ACP PEAK
PERFORMANCE, MODELING & ASSESSMENT CONFERENCE

Untangling turbulence profiles with new lidar algorithms

Andrew Black, Hazem Rabhi

October 30, 2025

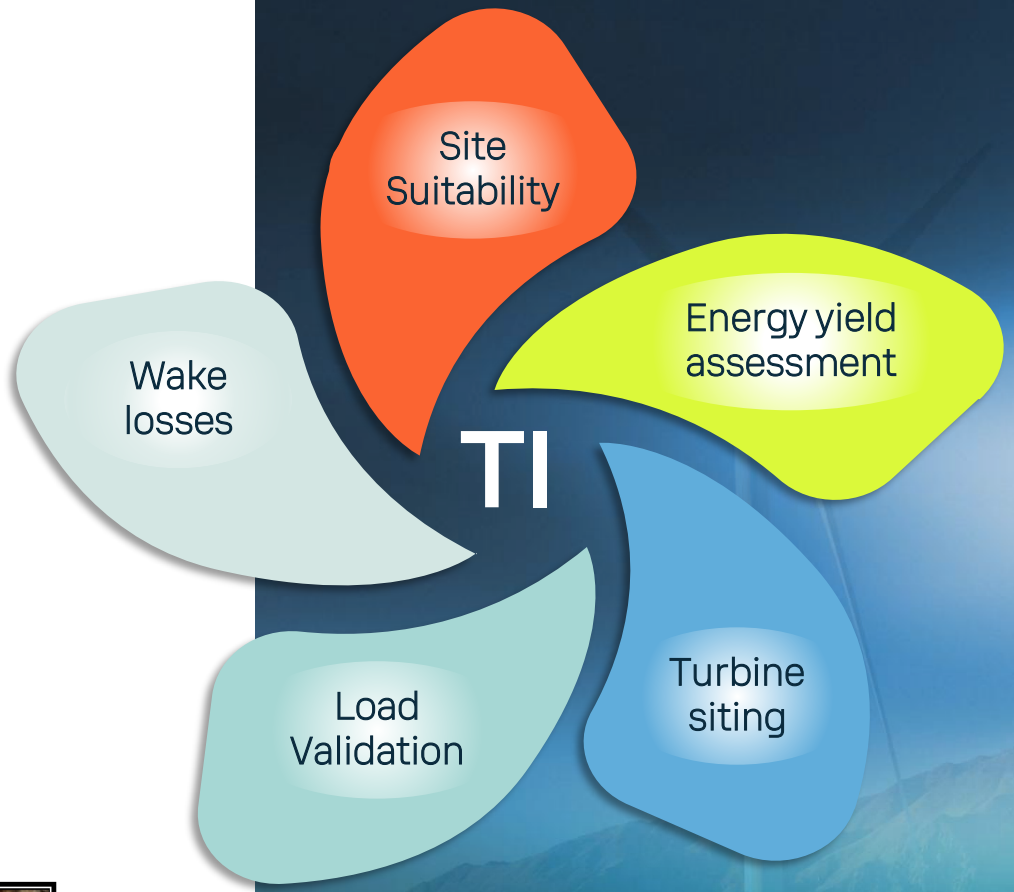
AMERICAN CLEAN POWER

VAISALA

Background

- Onshore, profiling pulsed lidar turbulence intensity (TI) measurements exhibit high biases compared to cup anemometers
- Improving lidar TI would streamline wind energy development (no permits!) and enable new research leveraging the full capabilities of lidar
- Vaisala and the lidar community in industry and academia have been pursuing new understanding of TI reconstruction and new solutions for many years
- Today, you'll see progress since 2024 ACP Peak in Austin

Javelina, courtesy NPS, 2020



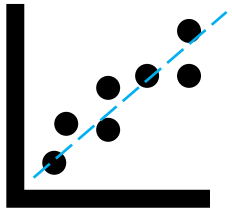
"Turbulence is the most important unsolved problem of classical physics."
– Prof. Richard Feynman (1964)
(…and for wind lidar in 2025)

AMERICAN CLEAN POWER PEAK

VAISALA

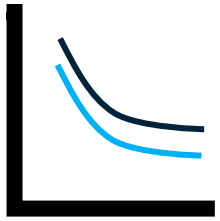
How do we evaluate TI algorithms?

Linear regression of 10-minute TI measurements with reference data



- Slope, Offset, R^2, RMSE, RMBE, RMAE

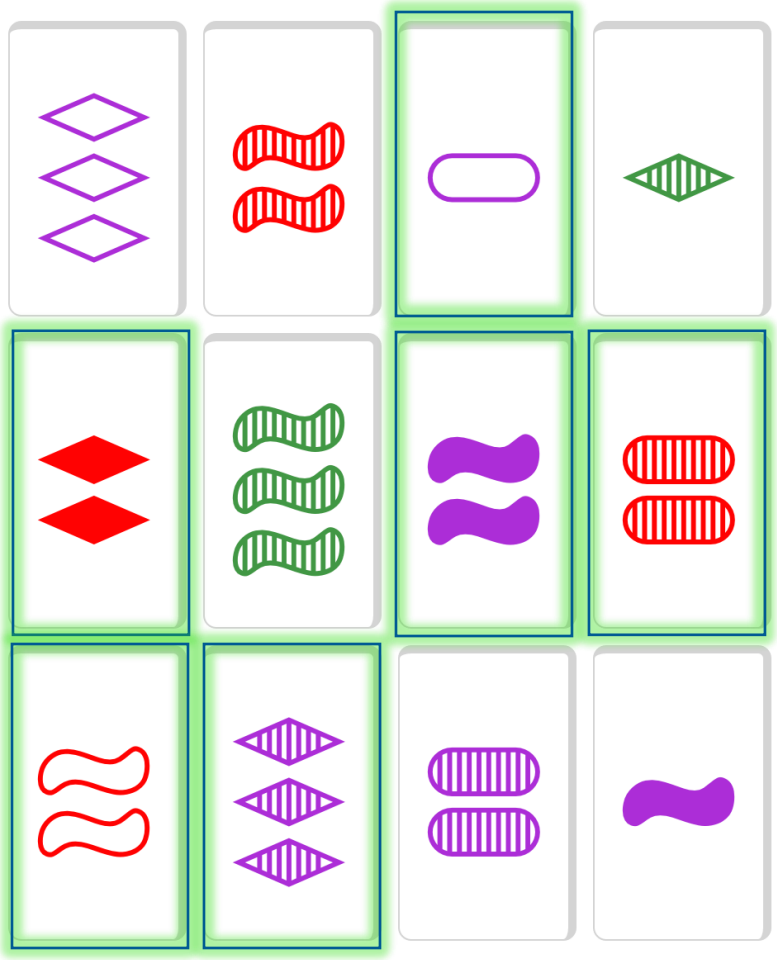
Characteristic TI curves from lidar and from reference



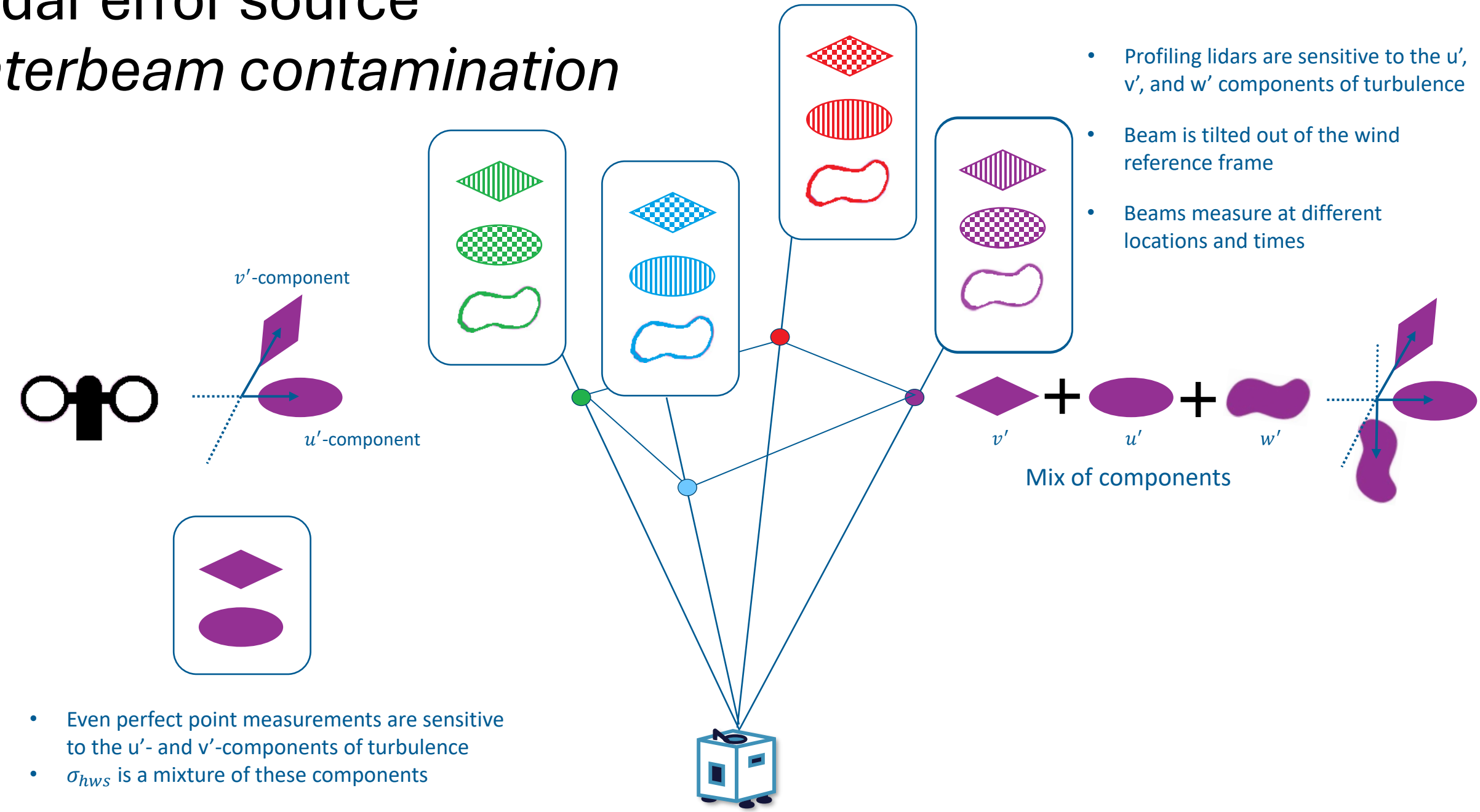
- Linear regression of bin-average data
- DNV-RP 0661 KPIs : RMBE, RMSE for use cases

