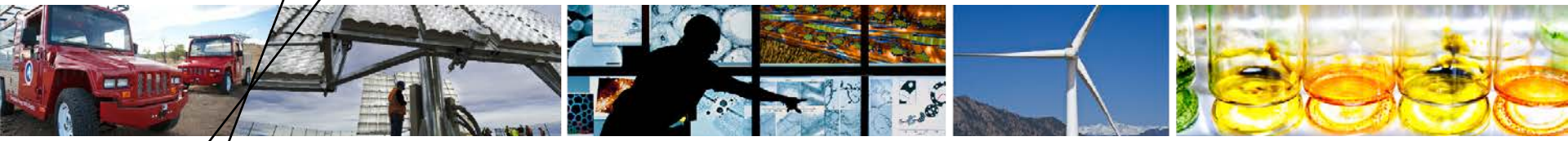
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Field Test Results of Using a Nacelle-Mounted Lidar for Improving Wind Energy Capture by Reducing Yaw Misalignment



Paul Fleming, Andrew Scholbrock, Alan Wright

Nordic Wind Power Conference

November 4–5, 2014

Stockholm, Sweden

NREL/PR-5000-63206
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Lidar-Enhanced Controls Research at NREL

- **NREL, working collaboratively with research partners, has developed, analyzed, and field tested lidar-enhanced strategies for improving:**
  - Pitch control
  - Torque control
  - Yaw control
  - Active power control.
- **Several research campaigns ongoing**
- **Focus of this presentation is yaw control.**

Note on References

- **Most of the results to follow are more fully described in available publications, or else articles under review**
- **Contact paul.fleming@nrel.gov to request references and for an explanation of slides and further details.**

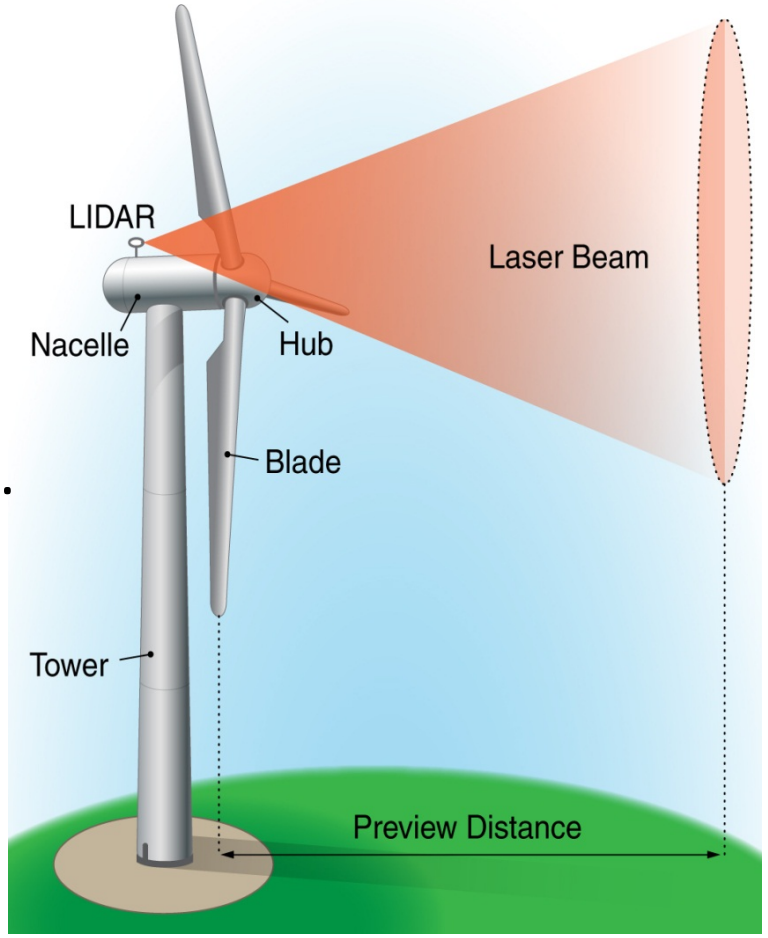
Motivation

- **Modern commercial turbines use active yaw control, typically based on measurements from nacelle-mounted wind vanes**
- **Static errors in measurement can occur as a result of:**
  - Rotor wake
  - Complex flow from nacelle
  - Environmental impacts on the wind vane
  - Poor calibration or installation.
- **Yaw misalignment can lead to reduced power production.**

Photo by Lee Jay Fingersh, NREL

Yaw Misalignment Research Campaigns

- **Campaign one:**
  - Learned and applied nacelle vane correction function
  - Partnered with:
    - Avent Lidar Technology
    - Renewable NRG Systems (RNRG).
- **Campaign two:**
  - Directly used lidar as control signal for yaw controller
  - Partnered with:
    - ZephIR Lidar.



Turbine Descriptions

- **Controls Advanced Research Turbines (CARTs) 2/3:**
  - Hub height of 36.6 meters
  - Rotor diameter of 42.6 meters
  - Power rated at 600 kilowatts
  - Two or three blades.
- **Extensively instrumented:**
  - Dedicated meteorological (met) mast
  - Strain gauges
  - Accelerometers.

Photo by Lee Jay Fingersh, NREL

Research Campaign One

- **NREL/Avent/RNRG collaborated on uses of lidars for improved turbine control**
- **Phase one used the lidar measurement to determine yaw misalignment correction function running the baseline controller**
- **Phase two collected data with and without the correction function (two hours per cycle).**

Lidar Specifications

- **Avent Wind Iris**
  - Sample rate of 2 hertz
  - Pulsed lidar
  - Ten measurement ranges
  - Two horizontal beams
  - Half-angle of 15°
  - Calibrated to the rotor axis to within 0.1°.

