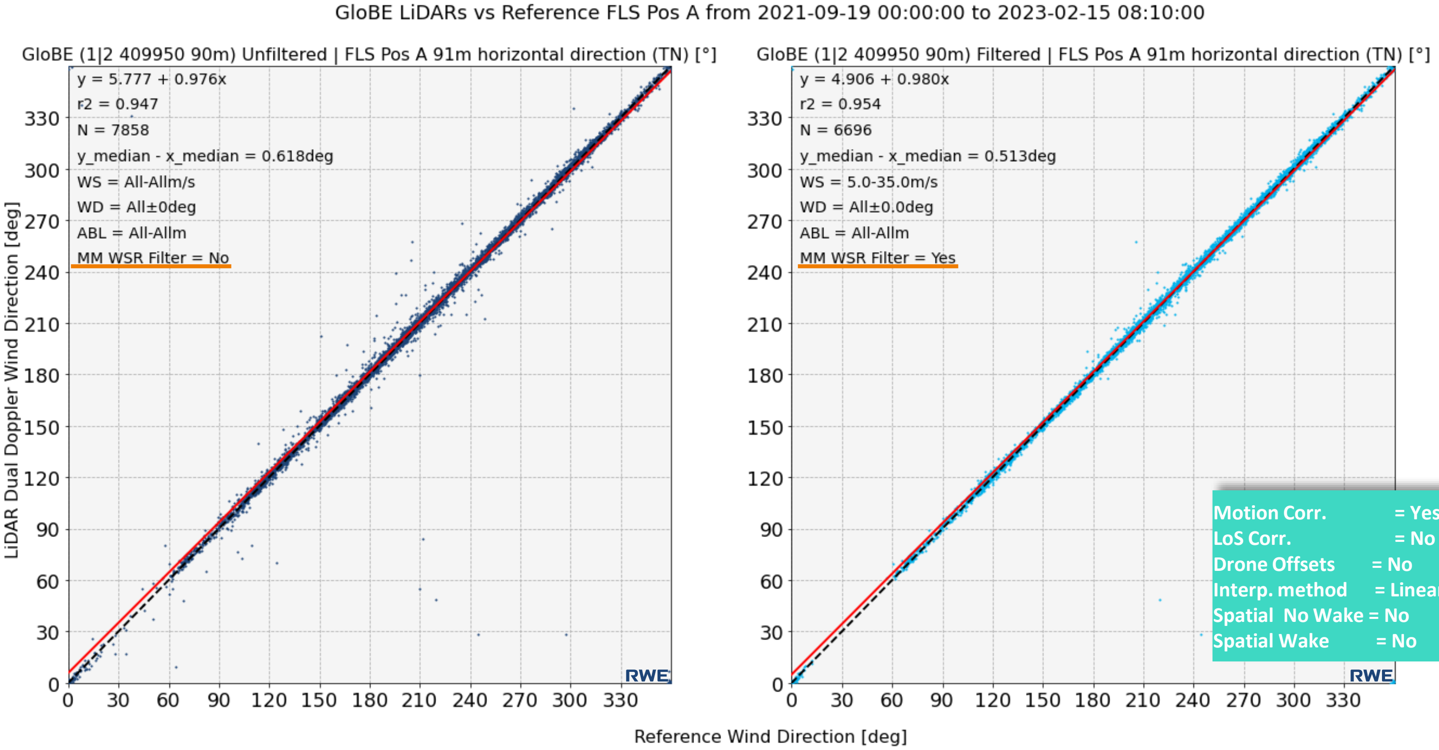


Results & observations

Impact of correction steps on LiDAR data



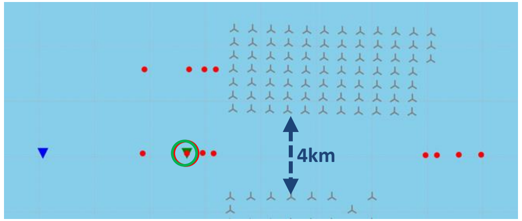
Scanning LiDAR Pair 1|2 Loc. 3 vs FLS Pos A – Wind Direction



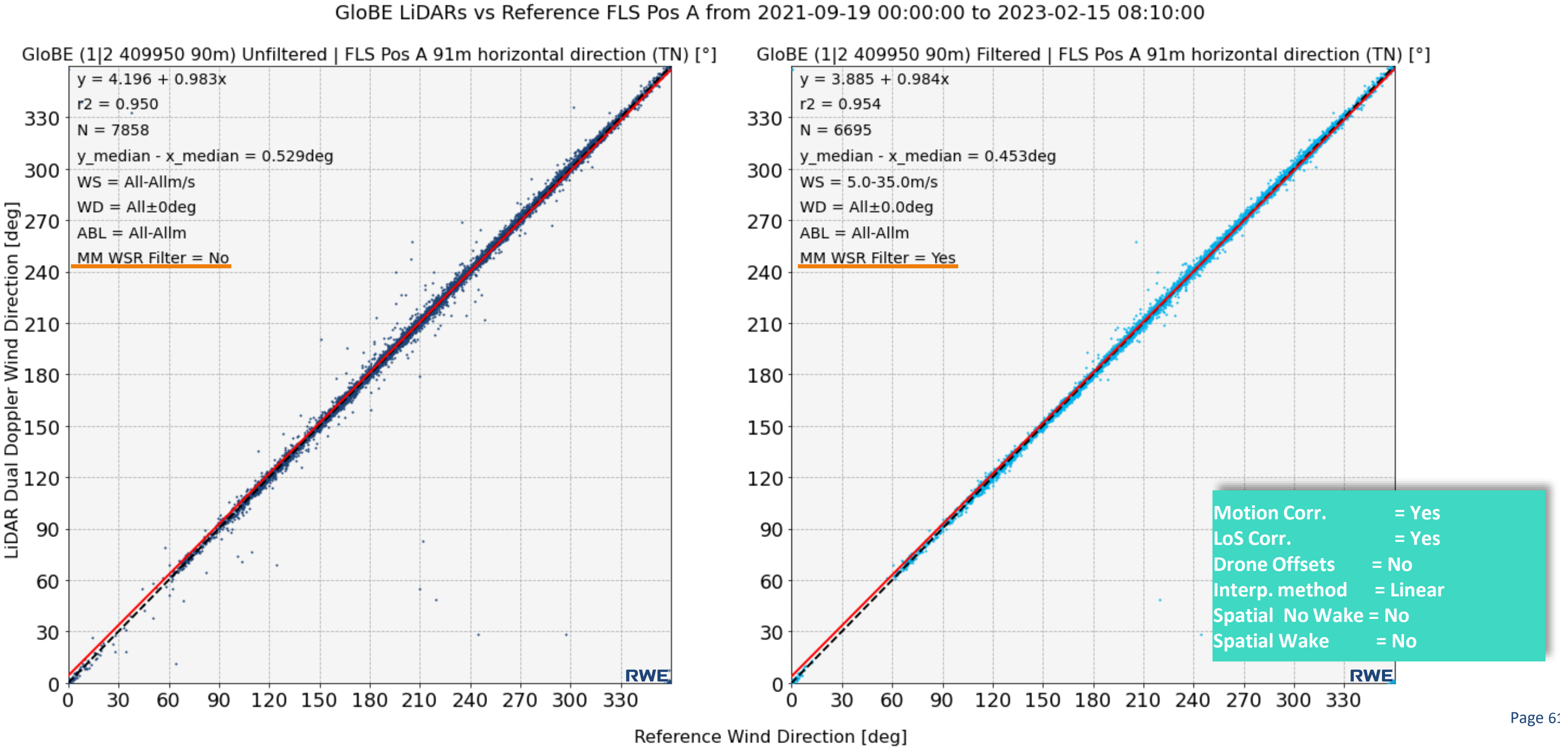
Motion Corr. = Yes
LoS Corr. = No
Drone Offsets = No
Interp. method = Linear
Spatial No Wake = No
Spatial Wake = No

