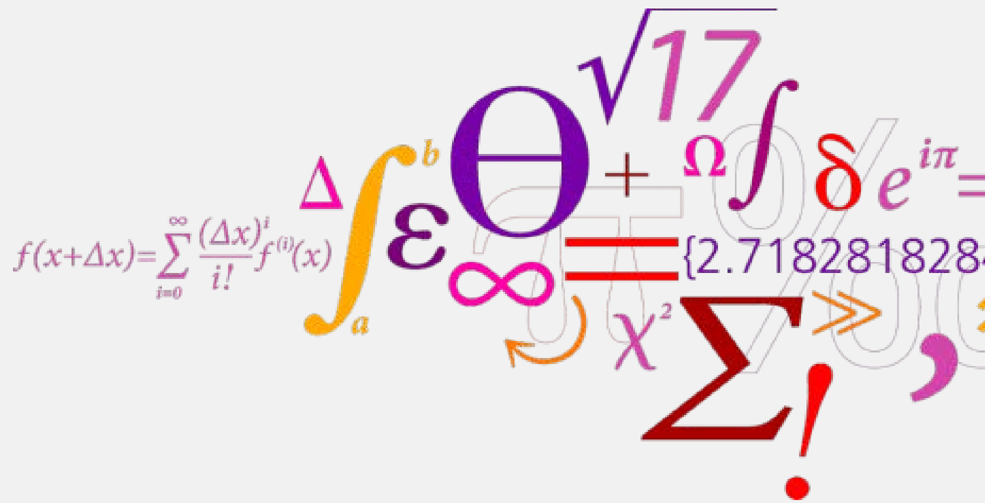
# Radial wind speed uncertainty of ~~profiling nacelle~~ lidars

5-beam Avent demonstrator lidar

ZephIR Dual-Mode



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# Outline

1. RWS calibration: setup and procedure
2. Uncertainty components
3. Uncertainty assessment methodology (-ies)
4. Results and prevailing sources

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- RWS calibration: setup and procedure

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- Results and prevailing sources

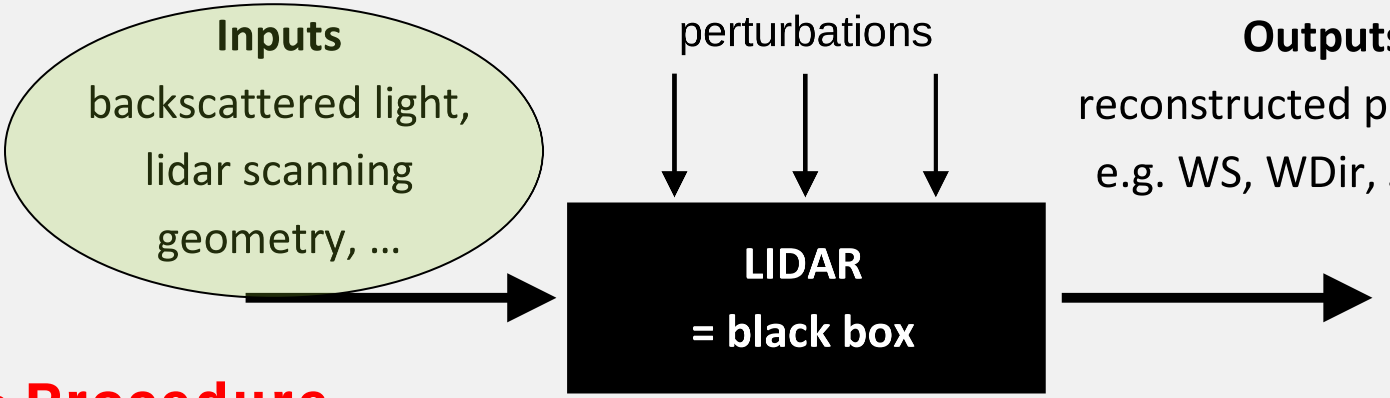
# Why calibrating nacelle lidars?

- **Nacelle lidars applications**
  - Power performance testing: potential to reduce costs (offshore, complex terrain)
  - Wind turbine controls (e.g. feed-forward)
- **Uncertainty assessment in power curves**
  - Because it involves 
  - Guaranteed power curves from turbine manufacturer
- **A calibration**
  - establishes a relation between a measurand and a calibrated reference quantity value ➔ **traceability**
  - transfers the reference instrument(s) **uncertainties** to the tested measurement system through a calibration process
  - provides the **correction to apply** to the measurements

# RWS calibration of profiling nacelle lidars

- **Principles**
  - calibrate the lidar RWS and other inputs rather than reconstructed parameters (subject to strong flow assumptions)

    ➔"White box" methodology calibrates




- **Procedure**

1) Calibrate the geometry of the lidar: inclinometers + e.g. cone angle
2) Position the beam close to reference instrument(s)
3) Calibrate RWS by comparing to reference
4) Derive uncertainties: reference ➔ RWS
5) Combine RWS (reconstruction algorithms), propagate uncertainties

