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Improving Lidar Turbulence Estimates for Wind Energy

Jennifer F. Newman,[1] Andrew Clifton,[1] Matthew J. Churchfield,[1] and Petra Klein[2]

[1] National Renewable Energy Laboratory
[2] University of Oklahoma

The Science of Making TORQUE from Wind
Munich, Germany
October 6, 2016

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Can We Replace Meteorological Towers with Lidars?

Photo by Don Buchanan, NREL 19340

Photo by Jennifer Newman, NREL

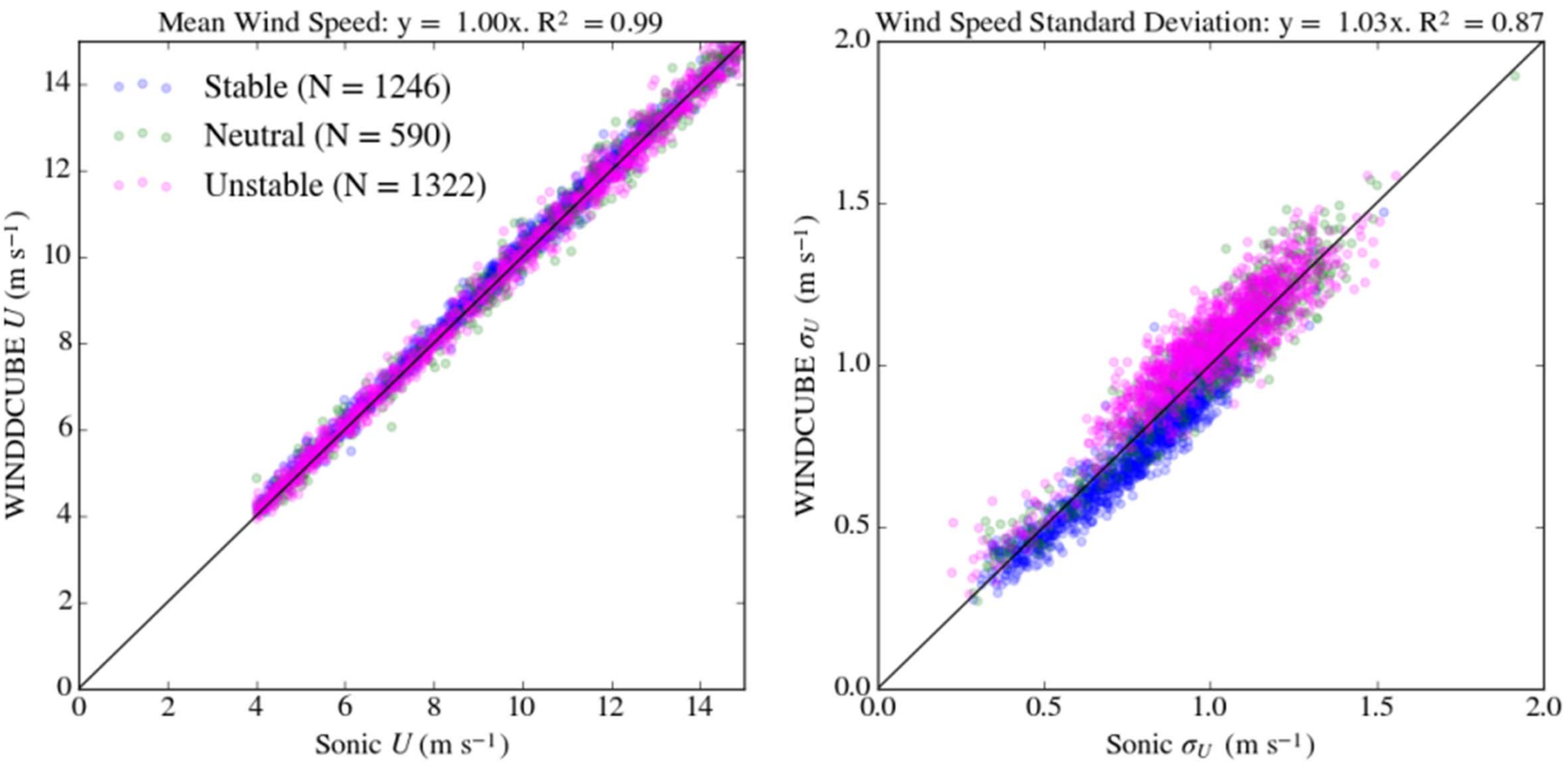
Meteorological (Met) Towers

- Costly to build
- Not mobile
- Limited by height
- Measure at a point.

Lidars

- Mobile
- Measurements typically extend to 200 meters (m) above ground level
- Measure in a volume.

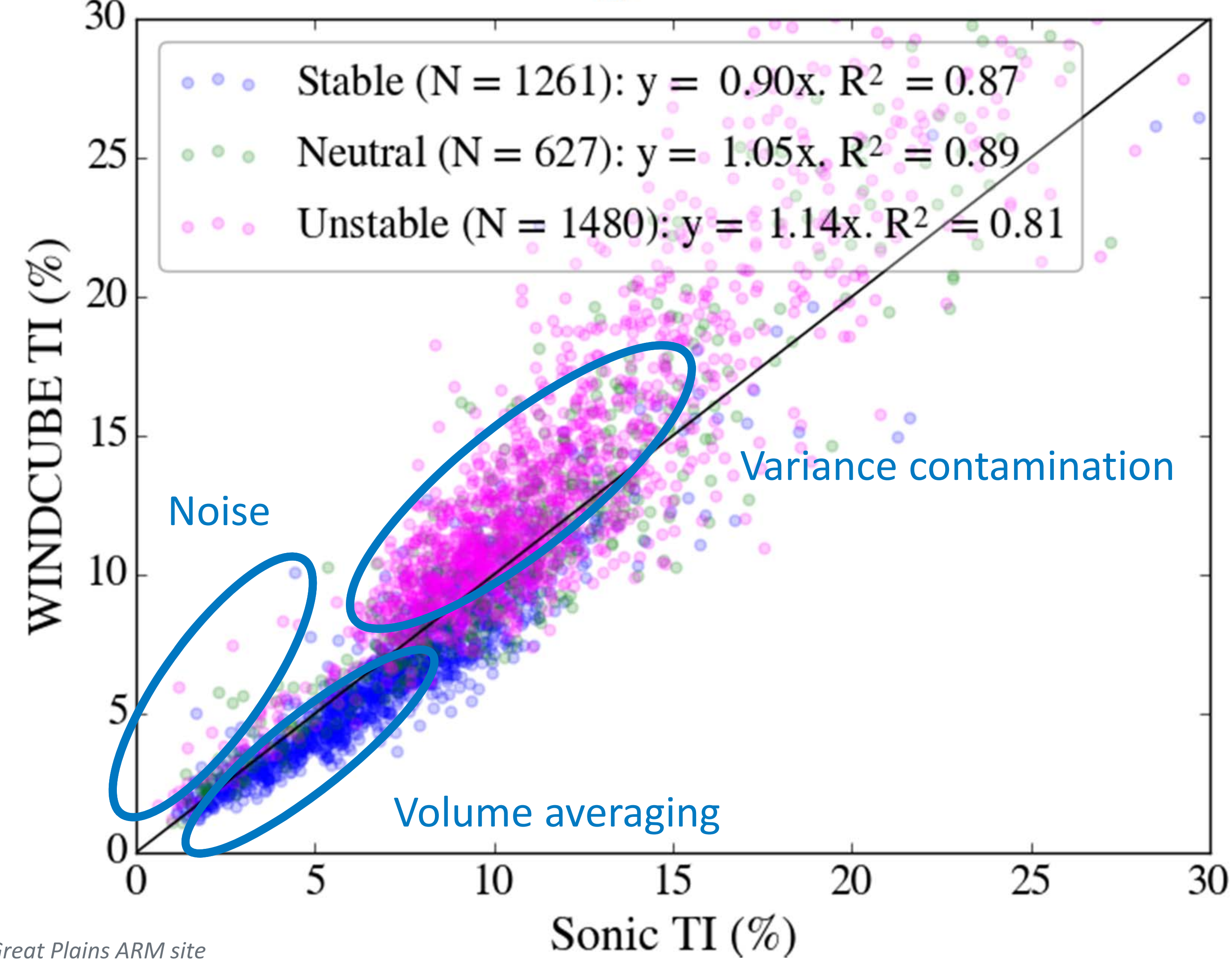
Sample Lidar Measurements: Atmospheric Radiation Measurement Site



Data from 60 m AGL at Southern Great Plains ARM site

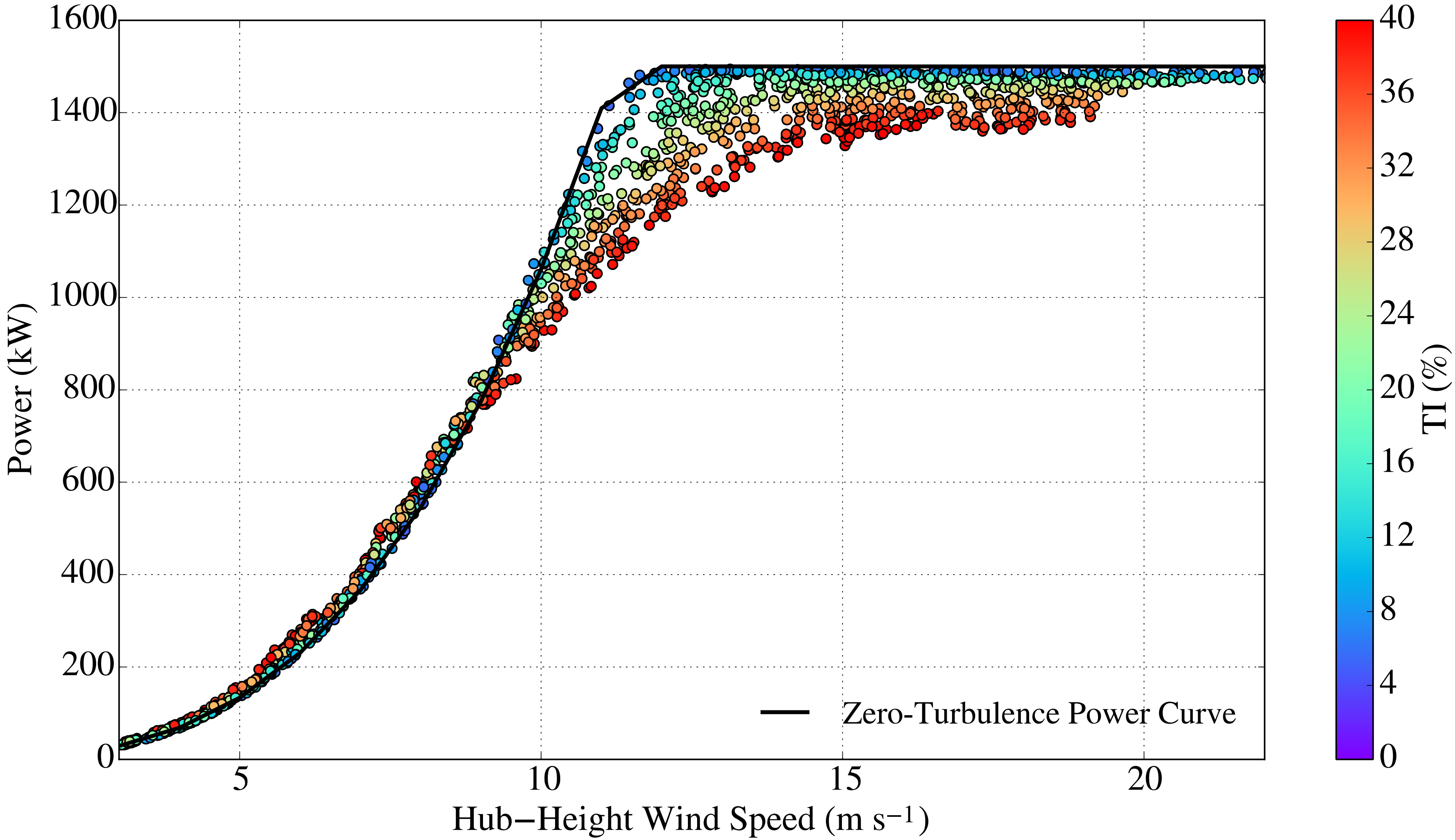
Example of Lidar Versus Sonic Turbulence Intensity

$$TI = \frac{\sigma_u}{U} \times 100\%$$



Data from Southern Great Plains ARM site

Impact of Turbulence Intensity on Turbine Power Curve



Power curves from FAST simulations of 1.5-MW WindPACT turbine. After Clifton and Wagner (2014).

A. Clifton and R. Wagner. 2014. "Accounting for the Effect of Turbulence on Wind Turbine Power Curves." *Journal of Physics: Conference Series*, **524(1)**, p. 012109.

What Could We Do with Improved Lidar Turbulence Intensity?

