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Test Plan for the Wake Steering Experiment at the Scaled Wind Farm Technology (SWiFT) Facility

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Test Plan for the 2016 Wake Steering Experiment at the Scaled Wind Farm Technology (SWiFT) Facility

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Abstract

This document is a test plan describing the objectives, configuration, procedures, reporting, roles, and responsibilities for conducting the joint Sandia National Laboratories and National Renewable Energy Laboratory Wake Steering Experiment at the Sandia Scaled Wind Farm Technology (SWiFT) facility near Lubbock, Texas in 2016 and 2017. The purpose of this document is to ensure the test objectives and procedures are sufficiently detailed such that all involved personnel are able to contribute to the technical success of the test. This document is not intended to address safety explicitly which is addressed in a separate document listed in the references titled *Sandia SWiFT Facility Site Operations Manual*. Both documents should be reviewed by all test personnel.

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NOMENCLATURE

SNL	Sandia National Laboratories
NREL	National Renewable Energy Laboratory
DOE	Department of Energy
TWD	Technical Work Document
SWiFT	Scaled Wind Farm Technology
DTU	Technical University of Denmark
LHR	Left-hand Rule
RHR	Right-hand Rule
CART	Controls Advanced Research Turbine

APPROVALS

The following test plan may not be implemented until the following individuals approve by signing and dating below.

Approved by: ____________________ Date: 12/20/2016
Tim Crawford, SWiFT Site Lead

Approved by: ____________________ Date: 12/20/2016
David Mitchell, SWiFT Site Supervisor

Approved by: ____________________ Date: 12-19-2016
Brian Naughton, Project PI

Approved by: ____________________ Date: 12/19/2016
Wesley Johnson, 6121 ES&H Coordinator

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1. INTRODUCTION

Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) will jointly execute an experimental campaign on wind farm controls and wake characterization at the Scaled Wind Farm Technology (SWiFT) facility in 2016. The goal of the experiment is to demonstrate the capability of wake steering control to improve total wind turbine array power production through an experimental campaign at the SWiFT Facility. The experimental campaign will be conducted in two phases.

In Phase I an Offset Controller is applied to the SWiFT turbine WTGa1. This controller applies an offset to a nacelle-based wind direction sensor used to align the turbine to the wind direction in order to achieve a prescribed misalignment to the wind. Wake position data will be collected under multiple yaw misalignment angles and inflow conditions as simulated using the SOWFA code to both verify the ability to steer the wake at the SWiFT facility and to develop a look-up table for the FLORIS control model to be implemented in the Phase II controller.

In Phase II, the offset controller on WTGa1 is replaced by a Wake Steering Controller which operates in a similar fashion to the offset controller, however it uses a look-up table based on the FLORIS model to prescribe offsets in order to produce a desired wake steering amount based on the inflow parameters. The wake deflection will be verified by scanning lidar along with turbine performance data (loads and power) for both WTGa1 and WTGa2 turbines. This data will be used to partially validate the FLOw Redirection and Induction in Steady-state (FLORIS) and Simulator fOr Wind Farm Applications (SOWFA) models.

2. TEST OBJECTIVES AND SUCCESS CRITERIA

The following table summarizes the primary and secondary test objectives for the test plan along with the criteria used to evaluate the success of the test in achieving the objectives. Primary objectives are required to be completed while secondary objectives are only to be pursued after successful completion of the primary objectives.

Table 1. Test objectives and success criteria

Primary Test Objective(s) – Must be completed for a successful test
PTO1: Collect inflow, turbine (WTGa1) and wake data under various yaw misalignment states and populate a look-up-table and to calibrate the FLORIS control model.
Success Criteria: Sufficient wake position data under multiple inflow and yaw misalignment cases to calibrate the FLORIS model and develop a look-up table for the Phase II controller.
PTO2: Collect inflow, wake, and turbine (WTGa1 & WTGa2) power a loads data under select yaw control states to demonstrate the impact of wake steering on wind plant performance.
Success Criteria: Sufficient correlated inflow, controller state, wake position, and wind turbine performance data to determine effectiveness of wake steering control concepts to improve wind plant performance over baseline operation.
Secondary Test Objective(s) – May be completed after primary test objective is complete
STO1: Collect wake characterization data under multiple inflow conditions to improve the wake models within the SOWFA code
Success Criteria: Time synchronized inflow, turbine, and wake data with uncertainty to match SOWFA simulations.

3. ROLES AND RESPONSIBILITIES

Describe all the roles and responsibilities of the personnel that will be involved in all stages of the test plan.

Table 2. Roles and Responsibilities

Title	Name(s)	Responsibilities
Test Controller	Turbine Operator or SWiFT Site Supervisor	• Conduct daily safety briefing and review test objectives for the day
Principal Investigator	Brian Naughton	• Manage planning and execution of experiments at SWiFT • Coordinate with SWiFT Lead on SWiFT and Wake Steering Priorities
SWiFT Site Lead	Tim Crawford	• Manage SWiFT site activities • Prepare and maintain SWiFT site per experiment requirements (priority sensor list) • Coordinate with SWiFT Lead on SWiFT and Wake Steering Priorities
SWiFT Site Supervisor	David Mitchell	• Manage and coordinate daily activities at the SWiFT site • Lead daily safety brief and debriefs on-site with personnel at SWiFT
Lidar Operator and Analyst	Tommy Herges	• Monitor and control DTU SpinnerLidar instrument • Process and analyze SpinnerLidar data for QC and experimental needs
Met and Turbine Analyst	Chris Kelley Brandon Ennis	• Process and analyze met tower and turbine data for QC and experimental needs • Perform simulations to analyze loads and performance of turbine • Develop sensor calibration plans
Management of Change (MOC) Preparers	Jon White Josh Paquette	• Prepare and submit MOC documentation for experiment activities that exceed the standard operating envelope of the SWiFT site
Turbine Operator	Jon Berg Josh Bryant Jeroen van Dam Andy Scholbrock Dave Jager	• Operate the turbine(s) in attended mode to collect experimental data • Maintain daily test log entries and report any unusual events to Principal Investigator and SWiFT Site Lead and Supervisor

4. UNIQUE HAZARDS

The following table provides a high-level summary of major hazards that are unique to this test. Further information on hazards and controls for this test are provided in Appendix A.

Table 3. Unique Hazards

Hazard	Description
Non-standard turbine operation	New turbine control software will be used to command the turbine to yaw misalignments up to +/- 25 degrees, which exceeds the OEM controller design limits of +/- 18 degrees. Load simulations indicate this will lead to higher than normal structural loads on the turbine, namely in the nacelle yaw rotation and overturning moment under certain design load cases. This will be mitigated and documented through the Management of Change process prior to deployment.
Lasers	There are multiple laser flow diagnostic instruments that will be deployed as part of the experiment. A Management of Change package was submitted to approve the use of all unregulated lasers per Sandia policy. This covers the DTU SpinnerLidar.

5. SCHEDULE

Table 4. Test Schedule

Dates	Description
June, 2016	**Experimental Set-up** DTU SpinnerLidar delivered to SWiFT. SpinnerLidar mount and instrument installed on WTGa1. Calibration of experimental instrumentation.
July 2016–February 2017	**Phase I: Offset Controller** New turbine control software is deployed to the WTGa1 turbine to enable prescribed yaw offsets. Priority data channels from the METa1, WTGa1, and SpinnerLidar are collected per the Phase I test matrix where yaw offset and inflow are varied across a prescribed range. This data is used to calibrate the FLORIS model and build a look-up table for the Phase II experiment controller.
March – July 2017	**Phase II: Wake Steering Controller** In Phase II, the offset controller on WTGa1 is replaced by a Wake Steering Controller which operates in a similar fashion to the offset controller, however it uses a look-up table based on the FLORIS model to prescribe offsets in order to produce a desired wake steering amount. The wake deflection will be verified by scanning lidar along with turbine performance data (loads and power) for both WTGa1 and WTGa2 turbines. This data will be used to partially validate the FLORIS and SOWFA models.
July 2017	**Experimental tear-down** Experiment PI will indicate the end of the experiment to the SWiFT Site Lead and Supervisor. Any specialized equipment (e.g. SpinnerLidar) will be removed or transferred to another experiment.

6. CONFIGURATION

6.1. Definition of test area and conditions

<u>Test area and configuration for Phase I and Phase II</u>

The test configuration for both phases of the experiment will include the use of the METa1, WTGa1, and DTU SpinnerLidar as shown schematically in Figure 1. For phase II, the WTGa2 turbine will be added to the instrument suite. METb1 and WTGb1 are shown for reference but are not included in the experimental configuration.

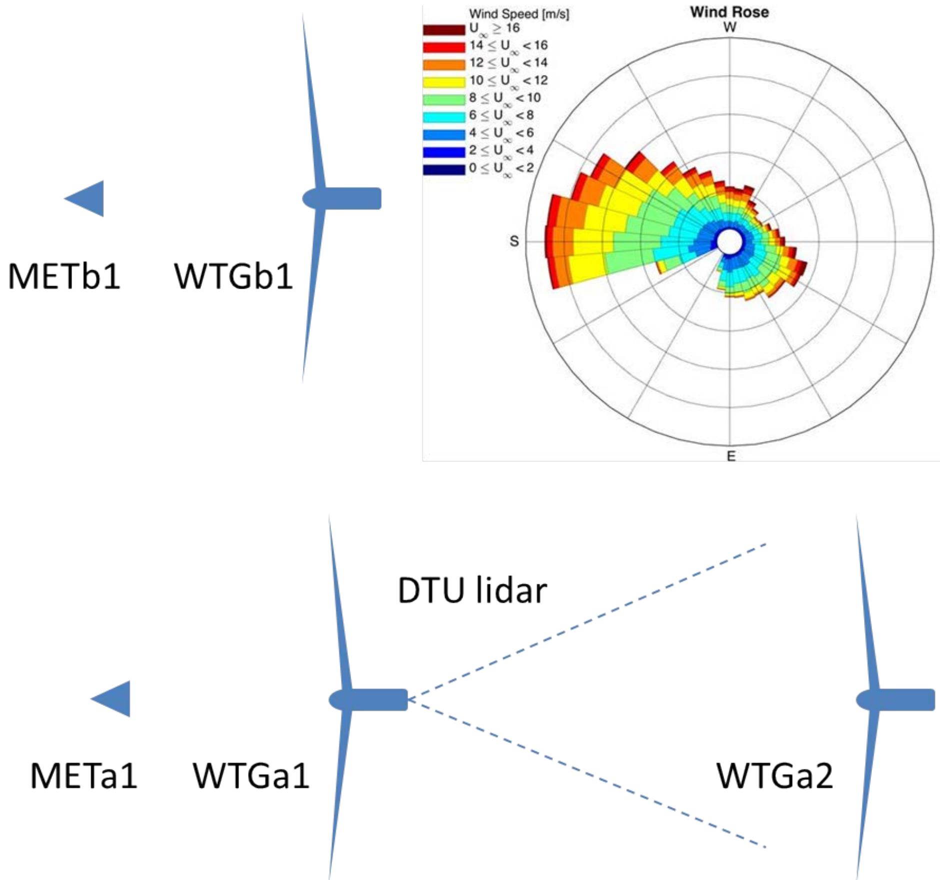

Figure 1. Basic configuration of the Wake Steering Experiment at the SWiFT facility along with the historical wind rose and instrument naming conventions used during the experiment.

The meteorological towers and turbines have a standard configuration that is explained in other reference documents. However, the DTU SpinnerLidar is not a standard SWiFT site instrumentation package. The SpinnerLidar will be installed in the nacelle of WTGa1, pointing out the rear hatch. The SpinnerLidar will be mounted on a custom-built mount that enables the lidar to manually swivel left and right such that it can always measure the wake downstream of the turbine within the range of prescribed yaw offsets. The SpinnerLidar scans a rosette pattern at a maximum rate of 1 second at a set focal length downstream of the turbine. This focal length can be changed in about 1 second and a new scan initiated. A schematic showing a rosette pattern at 4-diameters (4 x 27m) downstream is shown in Figure 2.

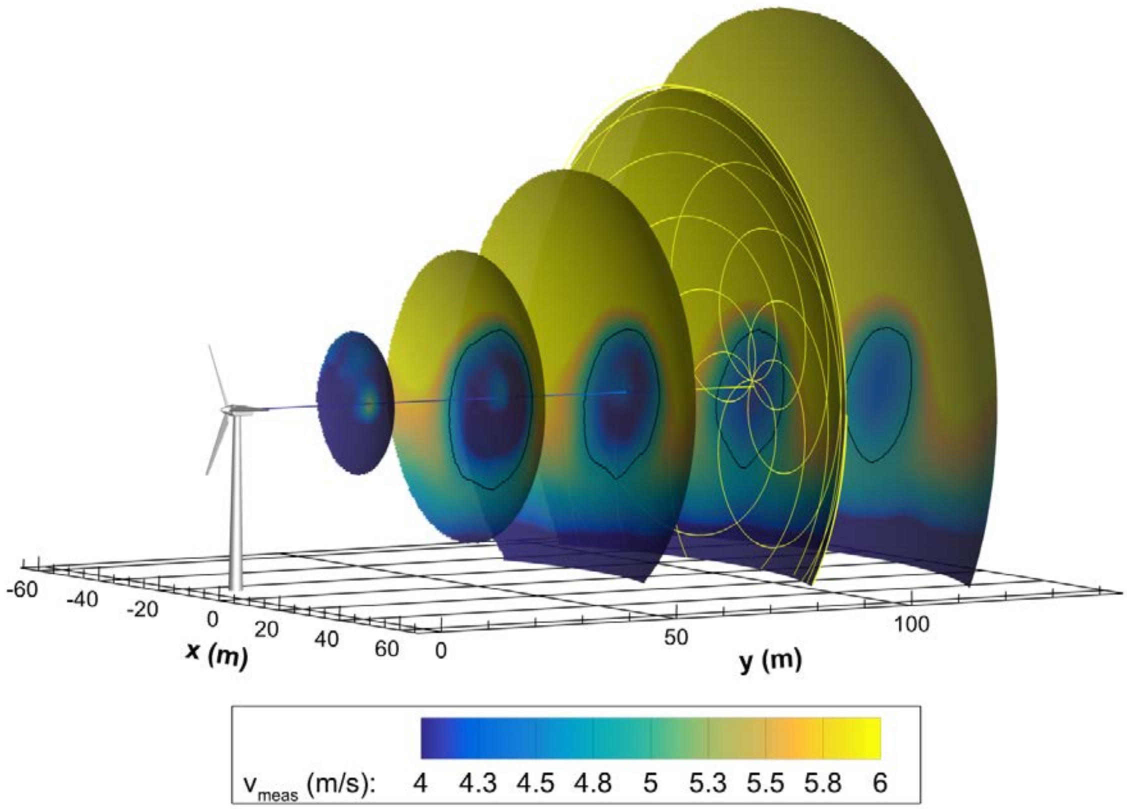

Figure 2. A schematic of the DTU SpinnerLidar scanning pattern from the nacelle of WTGa1 at the SWiFT site overlaid on velocity profiles extracted from virtual lidar simulations.

<u>Site conditions</u>

All activities will take place under safe environmental conditions per current SWiFT facility guidelines (Ref. 1) and within equipment operational windows. Generally this includes wind speeds below 20 m/s, no lightning, or extreme weather. A test matrix with wind speeds and turbulence intensities of interest is presented later for more detail.

A comprehensive study of the SWiFT site atmospheric characterization was completed in 2016 based on historical data from the nearby 200 meter meteorological tower owned and operated by Texas Tech University. The results of this study are available in reference 2.

The turbine will be operated in attended mode whenever the prescribed yaw misalignment is above the +/- 18 degree OEM design window. Operating outside this OEM window will only be conducted without the near-term threat of extreme weather conditions.

During very hot weather conditions (> 90 F) special attention will be paid by the lidar and turbine operators to the turbine and lidar temperature sensors to avoid exceeding the operating limits.

<u>Coordinate System Conventions</u>

The coordinate system conventions differ among the hardware and software systems utilized in this experiment and are described in Figure 3.

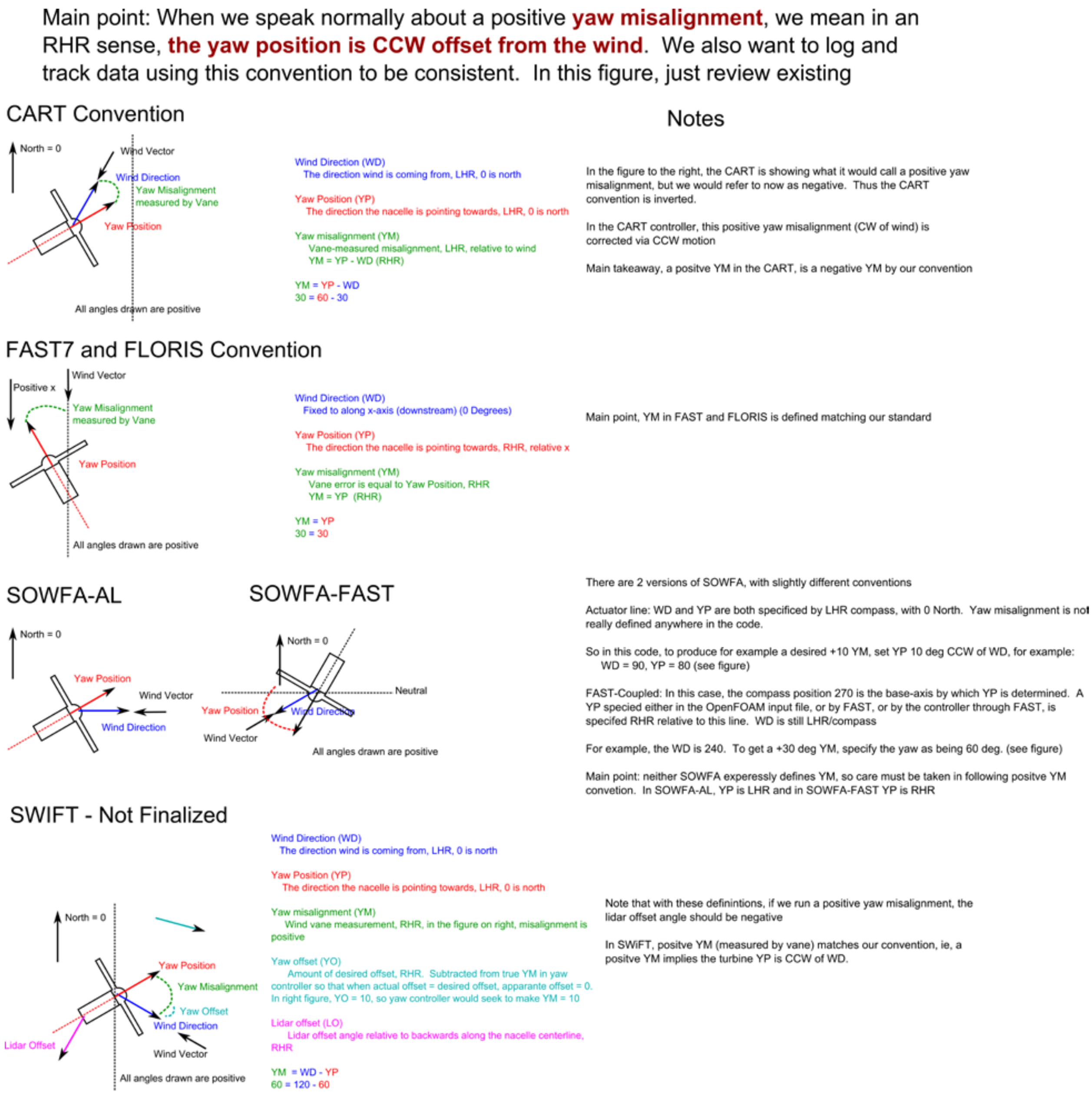

Figure 3. Coordinate conventions for the hardware and simulations referenced in the experiment. RHR is right-hand-rule and LHR is left-hand-rule.

6.2. Equipment, facilities, and materials

The following is a list of major equipment, facilities, and materials required for the test activities along with the responsible provider as indicated.

Equipment

Instrument	**Description**	**Owner/Provider**
METa1	60 meter meteorological tower to the south of wind turbine WTGa1	SWiFT
METb1	60 meter meteorological tower to the south of wind turbine WTGb1	SWiFT
WTGa1	Wind turbine on southeast of site	SWiFT
WTGb1	Wind turbine on southwest of site	SWiFT
WTGa2	Wind turbine on northeast of site	SWiFT
DTU SpinnerLidar	Scanning lidar mounted in the nacelle of WTGa1 aiming out of the rear hatch	NREL / Technical University of Denmark (DTU)

Power
The DTU SpinnerLidar requires 1kW peak power at 230V (50 or 60 Hz) available in the WTGa1 nacelle with a network connected switch to enable power on/off remotely. The SpinnerLidar also requires a cooling system to maintain an operating temperature below 50 C (122 F).

Data, Communications, and Security
A prioritized list of data channels from METa1, WTGa1, and WTGa2 are detailed in Appendix B. Priority 1 data channels require the highest availability and quality. The experiment cannot proceed when a priority 1 data channel is unavailable. Priority data channels should be logged and transferred to a network accessible location at Sandia each day. All data must be releasable to the public. See Appendix C for the approved Unrestricted, Unlimited Release (UUR) Memo.

The SpinnerLidar has a computer embedded in it for control and data acquisition and must be accessible via a network connection to research partners at the Technical University of Denmark. Due to this requirement, the lidar cannot be connected to the same network as the turbines for safety reasons. A non-Sandia computer must be directly connected to the lidar via a dedicated fiber optic line into the control building. This computer will then be connected to the internet via the wireless Texas Tech University network.

Structures
A mechanical swivel mount will be installed in the nacelle of WTGa1 to secure the lidar to the bedframe and allow the entire lidar to swivel clockwise and counterclockwise out of the rear hatch of the nacelle. The hatch will have to be removed or be secured open for the duration of the experiment. Details of this design are available in Appendix D.

A crane will be required to install and remove the SpinnerLidar and swivel mount. A lift plan will be developed for this activity and is available in Appendix E.

7. PROCEDURES

Daily briefings will be conducted by the Test Controller prior to the commencement of test activities using pre-test checklists in Appendix F.

7.1. Pre-test approvals

All experimental configurations and operations that are outside of the previously approved operating envelope of the SWiFT site must be approved through the Management of Change process (Ref. 3). For this experiment that includes the use of unregulated lasers and the turbine yaw controller software that allows yaw misalignments beyond the OEM limits of +/-18 degrees.

7.2. Setup

The experiment leverages the existing SWiFT meteorological tower and turbine hardware and sensors which are detailed elsewhere. The only unique additional instrumentation for the experiment is the DTU SpinnerLidar. The setup includes the design, manufacturing, and installation of the SpinnerLidar mount and lidar itself into the nacelle of WTGa1. The lidar mount design is detailed in Appendix D, and the lift plan is detailed in Appendix E.

7.3. Alignment and Calibration

The DTU SpinnerLidar will be aligned and calibrated in the test prep lab (Building 350) prior to installation in WTGa1 and then again once installed. The details of this alignment procedure can be found in Reference 4.

7.4. Test Matrix

Data collection will follow the test matrix detailed in Appendix G. The test matrix is divided into bins by three major parameters: turbulence intensity, wind speed, and yaw misalignment angle. Of these three, only the yaw misalignment angle can be prescribed by the experiment staff. The turbulence intensity and wind speed are dependent on the daily weather cycles and will be binned after the data is collected. Based on historical atmospheric statistics, the likelihood for certain wind speeds and turbulence to occur at certain times of the day is known and will be leveraged to prioritize data collection times. For example, low turbulence inflows tend to occur from sunset to sunrise. While turbine operation remains in attended-mode, appropriate staff will be required at atypical work hours (evening through morning) to acquire data at certain test bins.

7.5. Data Collection, Processing and Archive

Daily
All data from the site including the met, turbine, and lidar will be logged and transferred to a network location accessible by Sandia research staff. A daily report will be automatically generate to provide a high-level summary of the previous day's data.

Weekly
Data from the priority data channel list will be processed by the research staff for quality assurance and control. This data will then be shared with external research partners for further analysis in support of the experimental objectives.

End of experiment
At the end of the experiment, raw and processed data will be archived at Sandia. In addition, select data sets of interest for the experiment will be made public through the DOE A2e Data Archive and Portal available at the website: https://a2e.pnnl.gov/projects/wake. Further detail are provided in Appendix J.

7.6. Teardown

Upon the completion of testing, all equipment and materials will be removed from the site and returned to their respective owners. The site will be returned to the pre-test state as much as possible.