# RWS calibration of profiling nacelle lidars

- **Measurement setup (Høvsøre, DK)**

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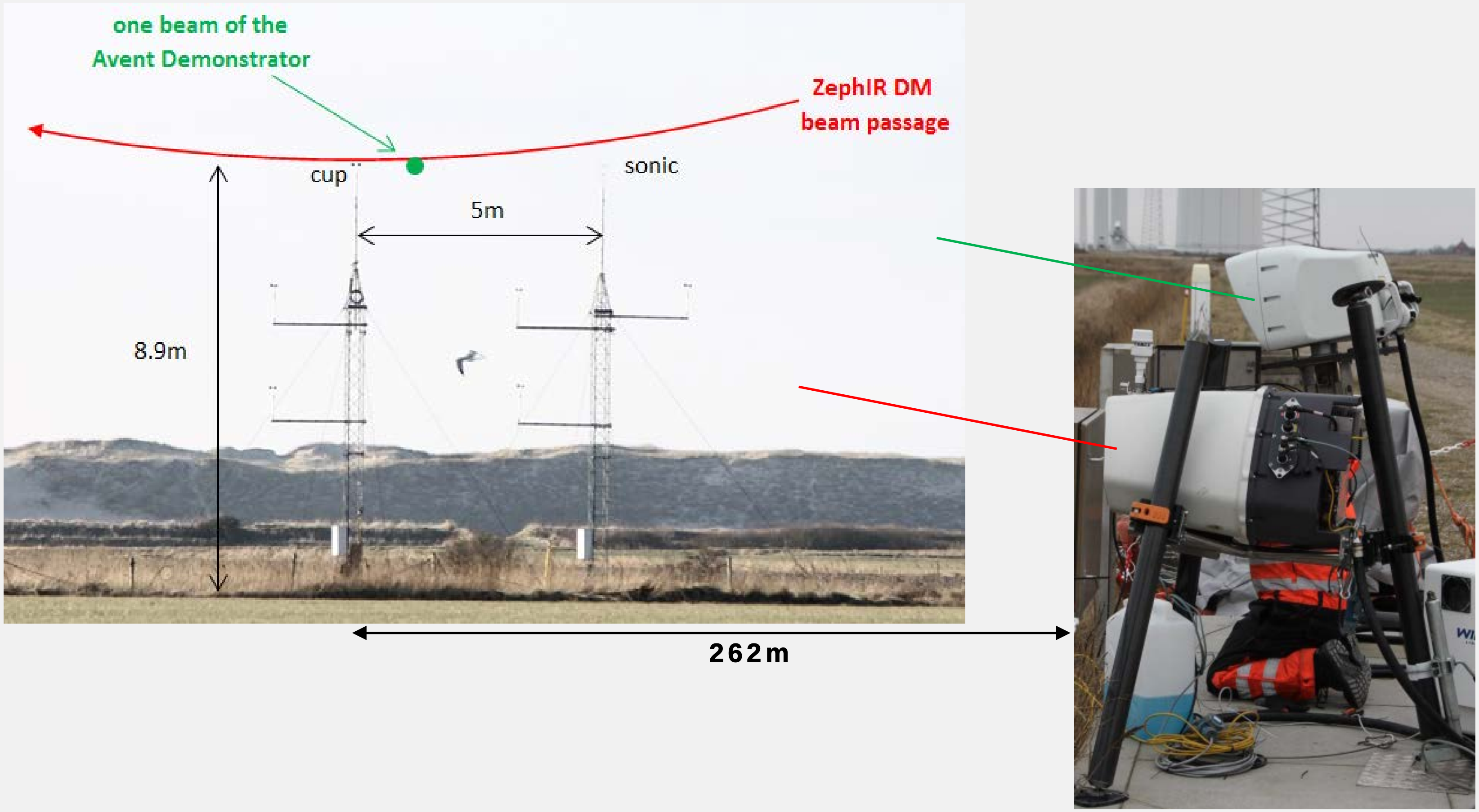
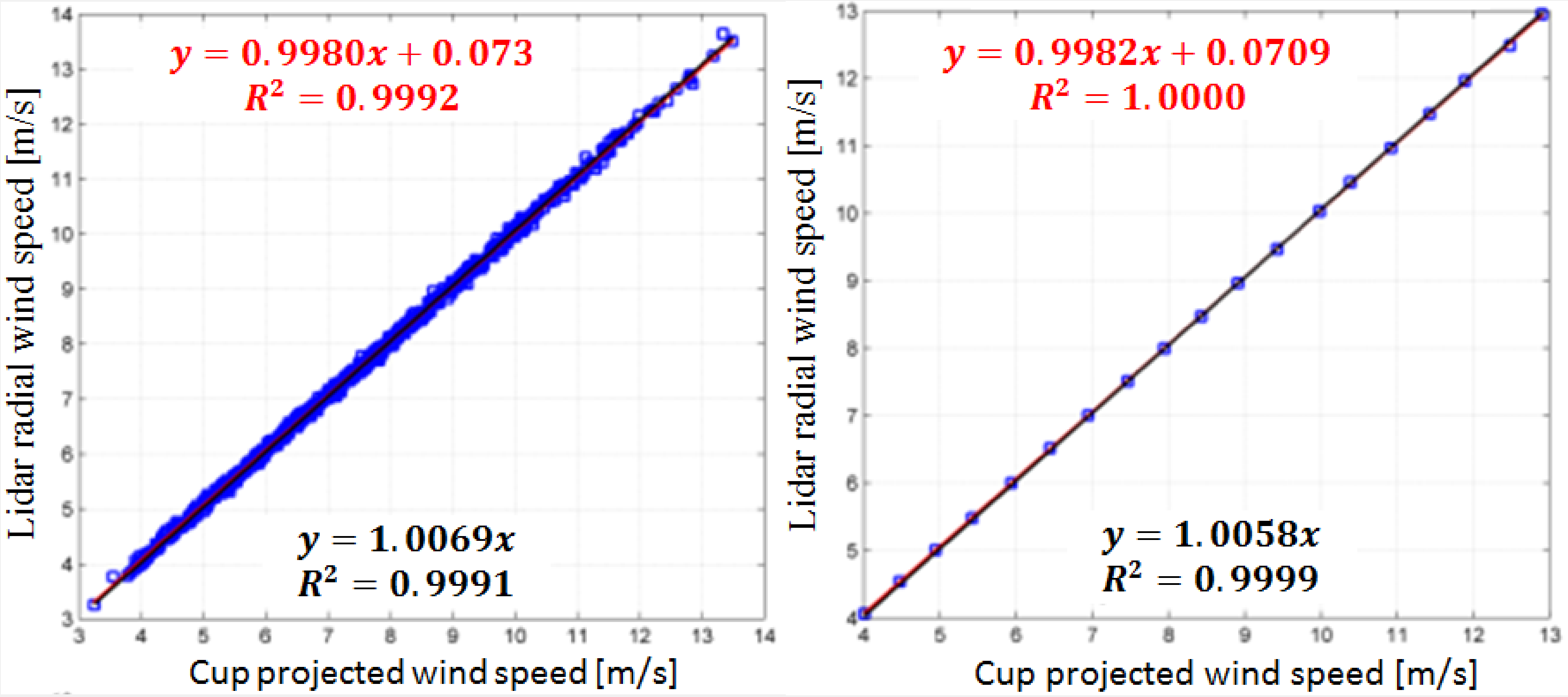
- **Measurement setup (Høvsøre, DK)**




$$Ref_{eq\ RWS} = \langle HWS \rangle_{vec} \cdot cos(\langle tilt \rangle) \cdot cos(\langle WD \rangle - LOS_{dir})$$

# RWS calibration of profiling nacelle lidars

- **Results**




➔ The method works ☺

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# What are the uncertainty sources?

