Benchmarking pulsed lidar TI solutions

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Motivation

- Onshore, profiling pulsed lidar turbulence intensity (TI) measurements exhibit high biases compared to cup anemometers
- Improving lidar TI would enable further replacement of met masts for wind energy applications

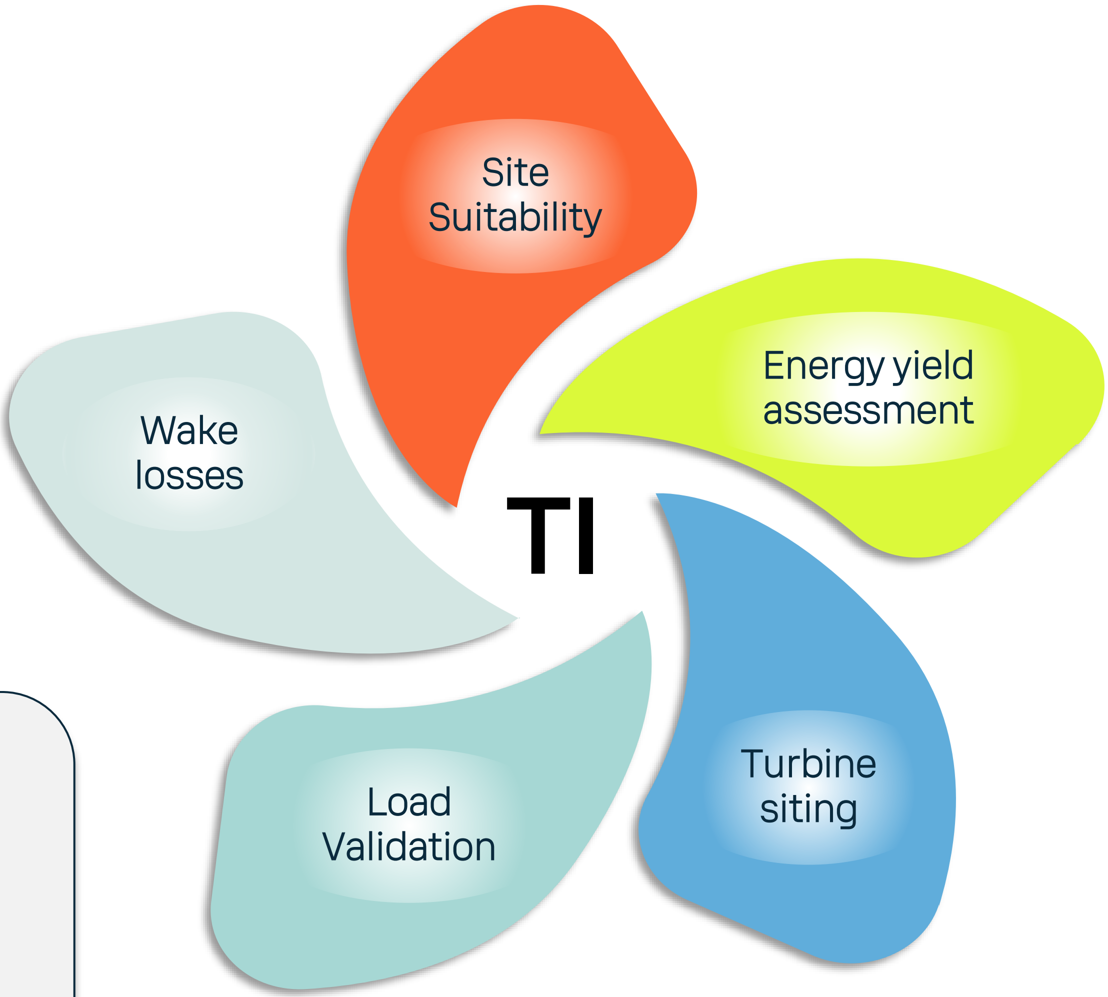
"Turbulence is the most important unsolved problem of classical physics."

– Prof. Richard Feynman (1964)

… and for wind lidar in 2025 !

Agenda

- ❑ New solutions
- ❑ Benchmarking
- ❑ Takeaways



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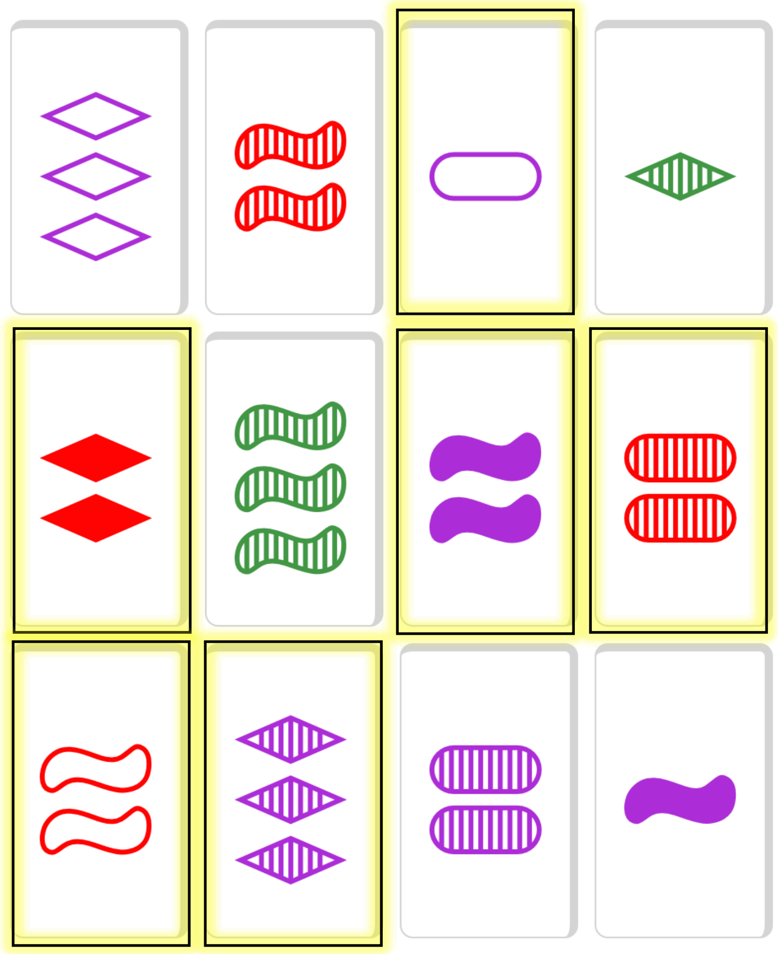
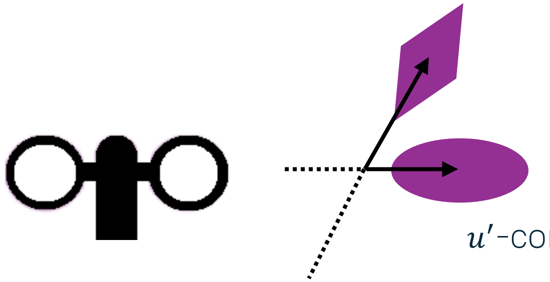
Measuring turbulence is multi-dimensional…

