Advancing wind resource assessment in complex terrain with scanning lidar measurements

Alkistis Papetta / Julia Gottschall

IEA Wind Task 32 *online seminar* – 2 July 2020

Fraunhofer IWES

Outline

What to expect in this seminar

- Standard Wind Resource Assessment (WRA) for complex terrain sites and related challenges → some introduction
- How we tackled these challenges in EWiNo → very brief project overview
- The developed approach → combining scanning lidar measurements with flow modelling (with results of demonstration campaigns)
- Some words on the business case, and conclusions

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Standard WRA procedure

According to Technical Guideline (TR) 6 by FGW

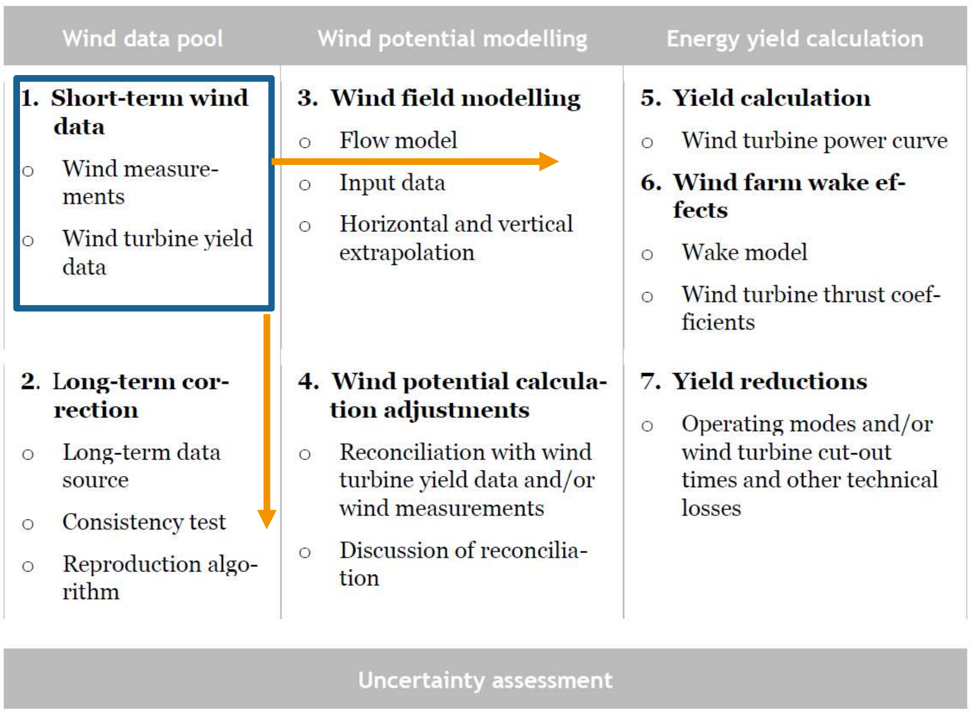

Fig. 2–1: Generalised structure of energy yield assessments

Components of an energy yield assessment (EYA) – and WRA, respectively – with reference to corresponding sections of TR 6

on-site data

→ *spatial* extrapolation

↓ *temporal* extrapolation

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Standard WRA procedure

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Wind data pool	Wind potential modelling	Energy yield calculation
1. Short-term wind data ○ Wind measure-ments ○ Wind turbine yield data	**3. Wind field modelling** ○ Flow model ○ Input data ○ Horizontal and vertical extrapolation	**5. Yield calculation** ○ Wind turbine power curve **6. Wind farm wake ef-fects** ○ Wake model ○ Wind turbine thrust coef-ficients
2. Long-term cor-rection ○ Long-term data source ○ Consistency test ○ Reproduction algo-rithm	**4. Wind potential calcula-tion adjustments** ○ Reconciliation with wind turbine yield data and/or wind measurements ○ Discussion of reconcilia-tion	**7. Yield reductions** ○ Operating modes and/or wind turbine cut-out times and other technical losses
Uncertainty assessment		

Fig. 2–1: Generalised structure of energy yield assessments

Components of an energy yield assessment (EYA) – and WRA, respectively – with reference to corresponding sections of TR 6

→ **on-site wind measurements** and **flow model** are key components (possibly making the difference)

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Where do **scanning lidar measurements** fit in?

- …

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1. Short-term wind data o Wind measurements o Wind turbine yield data	**3. Wind field modelling** o Flow model o Input data o Horizontal and vertical extrapolation	**5. Yield calculation** o Wind turbine power curve **6. Wind farm wake effects** o Wake model o Wind turbine thrust coefficients
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Fig. 2–1: Generalised structure of energy yield assessments

Where do **scanning lidar measurements** fit in?

- As substitute for the more standard on-site wind measurement (must be at least 12 months according to TR 6)
- As an additional short-term wind measurement (according to TR 6)
- …

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Where do **scanning lidar measurements** fit in?

- As substitute for the more standard on-site wind measurement (must be at least 12 months according to TR 6)
- As an additional short-term wind measurement (according to TR 6)
- Where it best improves the WRA (EYA) result… depends essentially on estimated ucertainties and business case

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Overview of joint R&D project EWiNo

Entwicklung eines zweistufigen Verfahrens für die Beurteilung von Windstandorten hinsichtlich ihres Windpotenzials nach der EEG-Novelle 2017

(Development of a two-stage procedure for the assessment of wind sites with regard to their wind potential after the EEG [German Renewable Energy Law] amendment 2017)

- Funded by BMWi for project duration 10.2017 – 03.2020
- Coordinated by Fraunhofer IWES, with GEO-NET Umweltconsulting GmbH and four associated partners (windwärts, Naturstrom, Energiequelle, ENERTRAG)
- Focus on moderately complex (typical German) terrain → some hills, roughness changes, forest, and not too large wind farms

Overview of joint R&D project EWiNo

Some of the project conclusions

- CFD tools more and more gaining ground but not without an on-site measurement
- Short-term measurements neither to replace the standard 1-year campaign nor to inform in an early project phase (acceptance, costs)
- Scanning lidar technology is of interest but related costs challenge the business case

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- More than a compromise: **use most cost-efficient scanning lidar approach to maximise value of flow modelling** (and with this optimise WRA / EYA result)

… what this means in terms of uncertainties…

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Fig. 2–1: Generalised structure of energy yield assessments

Wind data pool	Site-specific wind measurement	Mast measurement	Calibration
			Anemometer classification
			Installation effects
			Data recording and processing
			Any necessary data corrections
			Data integrity
		Remote sensing approach	Verification test
			Classification
			Monitoring/second verification test
			Site effects
			Data recording and processing
			Any necessary data corrections
			Data integrity
	Reference wind turbine	Data and their acquisition, degree of detail, information quality	
		Procedures for eliminating outliers and availability correction	
		Wind farm wake effects	
		Wind turbine "input data" uncertainties	
	Long-term correction	Consistency of the long-term data sources	
		Long-term => short-term modelling algorithm	
		Comparison period	
		Representativeness of the reference period in the past	
		Projection of the reference period to the future wind turbine operating lifetime	
		Representativeness of the long-term data for the site	
Modelling	Input data (such as topography)		
	Extrapolation method uncertainty, often usefully divided into:		Horizontal extrapolation
			Vertical extrapolation
Farm wake effects			
Wind turbine input data	Power curve		
	Series scatter		
	Validity of the curve for the site		
	Variation of wind turbine control parameters		
Energy loss factors			

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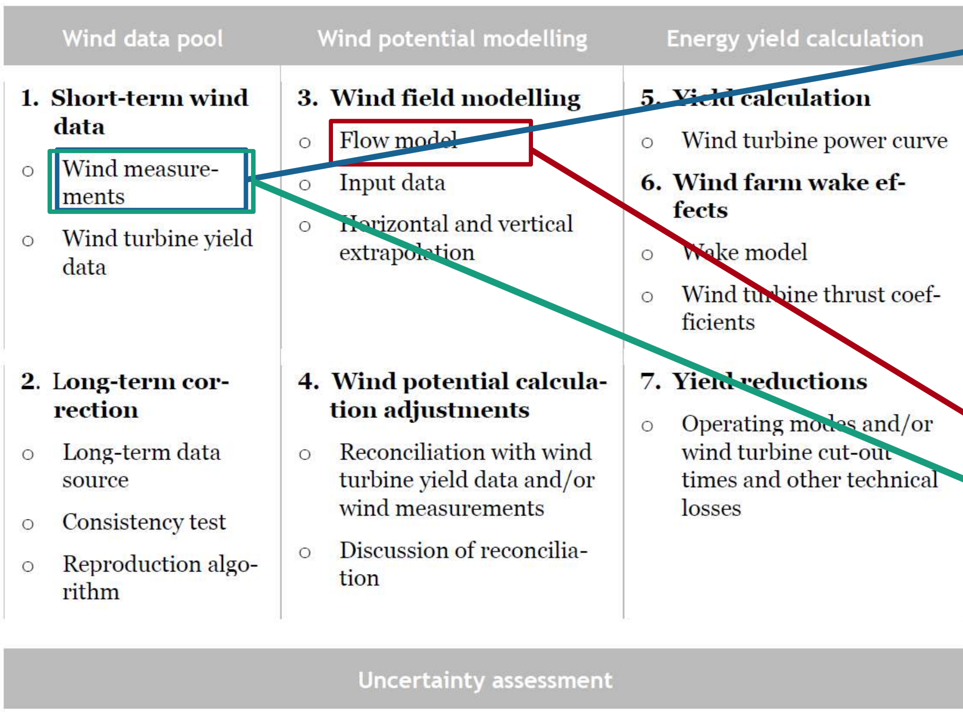
… what this means in terms of uncertainties…



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WRA

According to TR6

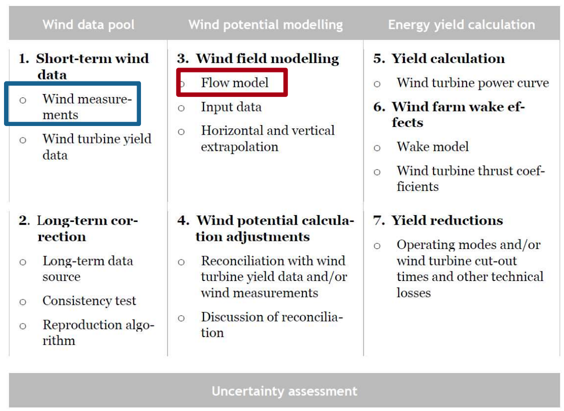
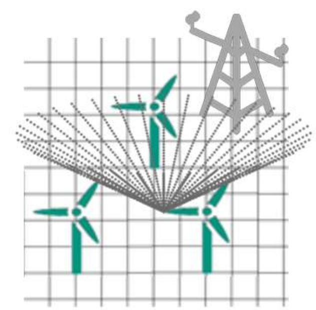