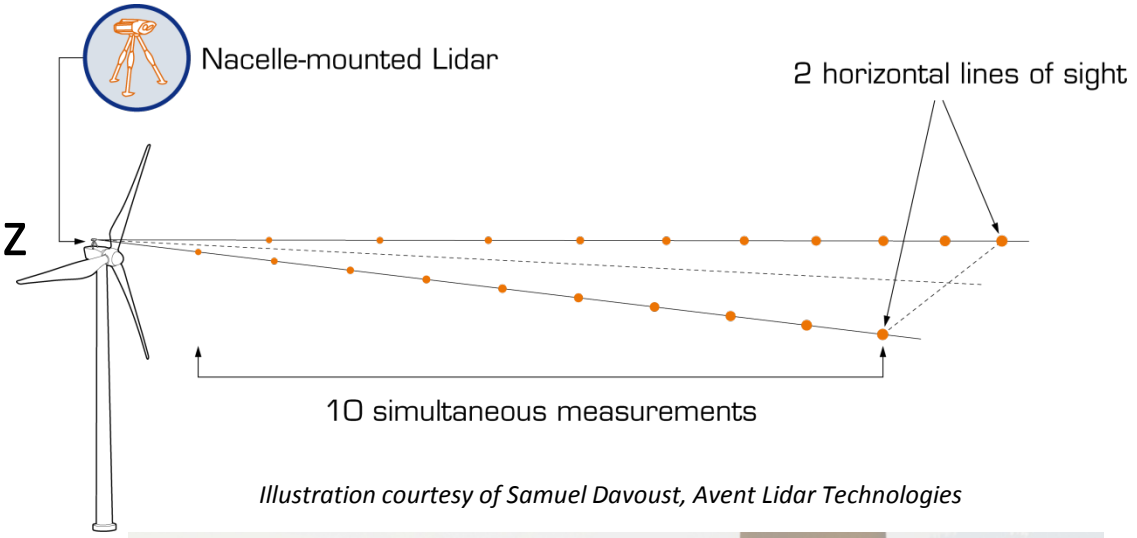
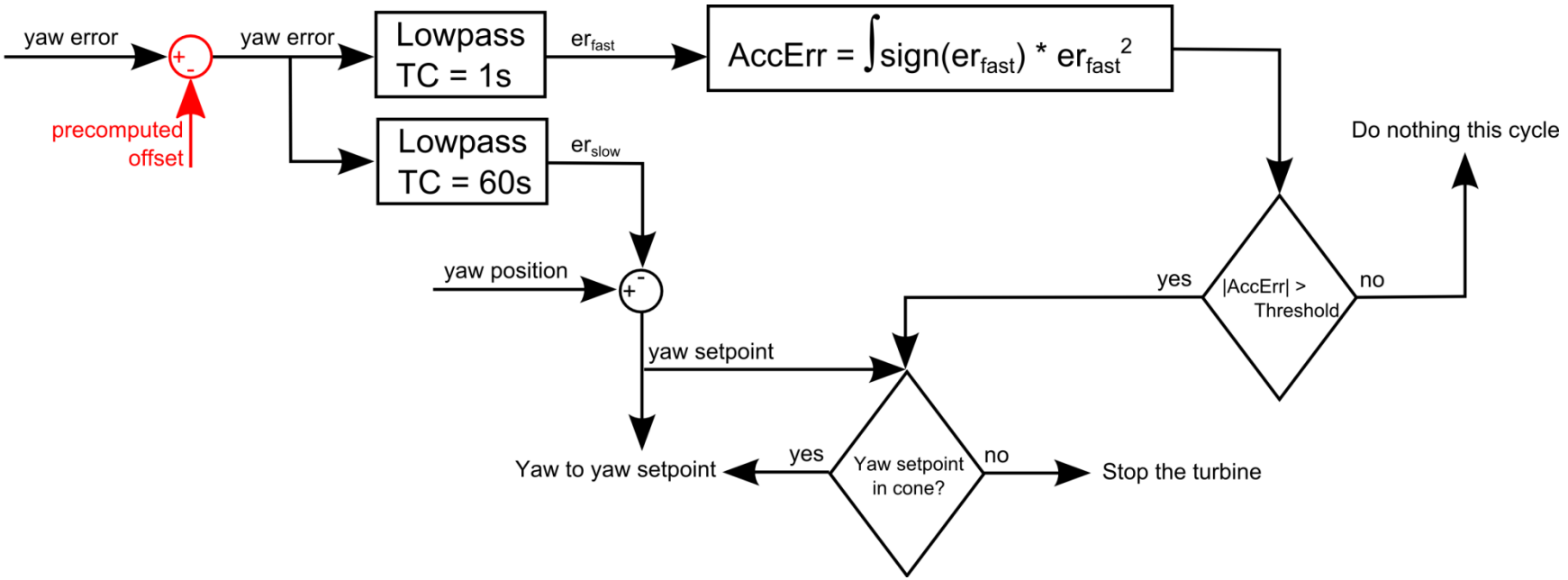