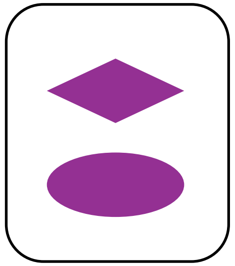
Like the game:

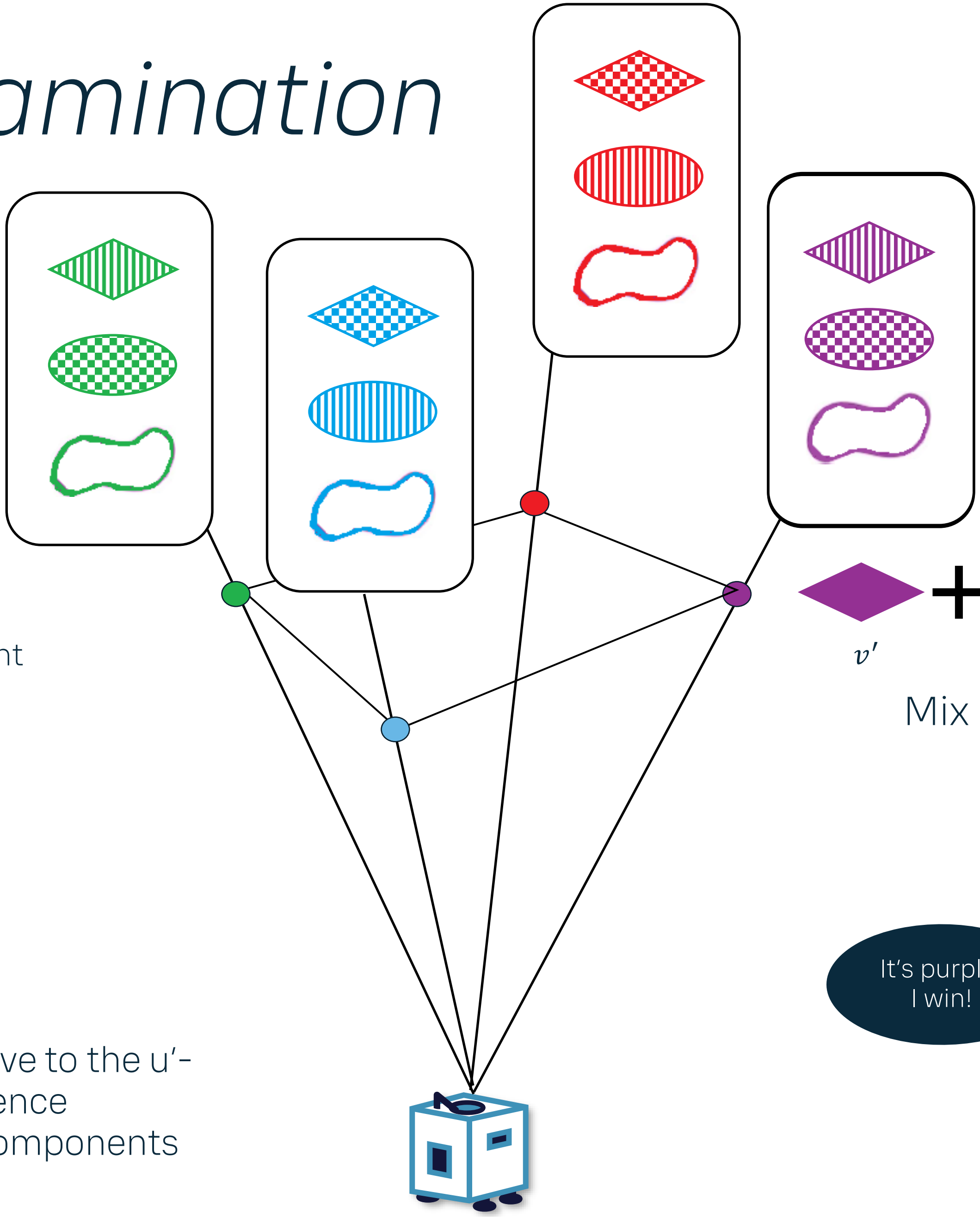


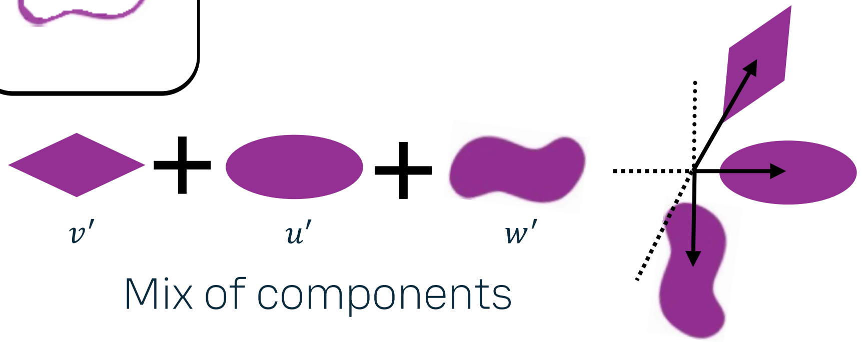
New Solutions
Interbeam contamination

- Profiling lidars are sensitive to the u′, v′, and w′ components of turbulence
- Beam is tilted out of the wind reference frame
- Beams measure at different locations and times