Fig. 2–1: Generalised structure of energy yield assessments

! For complex-terrain sites (orography variations, roughness variations)

- Poor representativeness of reference conditions
- Increased uncertainty of flow modelling

→ Use additional measurements to evaluate the performance of flow model and minimize uncertainties



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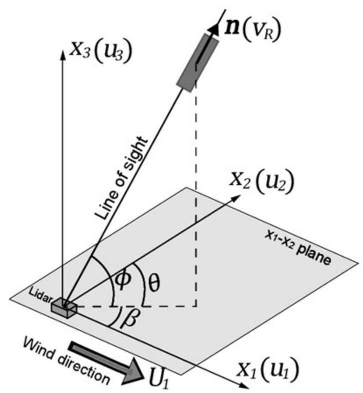
Scanning lidar technology

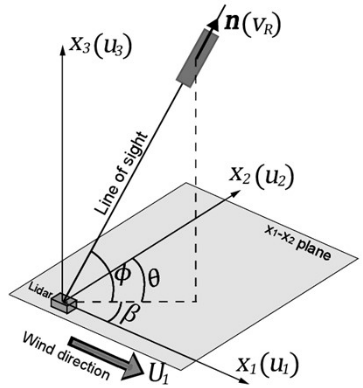
Measuring principle

- Measured wind speed is the projection on the LoS of the respective beam
- Pulsed lidars: simultaneous measurements in multiple "Range gates"
- Scanning: 2 degrees of freedom (elevation + azimuth)



Scanning lidar technology

Measuring principle



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- Benefit in combination with standard wind measurements:
  - Multi-location time series (reconstruction approach)

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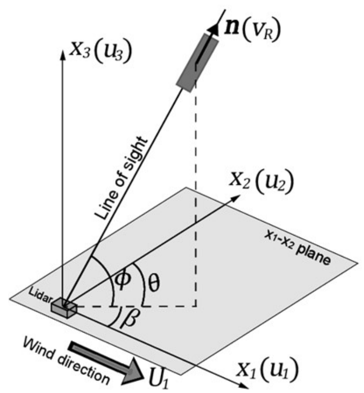

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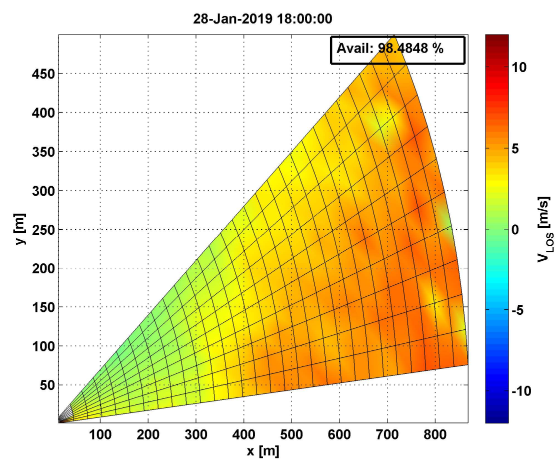
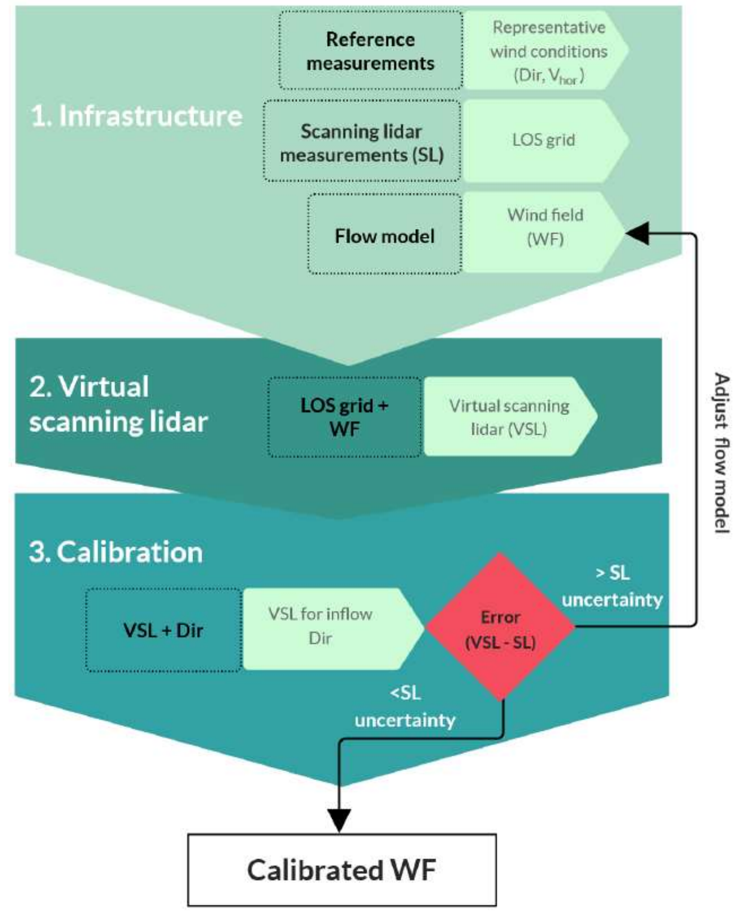
- Scanning: 2 degrees of freedom (elevation + azimuth)
- Benefit in combination with standard wind measurements:
  - Multi-location time series (reconstruction approach)
  - Flow visualization (snapshots)



Integrating scanning lidar in WRA

- Virtual scanning lidar method (VSL)
  - Create a simulation of the scanning lidar measurements in flow model

Direct comparison of measured and modelled wind fields (stability, terrain effects) by projection.



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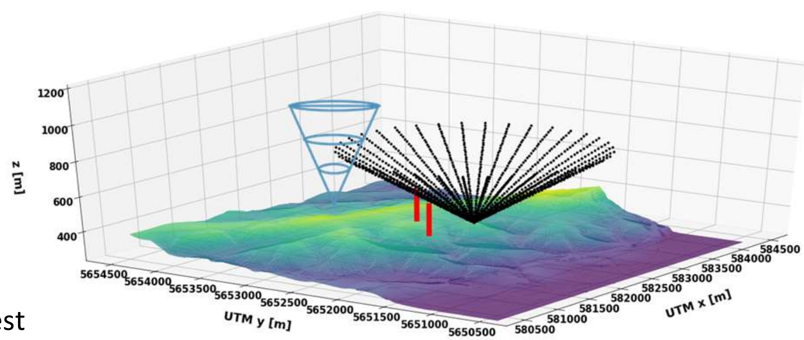
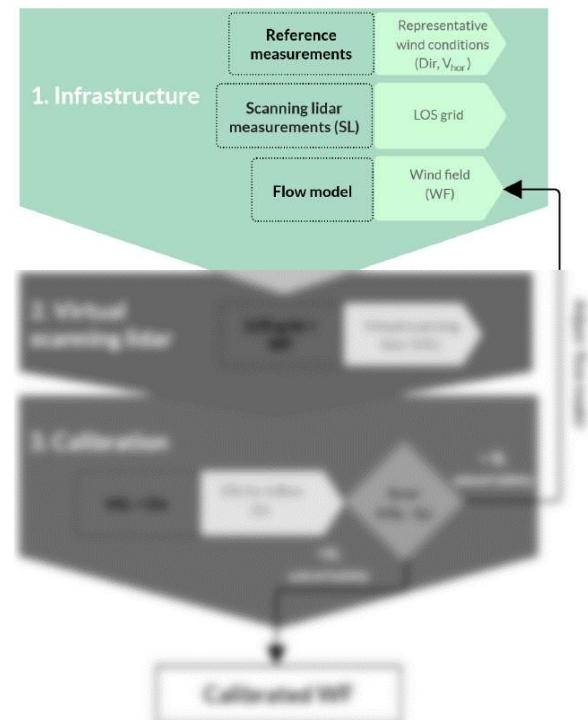
Virtual scanning lidar method

- Infrastructure:
  - Wind flow model (for preselected wind sectors) (microscale)
  - On-site 1 year measurements
  - Parallel PPI scanning lidar measurements over POI* (few weeks)