Measuring turbulence is multi-dimensional…

Like the game:



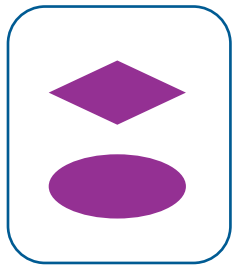
Lidar error source
Interbeam contamination



- 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

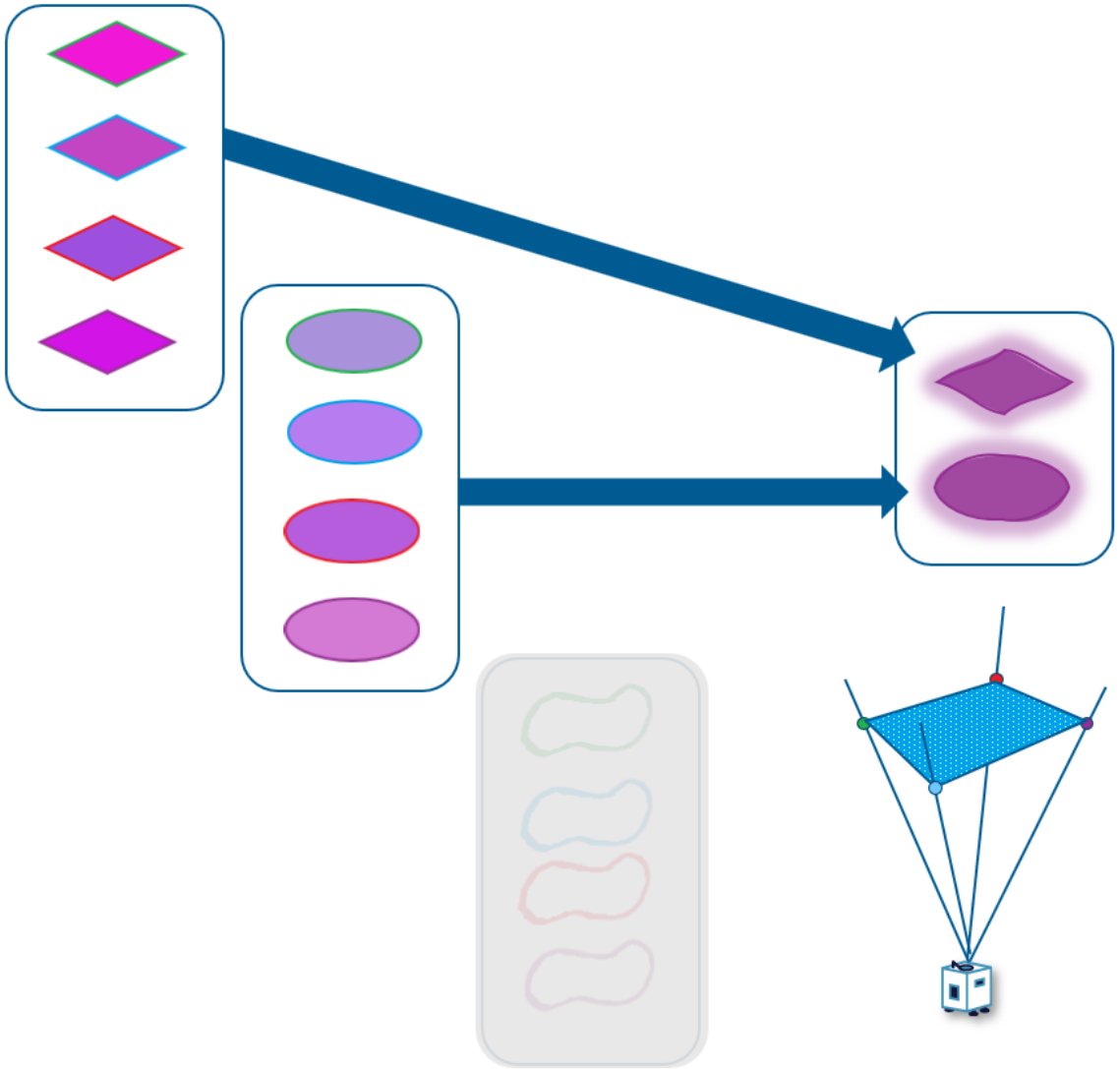
- Even perfect point measurements are sensitive to the u'- and v'-components of turbulence
- σ_{hws} is a mixture of these components

New Solutions
Enhanced TI Reconstruction



Cup anemometer TI

$$TI_{cup} = \frac{\sigma_{hws,10min}}{\mu_{hws,10min}}$$



$$TI_{lidar} = \frac{\hat{\sigma}_{hws,10min}}{\mu_{hws,10min}}$$

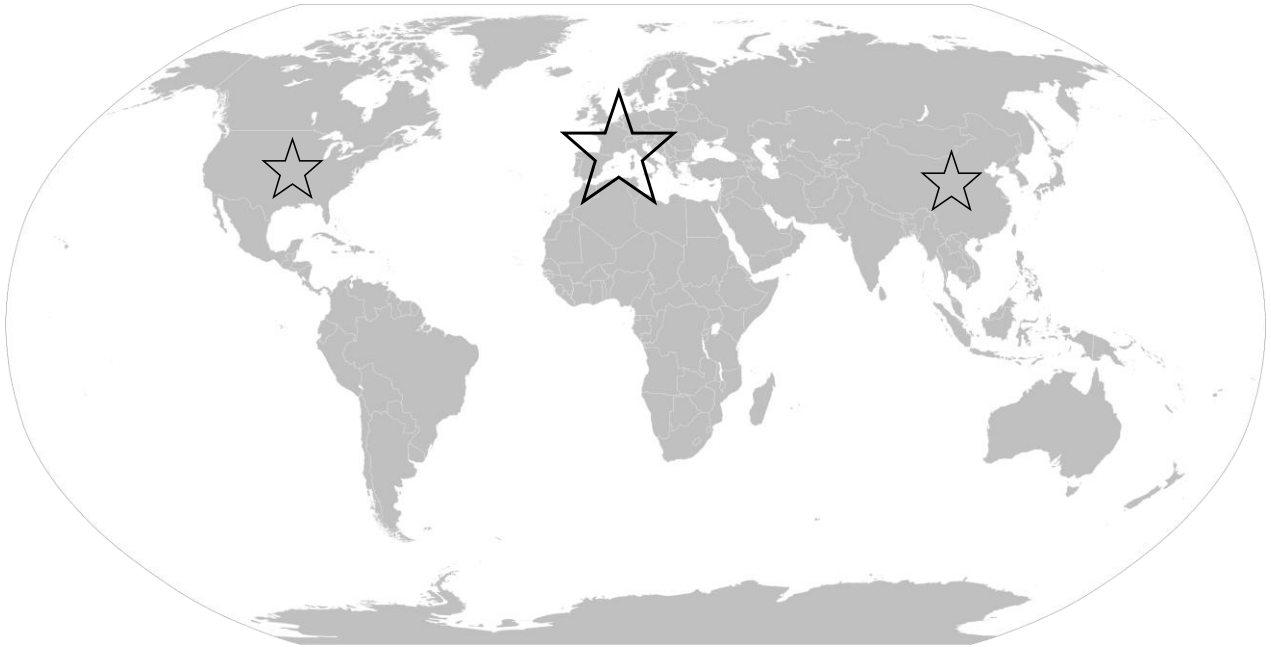
Enhanced TI Reconstruction

- **Input: high-frequency (~1 Hz) data**
- Combines u'-, and v'-components
- Corrects angles
- Suppresses w' influence
- **Output : $\hat{\sigma}_{hws,10min}$, an improved estimate of standard deviation**

Sites of study

The following presentation demonstrates the algorithm's performance on a total of **30 sites**
The locations range from moderately complex to flat terrain.