Photo by Andrew Clifton, NREL 24383

Research
- Study the ABL
- Characterize inflow
- Collect wake observations

Resource
- Replace met towers
- Classify sites
- Validate flow models

Turbine testing
- Test power curves
- Complete warranty tests
- Monitor sites

Offshore wind
- Evaluate design conditions
- Conduct resource assessments

Need for Improved Turbulence Intensity Estimates

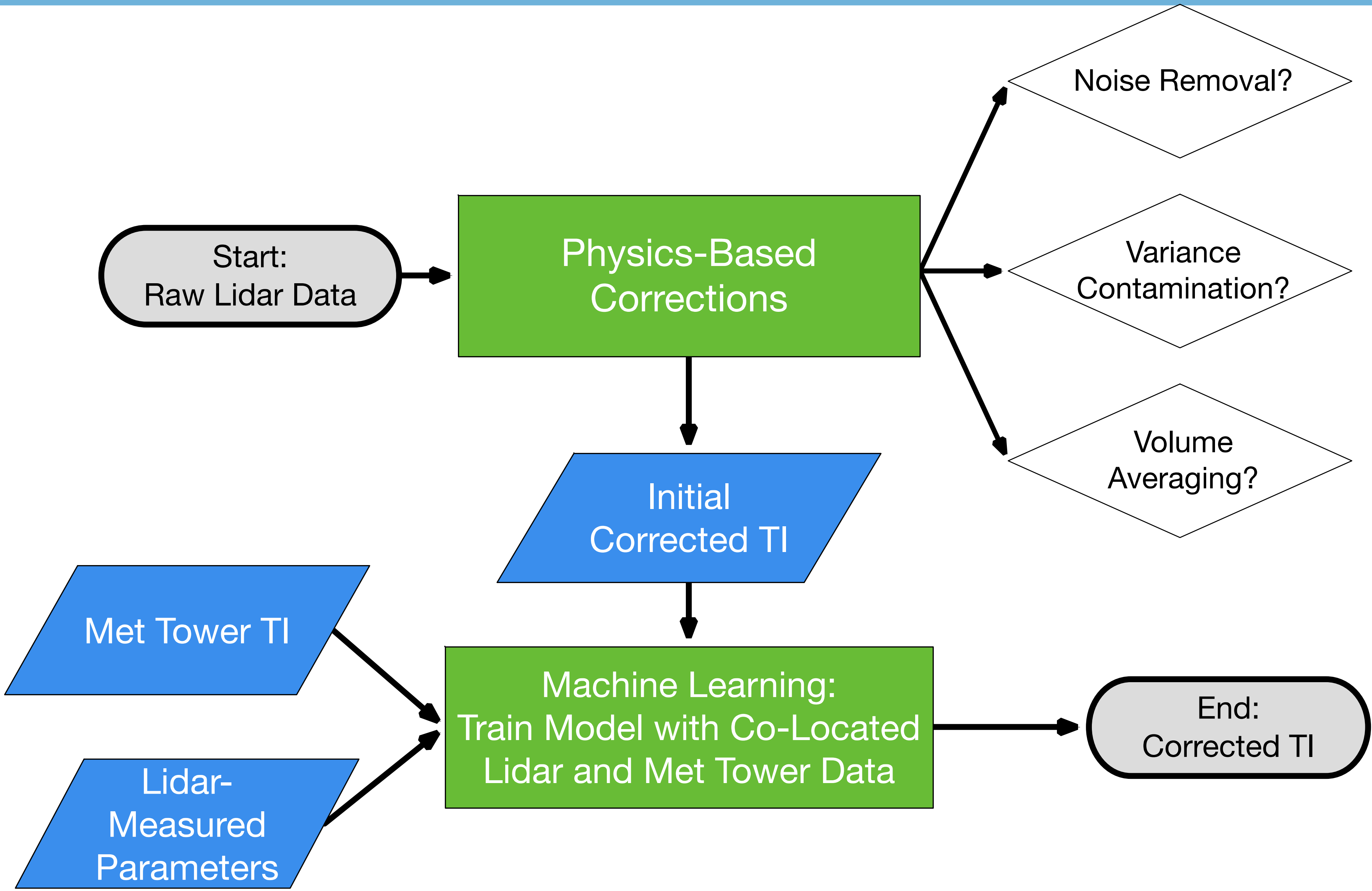
- The problem: Lidars measure different values of turbulence intensity (TI) than a cup or sonic anemometer. This makes it difficult to use lidars for resource assessment or turbine site suitability.

- Proposed solution:

  Improve TI estimates using a combination of physics and machine learning in the Lidar Turbulence Error Reduction Algorithm (L-TERRA).

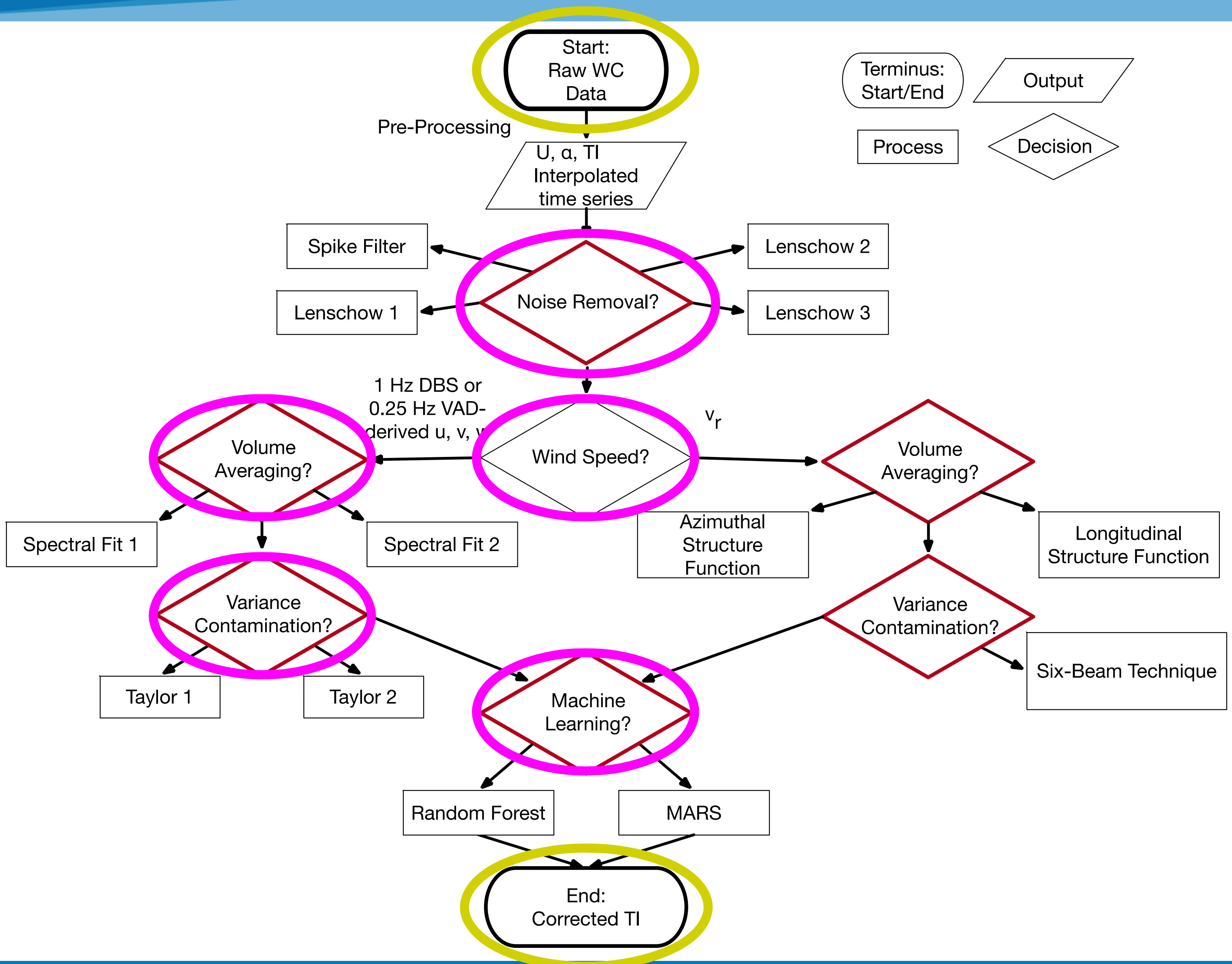
Photo by Sonia Wharton

L-TERRA Framework—Patent Pending



More information: J.F. Newman and A. Clifton. 2016. “Improving Lidar-Derived Turbulence Estimates for Wind Energy.” *Wind Energy Science Discussions.* doi: 10.5194/wes-2016-22, in review.

Detailed L-TERRA Framework



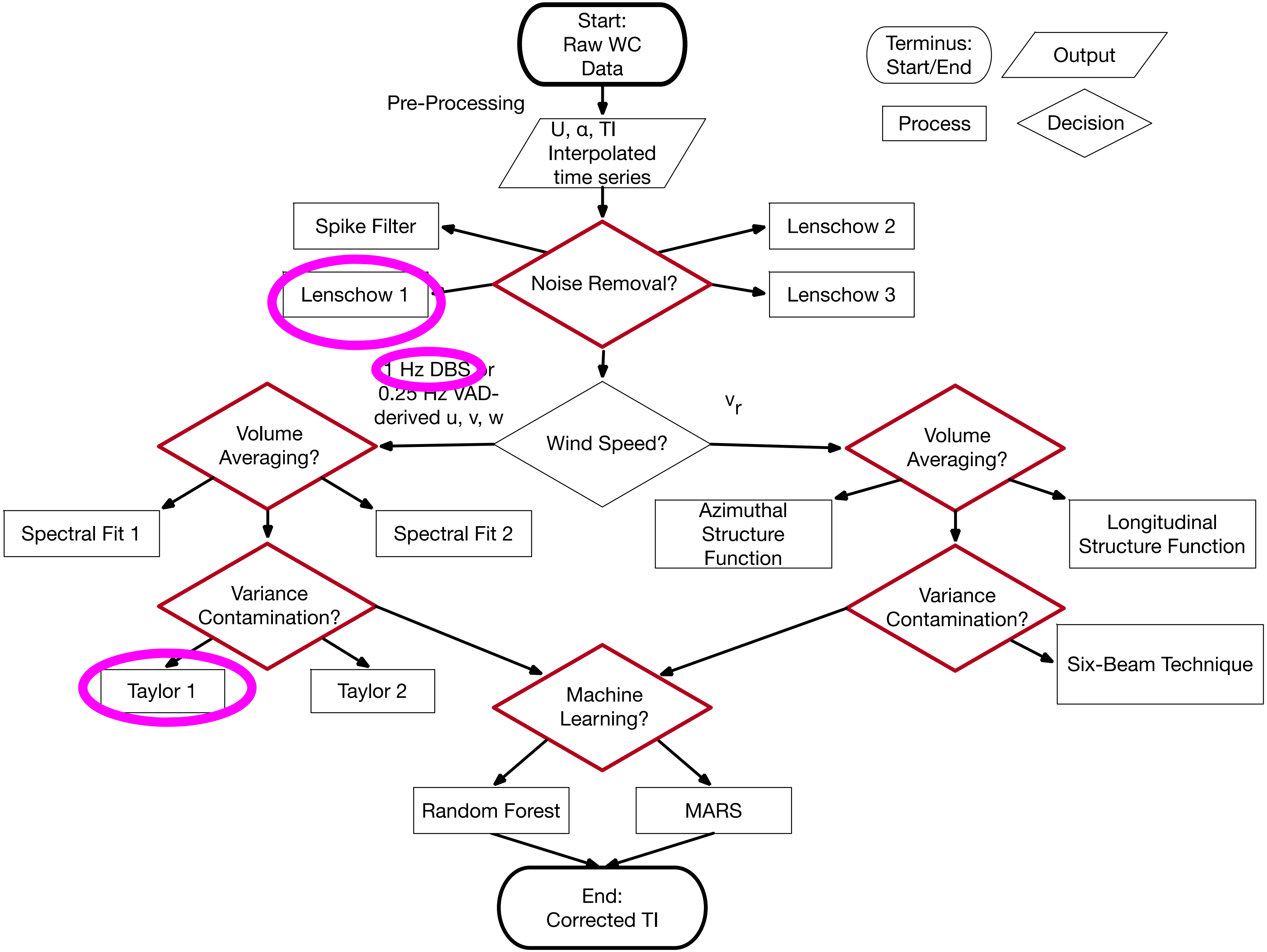
Determining the Optimal Model Chain

- Testing data sets: Atmospheric Radiation Measurement (ARM) site in Oklahoma and wind power plant in Southern Plains region of United States

- WINDCUBE v2 vertically profiling lidar deployed at both sites near met towers.

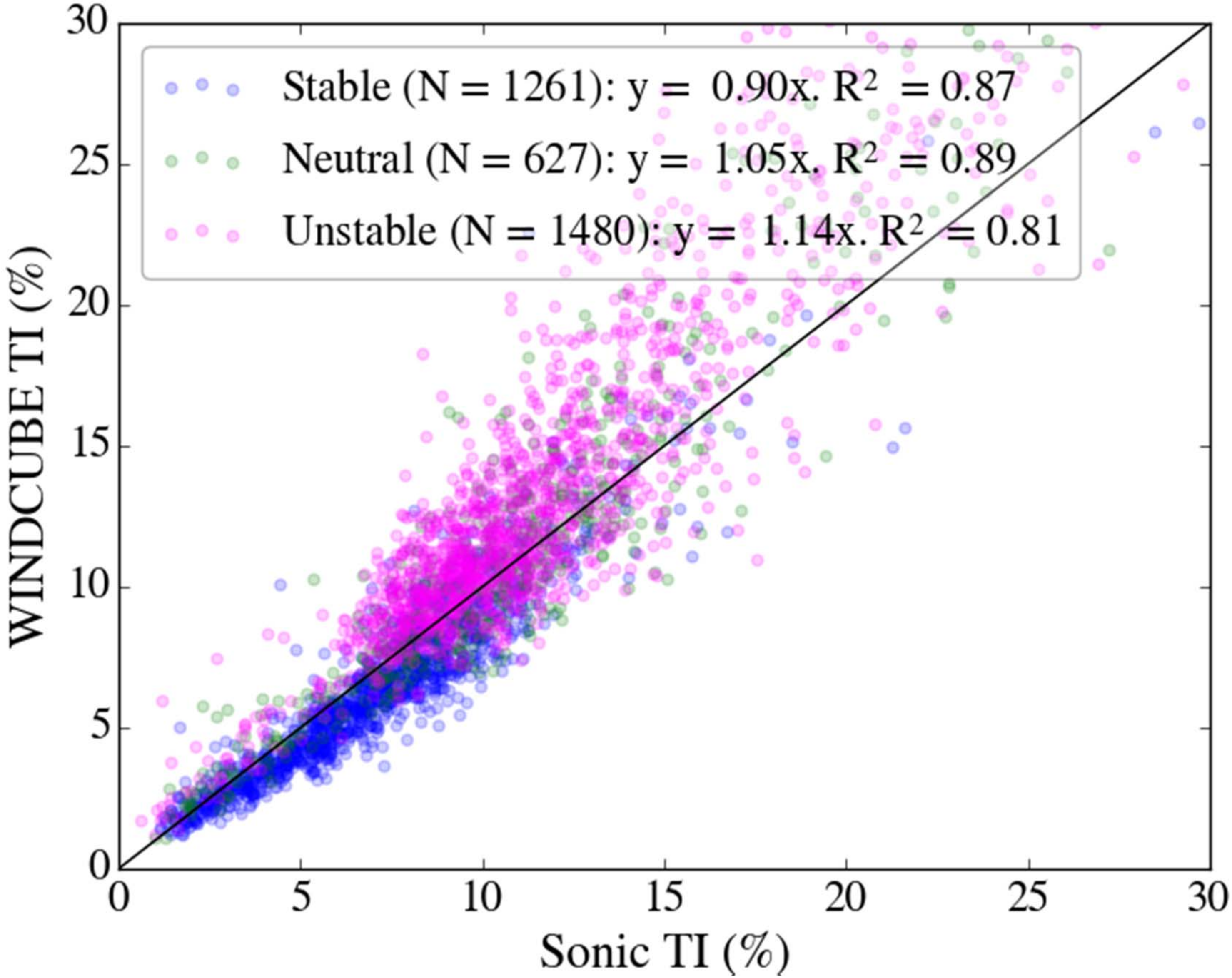
Photo by Sonia Wharton

Which Model Chain Minimizes Turbulence Intensity Mean Absolute Error?