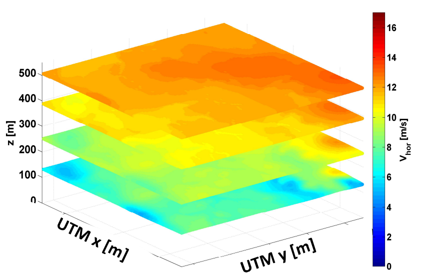
* Positions of interest

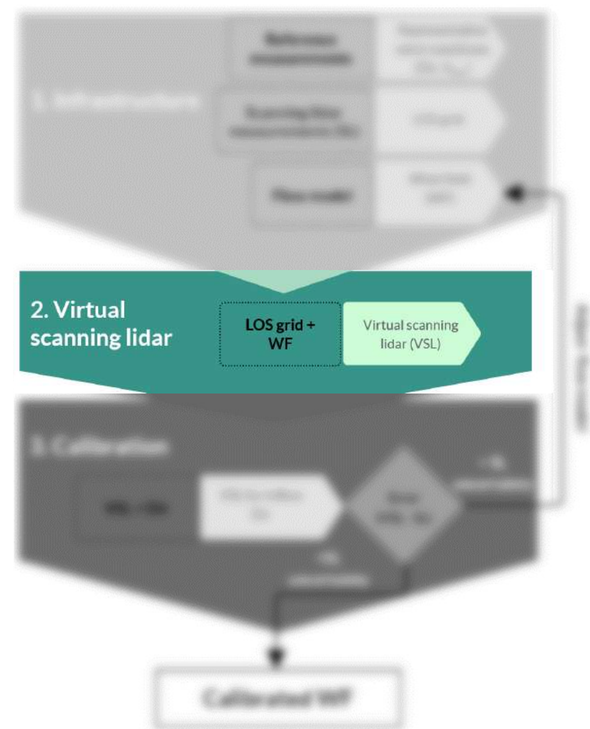


Virtual scanning lidar method

Constructing VSL

- Simulated wind field projected on the LOS geometry

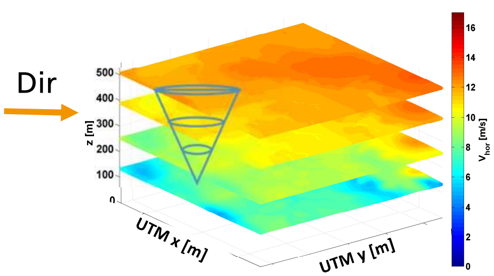


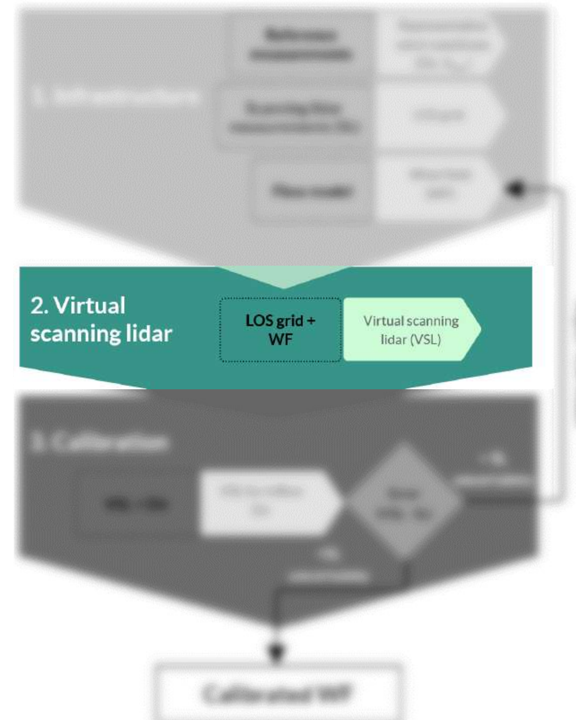


Virtual scanning lidar method

Constructing VSL

- Simulated wind field projected on the LOS geometry
  - For a reference wind direction:

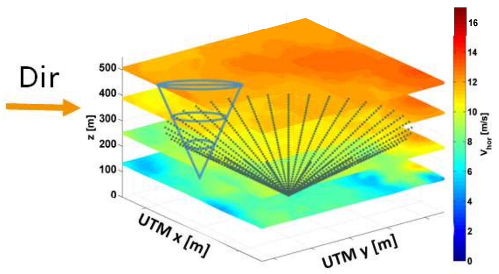


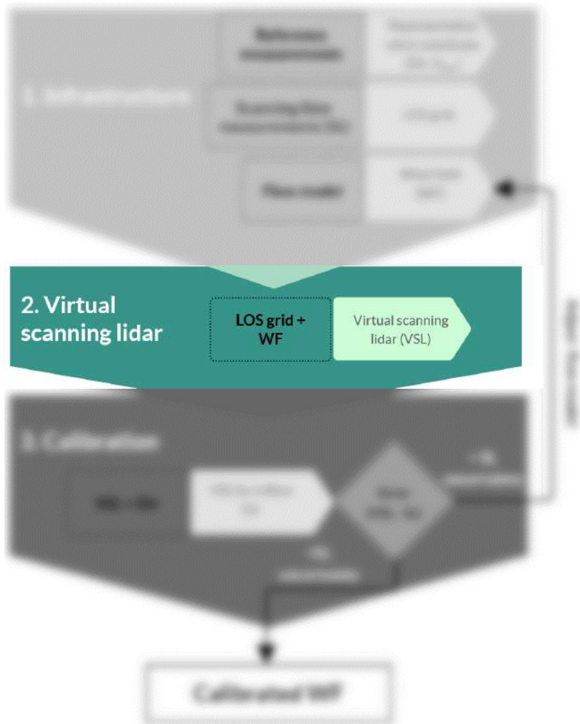


Virtual scanning lidar method

Constructing VSL

- Simulated wind field projected on the LOS geometry
  - For a reference wind direction:
    1. Extract simulated wind vector at LoS locations





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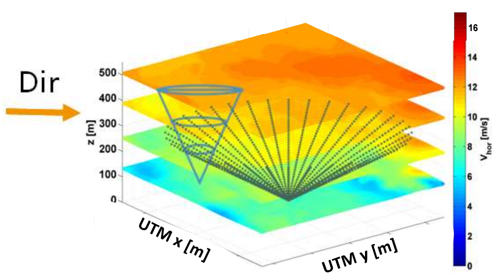
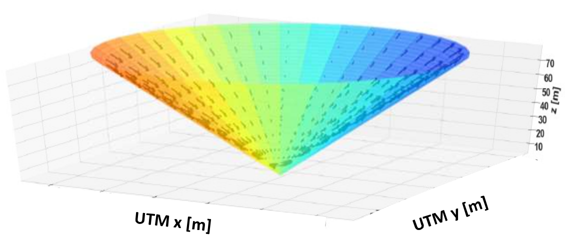
Virtual scanning lidar method

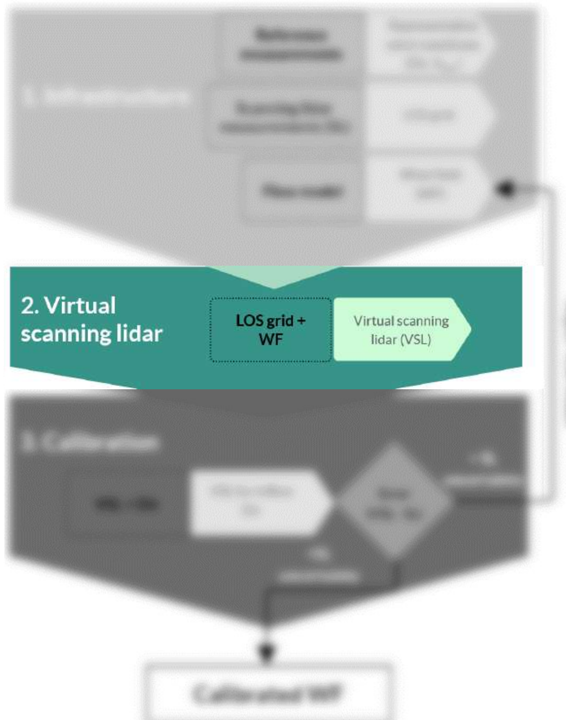
Constructing VSL

- Simulated wind field projected on the LOS geometry
  - For a reference wind direction:
    1. Extract simulated wind vector at LoS locations
    2. Project simulated vector on LoS geometry





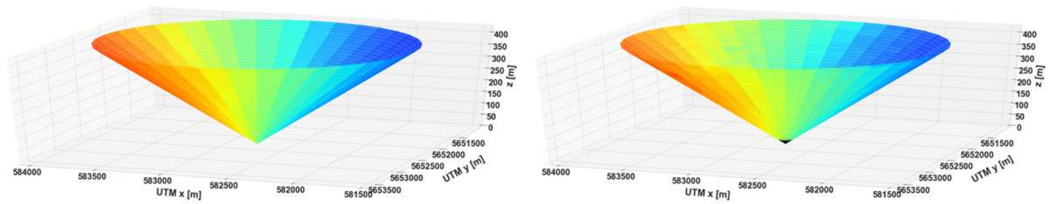
VSL



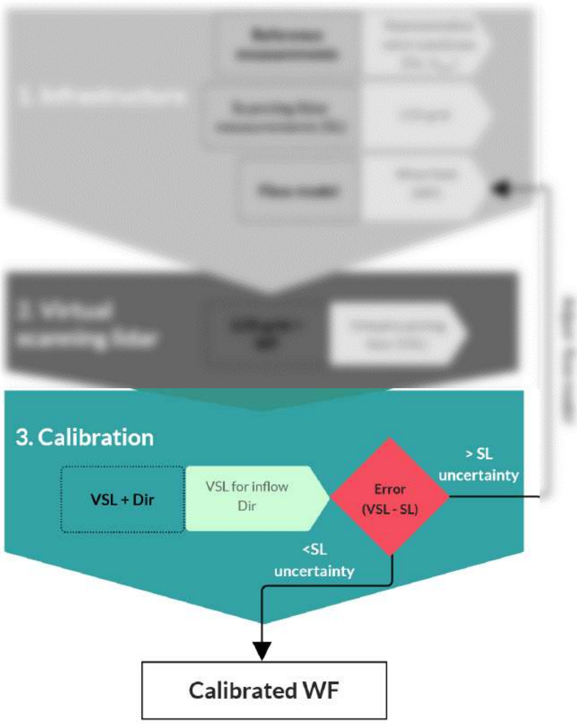
Virtual scanning lidar method

Calibration of flow model

- Compare VSL and actual scanning lidar measurements



VSL *Scanning lidar*



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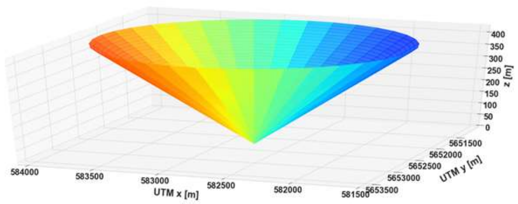

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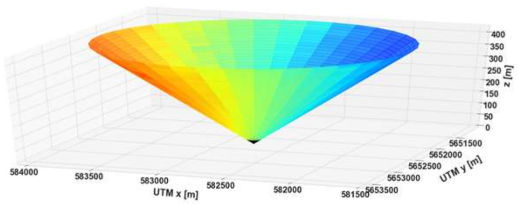
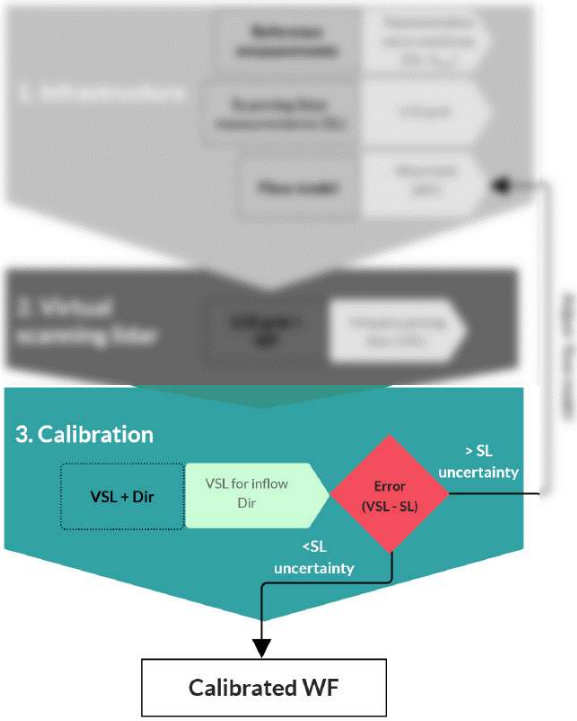