Results & observations

Impact of correction steps on LiDAR data

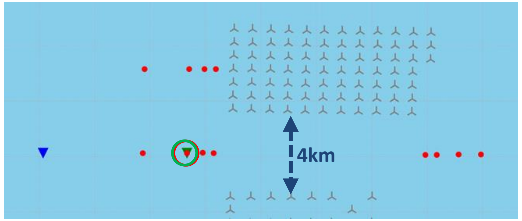


Scanning LiDAR Pair 1|2 Loc. 3 vs FLS Pos A – Wind Direction



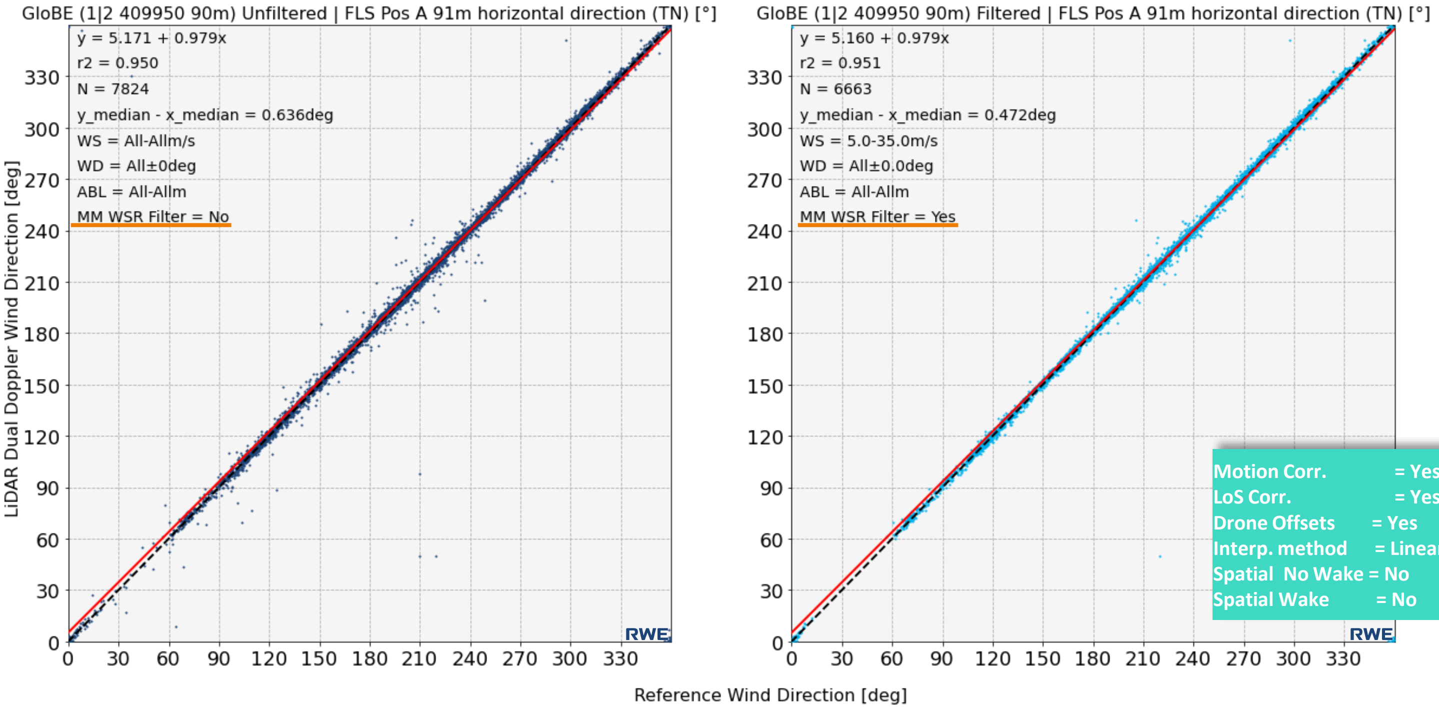
Results & observations

Impact of correction steps on LiDAR data



Scanning LiDAR Pair 1|2 Loc. 3 vs FLS Pos A – Wind Direction

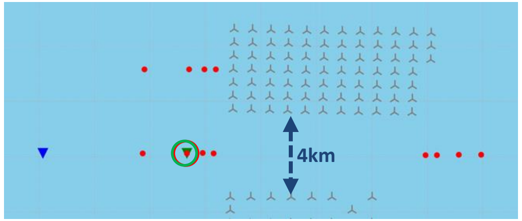
GloBE LiDARs vs Reference FLS Pos A from 2021-09-19 00:00:00 to 2023-02-15 08:10:00



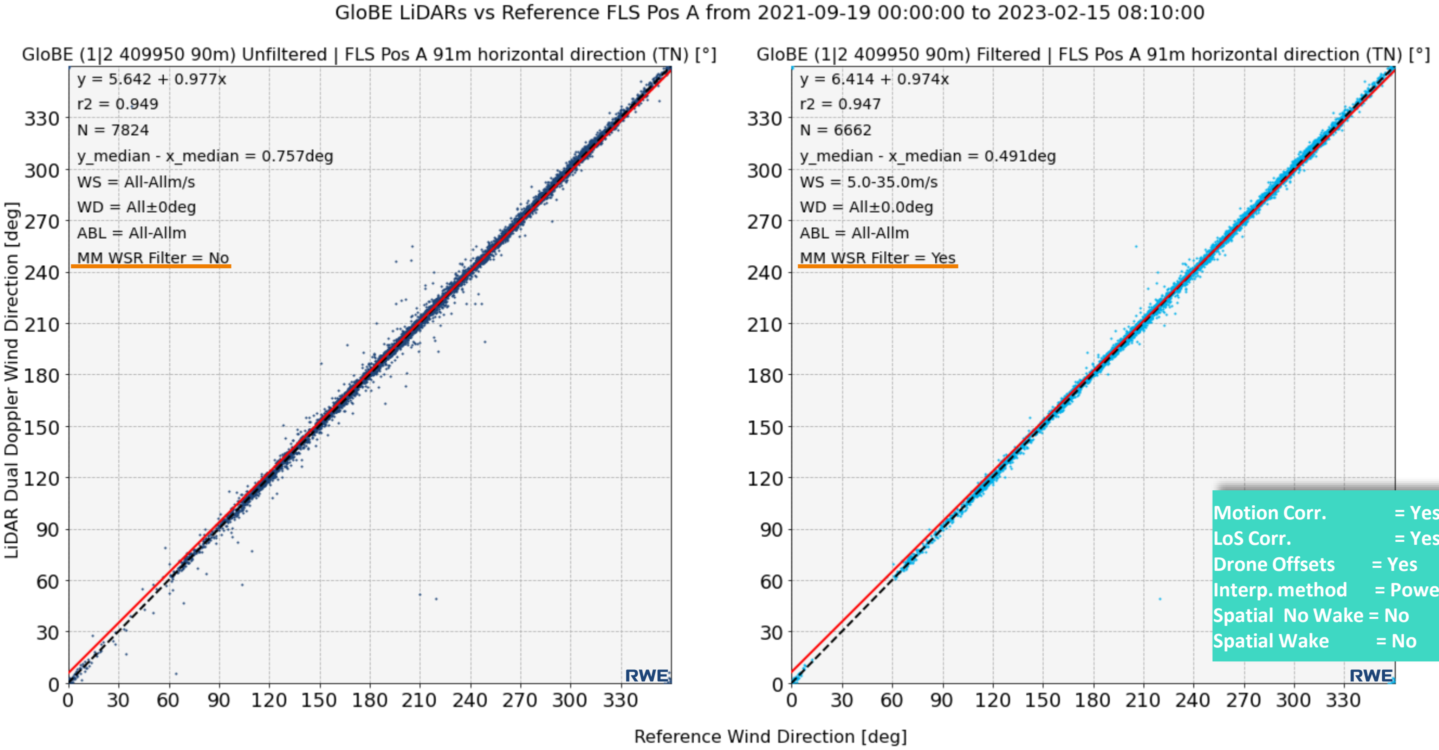
Motion Corr. = Yes
LoS Corr. = Yes
Drone Offsets = Yes
Interp. method = Linear
Spatial No Wake = No
Spatial Wake = No