Illustration courtesy of Samuel Davoust, Avent Lidar Technologies

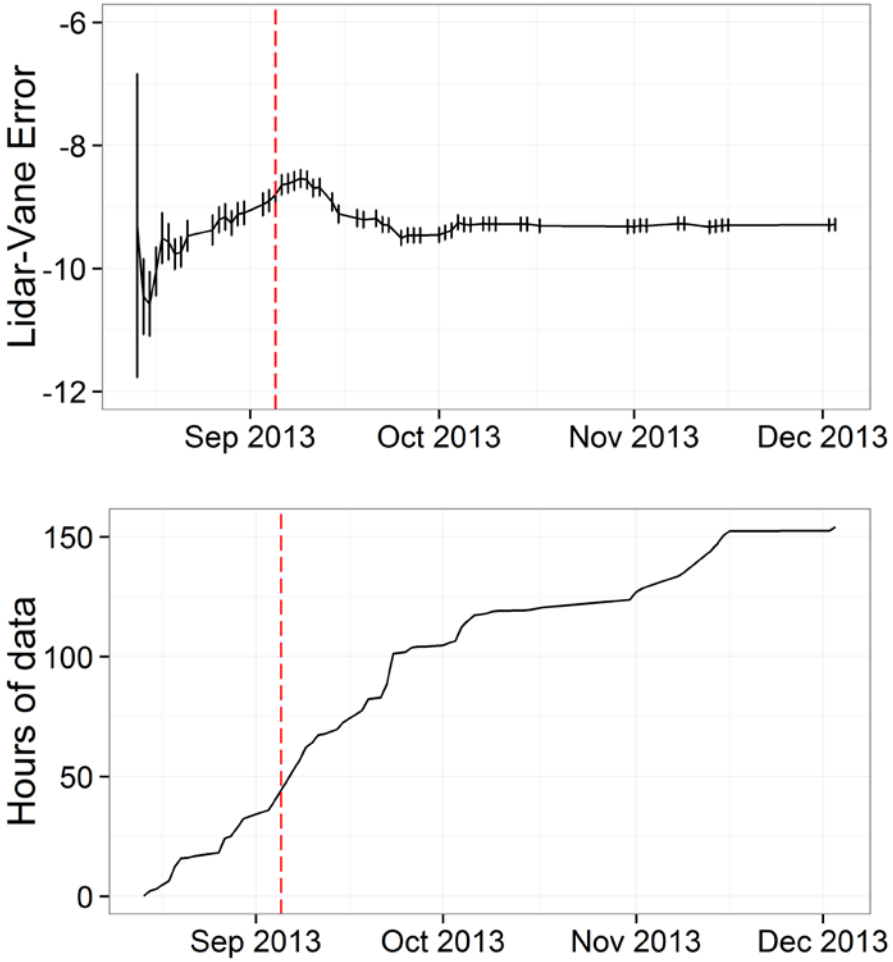
Photo by Lee Jay Fingersh, NREL

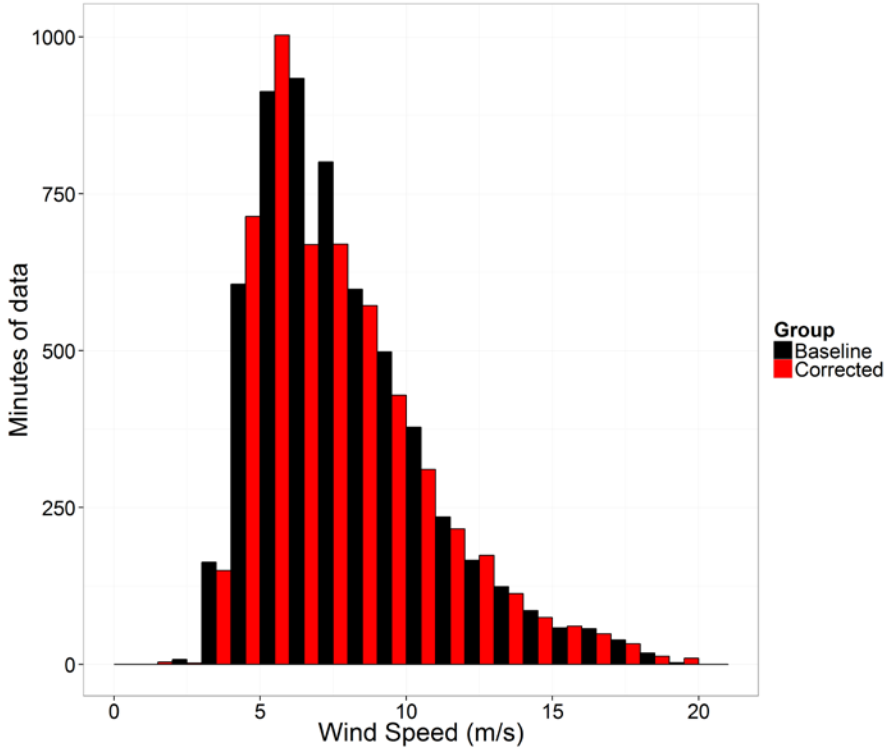
Yaw Controller Schematic



Measurement Campaign

Red line indicates point when offset was computed

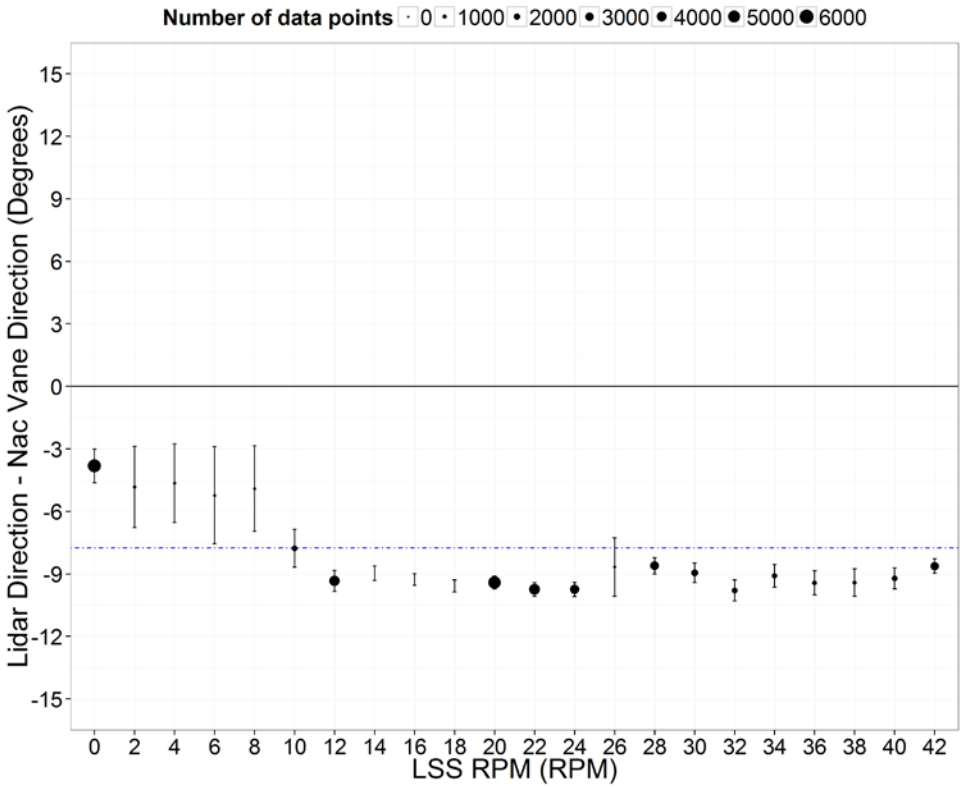




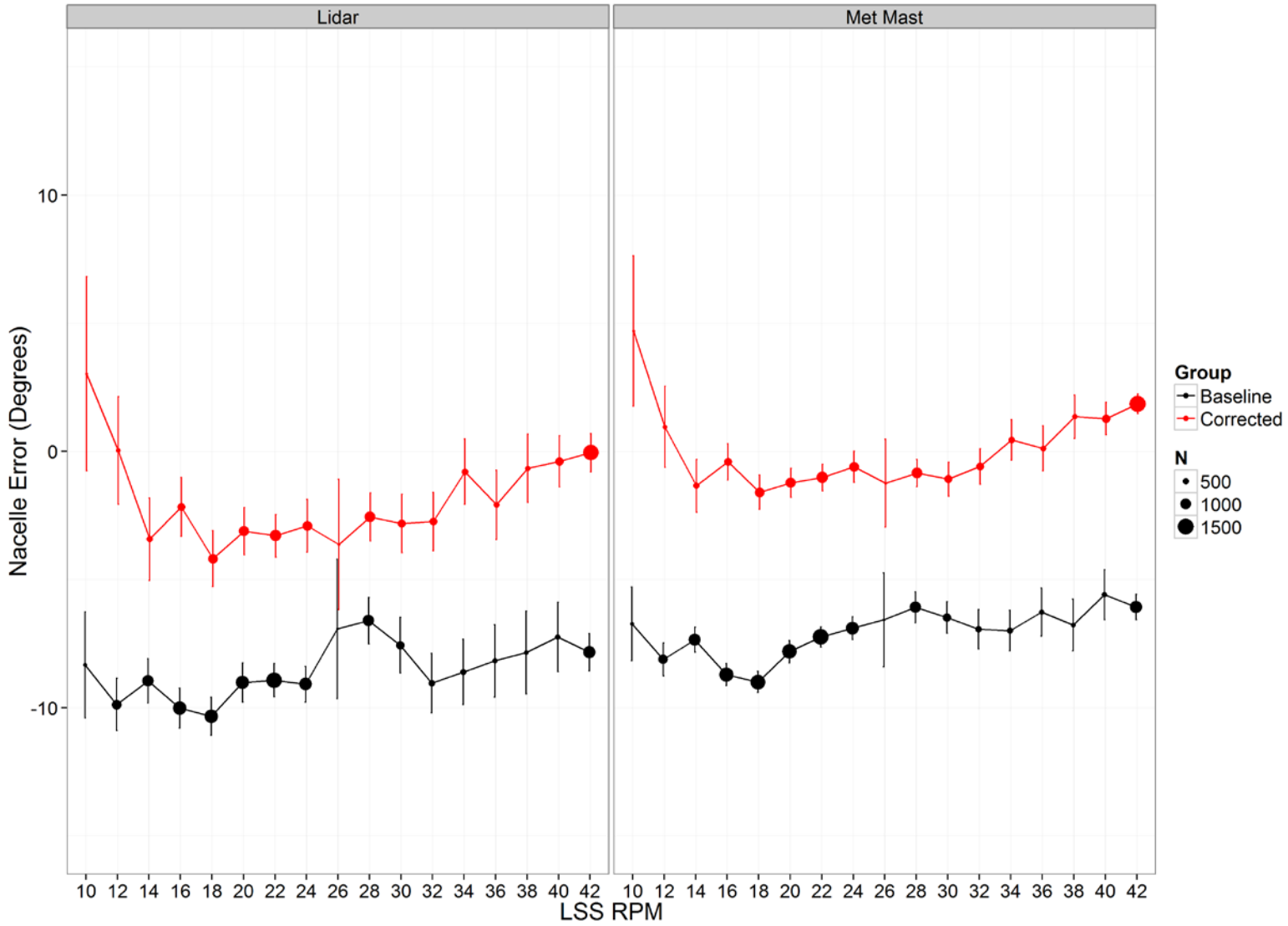
Figures on slides 10-13 from P. A. Fleming, A. K. Scholbrock, A. Jehu, S. Davoust, E. Osler, A. D. Wright, and A. Clifton, "Field-test results using a nacelle-mounted lidar for improving wind turbine power capture by reducing yaw misalignment," in The Science of Making Torque from Wind, 2014, vol. 012002.