Scanning lidar

- Identify mismatches (larger than measurement statistical uncertainty)



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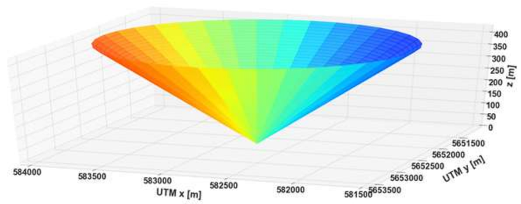

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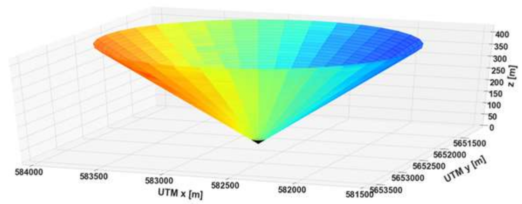
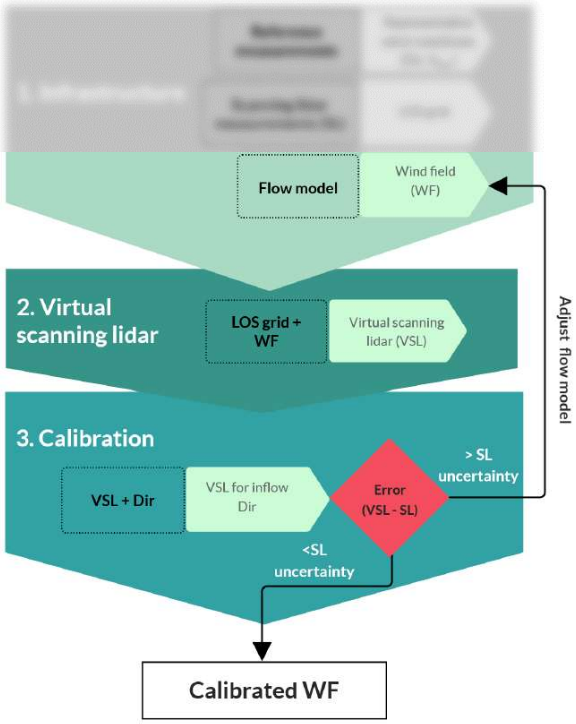


Scanning lidar

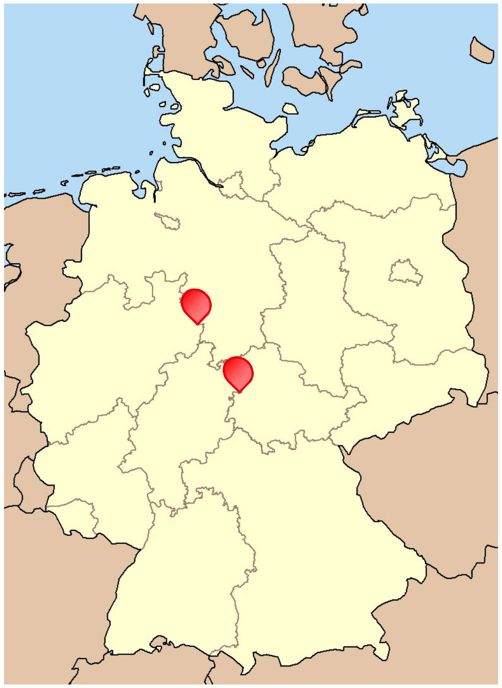
- Identify mismatches (larger than measurement statistical uncertainty)
- Tune flow model (terrain, stability) to reduce disagreement



Demonstration campaigns

- Two demonstration campaigns during EWiNO project
- Sites in Germany:
  1. Herleshausen (site in Hessen)
  2. Lügde (site in Nord-Rhine Westphalia)
     - Sites with moderately complex terrain
     - Pre-construction stage
- Simulations by two steady state microscale models:
  - FITNAH (GEO-NET)
  - FIWind (Fraunhofer IWES)

*both models had good performance over the site but here we only show FIWind



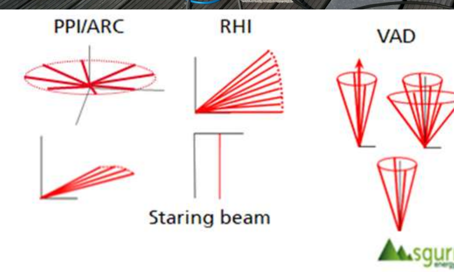
Setting up the infrastructure

Scanning lidar

<u>Galion 4000 – Scanning lidar</u>

- Range 0-4 km (along „Line of Sight” [LoS])
- Pulsed LiDAR: Simultaneous measurements„Range Gates“
- Flexible Geometry (Azimuth, Elevation)
- Measured quantity is fraction of the wind speed along beam direction (LoS)

- Verified at Fraunhofer IWES premises



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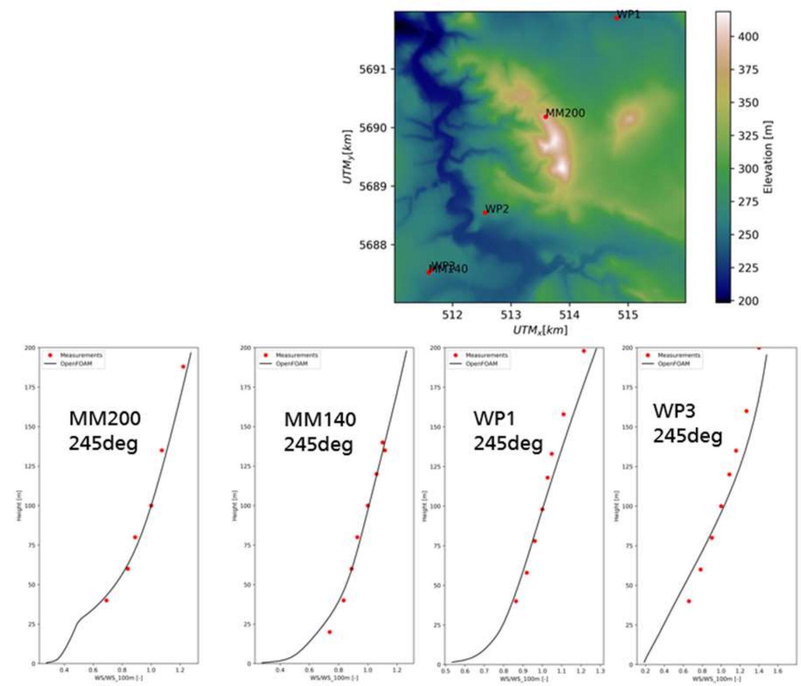
Setting up the infrastructure

Model

OpenFOAM

- FIWind : Fraunhofer IWES Wind simulation environment
- IWES in-house development: Flow solver based on open source code OpenFOAM with own optimizations for wind energy applications (forest, stratification, complex terrain, ...)
- FIWind was validated at different locations in complex terrain (Kassel, NEWA project[1]) →



[1]Chang, Chi-Yao, et al. "A consistent steady state CFD simulation method for stratified atmospheric boundary layer flows." *Journal of Wind Engineering and Industrial Aerodynamics* 172 (2018): 55-67

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Results

Infrastructure

Model

- Steady state microscale flow model (FIWind)

Input/Intial conditions:

- Neutral stratification
- 36 (Site 1) / 12 (Site 2) directional sectors
- 25 x 25 m mesh resolution
- Terrain maps
- Landcover maps

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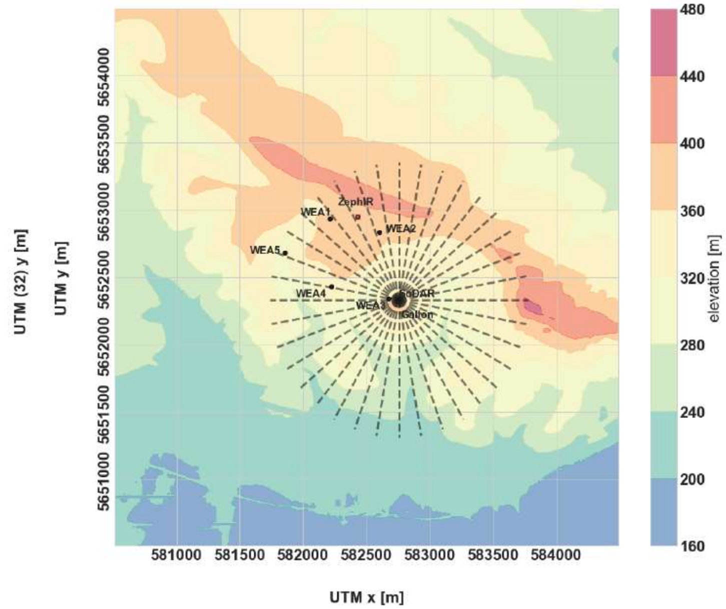
Scanning lidar

Beams in scan	36
Azimuth φ [°]	0-360
$\Delta\ \varphi$ [°]	10
Elevation ϑ [°]	20
Completion time (min:sec)	1:25



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Site 1

Site 2

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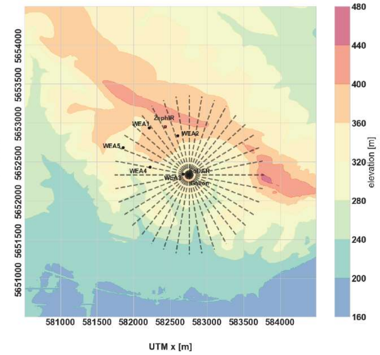

Reference instrument

- Profiling lidar
  - 1 year data (not overlapping with scanning lidar campaign)
- SoDAR
  - 1 month (overlapping with scanning lidar campaign)

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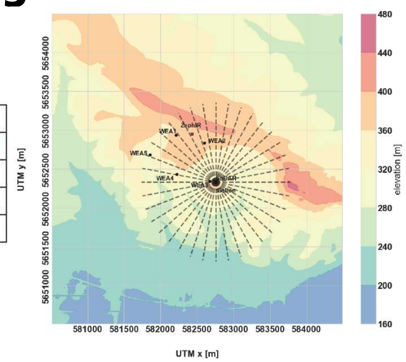
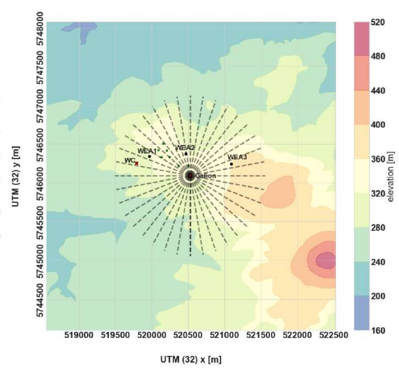
Azimuth φ [°]	0-360
$\Delta\ \varphi$ [°]	10
Elevation ϑ [°]	20
Completion time (min:sec)	1:25