8. REPORTING

The reporting requirements for the experiment include:

- Daily reports from the SWiFT Site Supervisor to the PI
- Automated daily data reports generated from the logged data
- Maintenance of the Test Log by the turbine operator when the experiment is active

9. REFERENCES

References to related documents such as equipment spec sheets, technical reports, etc. to support more in-depth test plan understanding

1. Jonathan White, *Sandia SWiFT Facility Site Operations Manual*, SAND2016-0651, Sandia National Laboratories, Albuquerque, NM, January, 2016
2. Christopher L. Kelley, Brandon L. Ennis, *SWiFT Site Atmospheric Characterization*, SAND2016-0216, Sandia National Laboratories, Albuquerque, NM, January 2016
3. Jonathan White, *Sandia SWiFT Site Safe Work Planning Manual*, SAND2016-0857, Sandia National Laboratories, Albuquerque, NM, January, 2016
4. Thomas G. Herges, David C. Maniaci, Brian Naughton, Kasper Hansen, Mikael Sjoholm, Nikolas Angelou, and Torben Mikkelsen. "Scanning Lidar Spatial Calibration and Alignment Method for Wind Turbine Wake Characterization", 35th Wind Energy Symposium, AIAA SciTech Forum, (AIAA 2017-0455)

APPENDIX A: HAZARD ANALYSIS

Overview

Sandia National Laboratories has a corporate procedure for Environmental Safety and Health (ES&H) that provides guidance for performing work in a safe and environmentally responsible manner. A key portion of the ES&H policy is to analyze and control hazards. For the Wake Steering Experiment, there are two different scopes for the ES&H procedures, the Scaled Wind Farm Technology (SWiFT) Facility, and the Wake Steering Experiment itself. The SWiFT Facility already has a comprehensive set of ES&H procedures based on the normal operating envelope of the site. Therefore, for the purposes of the Wake Steering Experiment, only the unique hazards that are added by the planned activities of the experiment need to be analyzed. A preliminary assessment of the Wake Steering experiment identified the use of laser systems (Lidars) and changes to the wind turbine controller as the unique hazards to be analyzed and controlled as needed. These two areas are detailed in the following sections.

Lidar

The primary wake measurement instrument is a custom lidar designed and manufactured by the Technical University of Denmark named the SpinnerLidar. The lidar is based on a commercially available lidar manufactured by ZephIR. The ZephIR has a laser that produces less than 1 W of peak power in wavelengths between 1560 nm and 1565 nm. This laser system is a Class 1 laser according to IEC-60825-1 eye safety standards.

Sandia National Laboratories Corporate Procedure *ESH100.2.IH.7 Evaluate and Control Laser Hazards* applies to all Members of the Workforce who engage in regulated laser activities. The overview of the policy states that only class 3b and class 4 lasers are regulated by Sandia National Laboratories. Class 1 and class 1M lasers are not regulated under corporate policy.

Wind Turbine Controller

The Wake Steering Experiment requires changes to the baseline wind turbine controller, primarily in the yaw system sub-controller. The new control system will apply a bias to the wind direction sensor input to the yaw controller, causing the turbine to operate at an intentional misalignment with respect to the incoming flow direction. The impacts of this controller change to the safety systems and design load envelope of the wind turbines must be analyzed prior to and verified during the experiment. The general approach is to first simulate the yaw cases in an aeroelastic code such as FAST, then to test the impact on the actual controller using a Hardware-in-the-Loop (HIL) system, and finally deploying the new controller in the field with conservative alarms from key sensors and carefully expanding the operating envelope as confidence is built up with respect to experimental versus predicted loads.

Turbine safety systems

All wind turbine safety systems that check the correctness of the wind vane should be based on the unbiased signal, whereas any logic about when to yaw, or what direction to yaw should be based on the biased signal. This controller change has been made successfully in the past on both the NREL CART2 and CART3 wind turbines without incident but will need to be assessed for use on the SWiFT turbines. Potential impacts on the safety systems will be assessed in the software logic and using the HIL test fixture for confirmation.

Turbine operating envelope

The Vestas V27 turbine that serves as the basis for the retrofitted SWiFT turbines had an original design envelope that included an acceptable yaw error of +/- 18 degrees. In addition, Romax Technology was hired to perform an assessment of the load limits of the actual SWiFT turbines to establish a safe operating envelope. The Wake Steering Experiment will include test cases where the turbine spends extended time in yaw misalignments exceeding 18 degrees, and therefore the extreme and fatigue loads incurred in these operating states will require analysis and comparison to the baseline operation as well as the Romax analysis of the load envelope for the turbine.

NREL CART Turbine Analyses

The hazard analysis began with a comparison between experimental and simulated loads on the NREL CART turbines. The CART turbines were operated for many months in yaw misalignment states that will be similar to the cases run on the SWiFT turbines. Experimental loads data were collected from the CART turbines and compared against FAST simulations. Figure 6 through Figure 15 show side-by-side experimental and simulated load values at various key load points at different yaw misalignments and wind speeds. The general trend is that the FAST simulations over-predict the loads, and are therefore a conservative estimate of the anticipated ultimate loads.

The small points in Figure 6 through Figure 10 are computed by binning the data into 45s intervals and for each bin computing a damage equivalent load. The intervals are then binned by mean wind speed and then plotted versus mean yaw alignment. For each alignment bin, a mean and standard deviation is also computed and plotted as a circle with bars. For Figure 11 through Figure 15 the standard deviation (not DEL since it is not a load) of the CART3 inertial measurement unit (IMU) are plotted. Only x (fore-aft) and y (side-side) acceleration were included in the FAST load suite. The IMU is mounted on the front thrust bearing of the CART3 and increase in standard deviation indicates an increasing vibration.

The general observation is that for many signals, small to no change would be expected. IMU-Y yaw and roll show some tendency to increase, however in regimes where there is a good amount of data, the change seems limited to about 10% at 30 degrees.

The FAST simulation and CART3 experimental results demonstrate that one direction of misalignment tends to increase loads, whereas the other decreases it which is consistent with literature on the subject (c.f. [Kragh2013]). In the wind speed range up to rated power (12.5 m/s for the CART3), the change in loads vs baseline in positive and negative misalignment are about +10% and -10%. For the Wake Steering Experiment, the SWiFT turbine WTGa1 will spend roughly equal time at equivalent positive and negative yaw misalignments, and therefore it is expected that the net change in loads overall will be near zero vs baseline operation, with fatigue loads being a possible exception. Above rated, FAST begins to predict a change in the pattern (again, matching predictions from [Kragh2013]), however it is difficult to see much pattern at all in the field data from the CART3 and there are no plans to operate the SWiFT turbine at those wind speeds for extended periods of time.

SWiFT Turbine Analysis

The next analysis step was to perform a loads analysis for the SWiFT turbines with the V27 rotor. These simulations were performed using the wind turbine aeroelastic simulator FAST and the V27 reference model produced by the SNL wind energy department [REF?]. The loads analysis performed was in accordance with the IEC 61400-1 Ed. 3 wind turbine design standard, using the power production (IEC DLC 1.x) and extreme case, parked (IEC DLC 6.x) design load cases. Loads exceedance is defined where the simulation loads exceed known strengths for the machine, or, in the absence of known strengths, where the loads from the experiment's simulations exceed the baseline set of simulations for normal operation of the SWiFT turbine. Specific, ultimate loads were obtained by a previous analysis of the SWiFT turbine performed by Romax.

The baseline set of simulations is meant to represent the design loads of the SWiFT turbine, as would be experienced at the SWiFT site, an IEC class III-C wind site. The **baseline loads analysis** was performed with the following:

- wind speeds from 0 - 25 m/s in 1 m/s steps
- yaw misalignment from -18 - 18 degrees in 2 degree steps
- SWiFT turbine Simulink production controller, but with no yaw controller
- 12 turbulent wind seeds

This load set was compared to that for the proposed experimental campaign to understand the limits of operation. After a few iterations, the following parameters were used for the **experimental loads analysis**:

- wind speeds from 0 - 15 m/s in 1 m/s steps
- yaw misalignment from -40 - 40 degrees in 5 degree steps
- SWiFT turbine Simulink production controller, with the experimental center-seeking yaw controller
- 12 turbulent wind seeds

The analysis compared critical loads, including:

- Blade root bending moments
- Blade spanwise forces/moments, and resulting blade strain
- Blade tip deflection and tower clearance
- Low speed shaft bending moments and torque
- Nacelle overturning moments
- Yaw bearing forces and yaw moment
- Tower base bending moments
- Extrapolated 50-year loads
- Blade fatigue analysis

This analysis has some known assumptions and limitations. The baseline loads analysis did not utilize a yaw controller which means there may be some cases in the turbulent wind simulations (DLC 1.2 and 1.3) where the SWiFT turbine would have in reality yawed towards the actual wind direction. The SWiFT V27 controller was designed to only yaw when the filtered, averaged wind direction reading was outside of the +/- 18 degree bounds so this is not considered to be a substantial deviation from the conditions experienced in the operational life of the machine. Additionally, the full set of alarms were not used in either of the simulation sets and the DLC 2.x simulations were not performed in the comparison which would test power production operation plus fault detection which could increase the loads. The resulting maximum loads from DLC 1.x were all from either DLC 1.3 or DLC 1.4, which are models that aren't tested in the DLC 2.x load cases. This gives confidence that the DLC 2.x load cases would likely not produce higher loads than the simulated design load cases.

Limitations of this analysis come in from the FAST simulation models which are not intended to be used with high yaw errors. This is particularly true for the Prandtl tip loss wake model, which can be replaced using the generalized dynamic wake (GDW) model that is recommended for high yaw errors. The two models were compared for the extreme operating gust with direction change case (DLC 1.4) to understand how they perform and the loads compare. The load magnitude was seen to be comparable when using the two wake models, but the GDW model produced frequencies that seemed to be purely numerical and therefore was not trusted for the final loads comparison. An additional model that was tested was the Beddoes-Leishman dynamic stall model, which operates on airfoils pitching relative to the wind in a manner that affect the forces produced. This model was tested for the DLC 1.4 design load case as well and it was found to not affect the maximum loads for these cases. The dynamic stall model was used for all of the simulations.

Before describing the results, attention will be given to the coordinate system used in FAST and the coordinate system for the SWiFT site as regards yaw error. The two coordinate systems are shown for the same flow case in Figure 1. The coordinate definition at the site and used internally in FAST have the same convention for yaw misalignment, γ, but reach that same convention with opposite conventions for positive yaw commands. FAST uses a positive z_n-rotation to define positive yaw (CCW), and the site uses the conventional atmospheric definition of wind direction for positive yaw (CW). The opposite definition of positive yaw produces the same direction of yaw misalignment through differing reference definition, where the reference in the FAST convention is the wind direction and the reference in the SWiFT convention is the nacelle heading.

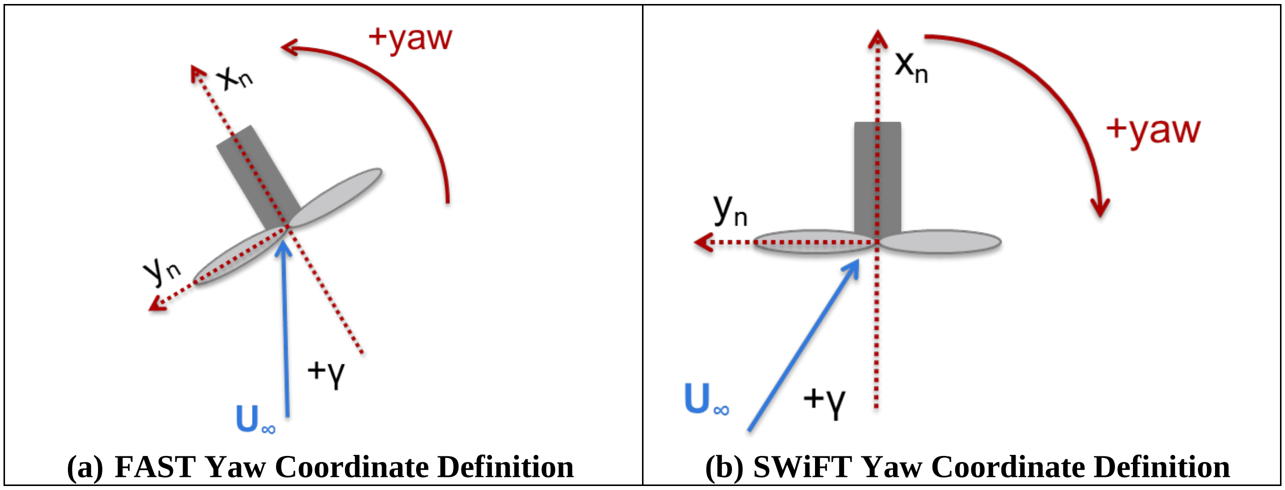

Figure 4. Yaw Coordinate System Definition.

A summary table containing the known design strengths of the SWiFT machines and the simulated loads for the baseline and experimental cases is shown in Table 1. The baseline and experimental design loads are all within the known design strengths. The design strength for Blade Root Bending produces the limitation for the wake steering experiment wind speed to not exceed 15 m/s, at 40 degree yaw. This wind speed limitation can be revisited with a reduced yaw misalignment simulation.

Table 1. SWiFT Machine Design Strengths and Loads Analysis.

Load Direction	**Design Strength**	**SWiFT Rotor Design Loads**	**SWiFT yawed case 3**
Blade Root Bending	210 kN-m	191.0 kN-m (DLC 1.3 ETM; 13 m/s, -18 deg yaw)	209.9 kN-m (DLC 1.3 ETM; 14 m/s, -40 deg yaw)
Blade Tip Deflection	1.97 m	1.01 m (DLC 1.3 ETM, 18 m/s, -18 deg yaw)	1.05 m (DLC 1.3 ETM, 15 m/s, 35 deg yaw)
Tower Base Moment (S-S)	4510 kN-m	1388.4 kN-m (DLC 6.1 EWM50, 15 deg)	1388.4 kN-m (DLC 6.1 EWM50, 15 deg yaw)
Tower Base Moment (F-A)	4510 kN-m	1747.3 kN-m (DLC 1.3 ETM, 17 m/s, 16 deg yaw)	1638.5 kN-m (DLC 1.3 ETM, 13 m/s, 10 deg yaw)

The remainder of the loads that were compared do not have corresponding known design strength values. The process for these loads was to identify which experimental loads are greater than the baseline loads and then to determine if this exceedance was of concern, and, if so, to determine a mitigation route. A summary table of a subset of the loads pertaining to the yaw bearing is shown in Table 2. This table highlights the two resulting loads that were of concern for the experiment, nacelle overturning moment (AmplYawBrMxnMyn) and the nacelle yaw moment (YawBrMzn), that exceed the baseline loads. A more complete summary of the loads exceeded that were still deemed safe can be found in Ref 2.

Table 2. Yaw Loads Comparison (Loads Ratio; Experimental Loads; Baseline Loads).

DLC Name	MaxYawBrFxn	in File
Ratio: yaw/orig	0.977556296	n/a
IECDLC1p3ETM	51.203475	out/IECDLC1p3ETM_yaw-40_15mps_seed6.out
IECDLC1p3ETM	52.379055	out/IECDLC1p3ETM_yaw16_14mps_seed8.out
DLC Name	MinYawBrFxn	in File
Ratio: yaw/orig	1.245584721	n/a
IECDLC1p4ECD	-38.84625	out/IECDLC1p4ECD_yaw-40_ECD-R-2.0.out
IECDLC1p3ETM	-31.18716	out/IECDLC1p3ETM_yaw-18_6mps_seed2.out
DLC Name	MaxYawBrFyn	in File
Ratio: yaw/orig	1	n/a
IECDLC6p2EWM50	36.91611	out/IECDLC6p2EWM50_EWM50-80.out
IECDLC6p2EWM50	36.91611	out/IECDLC6p2EWM50_EWM50-80.out
DLC Name	MinYawBrFyn	in File
Ratio: yaw/orig	1	n/a
IECDLC6p1EWM50	-44.28891	out/IECDLC6p1EWM50_EWM50+15.out
IECDLC6p1EWM50	-44.28891	out/IECDLC6p1EWM50_EWM50+15.out
DLC Name	MaxYawBrMxn	in File
Ratio: yaw/orig	1	n/a
IECDLC6p2EWM50	170.5539	out/IECDLC6p2EWM50_EWM50+95.out
IECDLC6p2EWM50	170.5539	out/IECDLC6p2EWM50_EWM50+95.out
DLC Name	MinYawBrMxn	in File
Ratio: yaw/orig	1	n/a
IECDLC6p2EWM50	-162.5756	out/IECDLC6p2EWM50_EWM50-80.out
IECDLC6p2EWM50	-162.5756	out/IECDLC6p2EWM50_EWM50-80.out
DLC Name	MaxYawBrMyn	in File
Ratio: yaw/orig	0.828966181	n/a
IECDLC1p3ETM	165.1563	out/IECDLC1p3ETM_yaw-40_15mps_seed9.out
IECDLC1p3ETM	199.23165	out/IECDLC1p3ETM_yaw18_25mps_seed10.out
DLC Name	MinYawBrMyn	in File
Ratio: yaw/orig	1.560793979	n/a
IECDLC1p4ECD	-239.3739	out/IECDLC1p4ECD_yaw-40_ECD-R.out
IECDLC1p3ETM	-153.36675	out/IECDLC1p3ETM_yaw-18_25mps_seed5.out
DLC Name	AmplYawBrMxnMyn	in File
Ratio: yaw/orig	1.092557968	n/a
IECDLC1p4ECD	240.9494779	out/IECDLC1p4ECD_yaw-40_ECD-R.out
IECDLC1p3ETM	220.5370194	out/IECDLC1p3ETM_yaw18_25mps_seed3.out
DLC Name	MaxYawBrMzn	in File
Ratio: yaw/orig	1.112414757	n/a
IECDLC1p3ETM	125.193465	out/IECDLC1p3ETM_yaw-35_13mps_seed1.out
IECDLC1p3ETM	112.542075	out/IECDLC1p3ETM_yaw0_25mps_seed11.out
DLC Name	MinYawBrMzn	in File
Ratio: yaw/orig	1.033010417	n/a
IECDLC1p3ETM	-139.104	out/IECDLC1p3ETM_yaw40_14mps_seed10.out
IECDLC1p3ETM	-134.658855	out/IECDLC1p3ETM_yaw-18_25mps_seed3.out

From this comparison, the Nacelle Overturning Moment design load (including the IEC specified safety factor) is seen to increase from 220 kN-m to 240 kN-m as a result of the intentional yaw misalignment. This extreme load is compared further in Table 3 which shows the maximum load case for each DLC for the two simulation sets. From this detailed comparison, it is seen that the only design load case that produces a higher load than the baseline case is DLC 1.4, the extreme gust with direction change simulation. For this design load case combined with high yaw misalignment the wind direction actually shifts to where it is coming from behind the rotor and produces a negative rotor thrust that gets added to negative overturning moment contributions from the rotor moment and the nacelle/rotor weight induced moment.

Table 3. Nacelle Overturning Moment.

(a) Experimental Loads Analysis

DLC Name	AmplYawBrMxnMyn	with Safety Factor	in File
IECDLC1p2NTM	113.00	152.55	out/IECDLC1p2NTM_yaw-40_15mps_seed9.out
IECDLC1p3ETM	127.71	172.41	out/IECDLC1p3ETM_yaw-40_15mps_seed9.out
IECDLC1p4ECD	178.48	240.95	out/IECDLC1p4ECD_yaw-40_ECD-R.out
IECDLC1p5EWS	96.11	129.75	out/IECDLC1p5EWS_yaw30_EWSV+20.0.out
IECDLC6p1EWM50	117.98	159.27	out/IECDLC6p1EWM50_EWM50-05.out
IECDLC6p2EWM50	158.73	174.61	out/IECDLC6p2EWM50_EWM50+95.out
IECDLC6p3EWM01	77.46	104.57	out/IECDLC6p3EWM01_EWM01-05.out

(b) Baseline Loads Analysis

DLC Name	AmplYawBrMxnMyn	with Safety Factor	in File
IECDLC1p2NTM	153.19	206.80	out/IECDLC1p2NTM_yaw16_24mps_seed2.out
IECDLC1p3ETM	163.36	220.54	out/IECDLC1p3ETM_yaw18_25mps_seed3.out
IECDLC1p4ECD	118.20	159.56	out/IECDLC1p4ECD_yaw-16_ECD+R+2.0.out
IECDLC1p5EWS	91.77	123.89	out/IECDLC1p5EWS_yaw18_EWSV+20.0.out
IECDLC6p1EWM50	117.98	159.27	out/IECDLC6p1EWM50_EWM50-05.out
IECDLC6p2EWM50	158.73	174.61	out/IECDLC6p2EWM50_EWM50+95.out
IECDLC6p3EWM01	77.46	104.57	out/IECDLC6p3EWM01_EWM01-05.out

To gain understanding of how to mitigate this particular load, the DLC 1.4 simulation results are shown in Figure 2. This figure shows the loads results for the simulation set which combines the IEC wind input files and the tested yaw misalignment values. It is observed that positive yaw misalignment values are not of concern for this load, and can go up to and possibly beyond +40 deg. This result is caused by the moment due to the wind shear generated rotor load imbalance moment opposing the other two contributions to the overturning moment. For negative yaw misalignment values the loads need to remain within the characteristic load (no safety factor) for the baseline case shown in Table 3 of 163.4 kN-m. In order to satisfy the requirement of staying within the baseline loads the yaw misalignment can have a maximum negative value of -25 deg.

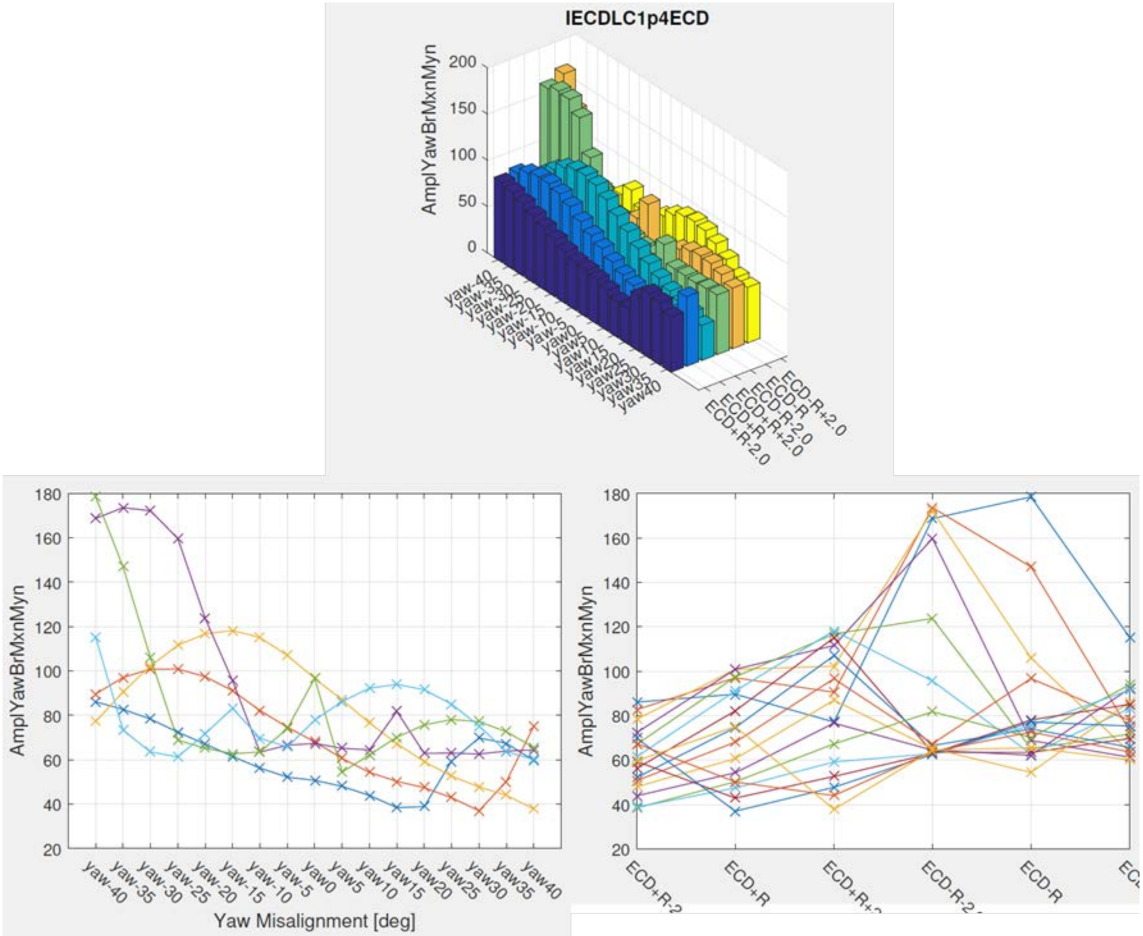

Figure 2. Experimental Loads Case, Nacelle Overturning Moment from DLC 1.4.

The same analysis procedure was performed for the second load of concern, the nacelle yaw moment (YawBrMzn). This load is of lesser concern as the experimental loads analysis revealed only a 3% increase in the load, and because failure would not be catastrophic. Regardless, in order to reduce the nacelle yaw moment from the experimental loads to being within the baseline case an additional limit is placed on the experimental campaign of not exceeding -30 deg yaw or +25 deg yaw misalignment. The detailed loads results for this variable can be found in Ref 2.