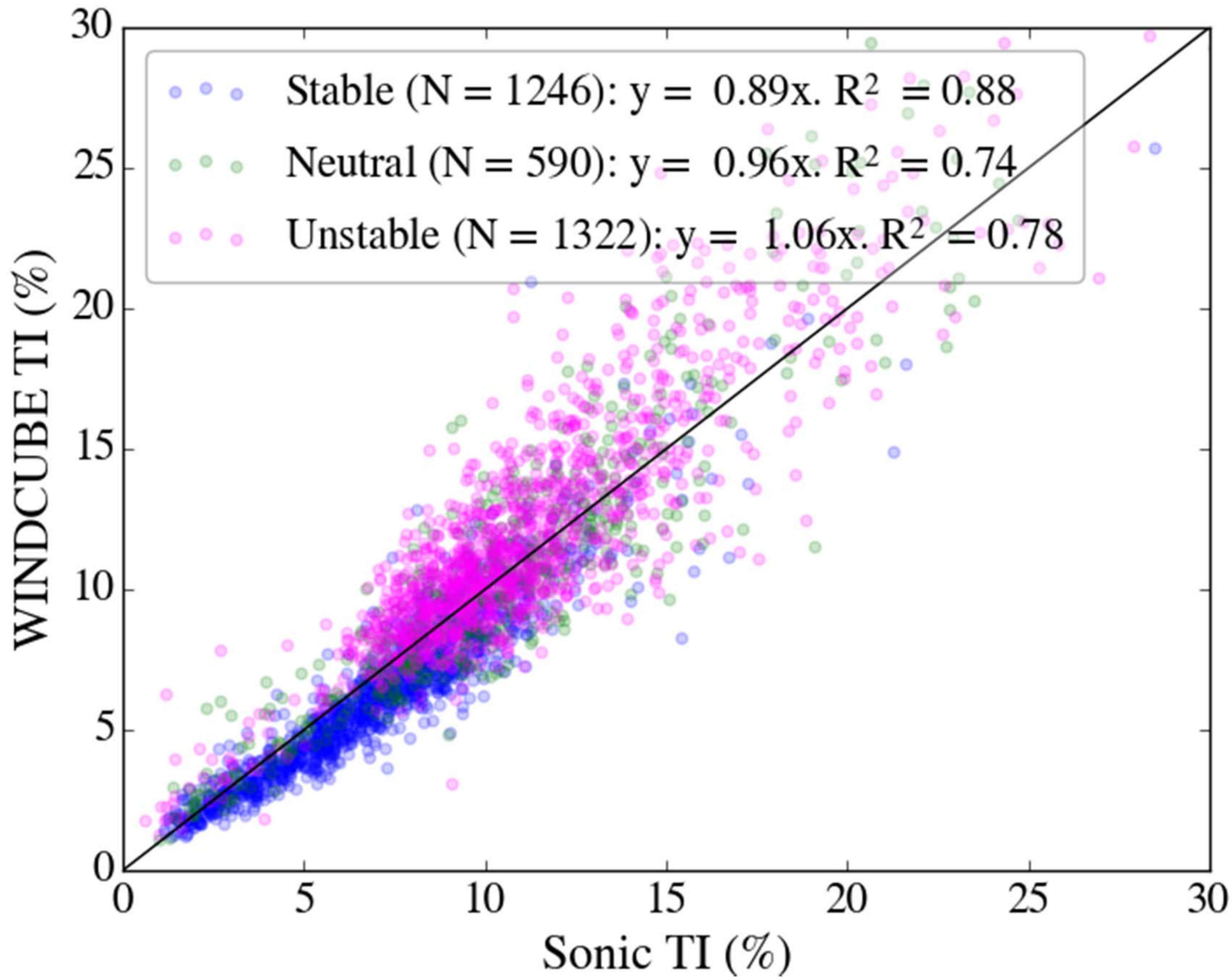
ARM Site: Raw

Raw mean absolute error (MAE): 1.5%



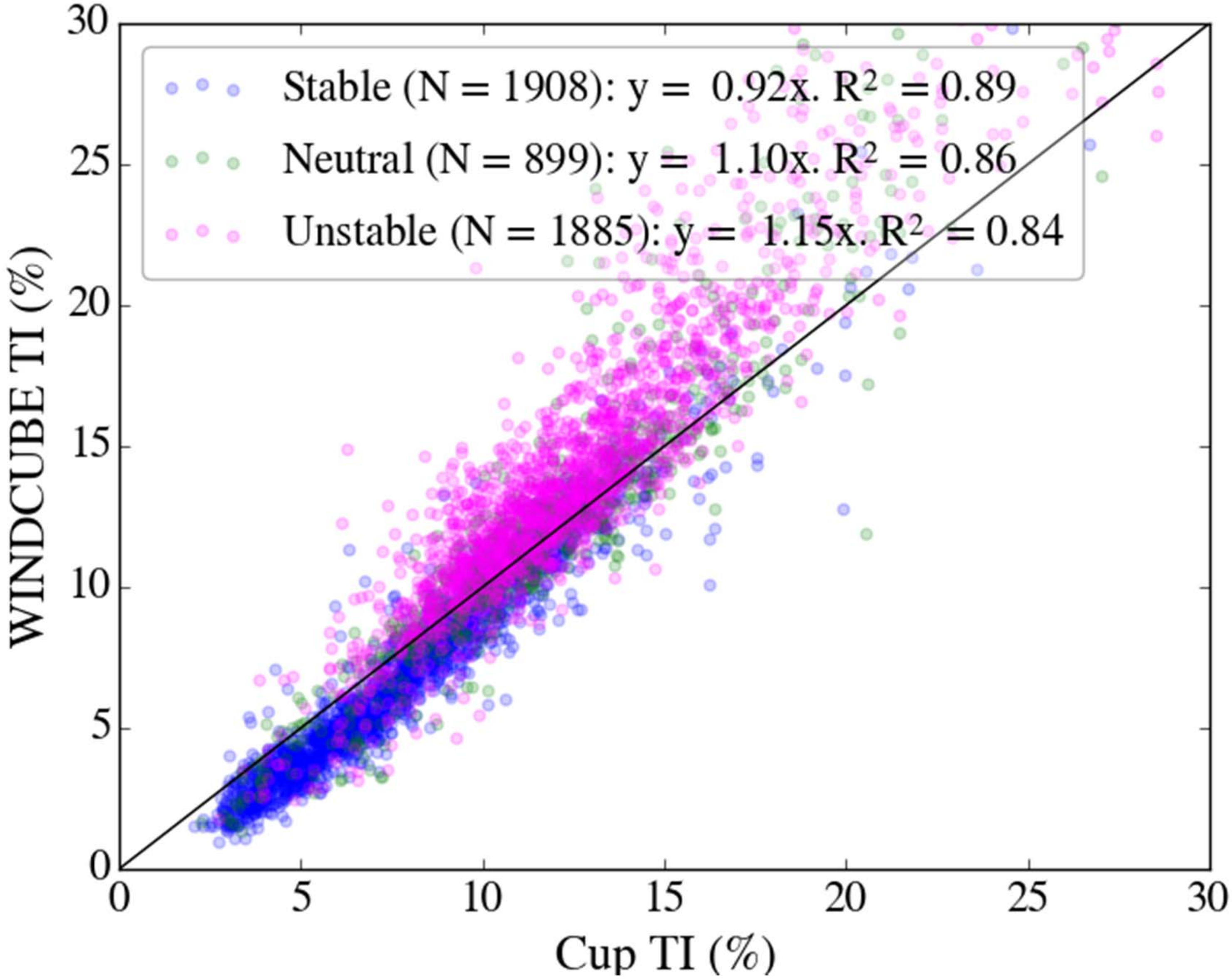
ARM Site: After L-TERRA

Raw MAE: 1.5%   L-TERRA MAE: 1.4%



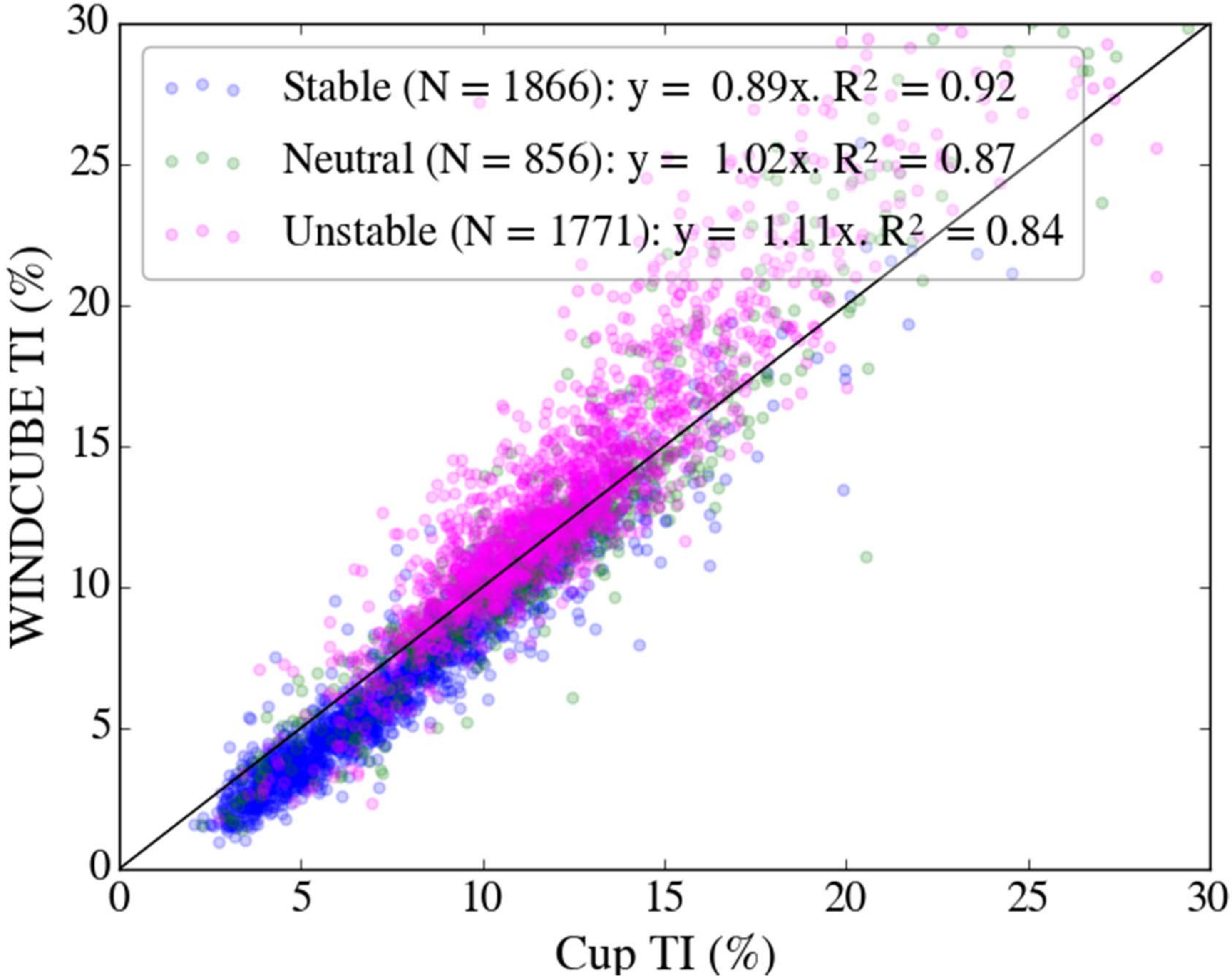
Wind Power Plant: Raw

Raw MAE: 1.48%



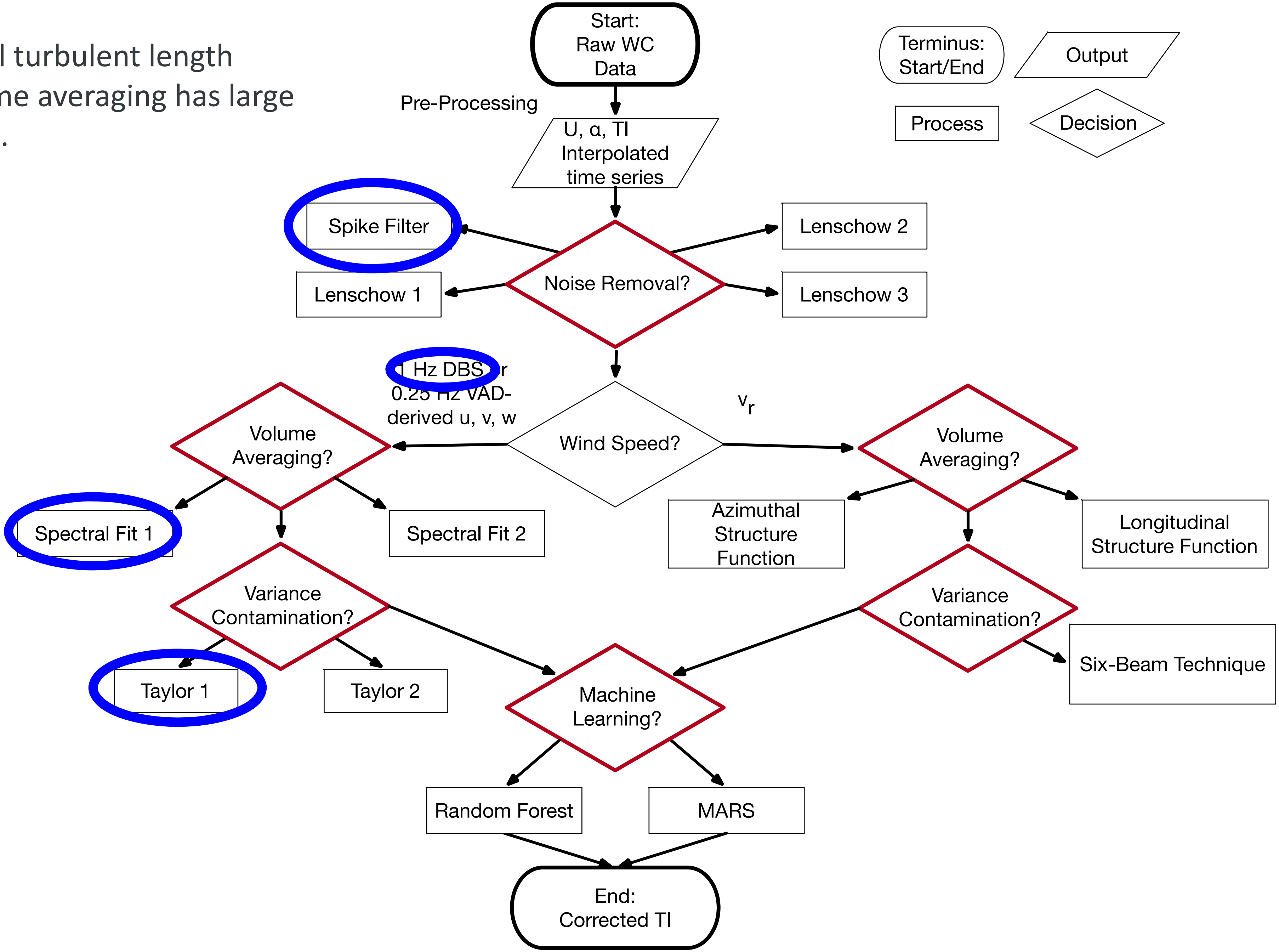
Wind Power Plant: After L-TERRA

Raw MAE: 1.48%   L-TERRA MAE: 1.39%



Which Model Chain Minimizes Mean Absolute Error for Different Stability Classes?

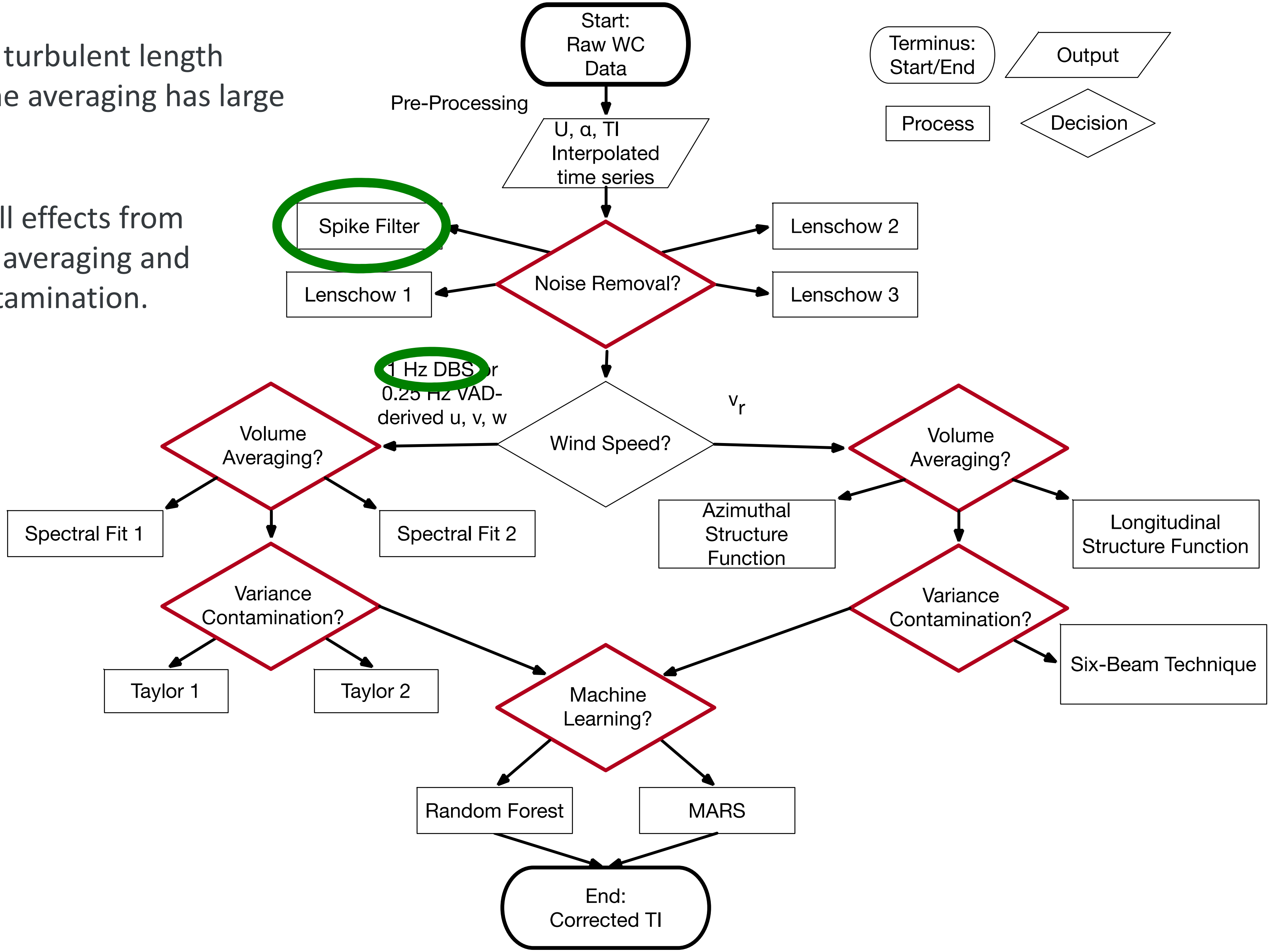
Stable: Small turbulent length scales; volume averaging has large contribution.