Yaw Error Correction

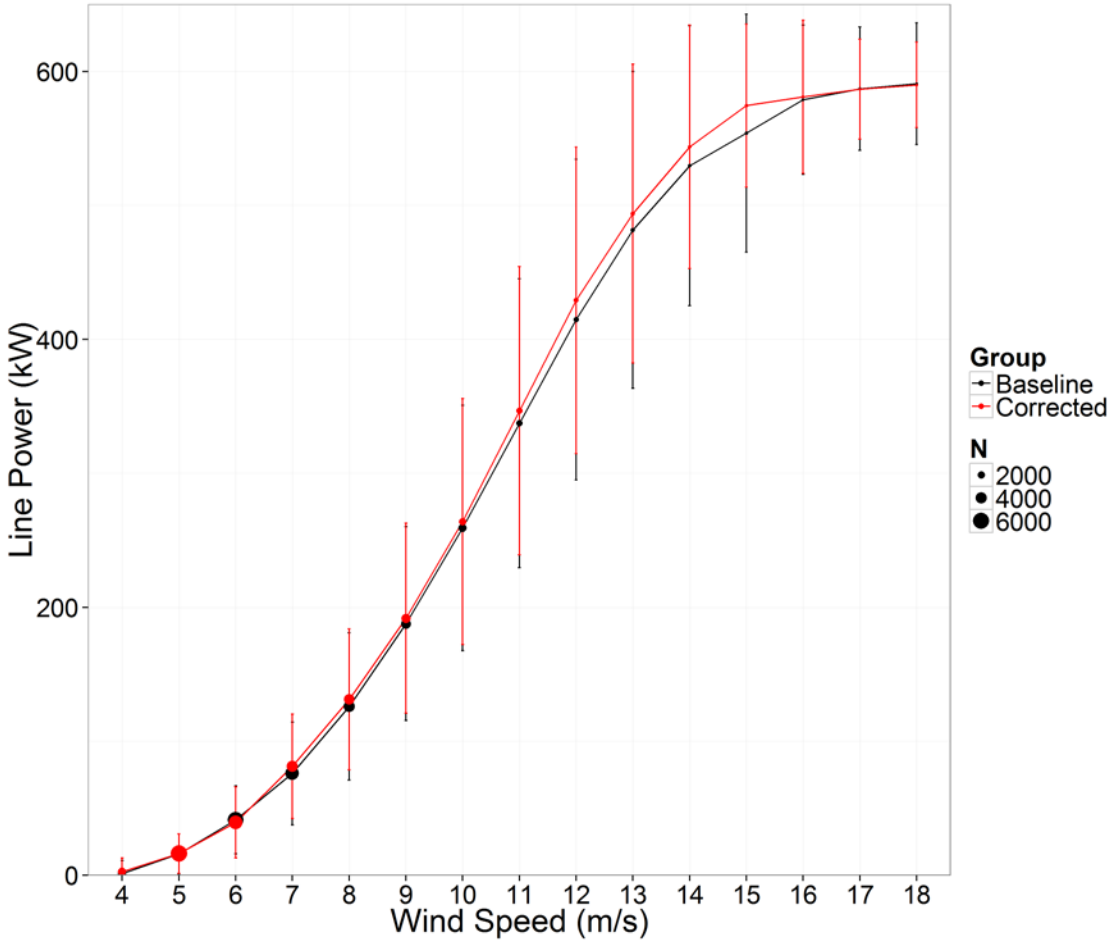
- Group chose a 7.5° initial offset after 40 hours of data were collected
- A better choice would have been a ~9.5° offset if all data from the experiment had been used.



