Technical University of Denmark

Generic calibration procedures for nacelle-based profiling lidars

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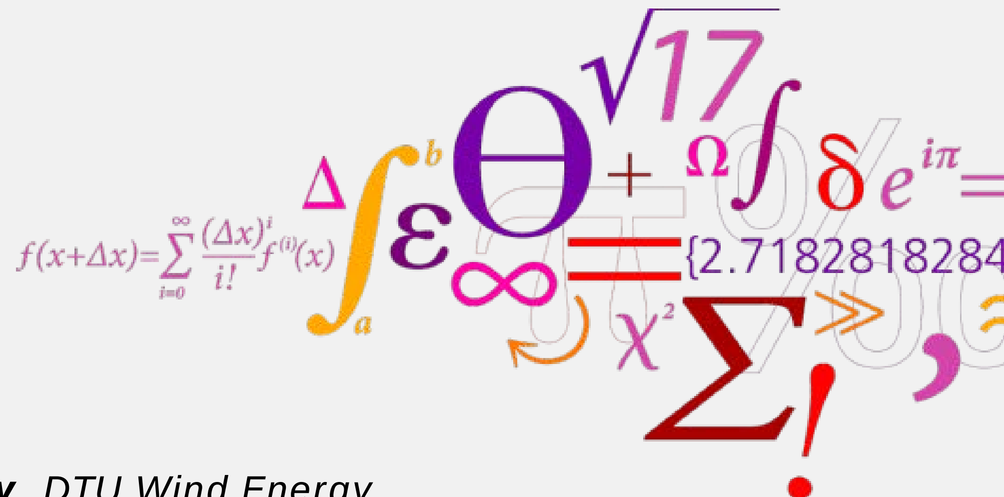
Generic calibration procedures for nacelle-based profiling lidars

Concept, setup and results

5-beam Demonstrator
(Avent Lidar Technology)

ZephIR Dual Mode
(ZDM, ZephIR lidar)



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Outline

1
- Metrological definition
- White box method & steps

2
- RWS calibration setup
- Locating the beam

3
- Calibration results

4
- Uncertainty sources

1

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What is meant by calibration?

Let's speak the same metrological language !!

- **VIM (cf. JCGM 200:2012)**
  http://www.bipm.org/fr/publications/guides/vim.html

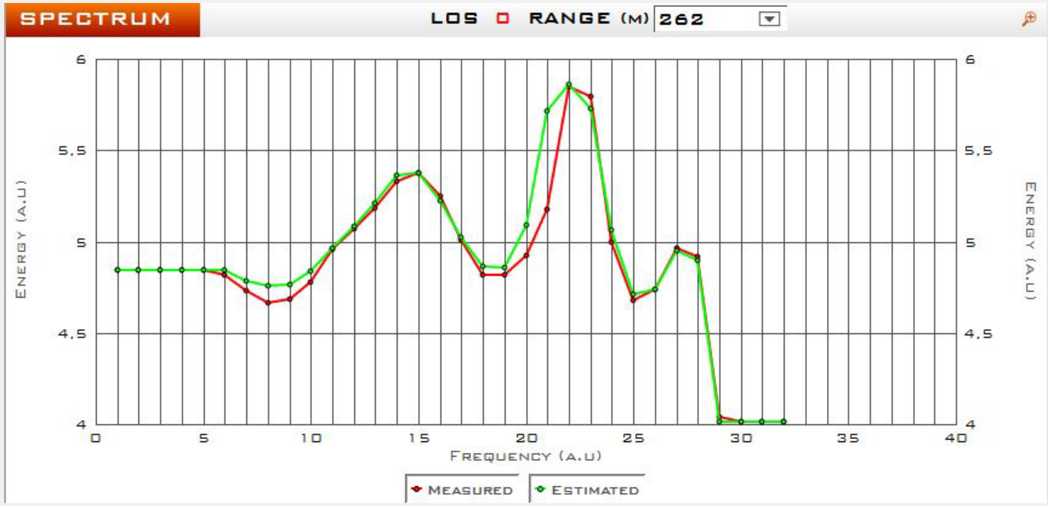
operation that, under specified conditions, in a first step, establishes a relation between the ***quantity values*** **– i.e. the reference –** *with* ***measurement uncertainties*** *provided by measurement standards and corresponding* ***indications*** **– i.e. measurand to calibrate –** *with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a* ***measurement result*** *from an indication.*

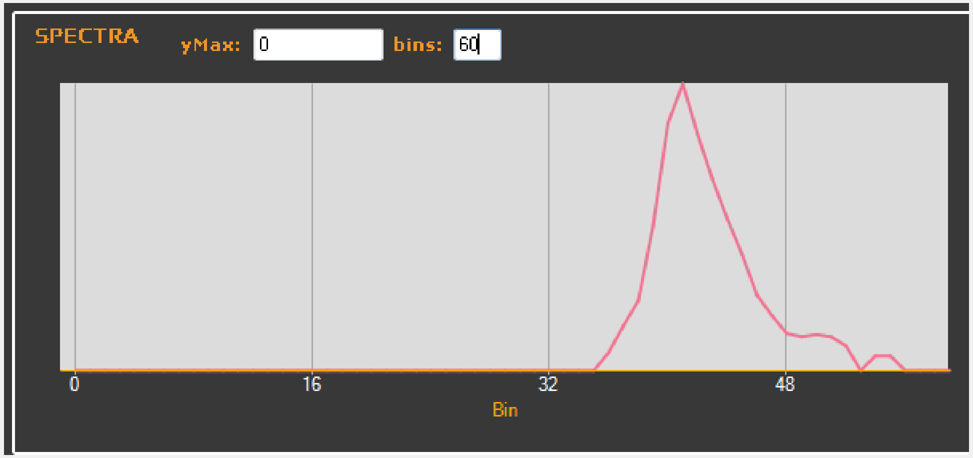
NOT CLEAR?