Results & observations

Impact of correction steps on LiDAR data



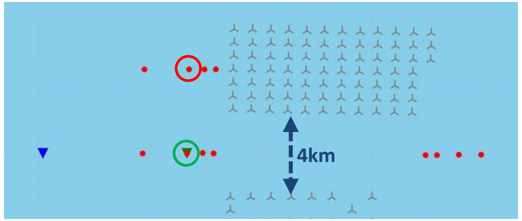
Scanning LiDAR Pair 1|2 Loc. 3 vs FLS Pos A – Wind Direction



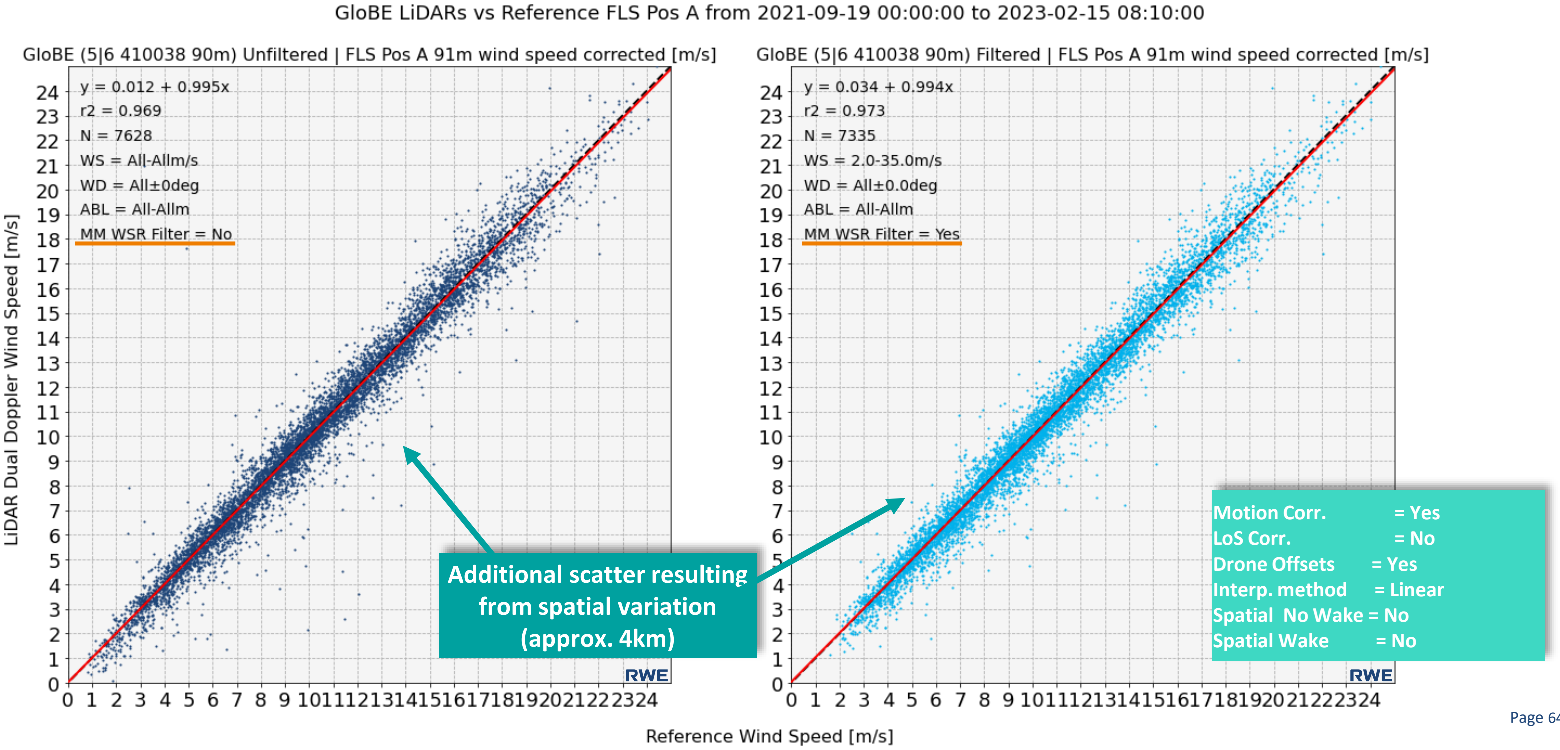
Motion Corr. = Yes
LoS Corr. = Yes
Drone Offsets = Yes
Interp. method = Power 0.09
Spatial No Wake = No
Spatial Wake = No

Results & observations

Impact of correction steps on LiDAR data



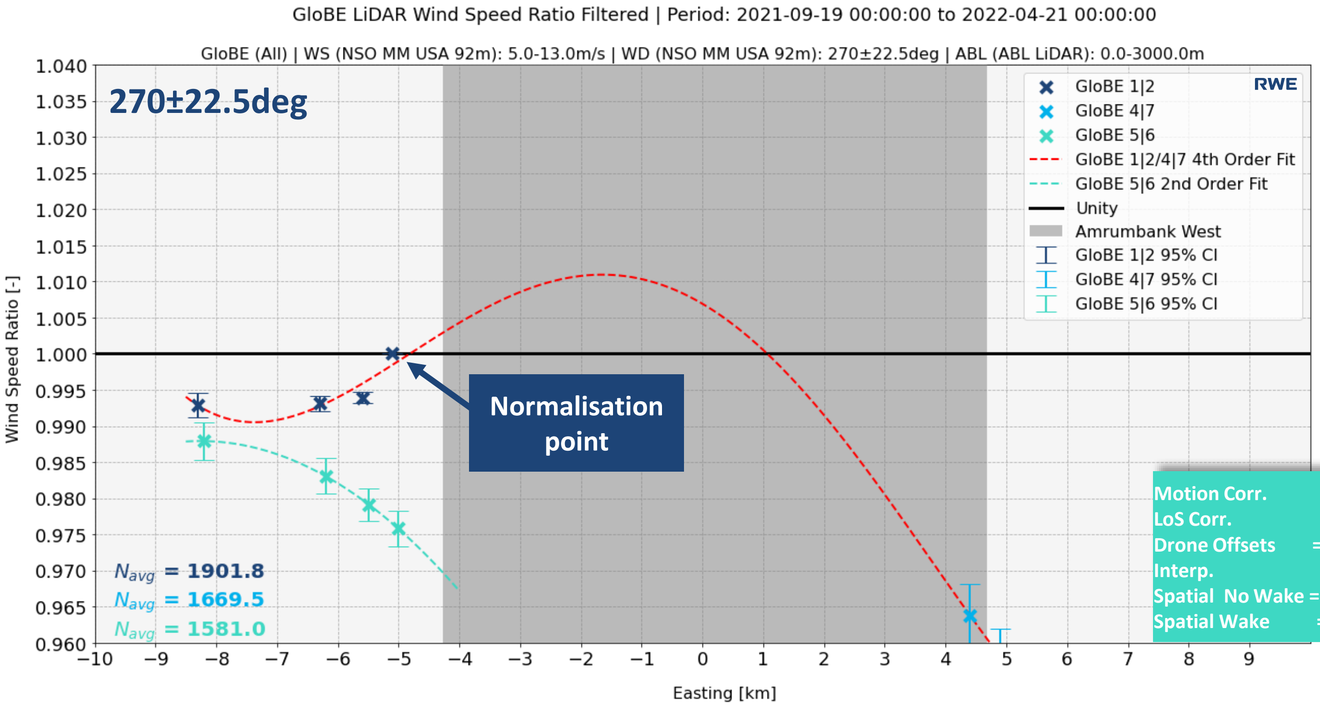
Scanning LiDAR Pair 5|6 Loc. 3 vs FLS Pos A – Wind Speed