The resulting loads for the experimental case further reduced the suggested operating window from previously described to remain within the baseline load values, and the <u>safe experimental operating region is recommended as follows</u>:

- wind speeds from 0:1:15 m/s
- yaw misalignment from -25 to +25 degrees

If it is later decided to allow exceedance from the baseline loads then this window can be opened up beyond the yaw limits, however, the wind speed limit was based on blade root bending moment (although, at +/- 40 deg yaw). Additional support may be derived from some Vestas design documents which analyze loads (loads, not strength) at a site where V27 turbines were known to be installed and operated which are significantly greater than the loads found from the preceding analysis.

An additional analysis was performed looking at the effect of alarms on the nacelle overturning moment. The center-seeking controller as it was implemented in the simulations had options for a ‘fast’ and ‘slow’ wind direction error alarms, where once the calculated wind direction relative to the turbine exceeded certain set points it would send the turbine into an alarm state. Simulations were performed testing ‘stop’ and ‘pause’ states at different set points for the ‘fast’ wind direction alarm. The analysis revealed that the ‘fast’ alarm, in some cases, actually caused the otherwise acceptable load to increase beyond what was seen in the baseline case, making this alarm more dangerous than not having it. Additionally, Vestas did not have a ‘fast’ wind direction error alarm in their original controller provided to Sandia. As a result of this analysis, it is determined that the ‘fast’ wind direction alarm should not be implemented as it can potentially increase the loads for the otherwise acceptable limits described above. This analysis is shown in greater detail in Ref 2.

SWiFT Turbine Hardware-in-the-Loop (HIL) Analysis

Prior to deploying the new software controller to the turbine, the dynamic behavior of the controller must be tested using the Hardware-in-the-loop turbine simulator. This analysis captures more realistic dynamic responses of the turbine controller and key hardware.

The SWiFT Turbine yaw controller is being converted to a center-seeking control strategy developed by NREL. The previous SWiFT Turbine yaw controller had been implemented with logic from the V27 OEM controller which would yaw when the filtered yaw error was more than 18 degrees. Filtering was exponential smoothing with a time constant that would change based on whether the yaw drive was active. The time constant was 100 seconds while not yawing but it would switch to 10 seconds while yawing. The OEM controller would stop yawing when the filtered yaw error was less than 18 degrees, meaning that the turbine would typically not return all the way to 0-degree yaw error.

The center-seeking yaw controller developed by NREL estimates the current wind direction and yaws to the position which should bring the yaw error to 0 degrees. The new yaw controller is also able to create a specified yaw offset (intentional yaw error) for the purpose of studying wake dynamics. The new yaw controller logic will start yawing when the accumulated error reaches a threshold called ‘yawIncThreshold’. The accumulated error is calculated by squaring the yaw error, multiplying by the original sign of the error, and then summing the signed-square-error over time. For example, if yawIncThreshold=30e3 and there is a constant 10-degree error, then the turbine will begin yawing after 30e3 / (10^2) = 300 seconds or 5 minutes. If there is a constant 18-degree error with the same threshold, then the turbine will begin yawing after 30e3 / (18^2) = 92.6 seconds. After the threshold has been reached, the control logic stores the current estimate of the wind direction and yaws until it reaches this direction. The wind direction estimate is calculated by exponential smoothing with a time constant of 60 seconds. To be clear, the yaw controller uses the raw measured wind direction to calculate accumulated error and uses the exponentially smoothed wind direction to calculate how much to yaw.

The following figures show how the two controllers respond to ramping wind direction. The yaw drive's yaw rate is about 34 deg/min and therefore will be able to keep pace with wind ramping 30 degrees in 60 seconds.

First example: starting at 0-degree yaw error, wind ramping 30 degrees in 60 seconds

OEM yaw controller begins yawing 123 seconds after the ramp begins and stops with a yaw error of 13.5 degrees.

The new yaw center-seeking yaw controller responds more quickly for every value of yawIncThreshold that was tested. With yawIncThreshold=60e3, the new controller begins yawing 107 seconds after the ramp begins and stops with a yaw error of 8.5 degrees (which is eventually zeroed out after another 850 seconds). With yawIncThreshold=10e3, the new controller is able to keep the yaw error below 25 degrees. In the OEM yaw controller, an alarm would trigger if the yaw error was above 25 degrees and the wind speed was above 8 m/s.

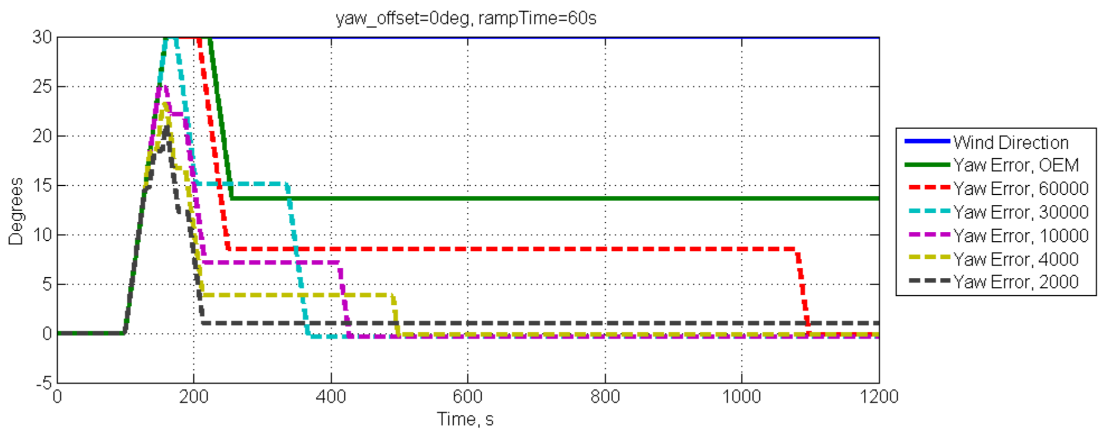

Figure 5. First example

Second example: starting at 0-degree yaw error, wind ramping 30 degrees in 120 seconds

OEM yaw controller begins yawing 157 seconds after the ramp begins and stops with a yaw error of 13.5 degrees. With yawIncThreshold=10e3, the new controller is able to keep the yaw error below 25 degrees.

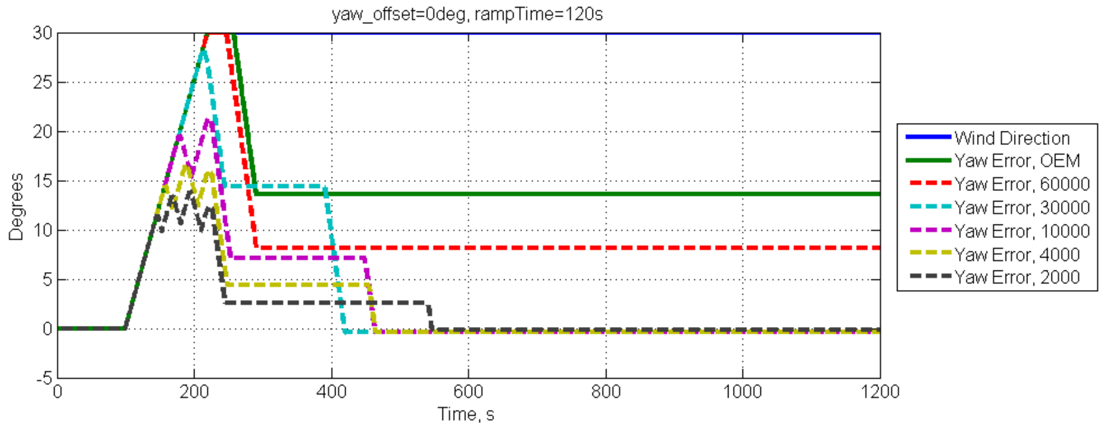

Figure 6. Second example

Third example: starting at 17-degree yaw error, wind ramping 30 degrees in 60 seconds, new controller has 10-degree yaw offset target

OEM yaw controller begins yawing 20.8 seconds after the ramp begins, reaches a maximum error of 27.5 degrees, and reduces the yaw error to 13.2 degrees within 88 seconds.

With yawIncThreshold=60e3, the new controller begins yawing 58 seconds after the ramp begins and reaches a maximum yaw error of 46 degrees.

With yawIncThreshold=2e3, the new controller is able to correct for the initial 17-degree error quickly and hold the specified 10-degree yaw offset. When the ramp occurs, the new controller begins yawing 24.6 seconds after the ramp begins, reaches a maximum error of 31 degrees, and reduces the yaw error to 11 degrees within 113 seconds.

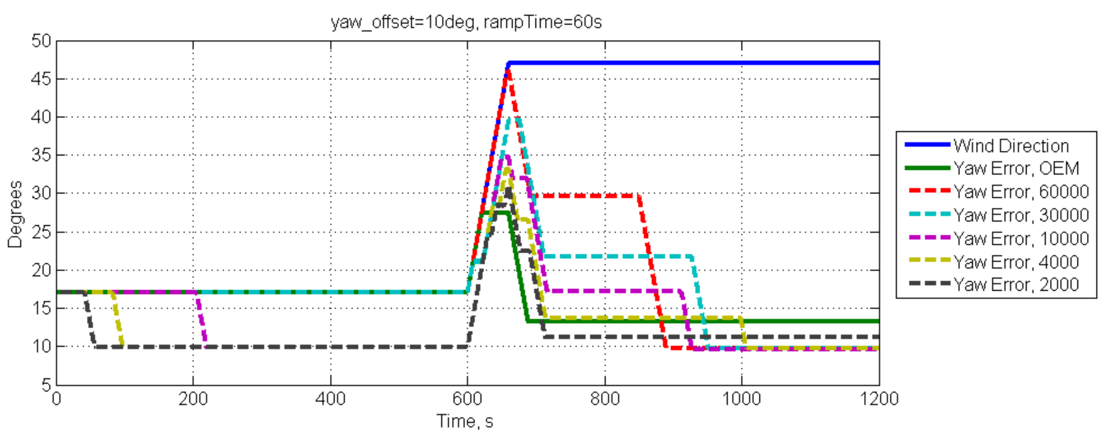

Figure 7. Third example

Fourth example: starting at 17-degree yaw error, wind ramping 30 degrees in 60 seconds, new controller has 15-degree yaw offset target

Same as third example, OEM yaw controller begins yawing 20.8 seconds after the ramp begins, reaches a maximum error of 27.5 degrees, and reduces the yaw error to 13.2 degrees within 88 seconds.

With yawIncThreshold=60e3, the new controller begins yawing 95 seconds after the ramp begins and reaches a maximum yaw error of 47 degrees.

With yawIncThreshold=2e3, the new controller is able to correct for the initial 17-degree error and hold the specified 15-degree yaw offset. When the ramp occurs, the new controller begins yawing 29.2 seconds after the ramp begins, reaches a maximum error of 35.7 degrees, and reduces the yaw error to 15.4 degrees (target yaw offset) within 117 seconds.

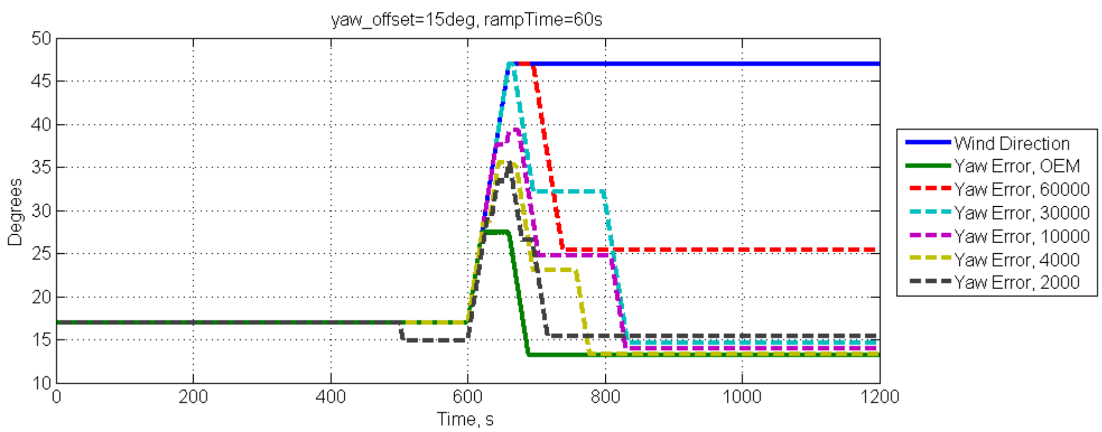

Figure 8. Fourth example

The new yaw center-seeking yaw controller responds more slowly in these ramping wind scenarios if a yaw offset has been enabled. With a 15-degree yaw offset and 25-degree yaw error, the effective error is only 10 degrees. With yawIncThreshold=2e3, a constant 25-degree yaw error triggers a response in 3.2 seconds whereas a constant 10-degree effective yaw error triggers a response in 20 seconds.

<u>Load Monitoring with new controller</u>

The new control software will be deployed in two phases to build experience with the new behavior and to verify simulations at low yaw offset angles prior to testing beyond the original limits of the original controller.

Phase I will limit the allowable offsets to +/- 18 degrees, the same limits of the original controller. During this phase, the loads and alarms on the turbine will be monitored and compared against the FAST simulations. After a sufficient amount of data has been collected, a review will take place prior to expanding the operating window.

Phase II will open up the allowable yaw offset to +/- 25degrees to capture the full range of desired test bins. Additional instrumentation may be added such as current meters on the yaw drives to estimate yaw torque loads, but is not required for safety purposes. Loads will continue to be monitored as the yaw angles increase.

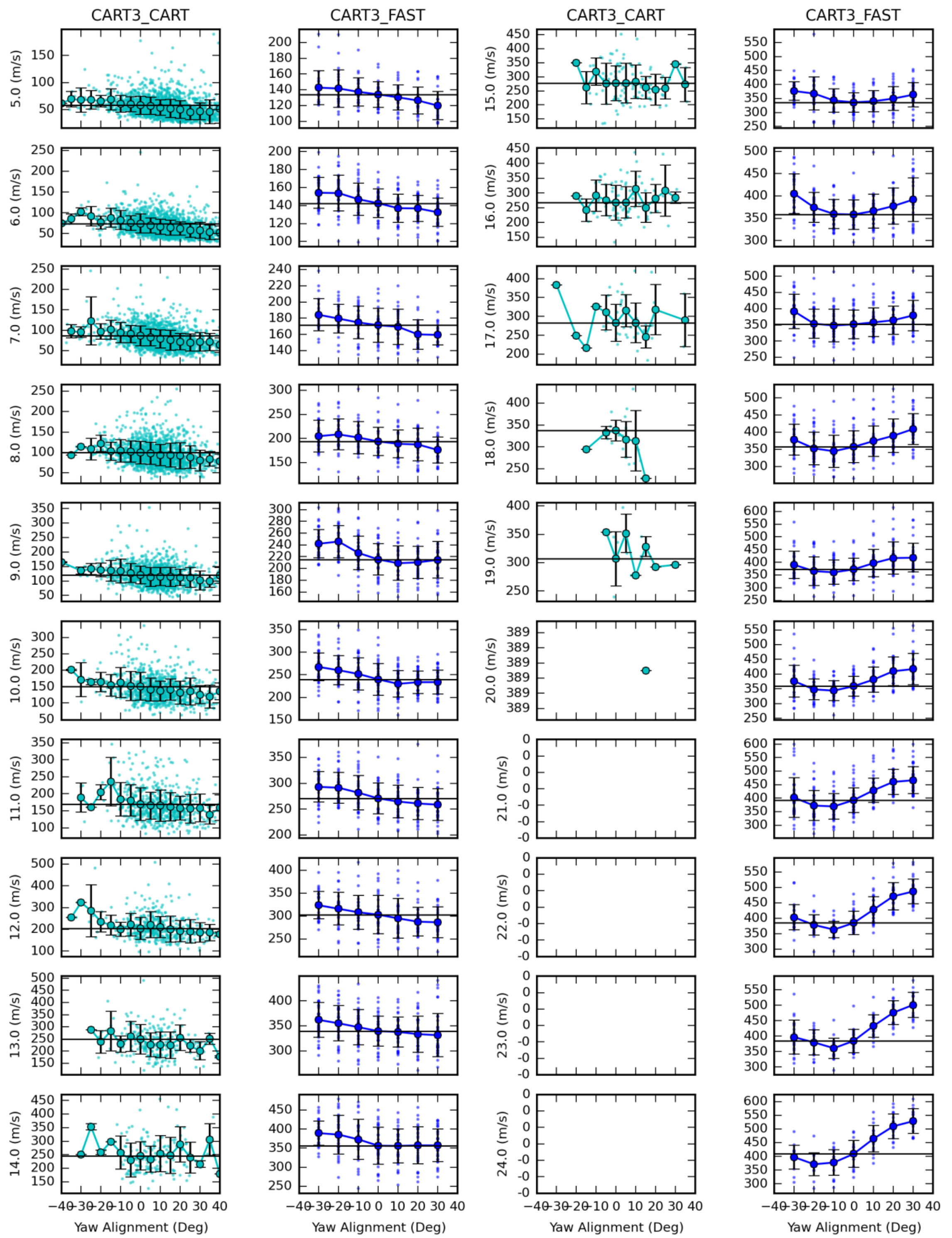

Figure 9: Flap Bending for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

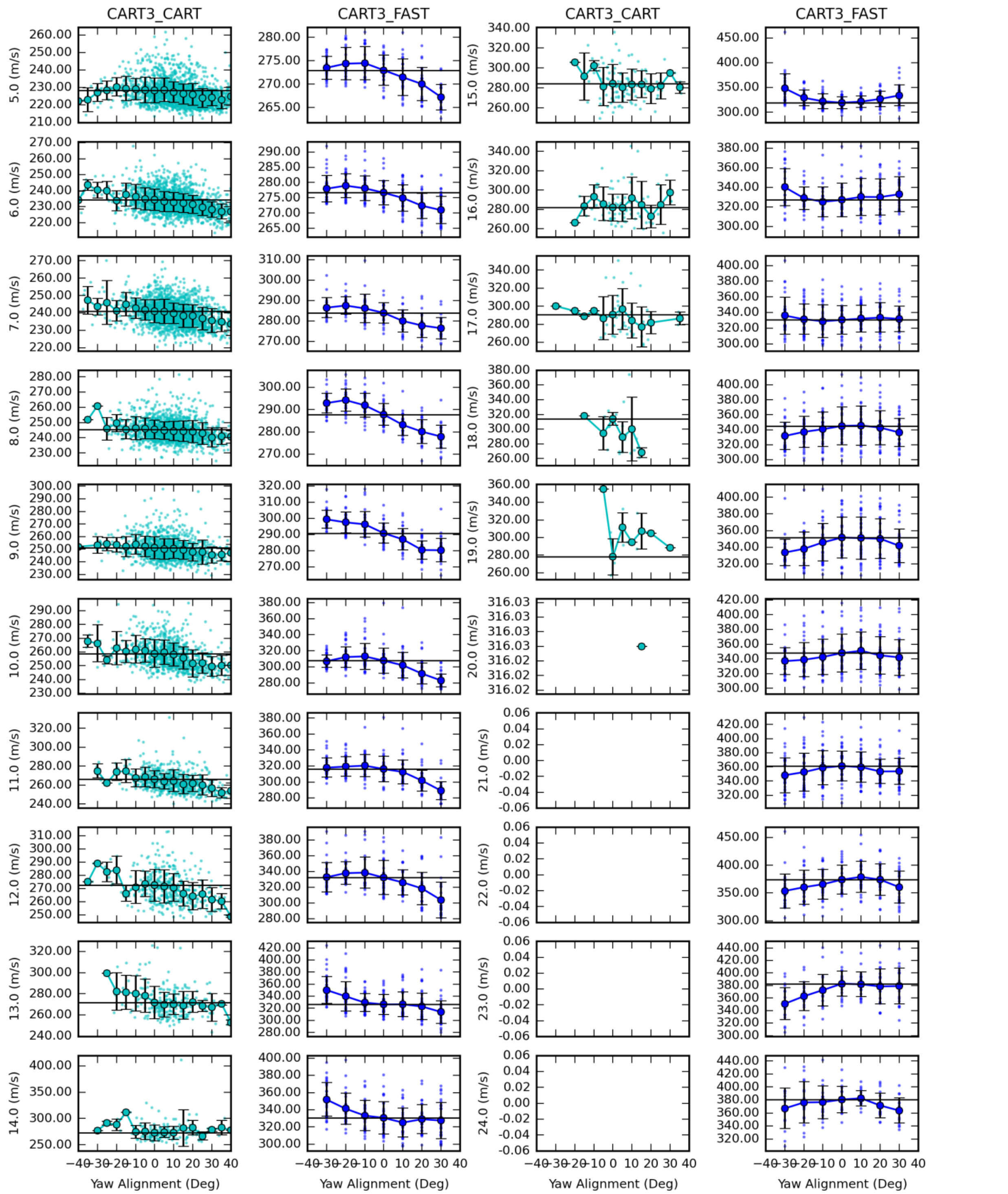

Figure 10: Bladed Edge Bending for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

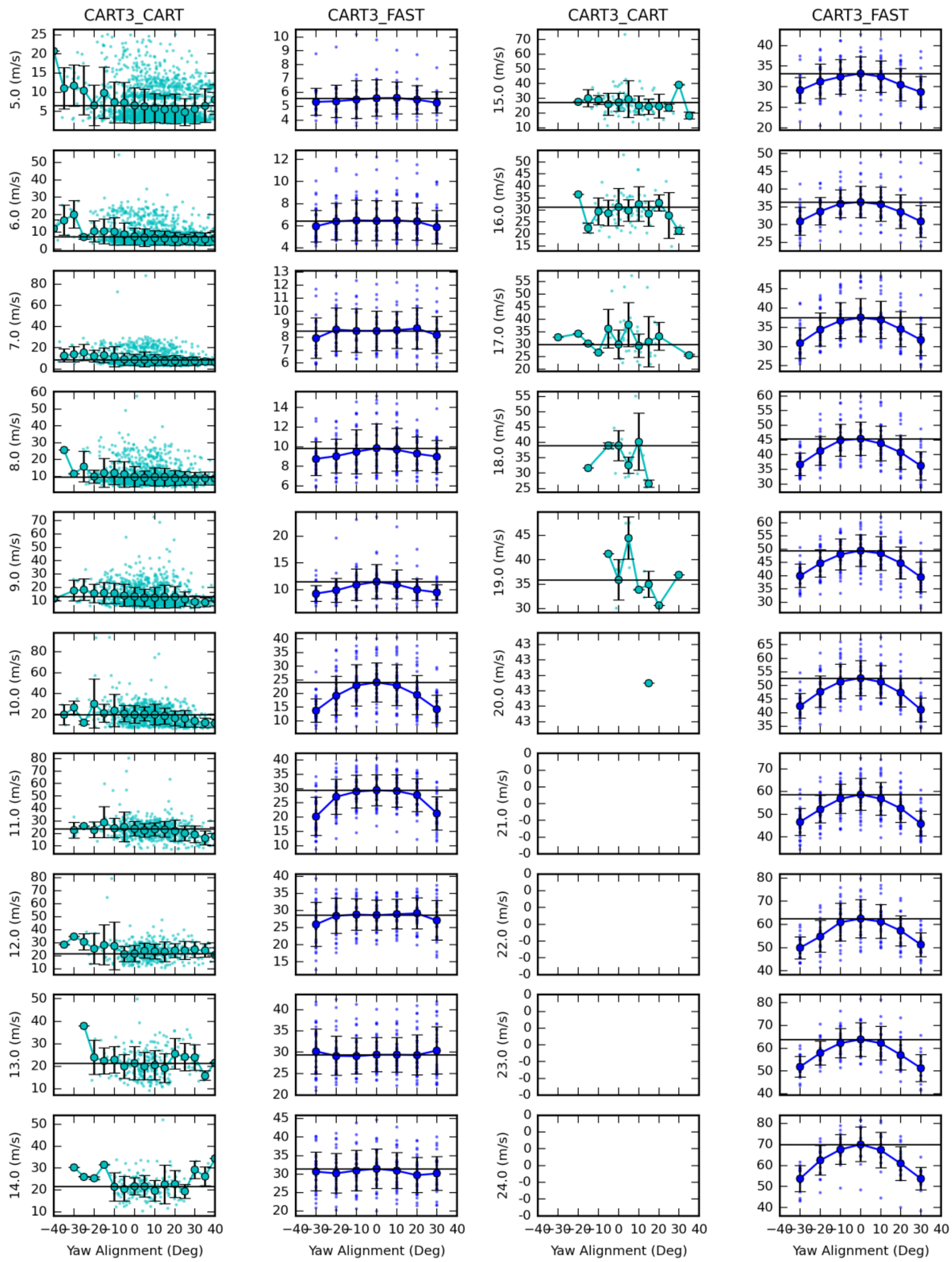

Figure 11: LSS Torque for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

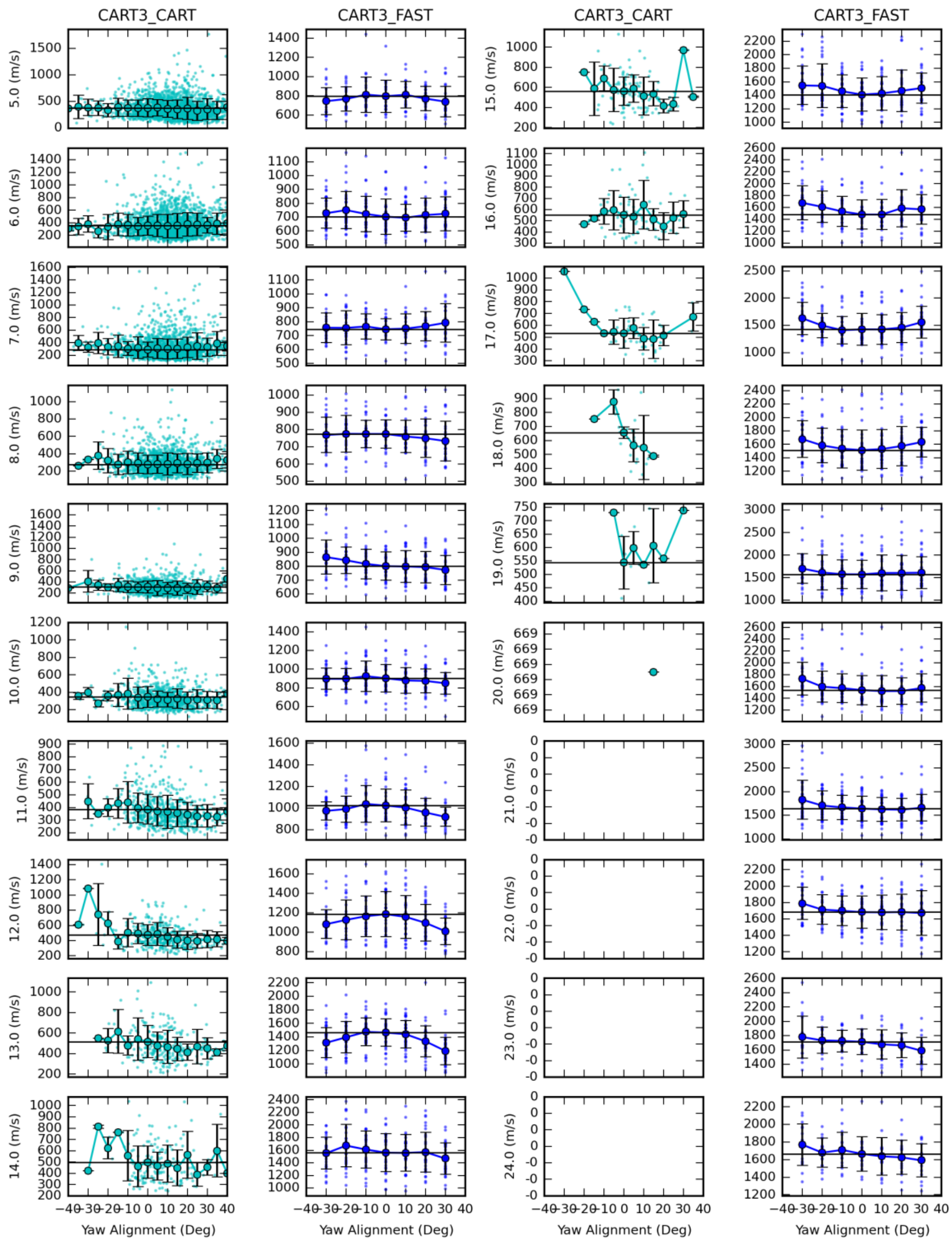

Figure 12: Tower Fore-Aft Bending for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