- **Reformulation in 3-step process**
  1. **Relation**: measurand = f(reference)
  2. **Uncertainties on measurand**
     = uncertainties on reference + measurements uncertainties
  3. Use calibration relation = apply a correction on measurand
     ➔ ensures link in measurement chain and **traceability**

White box principles

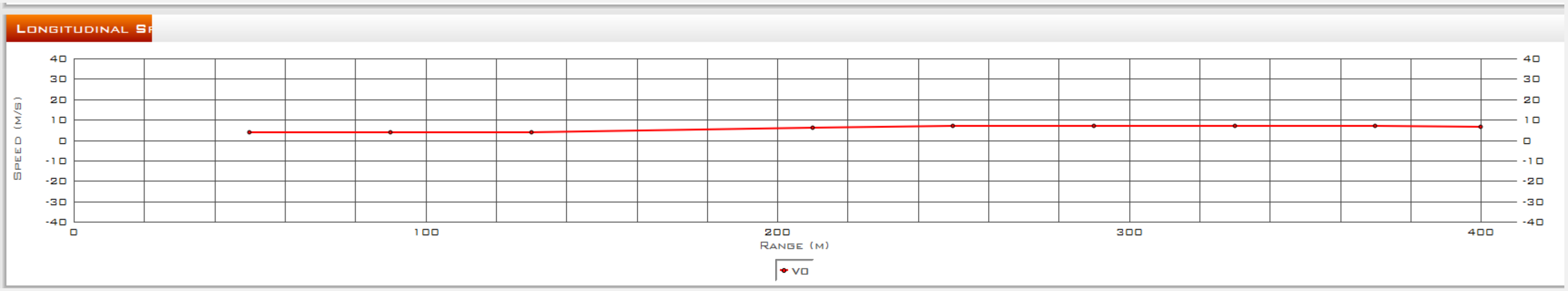
- **3 levels of measurands in a lidar**
  - Raw Doppler spectra

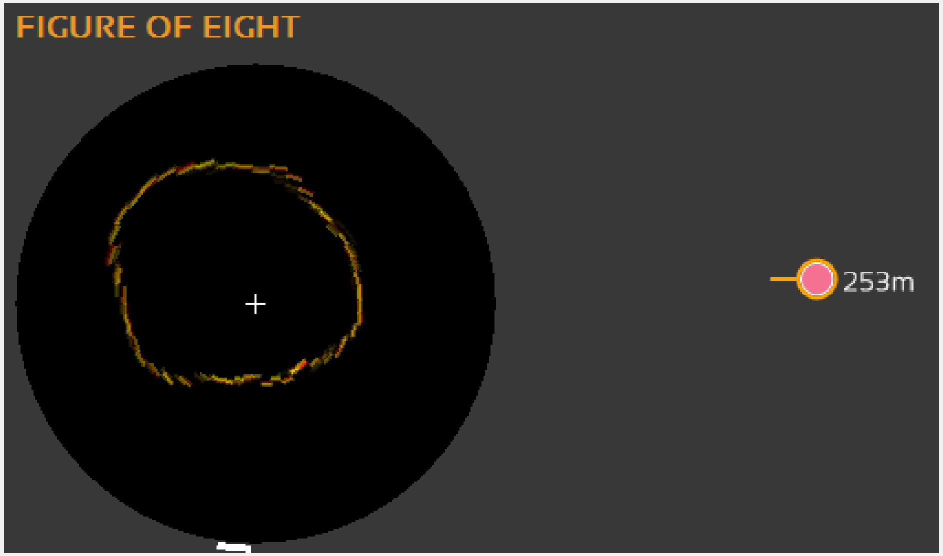




White box principles

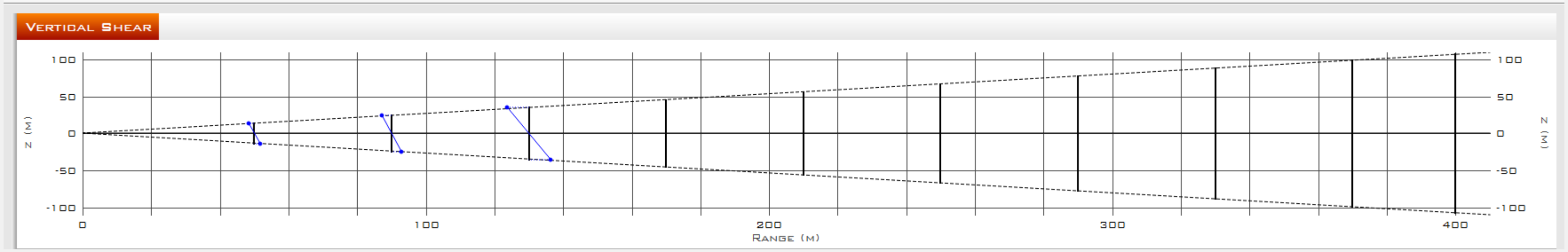
- **3 levels of measurands in a lidar**
  - Raw spectra
  - Radial wind speed (RWS) or Line-of-sight velocity

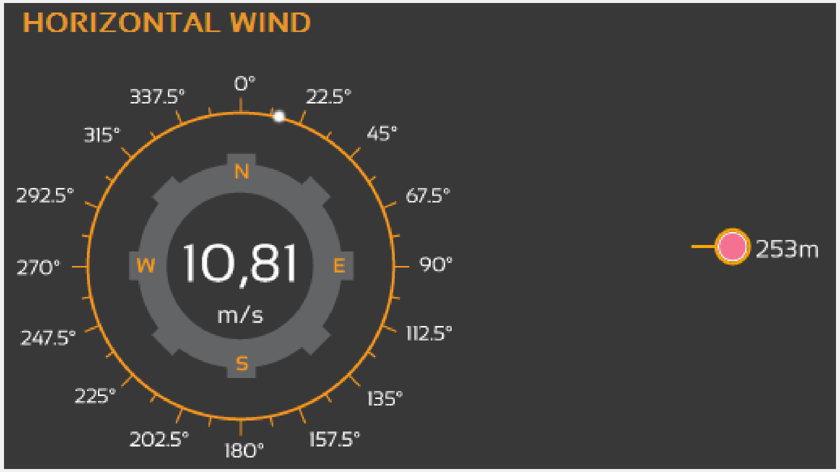




White box principles

- **3 levels of measurands in a lidar**
  - Raw spectra
  - Radial wind speed or Line-of-sight velocity
  - **Reconstructed parameters**: wind speed & direction, shear (horizontal, vertical, longitudinal), veer, turbulence





White box principles

- **Black box: calibration of reconstructed parameters**
- **White box: calibration of reconstruction algorithms' 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 RWS by comparing to reference
  4) Derive uncertainties: reference ➔ RWS
  5) Combine RWS according to reconstruction algorithms
  6) Derive uncertainties on ANY reconstructed parameter
     ➔ as long as the algorithm is known
     ➔ and correlation between the parameters