Results & observations

Impact of correction steps on blockage observation

Transects upstream of AMK and "Kaskasi gap"

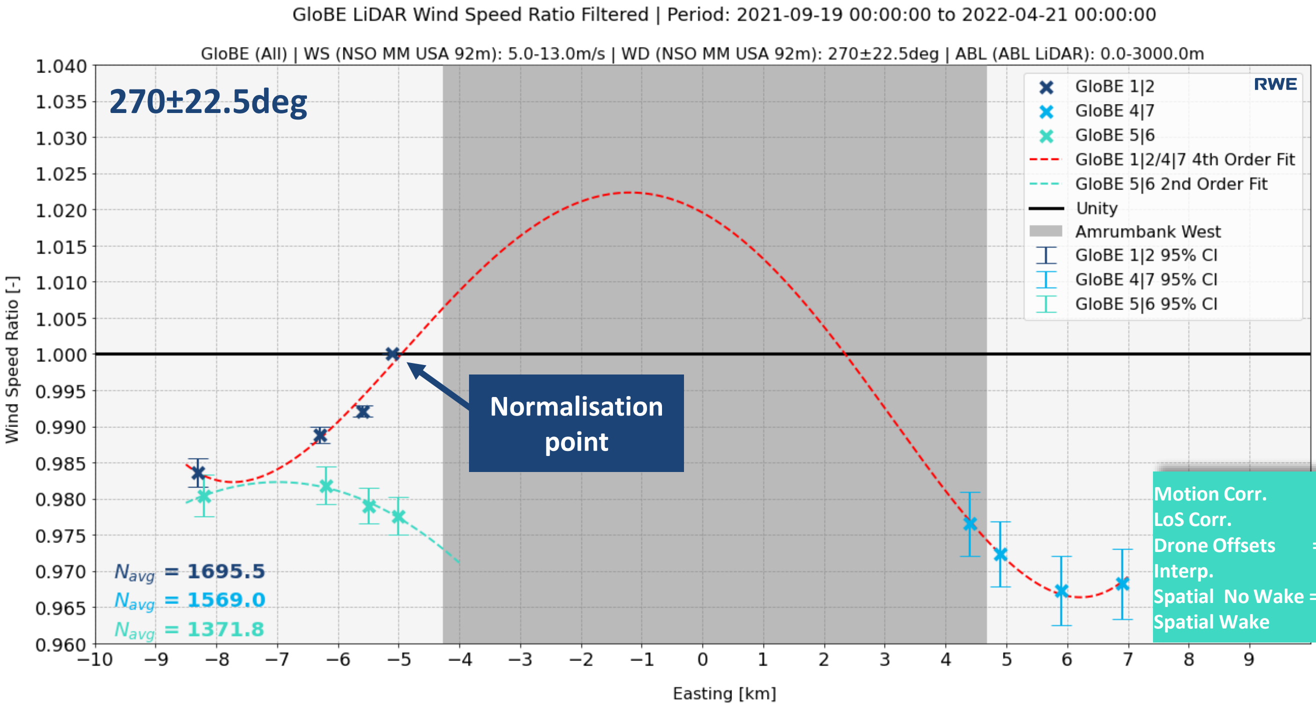


Motion Corr. = No
LoS Corr. = No
Drone Offsets = No
Interp. = Linear
Spatial No Wake = No
Spatial Wake = No

Results & observations

Impact of correction steps on blockage observation

Transects upstream of AMK and "Kaskasi gap"

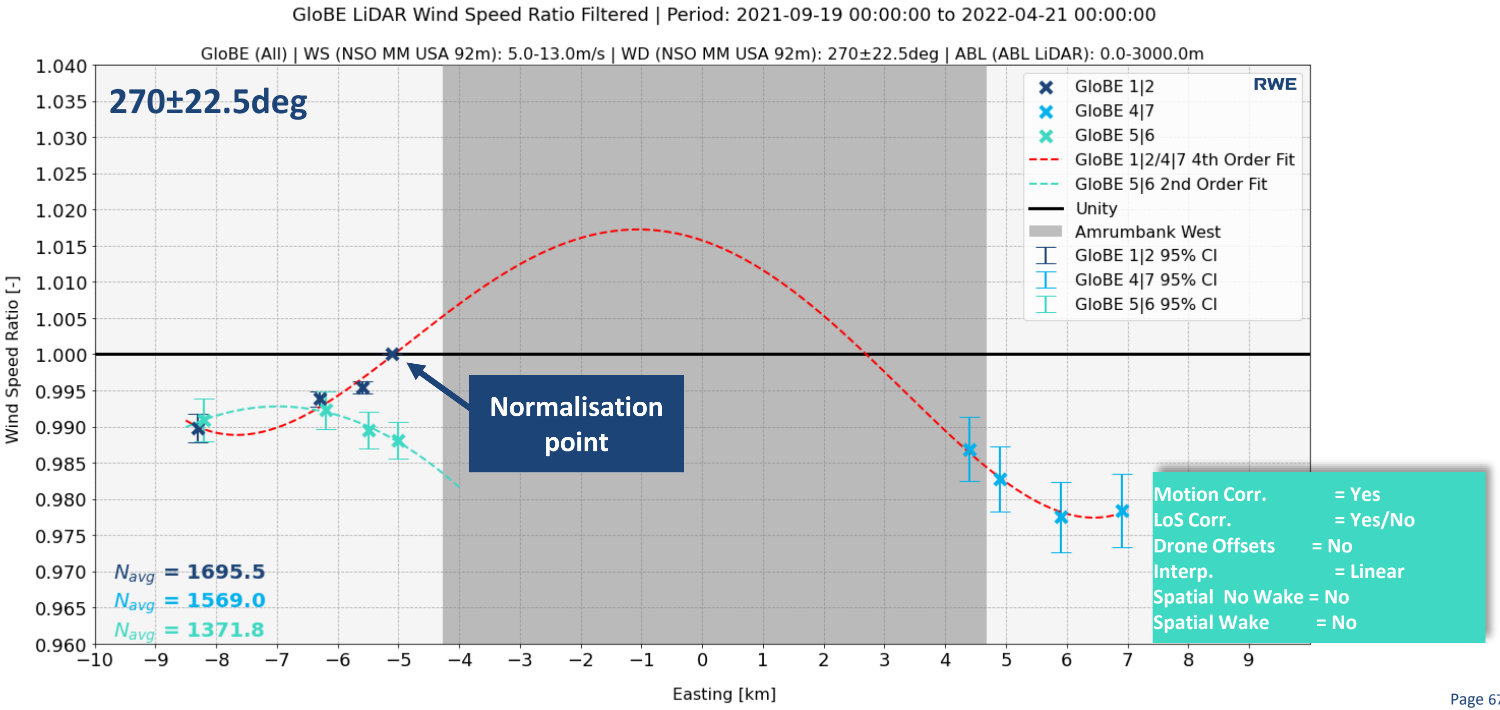


Motion Corr. = Yes
LoS Corr. = No
Drone Offsets = No
Interp. = Linear
Spatial No Wake = No
Spatial Wake = No

