

Generic methodology for field calibration of (nacelle-based) lidars and uncertainties

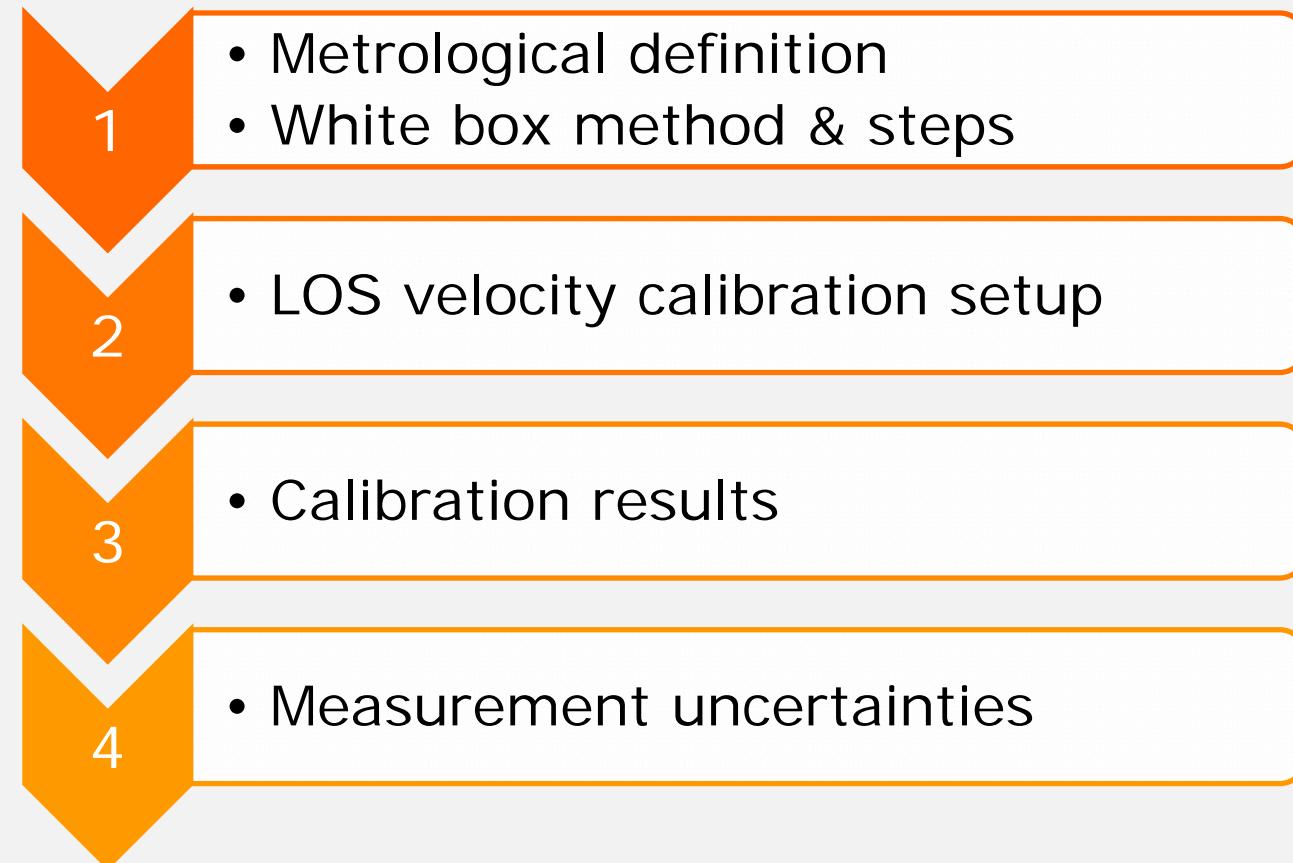
A. Borraccino, M. Courtney, DTU Wind Energy

Application to
Avent 5-beam Demonstrator and ZephIR Dual-Mode

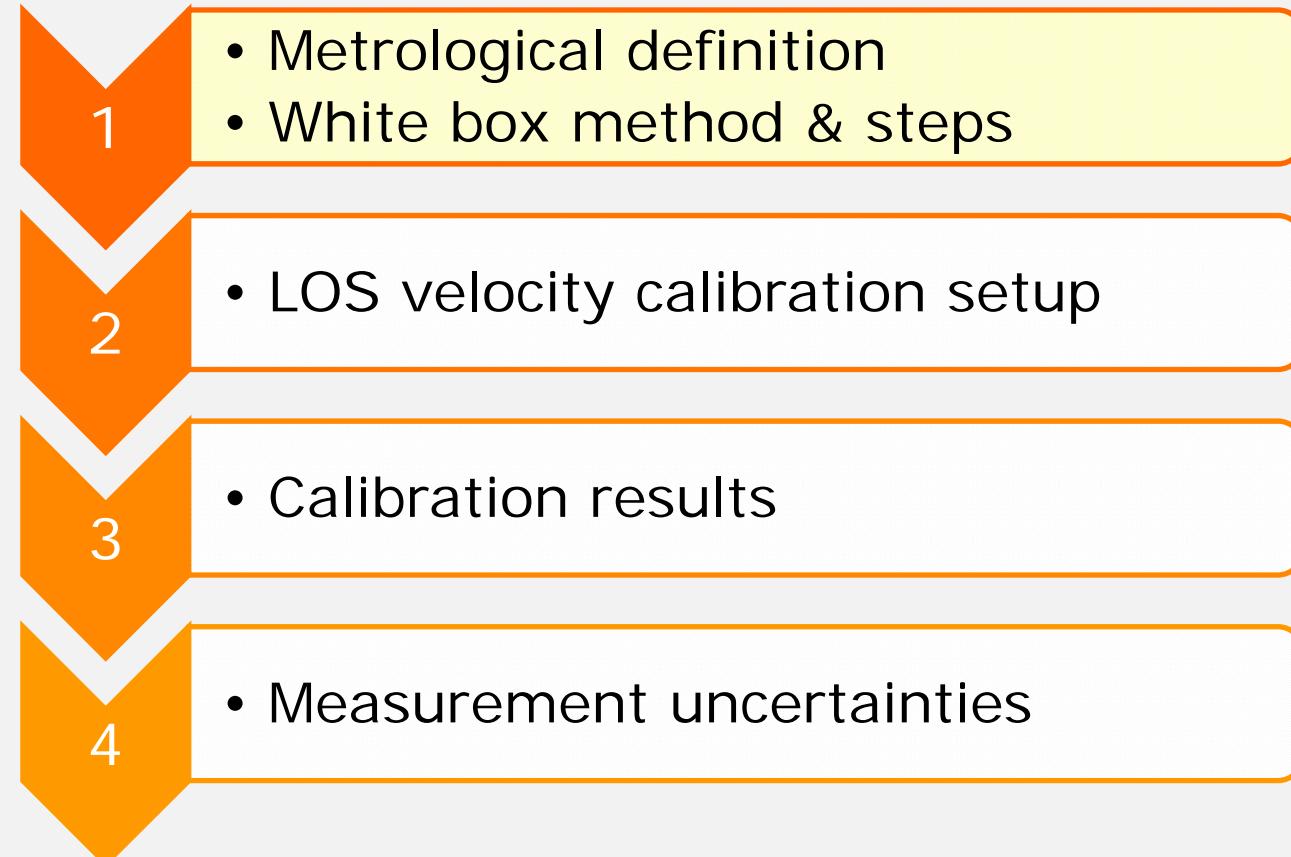


$$f(x+\Delta x) = \sum_{i=0}^{\infty} \frac{(\Delta x)^i}{i!} f^{(i)}(x)$$
$$\int_a^b \mathcal{E} \Theta^{\sqrt{17}} + \Omega \int \delta e^{inx} =$$
$$\Theta_{\infty} = \{2.718281828459045\}$$
$$\chi^2 \Sigma \gg ,$$
$$!$$

Outline

- 
- 1 • Metrological definition
• White box method & steps
 - 2 • LOS velocity calibration setup
 - 3 • Calibration results
 - 4 • Measurement uncertainties

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What is a calibration?

Let's speak the same metrological language !!



- According to the VIM (International Vocabulary of Metrology), a calibration is:
operation that, under specified conditions, in a first step, establishes a relation between the quantity values – i.e. the reference – with measurement uncertainties provided by measurement standards and corresponding indications – i.e. measurand to calibrate – with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

NOT CLEAR?

- Reformulation in 3-step process

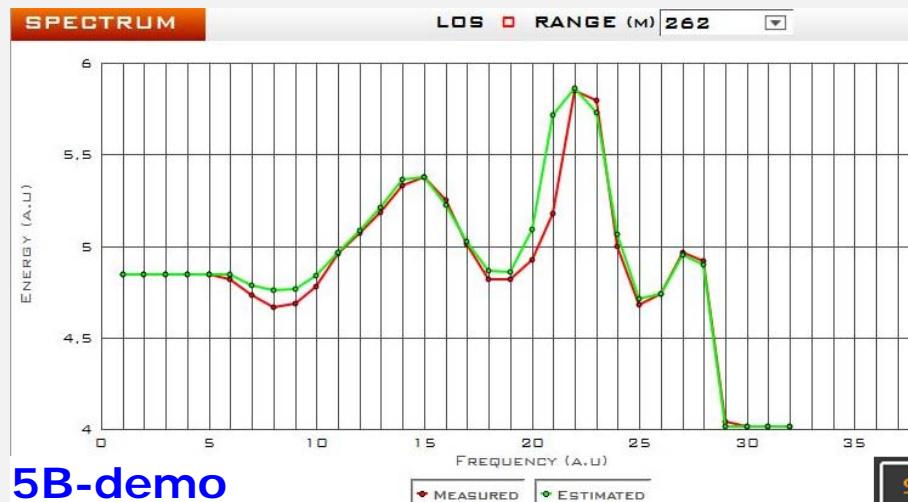
1. Establish the relation: measurand = $f(\text{reference})$
2. Uncertainties on measurand =
uncertainties on reference combined with calibration process and measurements uncertainties
3. Define and apply the correction on measurand → ensures **traceability**



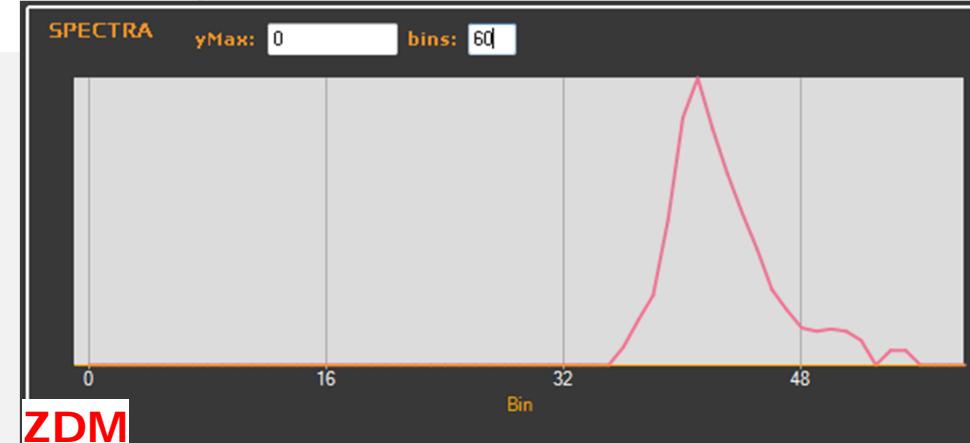
Lidar: measurements or estimates?