Which Model Chain Minimizes Mean Absolute Error for Different Stability Classes?

Stable: Small turbulent length scales; volume averaging has large contribution.

Neutral: Small effects from both volume averaging and variance contamination.

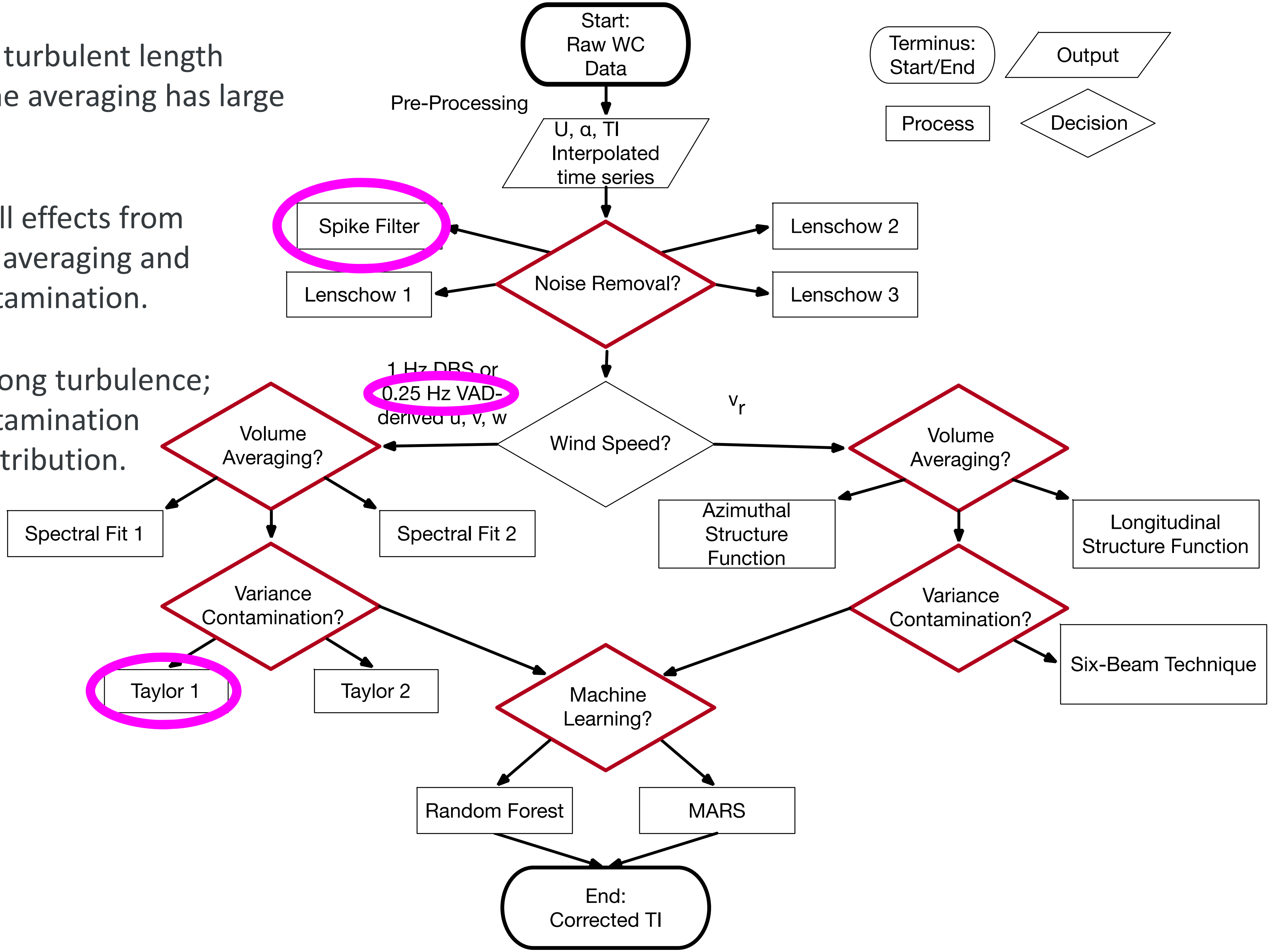


Which Model Chain Minimizes Mean Absolute Error for Different Stability Classes?

Stable: Small turbulent length scales; volume averaging has large contribution

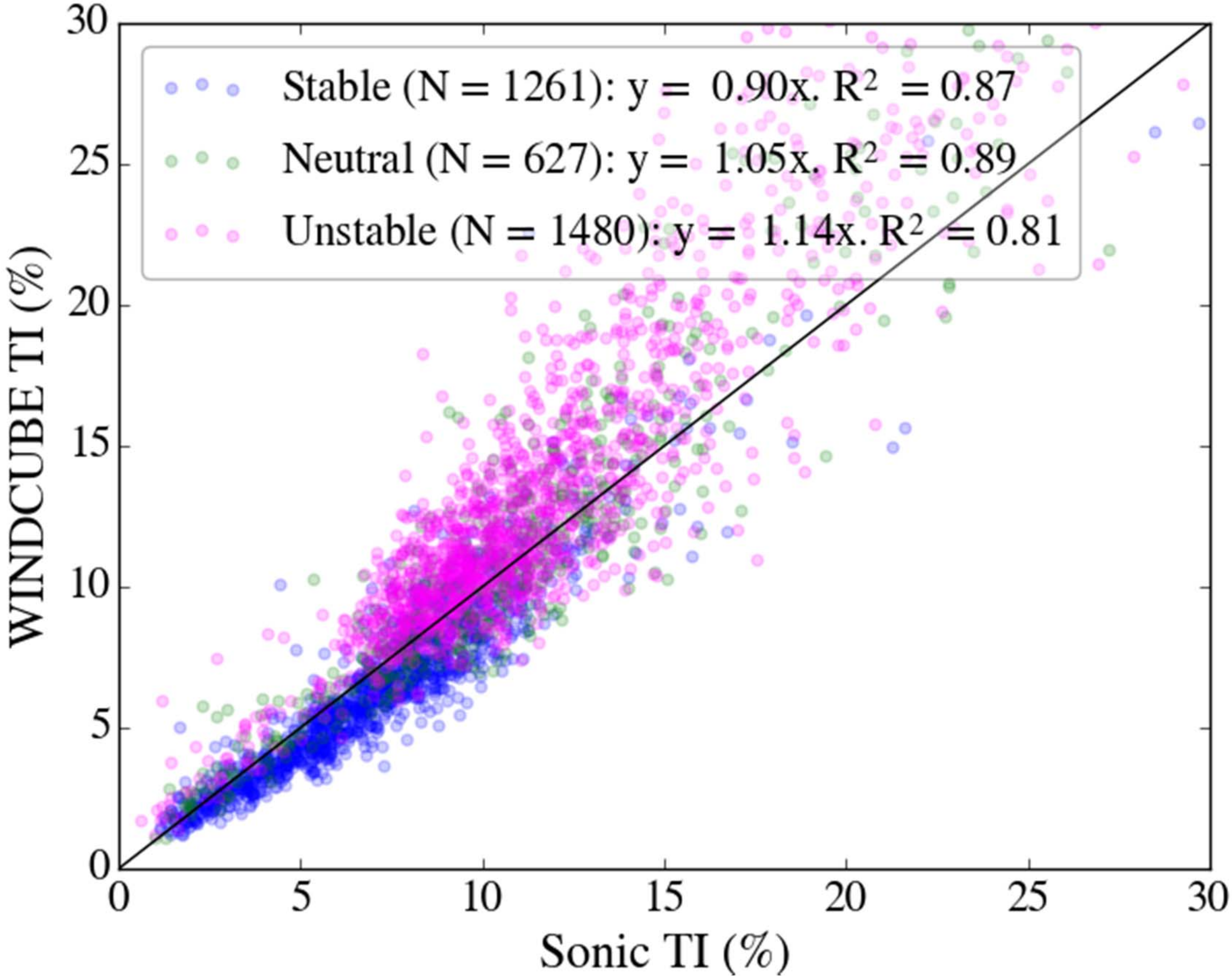
Neutral: Small effects from both volume averaging and variance contamination.