- **Reference instruments uncertainties**
  - HWS (IEC 61400-12 procedure for cups)
    - Wind tunnel calibration uncertainty

$$u_{cal} = u_{cal\,1} + \frac{0.01}{\sqrt{3}} \cdot \langle HWS \rangle$$

    - Operational uncertainty

$$u_{ope} = \frac{1}{\sqrt{3}} \cdot cup\ class\ number \cdot (0.05 + 0.005 \cdot \langle HWS \rangle\,)$$

    - Mounting uncertainty

$$u_{mast} = 0.5\% \cdot \langle HWS \rangle$$

  - Wind direction, from calibration certificate of sonic anemometer:

$$u_{WD} \approx 0.4°$$

# What are the uncertainty sources?

- **Calibration process uncertainties**
  - LOS direction uncertainty

$$u_{LOS\,dir} = 0.1°$$

  - Uncertainty of tilt inclination angle

$$u_{\varphi} = 0.05°$$

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

$$u_{pos} = \alpha_{exp} \cdot \frac{u_H}{H} \cdot \langle HWS \rangle \approx 0.23\% \cdot \langle HWS \rangle$$

  - Inclined beam and range uncertainty

$$u_{inc} = 0.052\% \cdot \langle HWS \rangle$$

"how the probe volume affects the RWS estimation when the beam is inclined"
(see model in DTU report E-0086)

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# Uncertainty assessment: how to combine components?

- **GUM methodology**: analytic method
  1) Define measurement model: $y_m = f(x_1, x_2, \ldots, x_n)$
  2) Law of propagation of uncertainties:

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

  3) Expanded uncertainty with coverage factor k

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

  typically, k=2 corresponds to 95% confidence interval

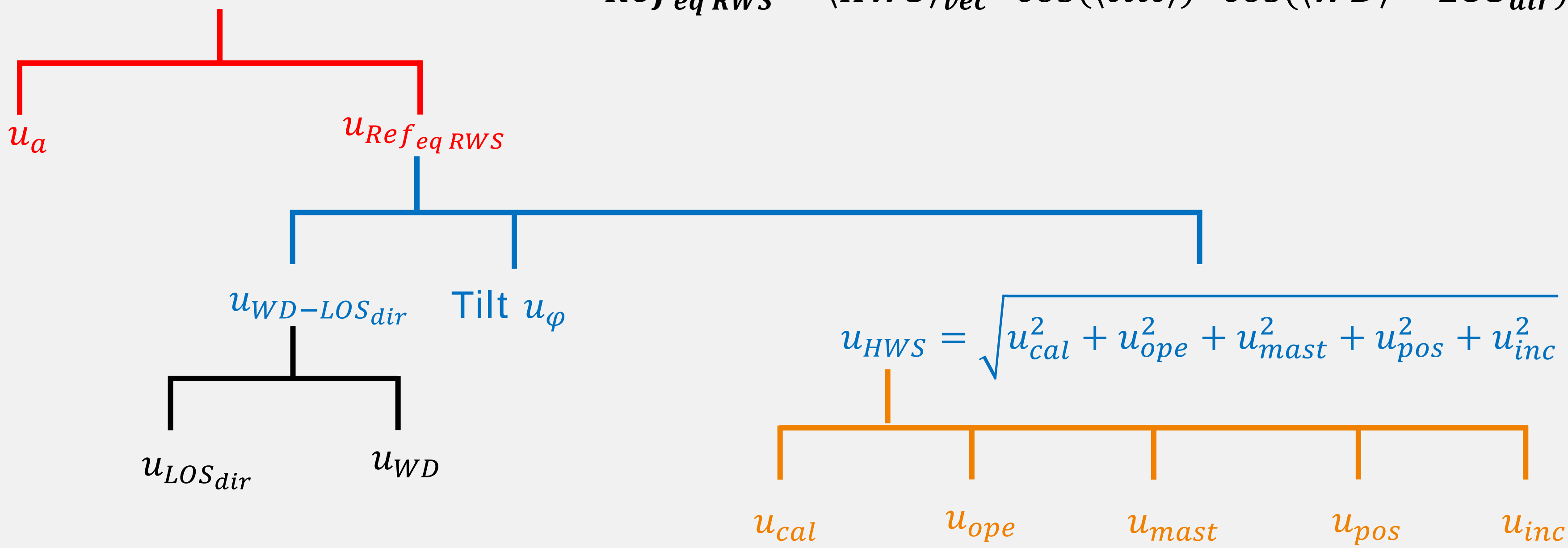
- **5 ≠ models studies**:
  - Lidar-ref measurement error: simple difference per bin
  - Forced linear regressions: **on binned data** / for each bin
  - Unforced linear regressions: on binned data / ~~for each bin~~

# Uncertainty assessment: how to combine components?

- **Propagating uncertainties:** *”the tree structure”*

$$y_m = a_{binned} \cdot Ref_{eq\,RWS}$$

$$Ref_{eq\,RWS} = \langle HWS \rangle_{vec} \cdot \cos(\langle tilt \rangle) \cdot \cos(\langle WD \rangle - LOS_{dir})$$




➔ result: combined uncertainty on $y_m$

➔ derive expanded uncertainty

- **RWS best estimate:**

$$\langle RWS_{BE} \rangle = \frac{\langle RWS_{indicated} \rangle}{a_{binned}}$$