Yaw Correction Compared to Met Mast



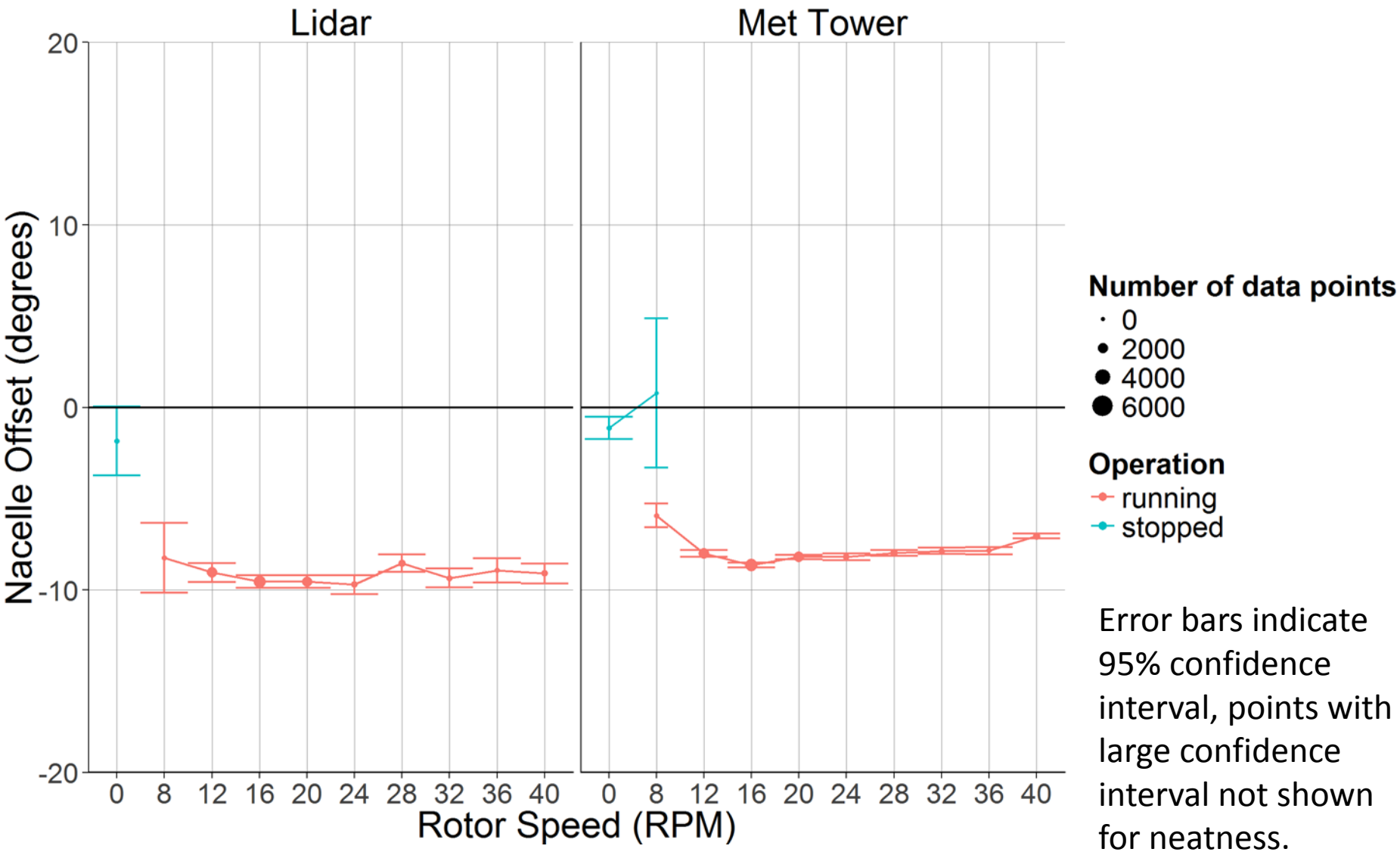
Results: Power Improvement



Calculated in 10-second windows

Annual energy production estimated to be increased by **2.4%** for a 7.5° offset.

Results: Error Function

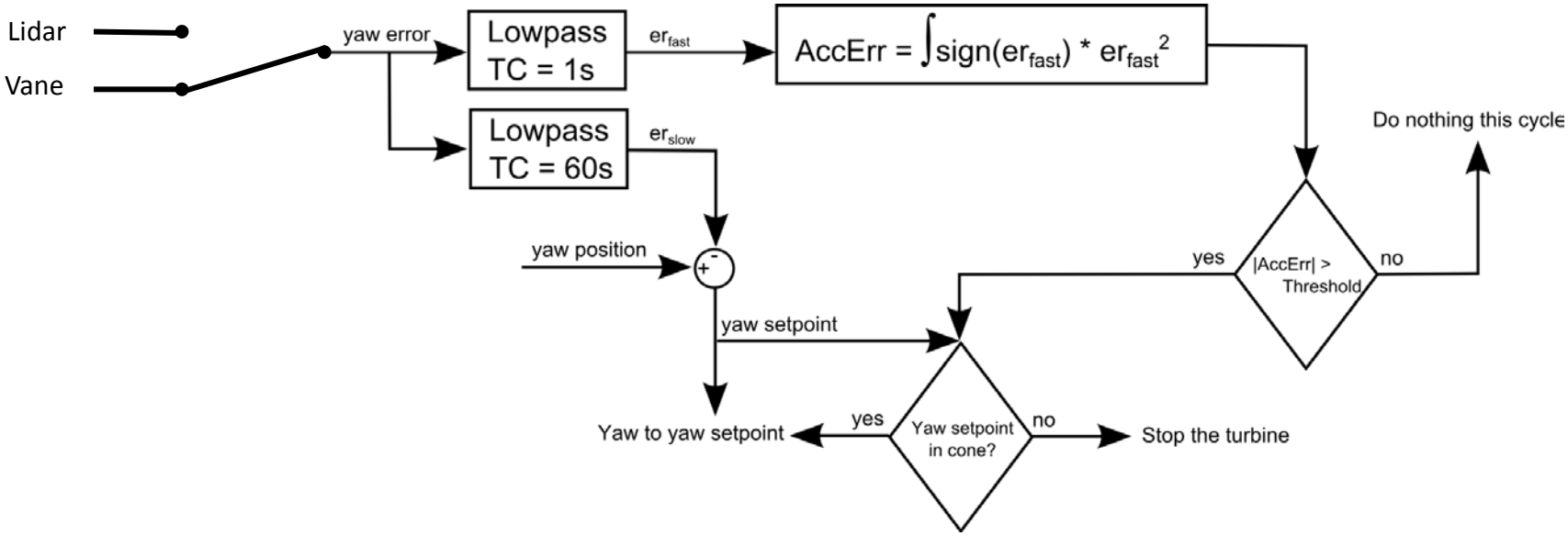


Error bars indicate 95% confidence interval, points with large confidence interval not shown for neatness.