- Different levels of measurands in a wind lidar

1. Backscattered light signal from photodetector (RAW data)
2. Doppler spectra (after FFT processing)



5B-demo

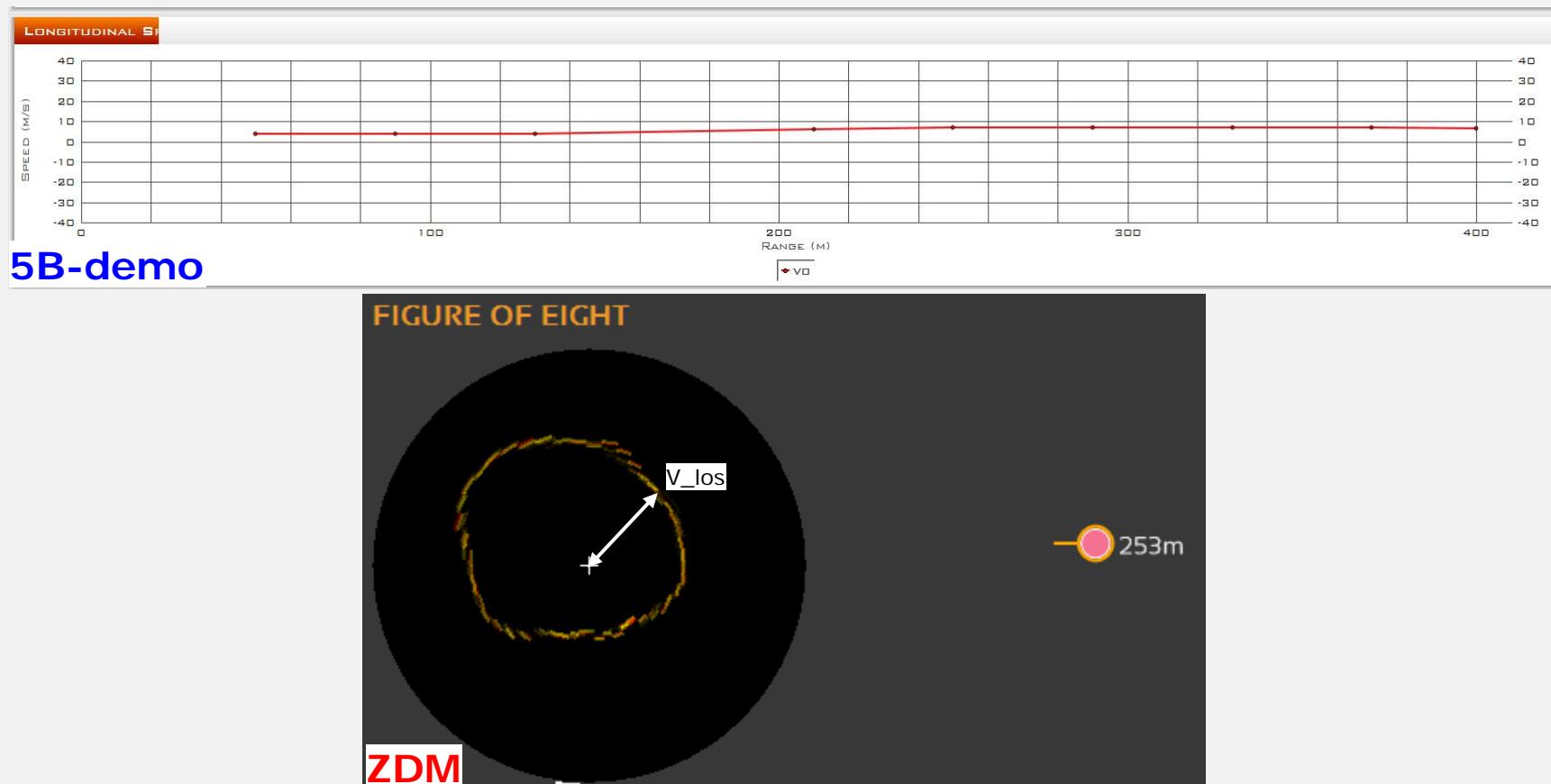


ZDM

Lidar: measurements or estimates?

- Different levels of measurands in a wind lidar

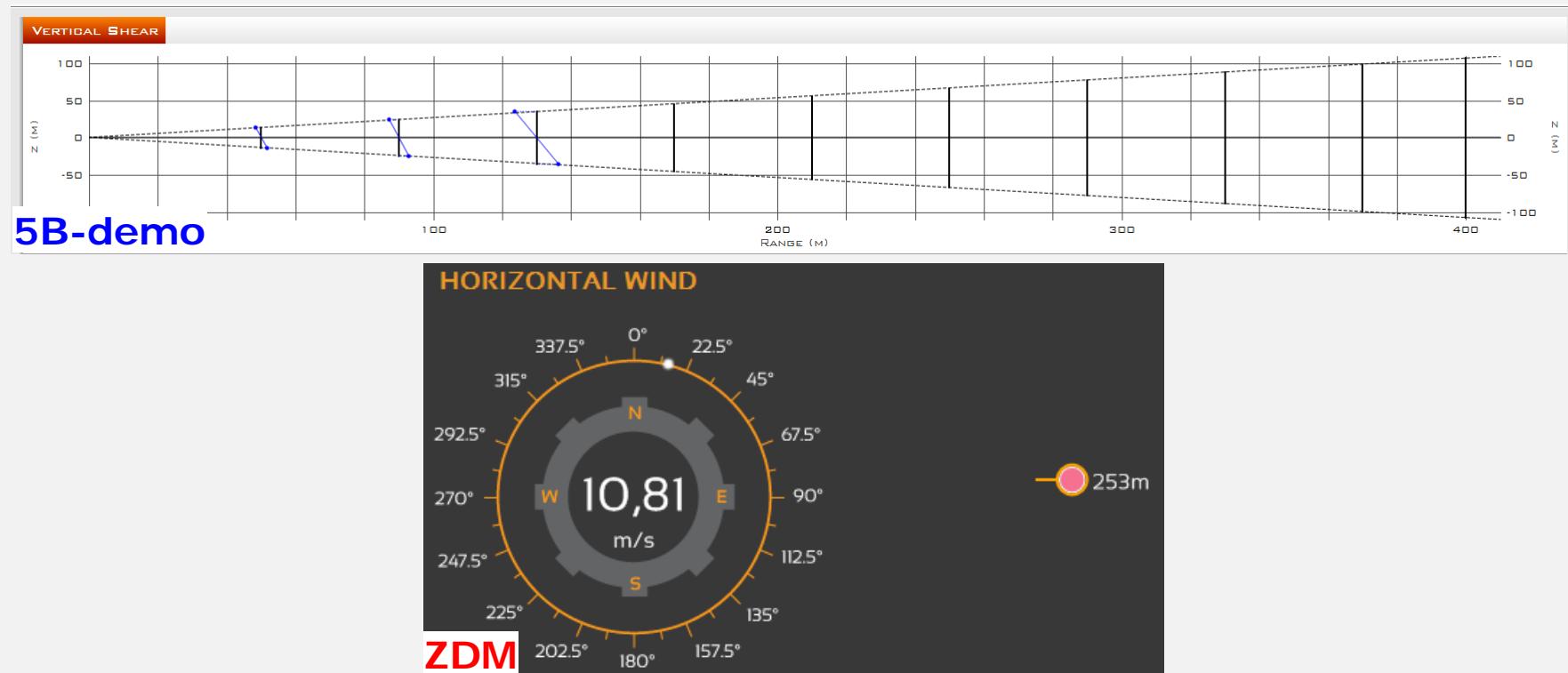
1. Backscattered light signal from photodetector (RAW data)
2. Doppler spectra (after FFT processing)
3. Line-of-sight velocity (estimators: peak, centroid, MLE, etc)



Lidar: measurements or estimates?

- Different levels of measurands in a wind lidar

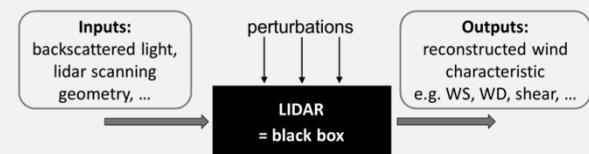
1. Backscattered light signal from photodetector (RAW data)
2. Doppler spectra (after FFT processing)
3. Line-of-sight velocity (estimators: peak, centroid, MLE, etc)
4. Reconstructed Wind Field Characteristics (uses inexact model of flow): wind speed & direction, shear, veer, turbulence, ...



White- vs. Black- box? Pros & cons

- **Black box:**

- Direct calibration of reconstructed parameters
- Pros: simple, limited knowledge required
- Cons: lidar-specific, practical setup unrealistic



- **White box:**

- Calibration of all the inputs of the Wind Field Reconstruction

PROS

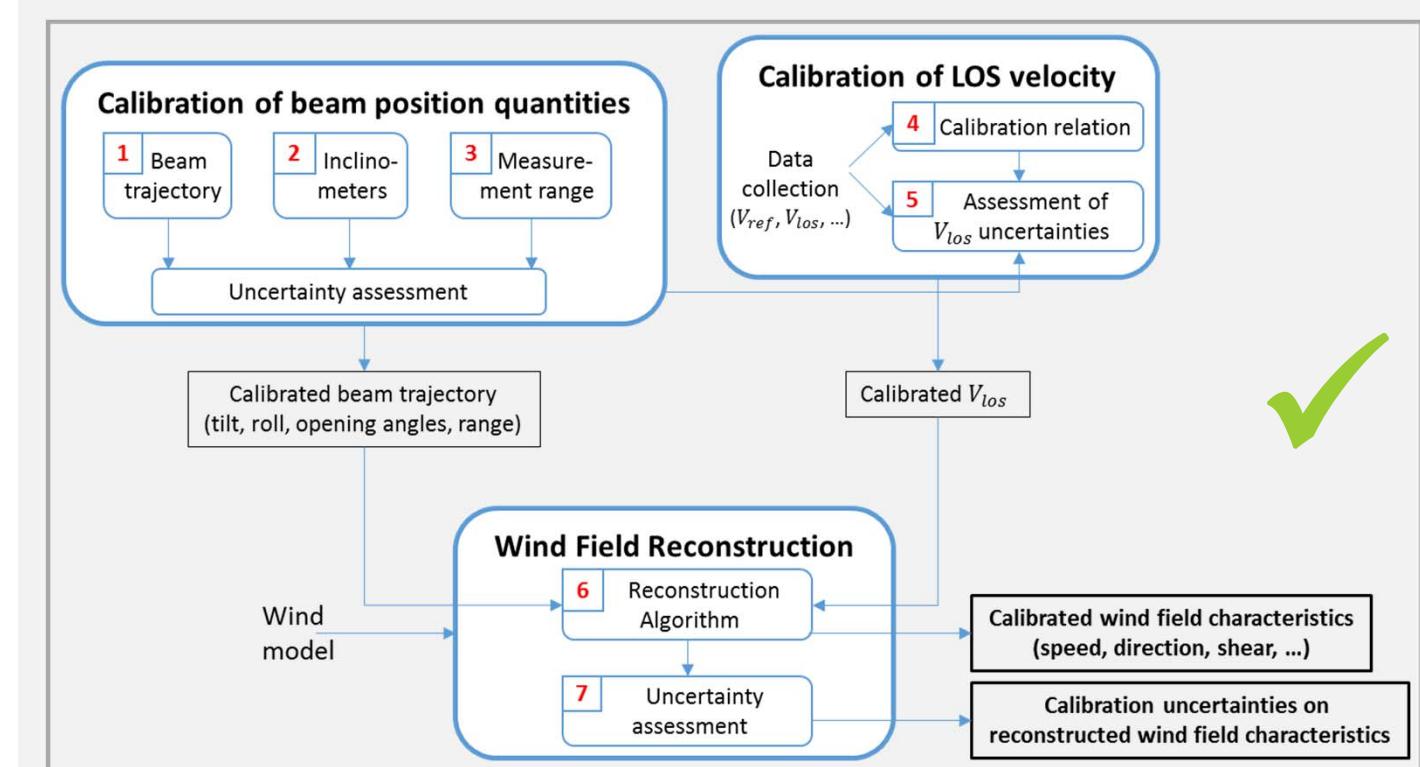
- Low sensitivity to WFR hyp.
- Genericity
- Uncertainties on any WFC