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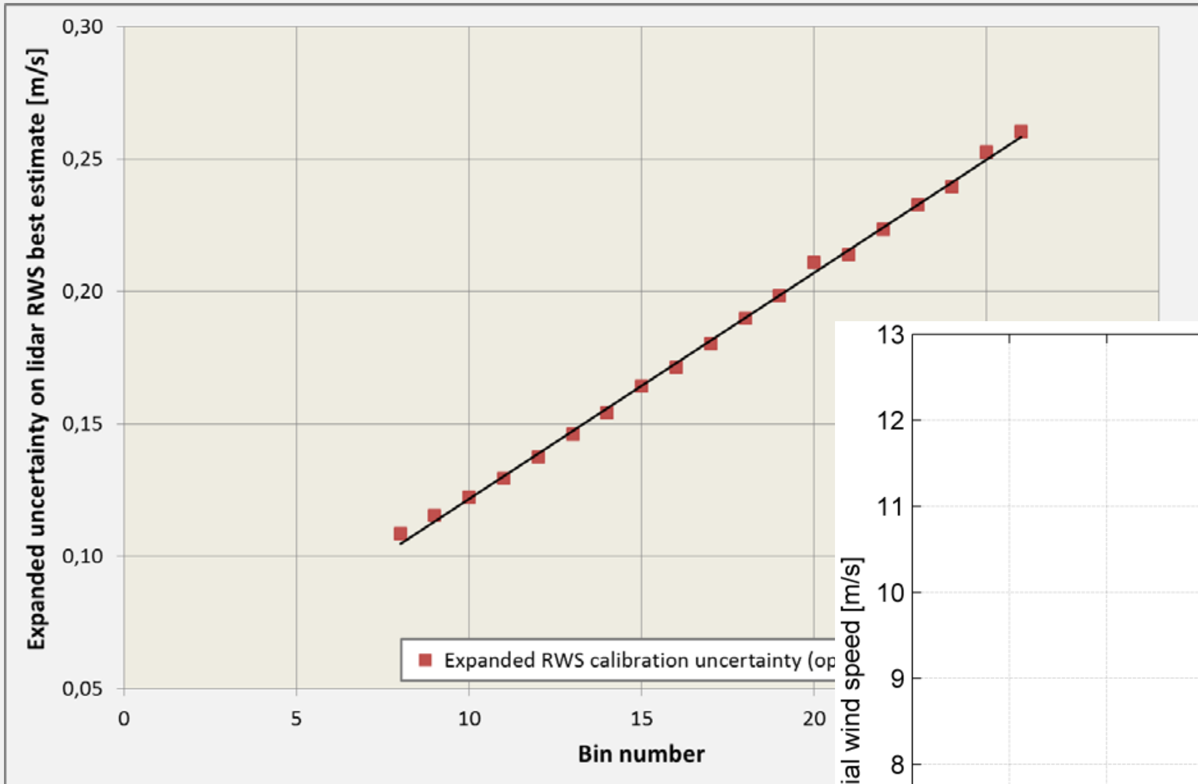
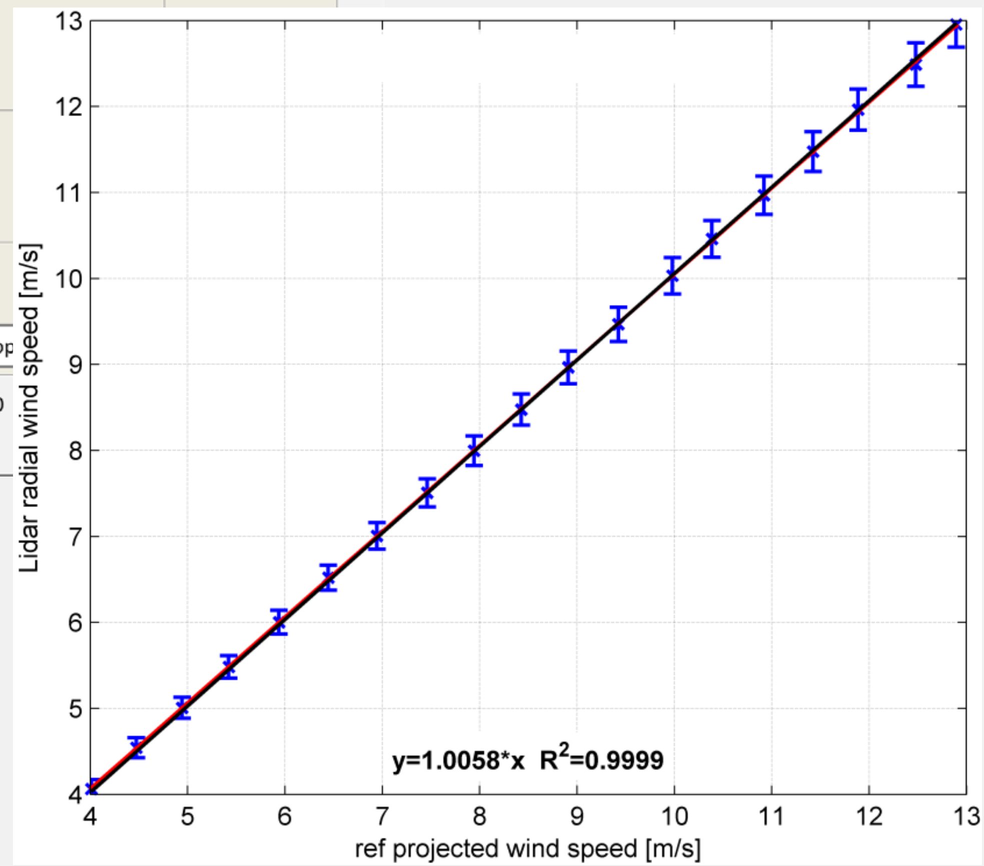
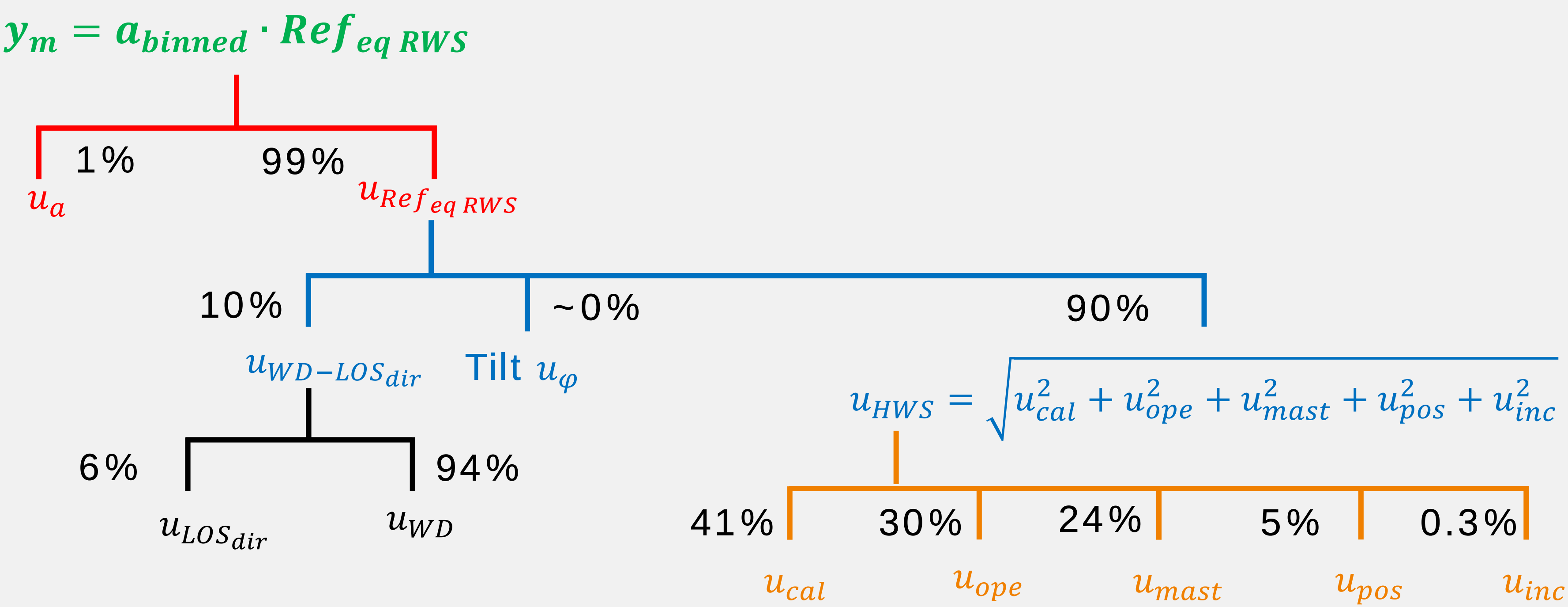
# RWS uncertainty results