Site 2

Beams in scan	36
Azimuth φ [°]	0-360
$\Delta\ \varphi$ [°]	10
Elevation ϑ [°]	34
Completion time (min:sec)	1:25



Reference instrument

Site 1:

- Profiling lidar
  - 1 year data (not overlapping with scanning lidar campaign)
- SoDAR
  - 1 month (overlapping with scanning lidar campaign)

Site 2:

- Profiling lidar
  - 1 year data (overlapping period with scanning lidar campaign)

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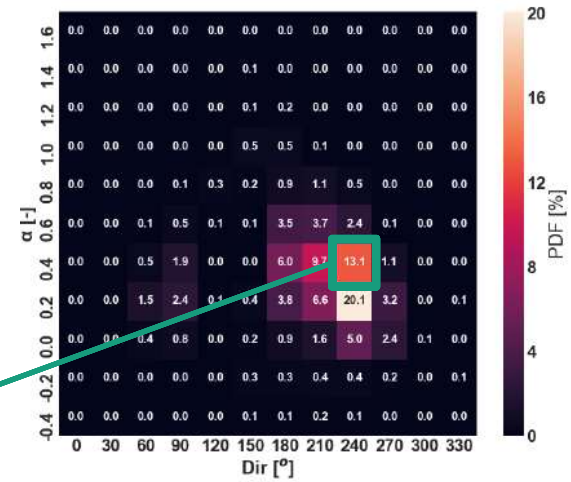
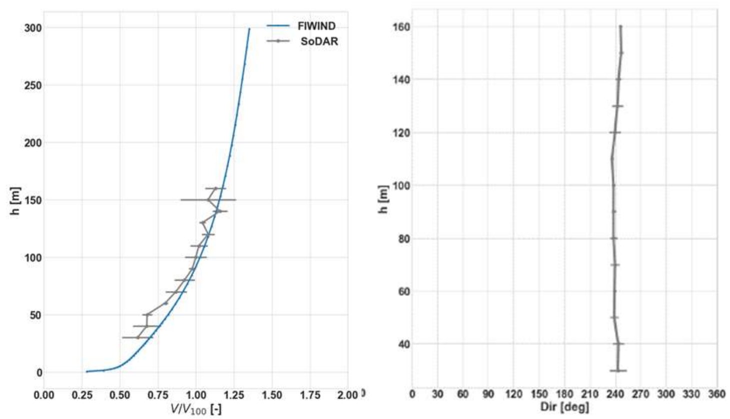
Results

Example single timestamp – Site 2

- Select common cases in the measured wind conditions capture matrix (α: shear exponent, Dir: inflow direction)
- 30 minute ensembles from reference and scanning lidar measurements



Capture matrix Herleshausen.



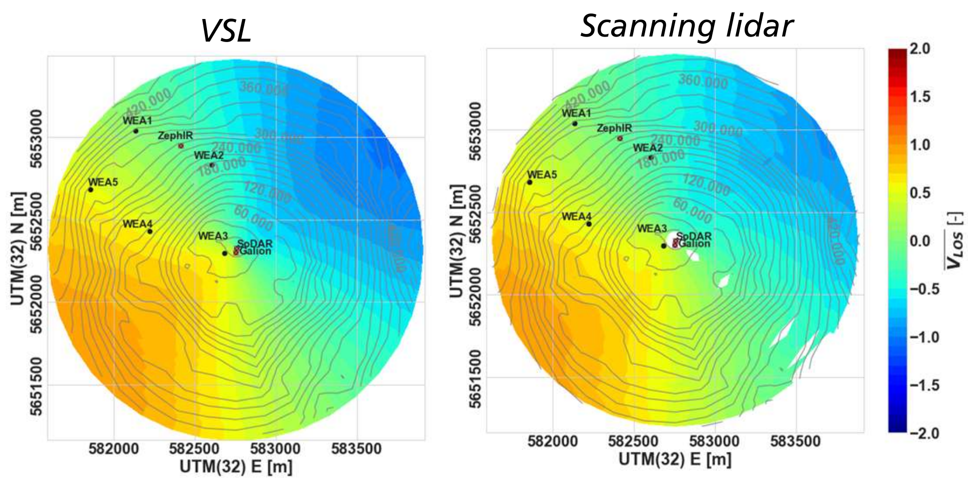
(a) Wind profile *(b) Direction*

5 *Reference wind conditions for selected timestamp on 12/02/2020ir = 240°)*

Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction



Example case for Herleshausen

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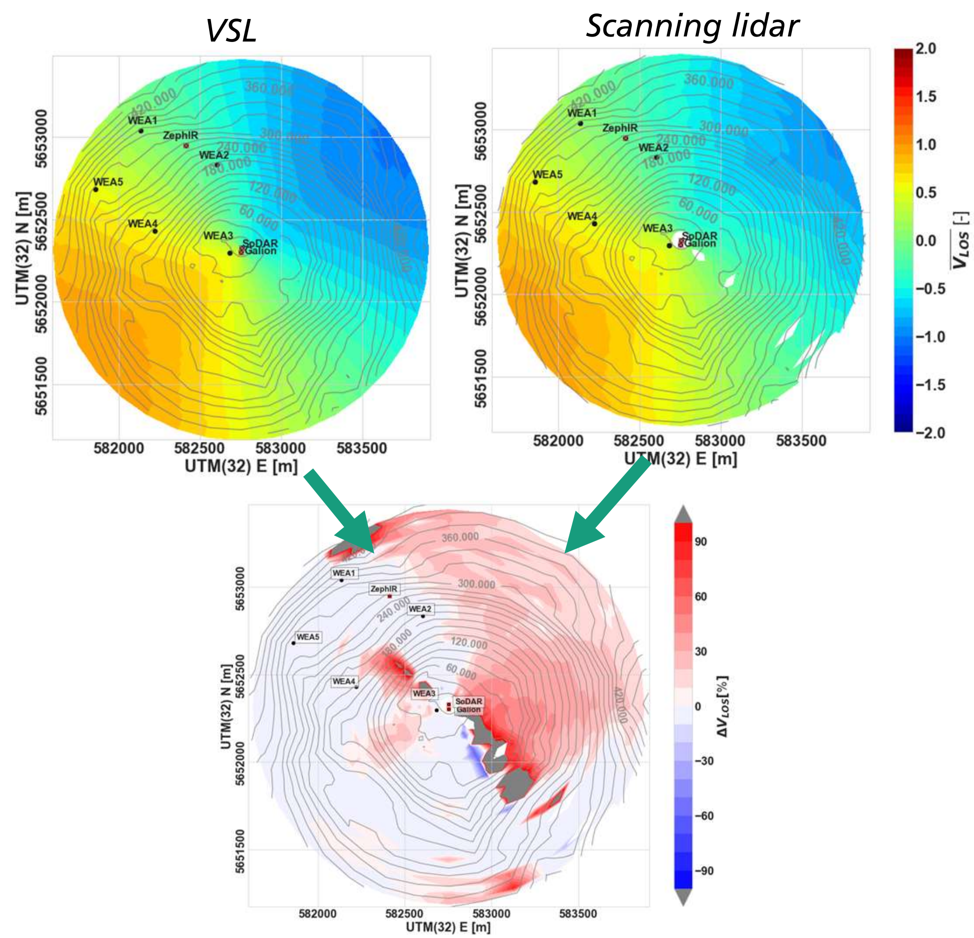
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)



Example case for Herleshausen

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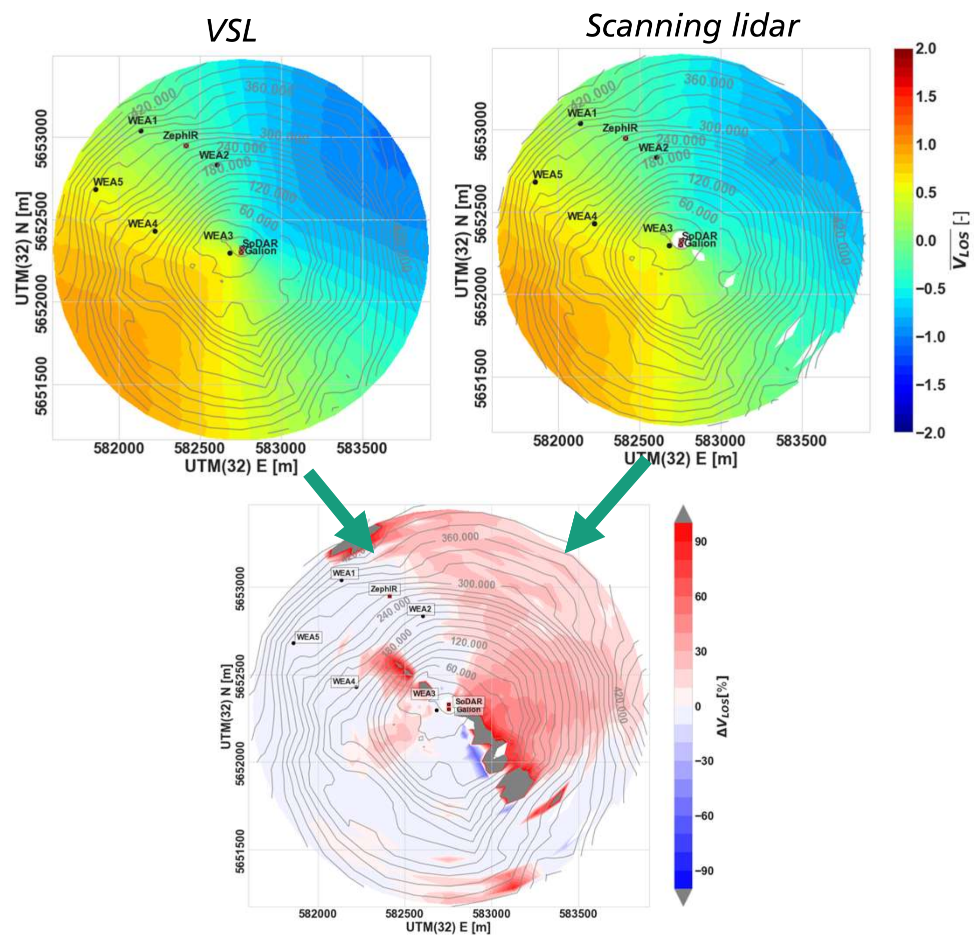
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
  - Any big structures still visible in the scanning lidar measurement?