CONS

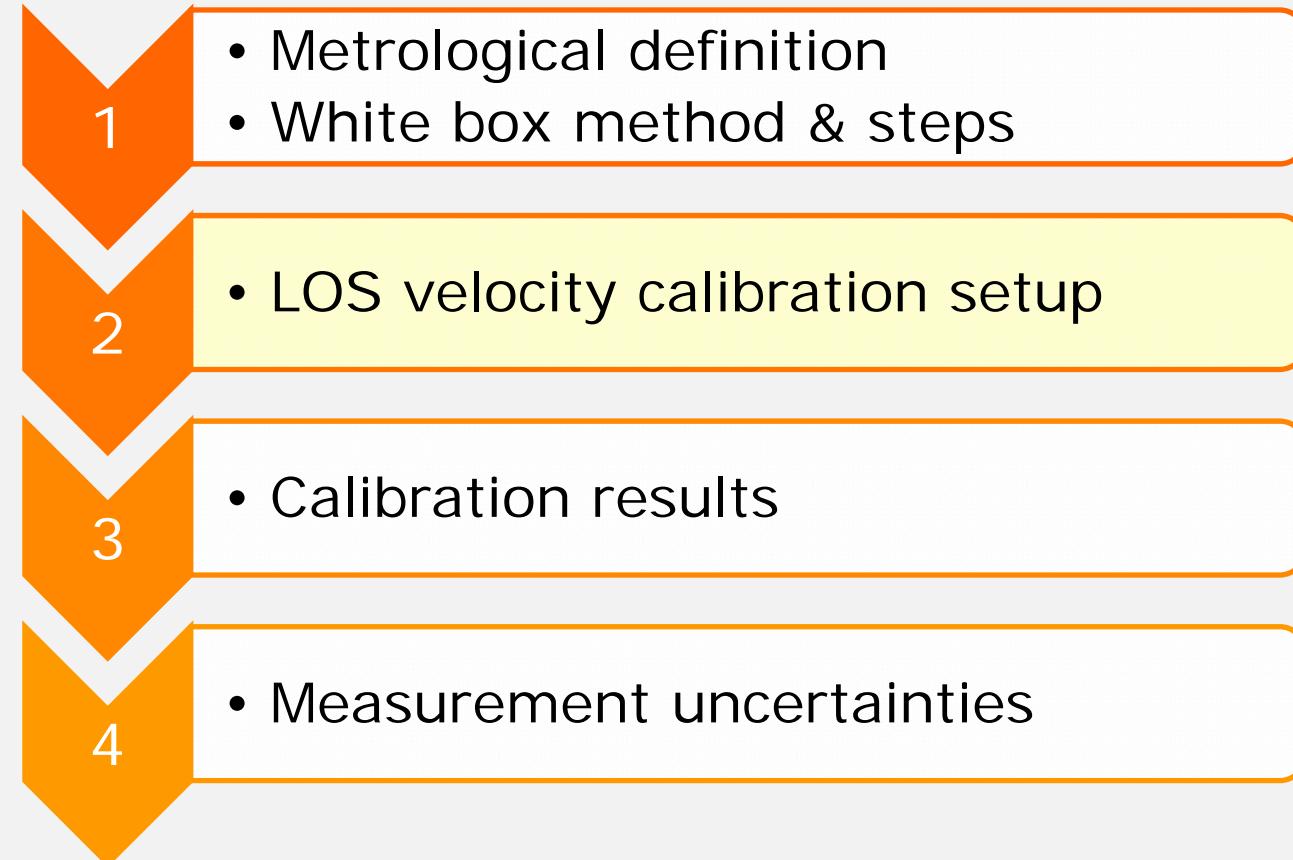
- Longer process (cal. all beams?)
- Need knowledge

[See also ECN report here](#), credit J.W.

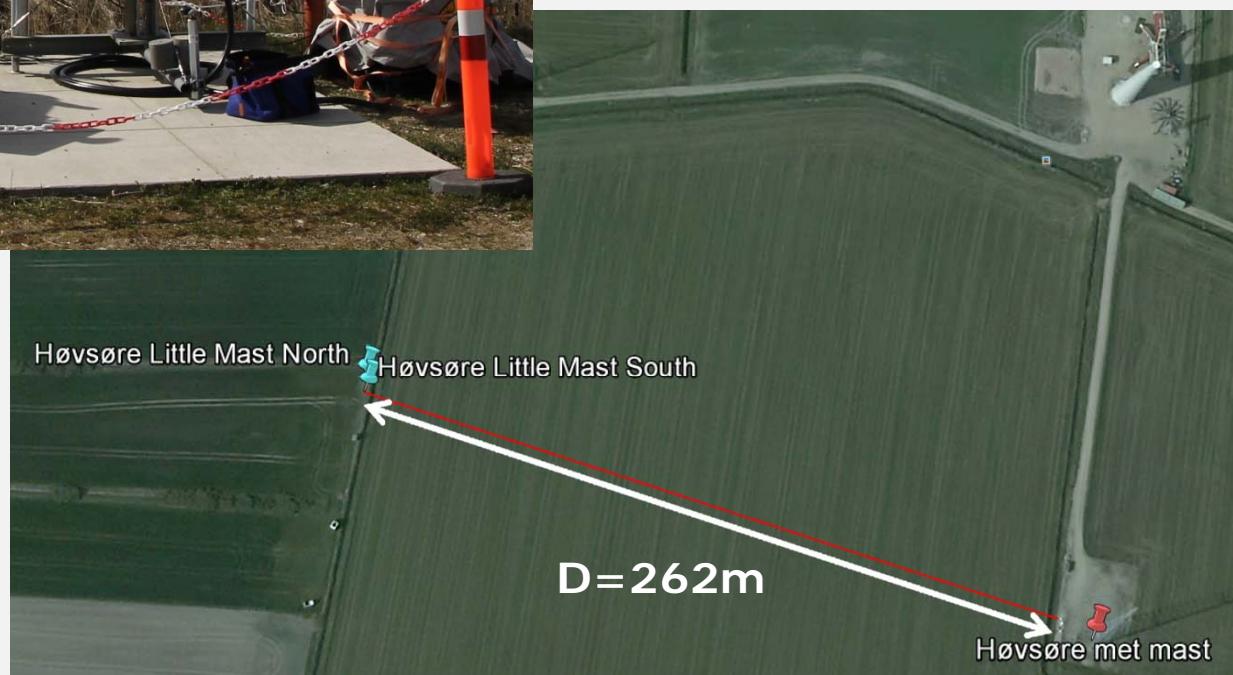
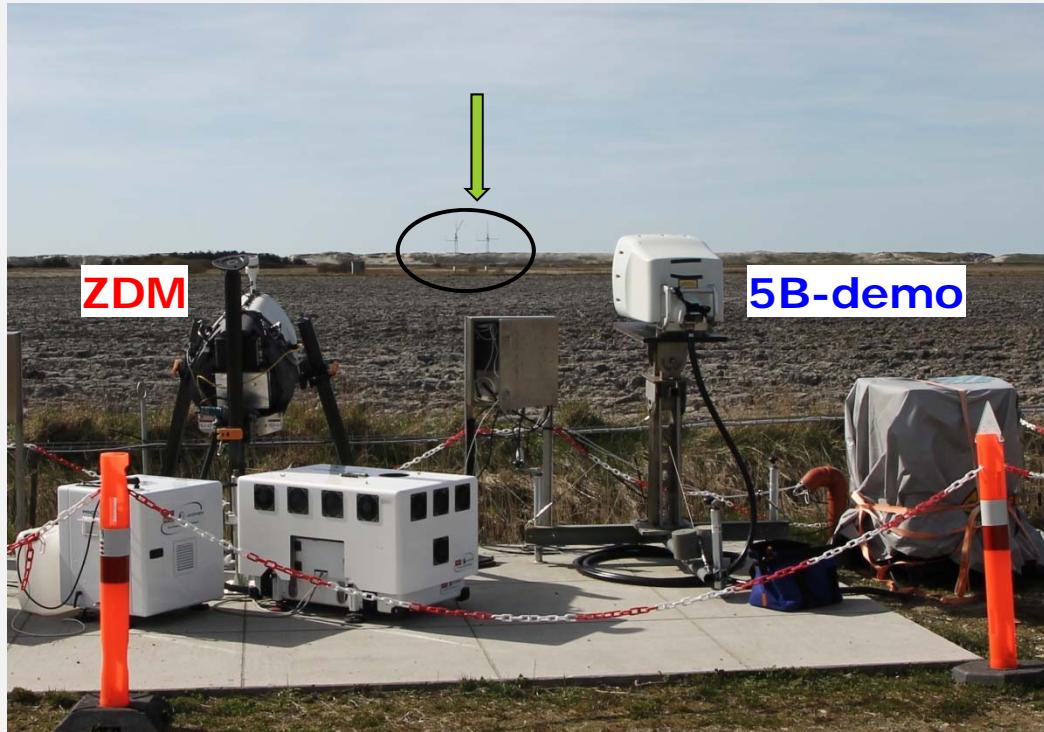
Wagenaar



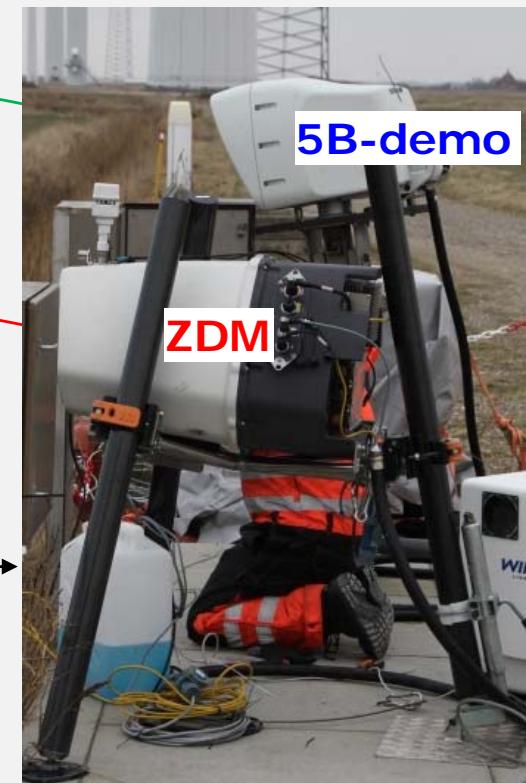
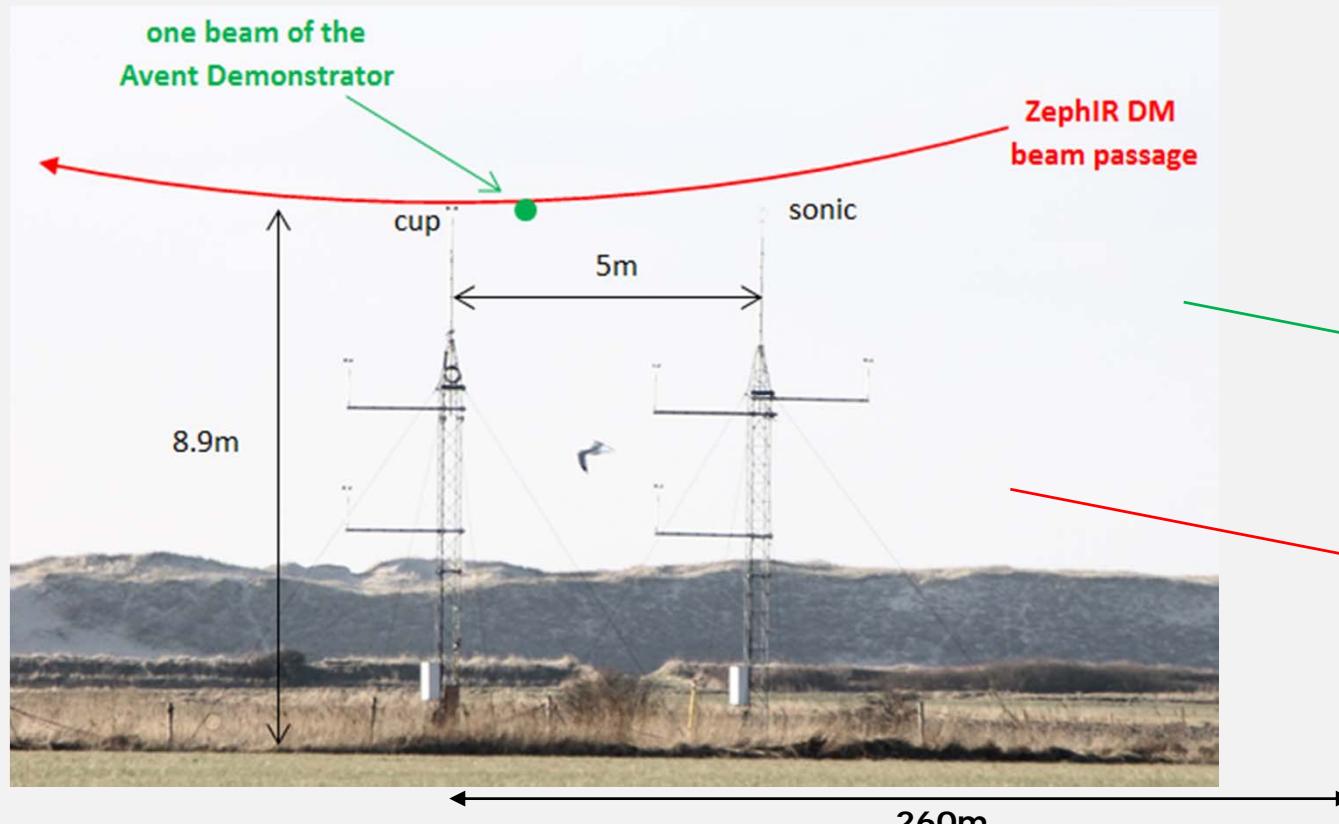
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V_{los} calibration: setup