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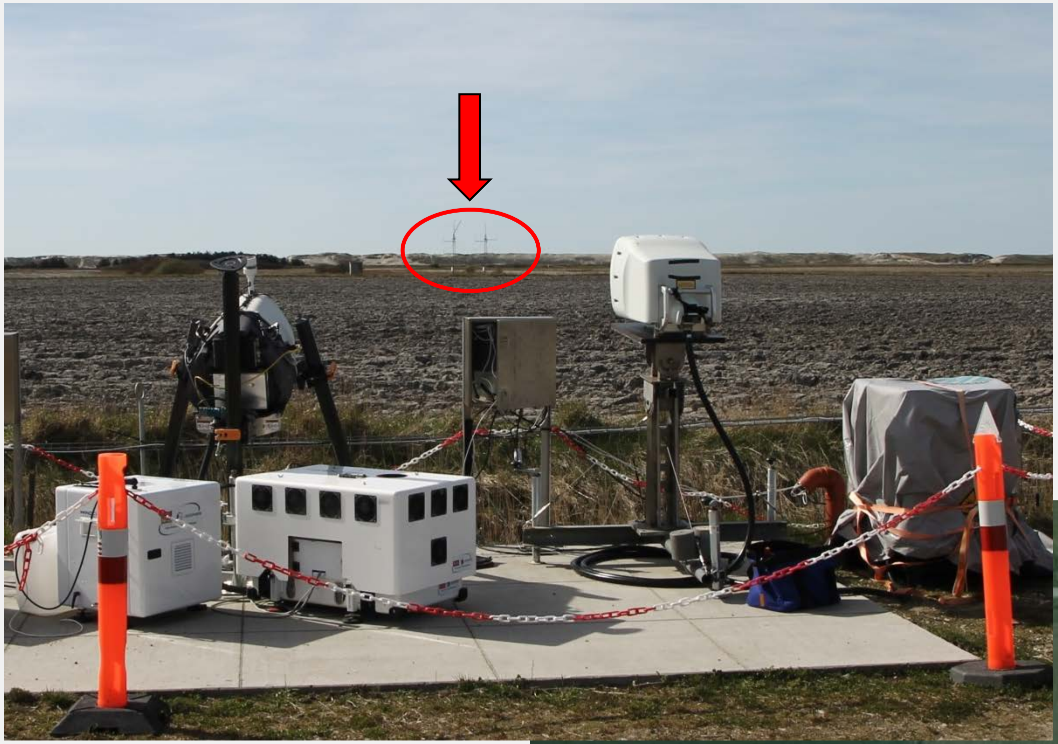
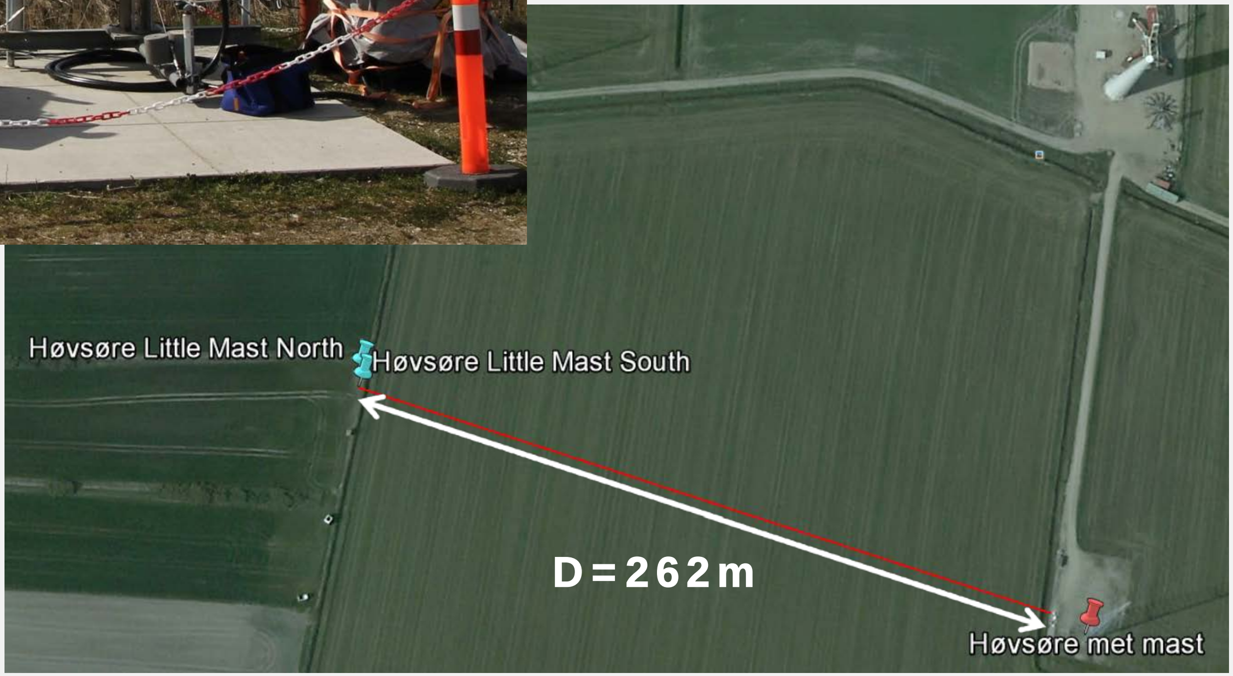
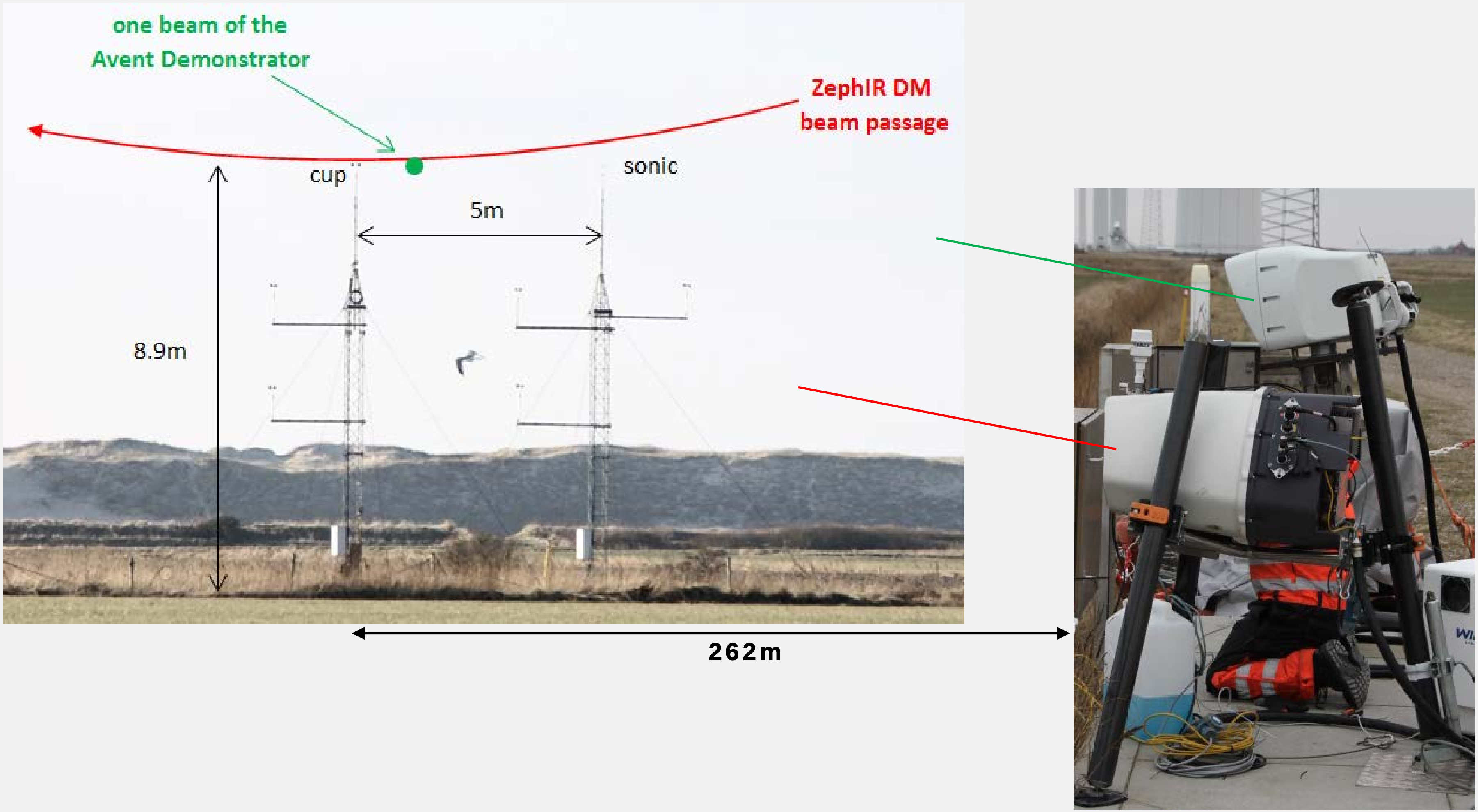
RWS calibration setup