- Expanded uncertainty ~2-3% of RWS

# Prevailing uncertainty sources




- A large majority of the total uncertainty comes from the cup anemometer uncertainties!!
- Very little is due to the calibration process

➔ **Explains the linearity observed in the expanded RWS uncertainty**

# Conclusion

- **Take-aways**
  - RWS calibration procedure provides valid results
  - RWS uncertainties ~2-3% with 95% confidence
  - Major contribution of cup anemometer uncertainties to the combined RWS uncertainties

  ➔Need for better cup calibration procedures!

  ➔+ more consistency between ≠ Measnet accredited wind tunnels

- **Future work**
  - create reconstruction algorithms
  - propagate RWS uncertainties to reconstructed wind parameters
  - derive uncertainties using commercial reconstruction algo (lidar manufacturers)
  - obtain power curve uncertainties! (AEP)

# Thanks for your attention!

More info:

- website www.unitte.dk
- contact borr@dtu.dk
- DTU E-0086 report

# Acknowledgements

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Thanks to Michael Courtney and Rozenn Wagner for all the lively discussions about uncertainties that leaded to these results.

# Preparing questions

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QUESTIONS from assessment committee EAWE

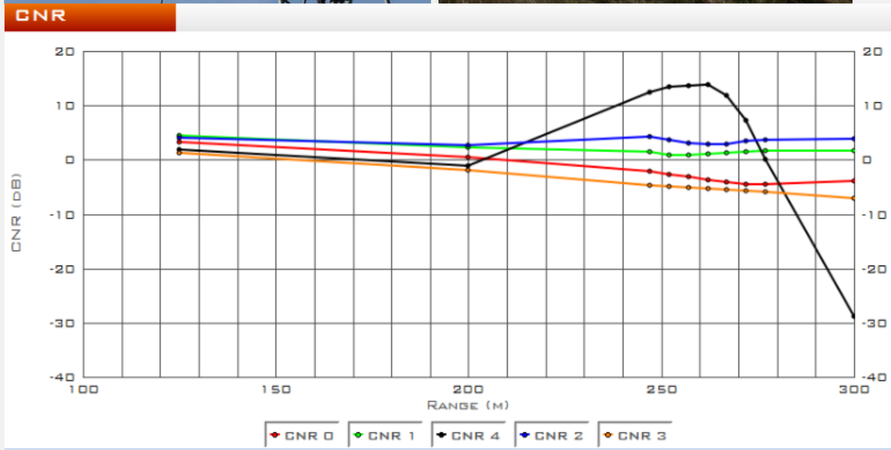
- Is the calibration process with the mast mounted instruments valid approach ? They have different probe lenghts, measurement process differs significantly, and hardly you will achive horizontal homogeneity of the flow almost anywhere.

- What would be different way of calibrating lidars?

- Would you consider using multi-lidar instrumentation for this?