Unstable: Strong turbulence; variance contamination has large contribution.



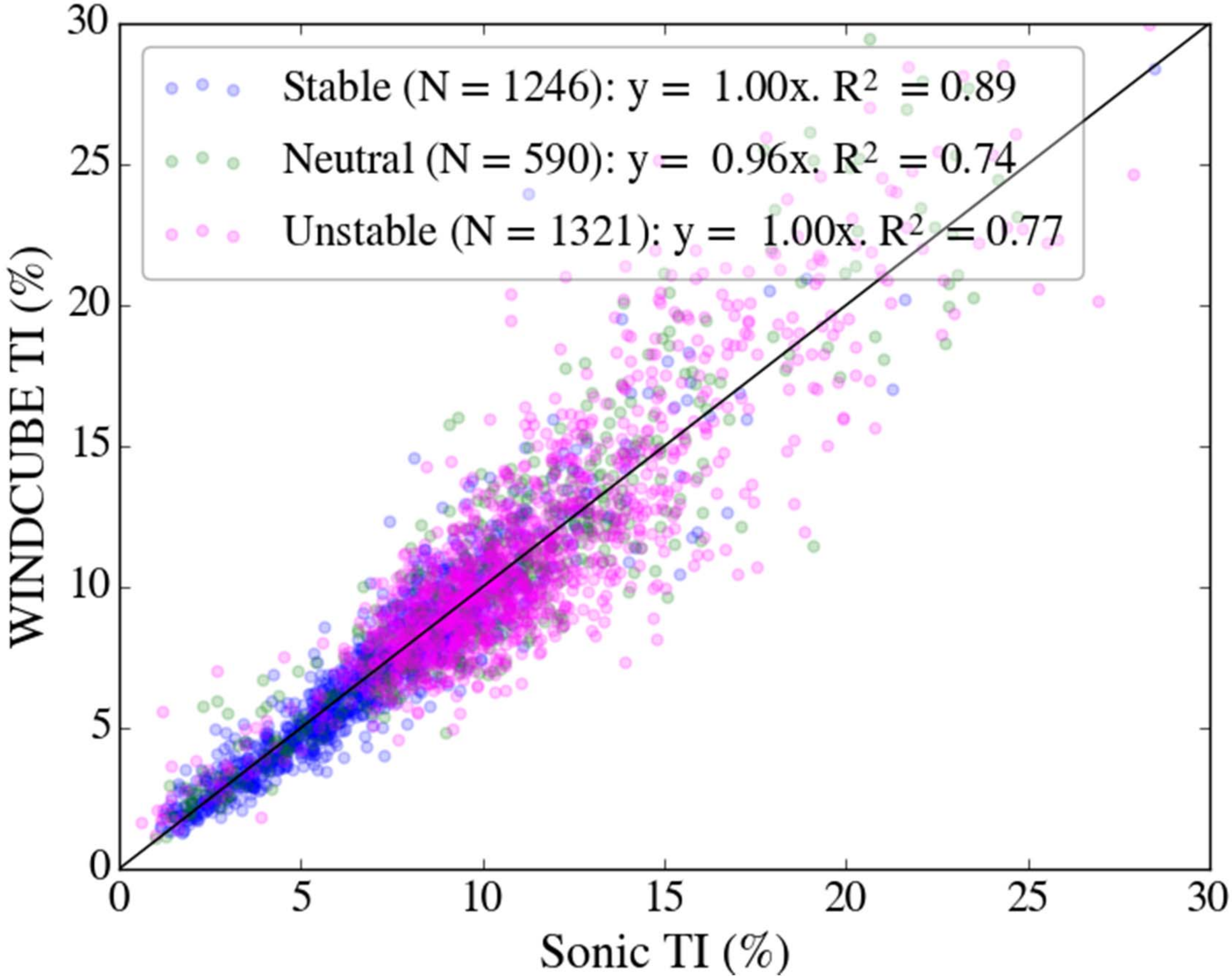
ARM Site: Raw

Raw MAE: 1.5%



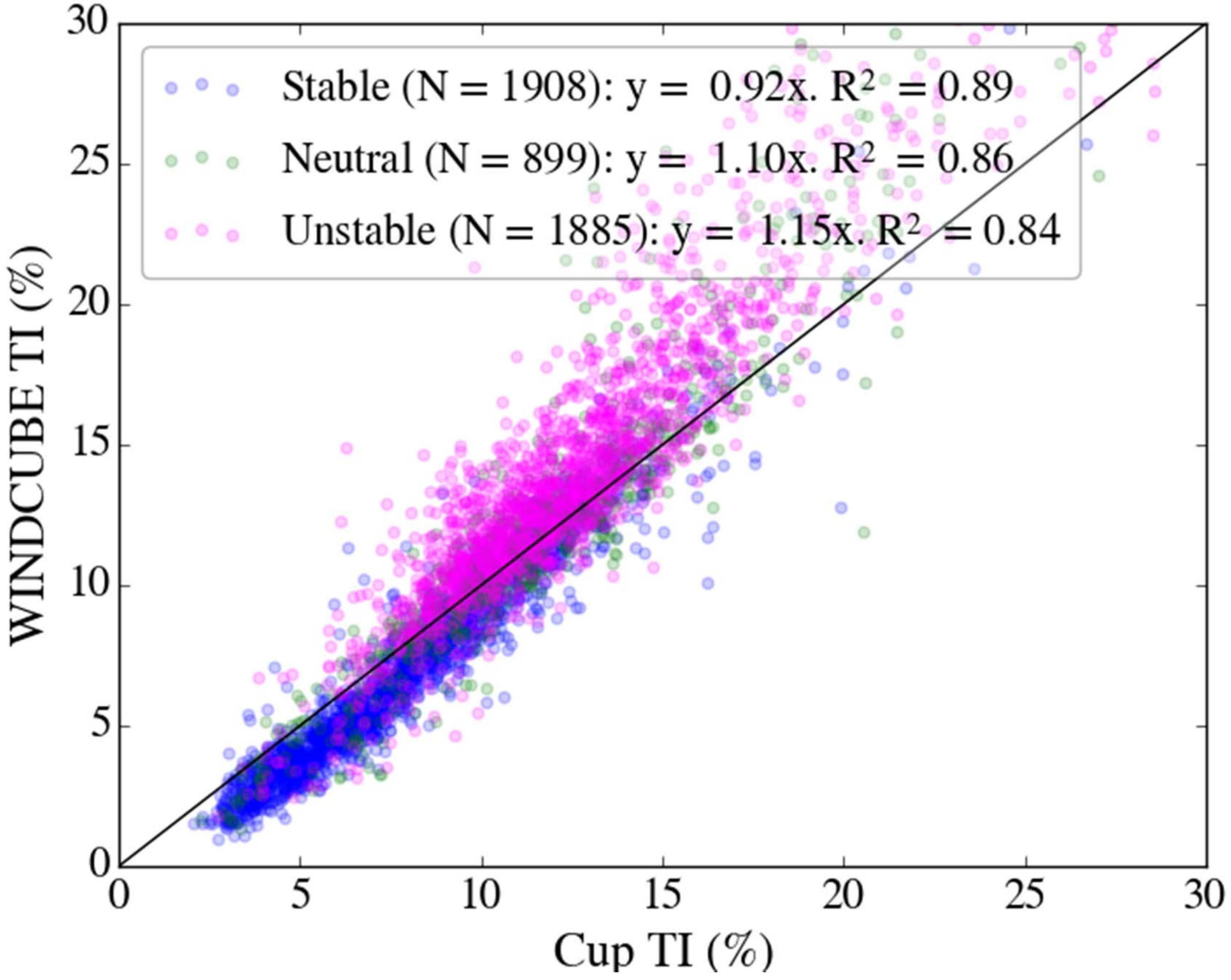
ARM Site: After L-TERRA—Stability

Raw MAE: 1.5%   L-TERRA MAE: 1.4%   L-TERRA-S MAE: 1.25%



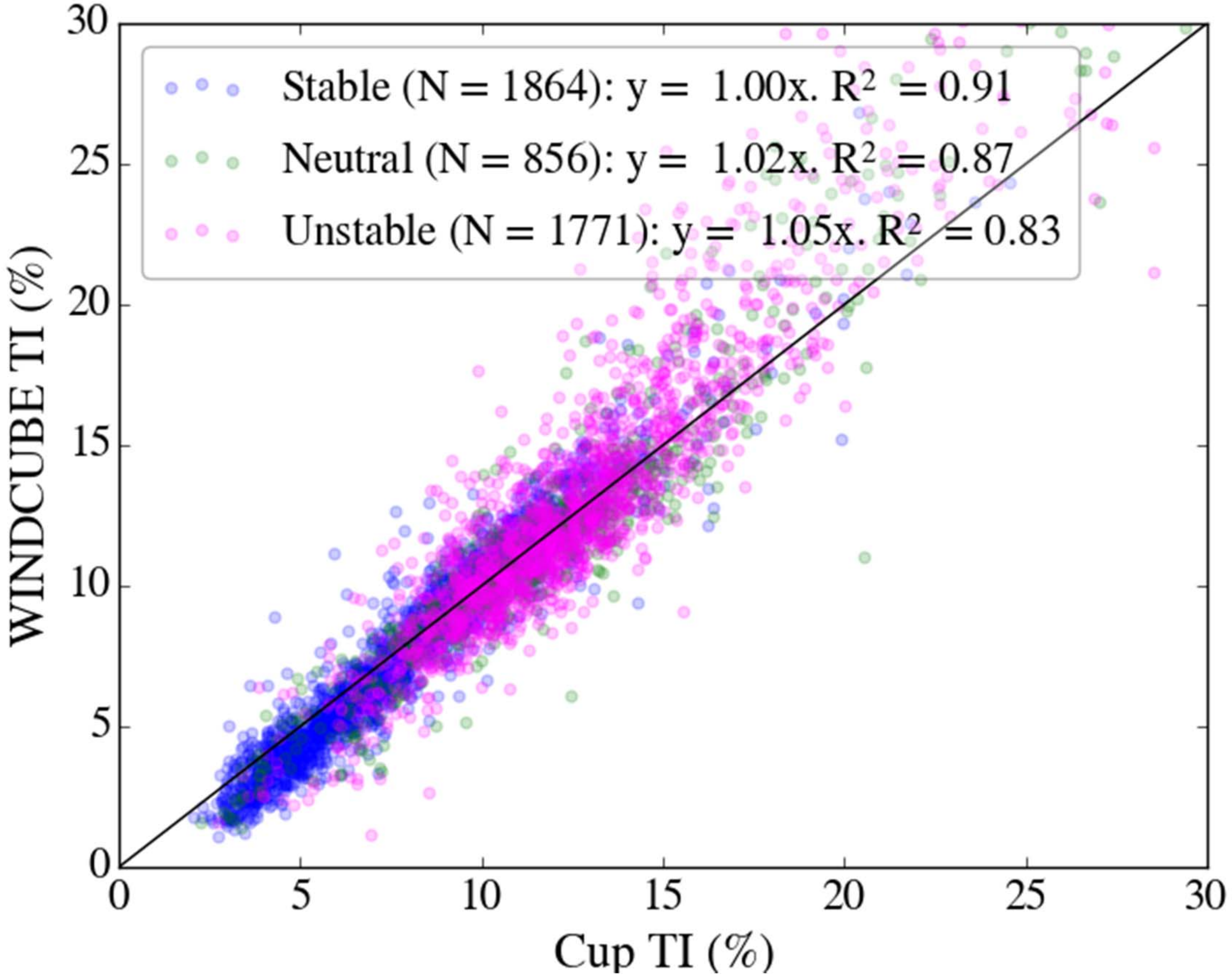
Wind Power Plant: Raw

Raw MAE: 1.48%

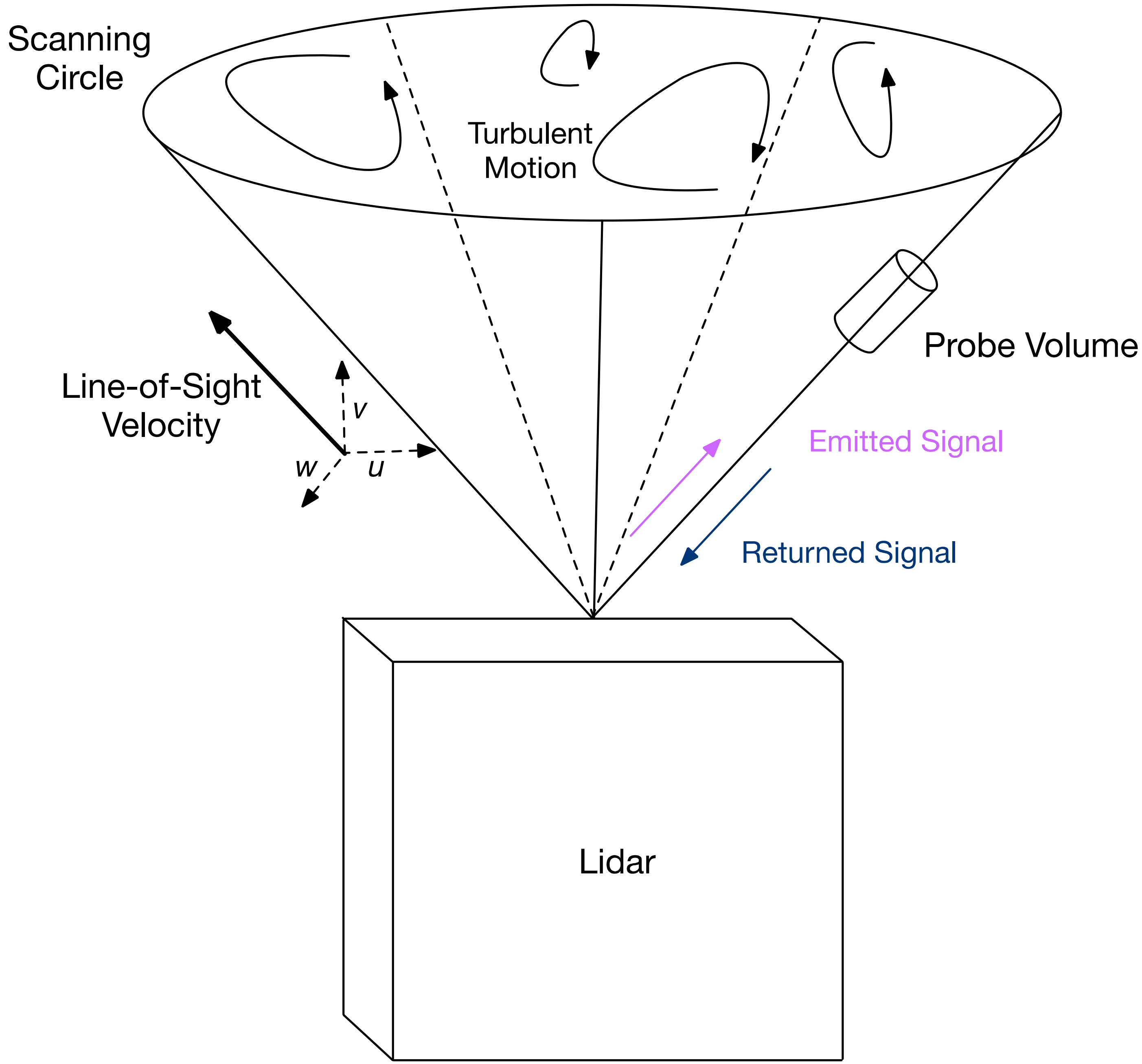


Wind Power Plant: After L-TERRA—Stability

Raw MAE: 1.48% L-TERRA MAE: 1.39% L-TERRA-S MAE: 1.19%