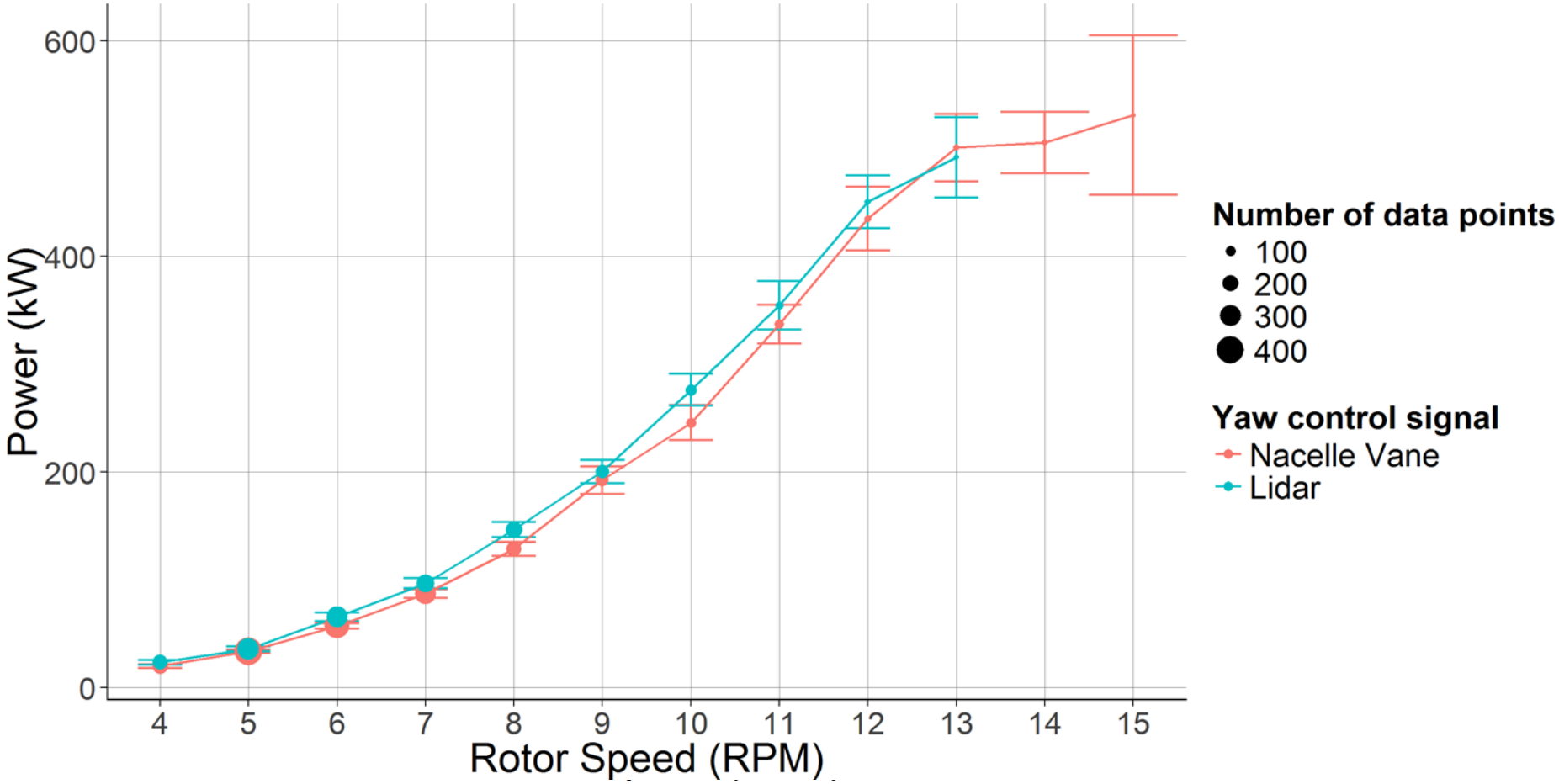
Research Campaign Two

- **CART3 mounted with ZephIR lidar**
- **Direct use of lidar signal in yaw control.**

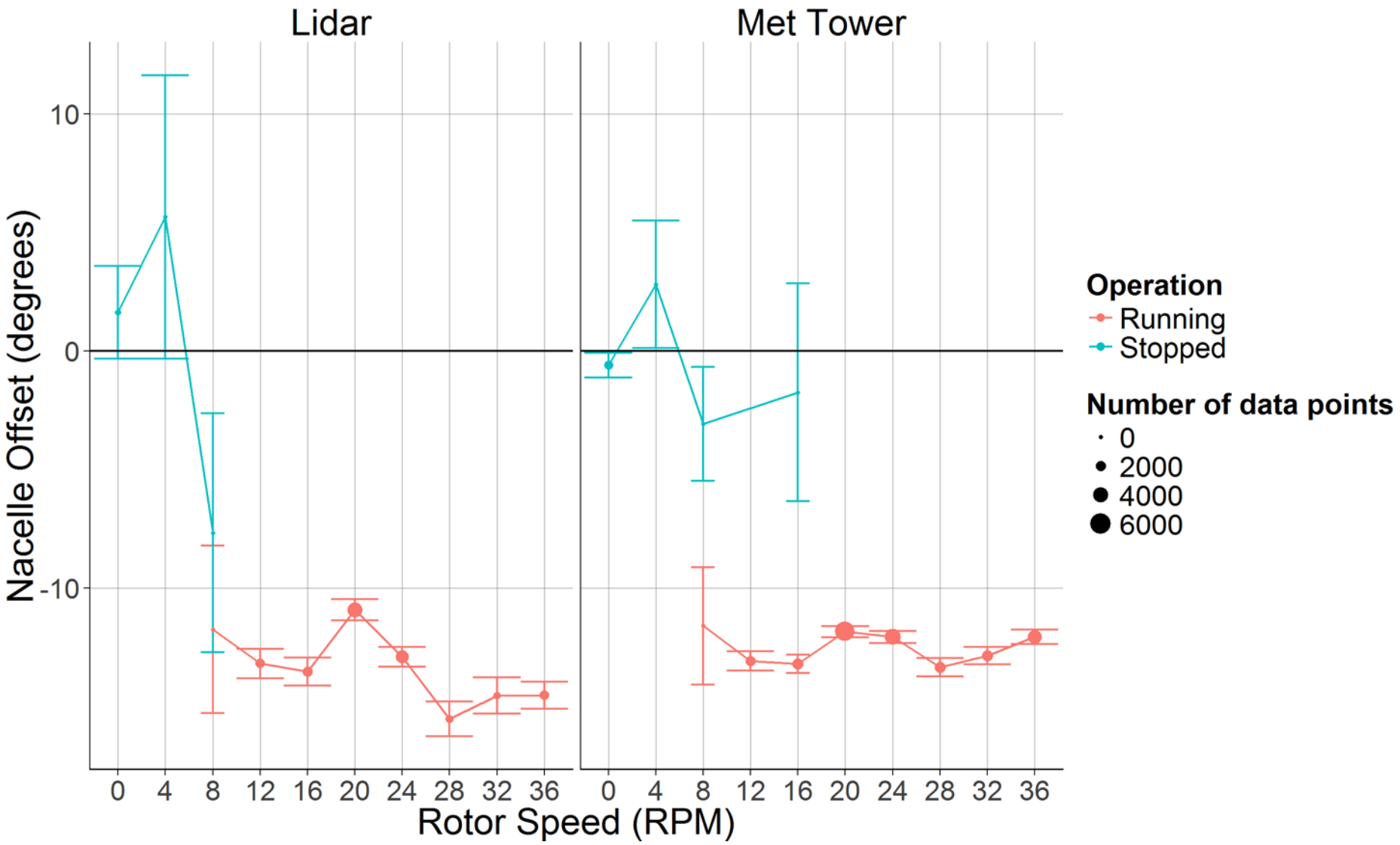
Photo by Lee Jay Fingersh, NREL



Results: Power Improvement



Results: Error Function



Results

- In this case, vane appeared to have had a fault occurring in one direction
- Rotor-induced bias toward that direction furthered the impact
- However, calibration with turbine offline appeared to have been correct

- See press release: http://www.zephirlidar.com/news/
- Paper to be presented at AIAA 2015.