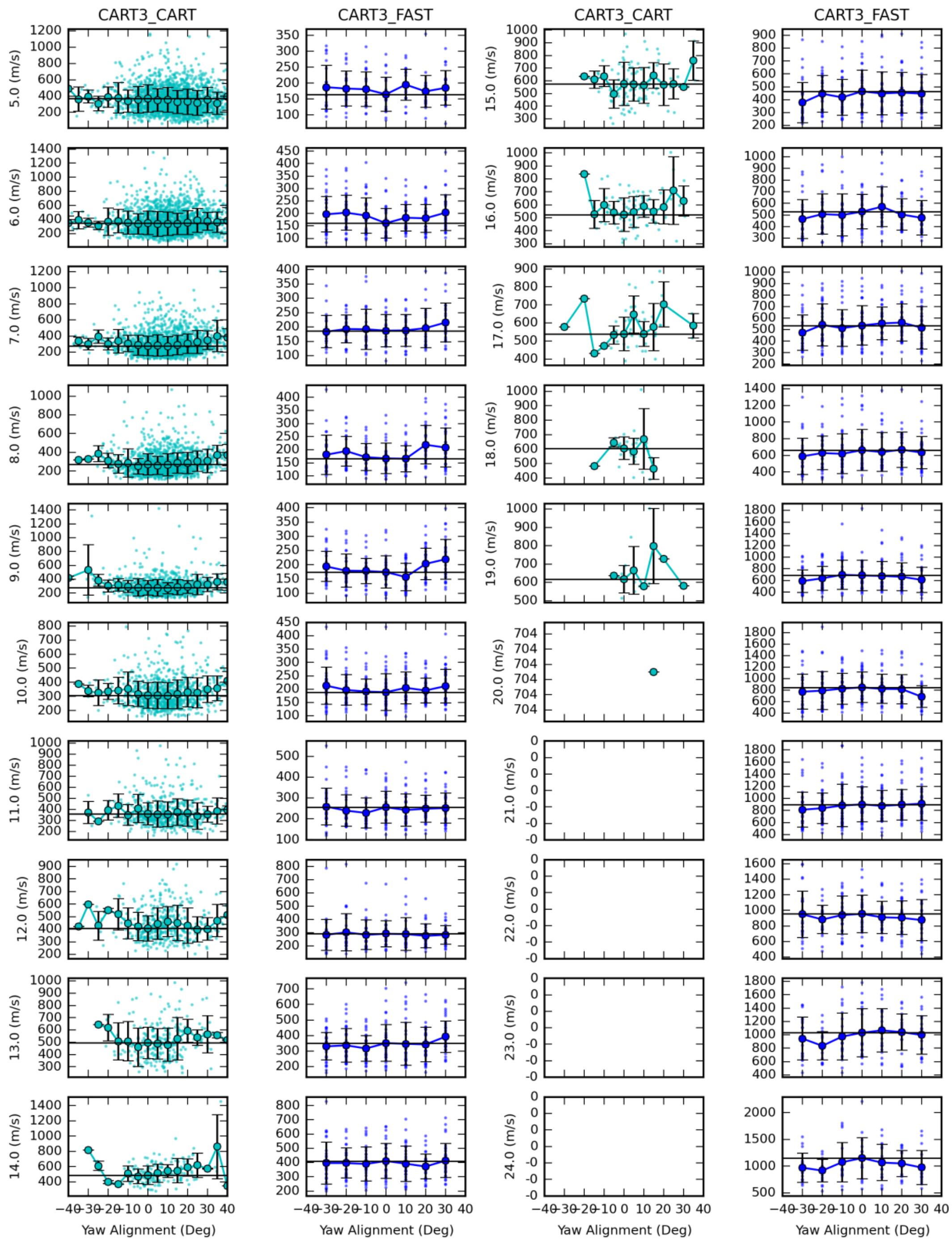

Figure 13: Side-side bending for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

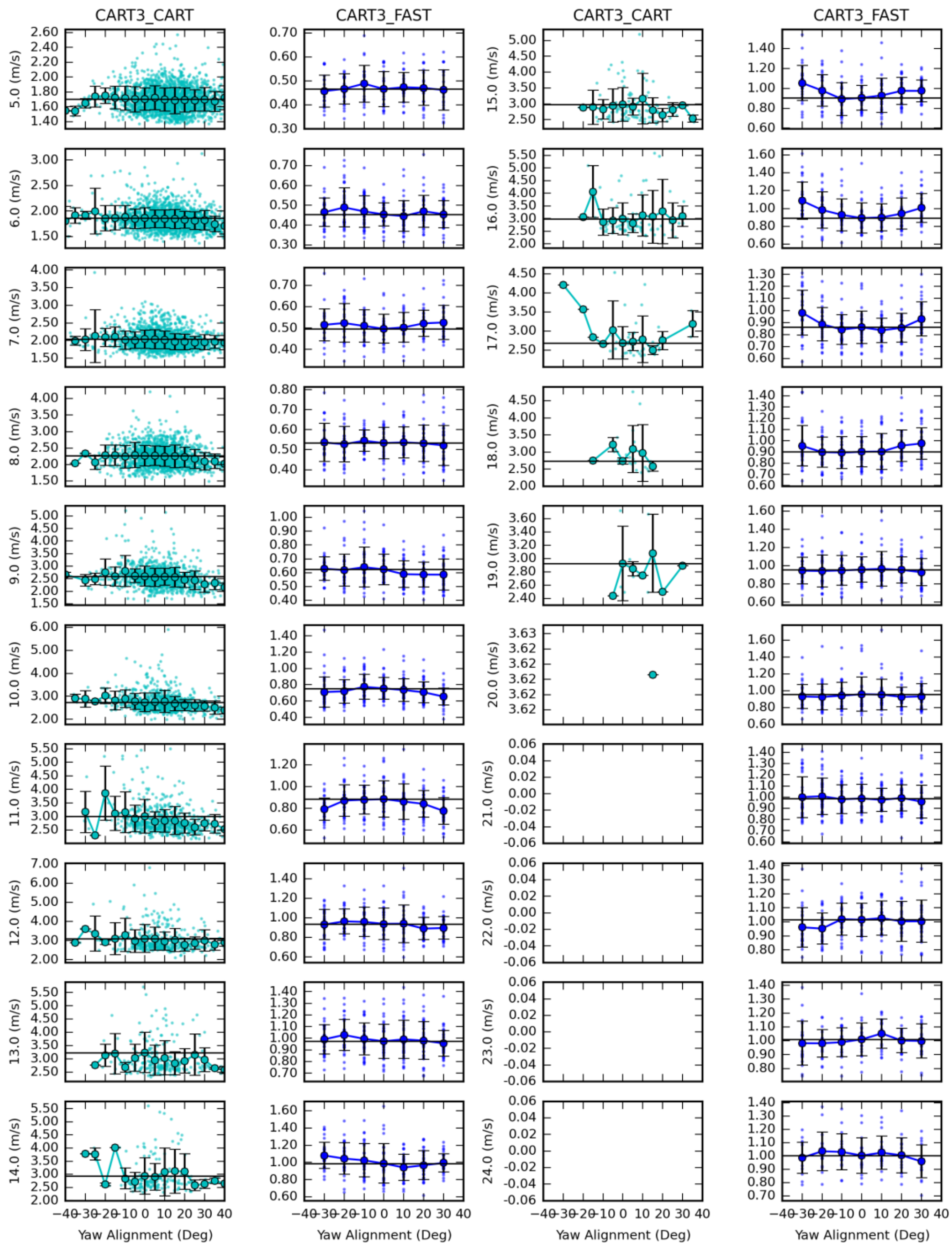

Figure 14: IMU X for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

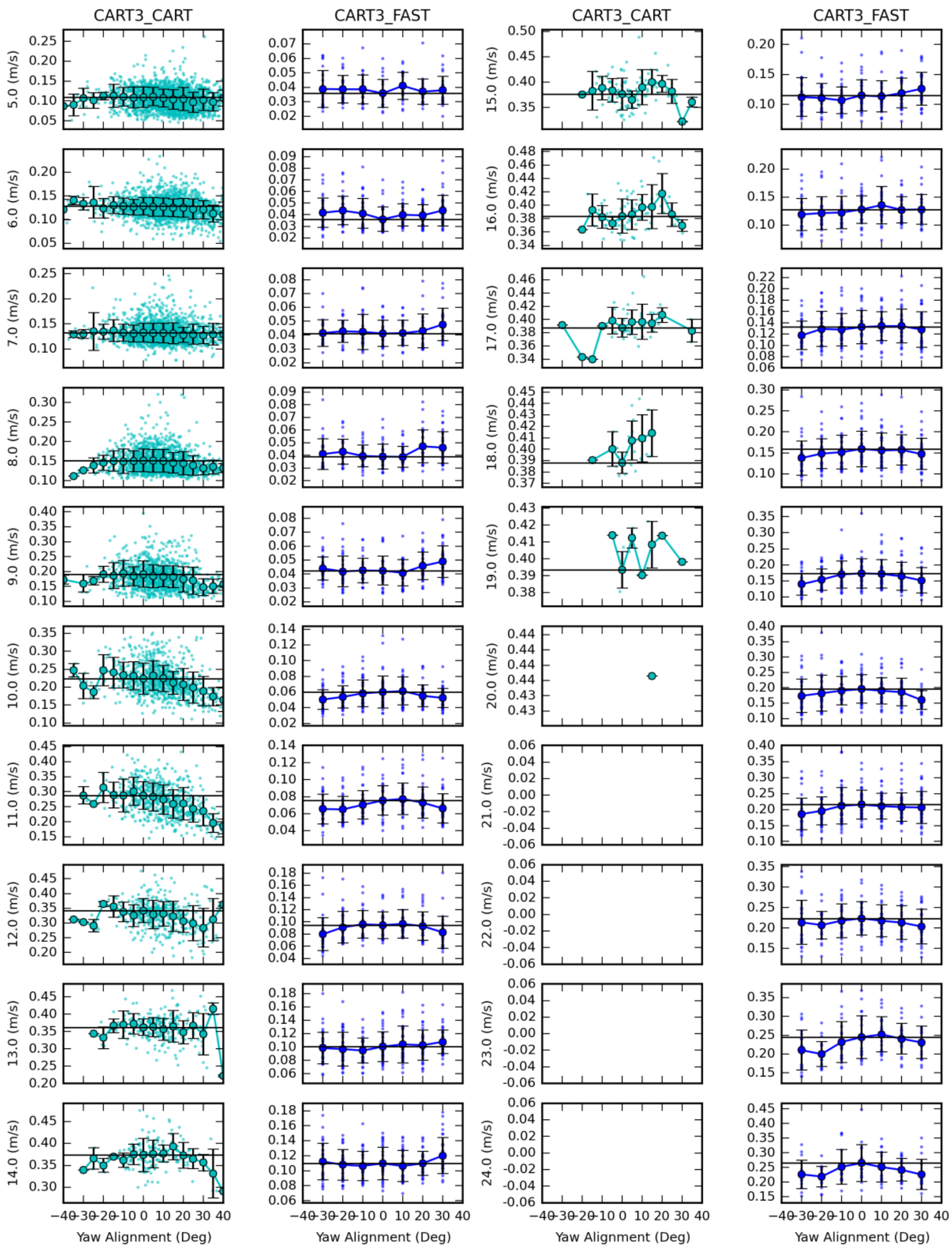

Figure 15: IMU Y for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

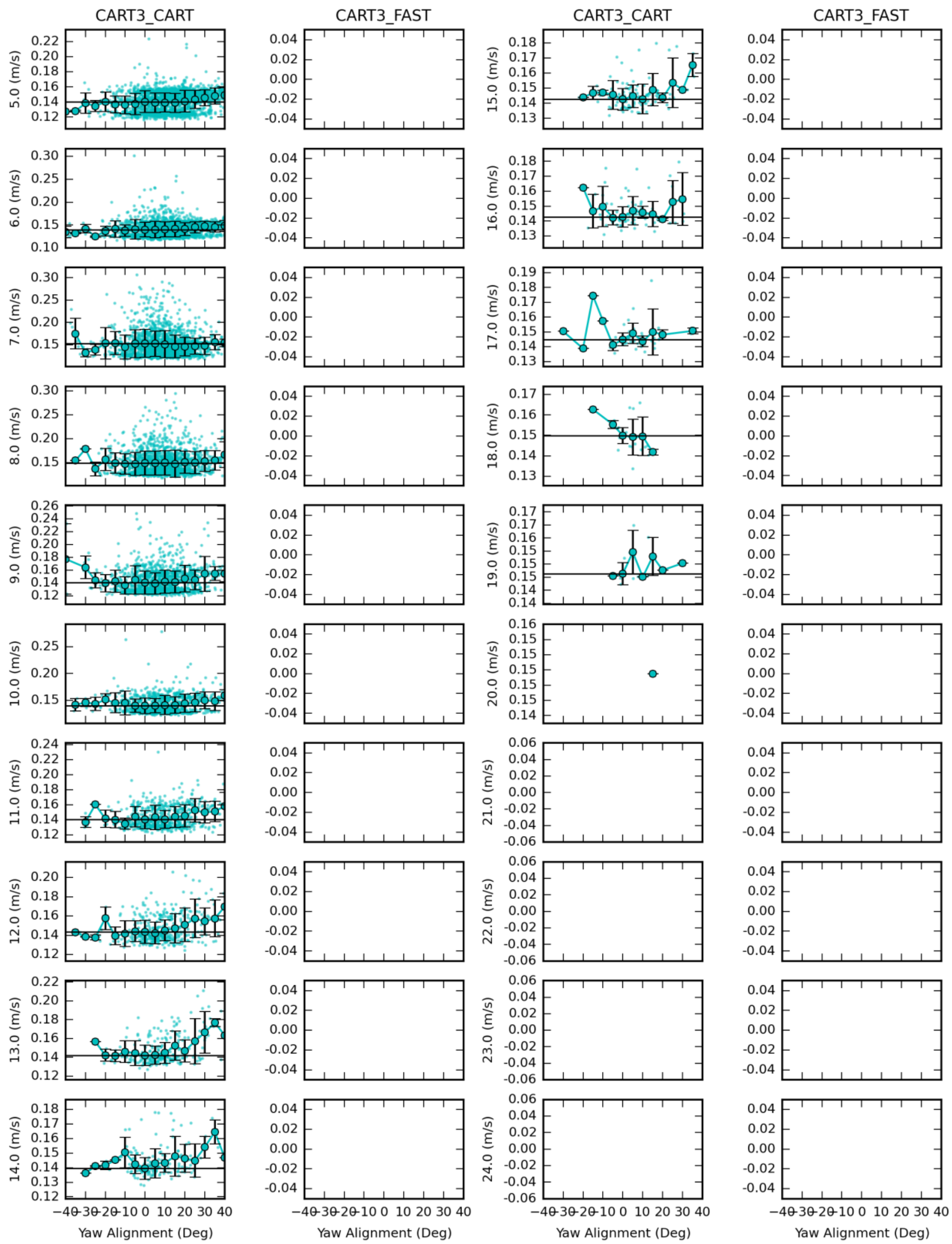

Figure 16: IMU Roll for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

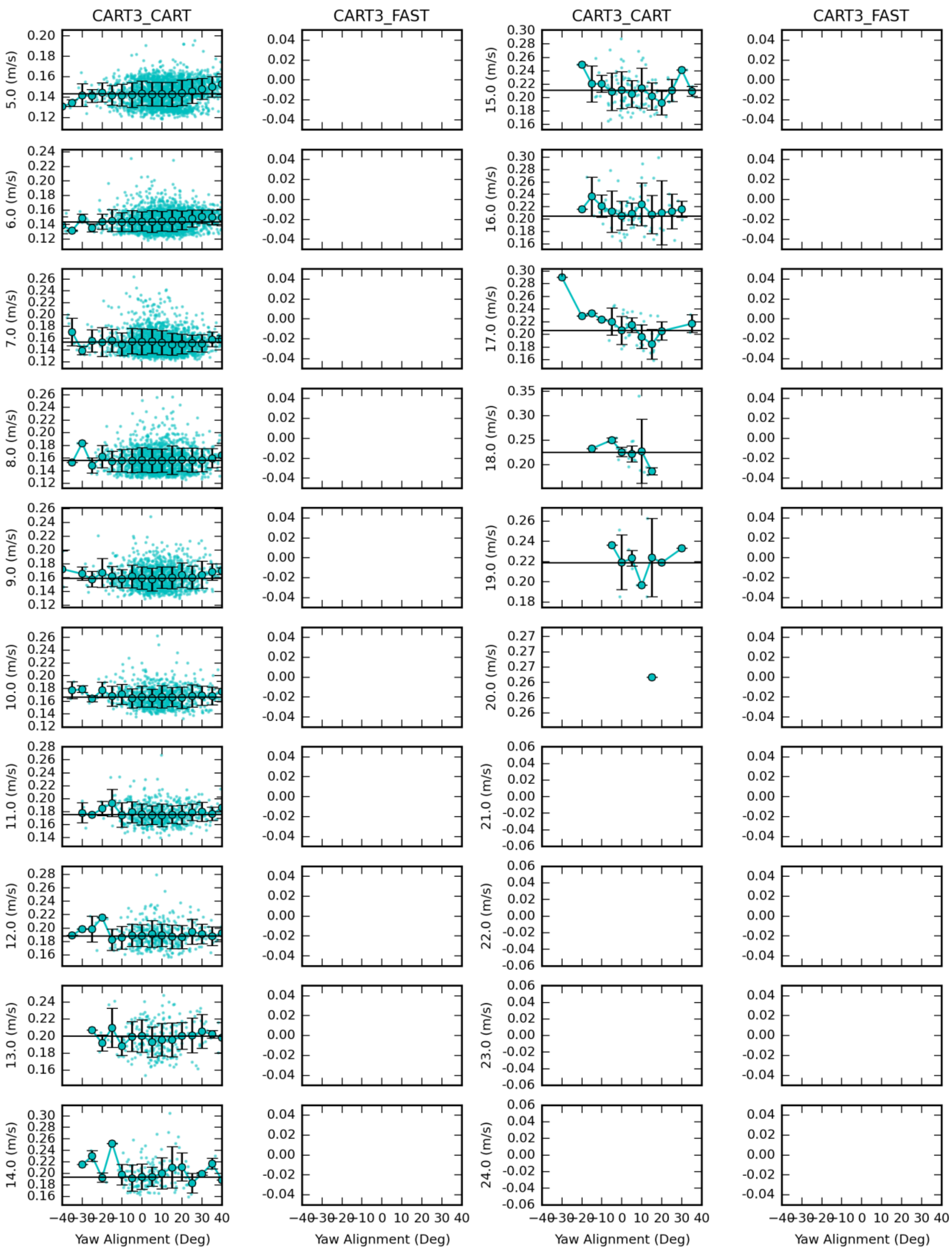

Figure 17: IMU Pitch for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

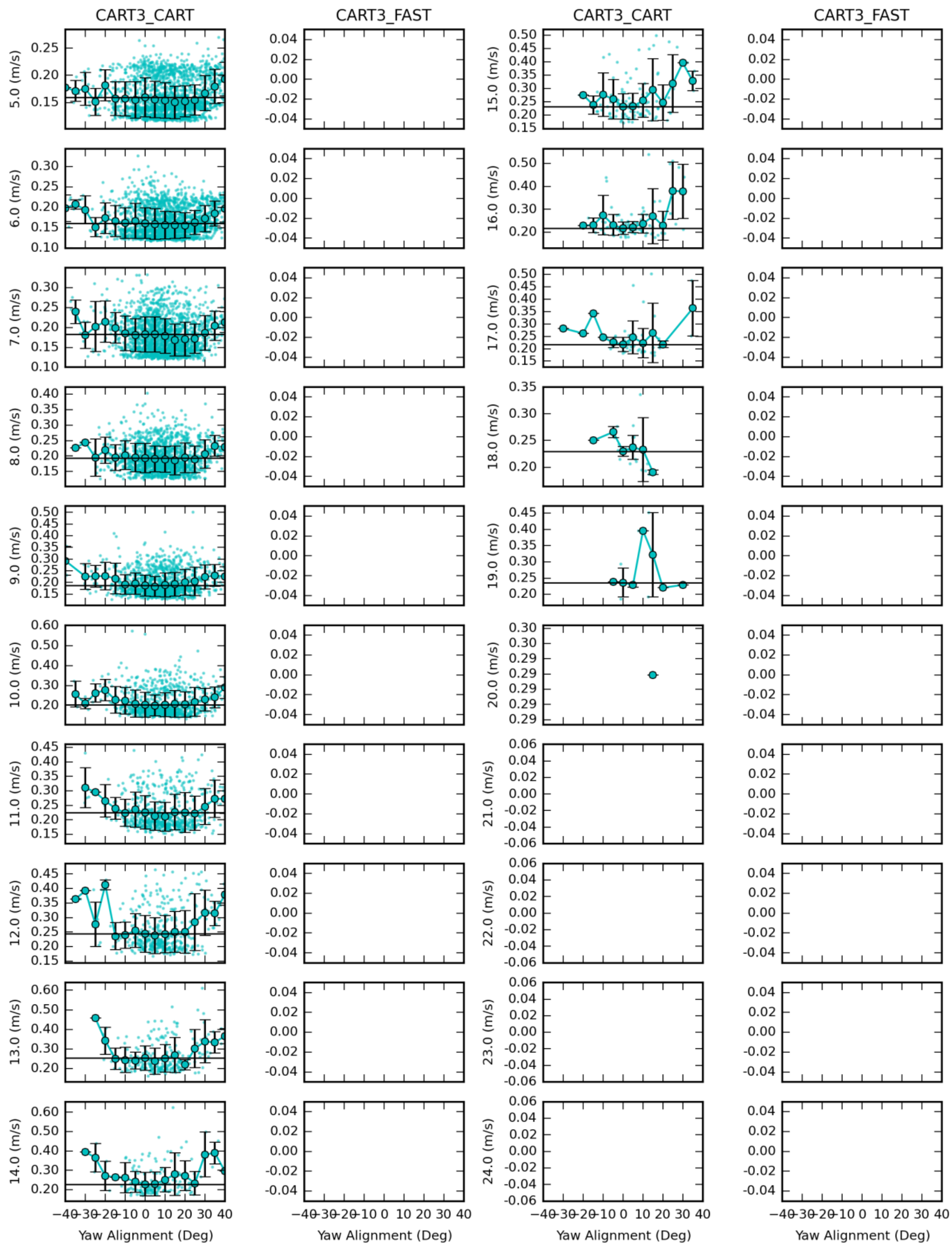

Figure 18: IMU Yaw for experimental and FAST-Simulated CART3 data. Small points are 45s values. Also shown are yaw misalignment bin average and standard deviation bars. The horizontal line indicates the mean value at 0 degree alignment.