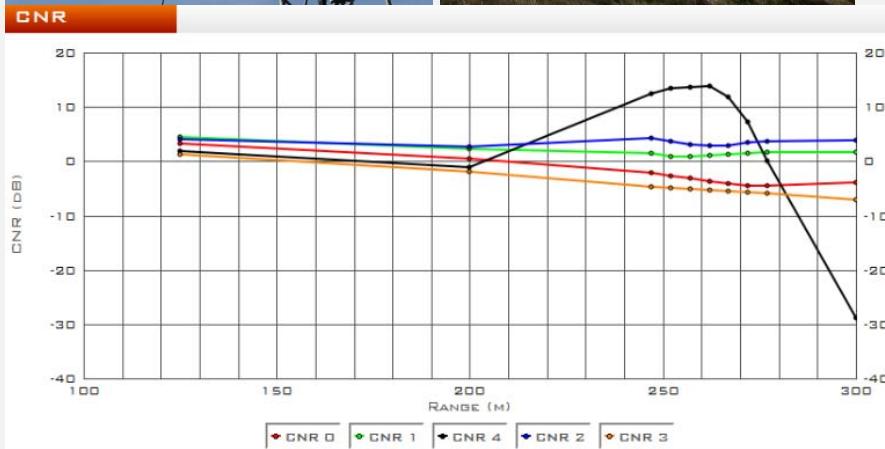


V_{los} calibration: setup



Beam positioning: using hard targets

Avent 5B-Demo

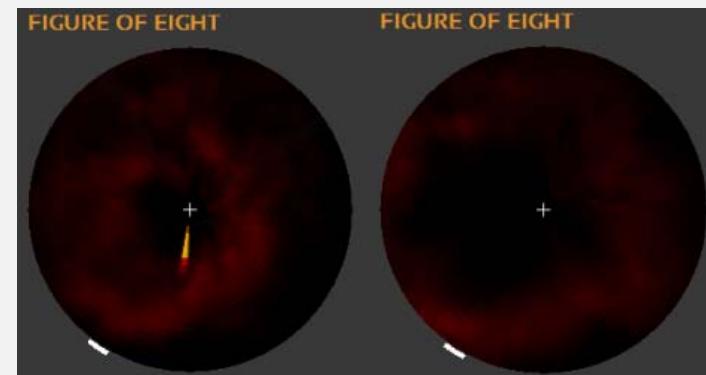


Zephir Dual Mode

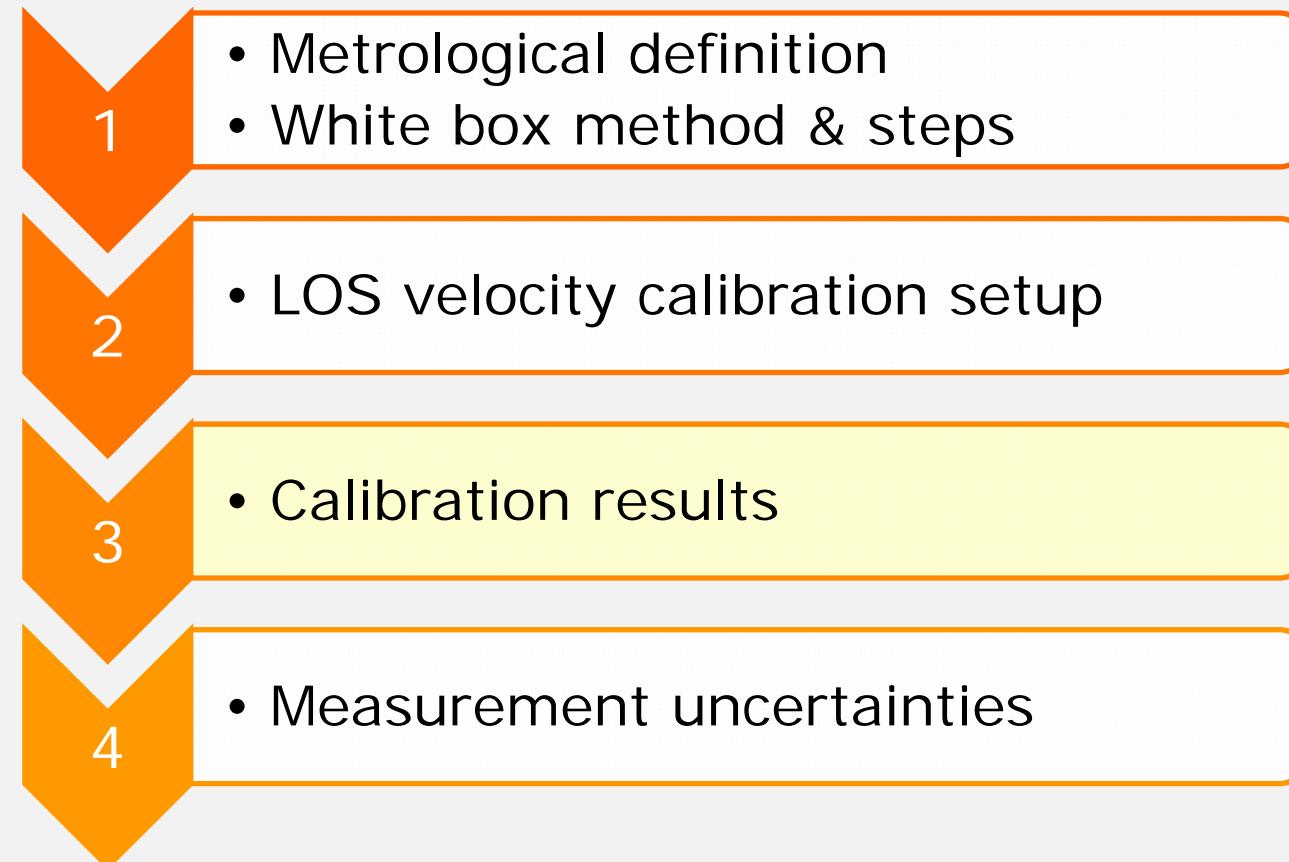
- adjust the tilting progressively



- Hit a moving target (e.g. cups)



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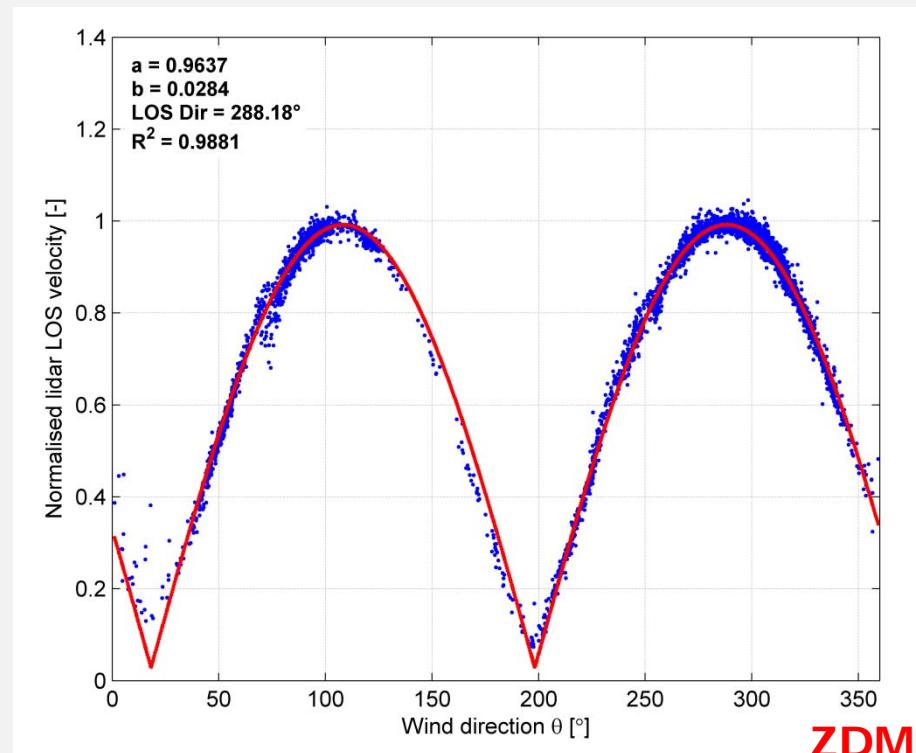
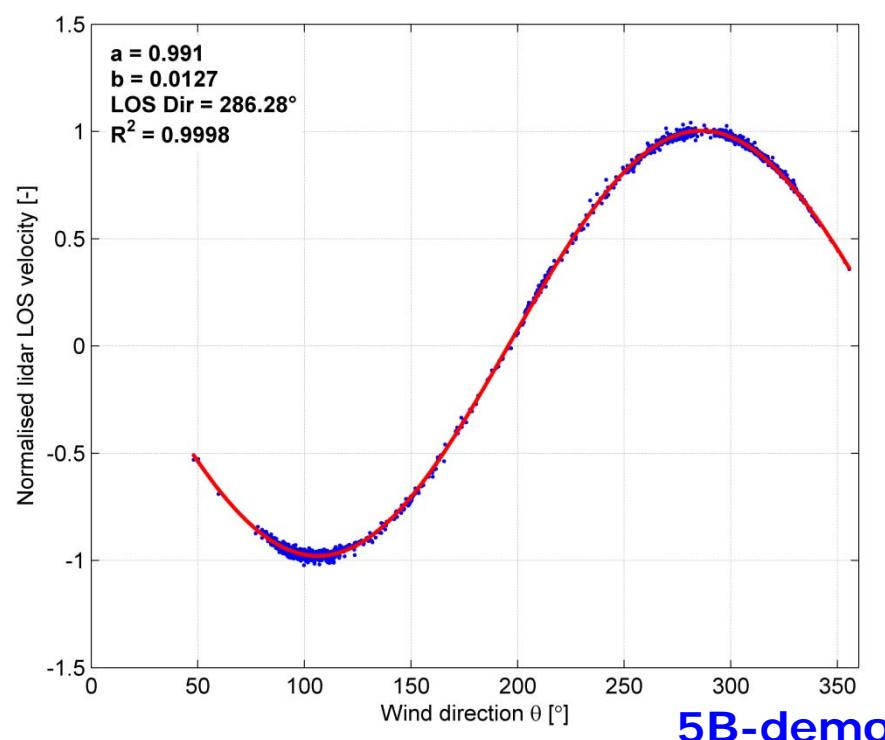
Data analysis

- Main data

- Cup: horizontal wind speed V_{hor}
- Sonic: wind direction θ
- Lidar: LOS velocity V_{los} ; tilt angle φ

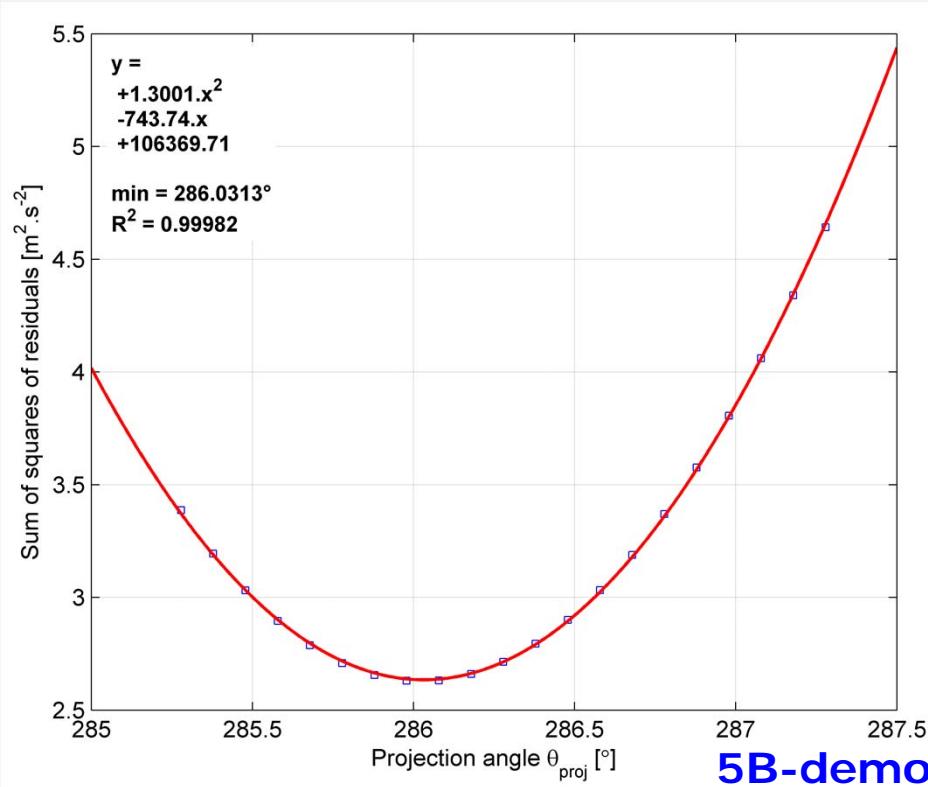
$$\left. \begin{array}{l} \\ \end{array} \right\} V_{ref} = V_{hor} \cdot \cos \varphi \cdot \cos(\theta - LOS_{dir})$$