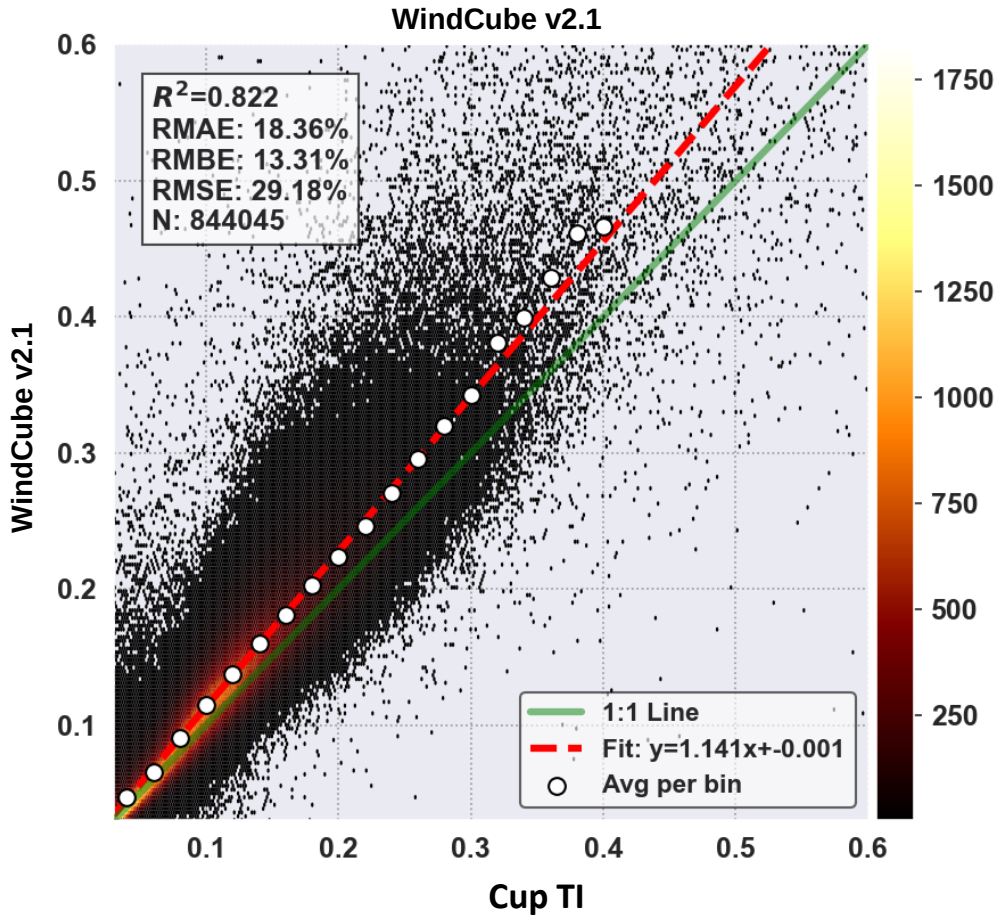
2 sites in USA **26** sites in Europe **2** sites in China

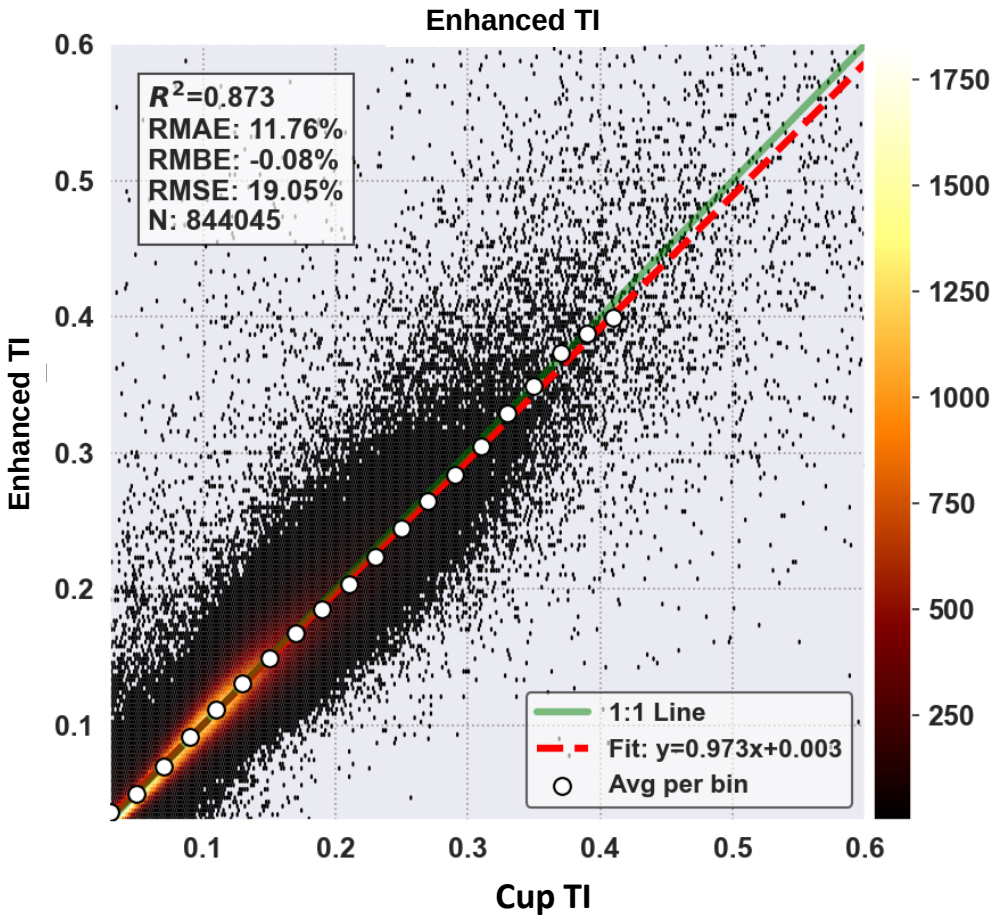


Turbulence class	I	II	III
A+	0	0	0
A	0	0	0
B	0	0	2
C	0	7	21

Distribution of sites per turbulence class

Overall Results: Scatterplot and Linear Regression



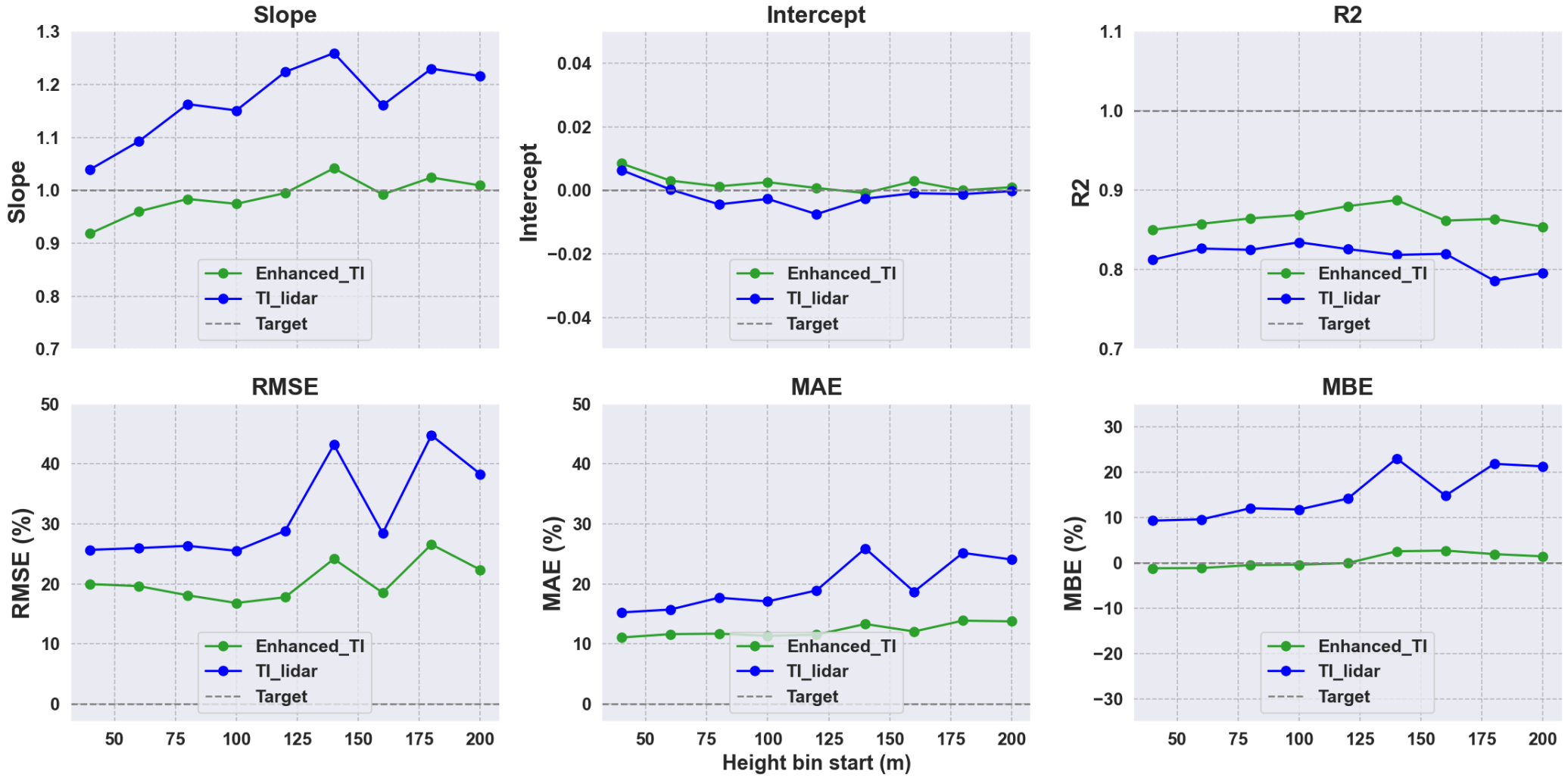


+5% R^2
–13% RMBE
–10% RMSE

- 30 measurement campaigns
- Almost 1 million datapoints
- 40m – 200m reference instruments