REFERENCES

1. [Kragh2013] Kragh, K., & Hansen, M. (2013). Load alleviation of wind turbines by yaw misalignment. Wind Energy. http://doi.org/10.1002/we
2. Ennis, B., SWiFT V27 Wake Steering Loads Analysis, SAND2017-0099 R, Sandia National Laboratories, 2017.

APPENDIX B: SWIFT TURBINE AND MET INSTRUMENTATION

The following two tables provide the full data channel list for the SWiFT met towers and the SWiFT turbines. The priority column represents the importance of the data channel to the current Wake Steering Experiment. The higher the priority, the more attention and resources that channel will receive if there are issues with the sensor.

Table 5. Data channel list for METa1 along with priority for Wake Steering Experiment

Software ID	Description	Application	Priority
SonicU_58m	Sonic Anemometer at 58.5m height	Velocity 13 m above top of rotor disc, helpful adjunct for FLORIS & SOWFA shear, veer distributions	2
SonicV_58m	Sonic Anemometer at 58.5m height	Velocity 13 m above top of rotor disc, helpful adjunct for FLORIS & SOWFA shear, veer distributions	2
SonicW_58m	Sonic Anemometer at 58.5m height	Velocity 13 m above top of rotor disc, helpful adjunct for FLORIS & SOWFA shear, veer distributions	2
SonicT_58m	Sonic Anemometer at 58.5m height	Prerequisite for sonic anemometer measurement of velocity at this station	2
Sonicx_58m	Sonic Anemometer at 58.5m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicy_58m	Sonic Anemometer at 58.5m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicz_58m	Sonic Anemometer at 58.5m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
SonicU_45m	Sonic Anemometer at 45m height	Velocity ~ 1 m below top of rotor disc, crucial for FLORIS & SOWFA shear, veer distributions	1
SonicV_45m	Sonic Anemometer at 45m height	Velocity ~ 1 m below top of rotor disc, crucial for FLORIS & SOWFA shear, veer distributions	1
SonicW_45m	Sonic Anemometer at 45m height	Velocity ~ 1 m below top of rotor disc, crucial for FLORIS & SOWFA shear, veer distributions	1
SonicT_45m	Sonic Anemometer at 45m height	Prerequisite for sonic anemometer measurement of velocity at this station	1
Sonicx_45m	Sonic Anemometer at 45m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicy_45m	Sonic Anemometer at 45m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicz_45m	Sonic Anemometer at 45m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
SonicU_31m	Sonic Anemometer at 31.5m height	Velocity ~ 1 m below rotor hub height, crucial for FLORIS & SOWFA shear, veer distributions	1
SonicV_31m	Sonic Anemometer at 31.5m height	Velocity ~ 1 m below rotor hub height, crucial for FLORIS & SOWFA shear, veer distributions	1
SonicW_31m	Sonic Anemometer at 31.5m height	Velocity ~ 1 m below rotor hub height, crucial for FLORIS & SOWFA shear, veer distributions	1
SonicT_31m	Sonic Anemometer at 31.5m height	Prerequisite for sonic anemometer measurement of velocity at this station	1
Sonicx_31m	Sonic Anemometer at 31.5m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicy_31m	Sonic Anemometer at 31.5m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicz_31m	Sonic Anemometer at 31.5m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
SonicU_18m	Sonic Anemometer at 18m height	Velocity ~ 1 m below bottom of rotor disc, crucial for FLORIS & SOWFA shear, veer distributions	1
SonicV_18m	Sonic Anemometer at 18m height	Velocity ~ 1 m below bottom of rotor disc, crucial for FLORIS & SOWFA shear, veer distributions	1
SonicW_18m	Sonic Anemometer at 18m height	Velocity ~ 1 m below bottom of rotor disc, crucial for FLORIS & SOWFA shear, veer distributions	1

SonicT_18m	Sonic Anemometer at 18m height	Prerequisite for sonic anemometer measurement of velocity at this station	1
Sonicx_18m	Sonic Anemometer at 18m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicy_18m	Sonic Anemometer at 18m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicz_18m	Sonic Anemometer at 18m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
SonicU_10m	Sonic Anemometer at 10m height	Velocity ~ 9 m below bottom of rotor disc, helpful adjunct for FLORIS & SOWFA shear, veer distributions	2
SonicV_10m	Sonic Anemometer at 10m height	Velocity ~ 9 m below bottom of rotor disc, helpful adjunct for FLORIS & SOWFA shear, veer distributions	2
SonicW_10m	Sonic Anemometer at 10m height	Velocity ~ 9 m below bottom of rotor disc, helpful adjunct for FLORIS & SOWFA shear, veer distributions	2
SonicT_10m	Sonic Anemometer at 10m height	Prerequisite for sonic anemometer measurement of velocity at this station	2
Sonicx_10m	Sonic Anemometer at 10m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicy_10m	Sonic Anemometer at 10m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Sonicz_10m	Sonic Anemometer at 10m height	Part of ATI sonics; maybe useful if boom/tower vibration is suspected; signal now very low amplitude, under-resolved	3
Cup_45m	Cup anemometer at 45m height	Useful for corroborating sonic anemometer speed measured at 45 m height	2
Cup_31m	Cup anemometer at 31.5m height	Useful for corroborating sonic anemometer speed measured at 31.5 m height	2
Cup_18m	Cup anemometer at 18m height	Useful for corroborating sonic anemometer speed measured at 18 m height	2
Vane_29m	Wind Direction Vane at 29m height	Useful for corroborating sonic anemometer direction measured at 31.5 m height	2
RH_58m	Relative Humidity at 58.5m height	With Temp_58m or onboard temp, may be able to get a virtual temperature profile, which is helpful for stability.	2
Temp_58m	Temperature at 58.5m height	Backup for sonic anemometer temperature measurement at 58.5 m height	3
BP_27m	Barometric Pressure at 27.5m height	Measure barometric pressure within 10 m of hub, for deriving air density for rotor flow, per IEC 61400-12	1
RH_27m	Relative Humidity at 27.5m height	Measure relative humidity within 10 m of hub, for correcting air density for rotor flow, per IEC 61400-12	1
Temp_27m	Temperature at 27.5m height	Measure temperature within 10 m of hub, for deriving air density for rotor flow, per IEC 61400-12	1
BP_2m	Barometric Pressure at 2m height	Back up for barometric pressure measurement at 27.5 m (see above)	3
RH_2m	Relative Humidity at 2m height	Back up for relative humidity measurement at 27.5 m (see above)	3
Temp_2m	Temperature at 2m height	Back up for air temperature measurement at 27.5 m (see above)	3

Table 6. Data channel list for WTGa1 along with priority ranking for the Wake Steering Experiment. These same channels will be available on WTGa2.

Measurement Type	Software ID	Description	Application	Priority
Power	ActualPower	Current power	Not identified/explained	1
Power	ActualPower_10min	Power averaged over 10 minutes	Not identified/explained	3
Power	ActualPower_ABB	ABB signal TxPDO 1 – ACT3 (Power)	Not identified/explained	3
Power	ActualPower_W	ABB drive Actual	Not identified/explained	3

		Power		
Power	PowerMean	Mean of Power Sample Data array	Not identified/explained	3
Power	PowerSTD	Standard Deviation of Power Sample Data array	Not identified/explained	3
Torque	ActualTorque_ABB	ABB signal TxPDO 1 – ACT2 (Torque)	Not identified/explained	3
Torque	ActualTorque_Nm	ABB drive Actual Torque	Not identified/explained	1
Torque	LSS_Torque	Torque on the Low Speed Shaft	Not identified/explained	3
RPM	Gen_RPM	Generator RPM	Need at least one generator RPM measurements, to get higher resolution LSS RPM measurement via gearbox ratio	3
RPM	GenRPM	High Speed Shaft RPM	Need at least one generator RPM measurements, to get higher resolution LSS RPM measurement via gearbox ratio	3
RPM	GenRPMSec	High Speed Shaft RPM (1 sec ave)	Need at least one generator RPM measurements, to get higher resolution LSS RPM measurement via gearbox ratio	3
RPM	GenRPMTick	Gen RPM (instant)	Need at least one generator RPM measurements, to get higher resolution LSS RPM measurement via gearbox ratio	3
RPM	GenSpeed_24ms	Gen RPM (24ms ave)	Need at least one generator RPM measurements, to get higher resolution LSS RPM measurement via gearbox ratio	
RPM	RotRPMSec	Low Speed Shaft RPM (One Sec Ave)	Crucial for defining rotor operating state pertaining to wake structure, specifically for deriving tip speed ratio	1
RPM	RotRPMTick	Low Speed Shaft RPM (Instant)	Crucial for defining rotor operating state pertaining to wake structure, specifically for deriving tip speed ratio	1
RPM	ActualSpeed_ABB	ABB signal TxPDO 1 – Transparent Actual Velocity	Not identified/explained	3
RPM	ActualSpeed_rpm	ABB drive Actual Speed	Need at least one generator RPM measurements, to get higher resolution LSS RPM measurement via gearbox ratio	3
Rotor azimuth		Rotor azimuth angle measurement via rotary encoder on LSS	Enable time accurate resolution & projection of blade root moments/forces for model validation/calibration	1
Rotor azimuth		Rotor azimuth reference using one-per-revolution reference pulse	Back up rotor azimuth angle measurement to be done using rotary shaft encoder on LSS	2
Voltage	ControlVoltageSTD	Standard deviation on the control voltage	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Voltage	PitchActual	Pitch position A800 (volts) converted to degrees	Blade pitch angle resolved to 0.1 deg is crucial to accurate aero modeling, need either this channel or A800	1
	A800	Pitchposition	Blade pitch angle resolved to 0.1 deg is crucial to accurate aero modeling, need either this channel or PitchActual	1
Velocity	PitchVel	Pitch velocity	While blade pitch position is crucial, blade pitch velocity has no identifiable need	3
Velocity	PitchVel_Service	Pitch velocity during Pitch tests 4,5,7,8	While blade pitch position is crucial, blade pitch velocity has no identifiable need	3
Velocity	PitchVelExpected	Soft signal for use in Pitch Service Calibration	Not identified/explained	3
Pressure	HydrPressure	Hydraulic Oil Pressure	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	OilTemp	Hydraulic Oil Temp (need to verify Tick or 10s ave)	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R206	Temperature hydraulic oil	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3

Temperature	Temp_R300	Temperature ambient	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R300_10s	Temperature ambient 10s average (TenSecUx)	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R402	Temperature gear oil	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R402_10s	Gear Oil Temp (10 sec ave)	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R402_1s	Gear oil temperature averaged over 1 sec	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R451	Temperature Gear Bearing 1	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R451_10s	10s ave of Gear Bearing 1	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R452	Temperature Gear Bearing 2	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R452_10s	10s ave of Gear Bearing 2	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R503	Temperature generator 1	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R503_10s	Gen Temp 1 (10 sec ave)	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R503_1s	Generator temperature 1 averaged over 1 sec	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R504	Temperature generator 2	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R504_10s	Gen Temp 2 (10 sec ave)	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Temperature	Temp_R504_1s	Do we have this signal???	Not identified/explained	3
Velocity	Wind_Speed	Wind speed	Nacelle wind speed corrupted by rotor and nacelle, but useful to corroborate met tower wind speed	1
Velocity	WindSpeed10s	IFSample.GenericProc(IFSample.WindSpeed, TenSecUx)	Nacelle wind speed corrupted by rotor and nacelle, will not be used. Met tower wind speed to be used instead.	3
Angle	Wind_Direction	Wind direction	Nacelle wind direction corrupted by rotor and nacelle, but useful to corroborate met tower wind direction	1
Angle	Wind_Direction_Filtered	Filtered wind direction	Nacelle wind direction corrupted by rotor and nacelle, will not be used. Met tower wind direction to be used instead.	3
Angle	YawHeading	Compass Direction of the Nacelle	Essential to deriving yaw misalignment, with wind direction measured at met tower.	1
Angle	NacIMUcompass	Magnetometer orientation of Nacelle	Corrupted by nacelle ferrous mass; not needed as "YawHeading" channel uses encoder ref'd to N-S survey line.	3
Number	YawRotations	Complete rotations of the turbine	Channel for machine safety/maintenance; no direct research utility for Wake Steering Project	3
Acceleration	NacIMUAx	Nacelle X acceleration	Might be useful for inferring rotor time varying loads in future phases of SWiFT project	2
Acceleration	NacIMUAy	Nacelle Y acceleration	Might be useful for inferring rotor time varying loads in future phases of SWiFT project	2
Acceleration	NacIMUAz	Nacelle Z acceleration	Might be useful for inferring rotor time varying loads in future phases of SWiFT project	2
Angular Velocity	NacIMUrVx	Nacelle X angular velocity	Might be useful for inferring rotor time varying loads in future phases of SWiFT project	2
Angular Velocity	NacIMUrVy	Nacelle Y angular velocity	Might be useful for inferring rotor time varying loads in future phases of SWiFT project	2
Angular Velocity	NacIMUrVz	Nacelle Z angular velocity	Might be useful for inferring rotor time varying loads in future phases of SWiFT project	2
Strain	TowerNS	Strain in the North-South direction	Could compare disc thrust induced moments with model predictions; compensating errors, differential heating likely	2

Strain	TowerEW	Strain in the East-West direction	Could compare disc thrust induced moments with model predictions; compensating errors, differential heating likely	2
Strain	TowerNESW	Strain in the NE-SW direction	Could compare disc thrust induced moments with model predictions; compensating errors, differential heating likely	2
Strain	TowerNWSE	Strain in the NW-SE direction	Could compare disc thrust induced moments with model predictions; compensating errors, differential heating likely	2
Strain	B1_Strain	Blade 1 Flap and edge root bending from Micron optics	Flap/edge bending induced moments could be compared with model predictions, but compensating errors likely	1
Strain	B2_Strain	Blade 2 Flap and edge root bending from Micron optics	Flap/edge bending induced moments could be compared with model predictions, but compensating errors likely	1
Strain	B3_Strain	Blade 3 Flap and edge root bending from Micron optics	Flap/edge bending induced moments could be compared with model predictions, but compensating errors likely	1

APPENDIX C: UNLIMITED RELEASE OF SWIFT DATA

Sandia National Laboratories

Operated for the U.S. Department of Energy's
National Nuclear Security Administration
by Sandia Corporation

Albuquerque, New Mexico 87185-0101

date: August 18, 2016

to: Sandia National Laboratories Review & Approval

from: Brian Naughton, Org. 6121, bnaught@sandia.gov, 505-844-4033

subject: Unlimited Release of non-proprietary experimental data from the Scaled Wind Farm Technology (SWiFT) Facility 8/18/2016 through 9/30/2017 - SAND2016-8101 O

To whom it may concern:

This memo serves as a proxy to represent non-proprietary data collected at the Scaled Wind Farm Technology (SWiFT) Facility managed by the Wind Energy Technologies Department (Org. 06121). As a DOE-funded facility, one of the primary goals of the SWiFT facility is to provide public datasets from wind energy systems to promote increased knowledge and improved technology to the broader wind energy industry. The baseline SWiFT Facility comprises five primary "instrument packages" as follows:

- Wind Turbine a1
- Wind Turbine a2
- Wind Turbine b1
- Meteorological Tower a1
- Meteorological Tower b1

Each instrument logs dozens of individual data channels at a rate up to 50 Hz, 24 hours per day. These datasets are then archived and available for internal Sandia use. Multiple external partners will require access to the data as part of defined research projects on a continual basis. There is currently a Designated Unclassified Subject Area (DUSA) for Renewable Energy Technologies (Wind Energy) in place which classifies all testing data as UUR as long as it avoids exclusions under the DUSA (e.g. Export Controlled, UCI/Proprietary). This memo is intended to facilitate the unlimited release of all test data collected at the SWiFT site that does not fall under the DUSA exclusions. A copy of all test data will be stored within a Sandia Corporate Database as an archival reference with the specific location provided by Org. 6121 upon request. The duration of this R&A is requested from 8/18/2016 through 9/30/2017.

APPENDIX D: DTU SPINNERLIDAR AND MOUNT

POC:
Andrew Scholbrock
Field Test Engineer
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Objective:

Design a custom mounting system that enables the DTU SpinnerLidar to be installed inside the nacelle of the SWiFT WTGa1 turbine to meet the data collection needs of the Wake Steering Experiment.

Requirements:

- Allow temporary (~6 month) mounting of the lidar in the nacelle of WTGa1
- No interference with existing machinery and critical operations within the nacelle
- Protect the sensitive portions of the lidar from outdoor conditions (sun, precipitation)
- Allow the lidar to manually swivel +/- 20 degrees from center, out the rear hatch of the nacelle

DTU SpinnerLidar Specifications

The following lidar information has been provided by DTU staff (Steen Andreasen)

Table 7. Physical specifications for DTU Lidar

Parameter	**Value**
Total system mass	110 kg
Maximum length dimension	1464 mm
Maximum girth dimension	674 mm
Center of Gravity	See Figure 2 and CAD model
Power requirements	230V, 50 or 60 Hz
Peak electrical load	1 kW
Average electrical load	250 W
Communications protocol	TCP/IP

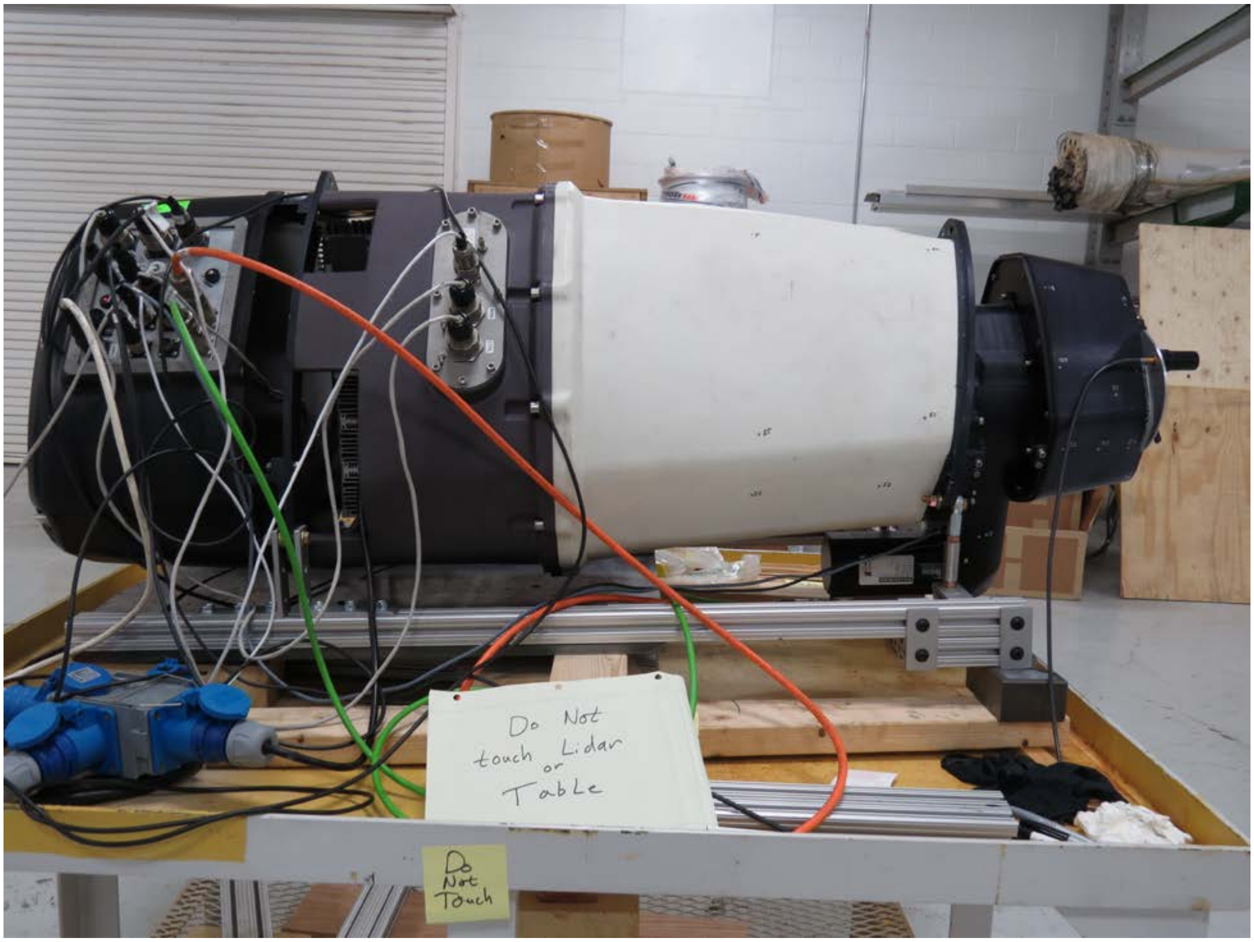


Figure 19. DTU Lidar on calibration stand in Building 350 at the SWiFT Facility

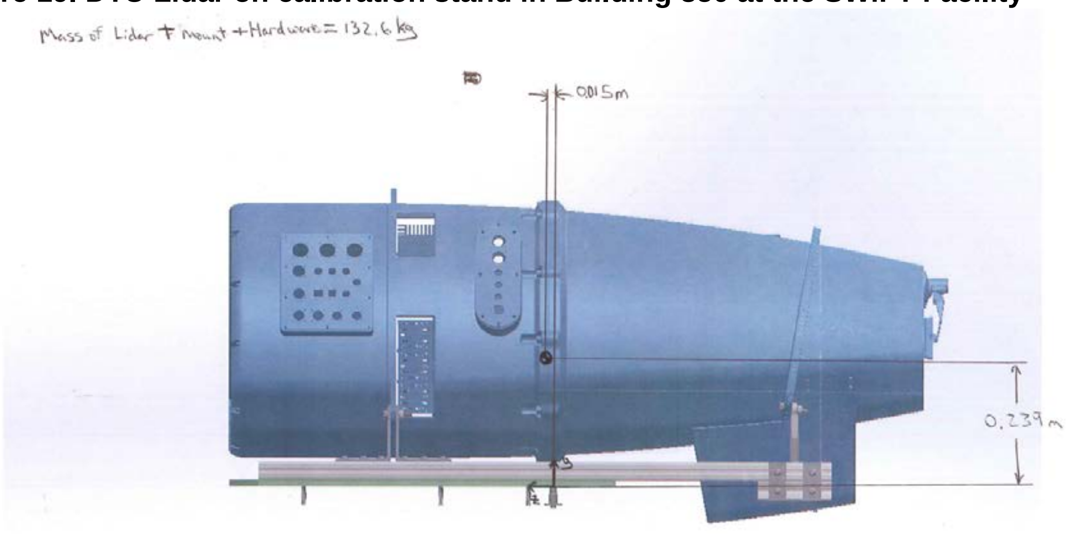


Figure 20. DTU SpinnerLidar CAD model with center of mass identified

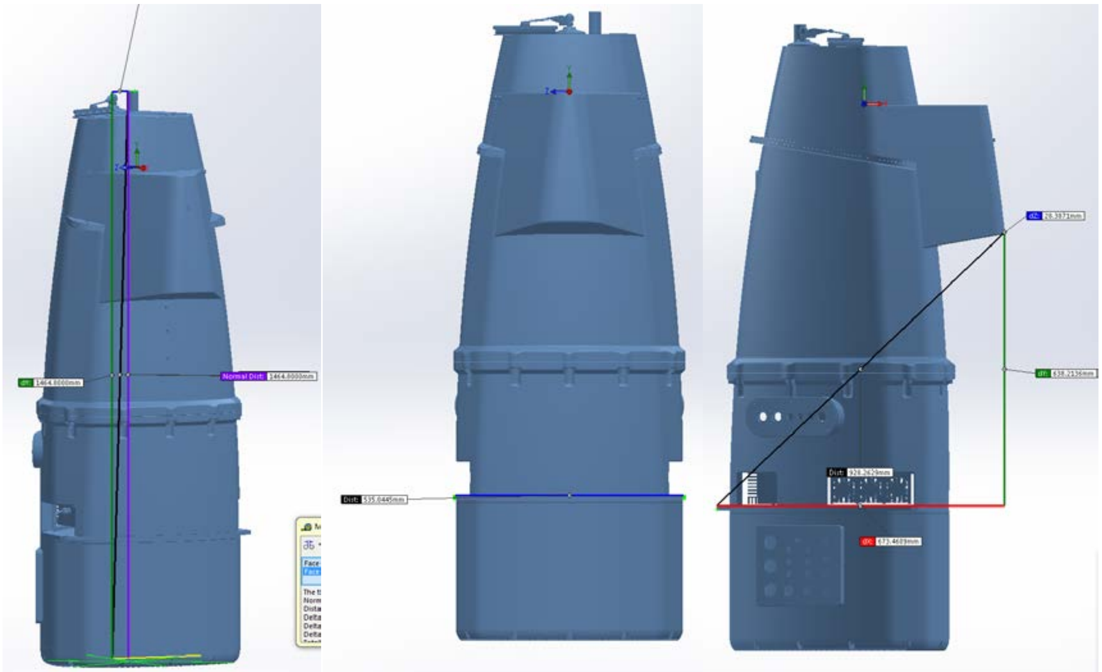


Figure 21. DTU SpinnerLidar maximum outer dimensions

Power
A step-up transformer will be installed to provide up to 1500 Watts at 230V from an existing 115 V auxiliary line in the WTGa1 nacelle.