- LOS direction evaluation (1): cosine/rectified cosine fit of Wdir response

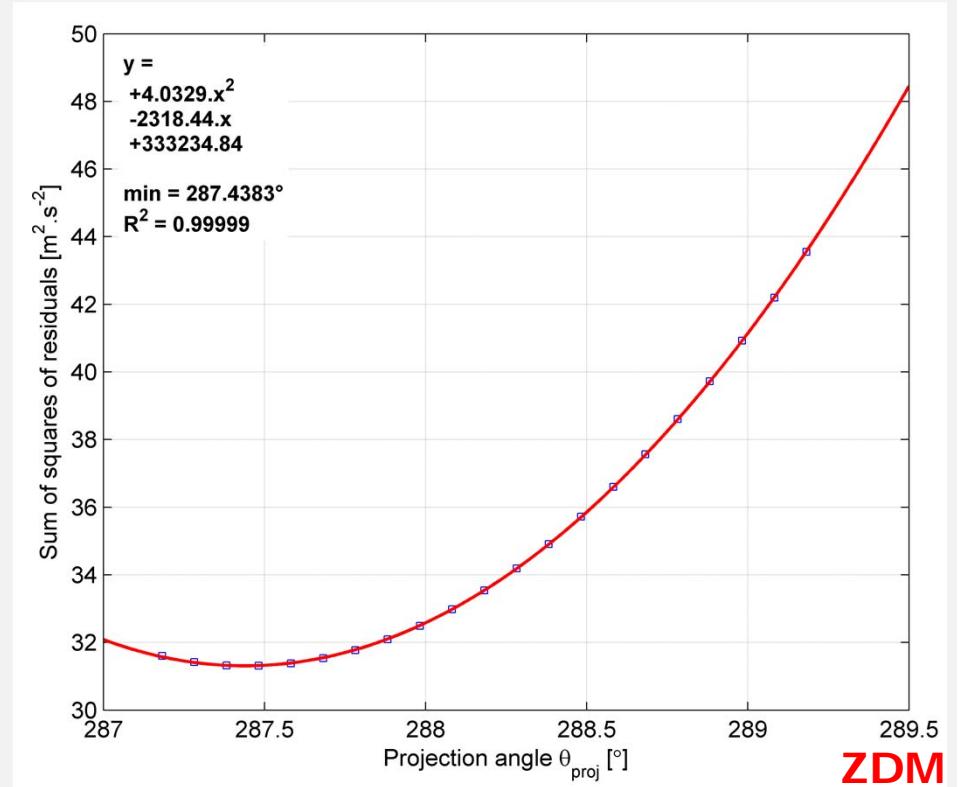


Data analysis

- **LOS direction evaluation (2)**
 - Projection angle range: $\pm 1^\circ$ to cosine fitted LOS_dir
 - Linear reg. each 0.1°
 - **LOS dir = min parabola**



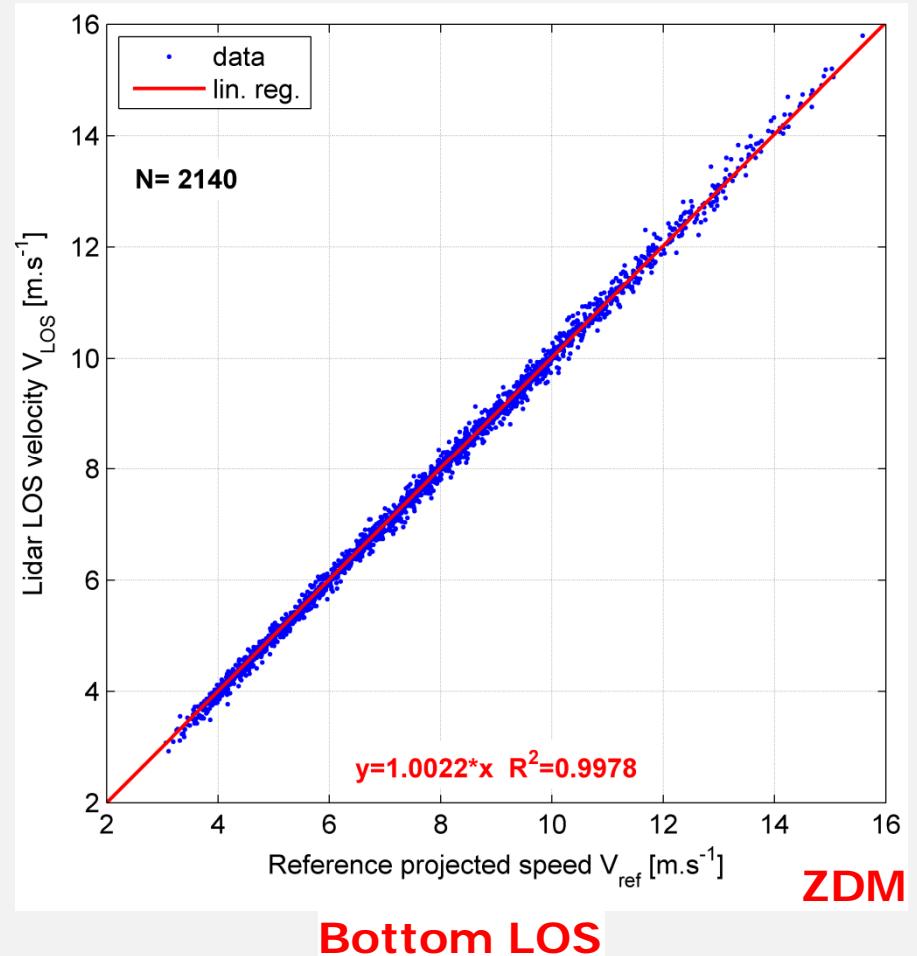
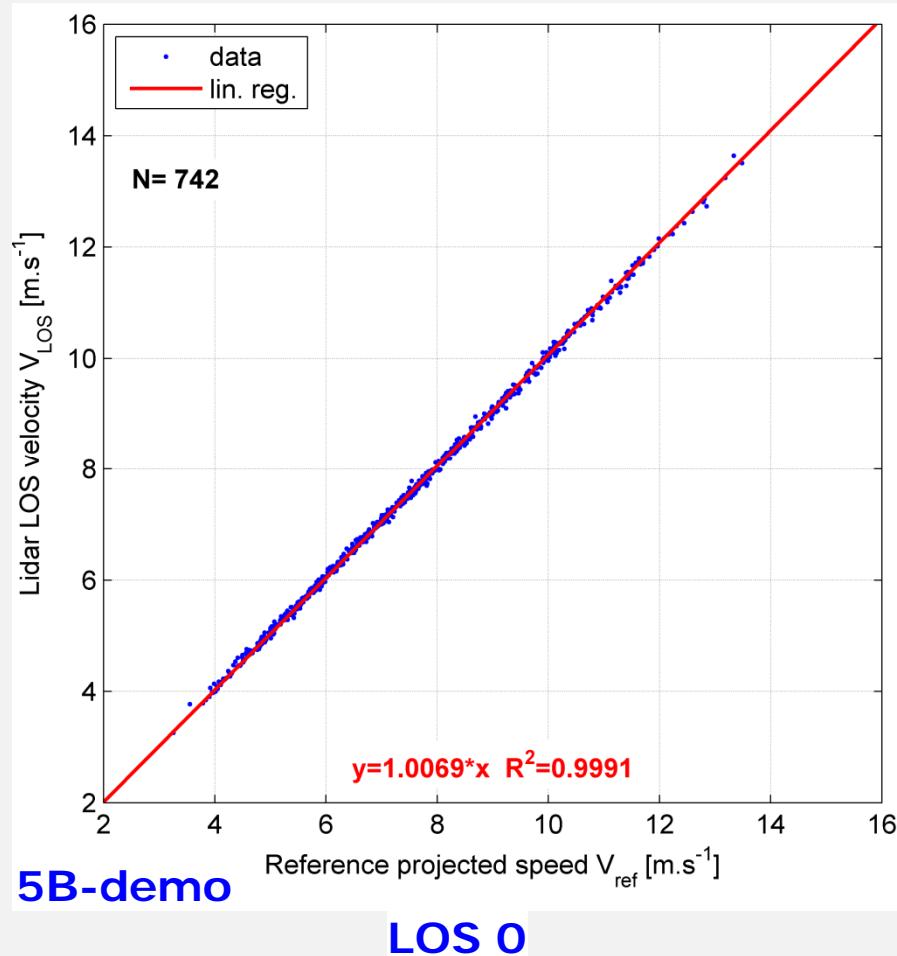
LOS 0