Example case for Herleshausen

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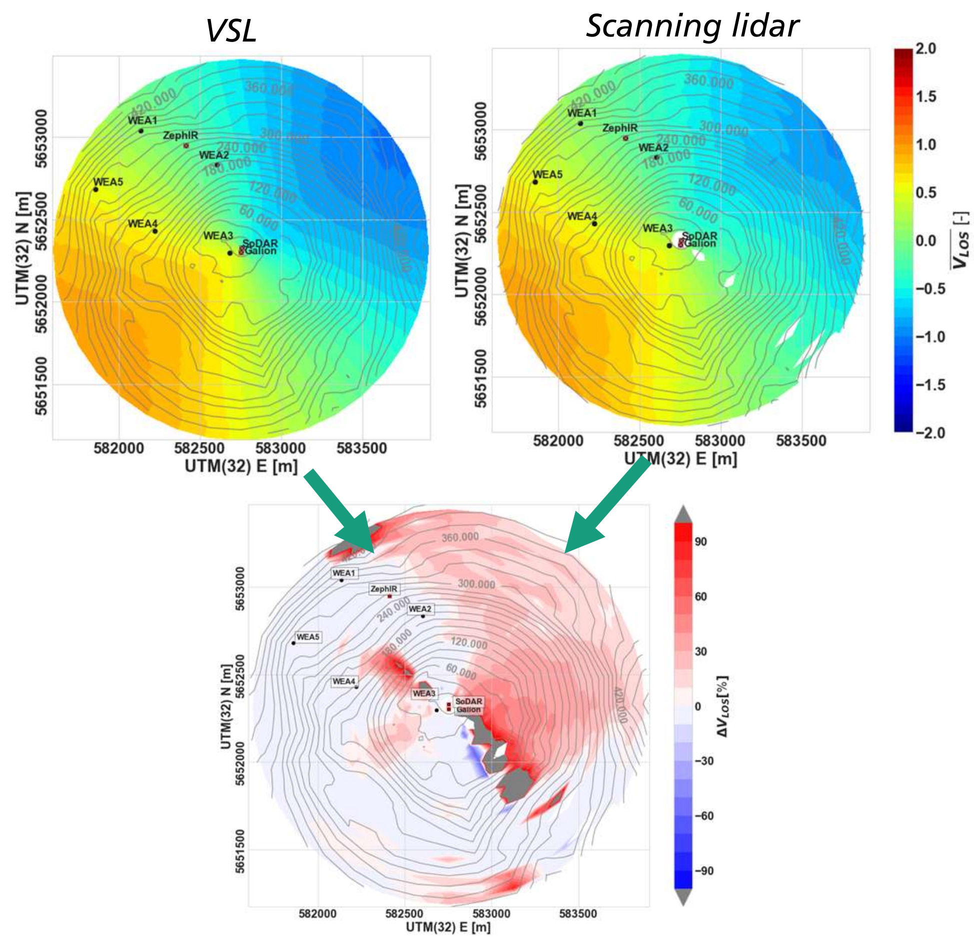
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
  - Any big structures still visible in the scanning lidar measurement? NO

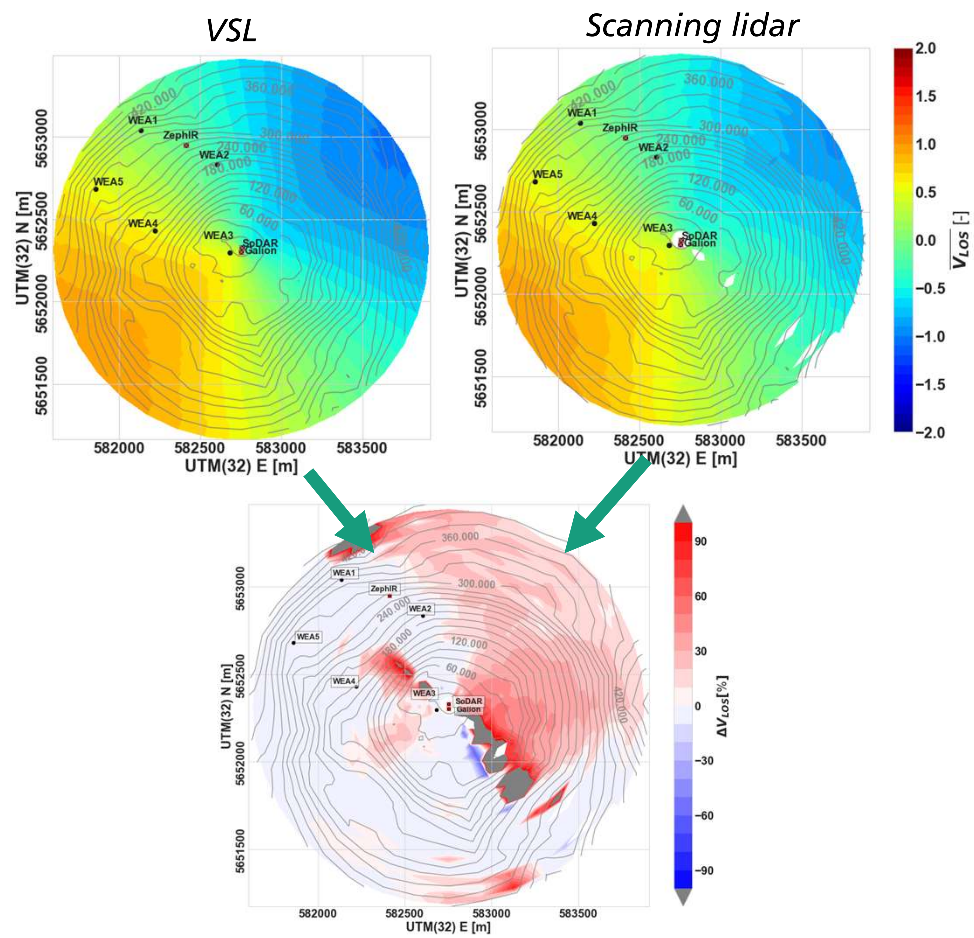


Example case for Herleshausen

Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
  - Any big structures still visible in the scanning lidar measurement? NO
  - Terrain / landcover mismatches?

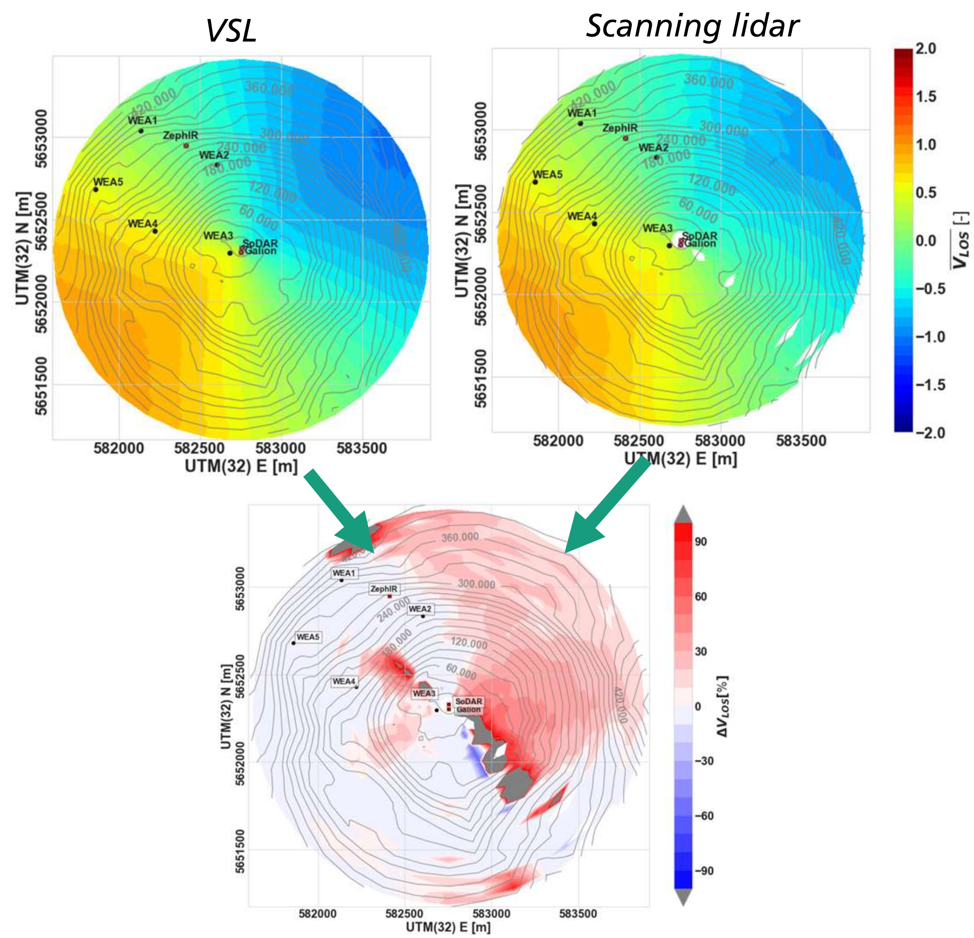


Example case for Herleshausen

Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
  - Any big structures still visible in the scanning lidar measurement? NO
  - Terrain / landcover mismatches? YES - Over speeding in front and behind hill (on average 30% over prediction)