RWS calibration setup



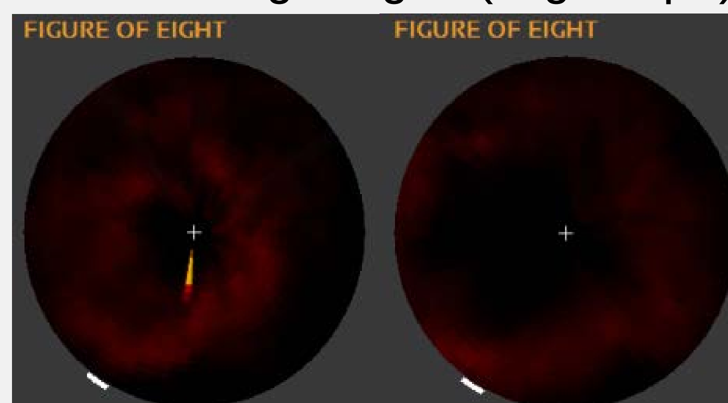
Locating the beam

Avent Demonstrator

Zephir Dual Mode

- adjust the tilting progressively

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



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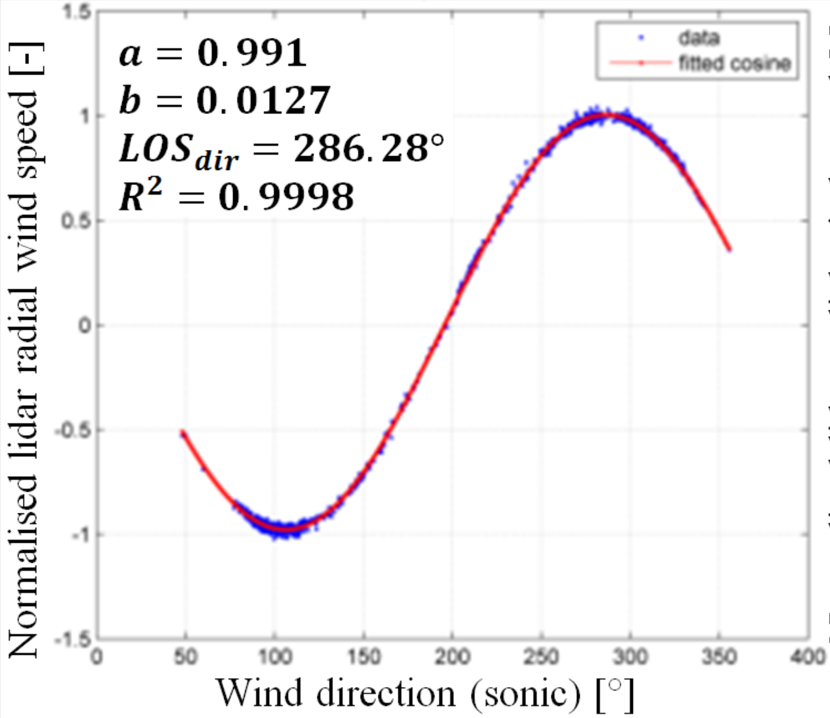
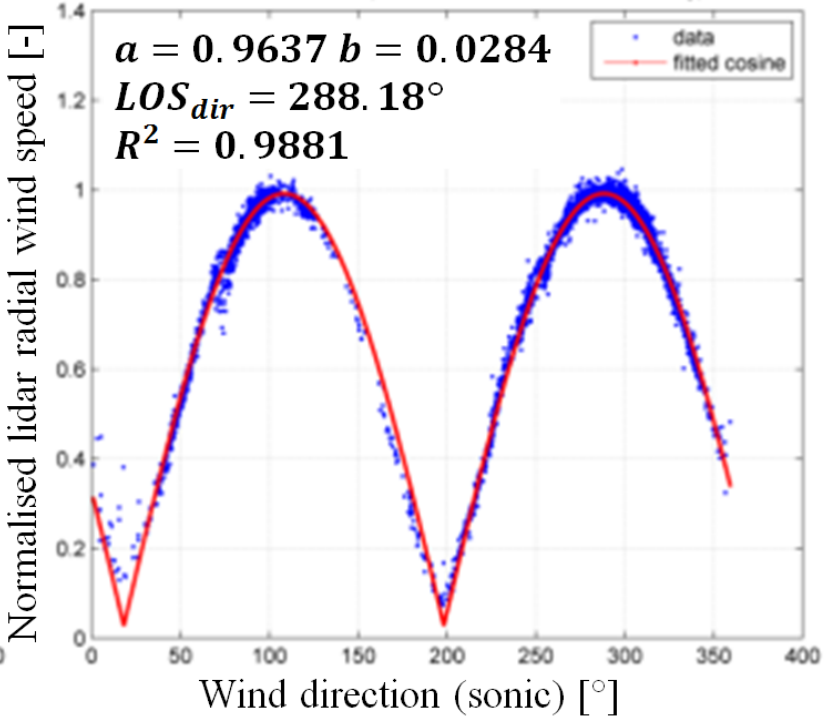
- Uncertainty methods
- Uncertainty sources