Bottom LOS

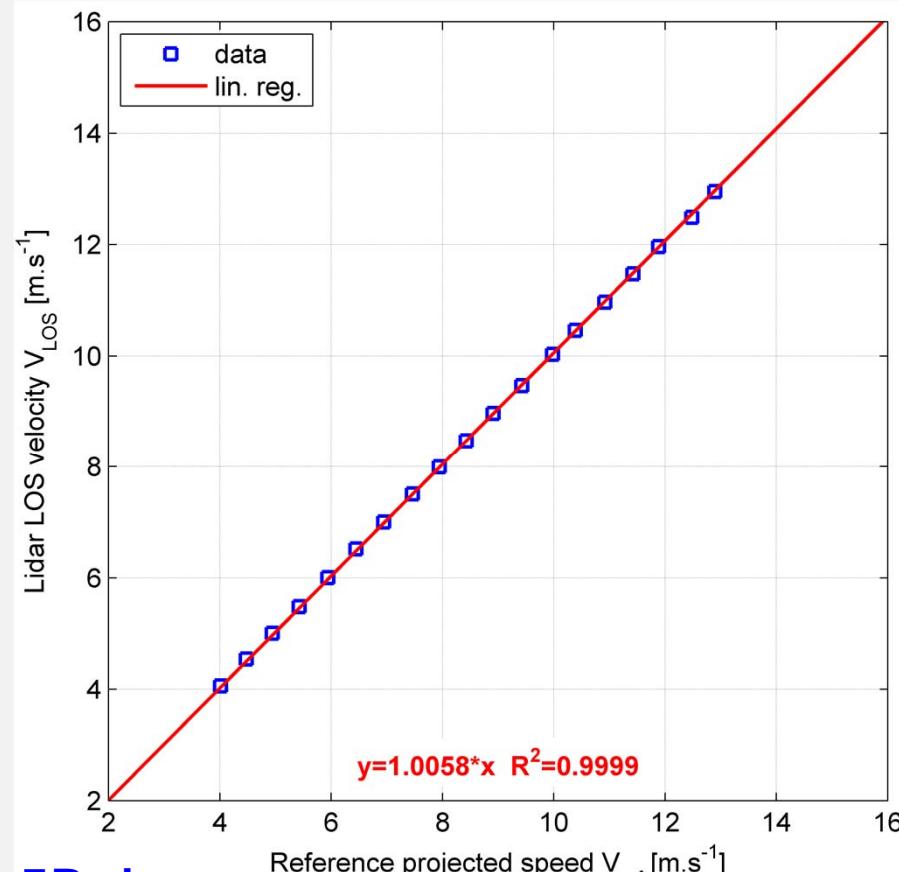
Calibration results

- Linear regression on 10-minute data



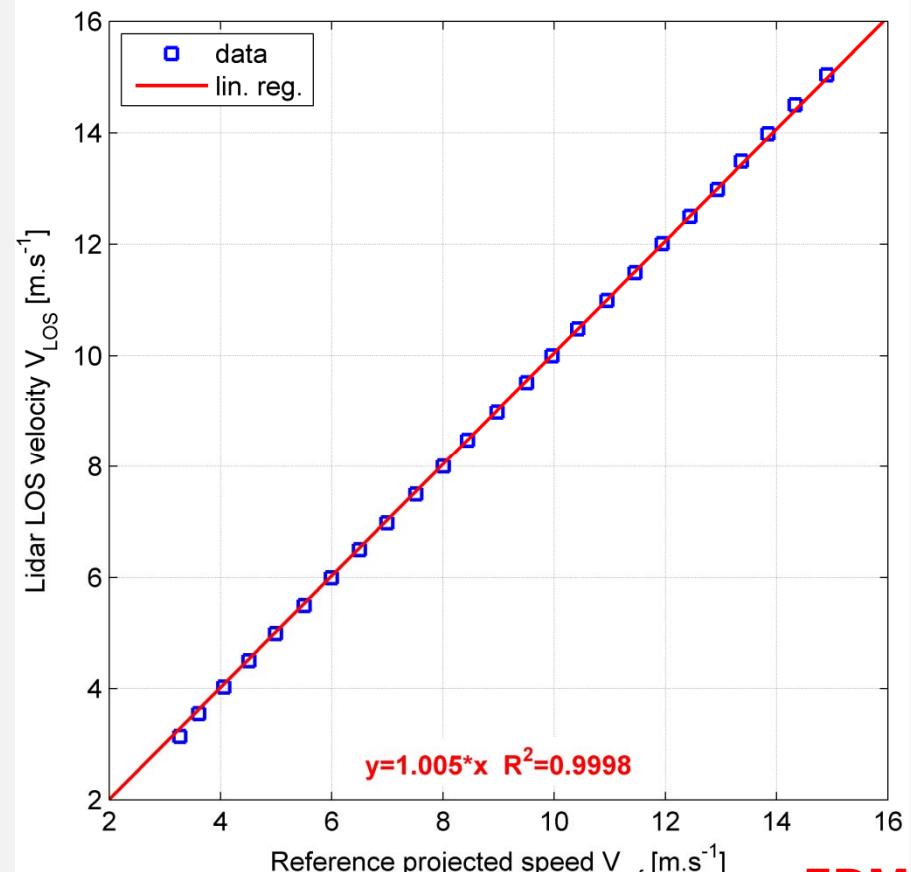
Calibration results

- Calibration relation = forced linear regression on binned data



5B-demo

LOS 0



ZDM

Bottom LOS

Calibration results

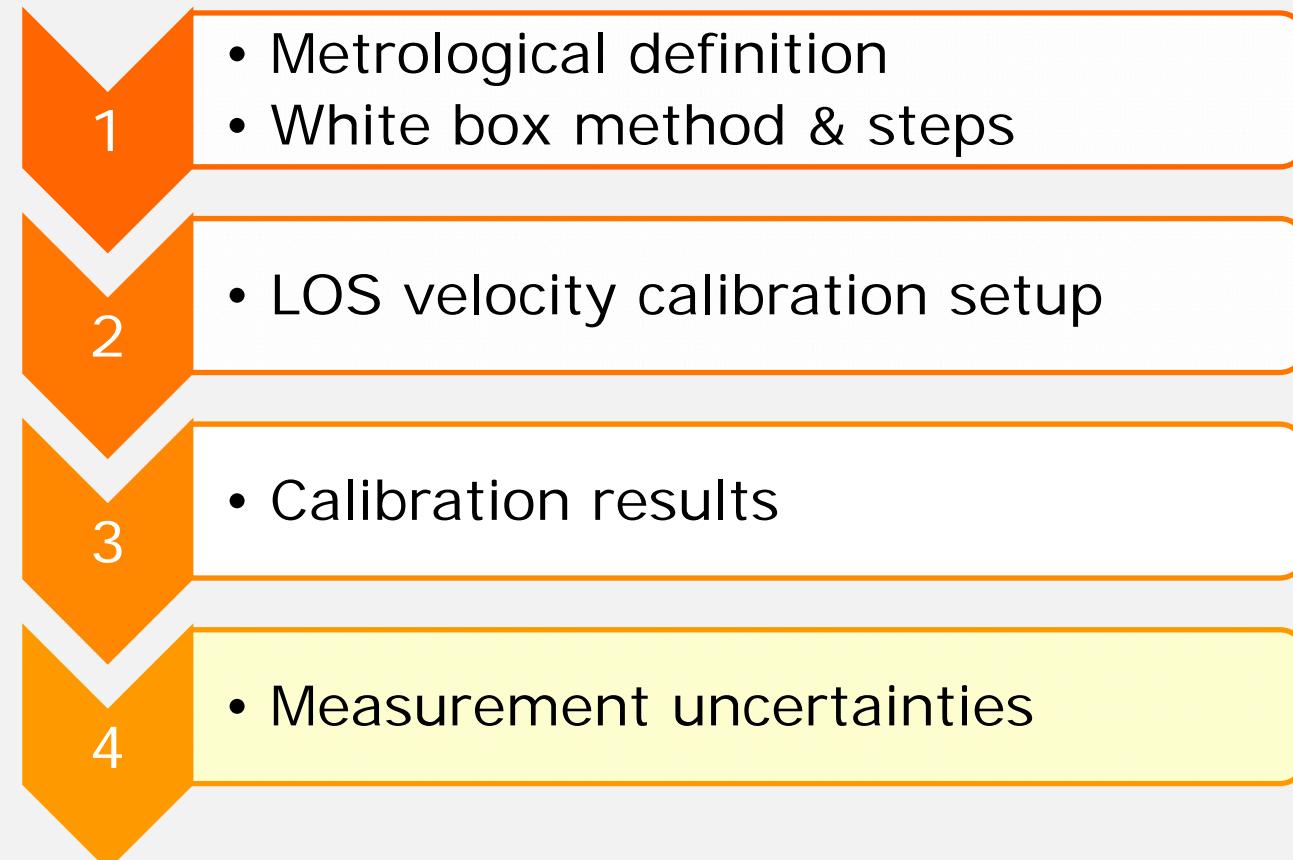


- **Summary:**

- lidar-measured LOS velocity: error of ~0.5 – 0.9%
- excellent agreement with the reference quantity V_{ref} : $R^2 > 0.9998$
- LOS direction method provides robust results ($\pm 0.05^\circ$)

Lidar	LOS	Calibration relation			
		θ_{los}	a	R^2	$Npts$
5B	LOS 0	286.03°	1.0058	0.9999	742
	LOS 1	285.99°	1.0072	0.9999	502
	LOS 2	285.99°	1.0084	1.0000	1087
	LOS 3	286.06°	1.0090	0.9999	446
	LOS 4	285.99°	1.0059	1.0000	1508
ZDM	179° – 181° azimuth	287.44°	1.0050	0.9998	2140

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What are the uncertainty sources?

$$V_{ref} = V_{hor} \cdot \cos \varphi \cdot \cos(\theta - LOS_{dir})$$

- Reference instruments uncertainties (type B)

– HWS (IEC 61400-12 procedure for cups)

- Wind tunnel calibration uncertainty + Measnet deviation

$$u_{cal} = \sqrt{u_{cal_1}^2 + \left(\frac{0.01}{\sqrt{3}} \cdot V_{hor} \right)^2}$$

- Operational uncertainty

$$u_{ope} = \frac{1}{\sqrt{3}} \cdot \text{cup class number} \cdot (0.05 + 0.005 \cdot V_{hor})$$

- Mounting uncertainty

$$u_{mast} = 0.5\% \cdot V_{hor}$$

– Wind direction, from calibration certificate of sonic anemometer:

$$u_\theta \approx 0.4^\circ$$

What are the uncertainty sources?

$$V_{ref} = V_{hor} \cdot \cos \varphi \cdot \cos(\theta - LOS_{dir})$$

- **Calibration process uncertainties (type B)**

- LOS direction uncertainty

$$u_{LOS\ dir} = 0.1^\circ$$

- Uncertainty of tilt inclination angle

$$u_\varphi = 0.05^\circ$$

- Beam positioning uncertainty: $u_H = 10\ cm$, shear $\alpha_{exp} = 0.2$

$$u_{pos} = \alpha_{exp} \cdot \frac{u_H}{H} \cdot V_{hor} \approx 0.23\% \cdot V_{hor}$$

- Inclined beam and range uncertainty: "how the volume-averaging affects the V_los estimation when the beam is inclined" (see model in DTU report E-0086, Annex A)

$$u_{inc} = 0.052\% \cdot V_{hor}$$

- **Calibration relation uncertainty (type A, statistical)**

- Uncertainty on gain of forced linear regression on binned V_los:
→ half-width of 68% CI

$$u_a \sim 10^{-3} = 0.1\%$$

Uncertainties: how to combine components?



- **GUM methodology**: analytical method ([download](#))

- 1) Define measurement model: $y_m = f(x_1, x_2, \dots, x_n)$
- 2) Law of propagation of uncertainties for uncorrelated inputs x_i :

$$U_c = \sqrt{\sum_{i=1}^n \left(\frac{\partial y_m}{\partial x_i} \cdot u_{x_i} \right)^2}$$

- 3) Expanded uncertainty with coverage factor k

$$U_{exp} = k \cdot U_c$$

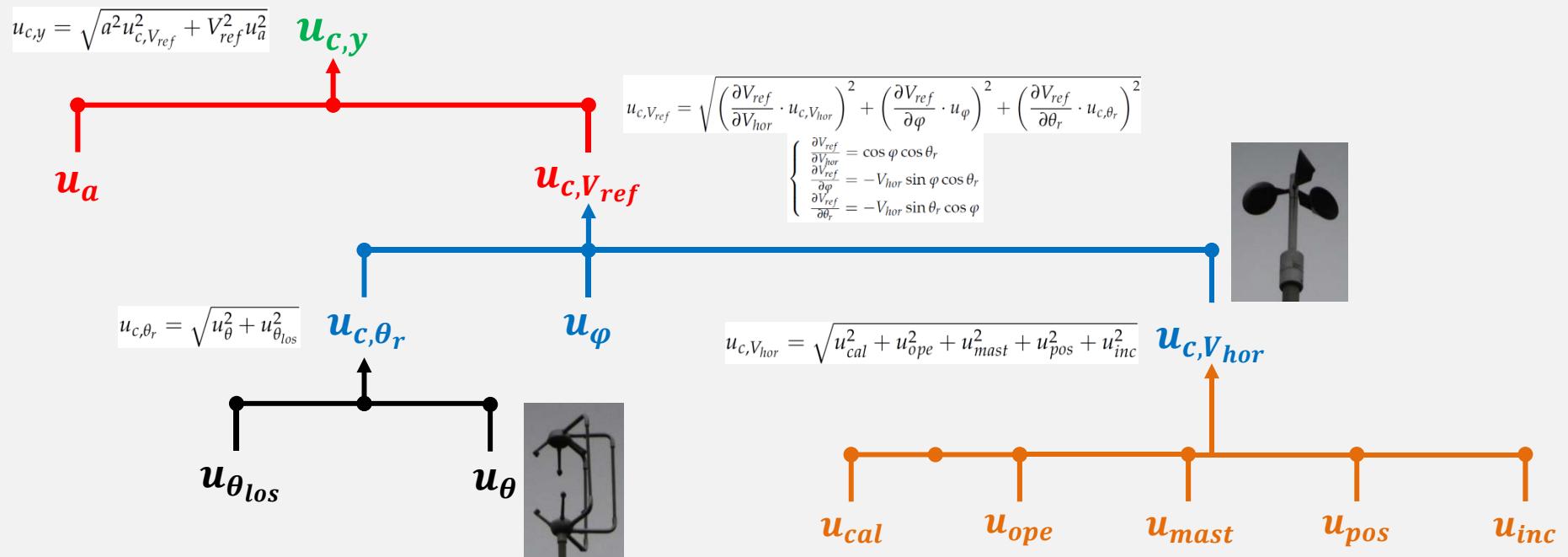
typically $k=2 \rightarrow U_{exp}$ corresponds to 95% confidence interval

Uncertainty propagation: "tree structure"

- Measurement model

$$a \cdot V_{ref} = y = a \cdot V_{hor} \cdot \cos \varphi \cdot \cos \underbrace{(\theta - LOS_{dir})}_{\theta_r}$$