Communications
A dedicated computer will be installed in the SWiFT control building to control and collect data from the DTU Lidar. The computer will be connected via a dedicated fiber line to the lidar in the nacelle. The computer will also be connected to the WiFi network available in the control building, allowing access for external collaborators to access the computer for data transfer and control needs.

SpinnerLidar Mount Design

Figure 4 shows a CAD model of the DTU SpinnerLidar (blue) attached to the mounting system where the lidar is bolted to the top lidar plate (green) which pivots on the nacelle plate (salmon) which is secured to the nacelle bedplate through a series of u-bolts. The full bill-of-materials for the lidar mount is listed in Table 2.

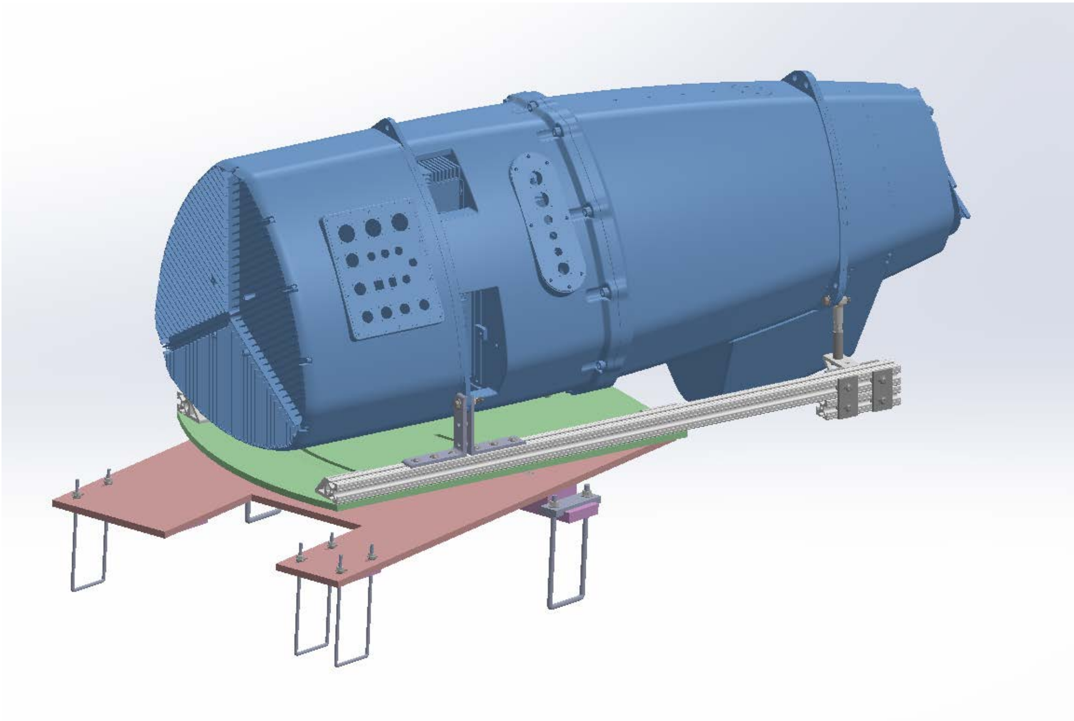


Figure 22. DTU SpinnerLidar and lidar plate for installation in SWiFT turbine nacelle

Table 8. Lidar Mount Bill of Materials

Part:	Material:	Part Number:	Supplier:	Quantity:	Notes:
Machined Parts:					
Nacelle Plate	6061-T6 Aluminum		J&B Industrial Services / Texcraft & Lubbock Tool & Die	2	To be machined
Lidar Plate	6061-T6 Aluminum		J&B Industrial Services / Texcraft & Lubbock Tool & Die	2	To be machined
Wedge 1	6061-T6 Aluminum		J&B Industrial Services / Texcraft & Lubbock Tool & Die	1	To be machined
Wedge 2	6061-T6 Aluminum		J&B Industrial Services / Texcraft & Lubbock Tool & Die	1	To be machined
Wedge 3	6061-T6 Aluminum		J&B Industrial Services / Texcraft & Lubbock Tool & Die	1	To be machined
3/8" U Bolt Plate	6061-T6 Aluminum		J&B Industrial Services / Texcraft & Lubbock Tool & Die	2	May need to be machined (unless a suitable plate can be found somewhere)
Made/Modified onsite:					
3/8" U Bolt	Grade 8 Steel		Custom	2	May need to be made on site for custom fit
1/4" U Bolt	Grade 8 Steel		Custom	4	May need to be made on site for custom fit
Corner Bracket	6105-T5 Aluminum	8020-4413	80/20 Inc.	4	Holes are 5/16"; some of them will need to be drilled out to 3/8"
80/20 6" Extrusion	6105-T5 Aluminum	8020-1515-1515	80/20 Inc.	2	Cut from bulk to 6" length
80/20 46" Extrusion	6105-T5 Aluminum	8020-1515-1515	80/20 Inc.	2	Cut from bulk to 46" length
Corner Bracket	6105-T5 Aluminum	8020-4336	80/20 Inc.	2	Will need to be drilled out for custom fit.
3/8" x 2.0" Spacer	18-8 Stainless Steel	92320A741	Mcmaster-Carr	2	Will need to be cut to size for custom fit.
Standard Parts (needs no modification):					
1/2" Locking Pin	Stainless Steel	92851A415	Mcmaster-Carr	1	Size: 1/2" diameter
3/8"-16 Nut	Grade 8 Steel	94895A031	Mcmaster-Carr	8	Size: 3/8" diameter; 16 threads per inch
3/8" Lock Washer	Grade 8 Steel	91104A031	Mcmaster-Carr	13	Size: 3/8" diameter

3/8" Washer	Grade 8 Steel	98023A031	Mcmaster-Carr	21	Size: 3/8" diameter
3/8"-16 x 2.0" Bolt	Grade 8 Steel	92620A632	Mcmaster-Carr	9	Size: 3/8" diameter; 16 threads per inch; 2.0" length; Grade 8
3/8"-24 x 3.5" Bolt	Grade 8 Steel	92620A661	Mcmaster-Carr	2	Size: 3/8" diameter; 24 threads per inch; 3.5" length; Grade 8
3/8"-24 Nut	Grade 8 Steel	94895A815	Mcmaster-Carr	4	Size: 3/8" diameter; 24 threads per inch
3/8"-24 Female Ball Joint	High-Strength PTFE-Lined	60745K441	Mcmaster-Carr	2	Size: 3/8" diameter; 24 threads per inch
5/16" Fastener for 80/20	Zinc-plated steel	47065T970	Mcmaster-Carr	40	Size: 5/16" diameter
5/16" Flat-Head Socket Cap Screw	Black-Oxide Alloy Steel	91253A583	Mcmaster-Carr	3	Size: 5-16" diameter; 18 threads per inch; 1.0" length; 82 degree countersink head
5/16" Socket Head Cap Screw	Black-Oxide Alloy Steel	91251A581	Mcmaster-Carr	8	Size: 5-16" diameter; 18 threads per inch; 3/4" length
5/16" Lock Washer for Socket Head Cap Screw	Steel	90073A030	Mcmaster-Carr	8	Size: 5/16" diameter
5/16" Washer	Grade 8 Steel	98023A030	Mcmaster-Carr	8	Size: 5/16" diameter
1/4" Nut	Grade 8 Steel	94895A029	Mcmaster-Carr	8	Size: 1/4" diameter; 20 threads per inch
1/4" Lock Washer	Grade 8 Steel	91104A029	Mcmaster-Carr	8	Size: 1/4" diameter
1/4" Spherical Washer	18-8 Stainless Steel	91944A430	Mcmaster-Carr	8	Size: 1/4" diameter
Corner Bracket	6105-T5 Aluminum	8020-4334	80/20 Inc.	4	Size: 5/16" diameter holes for 1.5" profile 80/20
Connecting Plate	6105-T5 Aluminum	47065T256	Mcmaster-Carr	8	Size: 5/16" diameter holes for 1.5" profile 80/20

Mock-up Construction and Fit

Objective:

Design, procure, build and test a low cost mock-up of a lidar and mount design to be integrated into a Sandia SWiFT facility research turbine nacelle. The mock-up is intended to serve two purposes, 1) to determine the fit and function of the lidar and mount within the nacelle, and 2) to test out methods of installation for both the mount and lidar assuming it will be installed up-tower in the field at the SWiFT site.

System overview:

The custom lidar will be installed in the SWiFT wind turbine nacelle, protruding from the rear hatch, and capable of swiveling left and right by 20 degrees in either direction about a pivot point. This will be accomplished through the use of a custom designed mount as shown in the figure below.

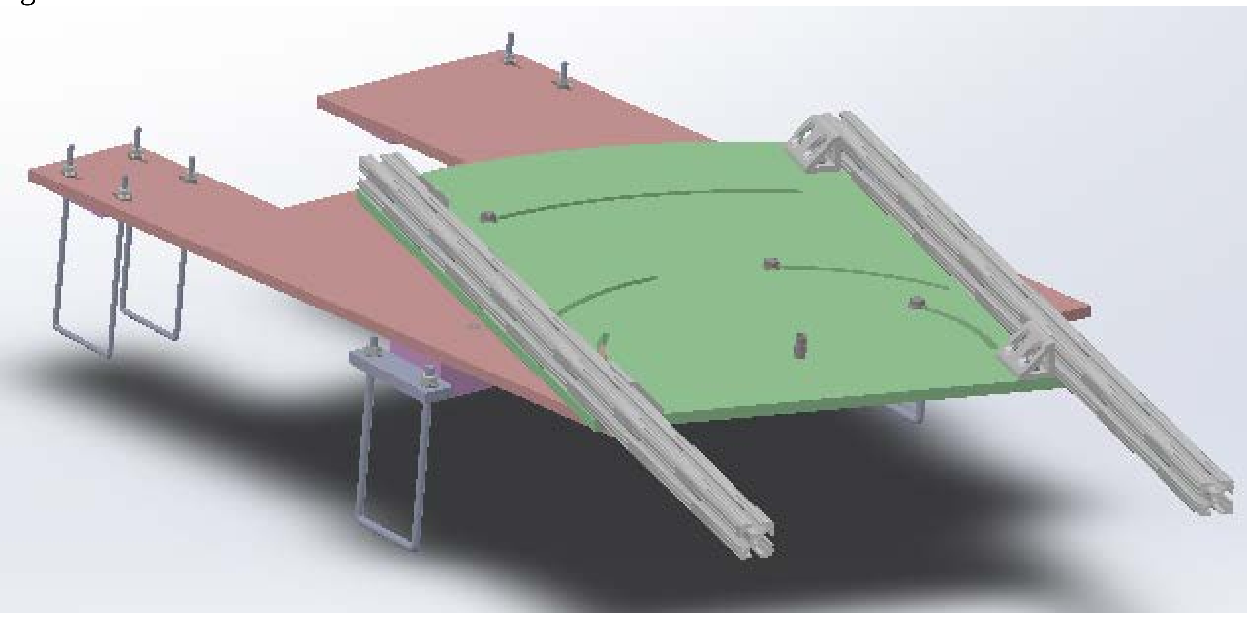


Figure 23. Lidar mount assembly from front top

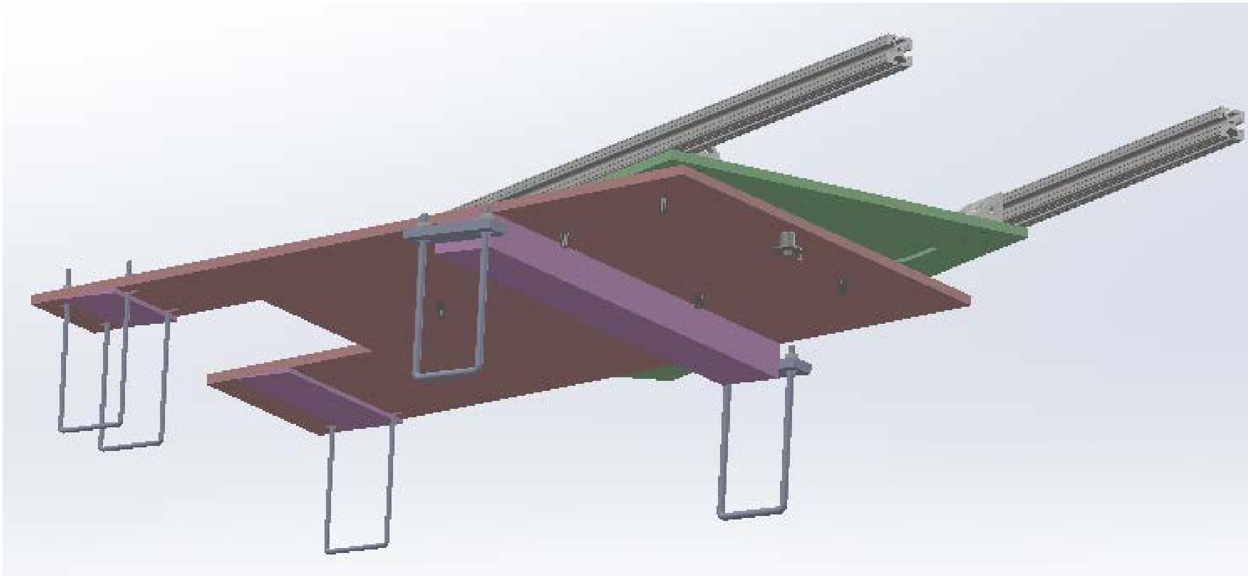


Figure 24. Lidar mount assembly from front bottom showing the wedge (magenta), bottom plate (salmon), top lidar plate (green) and mounting rails and u-bolts.

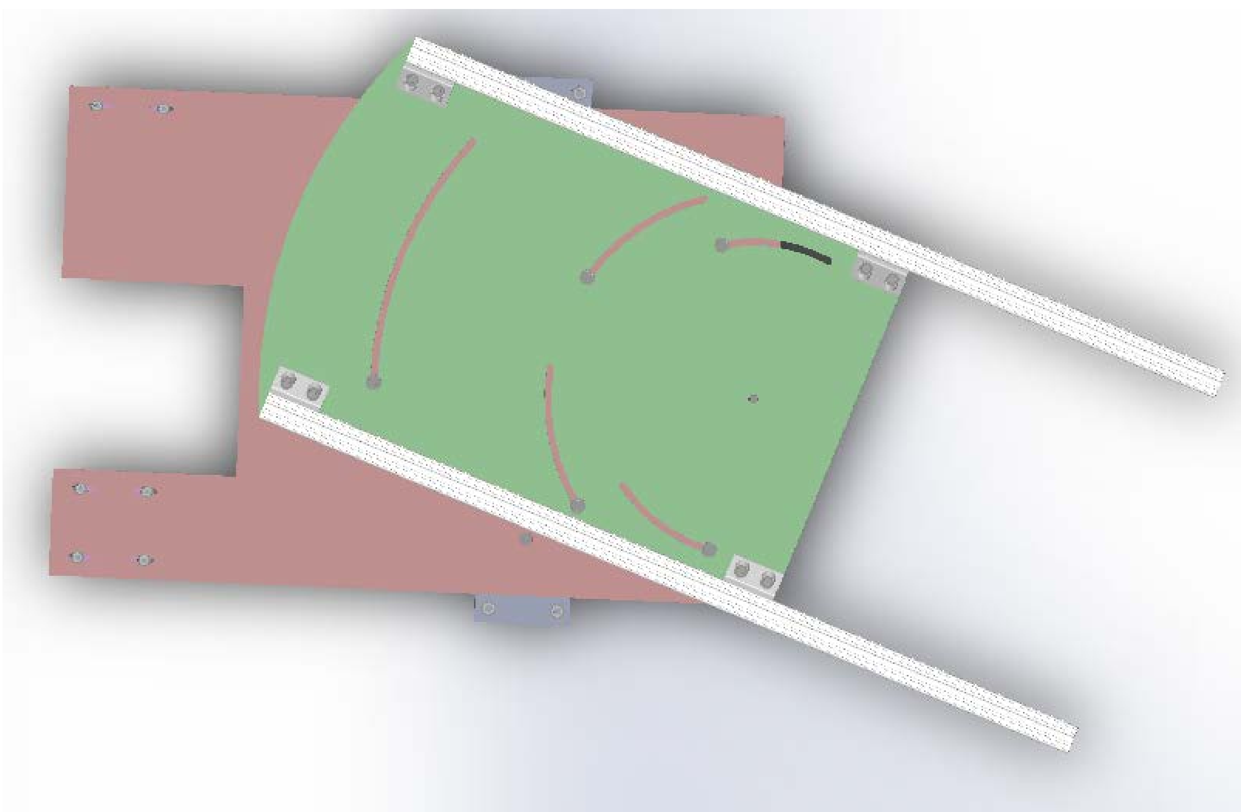


Figure 25. Lidar mount assembly from above.

Mock-up construction:
The mock-up should contain sufficient detail to meet the objectives of testing fit, function, and installation of the real system. This will consist of representing the following primary components:

- Lidar
- Wedges
- Nacelle plate
- Lidar plate
- Mounting hardware

Table 9. Lidar and mounting system component mass estimates from CAD model

Component	Mass (kg)
Lidar	110.0
Lidar plate	14.2
Nacelle plate	19.2
Wedges	6.6
Hardware	10.3
Total	**160 kg**

Lidar:
The lidar is shown in Figure 8 from a side view. The large protrusion on the top left will be outside of the nacelle and is not anticipated to cause any interference. It can therefore be ignored for the purposes of the mock-up. The lidar can most simply be represented by a hollow tube, such as a Sonotube. In this case the max diameter is 21 inches and the max length is 58 inches. The closest Sonotube appears to be 20 inches inner diameter, which should come close enough to 21 inches outer diameter.

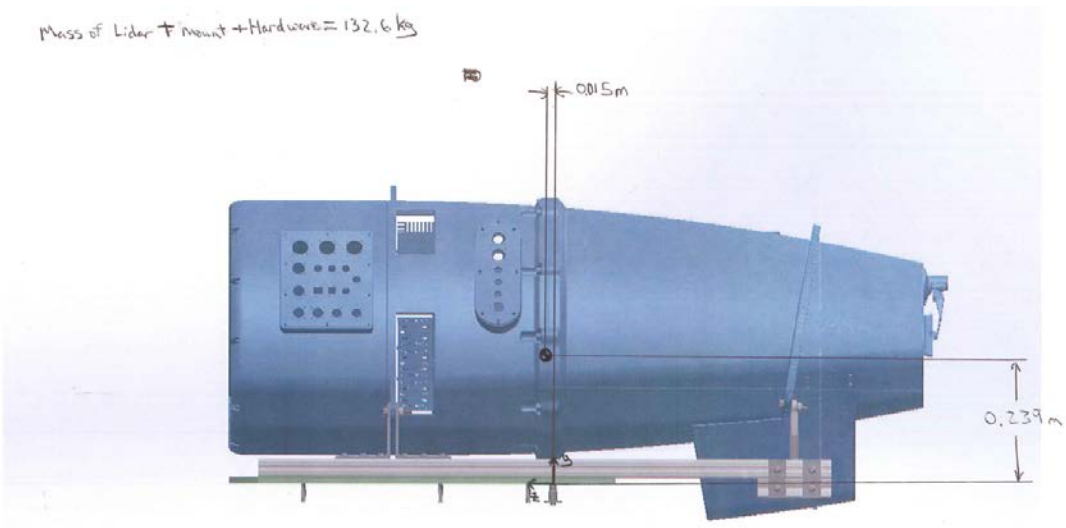


Figure 26. Screenshot of lidar CAD model from a side-view where the right side is the portion that will protrude from the nacelle.

Wedges:
There are 3 wedges located under the nacelle plate at the location of both crossbeams in the nacelle. The purpose of these wedges is to level the lidar to account for the 4 degree tilt of the nacelle with respect to horizon.

Material: Aluminum 6061-T6
Mass: 6.61 kg

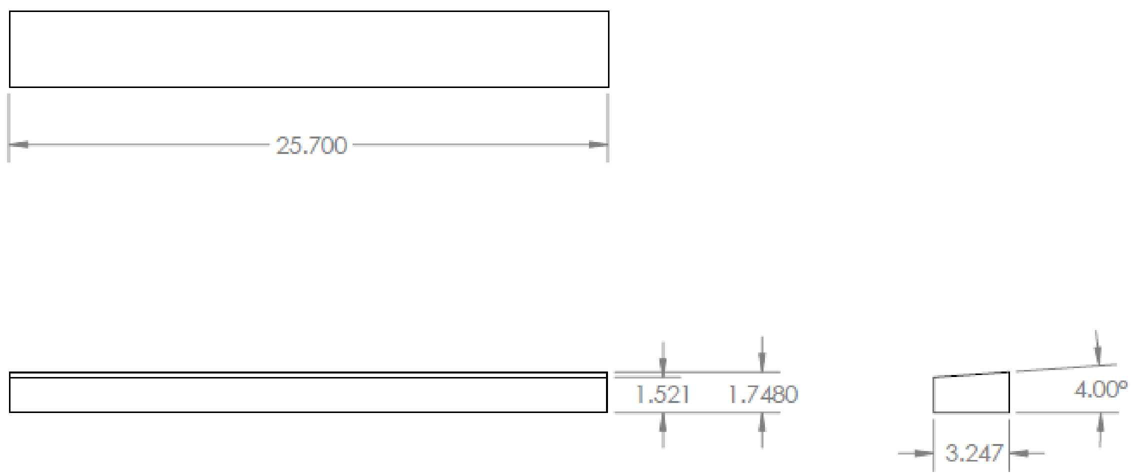


Figure 27. Wedge with dimensions in inches

Nacelle Plate:
The nacelle plate will attach to the cross-beams of the nacelle via custom-formed u-bolts. The 6 slots for the 3 u-bolts are shown towards the bottom "feet" of the drawing in Figure 10. The pivot point allows the top lidar plate to swing about the bottom plate plus and minus 20 degrees.

Material: Aluminum 6061-T6 ½" plate
Mass: 19.2 kg

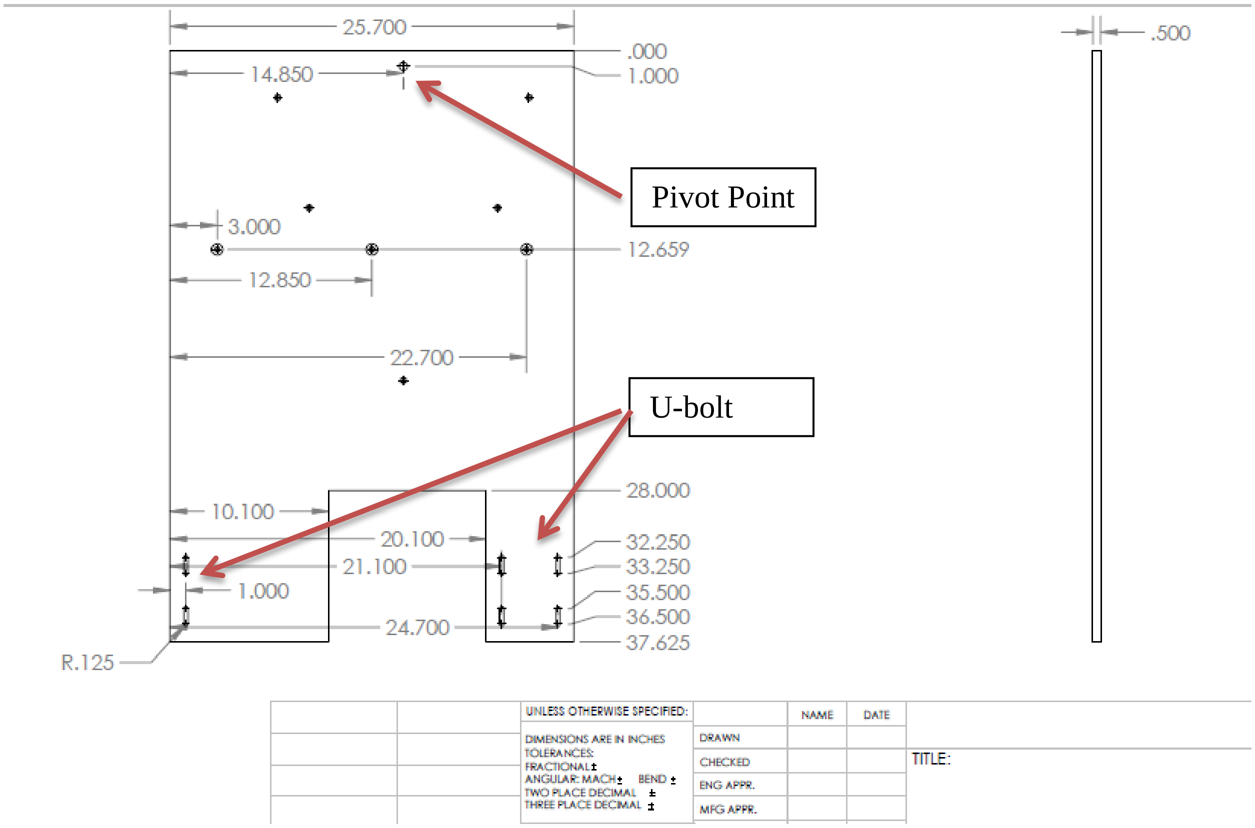


Figure 28. Dimensional drawing (inches) for the nacelle plate

Lidar Plate:
The lidar plate swivels about a pivot point that is connected to the bottom mounting plate. This top lidar plate also connects to the side mounting rails and the lidar itself via various brackets.