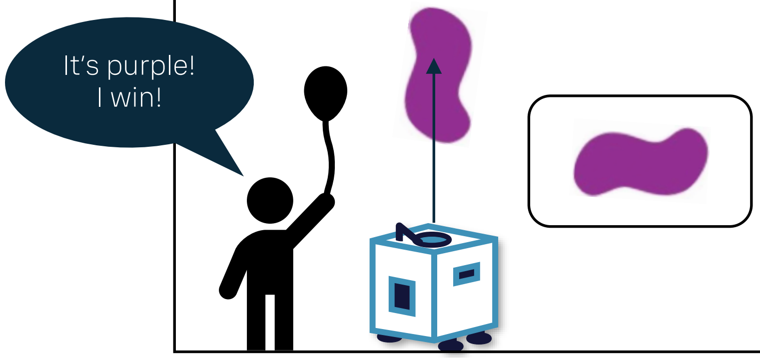






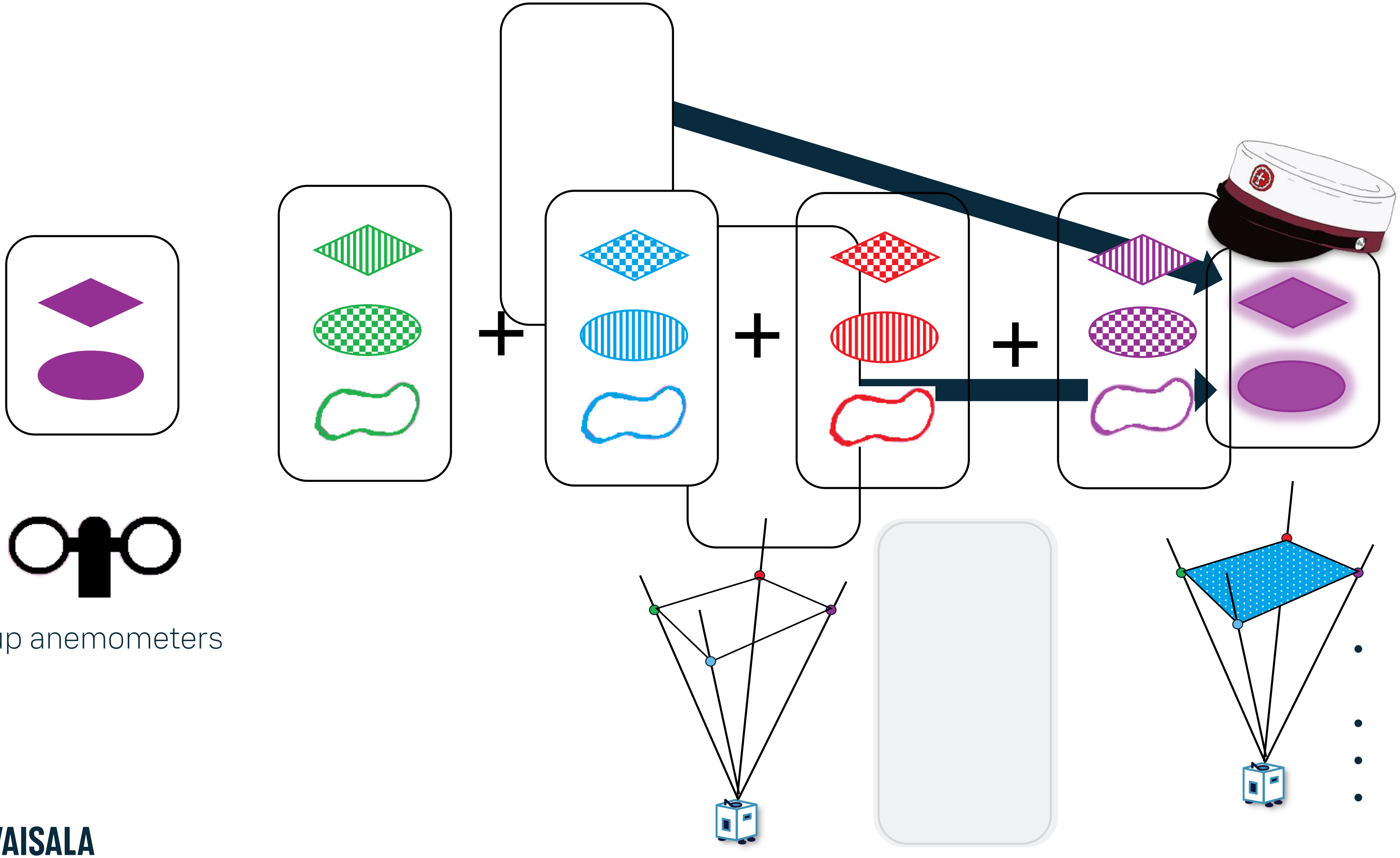


Note: the vertical beam is playing the simplest game…



- Cup anemometers are sensitive to the u′- and v′-components of turbulence
- Cup TI is a mixture of these components