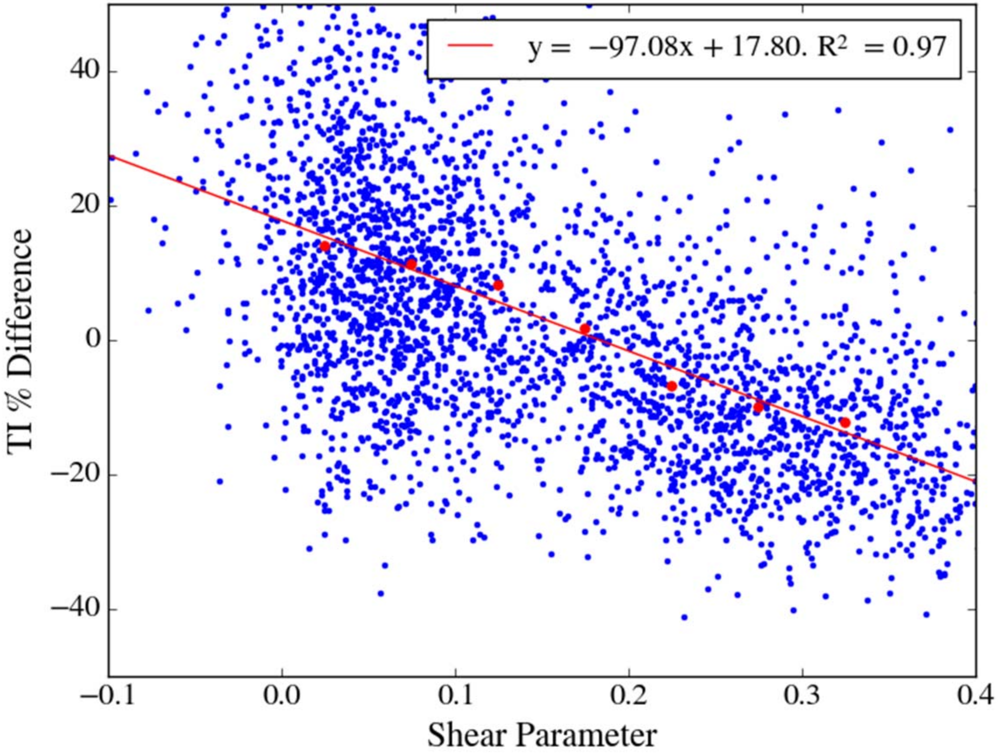


Sensitivity of Turbulence Intensity Error to Lidar-Measured Parameters

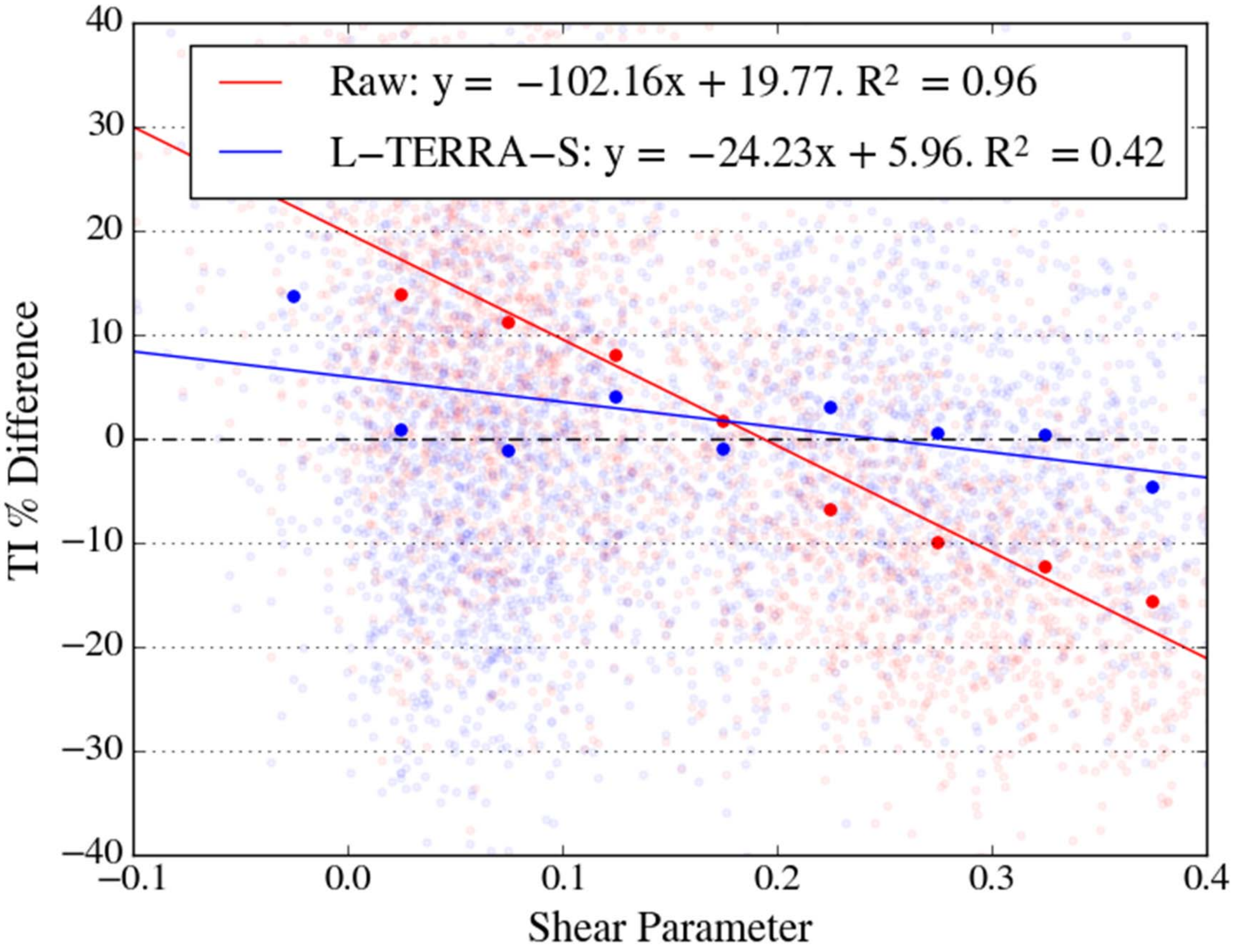


Conducting Sensitivity Analysis

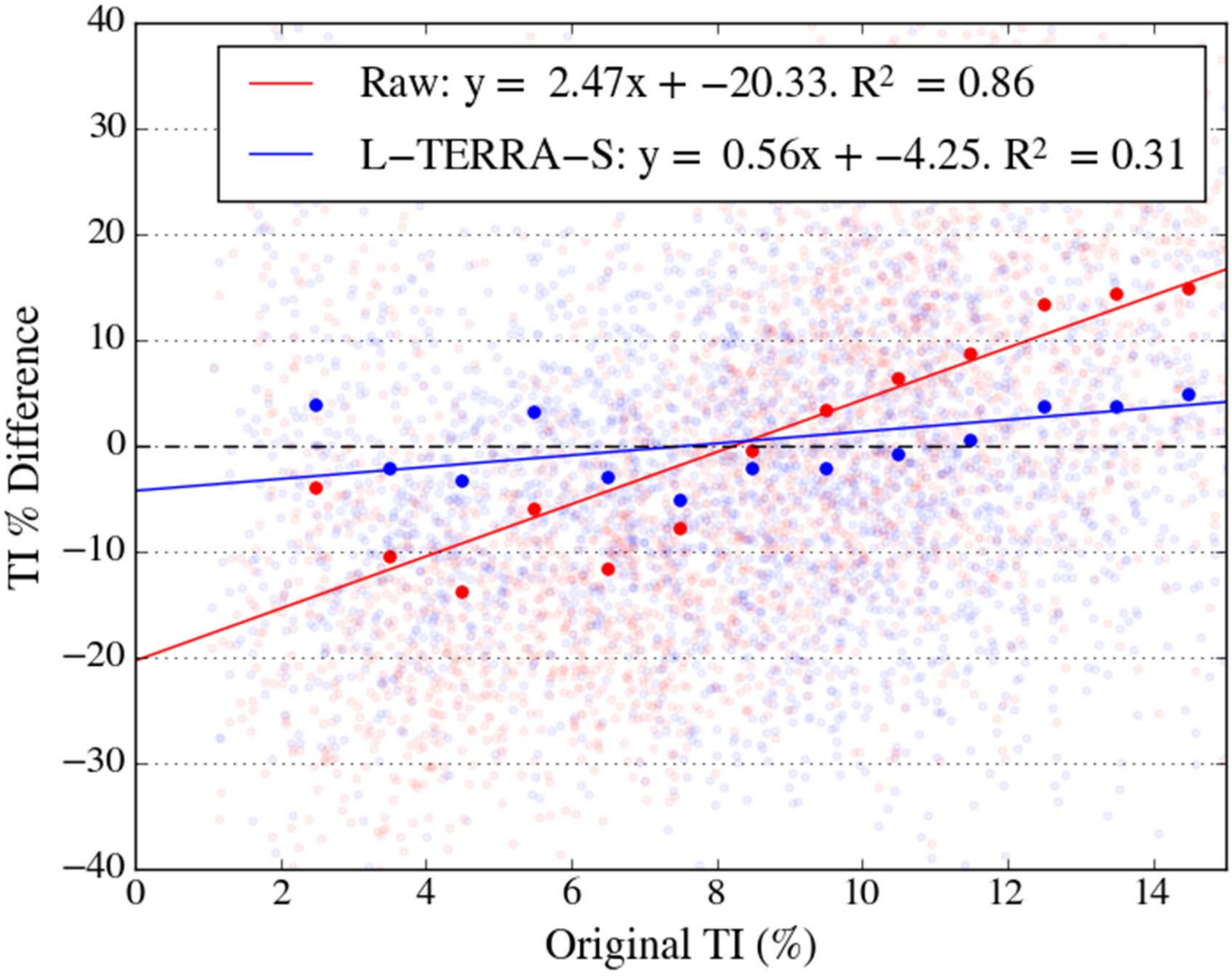
- New IEC 61400-12-1 standards, Annex L: Classification of remote sensing devices
- Sensitivity analysis: Bin input data, and calculate regression line for binned data vs. TI % difference
- **Sensitivity:** Product of slope of regression line and standard deviation of input variable