Data analysis (Avent: L, Zephir: R)

- **Main data** $$Ref_{eq\,RWS} = HWS \cdot cos(tilt) \cdot cos(WD - LOS_{dir})$$
  - Cup: horizontal wind speed
  - Sonic: wind dir
  - Lidar: LOS velocity + inclination
- **LOS direction evaluation 1: cosine / rectified cosine fitting**





Data analysis (Avent: L, Zephir: R)

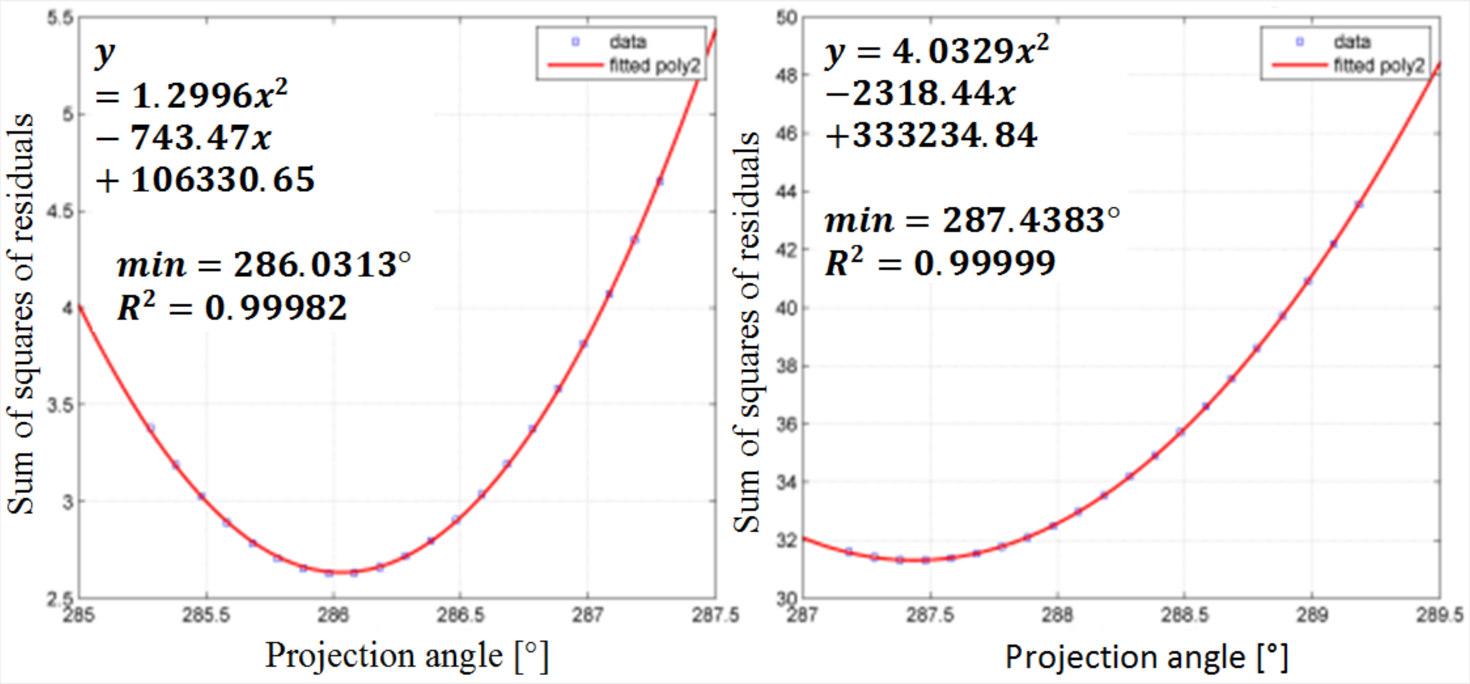
- **LOS direction evaluation 2 (finer)**
  - Projection angle range: LOS dir (V1) ±1°
  - Linear reg. each 0.1°