- TI-bin-averages shown as white dots
- Density shown in heatmap

Linear Regression KPIs by Height



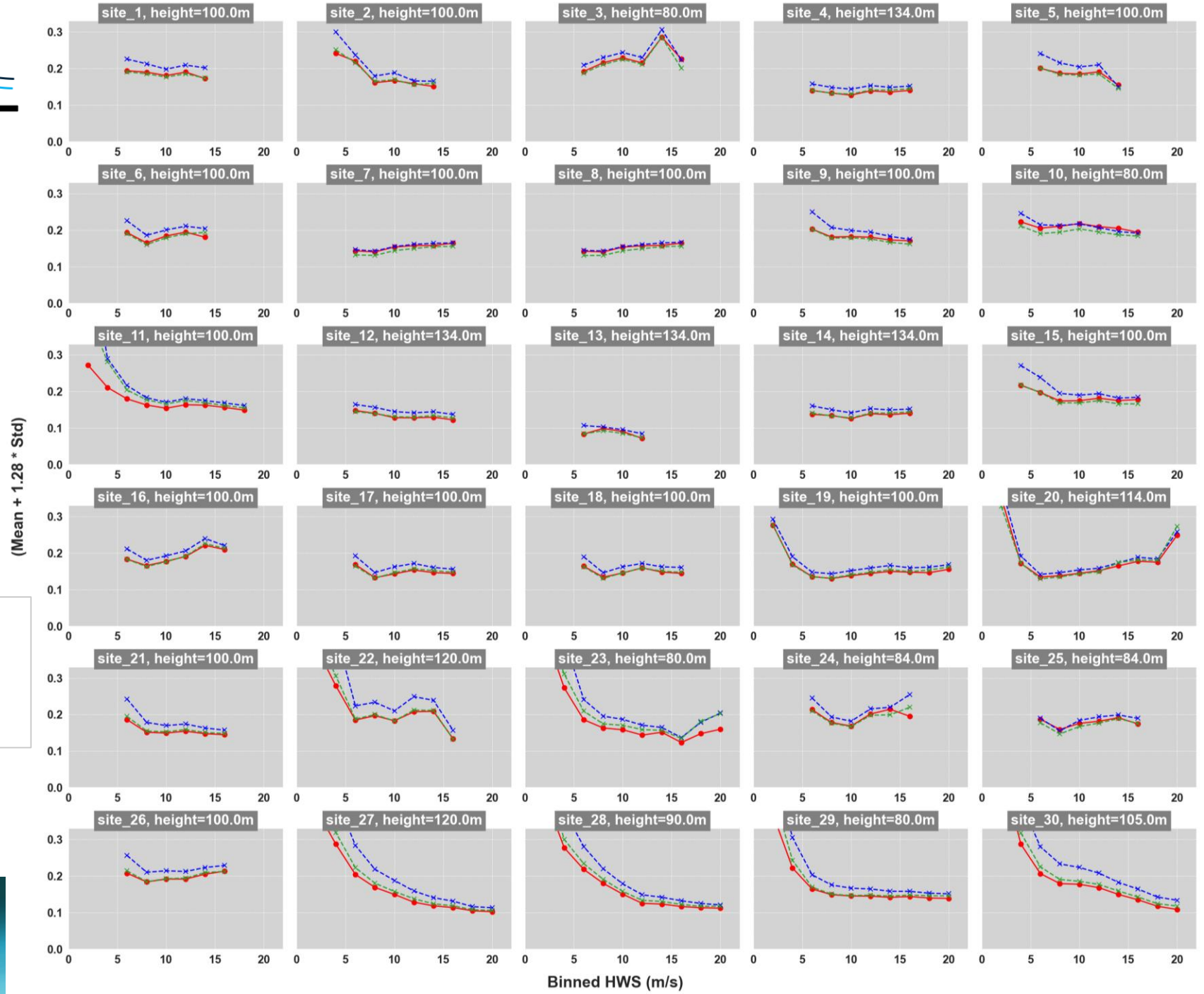
- 30 measurement campaigns
- Almost 1 million datapoints
- 40m – 200m reference instruments

- Stable performance over height
- Note that bins may contain different sites
- Improvement across all statistics

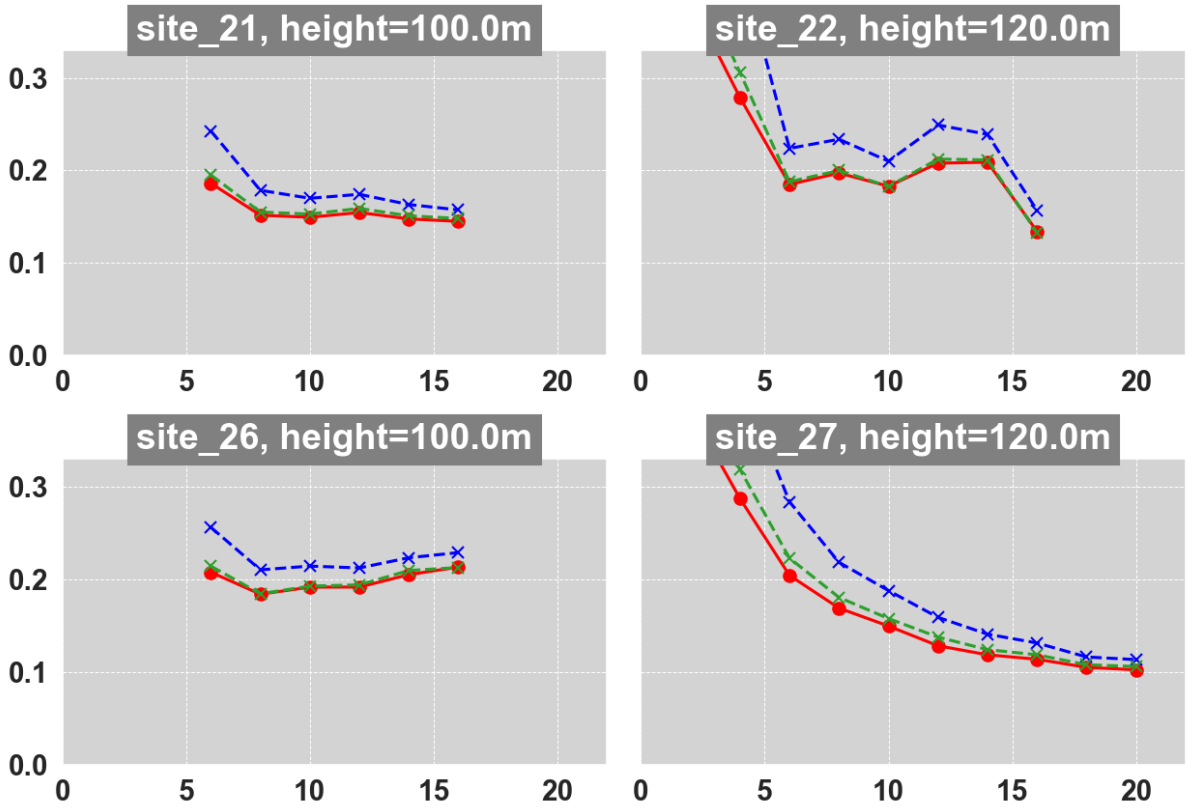
Characteristic TI Curves

- Used to select turbine based on upper distribution of bin-wise TI Defined in IEC 61400-1
- $y = \mu_{TI,i} + 1.28 * \sigma_{TI,i}$ in each wind speed bin, *i*

WindCube v2.1
Cup TI
Enhanced TI



Characteristic TI Curves (detail)