New Solutions
Interbeam TI Reconstruction



Ordinary TI

Danish "studenterhuer" hat worn at graduation

$$TI_{inter} = \frac{\sqrt{\overline{\sigma^2_{ws,inter}}}}{\mu_{hybrid}}$$

Interbeam TI Reconstruction

- Combines u'-, v'-, and w'-components
- Corrects angles
- Suppresses w' influence
- Adjusts for beam position

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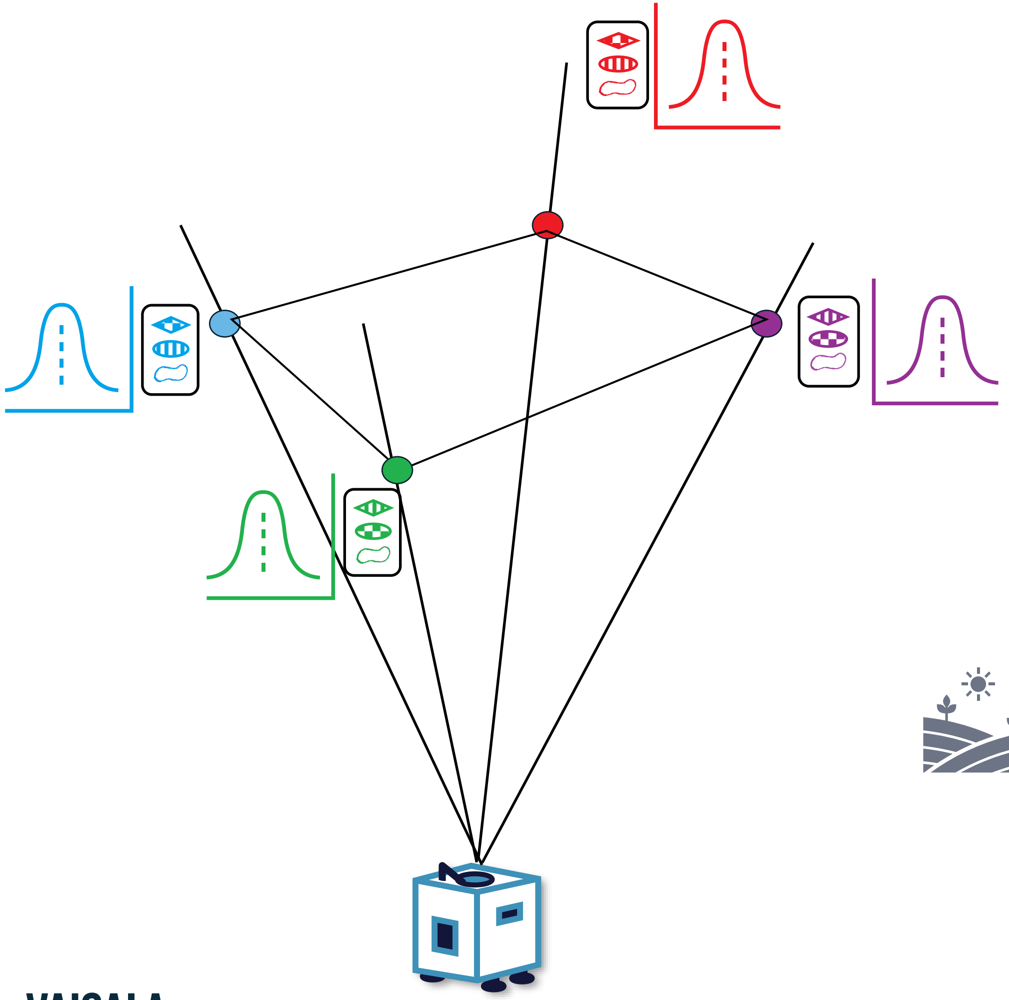
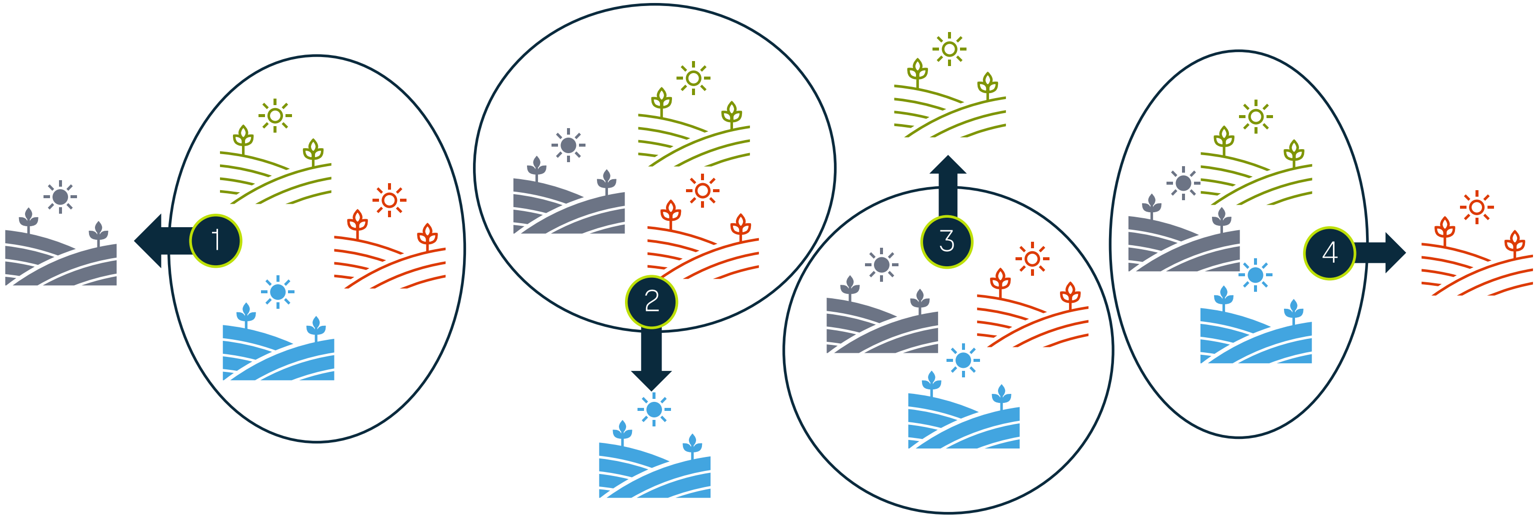
Hat image © 2010-2011 Studentershoppen.dk