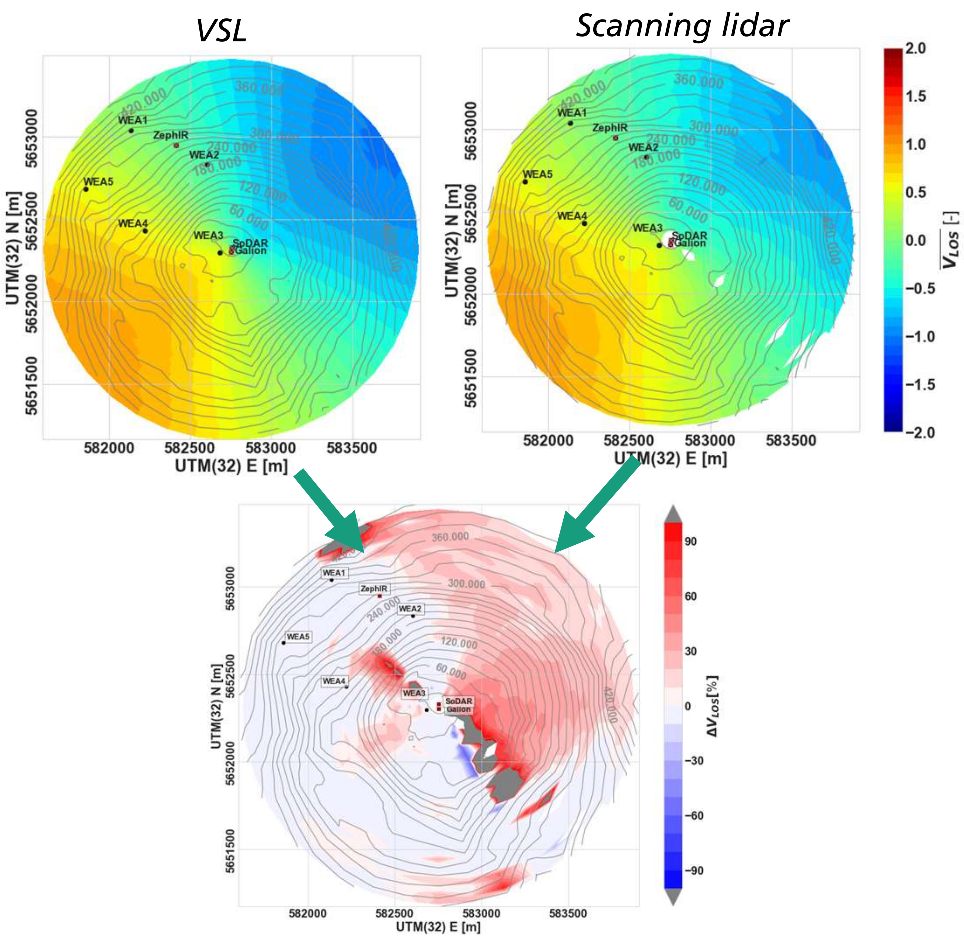
Example case for Herleshausen

Fraunhofer IWES

Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
  - Any big structures still visible in the scanning lidar measurement? NO
  - Terrain / landcover mismatches? YES - Over speeding in front and behind hill (on average 30% over prediction)
  - Atmospheric stability mismatch?

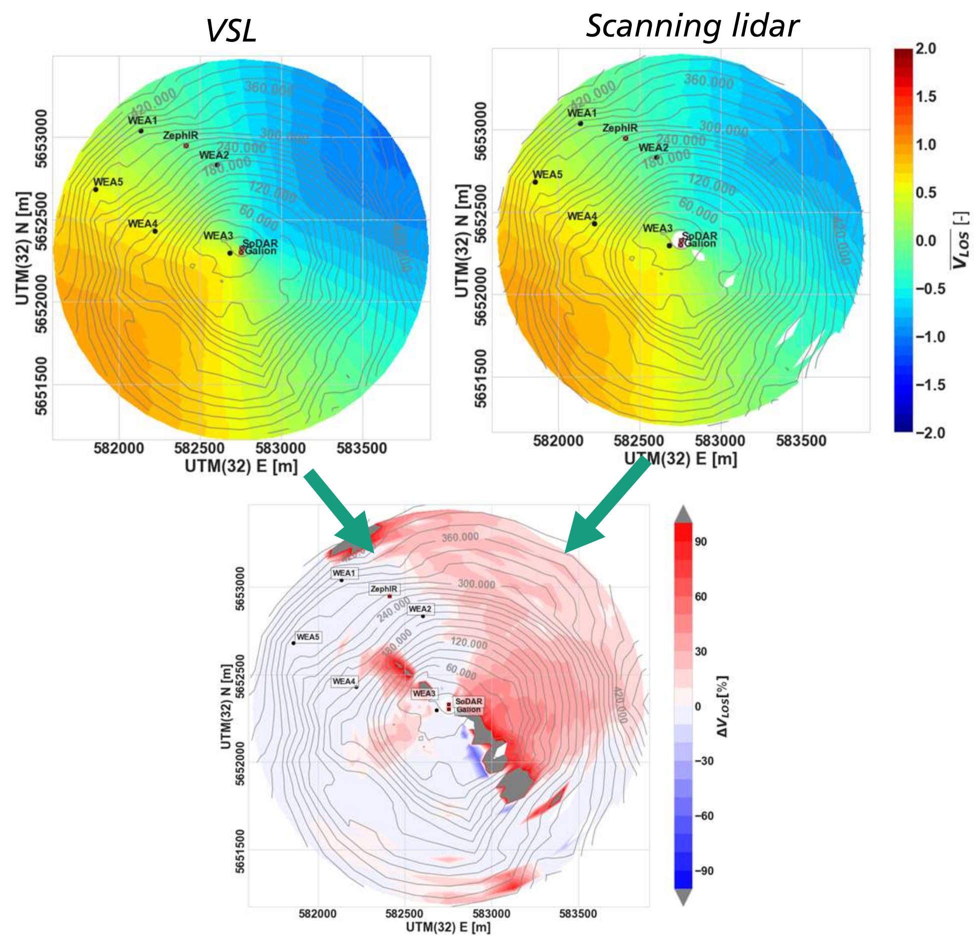


Example case for Herleshausen

Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
  - Any big structures still visible in the scanning lidar measurement? NO
  - Terrain / landcover mismatches? YES - Over speeding in front and behind hill (on average 30% over prediction)
  - Atmospheric stability mismatch? NO (Equal distribution of contours)



Example case for Herleshausen

Results

Clustering of cases

- Cluster cases with similar wind conditions
- Compare cluster's average with VSL

↳ Assess errors related to different wind conditions (shear profile)