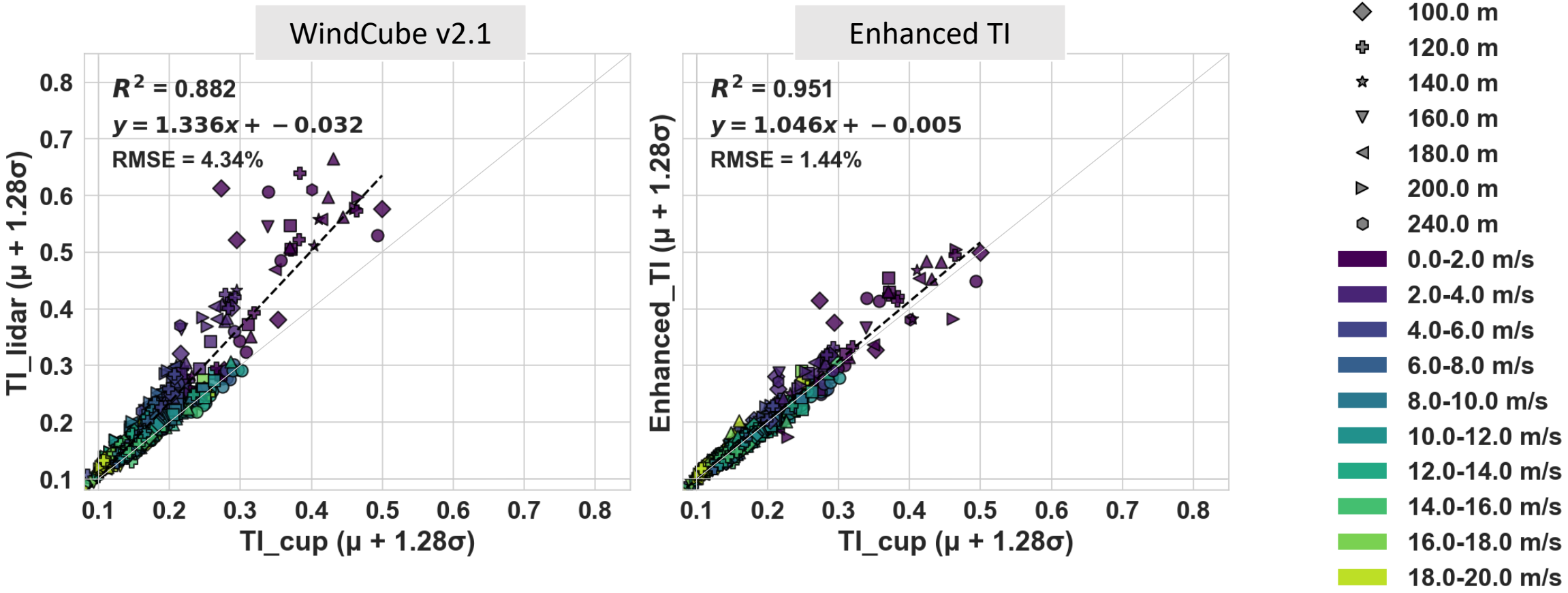


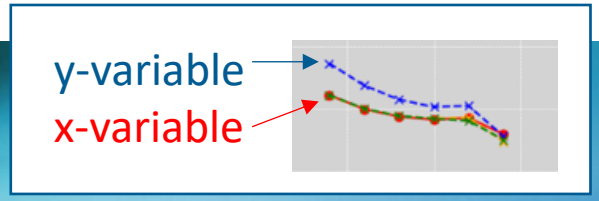
New algorithm yields nearly identical curves to co-located cups for Loads Validation and Site Suitability