New Solutions
Machine-learning Turbulence Intensity (MLTI)



- Machine learning approach using 10-minute LOS statistics and 10-min. reconstructions from ordinary WFR

- **Core model**: XGBoost
- **Cross Validation**: Leave-One-Site-Out (LOSO)
- **Dataset:** 5.5 years, ~300k samples



Benchmarking Methodologies

Reference

Four IEC-compliant lidar validation site met masts

DEUTSCHE WINDGUARD
Height: 134 m
Anems: Thies FCA

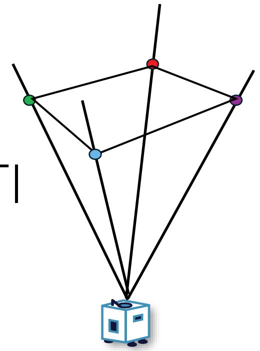
windtest grevenbroich gmbh
Height: 134 m
Anems: Thies FCA

UL
Height: 120 m
Anems: Thies FCA

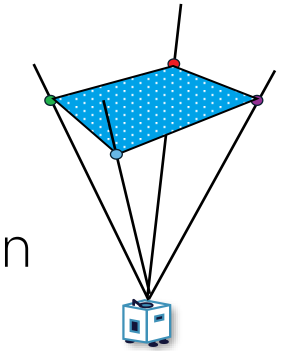
DNV
Height: 120 m
Anems: Thies FCA

Lidar TI Algorithms

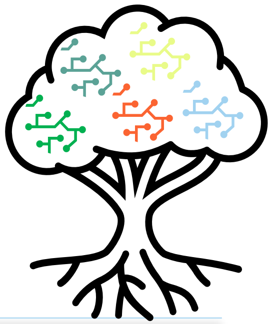
WindCube v2.1 TI
No correction



Interbeam TI Reconstruction



MLTI



KPIs

- Slope
- Intercept
- R^2 of linear regression
- Relative MBE
- RMAE
- RRMSE

DNV Recommended Practice 0661
Lidar-measured turbulence intensity for wind turbines

- Characteristic TI curves
- RMBE compared to Cup TI reference

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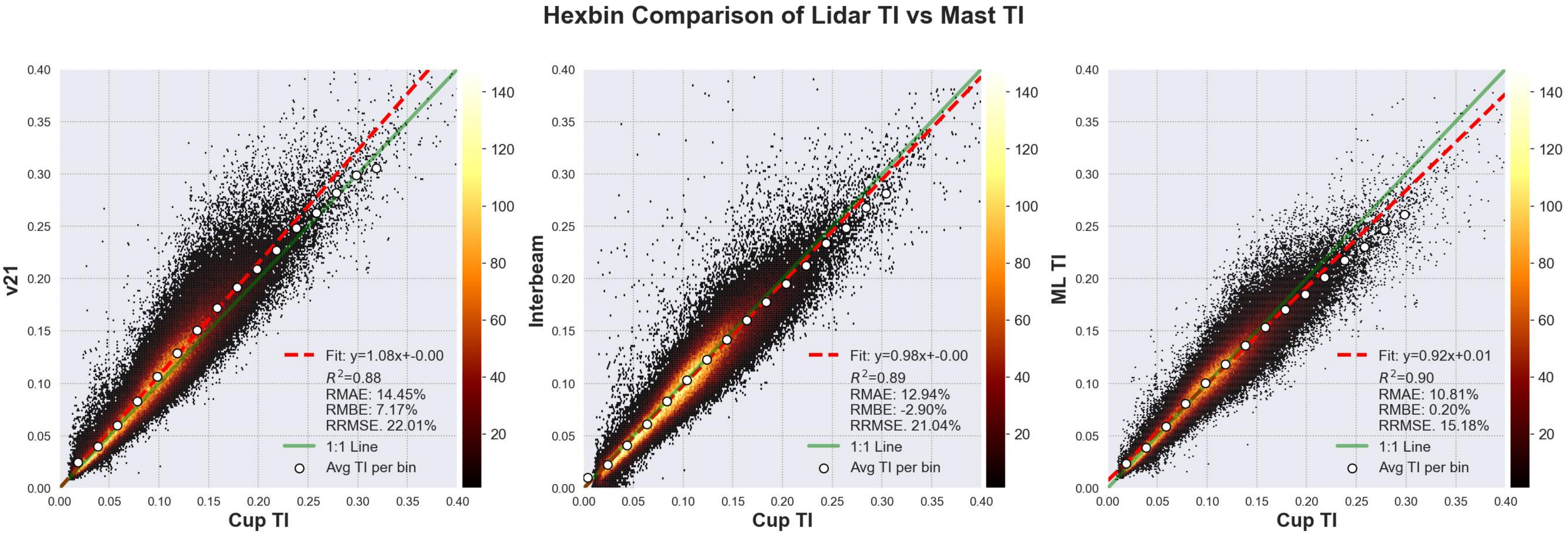
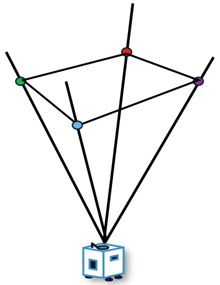
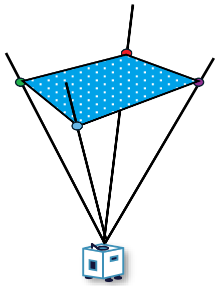
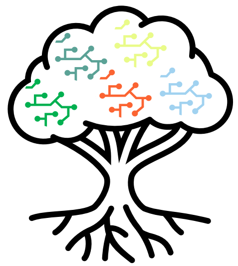
Scatterplot and Ordinary KPIs