Material: Aluminum 6061-T6 ½" plate
Mass: 14.15 kg

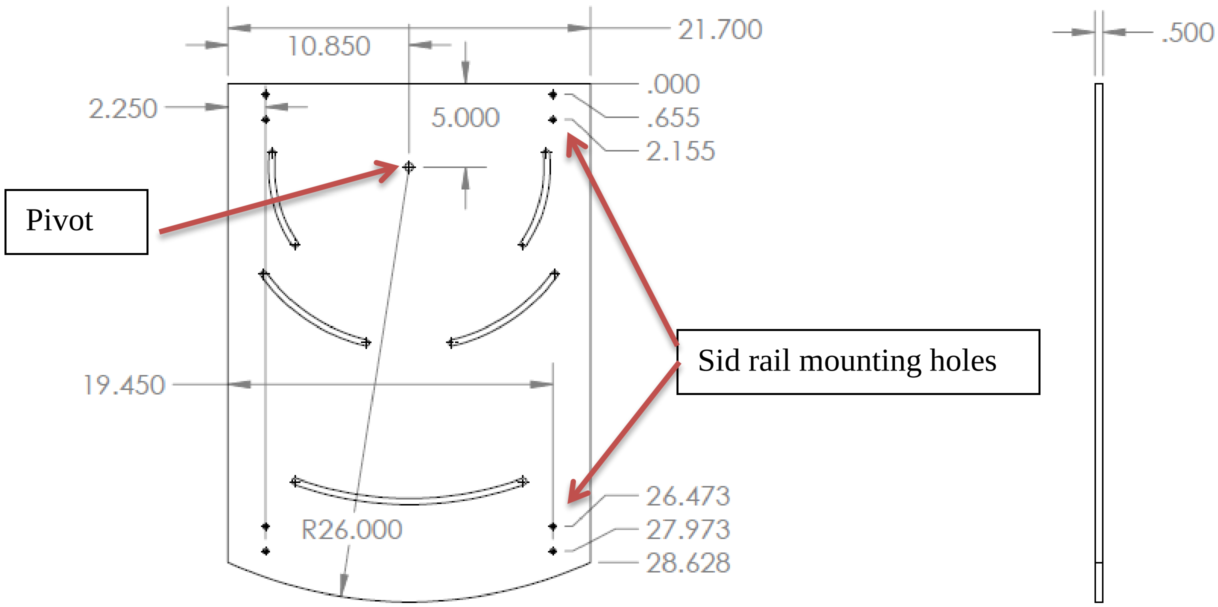


Figure 29. Lidar plate with dimensions in inches

Mounting Hardware:
The side mounting rails and 4 brackets are connected to the top lidar plateing plate via the appropriate hardware. For the purposes of the mock-up these pieces can be made from the actual materials specified for the final mount. These include:

- (Qty 4) 80/20 brackets: https://8020.net/4334.html
- (Qty 2) 80/20 slotted rail 46 inches long: https://8020.net/1515.html
- (Qty 8) 5/16" Fastener for 80/20 (McMaster-Carr item 47065T970)
- (Qty 8) 3/8" screw to attach 80/20 brackets to lidar plate (and not protrude through bottom)
- 3/8" bolt and nut to act as a pivot between the two mounting plates

Initial Mock-up Fit:
The mock-up was constructed as described above and fit into the nacelle (WTGa2) that was located in a Sandia facility in Albuquerque for refurbishment. After some modifications to the nacelle plate, the mock-up was successfully centered out of the rear hatch of the nacelle and articulated at least 20 degrees from center in both directions. The mount system without the lidar is shown installed in the nacelle looking through the rear hatch in Figure 12. Lidar mount mock-up fit on the WTGa2 turbine nacelle at SandiaFigure 12. An image of the sonotube installed on the mount and articulated 20 degrees is shown in Figure 13.

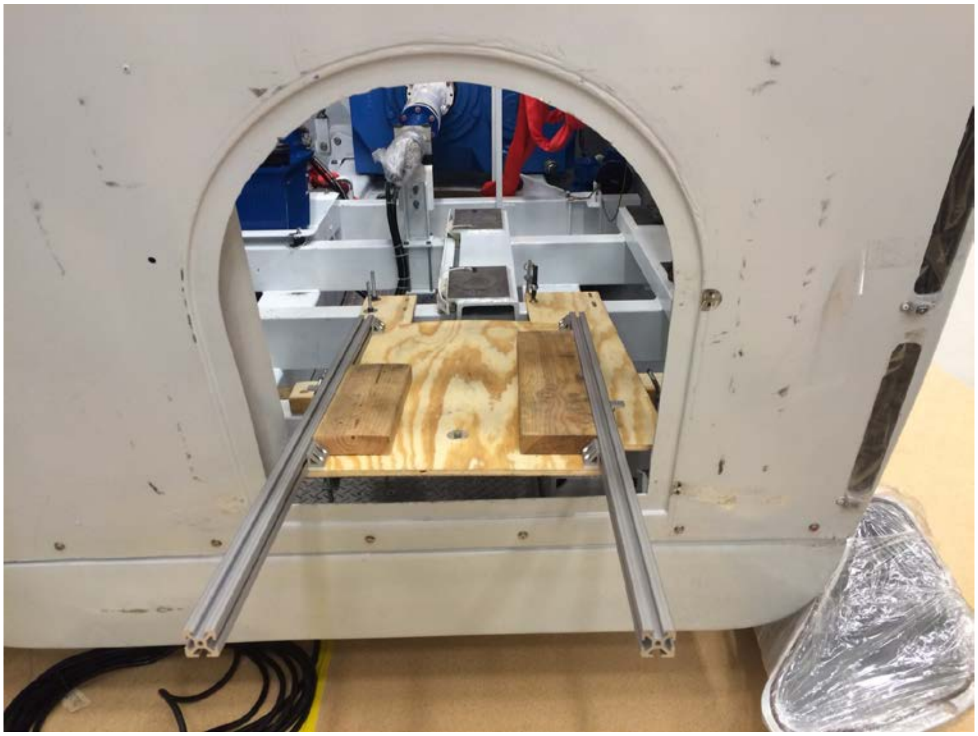


Figure 30. Lidar mount mock-up fit on the WTGa2 turbine nacelle at Sandia

Figure 31. Lidar mount mock-up with 20-inch diameter sonotube to represent the lidar installed in WTGa2 nacelle at Sandia.

Mock-up Fit on WTGa1:

The (WTGa2) nacelle used for the preliminary fit is not identical to the (WTGa2) nacelle that the lidar will be mounted in for the experiment. The preliminary fit was done without a generator installed, which is identified as a possible interference point. Also, the bedplate beams are potentially different which could impact the mounting location of the bottom mounting plate. For these reasons the mock-up was shipped out to the SWiFT site for fitting into the WTGa1 turbine. The notional installed configuration of the lidar and mount are shown in Figure 14.

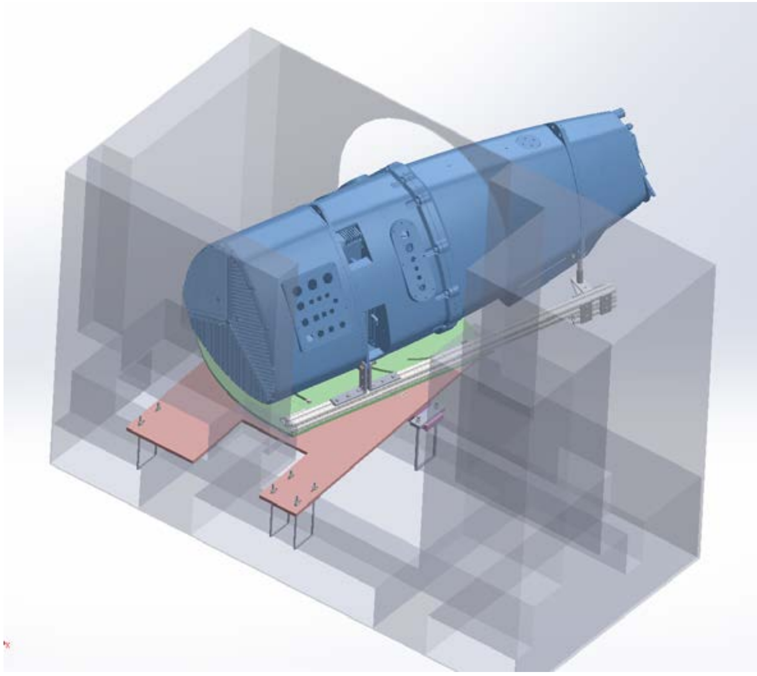


Figure 32. CAD model of the lidar mount installed in the WTGa1 nacelle

Figure 33. Bottom and side view of lidar on the lidar plate.

The objectives of the mock-up fit on WTGa1 are as follows:

- Confirm the design of the mount does not interfere with components or essential operations inside the nacelle.
- Confirm access to adjust and articulation of the lidar 20 degrees in both directions
- Confirm the lidar is near horizontal, compensating for the 4 degree tilt of the nacelle
- Develop a lifting and installation strategy for the mount and lidar once it is manufactured and assembled

Weatherization Covers

The lidar has two areas that are sensitive to weather (i.e. precipitation). The front portion of the lidar that extends beyond the hatch out of the nacelle will require a sheath to cover the gap between the lidar and rear hatch. This will need to be designed and installed as a custom fit to the nacelle. An example is shown in Figure 16 from the previous installation of the SpinnerLidar on top of the CART 3 turbine at NREL. The clear vinyl sheet is installed behind the optical head. It does not need to be water-tight, but rather just protect the front of the lidar from excessive rainfall. The system installed on WTGa1 will have to be more flexible to allow for the 20 degree articulation. The rear portion of the lidar contains control hardware that is not well weatherized, so another vinyl cover will need to be installed, similar to the metal cover shown in Figure 16 to prevent any water dripping on the lidar from the seam in the nacelle cover.

Figure 34. Mounting system of DTU SpinnerLidar at NREL showing the front and rear covers

APPENDIX E: DTU SPINNERLIDAR AND MOUNT LIFT PLAN

The following pages describe the lift plan to install the DTU SpinnerLidar and mounting hardware in the WTGa1 nacelle.

Figure 35. The SpinnerLidar fully installed in the turbine (top) a view from the nacelle of the SpinnerLidar being lifted (bottom).

National Renewable Energy Laboratory

Hoisting & Rigging / Lift Plan – Part 1

Lift Plan Number:

INTRODUCTION

The lift master or designated hoisting and rigging (H&R) operator prepares the lift plan. A Hoisting and Rigging Lift Plan is recommended for all lifts but is required for complex and/or critical lifts. Once the plan is developed, it must be submitted to the EHS POC for review and approval. Information developed in this plan must be reviewed with the H&R operator and workers involved in the work activity prior to the lift.

GENERAL INFORMATION

Project Name: DTU SpinnerLidar installation in the Scaled Wind Farm Testing (SWiFT) facility WTG-a1 wind turbine nacelle	**Project Location**: Sandia National Laboratory (SNL) SWiFT facility Lubbock, TX at the WTG-a1 Wind Turbine
Competent Persons: Don Baker, Andrew Scholbrock, Dave Mitchell (SNL), Wesley Johnson (SNL), and John White (SNL)	**Center**: 5000
Load Description: • DTU SpinnerLidar and lidar mounting plate • Nacelle mounting plate	**Weight of Load**: (Indicate Actual or Estimated) • 355 lbs. for lidar and lidar mounting plate (actual, not include rigging) • 127 lbs. for nacelle mounting plate (actual, not include rigging)

DESCRIPTION OF LIFTING ACTIVITY.

Describe the scope of work. Include specific information about the unique characteristics of the lift that warrant the development of a lift plan.

- Since this lift involves a one-of-a-kind piece of equipment (the DTU SpinnerLidar) that is essential to the success of several DOE milestones, it is considered to be a critical lift.
- The nacelle mounting plate will be lifted via crane and lowered through the open roof of the WTG-a1 nacelle.
- The DTU SpinnerLidar and lidar mounting plate will be lifted as a second lift via crane and passed through the rear hatch door of the WTG-a1 nacelle.
- A crane rented from Mark's Crane & Rigging (http://www.markscrane.com/) in Lubbock, TX will be utilized to lift the two following loads.

Component	Weight [lb]	Horizontal CG [in]
DTU SpinnerLidar and lidar mounting plate	355 lbs.	21.8 inches from the rear of the lidar (see figure 1-3)
Nacelle mounting plate	127 lbs.	21.2 inches from rear of plate (see figure 4)

Table 1: Expected Lift Loads

POSSIBLE CONSIDERATIONS.

Identify factors associated with this lift. Note, this list is not an exhaustive list.

- ☐ Weight Not Verified
- ☐ High Center of Gravity
- ☒ Stability of Load
- ☐ Awkward Size/Shape/Sharp Edges
- ☒ No Dedicated Lifting Points on Load
- ☐ No Lifting Point Directly Above Load
- ☒ Is the use of tag lines required? / If so, consider personnel positioning issues.
- ☒ Visibility issues? / Identify communication requirements
- ☒ Maintain Focus on Lift – Avoid distractions (cell phone)
- ☐ Rotation Of Load
- ☐ Multiple Crane Lift
- ☒ Other Dynamic Factors Involved
- ☐ Lack of Adequate Visibility
- ☐ Manbasket Lift
- ☐ Hazards to personnel in area
- ☒ Wind Limits and Considerations
- ☐ Environmental Factor (e.g. Freezing Conditions / Solar Flux) Describe:
- ☒ Other Considerations: No work beneath suspended loads.

ROUTE OF TRAVEL AND LAYDOWN AREA	Determination
1. Are the route and laydown area clear of obstructions?	☐ Yes ☒ No
2. Is the laydown/landing area adequate sized to accommodate the load?	☒ Yes ☐ No

3.	**Is suitable packing available to protect slings from sharp and small diameter edges?**	☒ Yes ☐ No
4.	**Have barricades been deployed to prevent access by unauthorized personnel?**	☒ Yes ☐ No
5.	**Have you confirmed that the laydown area is within the operating radius of the equipment?**	☒ Yes ☐ No
6.	**Have environmental conditions been considered regarding safety of the lifting operation?**	☒ Yes ☐ No
7.	**Does the crane operator have a clear view of the competent person directing the lift?**	☐ Yes ☒ No
8.	**Are other forms of communication available (e.g. radios)?**	☒ Yes ☐ No

STEP BY STEP DESCRIPTION OF THE LIFTING OPERATION

PHASE A - Pre-Lift Preparation

Stage Equipment

1. Site mobilization, staging of materials, and equipment.
2. Verify no loose components on the structure of the lidar mounting plate connecting it to the lidar.
3. Ensure cables located in the front/downwind side of the lidar are attached as they will not be accessible once installed. Secure these cables so they are not loose and the other end of the cable is accessible to a worker inside the nacelle after the lidar has been installed.
4. All shackles should have at least a 2 Ton rating and should be products that have been made in the USA.
5. All endless slings should have at least a 2 Ton rating and should be products that have been made in the USA.
6. Stage crane
7. As necessary, fall protection equipment will be used to facilitate safe access to interior of the nacelle. Established fall protection anchor point, Self Retracting Lifeline (SRL) / lanyard and full body harness will be used.
8. Inspect rigging, slings, and shackles. Verify condition and WLL for all rigging equipment
9. Wind turbine shall be stopped (LOTO applied) and placed in a rabbit ears configuration (one blade down). The turbine shall be facing the necessary direction given the predominant wind direction for the installation day.
10. The turbine roof shall be opened in order to maintain access above the top of the nacelle.
11. The rear hatch door of the nacelle secured so that it does not fall.
12. The rear hatch door's rivets will be drilled out (the rivets will be replaced with through bolts when reinstalled after the lidar is eventually removed).
13. Tools/miscellaneous hardware will be lifted into the nacelle using the tool haul rope through the rear of the nacelle. Ensure that the area below is clear of personnel during the lift.

PHASE B - Pre-Lift Safety Meeting

1. All lift participants to gather at central location after crane is in position and initial rigging is complete
2. Identify lift assignments (each person may have more than one assignment within the Table)
3. Assign radios, as deemed necessary by liftmaster; assign channel to be used and conduct radio check. Ensure that radios have adequate battery power or additional batteries available.
4. Step Through Pre-lift Safety Checklist
    - Discuss potential weather conditions for the lift. Determine actions to be taken in the event of high winds, or lightning in the area.
    - Warning: Lift must be suspended if prevailing winds exceed 10 m/s or more. Exclusions are permitted if agreed to in writing and signed by the machine operator, qualified rigging person in charge, and SWiFT Site Supervisor.
    - Communication between boom truck operator and the liftmaster will be provided by radio or hand signals agreed upon prior to lifting.
    - No access under the turbine or suspended loads is permitted during the lift
    - All persons have stop work authority

Handle	Person	Radio Required
Liftmaster	Don Baker	Yes
Uptower assembler	Andrew Scholbrock	No
Crane	TBD	Yes
Tag Line	TBD	Yes
Downtower assembler	TBD	Yes

PHASE C – Installation of nacelle mounting plate, lidar, and lidar mounting plate in nacelle of wind turbine

1. Place nacelle mounting plate in a haul bag rated for at least 1000 lbs. and pad any sharp corners around plate inside the haul bag to prevent damage and/or failure of the haul bag.
2. Attach haul bag straps to crane hook.
3. **Hold Point:** Ensure all personnel are clear of the load and its path of travel
4. Lift haul bag from ground up over the open roof of the nacelle. Total weight not to exceed 250 lbs.
5. Liftmaster will guide crane operator to lower the haul bag into the nacelle placing the bag to the port side of the generator.
6. **Hold Point**: Ensure all personnel are clear of any pinch points before setting the load down onto the nacelle.
7. The haul bag will be unhooked from the crane and the crane hook will go back to the ground in a reverse travel path.
8. The nacelle mounting plate will be fixed to the wind turbine nacelle before the next lift can occur The following steps will be used to fix the nacelle mounting plate:
    a. Use u-bolts to loosely fix wedge to aft cross beam
    b. Manually maneuver plate into place
    c. Loosely fit fore u-bolts (around generator pedestal)
    d. Align such that pivot point is centered under the centerline of the door and the plate is square with the rotor axis.
    e. Shim the nacelle plate so that it is level with the ground in fore-aft and side-side directions
    f. Realign plate as in 7d.
    g. Tighten down u-bolts to secure nacelle plate in place.
9. Setup rigging on ground for lidar and lidar mounting plate
    a. Using a choker configuration, place one sling (sling A) around the lidar in the "neck" in between the front optical head and white main lidar body.
    b. Using a choker configuration, place one sling (sling B) around the lidar in the "neck" in between the rear black control box and dark gray main lidar body.
    c. Using a choker configuration, place one sling (sling C) around the lidar in the "neck" in between the rear black control box and dark gray main lidar body. The connection of the choker to itself shall be made with a shackle so that it can be removed from this point by a worker in the nacelle. This sling will overlap sling B.
    d. Attach slings A and C to the crane hook.
    e. Add a tag line to the front of the lidar to aid in guiding the lidar and reducing the undesired rotation during the lift.
    f. Lift the lidar and lidar mounting plate a few inches off the ground to verify good pick and that determination of the center of gravity was correct. Lower and adjust if needed.
    g. Secure sling B so that it is not loose and is accessible to the worker inside the nacelle once the lidar outside the back of the nacelle.
10. **Hold Point**: Ensure all personnel are clear of the load and its path of travel
11. Lift lidar and lidar mounting plate from the ground and guide it to the rear of the turbine nacelle.
12. **Hold Point**: Ensure all personnel are clear of any pinch points before setting the load down onto the nacelle.
13. Continue guiding the lidar to the rear of the nacelle until the upwind side of the lidar mounting plate is just resting on the downwind side of the nacelle mounting plate.
14. Slowly slide the lidar inside the nacelle as much as the crane is capable of doing before the rigging touches the rear of the nacelle.
15. Use a rope and progress-capture-pulley to secure the lidar and lidar mounting plate in place by attaching the progress-capture-pulley to the gear box eye bolt and tying the rope to the upwind side of the lidar/mount assembly. Ensure that the pulley is oriented properly and the teeth cam is setup to capture the rope's progress of securing the load.
16. Have the crane lower the auxiliary hook and attach sling B to this hook through the roof and on the inside of the nacelle.
17. Raise the auxiliary hook slightly and maneuver the lidar/mount assembly until sling C becomes slack to the point that the choker shackle connection can be removed.
18. Remove sling C from the lidar (sling C will remain attached to the crane hook as it will not be accessible) and place the shackle aside in the turbine nacelle.
19. Slide the lidar the remaining distance until the lidar mounting plate slots are fairly aligned with the nacelle mounting plate tapped holes.
20. Bolt down the lidar mounting plate to the nacelle mounting plate. Fix the pivot pin to the pivot hole through both plates.
21. Remove the remaining slings from the crane hook and from the lidar, placing slings in the haul bag.
22. Remove the tag line and ensure no one is in drop path, then drop the tag line.
23. Remove the rope from the progress capture pulley, and remove rope from lidar.
24. Place loose rigging/positioning equipment in haul bag and attach haul bag to the main crane hook.
25. **Hold Point**: Ensure all personnel are clear of the load and its path of travel
26. Lift haul bag up, out and away from nacelle and lower haul bag to the ground.
27. **Hold Point**: Ensure all personnel are clear of any pinch points before setting the load down onto the ground.
28. Set haul bag on the ground and remove from crane hook.
29. Debrief and demobilize
    a. Collect comments from all lift members
    b. Stow equipment
    c. Complete lift debrief

LIFT PLAN – PART 2 (To be completed by the Competent Person)

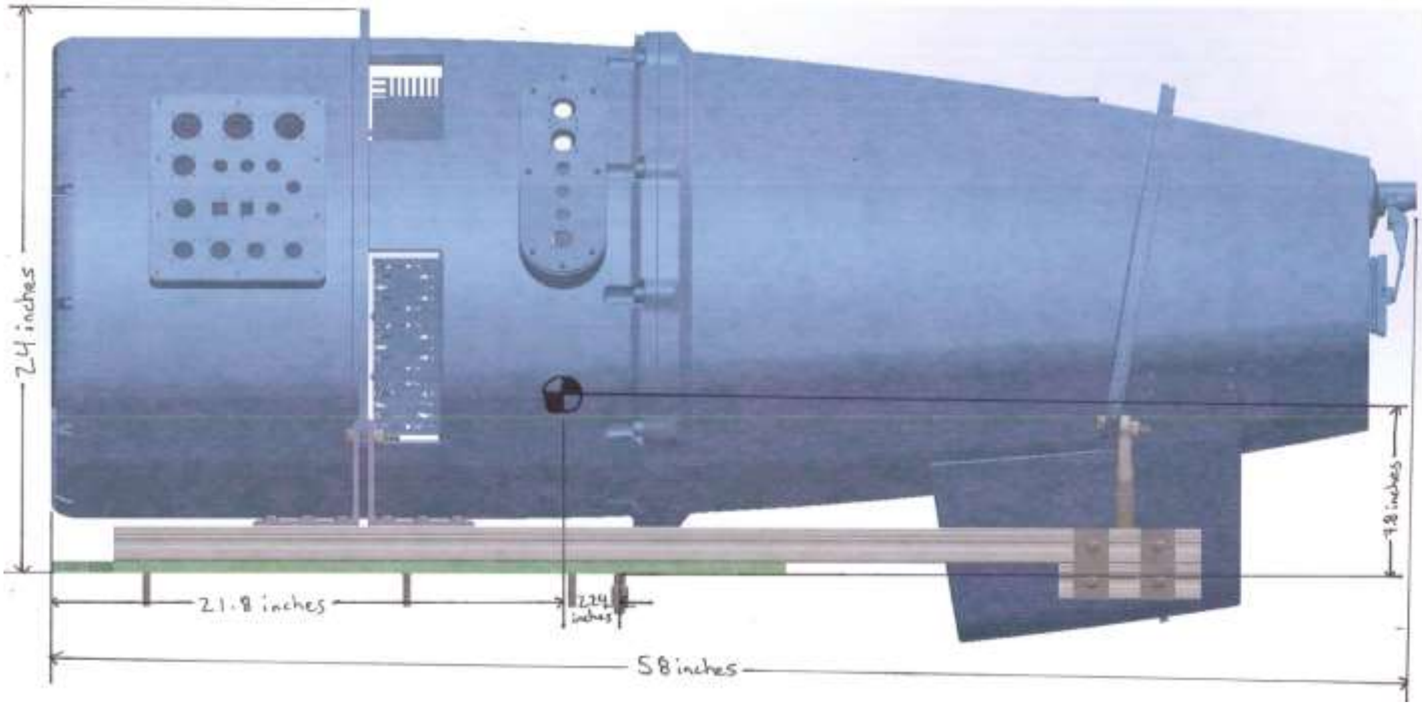


Figure 1 - Side view of lidar and lidar mounting plate with connecting hardware.