WindCube v2.1
Cup TI
Enhanced TI

Characteristic TI curve binned data

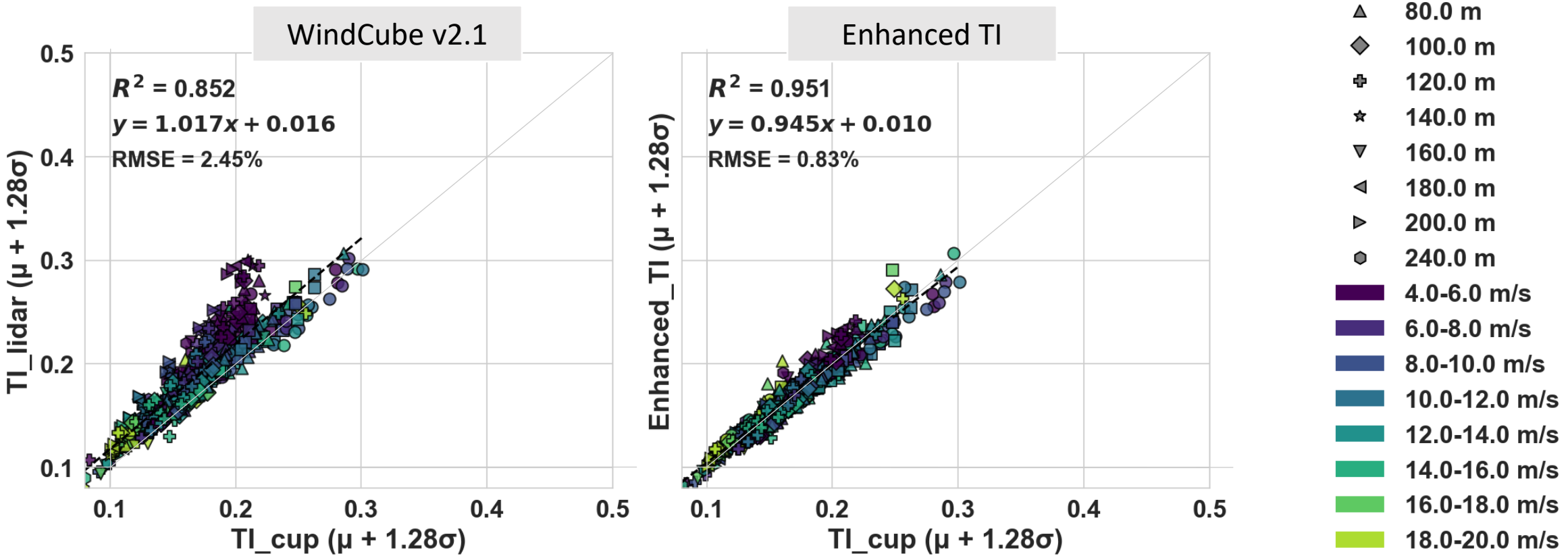
Including 0 - 20 m/s

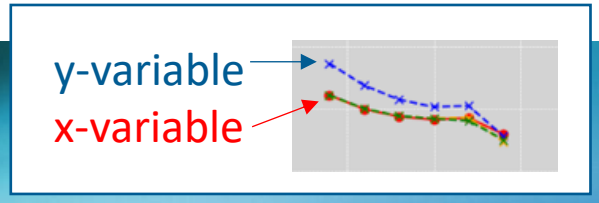




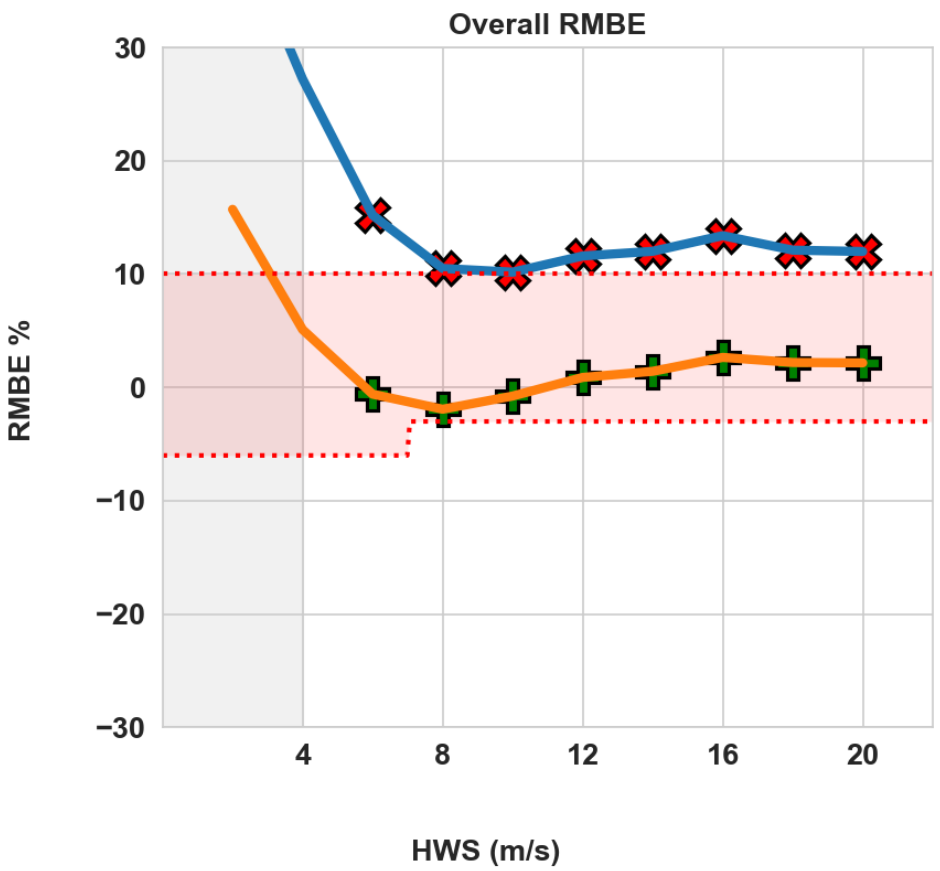
Characteristic TI curve binned data

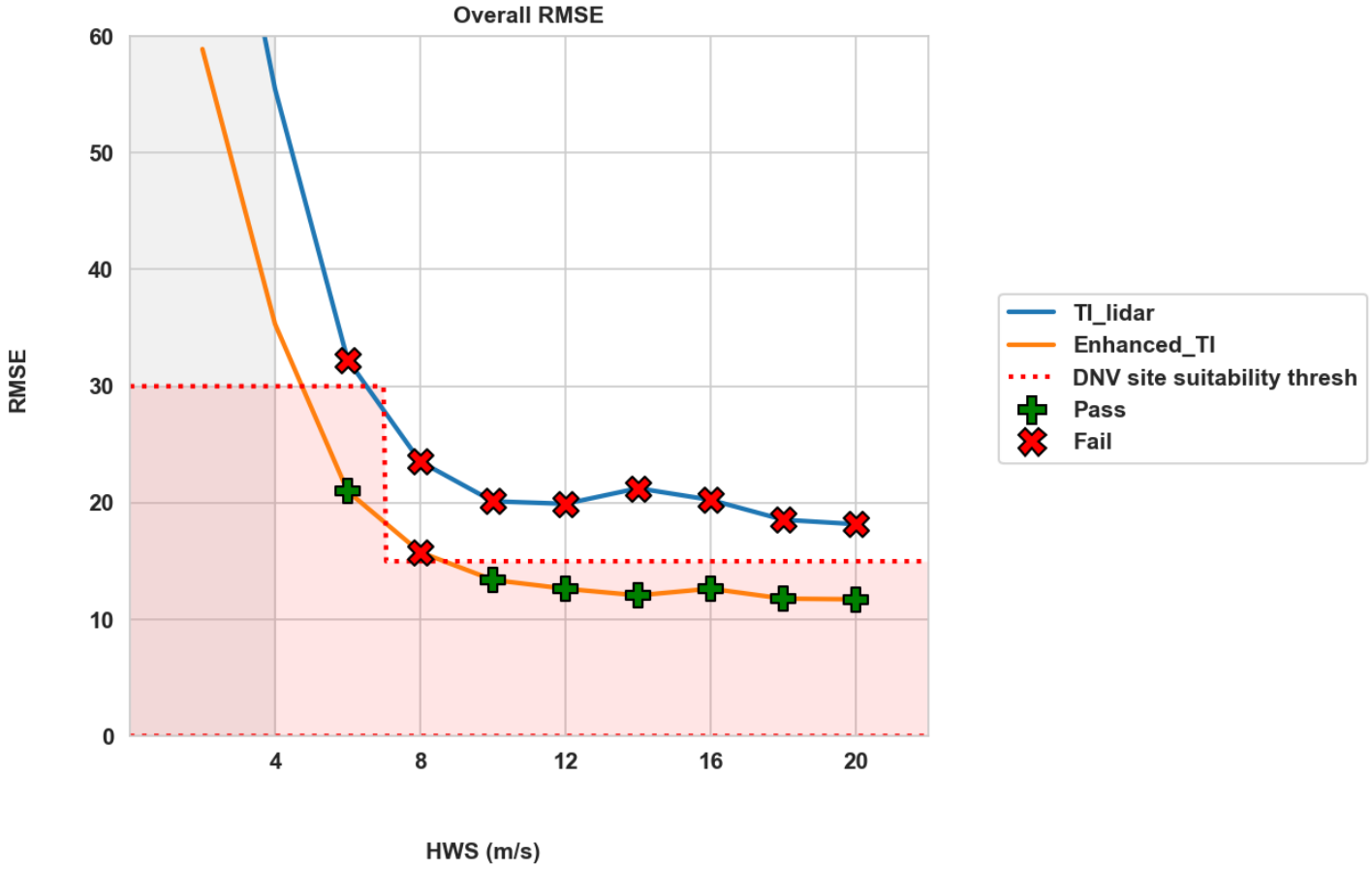
Including only 4 - 20 m/s





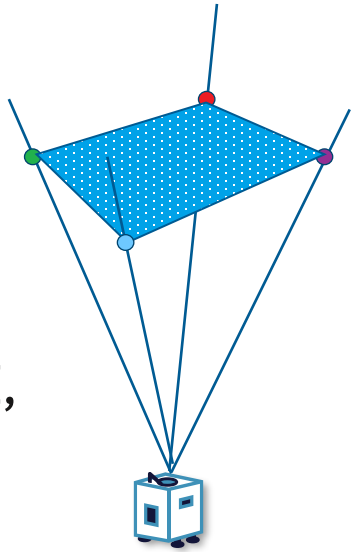
DNV-RP 0661 KPIs for Site Suitability

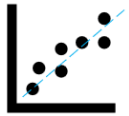




Conclusions and Next Steps

- **Enhanced TI Reconstruction** is a huge improvement over the traditional WindCube TI algorithm
- Reduced R2 and improved slope, intercept, RMSE, RMBE
- Meets DNV-RP 0661 KPIs
- Nearly identical Characteristic TI compared to co-located cups
- Excellent performance in diverse conditions
- Lidar can now measure speed, direction, TI, vertical speed and vertical turbulence, simultaneously, at 20 heights, up to 400m with WindCube v2.1 XP





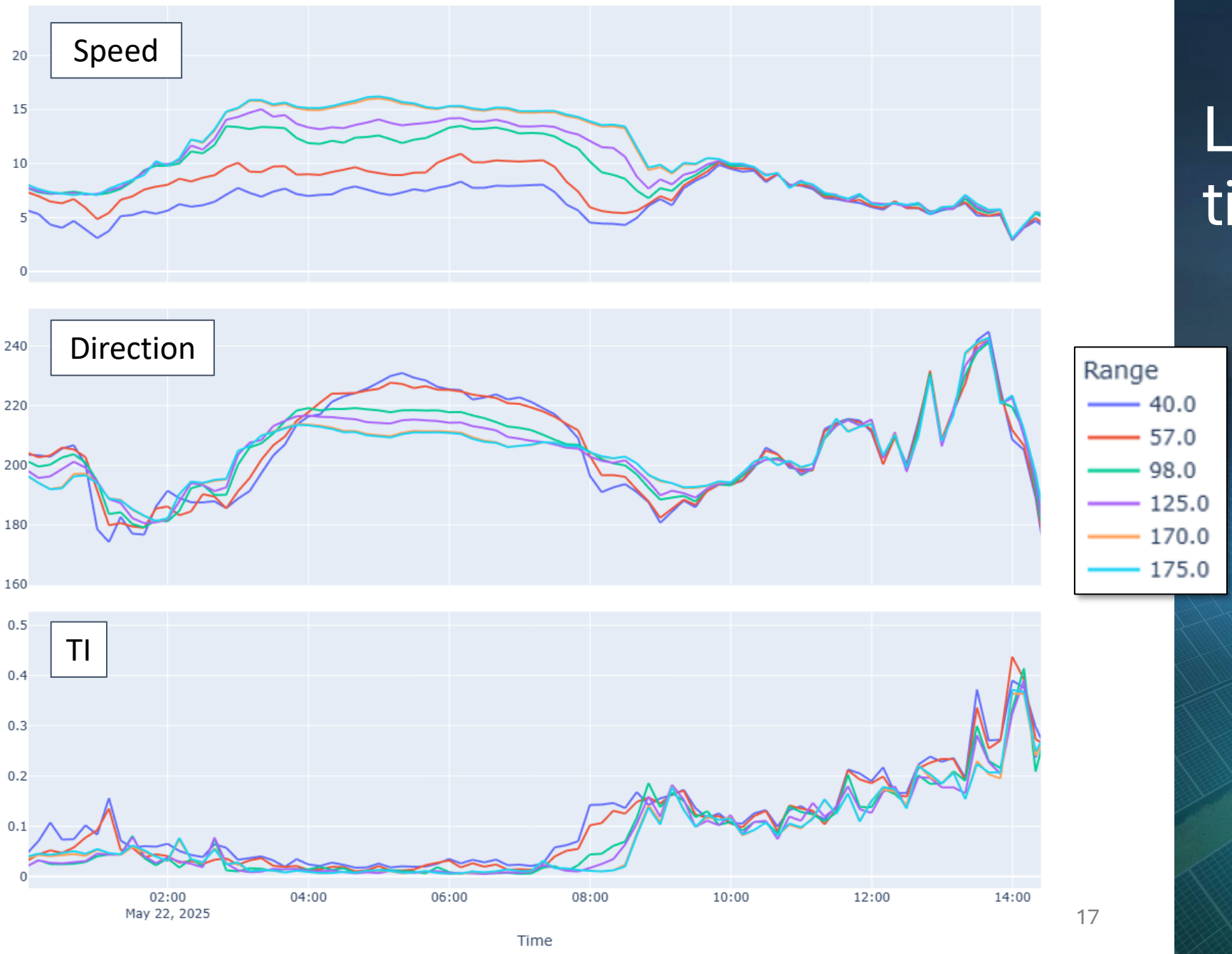
Apply to your data!

Send RTD files to Vaisala and we will send back STA files

andrew.hastingsblack@vaisala.com
hazem.rabhi@vaisala.com
ryan.matt@vaisala.com

VAISALA

Appendix



Let's investigate time series events..

Residual layer grows into nocturnal BL...