All sites and heights pooled together









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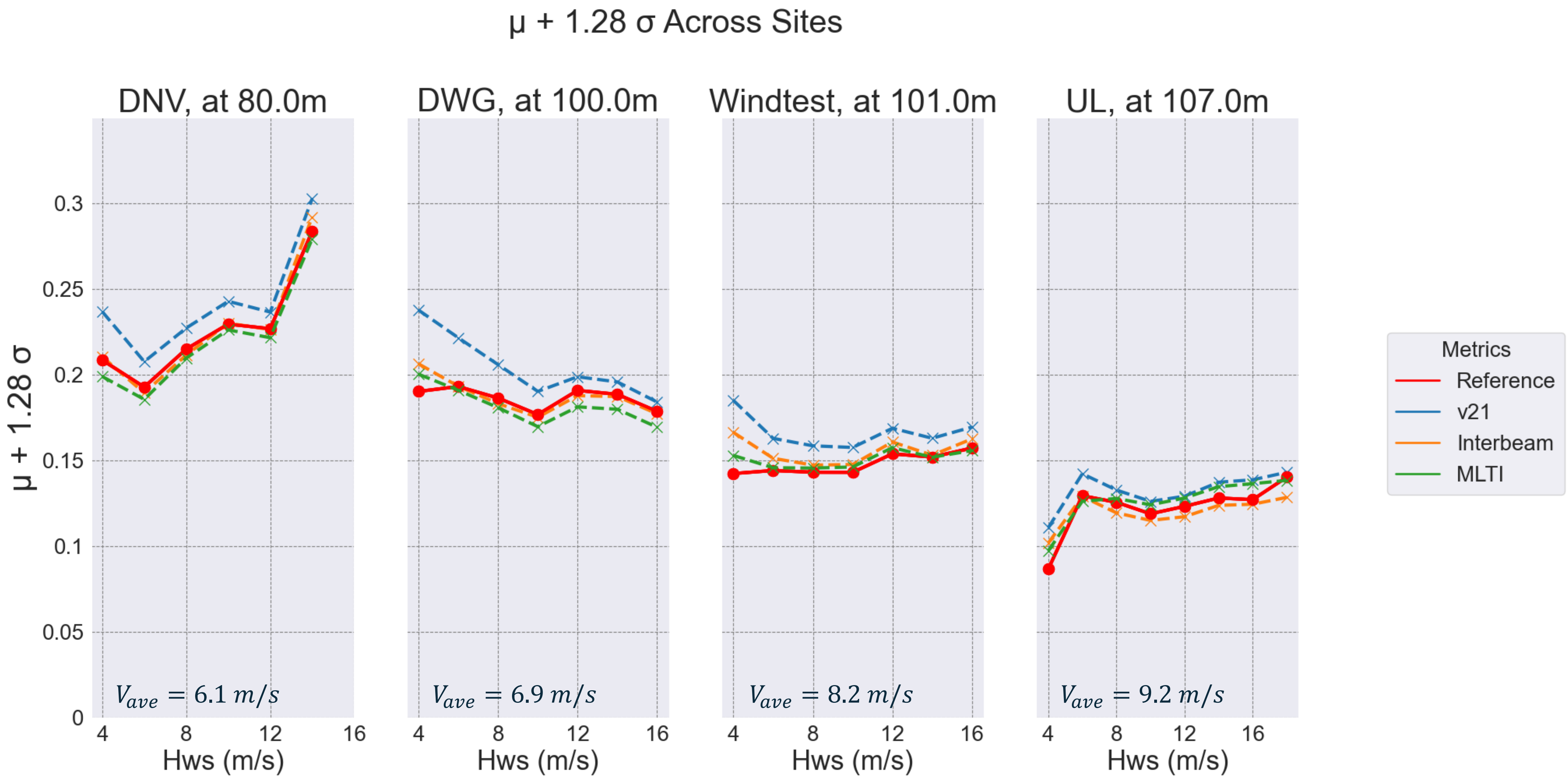
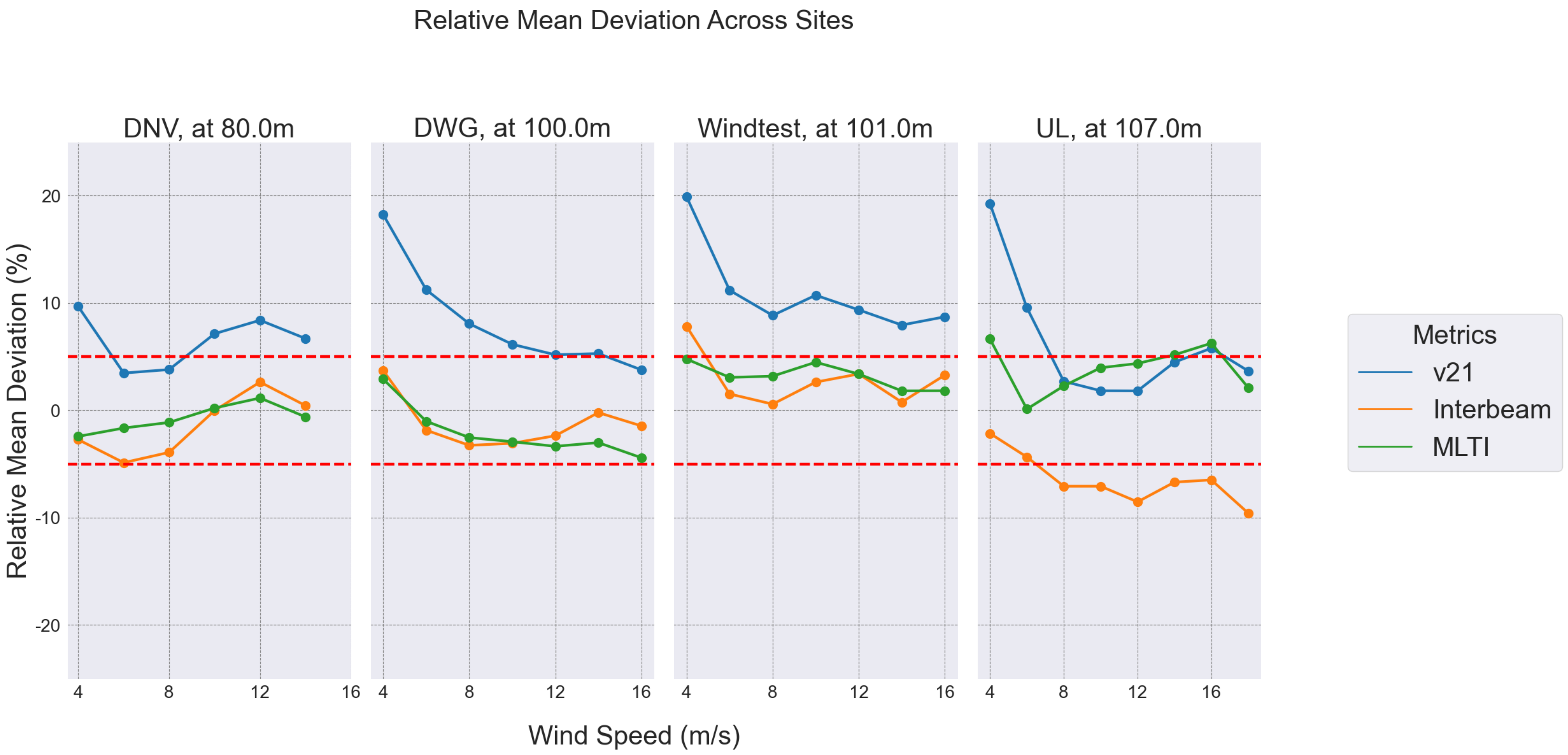
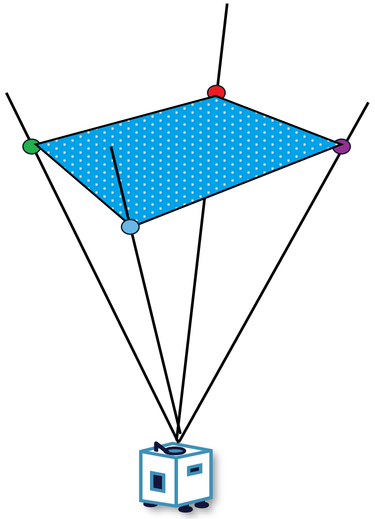
Characteristic TI Curves