Results & observations

Impact of correction steps on blockage observation

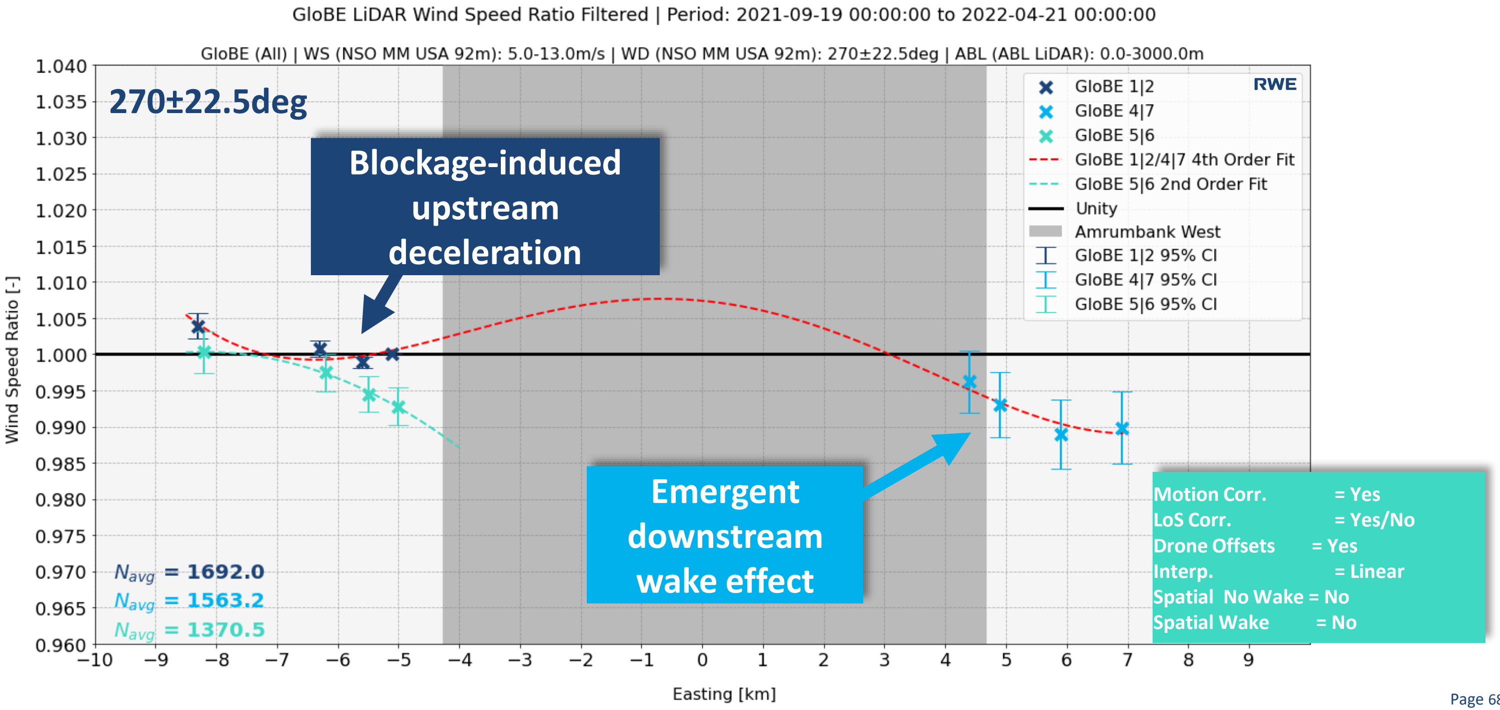
Transects upstream of AMK and "Kaskasi gap"



Results & observations

Impact of correction steps on blockage observation

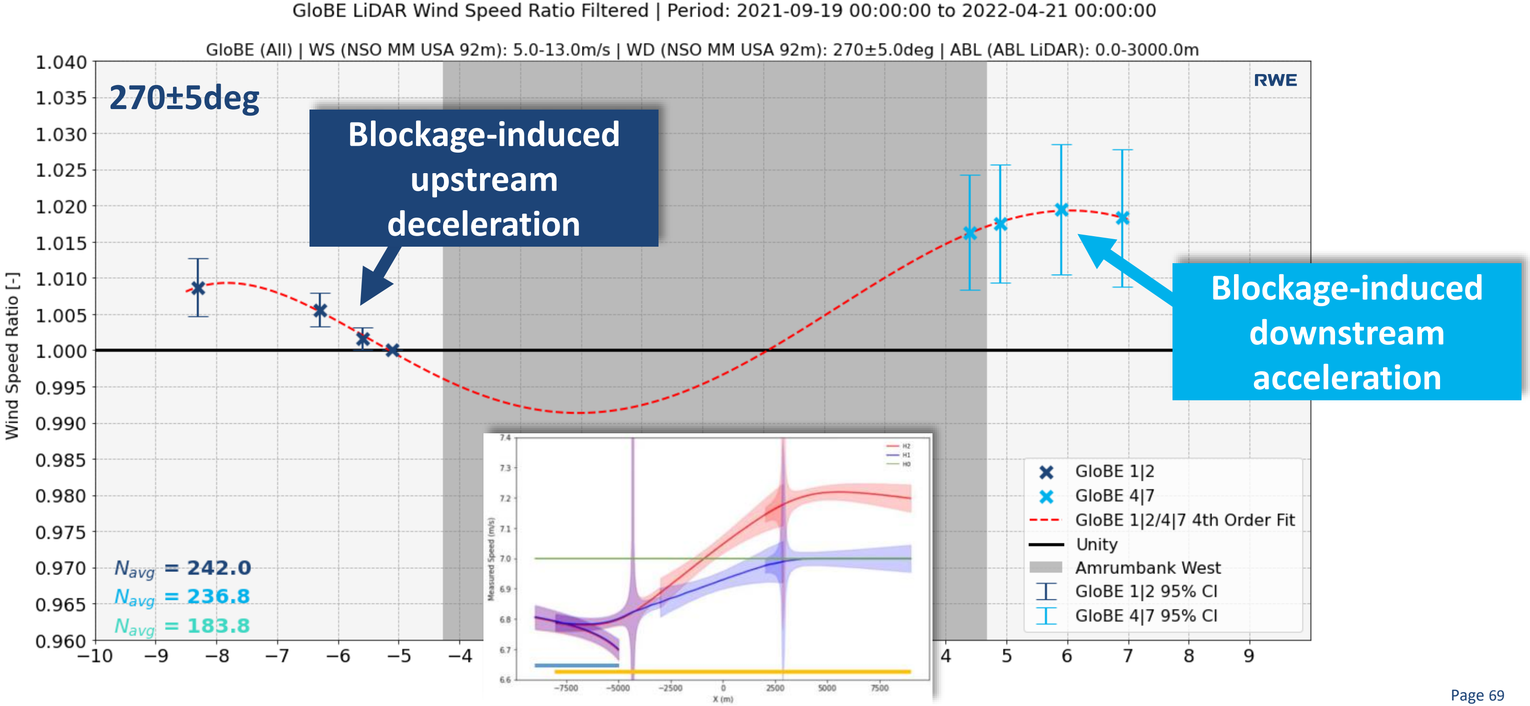
Transects upstream of AMK and "Kaskasi gap"