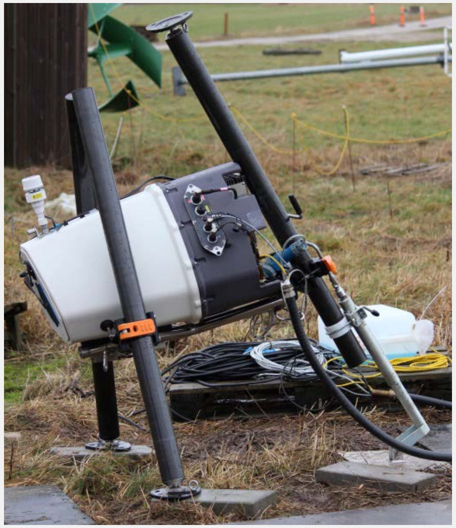
# Locating the beam

## Avent Demonstrator

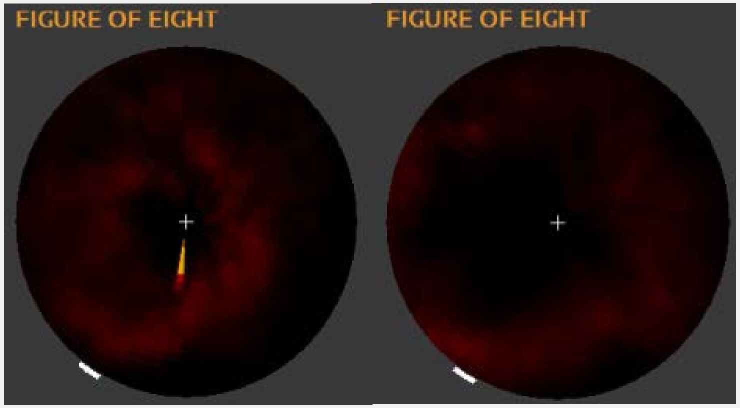



## Zephir Dual Mode

- adjust the tilting progressively

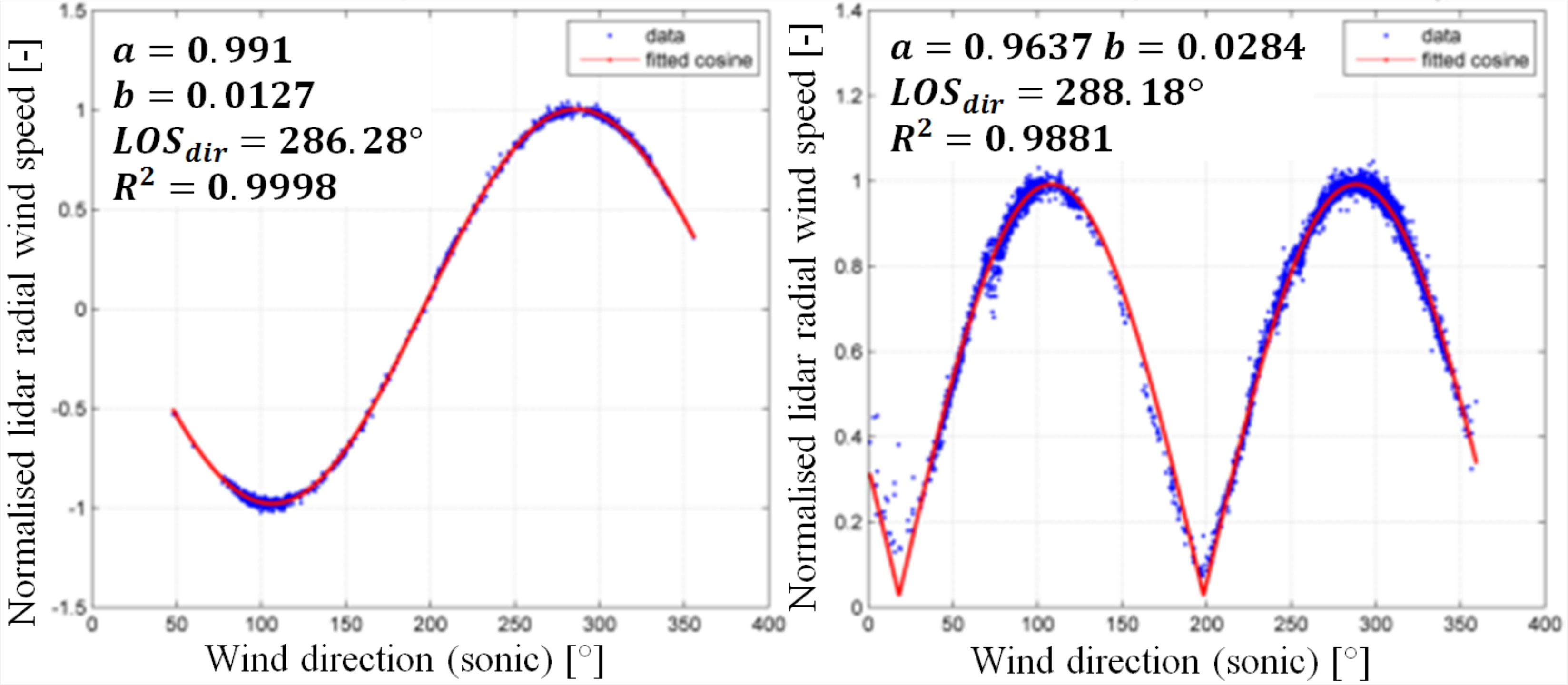


- Hit a moving target (e.g. cups)



# 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)

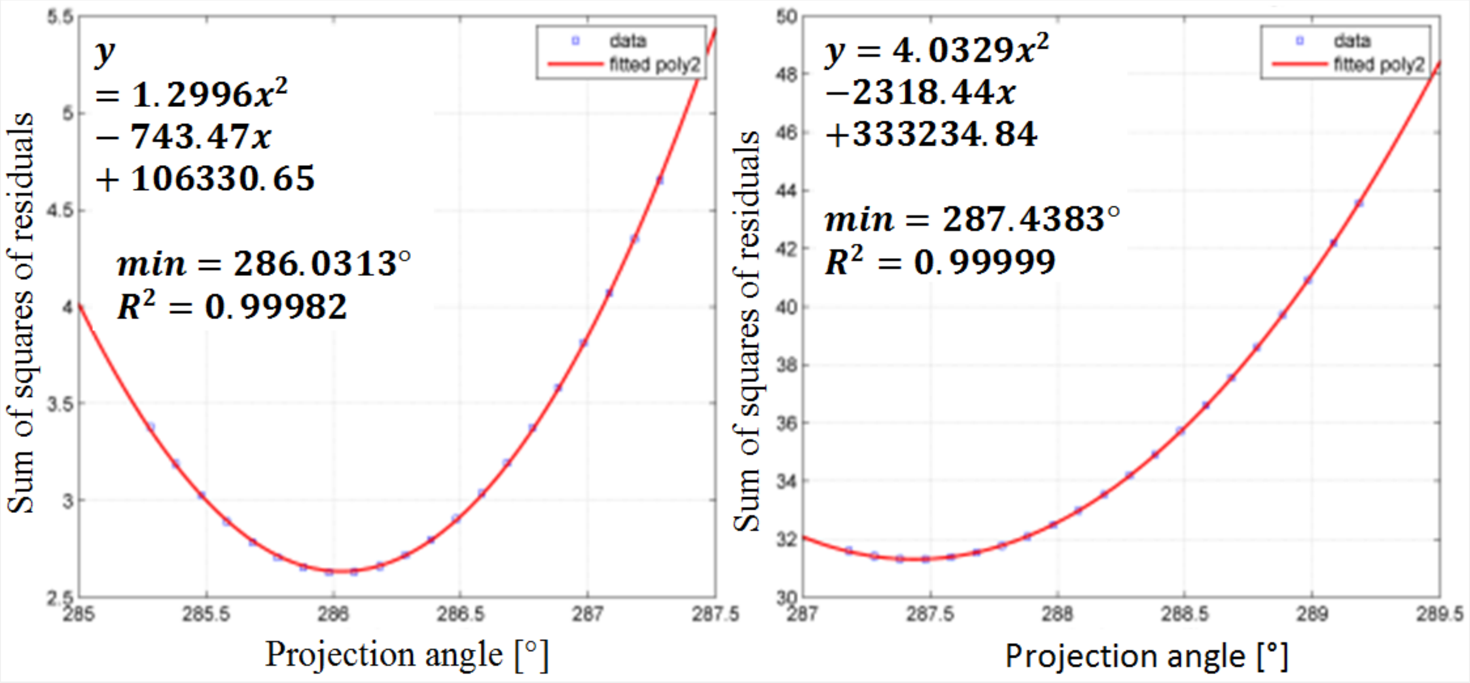
- **LOS direction evaluation 2 (finer)**
  - Projection angle range: LOS dir (V1) ±1°
  - Linear reg. each 0.1°