Conclusions

- **Lidars have been shown to be capable of resolving errors in yaw calibration by:**
  - Learning a correction function
  - Applying the lidar signal directly.

Further Research with Yaw Control

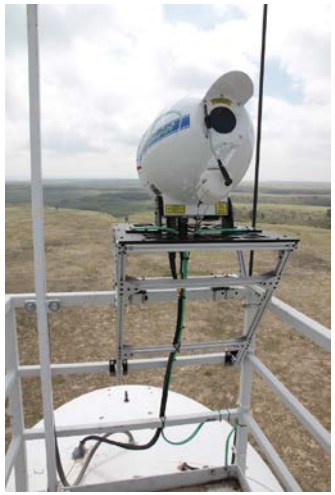
- Ongoing research at NREL and the Delft University of Technology is exploring control strategies for wind plants
- One topic of interest is the use of yaw control for the redirection of turbine wakes to optimize overall plant power
- Accurate yaw alignment detection is a must.

Further Research with Lidar-Enhanced Controls

- **NREL has collaborated with other research centers and lidar manufacturers on the use of lidars for enhanced:**
  - Pitch speed control
  - Torque control
  - Active power controls.

Lidar-Enhanced Pitch Control

- **Several test campaigns completed, and several more ongoing**
- **Use lidar wind speed preview information as feedforward input to pitch controller**
  - Improve speed regulation
  - Reduce turbine loads.



Photos by David Schlipf, Stuttgart Wind Energy (top left), and Lee Jay Fingersh, NREL (top right, bottom left, bottom right)

Results: Pitch Control

Photos by Lee Jay Fingersh, NREL

Rotor Speed

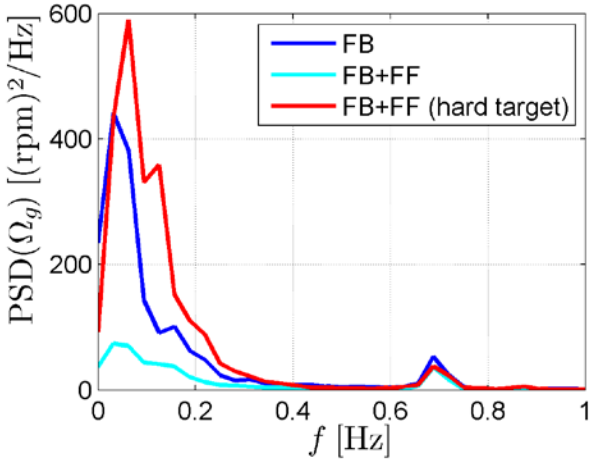
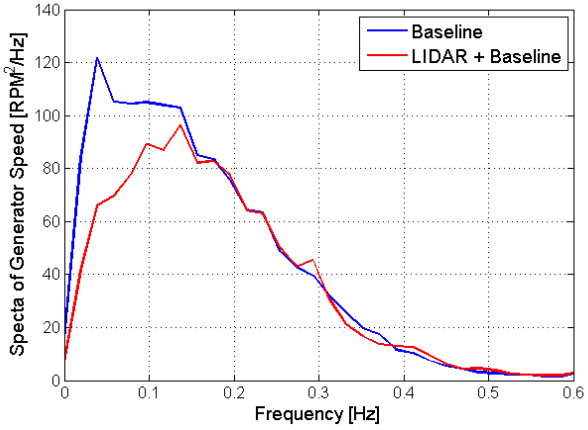


Figure courtesy David Schlipf, Stuttgart Wind Energy



Tower Bending

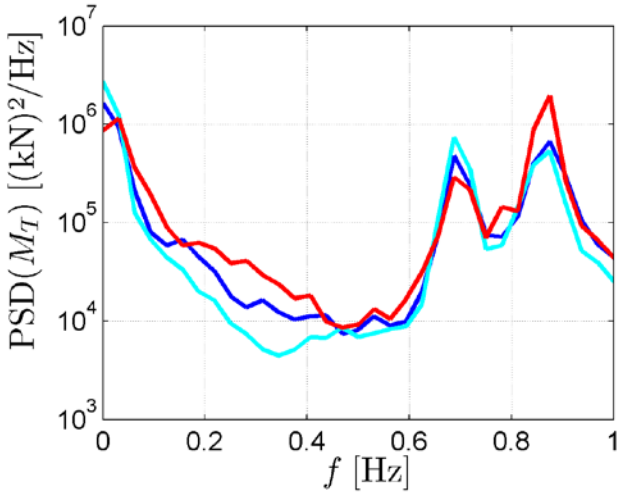
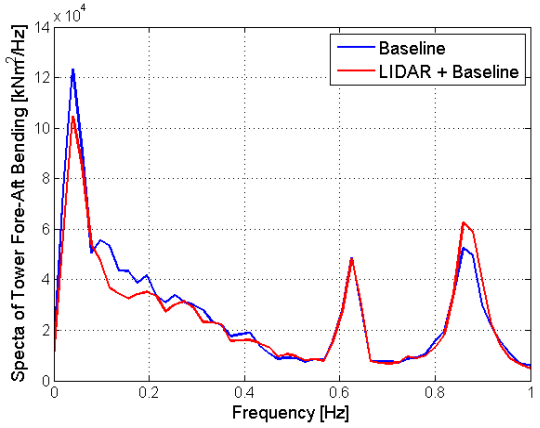


Figure courtesy David Schlipf, Stuttgart Wind Energy



Pitch Control

- **Recent demonstration with Stuttgart Wind Energy (SWE) and a ZephIR lidar mounted on CART3 showed successful application of lidar feedforward control.**

Photo by Lee Jay Fingersh, NREL

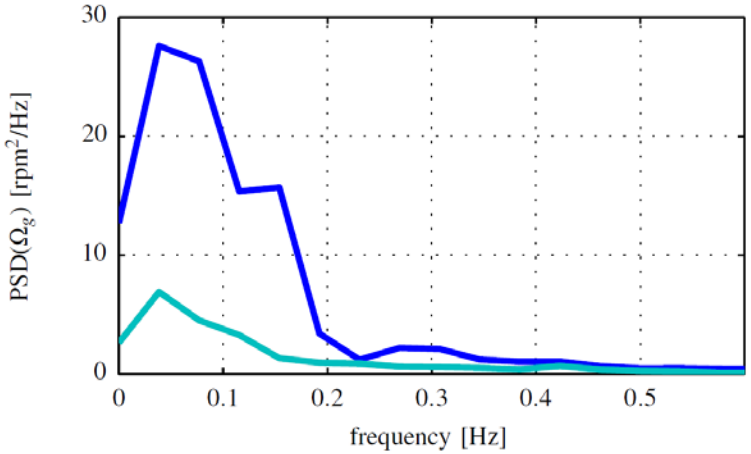


Fig. 13. PSD of generator speed Ω_g from de-rated and re-tuned controller: FF on (dark blue) and FF off (light blue)