Results & observations

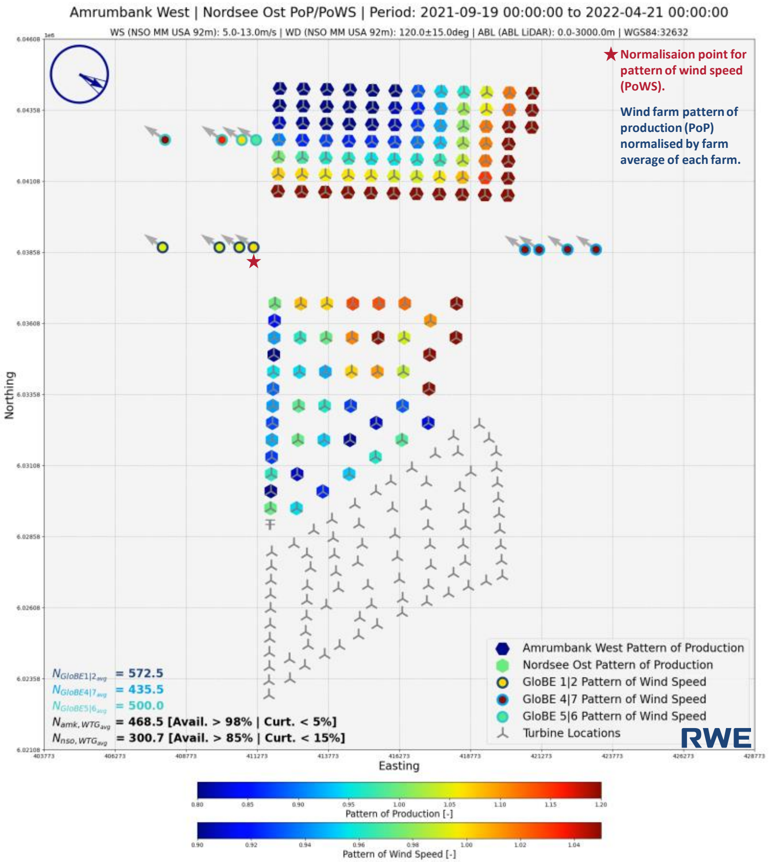
Blockage-induced speedups

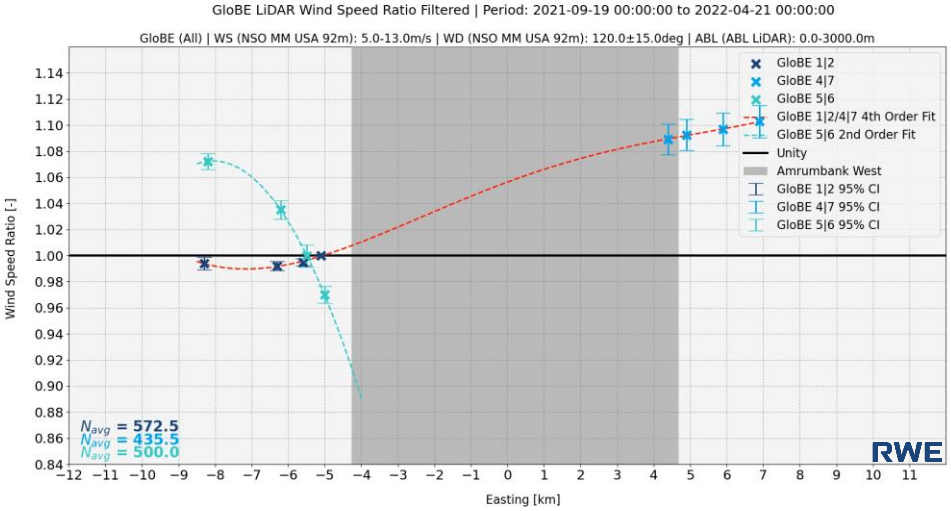
“Kaskasi gap” Transect Only



Results & observations

Pattern of wind speed & power





Assuming

Final dataset inc. all corrections

WS bin: 5-13m/s

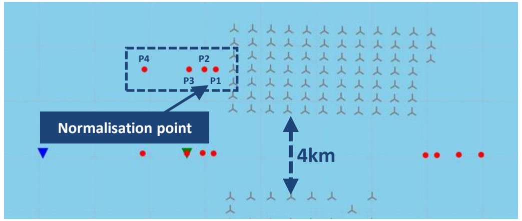
WD range: 120-360deg in 0.5deg increments