Intense direction change and veer in surface layer, ~50°

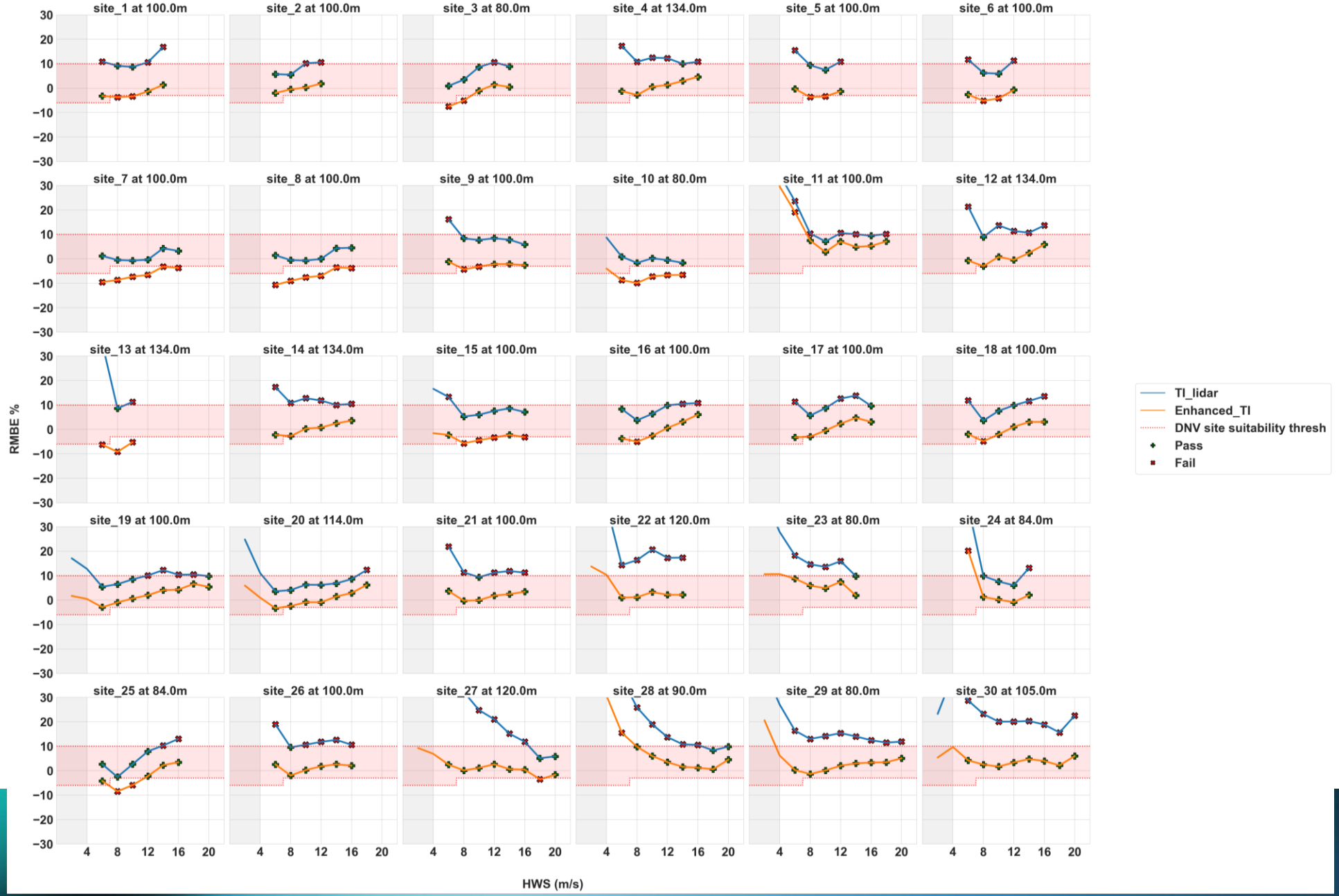
Reverses at sunrise...

Turbulence grows from surface upward...

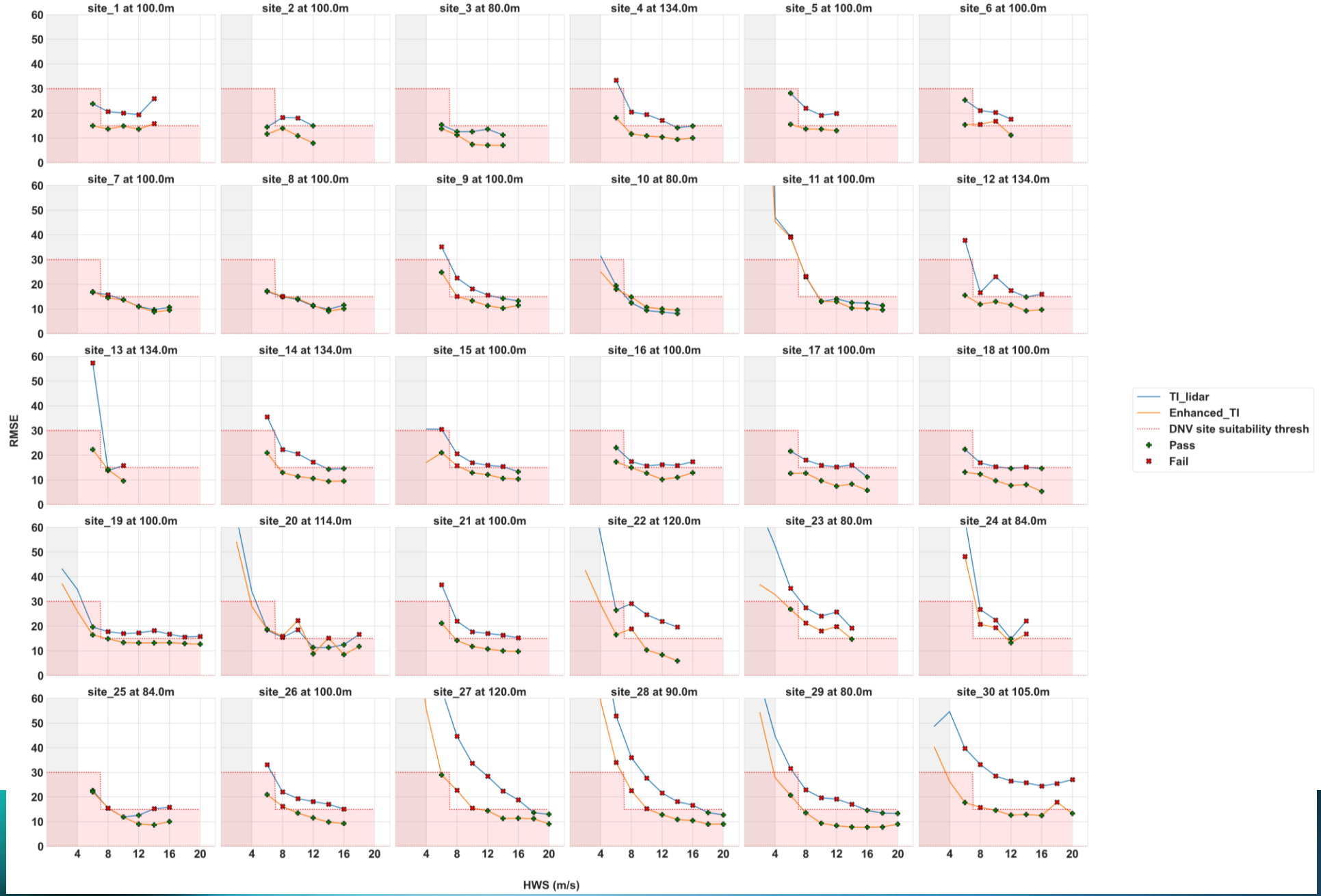
Shear and veer vanish, and TI grows throughout the day...