$y = RWS$

$x = HWS \cdot \cos(WD - proj\ angle) \cdot \cos(physical\ beam\ inclination)$

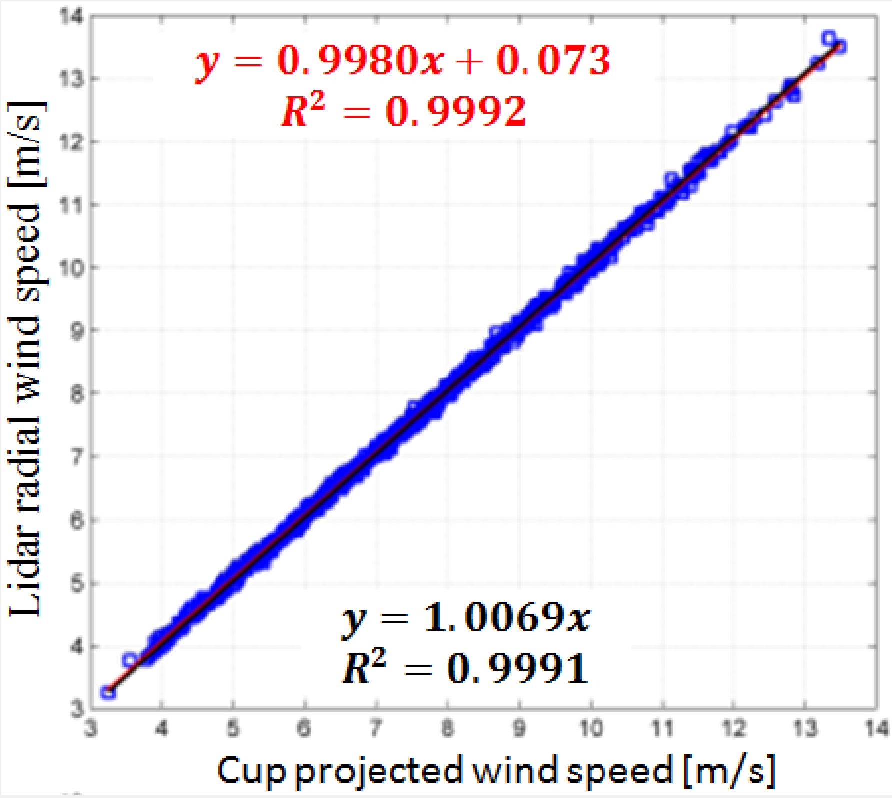
$y = a \cdot x + b$ ➔ 1 RSS value

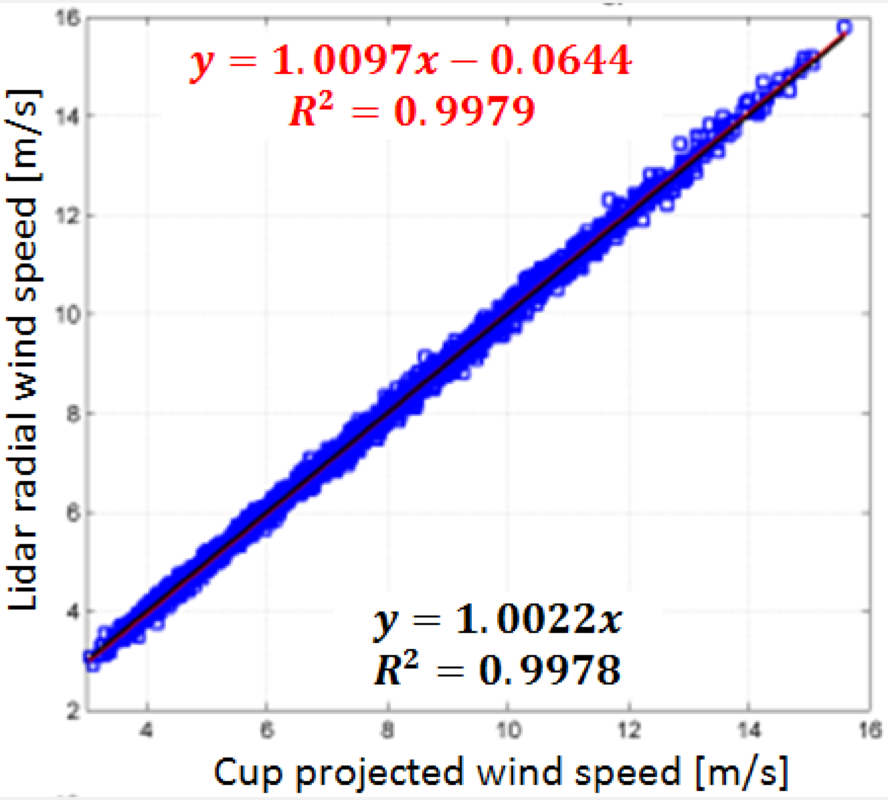
  - **LOS dir = min parabola**



Calibration results (Avent: L, Zephir: R)

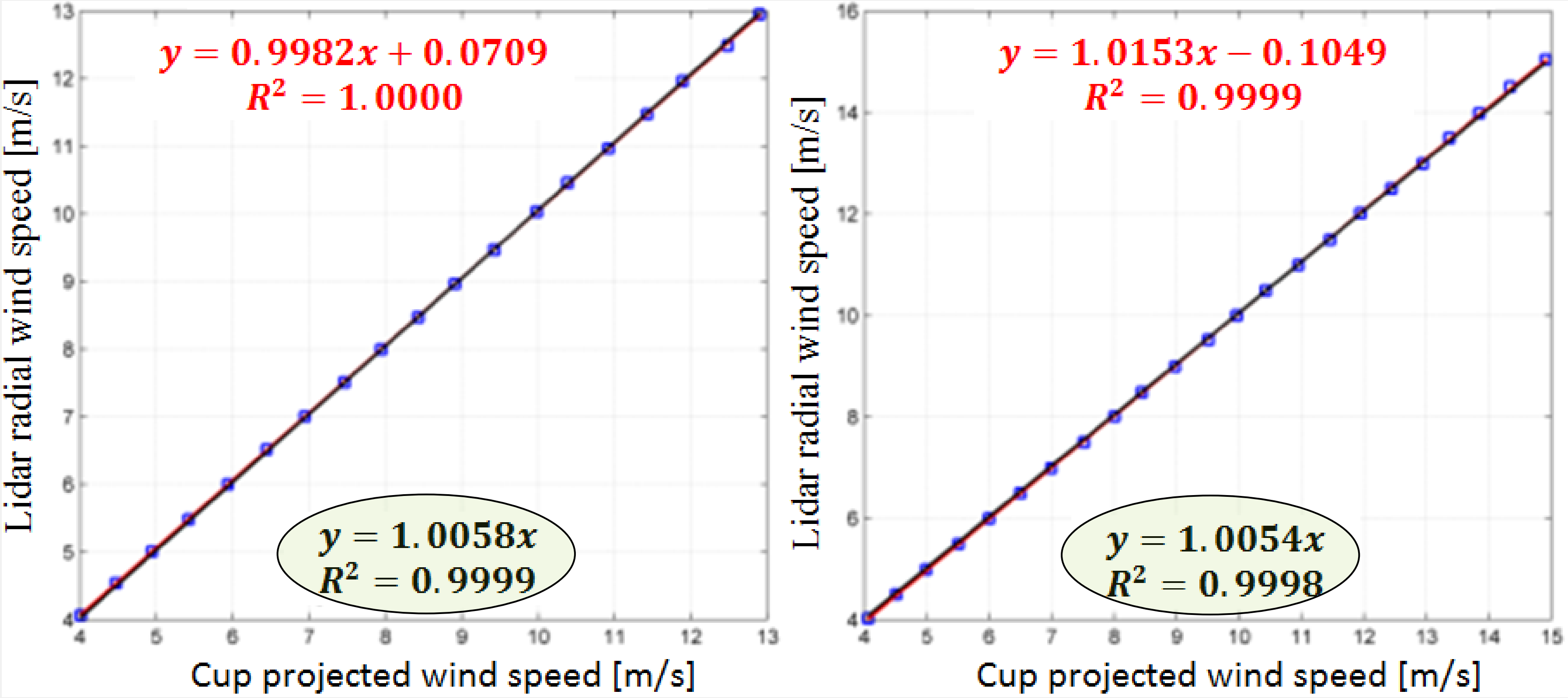
- **"RAW" calibration results**
  - Good agreement between lidars' RWS and the projection of the HWS on the LOS
  - Influence of the WS distribution ➔ use binned data instead