WD bin: x±15deg

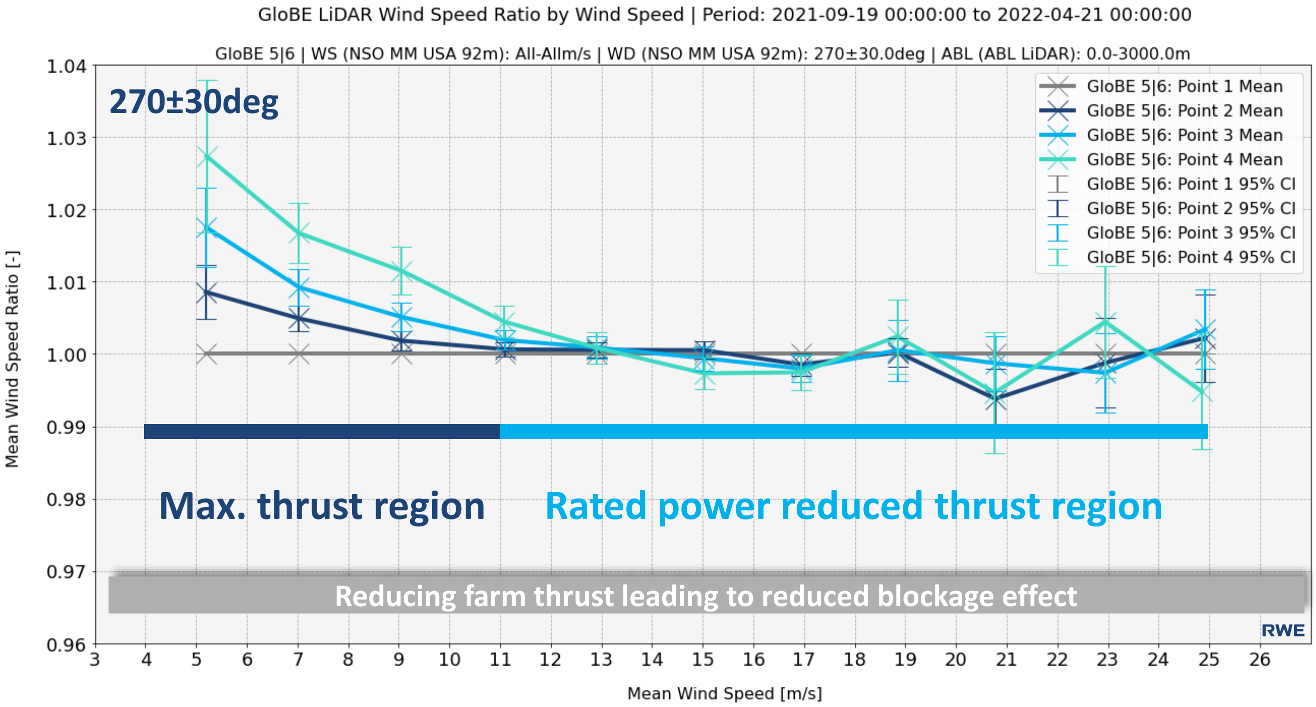
ABL: 0-3000m

Results & observations

Wind gradients by wind speed



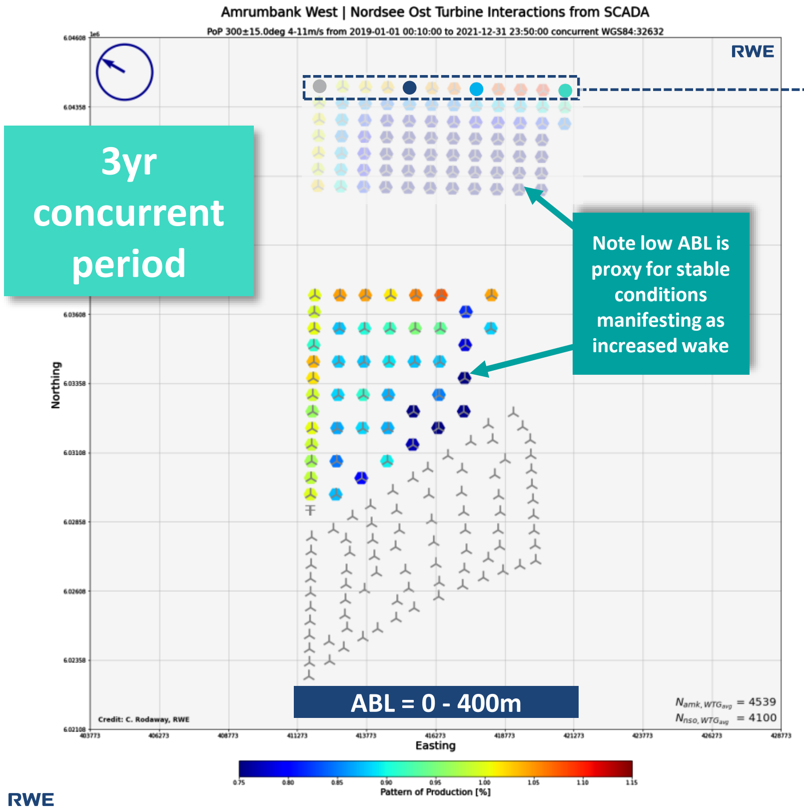
Trends by Wind Speed – Pair 5|6

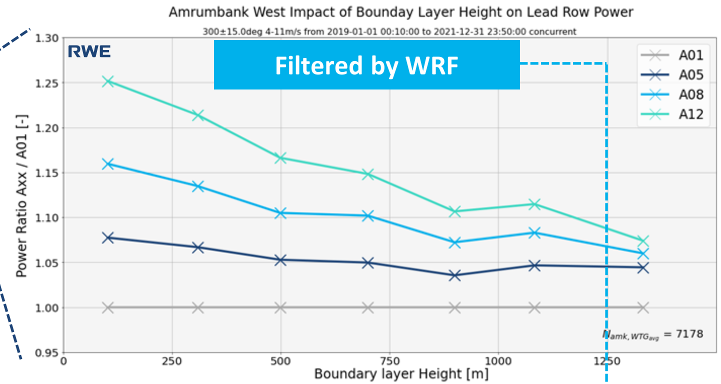


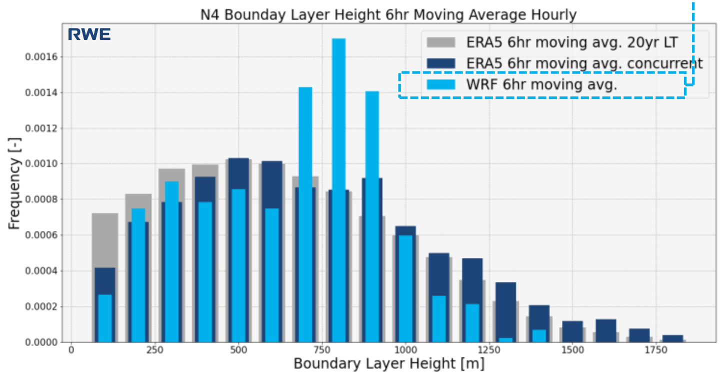
Results & observations

Impact of boundary layer height on pattern of production

GLoBE Global Blockage Effect



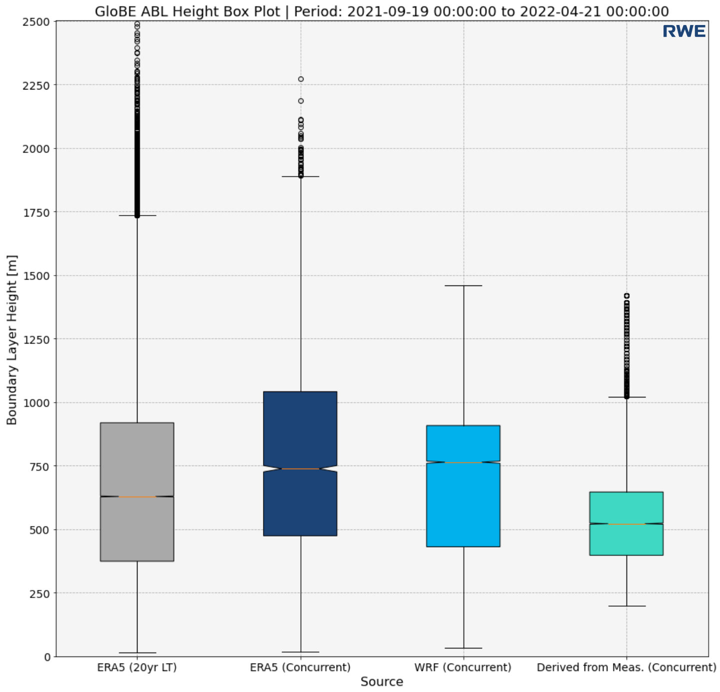




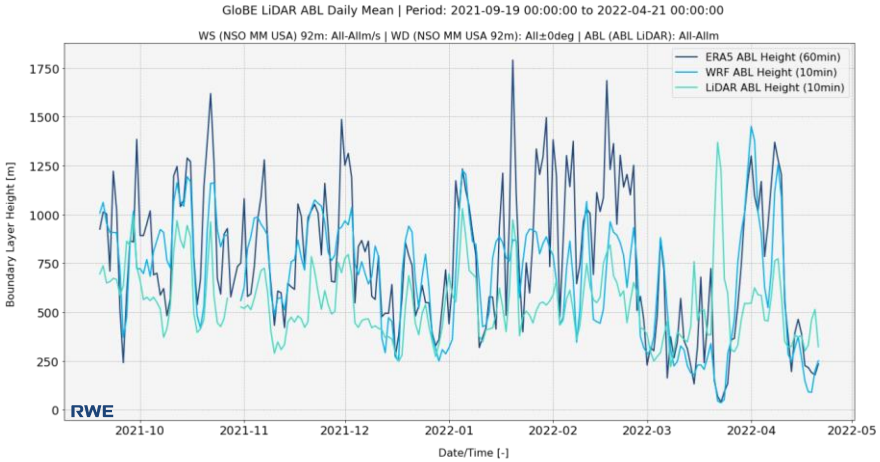
Results & observations

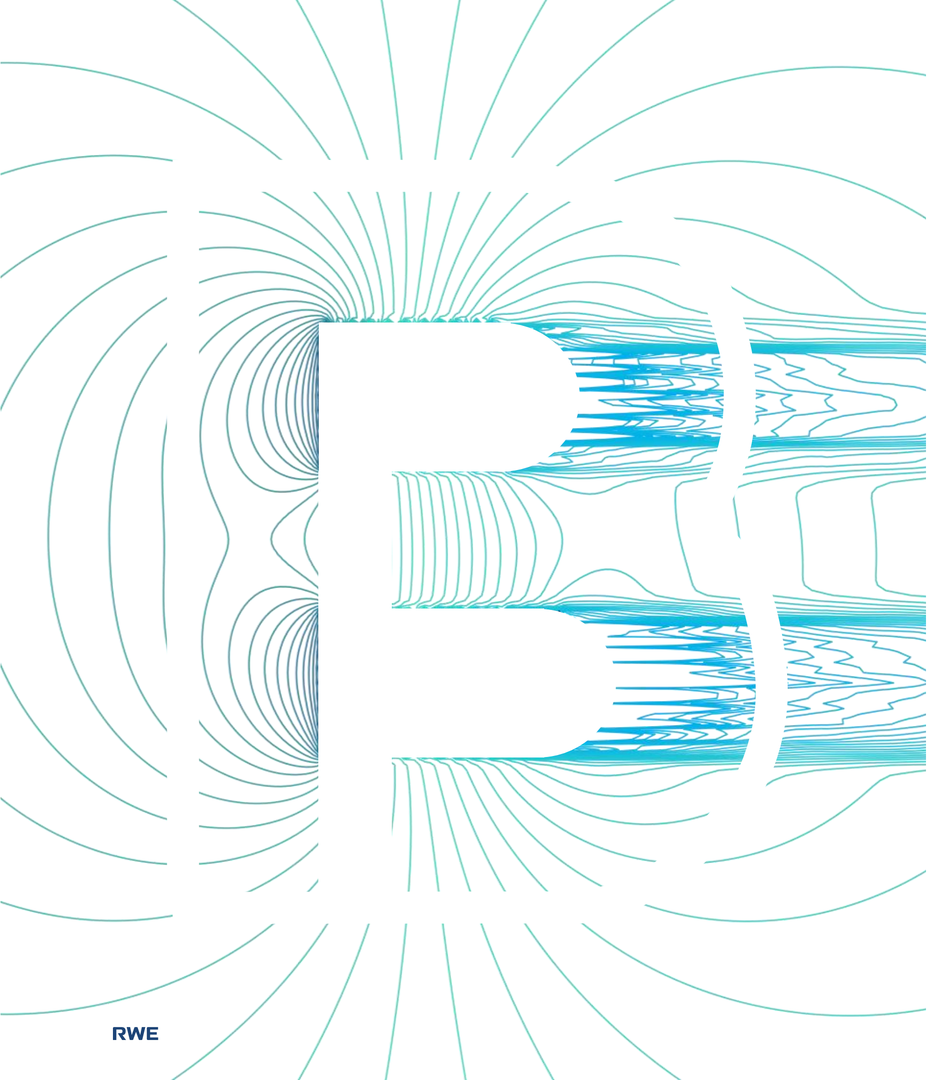
Comparisons of ABL height

Boundary layer heigh from different sources



Boundary layer height derived from measurement shows lower median and tighter distribution than modelled alternatives e.g. WRF or ERA5.





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Conclusions

Has GloBE achieved its goals?

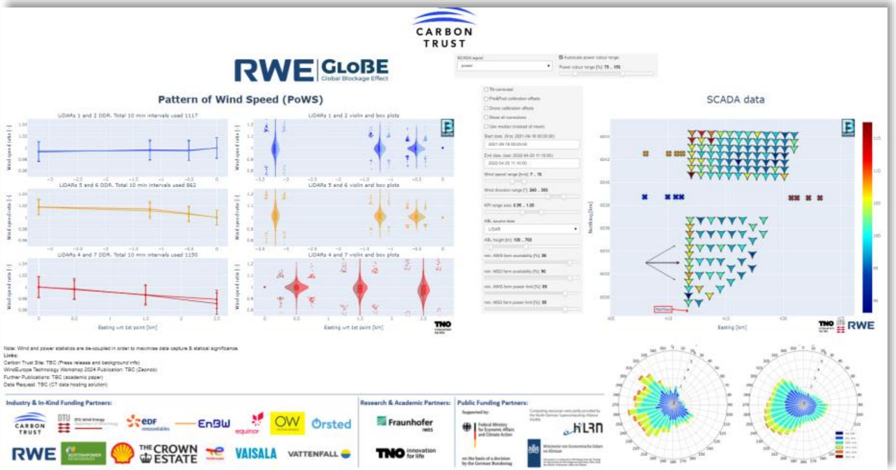
Mission Accomplished!

- GloBE has successfully executed (probably) the **largest single measurement campaign** (and certainly one of the most complex!) ever run offshore.
- Significant **known sources of bias** have been **identified, corrected and controlled** for to produce the most robust dataset possible at current technological limits.
- **New & novel techniques** have been used to ensure that we are left with a statistically meaningful blockage observation.
- **Wind and turbine operational data have been brought together** and processed to enable delineation of blockage.