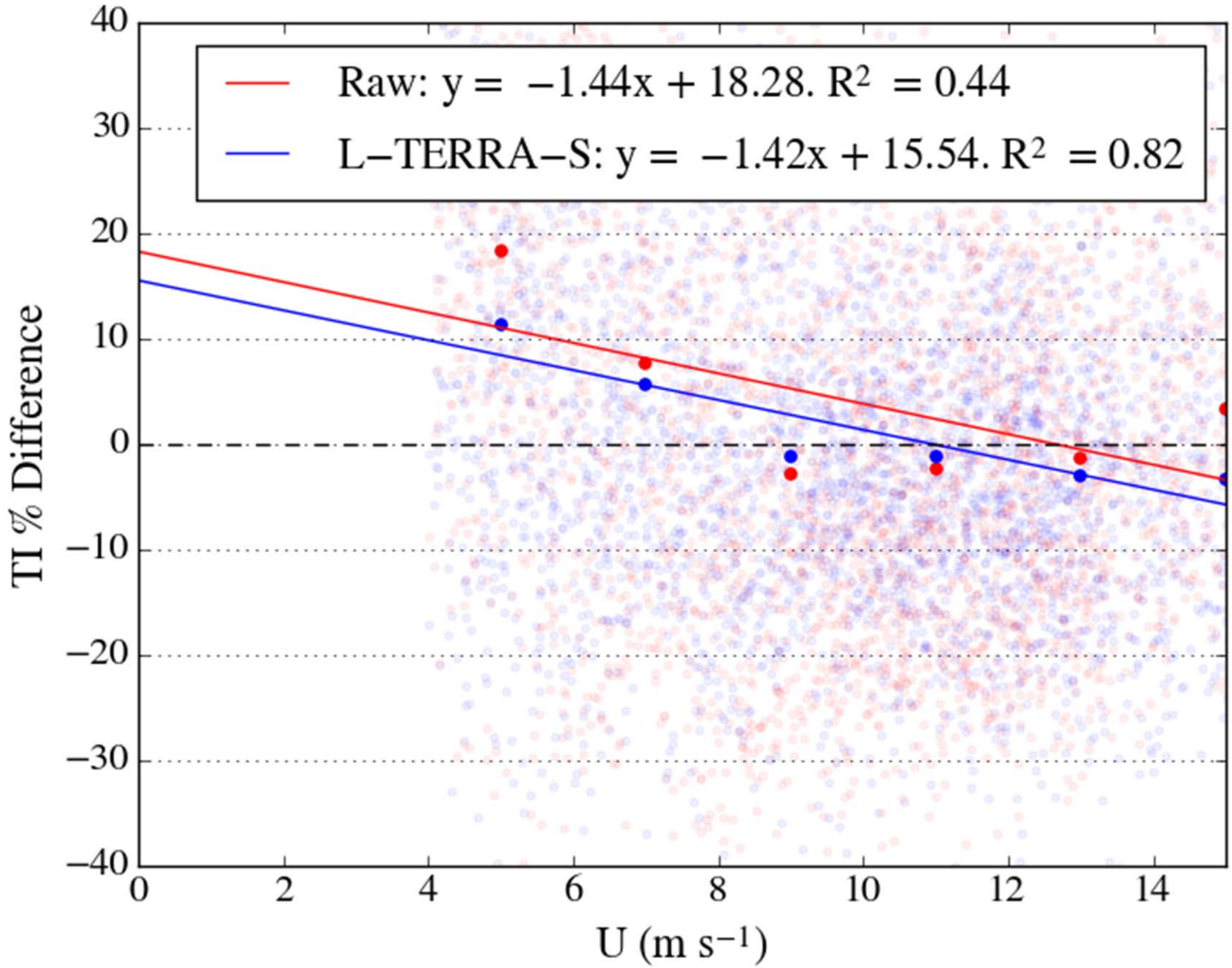
Sensitivity to Shear



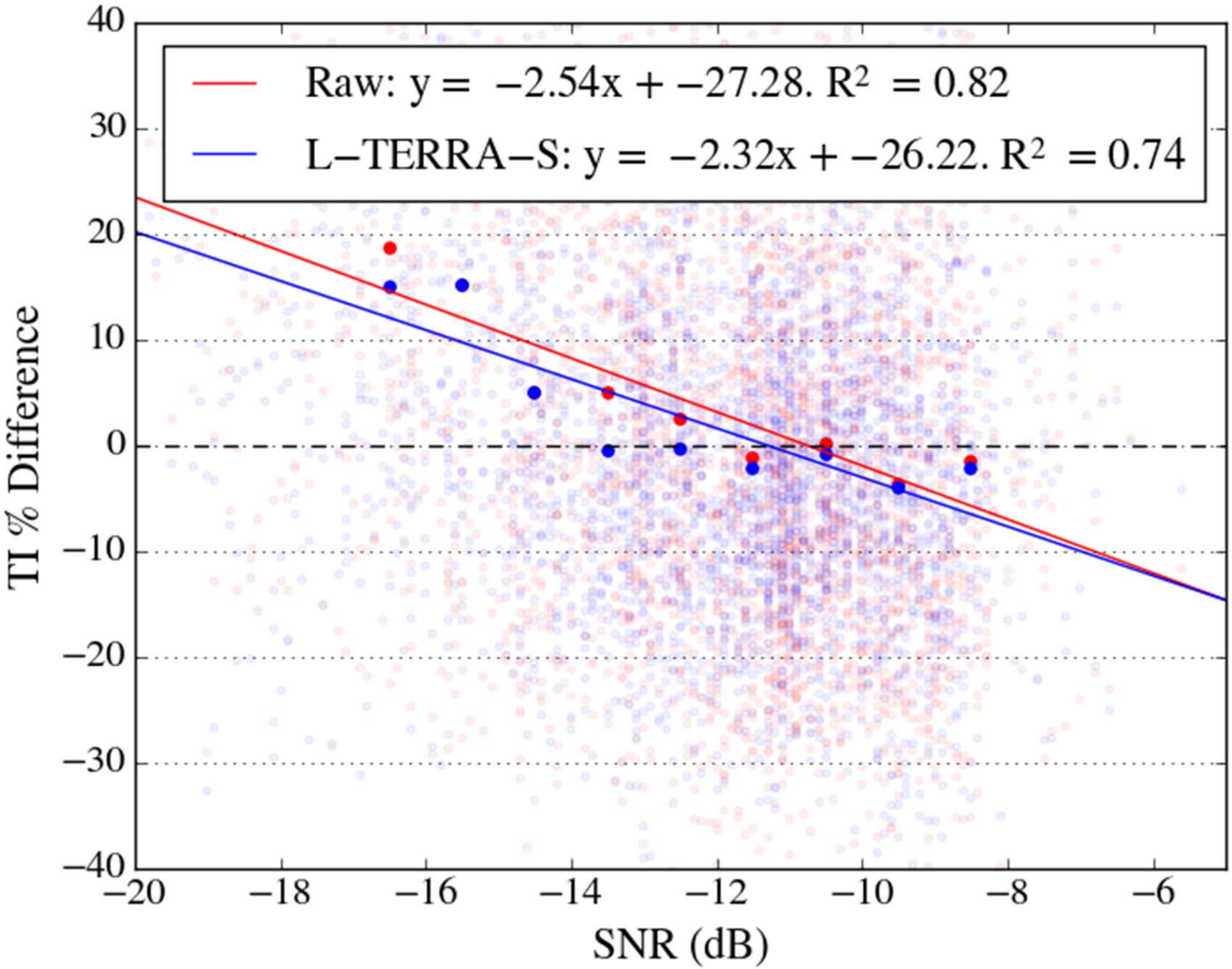
Sensitivity to Turbulence Intensity



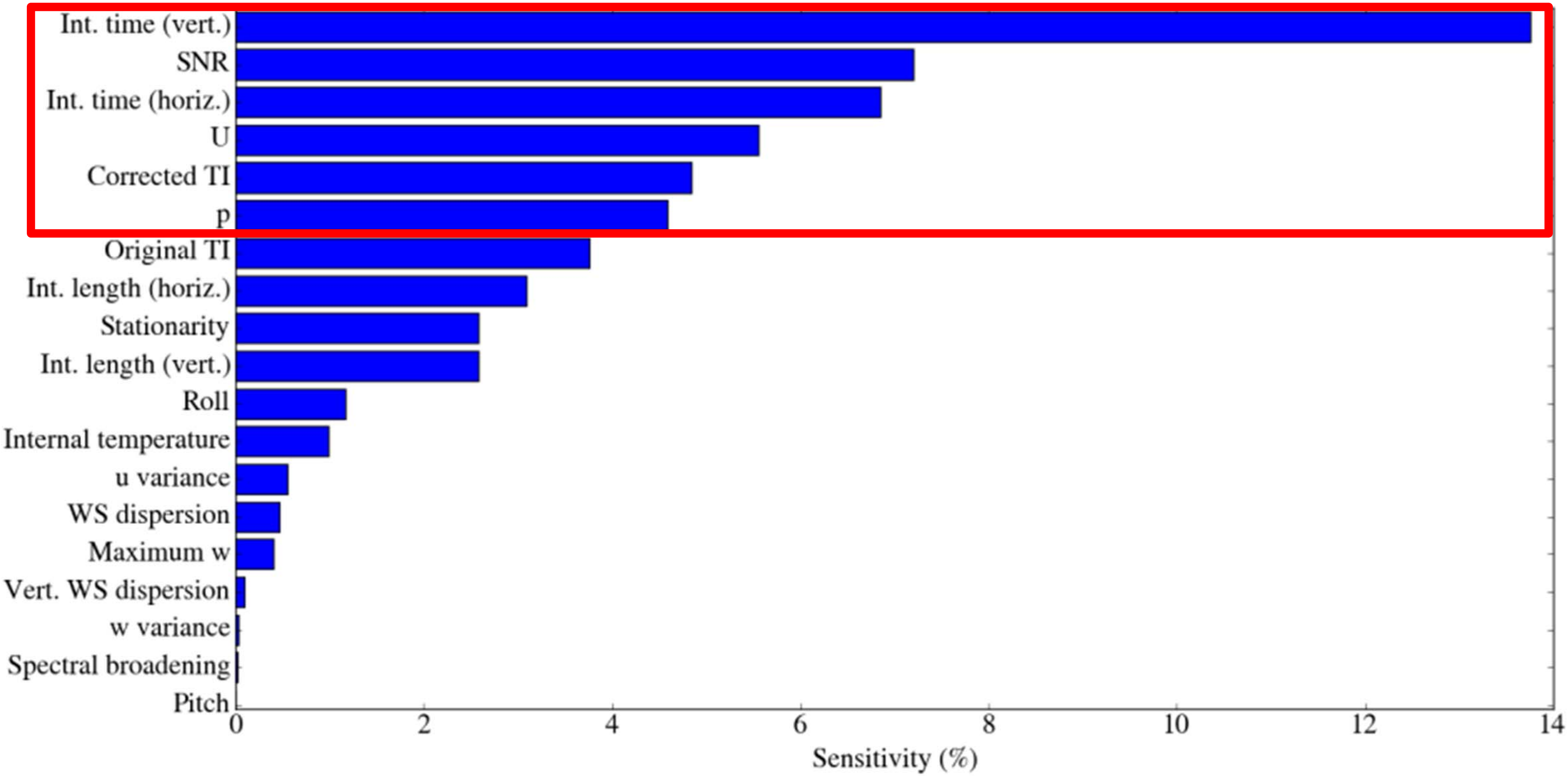
Sensitivity to Mean Wind Speed



Sensitivity to Signal-to-Noise Ratio



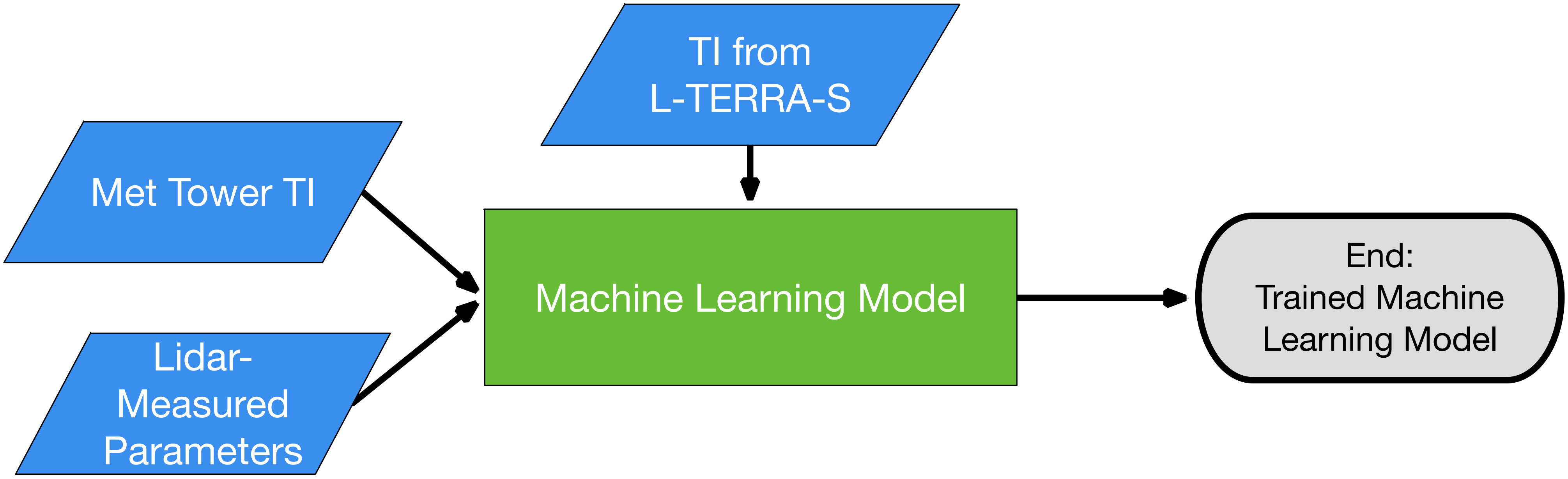
Variables with Highest Sensitivity



Option 1 to Reduce Turbulence Intensity Error: Machine Learning

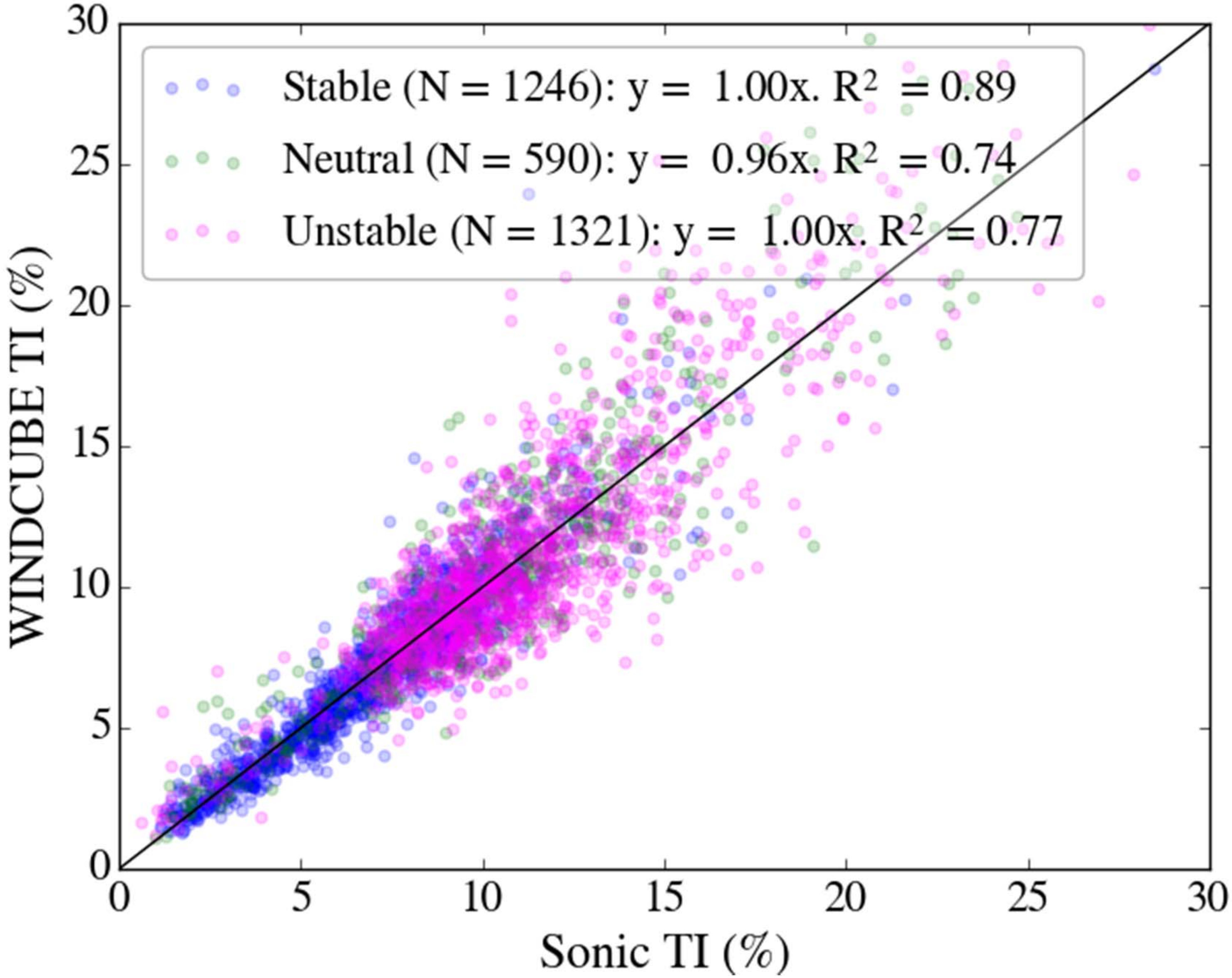
- Use most sensitive variables as input parameters for a machine-learning model.

- Train model with wind power plant data, and test on ARM site data.



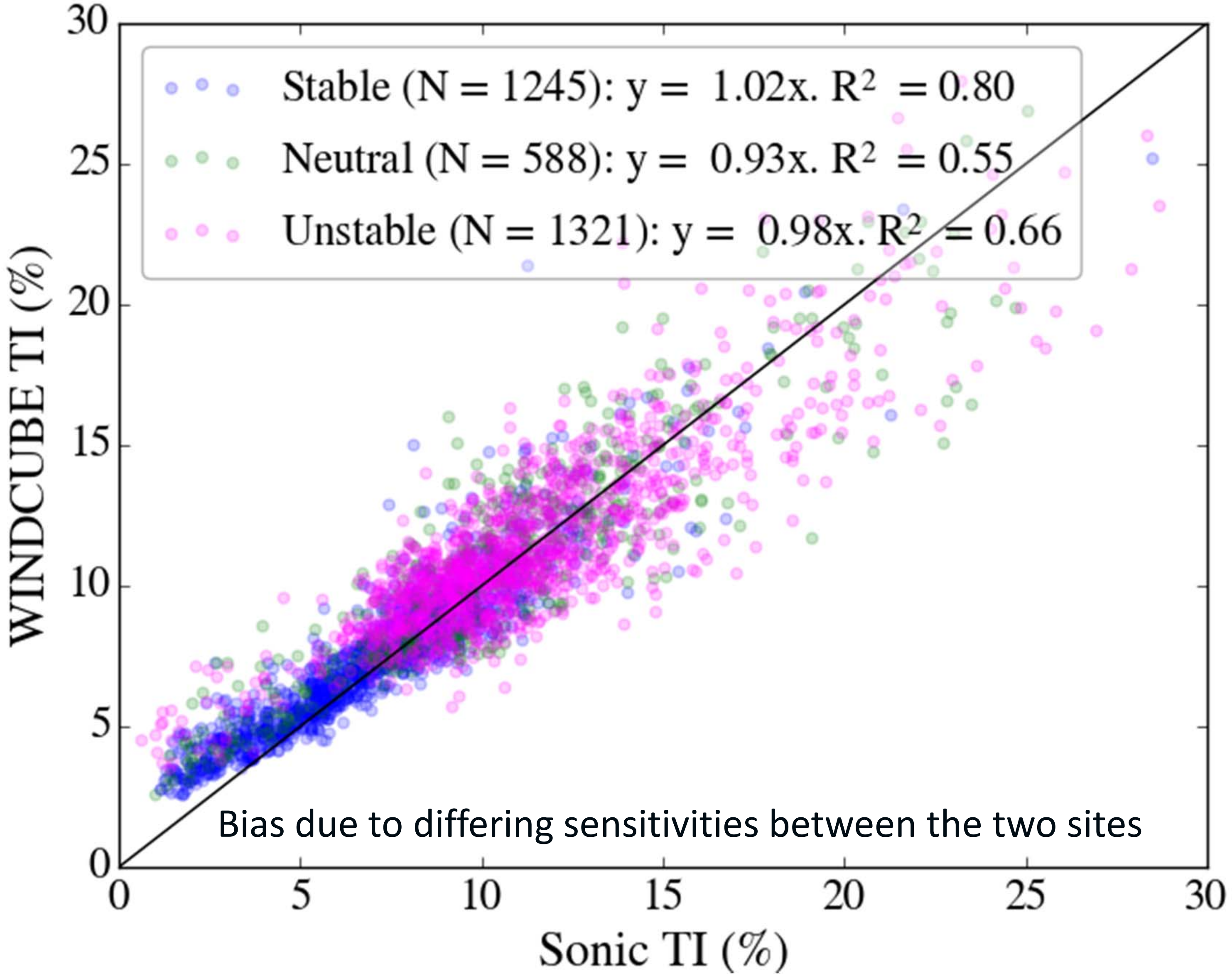
ARM Site: After L-TERRA-S

L-TERRA-S MAE: 1.25%



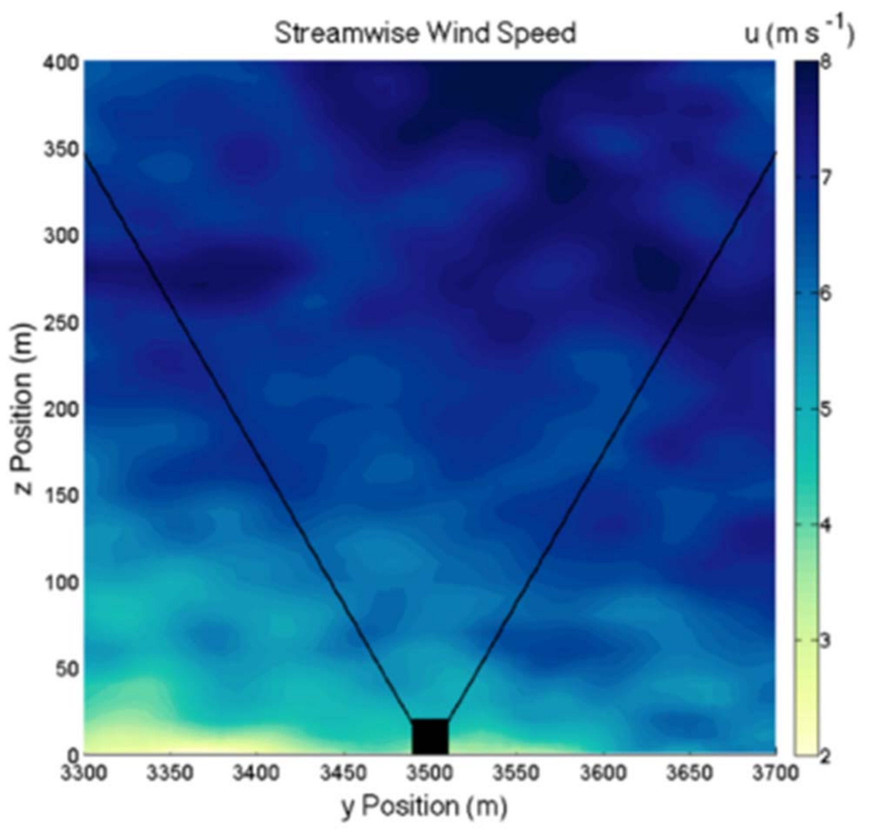
ARM Site: After L-TERRA-S + Machine Learning