Calibration results (Avent: L, Zephir: R)

- **"binned" calibration results**
  - Use the forced regression
    ➔ consistent gains
  - Offset is not physical



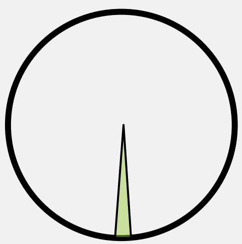
Calibration results
all 5 beams Demonstrator + ZDM

LOS / azimuth sector [deg]	Range selected [m]	LOS dir [deg]	Valid data points	Binned calibration					range of valid bins [m/s]	
				"Free" regression			Forced regression			
				gain	offset	R2	gain	R2	min	max
0	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
179-181	253	287,44	2140	1,0153	-0,1049	0,9999	1,0054	0,9998	4	15
175-185	253	287,49	2140	1,0157	-0,1032	0,9999	1,0059	0,9998	4	15

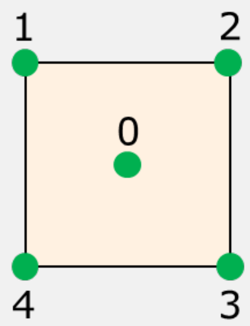
- **LOS direction**
  ➔ consistent results for each lidar

- **Forced regressions on binned data**
  ➔ gains error ~0.5 – 0.9%

ZDM



5-beam Demonstrator



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Uncertainty sources (Avent: L, Zephir: R)

- **Analytical methods (GUM)**
- **Expressed for each wind speed bin**
- **Sources**
  - **Reference wind speed** (cup) ➔ according to IEC 61400-12-1
    - Wind tunnel calib uncertainty (B)
    - Operational (B)
    - Mounting (B)
  - **Relative wind direction**: sonic WD – LOS direction
    - Sonic calibration in wind tunnel (B)
    - LOS direction estimation (B)
  - **Position of the beam**: accurately known to be close to cup
    - Physical beam inclination (inclinometers calib) for the projection (B)
    - Beam height ➔ $U_H = \alpha \cdot \Delta H / H \cdot V_{HWS} \approx 0.023\% \cdot V_{HWS}$ (B)
  - **Statistical uncertainty** in the RWS measurement characterising the dispersion of RWS measurements under "repeatable conditions" (A)
  - **TOTAL uncertainty**: $U_{RWS} = \sqrt{\sum U_i^2}$

Conclusion - further work

- **Conclusions**
  - White box method applicable to both pulsed / CW nacelle lidars
    ➔ **<u>generic</u>**
    ➔ potentially for all lidars irrespective of their application
    ➔ repeatable
  - RWS calibration
  - Limitations
    - Need for better cup anemometer calibration (uncertainty is predominant)
    - High TI at low height ➔ not ideal measurement setup, but still yielding good results
- **Further work**
  - Uncertainty derivation of parameters using custom reconstruction algorithms
  - Sensitivity analysis (variability of calibration results)
    - Amount of valid points
    - Atmospheric conditions: T° , TI, thermal stability

Thanks for your attention!

QUESTIONS?

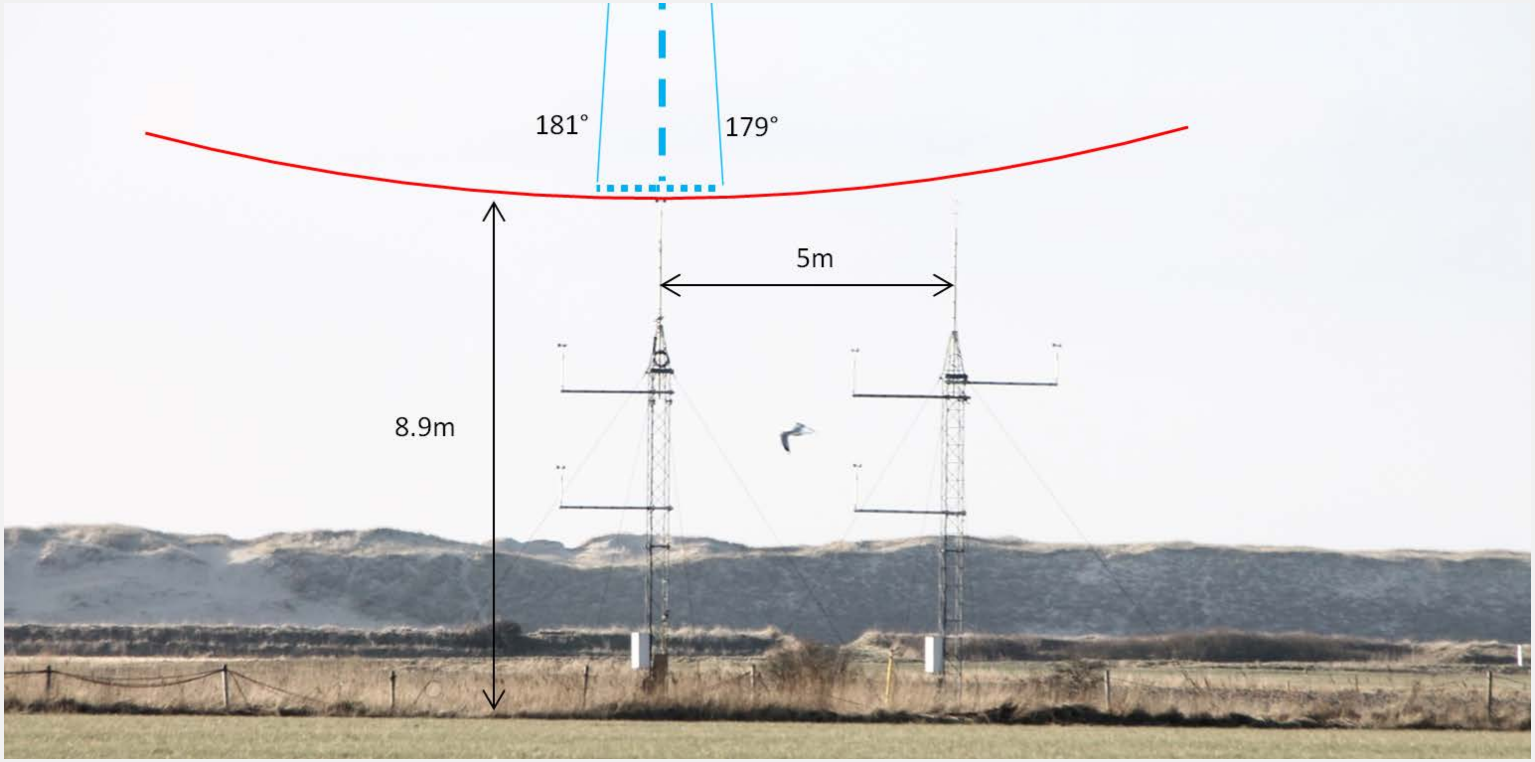
More info:

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

Preparing questions

Calibration results
ZDM

- **Parameter to adjust: width of valid azimuth sector**



- Used for averaging realtime data from ”RAW” files
- Only one beam to calibrate since scanning: here ”2-deg wide” sector
- NB: the selected arc is $\sim 20m$ large ➔ can influence results

Black & white box calibration of lidars

Two different principles

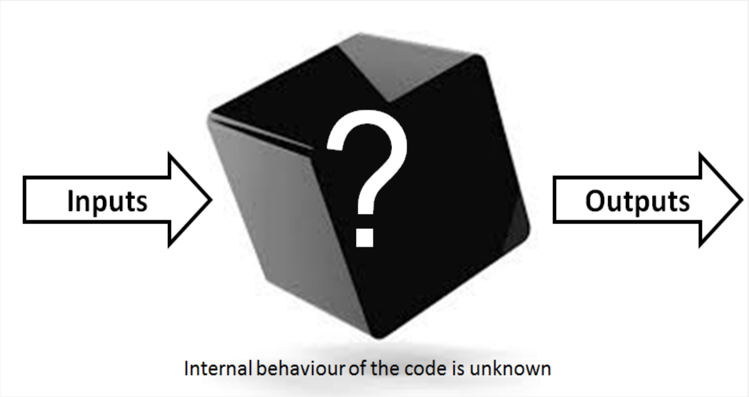
- **Lidar measurements and outputs**
  - Measurand: frequency of the backscattered light
  - Converts it in a Radial Wind Speed, i.e. the **component of the wind vector in the line of sight** (LOS, laser beam direction)
  - RWS considered as the "raw measured quantity"
  - Output parameters
    - obtained 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)



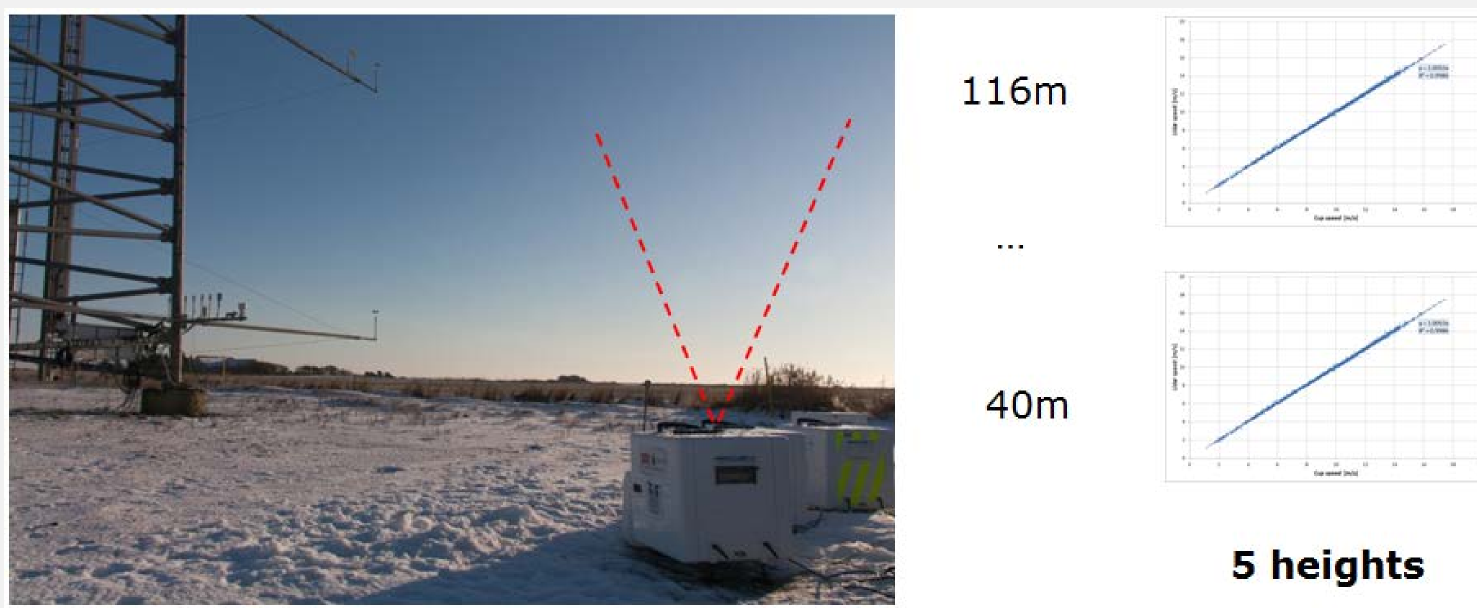
- **Requirements**
  - – availability / existence of a reference instrument for the type of data to calibrate
  - – reference instrument MUST be calibrated (certificate ...)
- **Pros**
  - – Direct comparison of the data:
    - reconstructed output vs. Reference
    - no additional algorithm to transform 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

DANAK
CAL. Reg. no. 363



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?)

Black & white box calibration of lidars

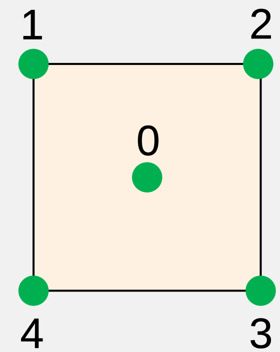
White box: requirements, pros, cons, example (2/2)

- **Cons**
  - Make sure that the reconstruction algorithm is correct
    - Does it get the physics right?
    - Suggestion 1: 3D flow simulation test cases
    - Suggestion 2: for each technology of lidar (different algorithm), at least two ”black box” calib
  - Longer duration
    - Calibration of successive LOS
      - ➔ 2-min average to fill the distribution quicker (not *5)
  - Need for:
    - Inclinometers calibration
    - Geometry verification
    - RWS calibration

- **Example: calibration of nacelle-based lidars**

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!