Figure courtesy Florian Haizmann, Stuttgart Wind Energy

Pitch Control

DNV GL

Avent Lidar Technology
Renewable NRG Systems

- **Ongoing campaign on the CART2 with an Avent five-beam demonstration lidar and DNV-GL is yielding promising results.**

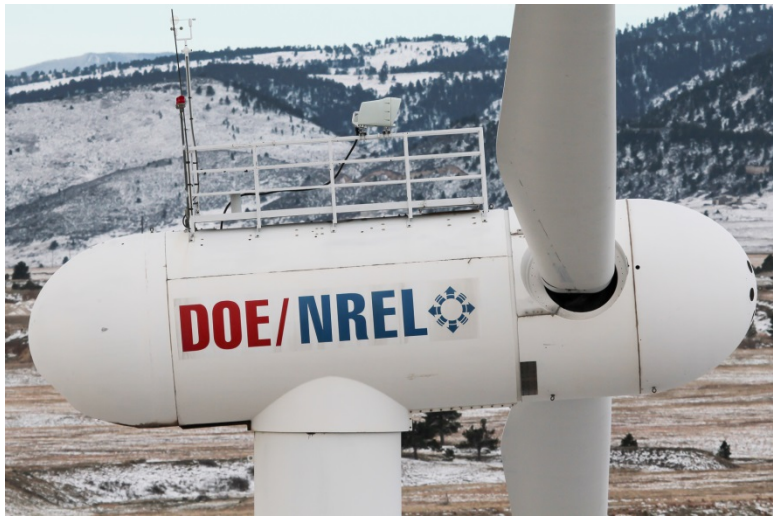
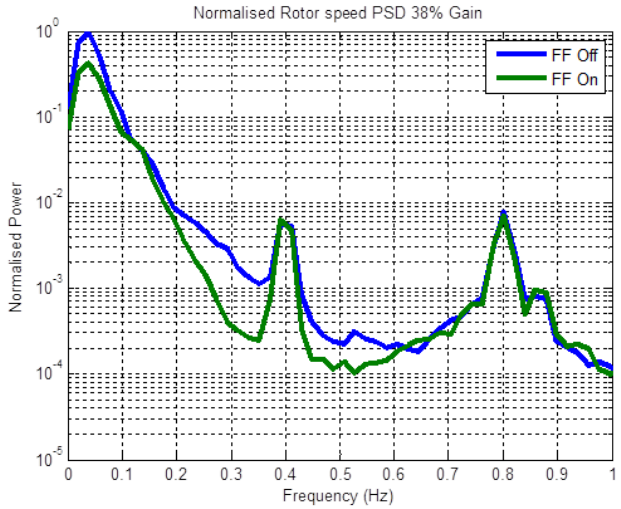
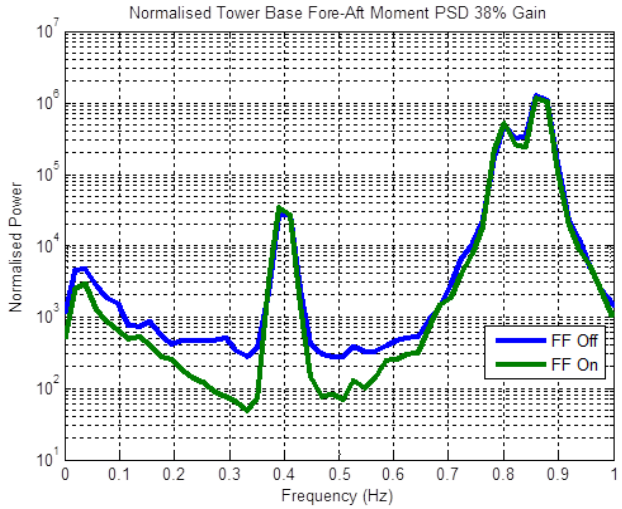


Photo by Jay Fingersh, NREL





Figures courtesy of Avishek Kumar and Ervin Bossanyi, DNV-GL

Active Power

CU Boulder

Avent Lidar Technology
Renewable NRG Systems

- Current research in active power controls investigates the use of wind energy in the provision of grid services
- In study, use lidar measurement of wind speed to maintain a fixed power overhead
- Field test with CART3 and Avent five-beam demonstration lidar.

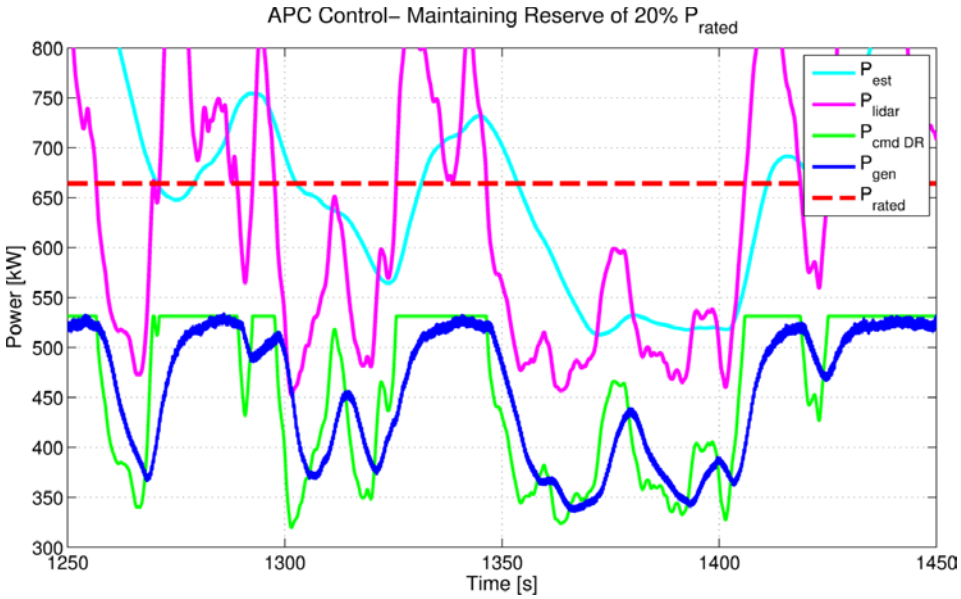


Figure courtesy of Jake Aho, CU Boulder

Photo courtesy of Florian Haizmann

Acknowledgments

- This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding for the work was provided by the DOE Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office.

Thanks for Your Attention!

Photo by Dennis Schroeder, NREL

Paul Fleming | paul.fleming@nrel.gov