DNV RP 0661 KPIs for Loads Validation

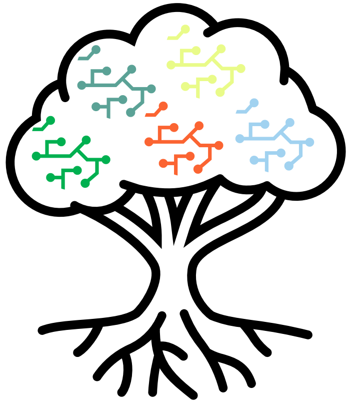


Conclusions



Interbeam

- Big improvement from WindCube v2.1
- Higher R^2, Lower RMAE and RMBE
- Average slope 0.98, within 2%
- Bin-means are stable across TI..
- .. but some underestimation at low TI
- Major improvement at low speeds
- Mostly meeting DNV-RP KPIs



MLTI

- Excellent R^2 and RMBE
- Slope and bin-means show some overfitting to center of distribution
- Underestimating at high TI..
- ..but very good at low TI
- Mostly meeting DNV-RP KPIs

Next Steps

- Continue refining Interbeam correction
- Expand machine learning training and testing to new sites
- Include Interbeam intermediate outputs as ML features
- Expand validation to other conditions (esp. Class I sites)
- DNV-RP evaluation for sites that are in development or pre-development

Thank you for listening!
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Appendix
1 Hz Wind Field Reconstruction

WindCube profiler measures 5 Lines of Sight (LOS)

S_{North}, S_{East}, S_{West}, S_{South}, $S_{Vertical}$

Each LOS lasts 0.8s

Relationship between radial wind speed and uvw components:

- $S_N = u \sin\theta + w\cos\theta$
- $S_E = v \sin\theta + w\cos\theta$
- $S_S = -u \sin\theta + w\cos\theta$
- $S_W = -v \sin\theta + w\cos\theta$

↔

- $u = \frac{S_N - S_S}{2\sin\theta} - \frac{W_N - W_S}{2\tan\theta}$
- $v = \frac{S_E - S_W}{2\sin\theta} - \frac{W_E - W_W}{2\tan\theta}$
- $w = S_V$