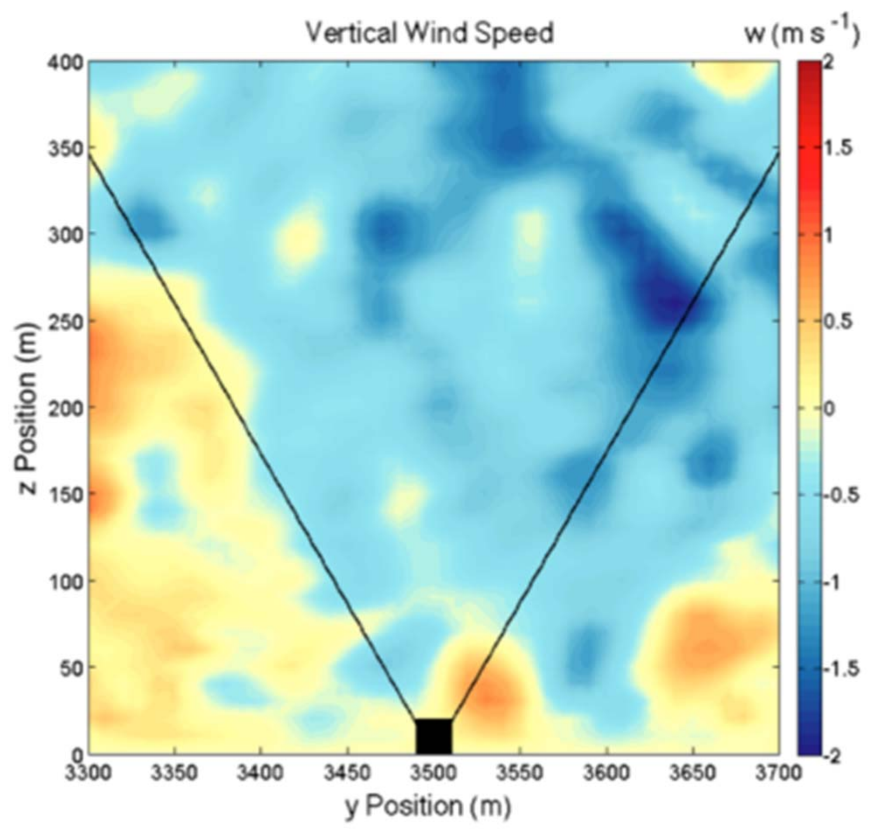
L-TERRA-S MAE: 1.25% L-TERRA-S + ML MAE: 1.29%



Option 2: Examining Error Sources with Virtual Lidar

- Use large-eddy simulation data from NREL's Simulator for On/Offshore Wind Farm Applications (SOWFA).
- Sample with virtual lidar.





For more information, see https://nwtc.nrel.gov/SOWFA.

Final Thoughts

- L-TERRA reduces lidar TI error under most conditions.

- Current work focuses on understanding all the physics that affect lidar TI error.

- Results highlight the importance of developing dynamic TI corrections that depend on current flow conditions.

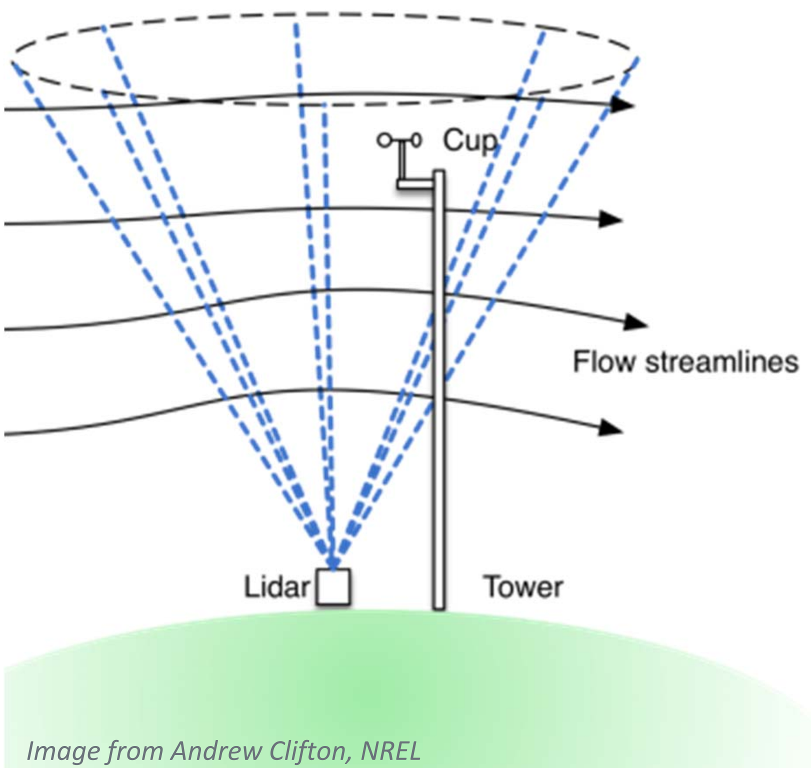


Image from Andrew Clifton, NREL

Photo by Sonia Wharton

Let's talk!
Jennifer.Newman@nrel.gov
+1 303-275-4998

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