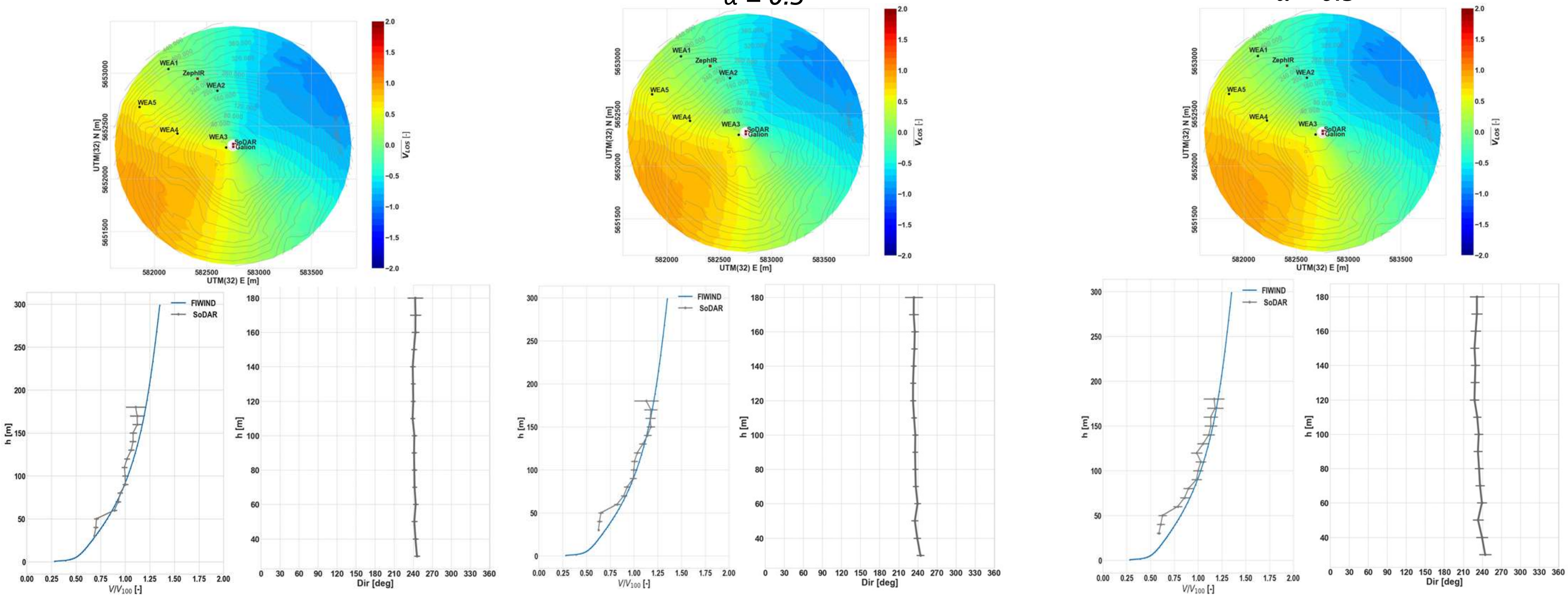
VSL

Results

Clustering of cases – Example 240°

Scanning lidar

α = 0.1 *α = 0.3* *α = 0.5*



Averaged clusters for 240° sector at Herleshausen

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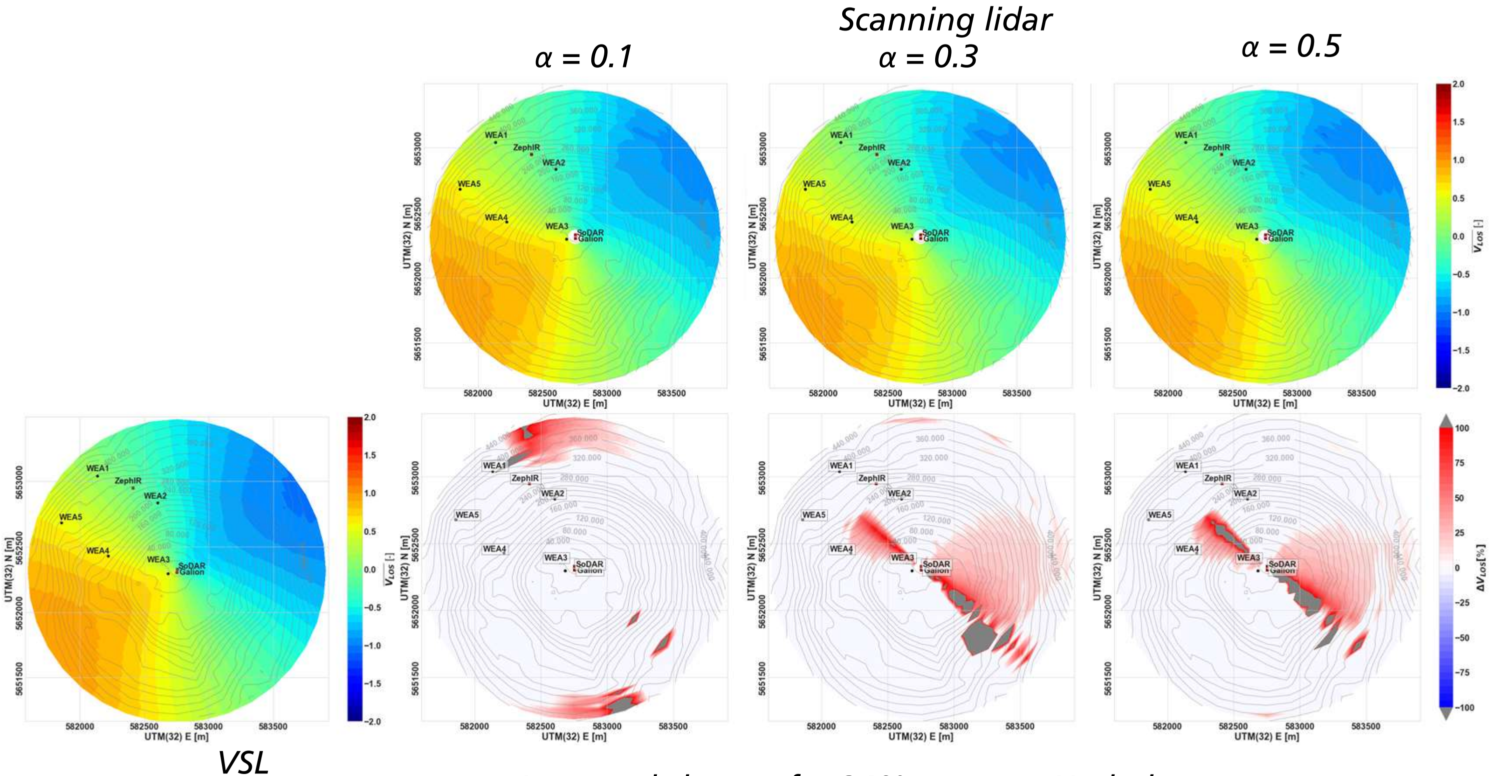
Results

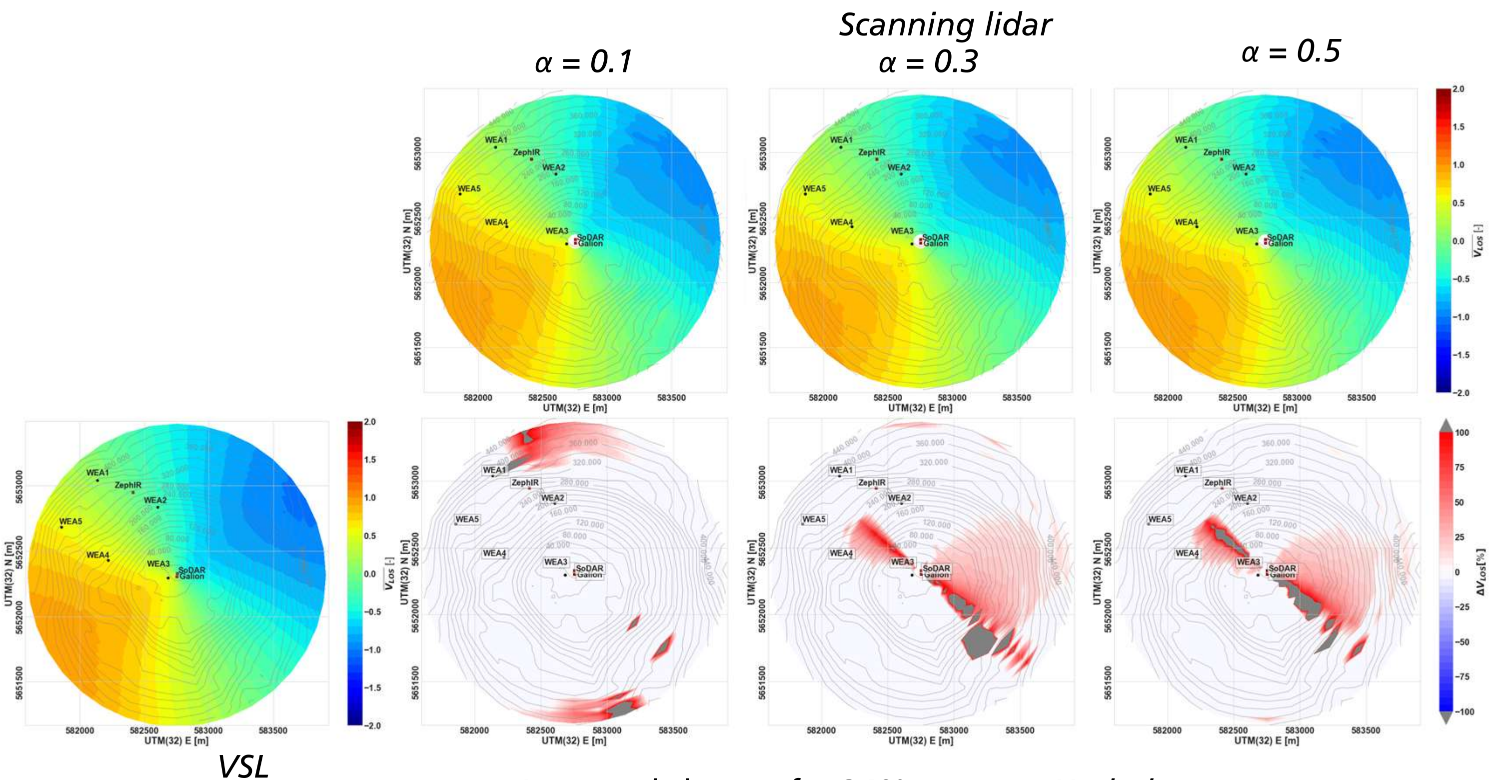
Clustering of cases – Example 240°



Averaged clusters for 240° sector at Herleshausen

Results

Clustering of cases – Example 240°



Averaged clusters for 240° sector at Herleshausen

- Mismatch in the blind zone increases with α
- Include differnet stability classes in the model
- **Good model performance for POI**

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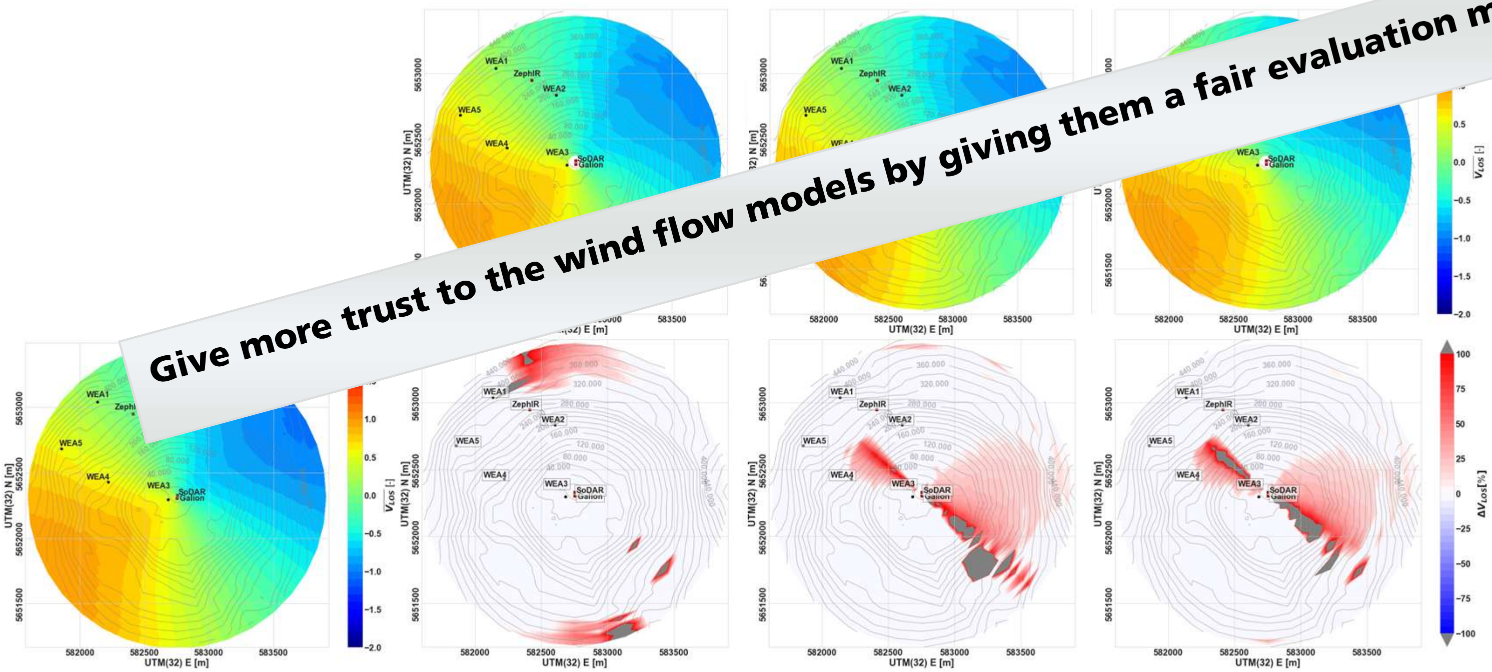
Results

Clustering of cases – Example 240°

Scanning lidar

α = 0.1 | *α = 0.3* | *α = 0.5*

Give more trust to the wind flow models by giving them a fair evaluation method



VSL

Averaged clusters for 240° sector at Herleshausen

- Mismatch in the blind zone increases with α
- Include differnet stability classes in the model
- **Good model performance for POI**

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Outlook

- Integrating a single scanning lidar only costs ~1.7 times more than conventional WRA
- VSL can be used:
  - to evaluate wind flow model performance
  - to quantitatively measure model uncertainty at POI

Conclusions (on use and business case)

How many scanning lidars will we see in future WRA campaigns?

Consider…

- German onshore market (starting point for EWiNo project)
- Costs of technology (how many devices)
- Use case / integration with WRA process and flow modelling in particular
- Significance of results (in the end, the estimated uncertainties decide)

Acknowledgements

Partners in EWiNo project

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Associated partners:

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- Senator of Science, Health and Consumer Protection
- Bremerhavener Gesellschaft für Investitionsförderung und Stadtentwicklung mbH

Federal State of Lower Saxony

Free and Hanseatic City of Hamburg

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Your feedback / questions / comments ?