- Tree of uncertainties: the GUM method applied to the V_los calibration

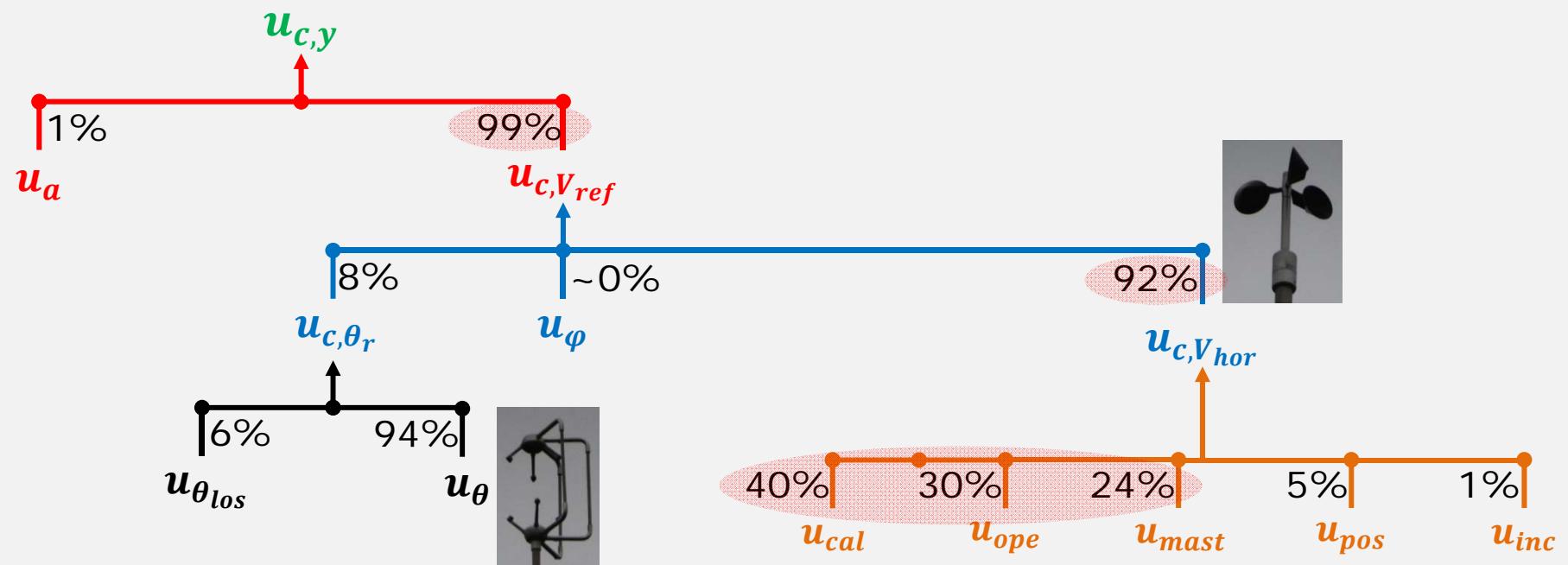


Uncertainty propagation: prevailing sources

- Measurement model

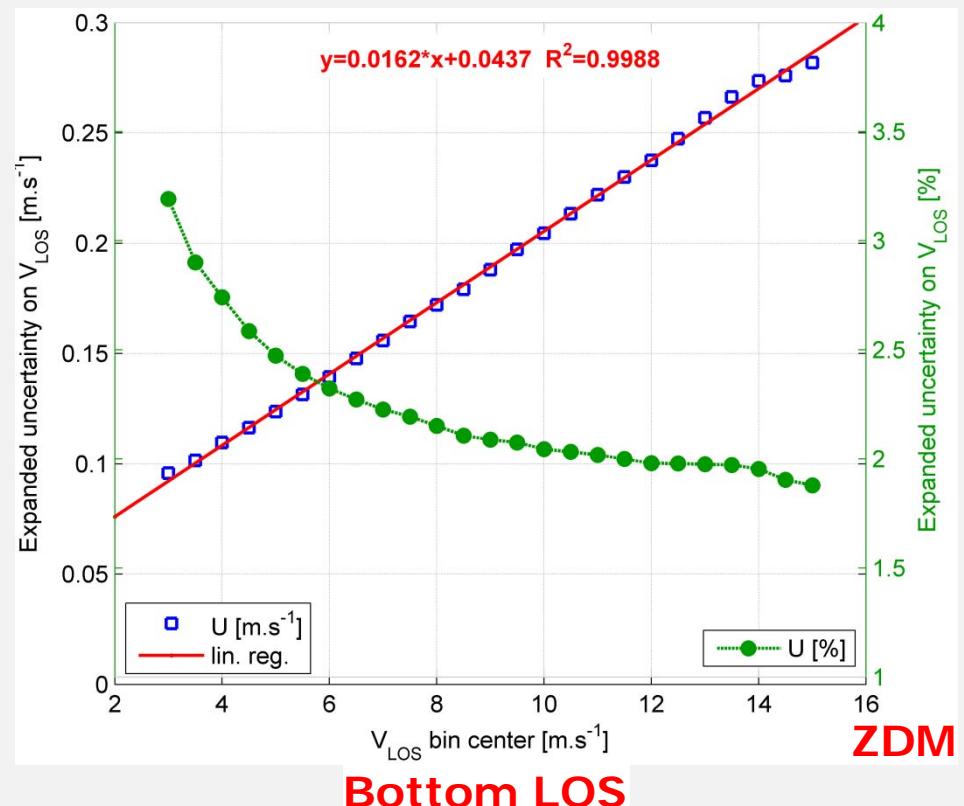
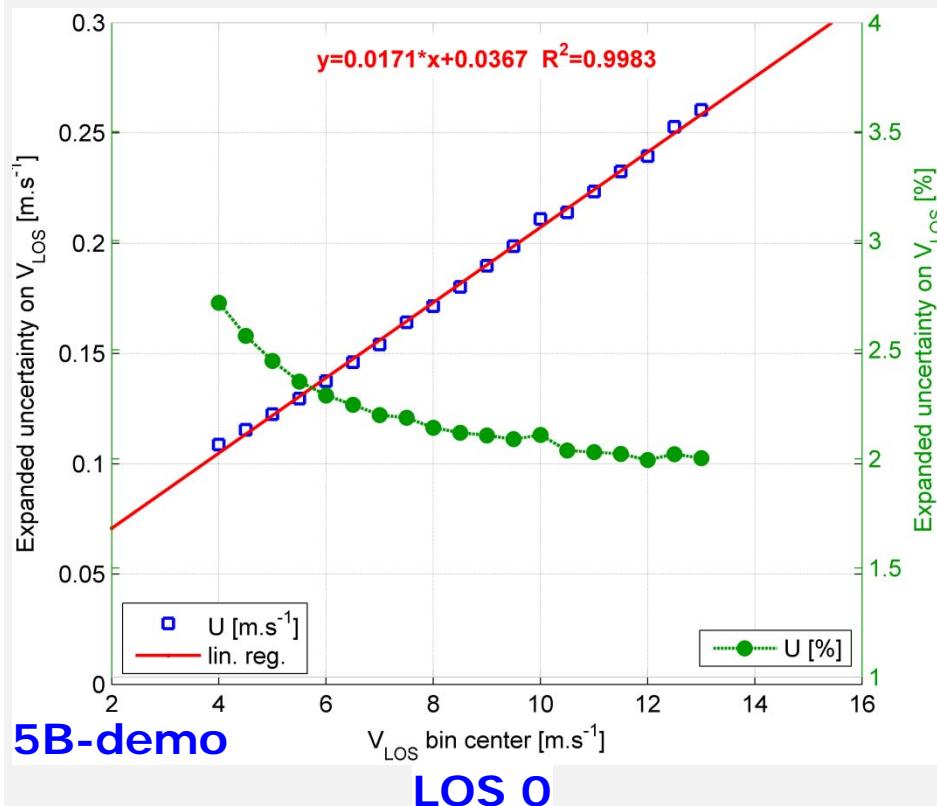
$$a \cdot V_{ref} = y = a \cdot V_{hor} \cdot \cos \varphi \cdot \cos \underbrace{(\theta - LOS_{dir})}_{\theta_r}$$

- Average contribution of: each uncertainty component to the "next level"



Measurement uncertainty: results

- Expanded uncertainties ($k=2$) vs. V_{los} : in m/s **and** in %
- U_{exp} increases linearly (m/s)
- ~3% at 4m/s
- ~2% at 10 m/s



Conclusion

- **Take-aways**

- White-box methodology: most generic approach
- It works, demonstrated!
- V_los uncertainties of ~2 – 3% at 95% confidence
- Reference uncertainty prevails: need for less uncertain ref. instruments

- **Do we have a workable calibration method for both lidars?**

- Repeatable? → yes
- Usable for measurement campaigns? → yes
- Uncertainty that we believe in? → yes
- Reconstructed outputs uncertainties?
 - yes, for simple analytical expressions: see example of two-beam lidar in journal paper
 - ongoing work: uncertainty propagation for advanced Wind Field Reconstruction techniques (see Antoine WFR presentation)

Publications



- **Publications:**

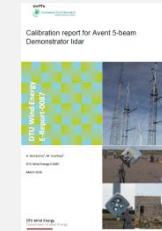
- [DTU E-0086](#) report

→ generic methodology



- [DTU E-0087](#) report

→ detailed procedure 5B-demo



- [DTU E-0088](#) report

→ detailed procedure ZDM



- [Journal paper](#)

→ *Remote Sensing of Wind Energy* (special issue)
→ methodology, results, discussions, 2-beam example
→ doi: 10.3390/rs8110907



Article

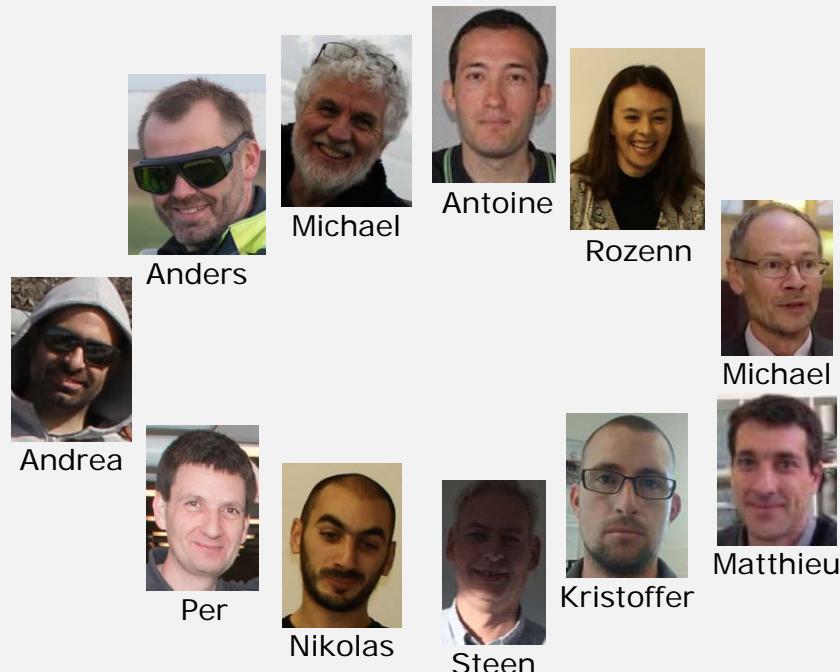
Generic Methodology for Field Calibration of Nacelle-Based Wind Lidars

Antoine Borraccino ^{*†}, Michael Courtney [†] and Rozenn Wagner [†]

Thanks for your attention!

More info:

- website www.unitte.dk
- contact borr@dtu.dk



Questions?



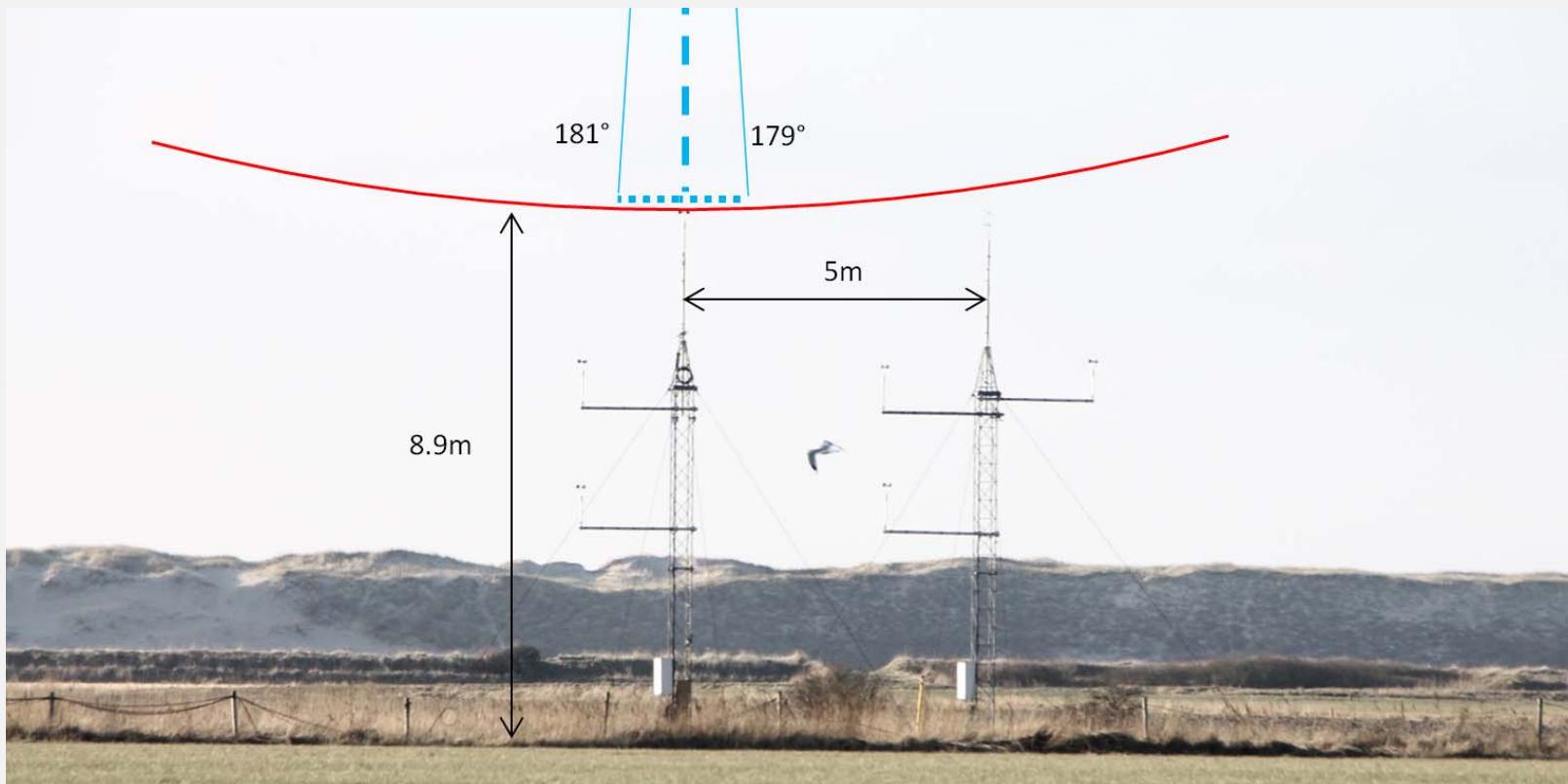
Preparing questions



Calibration results

ZDM

- Parameter to adjust: width of valid azimuth sector



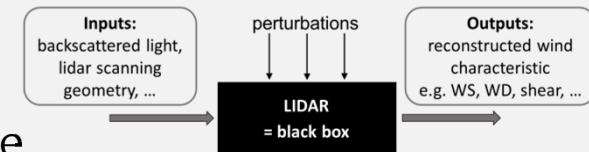
- Used for averaging realtime data from "RAW" files