$$y = RWS$$

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

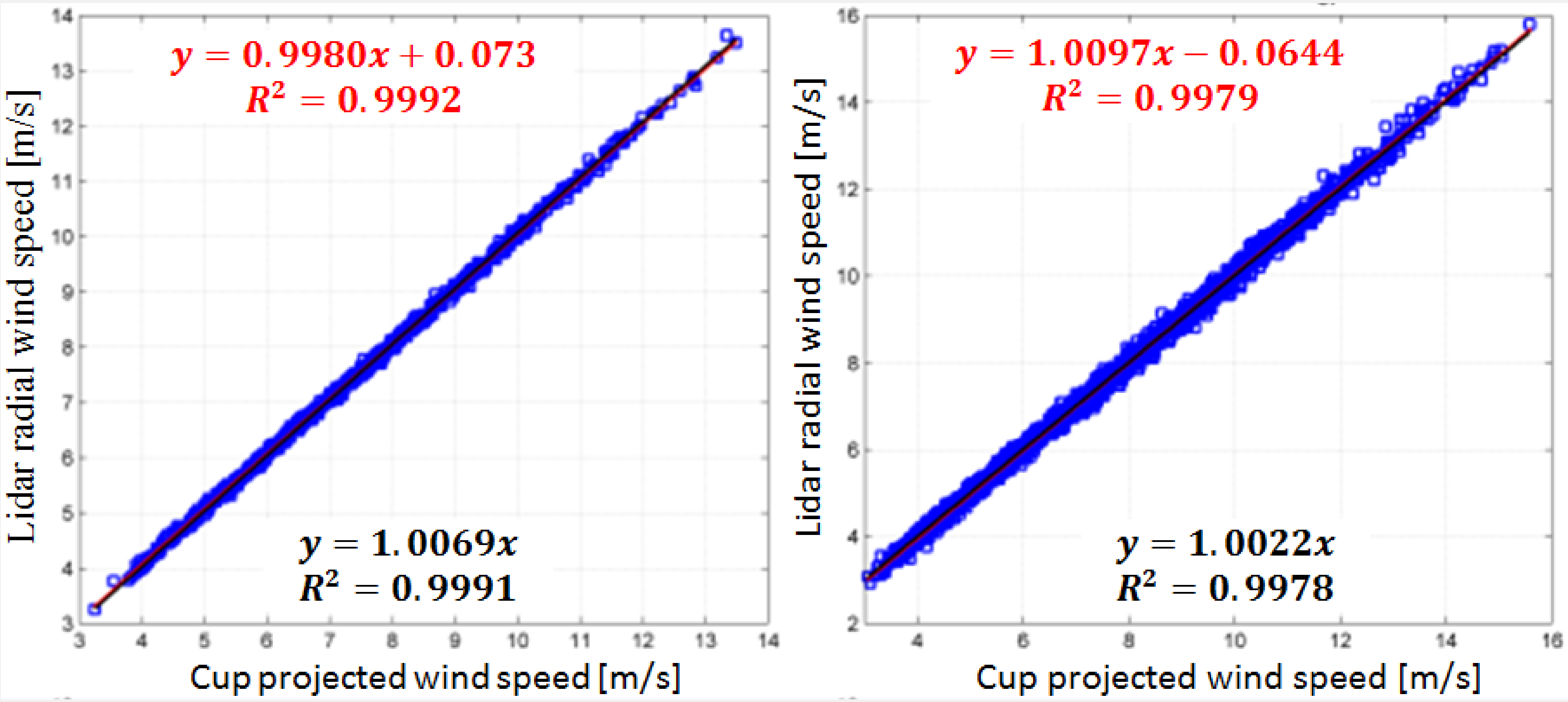
$y = a \cdot x + b$ ➔ 1 RSS value

  - **LOS dir = min parabola**



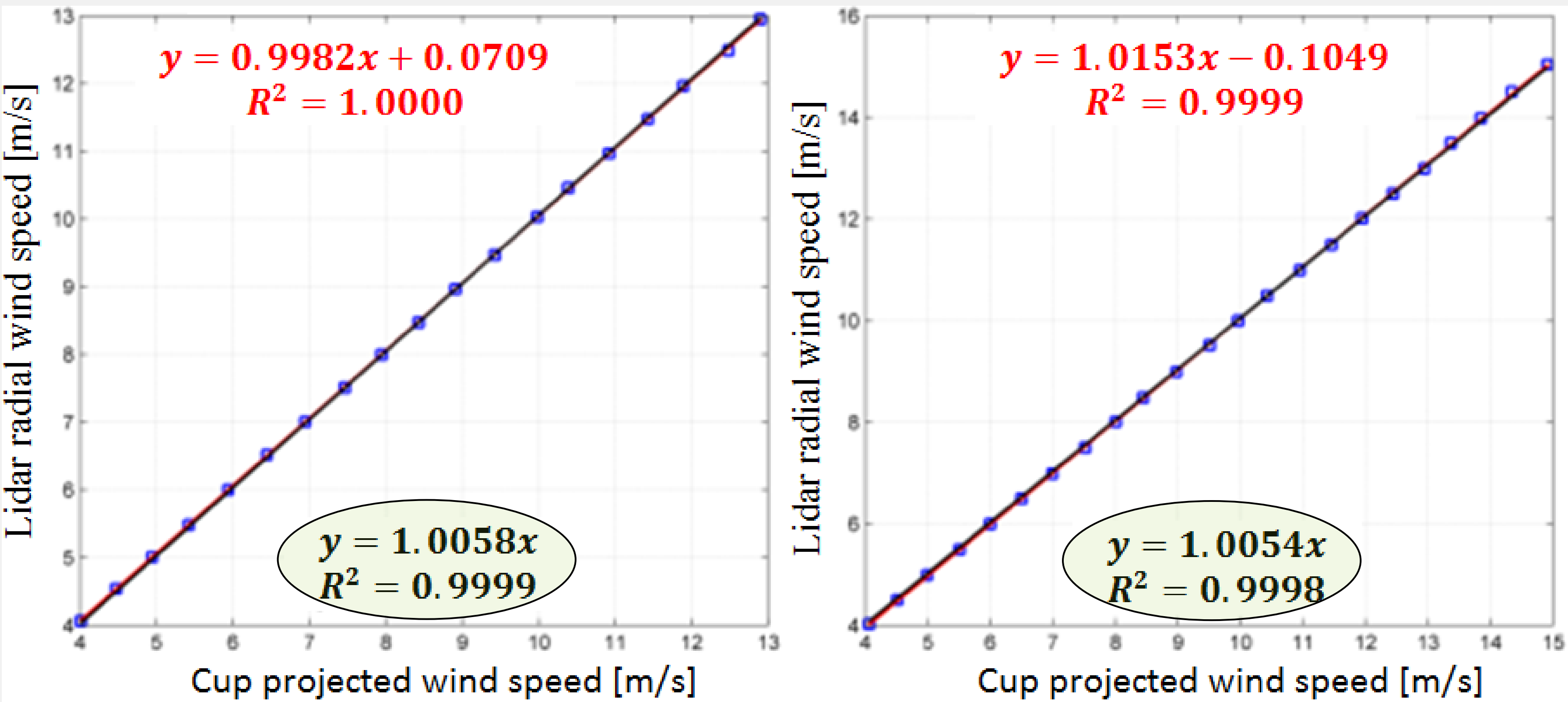
# Calibration results (Avent: L, Zephir: R)