- Measurements & observations alone are not enough to describe the impact of blockage, **modelling also required** → In the next webinar session!

Conclusions
“GloBE Dashboard” release

GloBE Dashboard

Scan me or go to https://globe-serving.tnodatalab.nl



Credentials

URL: https://globe-serving.tnodatalab.nl

USR: globe

PWD: GlobeCampaignDash!

Conclusions

Session 2: Modelling and accountancy of blockage

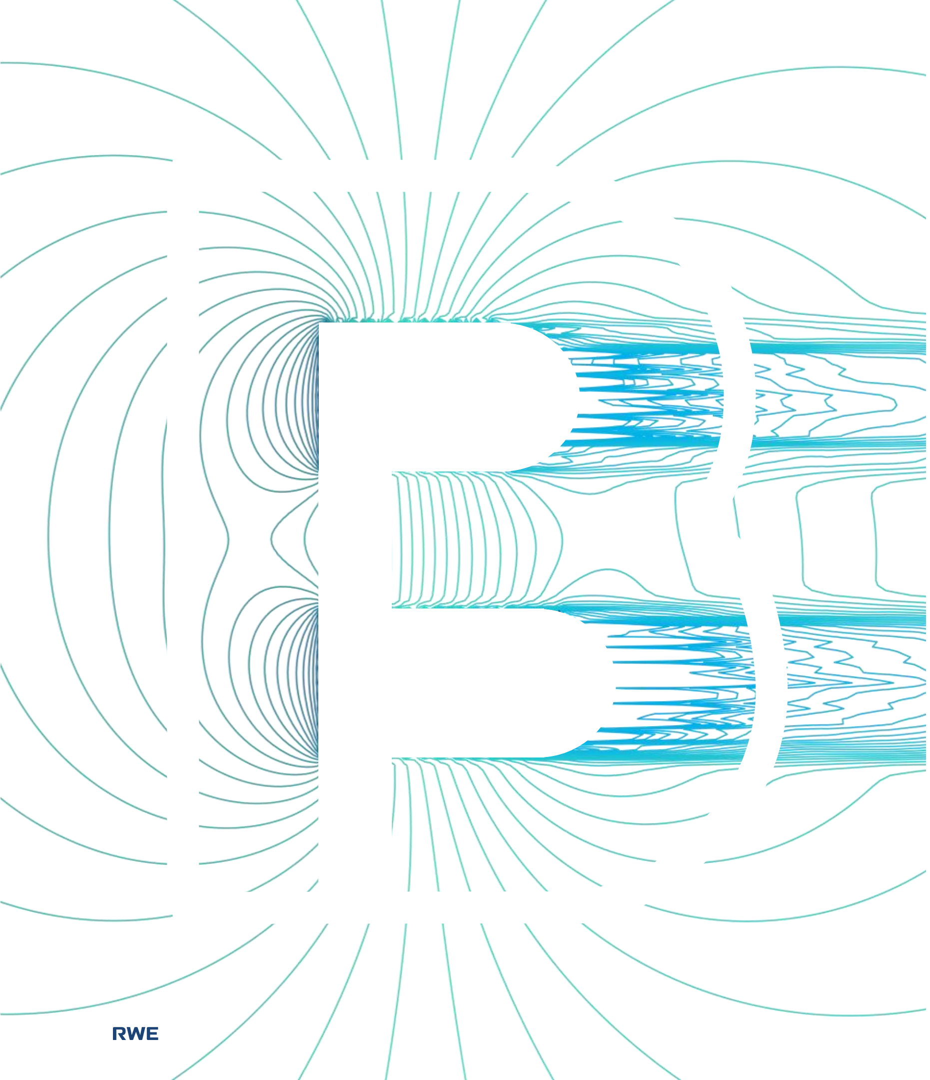
GloBE data

Blockage physics & model representation

Independent Technical Review Group

Blockage technical loss accountancy

Joint Statement on the Global Blockage Effect



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- Introduction & Motivation
- Experimental Design
- Results
- Conclusions
- Questions

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Prepared by:

Christopher Rodaway
Lead Scientist – Advanced Numerics
christopher.rodaway@rwe.com

Kester Gunn
Chief Scientist
kester.gunn@rwe.com

Sam Williams
Senior Scientist
sam.williams@rwe.com

Alessandro Sebastiani
Scientist
slessandro.sebastiani@rwe.com

Special acknowledgments:

DTU Wind Energy

Mike Courtney
Elliot Simon
Gunhild Thorsen
Emilie Clausen

Fraunhofer IWES

Julia Gottschall
Martin Dörenkämper
Erik Patschke
Lukas Vollmer
Lin-Ya Hung

TNO

Jan-Willem Wagenaar
Marco Turrini
Dennis Wouters
Yichao Liu

Additional acknowledgement for contribution: Pedro Santos (formerly Fraunhofer-IWES); Nassir Cassamo (formerly TNO)

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