White- vs. Black- box

- **Black box:**



- Direct calibration of reconstructed parameters
- Pros: simple, limited lidar knowledge required
- Cons: lidar specific, practical setup unreasonable



- **White box: calibration of all lidar reconstruction algo inputs**

1. Geometry of the lidar: where is the beam?
 - a. Inclinometer calibration
 - b. Opening / cone angles check
2. Position the beam close to a reference instrument
3. Calibrate **V_LOS** by comparing to a reference
4. Derive uncertainties: transfer reference → V_LOS
5. Combine several V_LOS according to reconstruction algorithms
6. Derive uncertainties on ANY reconstructed parameter as long as
 - the reconstruction algo is known
 - correlation between uncertainty distribution on input parameters



Black & white box calibration of lidars

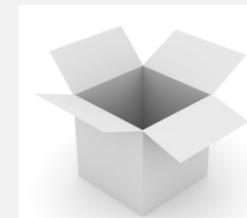
Two different principles

- **Lidar measurements and outputs**

- Measurand: frequency of the backscattered light
- Converts it in a Radial Wind Speed, i.e. the **component of the wind vector in the line of sight** (LOS, laser beam direction)
- RWS considered as the "raw measured quantity"
- Output parameters
 - obtained by applying mathematical models to a number of RWS measurements → reconstruction algorithms
 - Examples: HWS, shear, wind direction, veer, ...

- **Two principles**

- Black box: calibration of the "mathematically derived" parameter against the same type of parameter measured by a reference instrument
 - E.g. HWS vs. Cup anemometer wind speed
- White box: calibration of the parameters used as inputs to the reconstruction algorithm
 - ➔ individual beams RWS calib



Black & white box calibration of lidars

Black box: requirements, pros, cons, example (1/2)



- **Requirements**

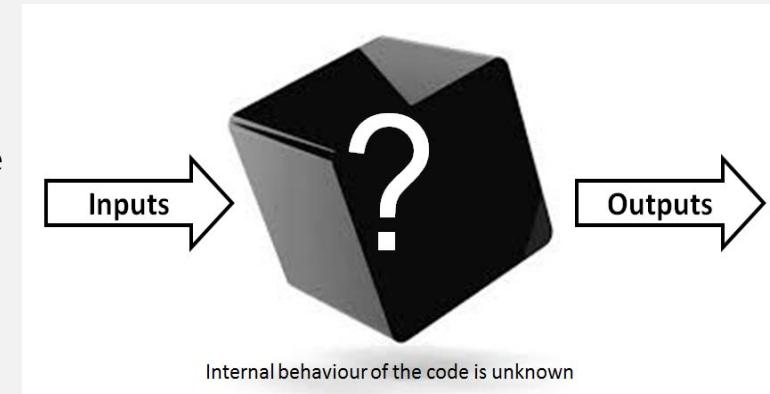
- availability / existence of a reference instrument for the type of data to calibrate
- reference instrument MUST be calibrated (certificate ...)

- **Pros**

- Direct comparison of the data:
 - reconstructed output vs. Reference
 - no additional algorithm to transform the data
 - fast and relatively easy

- **Cons**

- Need for multiple reference instruments: theoretically, one for each output
- Assumptions adding uncertainties
 - ➔ e.g. homogeneity, issue for nacelle-based lidars (horizontally shooting)
- **!! the reconstructed output can physically not exist !!**



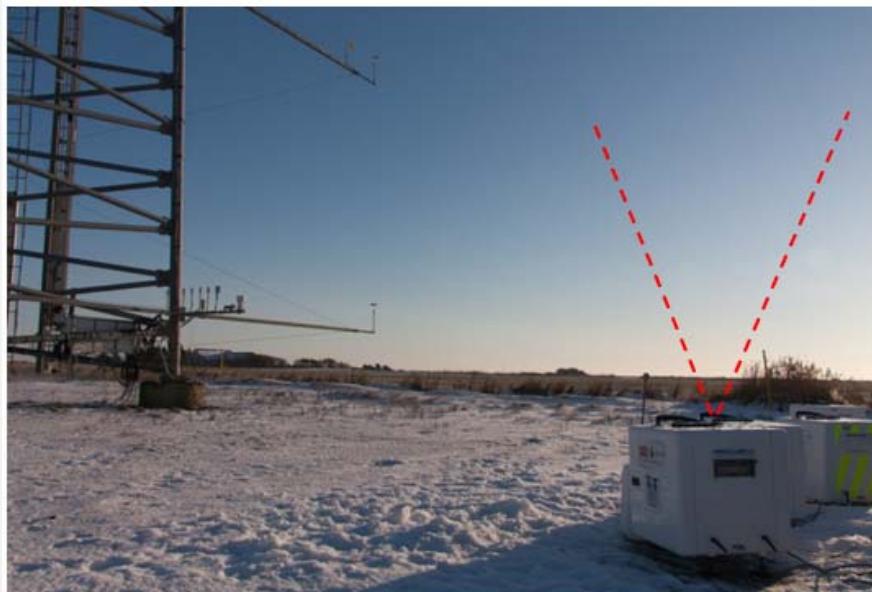
Black & white box calibration of lidars

Black box: requirements, pros, cons, example (2/2)



- **Example: calibration of ground-based profiling lidars**

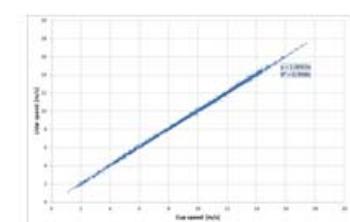
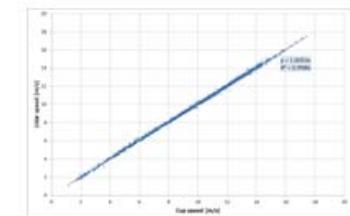
- Measurand: horizontal wind speed
- Reference: cup anemometers at several heights
- Additional uncertainties?
 - Measurement at same height?
 - Is the beam vertical? → inclinometer for roll angle
 - Homogeneity assumption is satisfied quite well



116m

...

40m



5 heights

Black & white box calibration of lidars

White box: requirements, pros, cons, example (1/2)



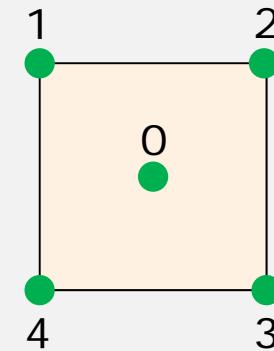
• Requirements

- ✓ – Being able to actually calibrate the RWS → availability / existence of reference instrument for wind speed and direction
- ✓ – Being able to check the geometry → e.g. angles used for HWS projection
- ✓ – Calibrate the inclinometers → roll and tilt
- ✗ – Having access to the mathematical model used by the manufacturer for reconstruction
 - ?
 - not the algorithms themselves
 - Mandatory in order to derive uncertainties on the reconstructed outputs

• Pros

- Calibration of a physically existing quantity
- For nacelle lidars, homogeneity is not needed or less sensitive
- Uncertainties
 - on theoretically any reconstructed parameter
 - even for parameters that cannot be measured by reference instruments (shear?)

Calibration results all 5 beams - Demonstrator



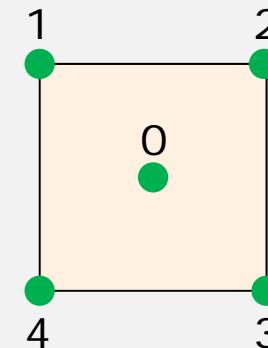
LOS	Range selected [m]	LOS dir [°]	Valid data points	Binned calibration					range of valid bins [m/s]					
				"Free" regression			Forced regression							
				gain	offset	R2	gain	R2	min	max				
0 (comb)	262	286,03	742	0,9982	0,0709	1,0000	1,0058	0,9999	4	13				
1	252	285,99	502	1,0043	0,0314	1,0000	1,0072	0,9999	3,5	15,5				
2	252	285,99	1087	1,0056	0,0267	1,0000	1,0084	1,0000	3	13,5				
3	252	286,06	446	1,0097	-0,0046	0,9999	1,0090	0,9999	3,5	10				
4	252	285,99	1508	1,0069	-0,0142	1,0000	1,0056	1,0000	3,5	15				

- **Linear regression(s)**
 - "free" vs. Forced
 - R2 perfect, offsets close to 0
 - diff on gains between 1,2,3,4 and 0 not explained by range

Calibration results all 5 beams - Demonstrator



- LOS 0 – LOS 4 – LOS 1 – LOS 0 – LOS 3 – LOS 2



LOS	Range selected [m]	LOS dir [°]	Valid data points	Binned calibration					range of valid bins [m/s]		TI range	T abs 2m range		
				"Free" regression			Forced regression							
				gain	offset	R2	gain	R2	min	max				
0 (comb)	262	286,03	742	0,9982	0,0709	1,0000	1,0058	0,9999	4	13	10-17%	3-10° C		
1	252	285,99	502	1,0043	0,0314	1,0000	1,0072	0,9999	3,5	15,5	10-16%	2-7° C		
2	252	285,99	1087	1,0056	0,0267	1,0000	1,0084	1,0000	3	13,5	10-17%	4-8° C		
3	252	286,06	446	1,0097	-0,0046	0,9999	1,0090	0,9999	3,5	10	9-16%	4-7,5° C		
4	252	285,99	1508	1,0069	-0,0142	1,0000	1,0056	1,0000	3,5	15	10-18%	4-9° C		

- TI
 - 10-17% → relatively high because of measurement height (8.9m)
- Temperature @2m
 - Winter time in DK
 - No negative T in valid dataset!

Calibration results

ZDM

- Range = 253m
- valid data points = 2140
- TI range = 10-17%
- T abs 2m range = 3-8 ° C
- 2 deg width of azimuth sector, 4 deg, 6 deg, 8 deg, 10 deg

Azimuth sector °	Range selected [m]	LOS dir [°]	Valid data points	Binned calibration					range of valid bins [m/s]	TI range	T abs 2m range			
				"Free" regression			Forced regression							
				gain	offset	R2	gain	R2						
179-181	253	287,44	2140	1,0153	-0,1049	0,9999	1,0054	0,9998	4	15	10-17%	3-8° C		
178-182	253	287,45	2140	1,0154	-0,1051	0,9999	1,0055	0,9998	4	15	10-17%	3-8° C		
177-183	253	287,48	2140	1,0148	-0,1007	1,0000	1,0053	0,9999	4	15	10-17%	3-8° C		
176-184	253	287,46	2140	1,0152	-0,1001	0,9999	1,0057	0,9999	4	15	10-17%	3-8° C		
175-185	253	287,49	2140	1,0157	-0,1032	0,9999	1,0059	0,9998	4	15	10-17%	3-8° C		

- Conclusion
 - consistent results between sectors
 - Free regression → not so good
 - Forced regression → better

Calibration results

ZDM & Demonstrator



Azimuth sector °	Range selected [m]	LOS dir [°]	Valid data points	Binned calibration					range of valid bins [m/s]	TI range	T abs 2m range			
				"Free" regression			Forced regression							
				gain	offset	R2	gain	R2						
179-181	253	287,44	2140	1,0153	-0,1049	0,9999	1,0054	0,9998	4	15	10-17%	3-8° C		
0 (comb)	262	286,03	742	0,9982	0,0709	1,0000	1,0058	0,9999	4	13	10-17%	3-10° C		

- **Consistent gain on forced regression**
 - coincidence? → probably not
- **LOS direction difference**
 - expected: ~0.3° (eq. 1.5m on the ground)
 - cannot be explained by different in location
 - Probably a misalignment of ZDM (done by eye)