VAISALA

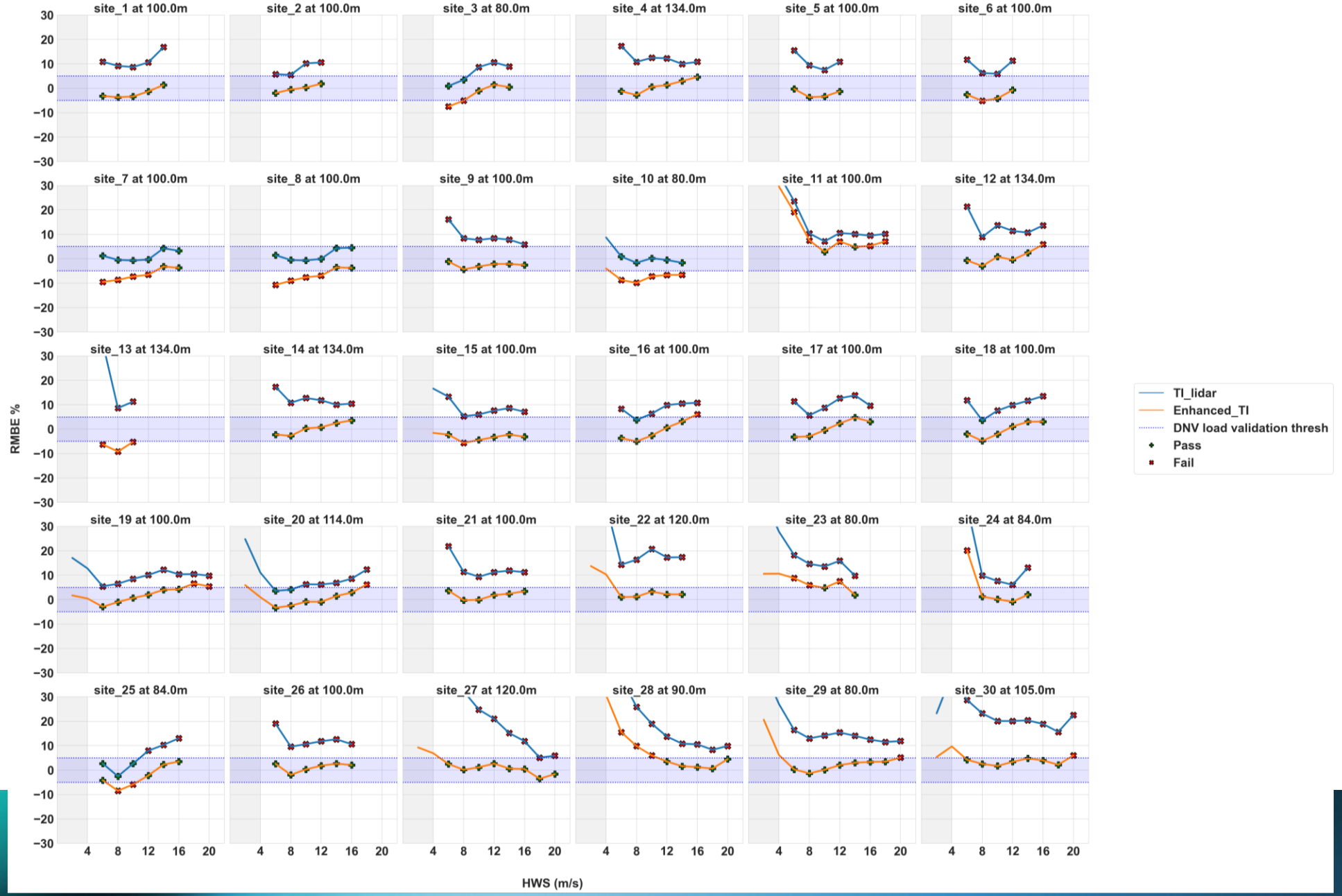
Site Suitability DNV-RP 0661 KPIs



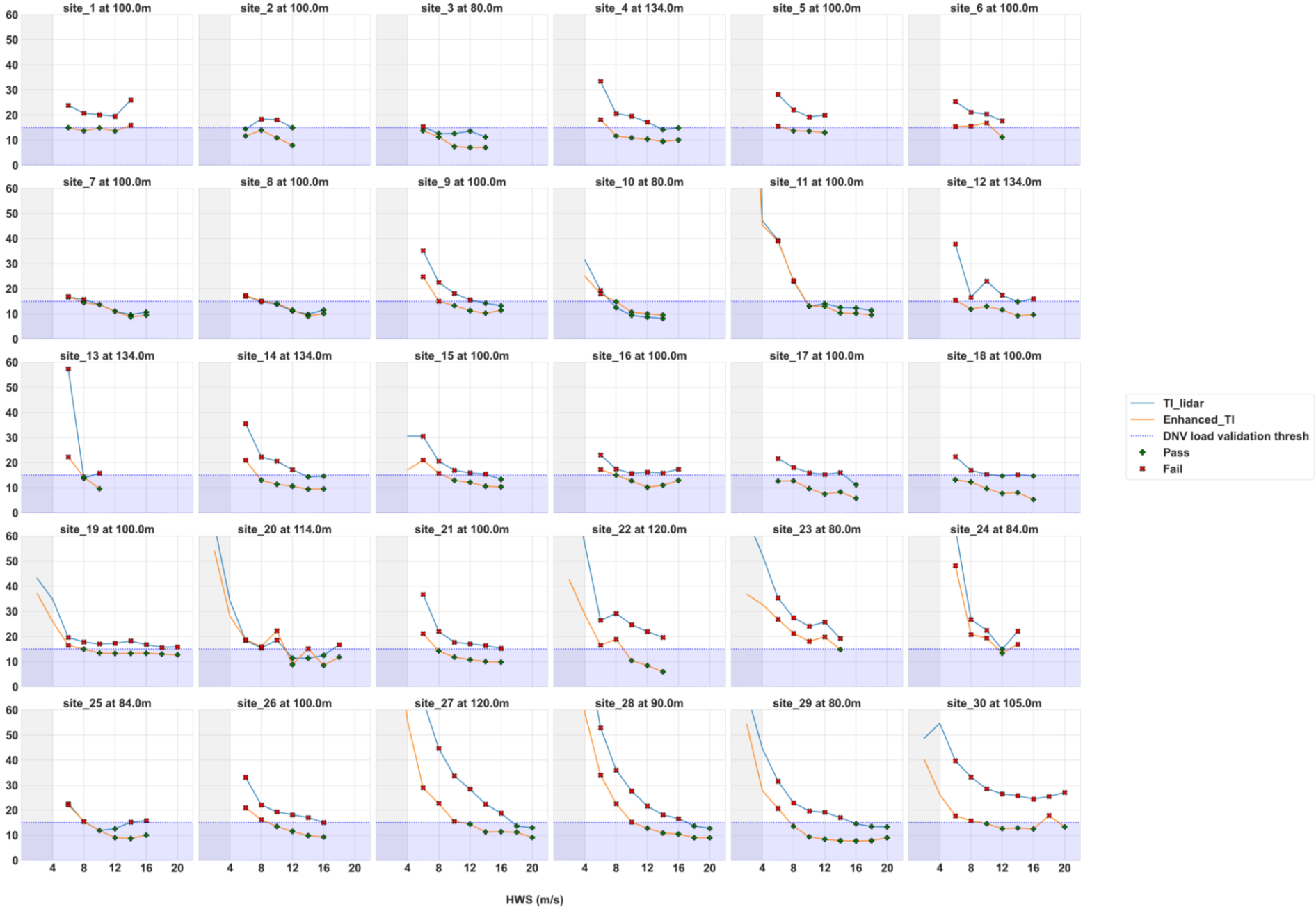
Site Suitability DNV-RP 0661 KPIs



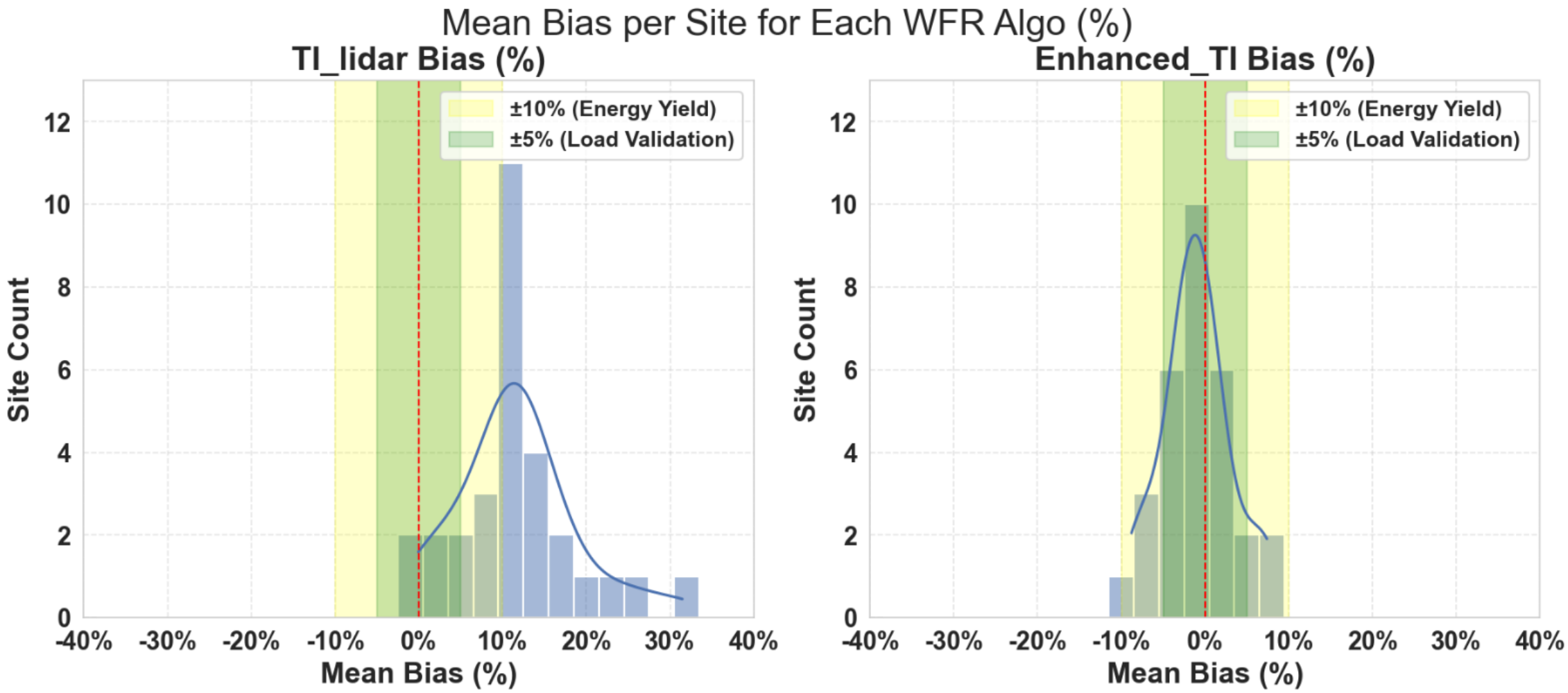
Loads Validation DNV-RP 0661 KPIs



Loads Validation DNV-RP 0661 KPIs



Histogram of overall bias



- Bias as percentage of cup-measured TI (normalized), RMBE
- Spread: -3% to +33% biases before, -10% to +10% after