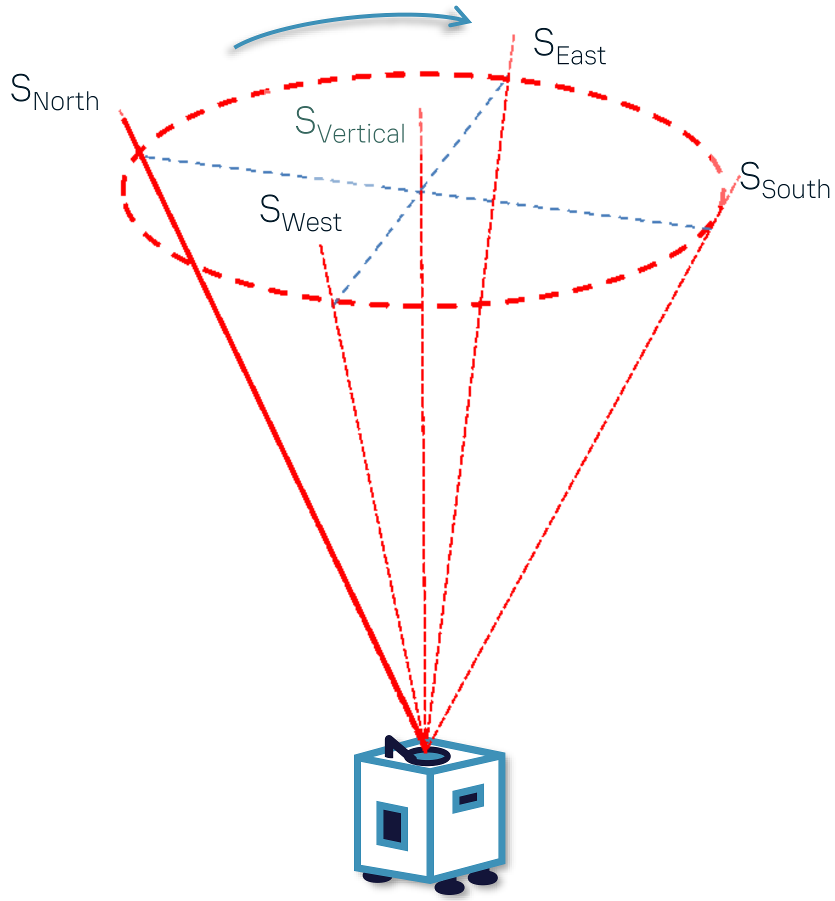
=0 if you assume the flow is homogeneous

Mean Wind Speed

$$\overline{U_{scalar}} = \frac{1}{N}\sum_{i=1}^{N}\sqrt{u_i^2 + v_i^2}$$

Standard Deviation of Wind Speed

$$\sigma_{scalar} = \sqrt{\overline{U_{scalar}^2} - \overline{U_{scalar}}^2}$$



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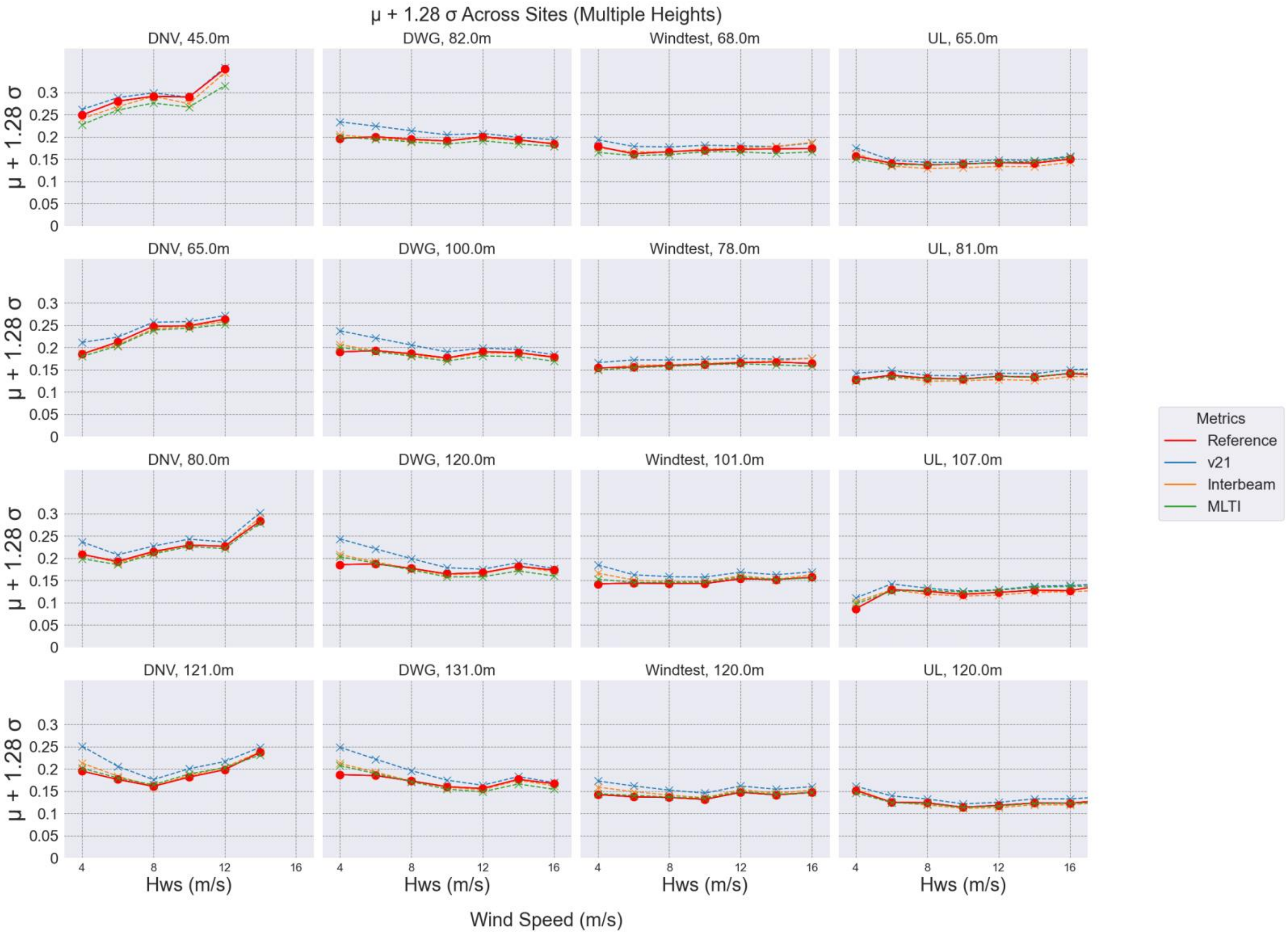
Appendix
Characteristic TI Curves at other heights



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Appendix
DNV RP 0661 KPIs at other heights