- **"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



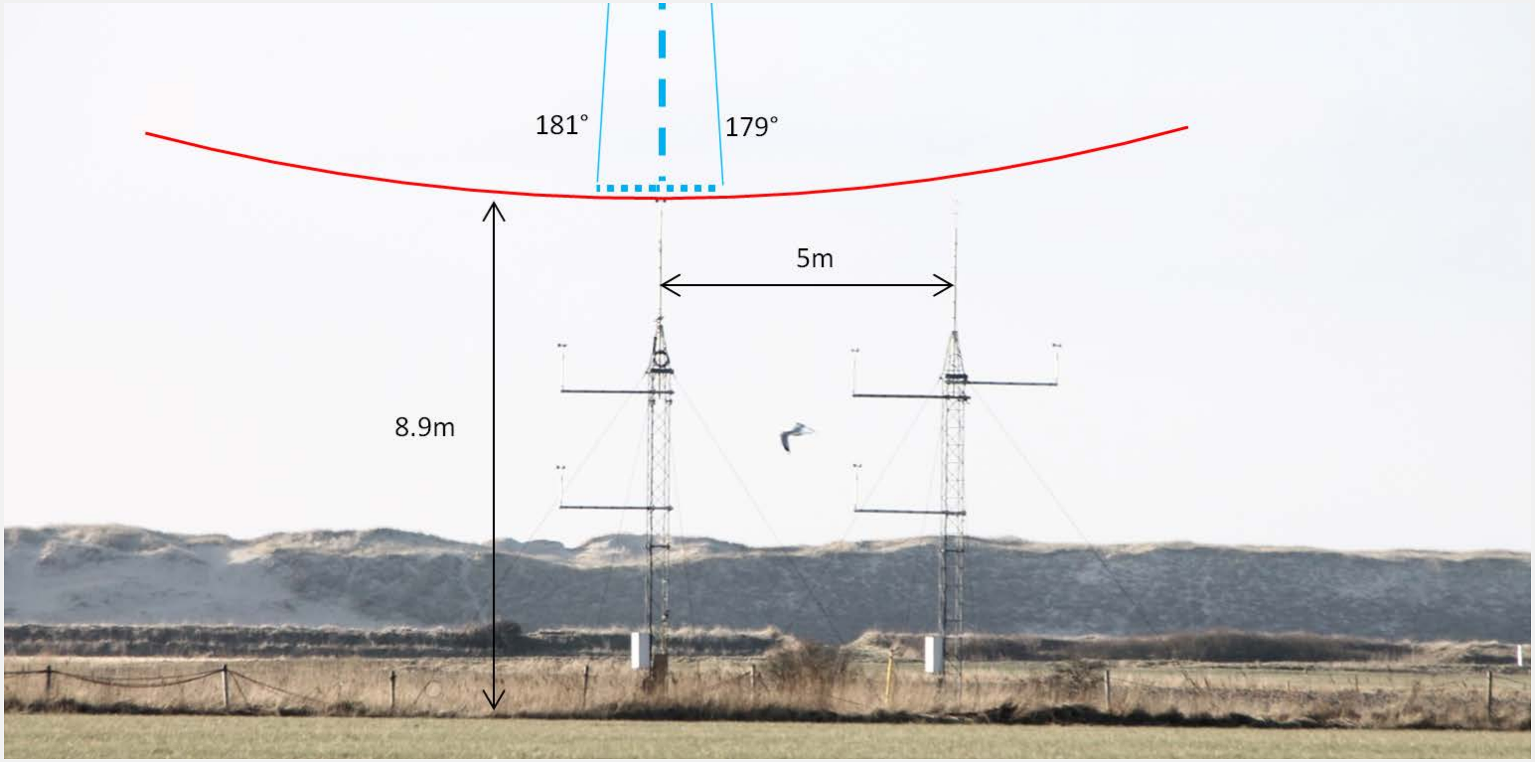
# Calibration results (Avent: L, Zephir: R)

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



# Calibration results
## 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