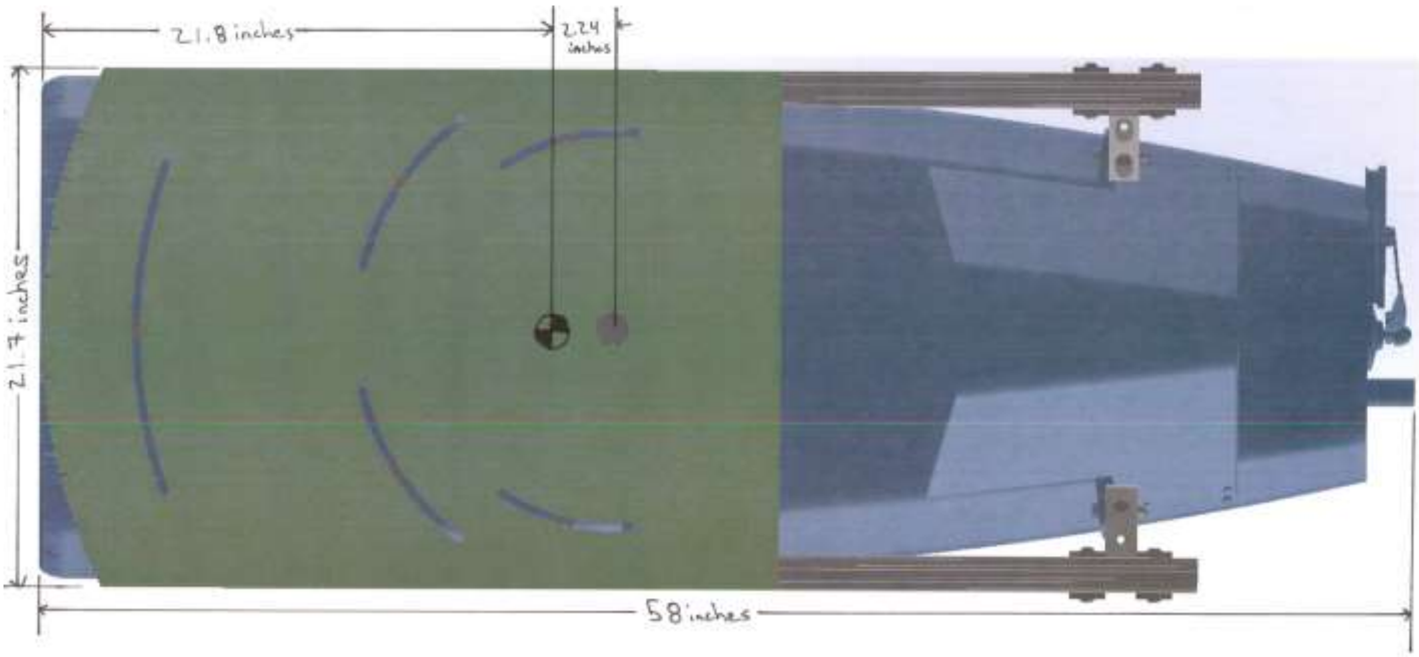


Figure 2 - Bottom view of lidar and lidar mounting plate with connecting hardware.

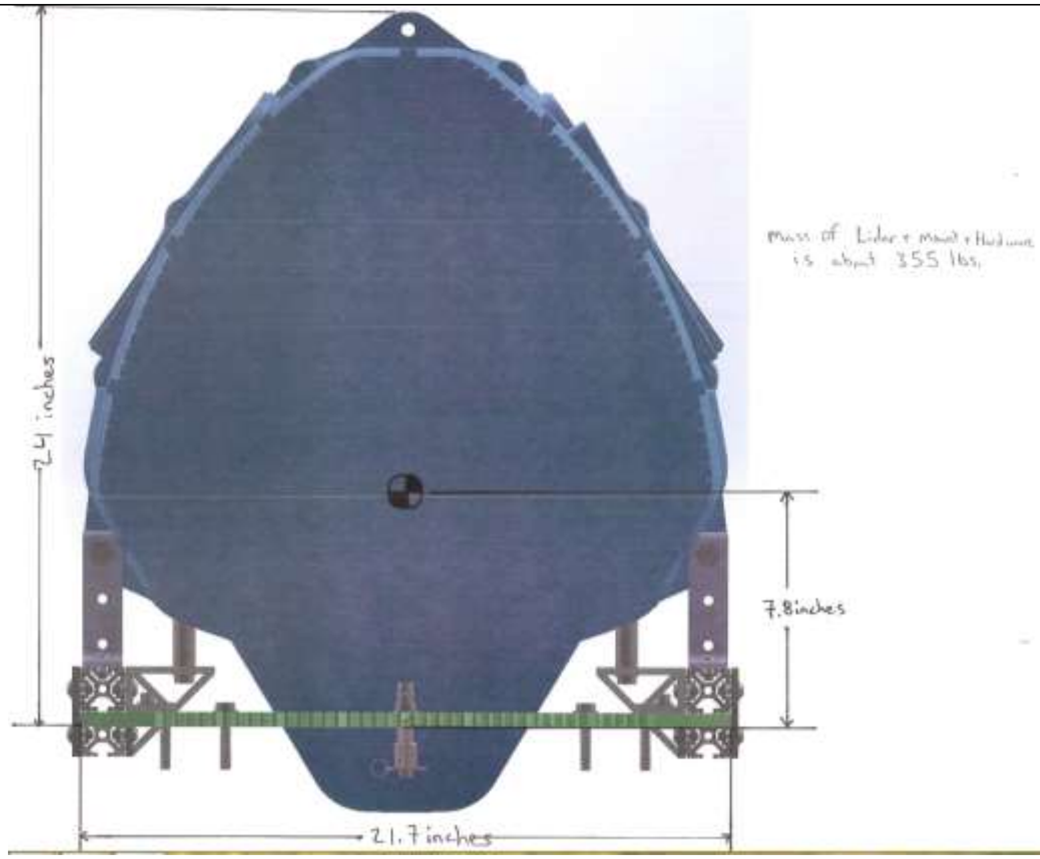


Figure 3 - Back view of lidar and lidar mounting plate with connecting hardware.

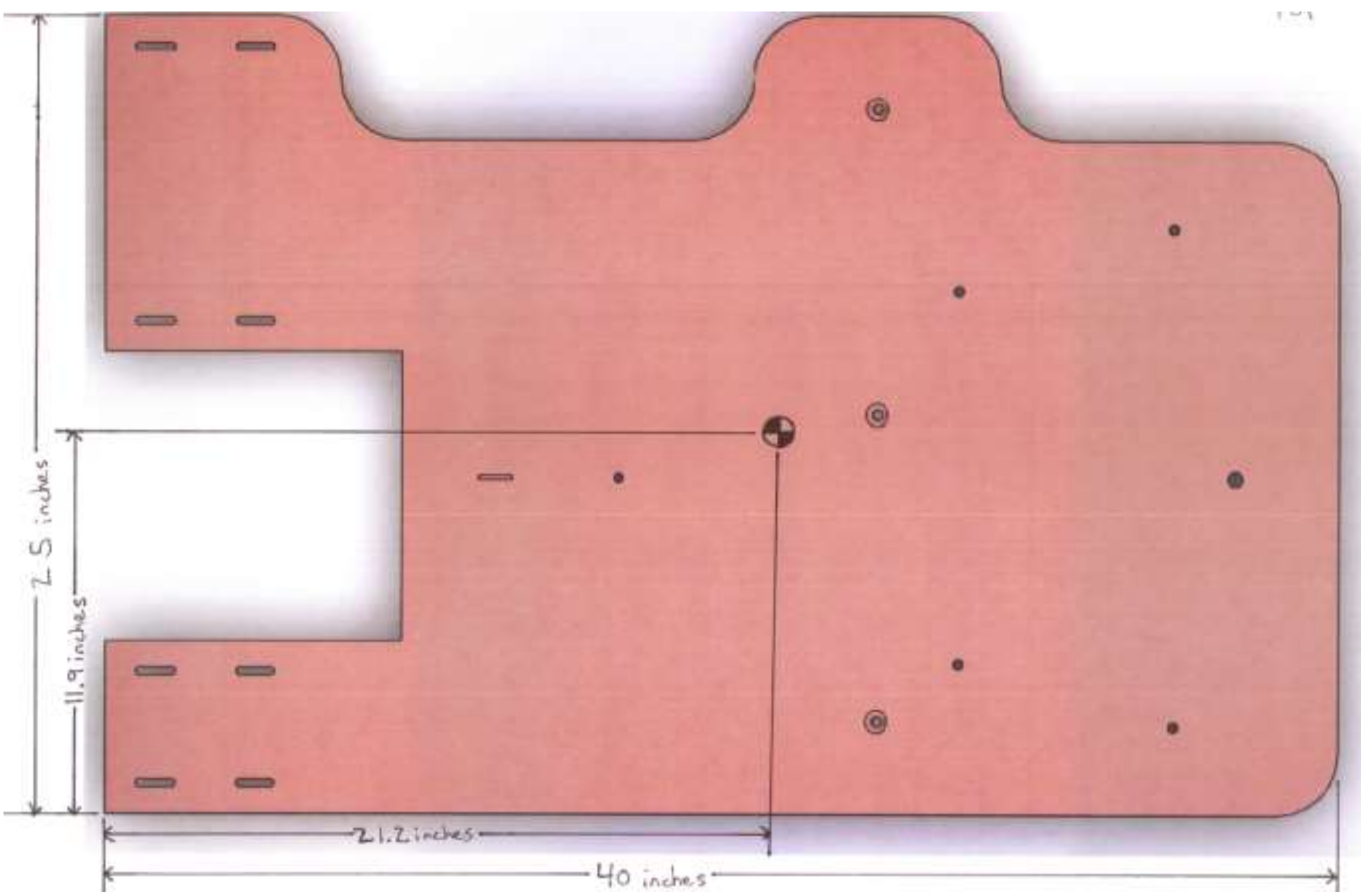


Figure 4 – Nacelle mounting plate

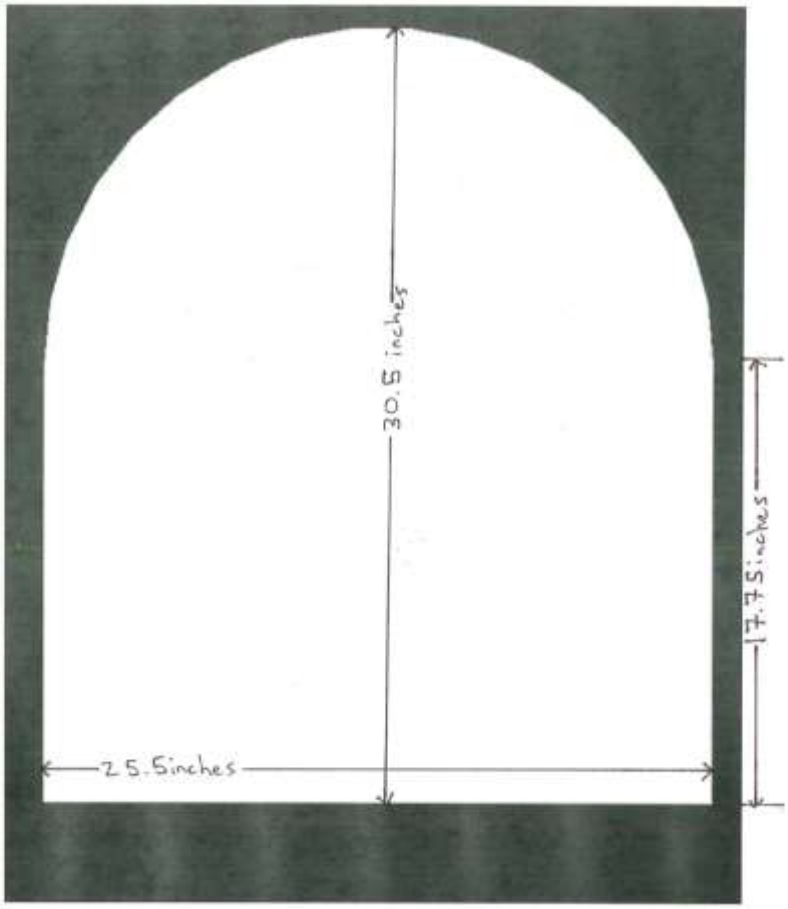


Figure 5 – Dimensions of rear door hatch in the back of the nacelle.

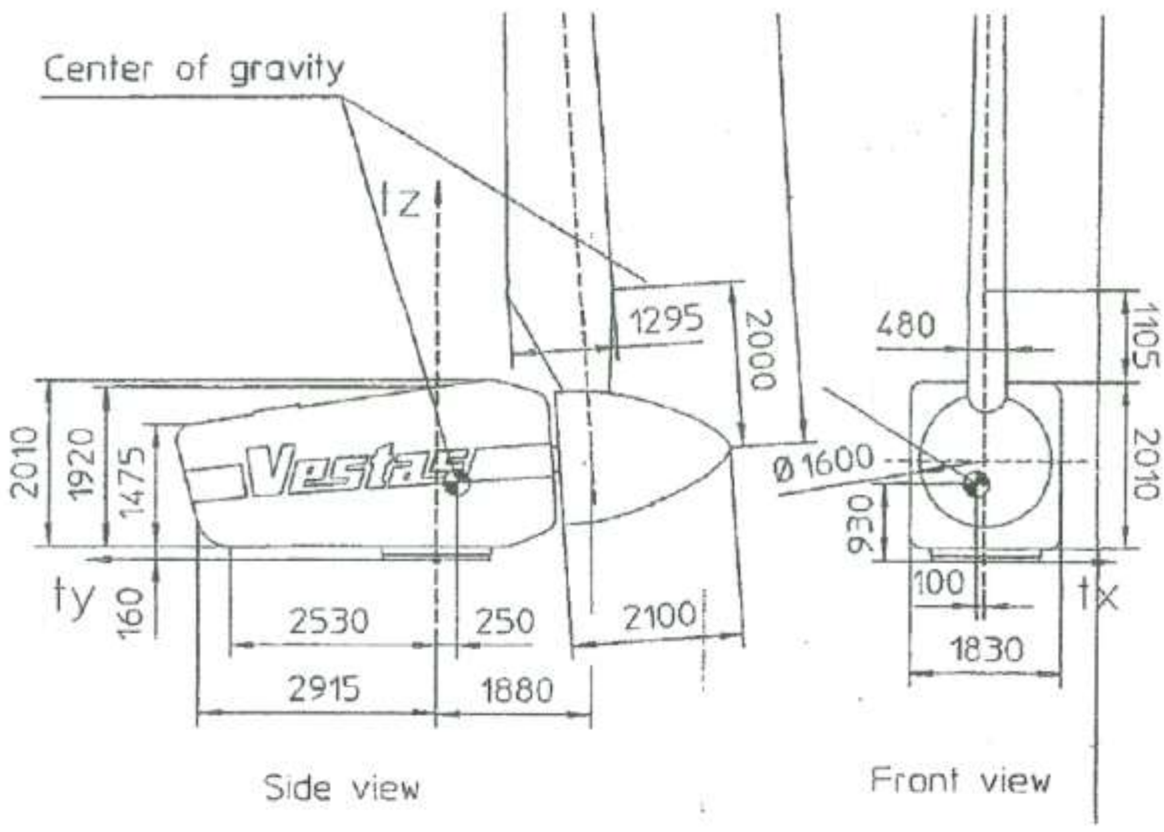


Figure 6 – Schematic showing dimensions of the nacelle.

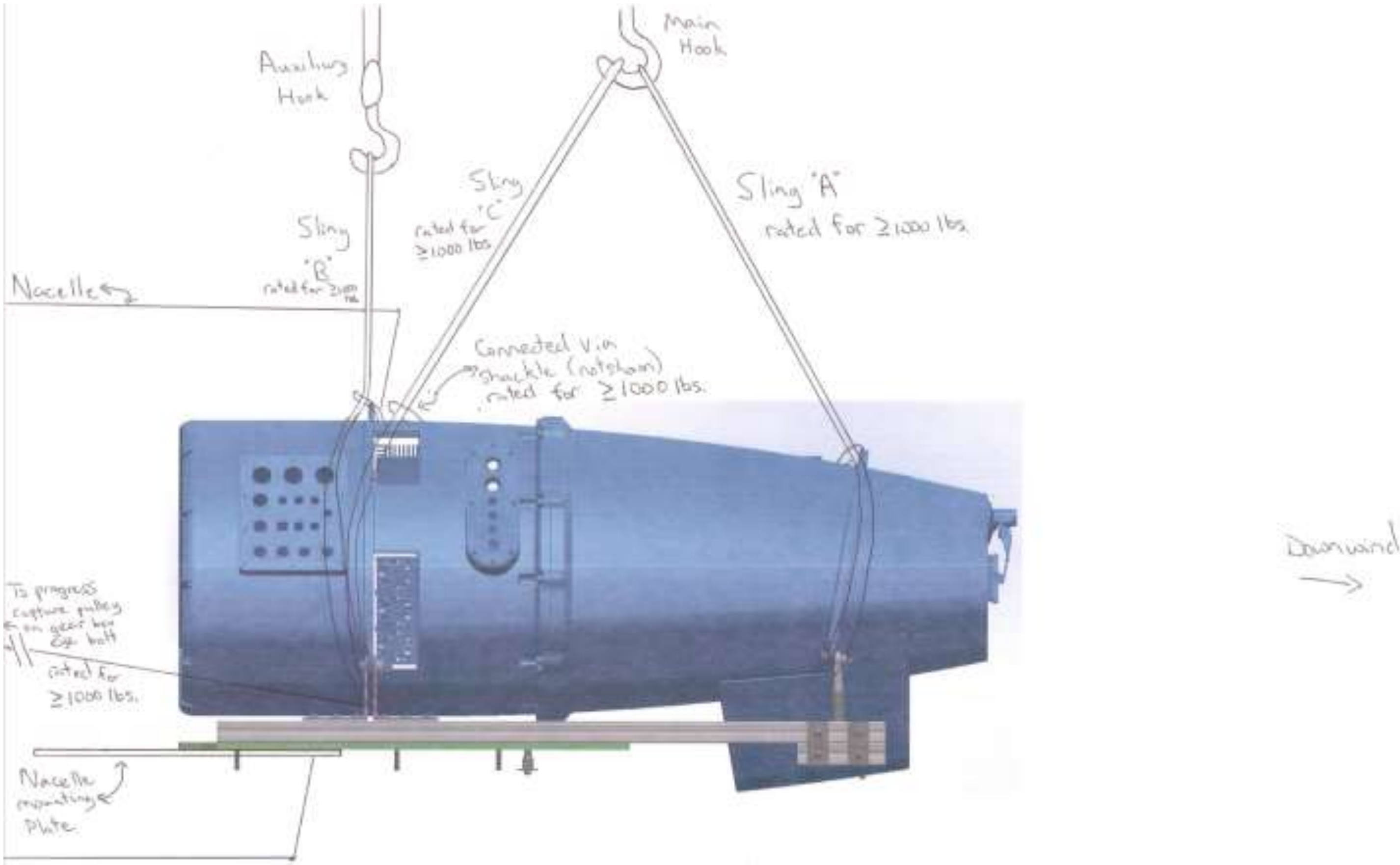


Figure 7 – Sketch of the rigging of the lidar when attached to both the main hook and the auxiliary hook (side view).

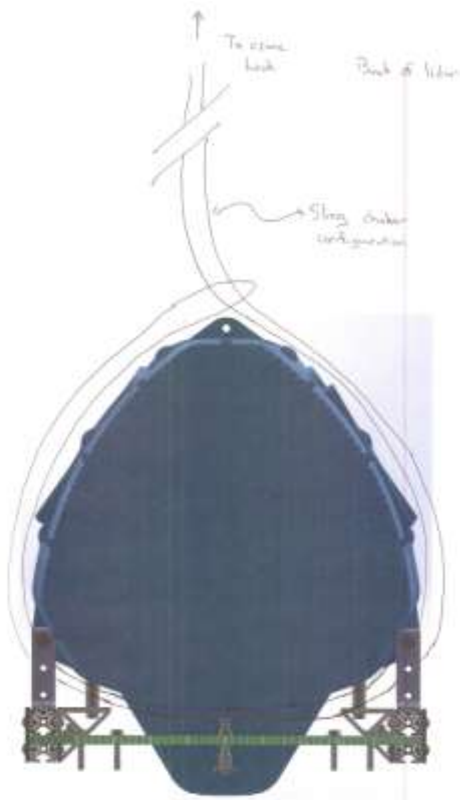


Figure 8 – Sketch of the rigging of the lidar when viewed from the back of the lidar looking downwind.

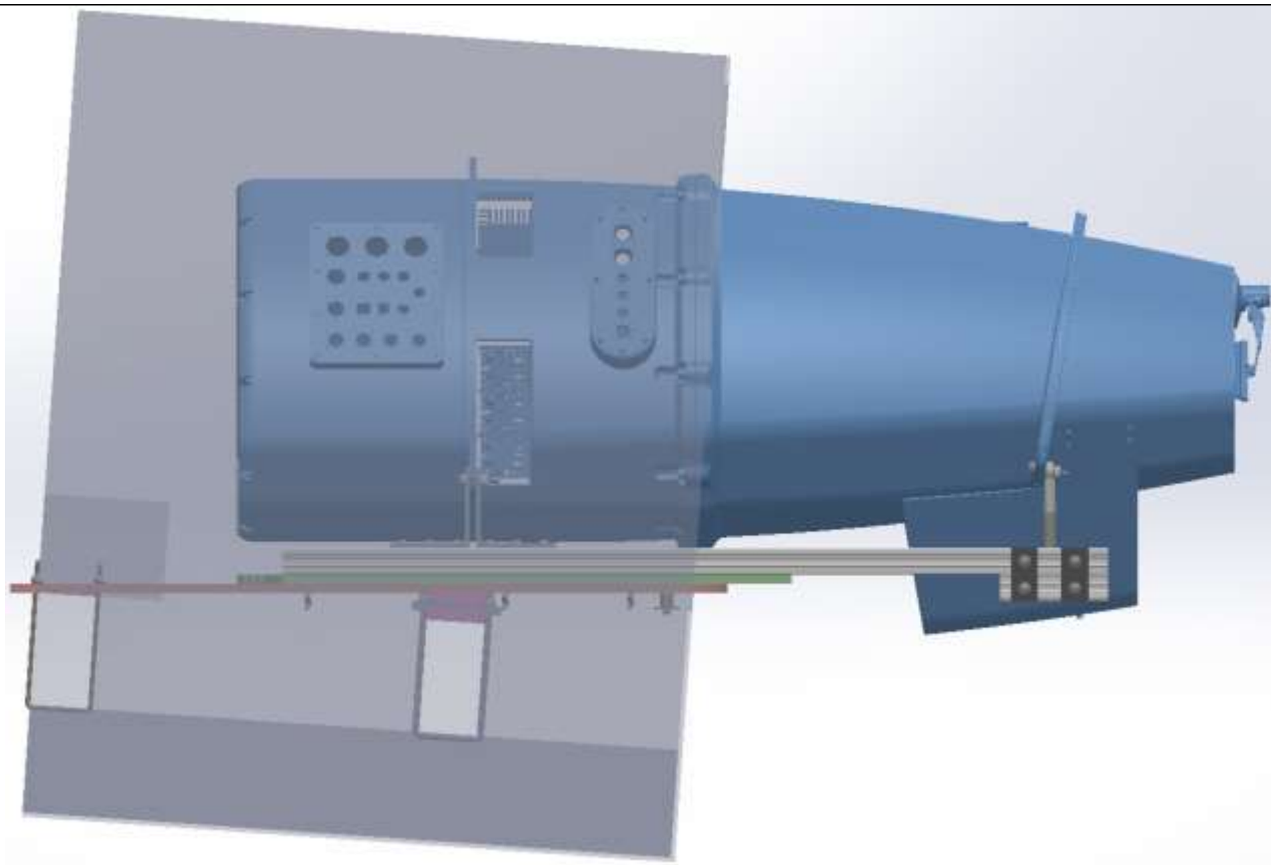


Figure 9 – Installed side view showing the lidar (blue), lidar mounting plate (green), nacelle mounting plate (red), and nacelle (transparent gray).

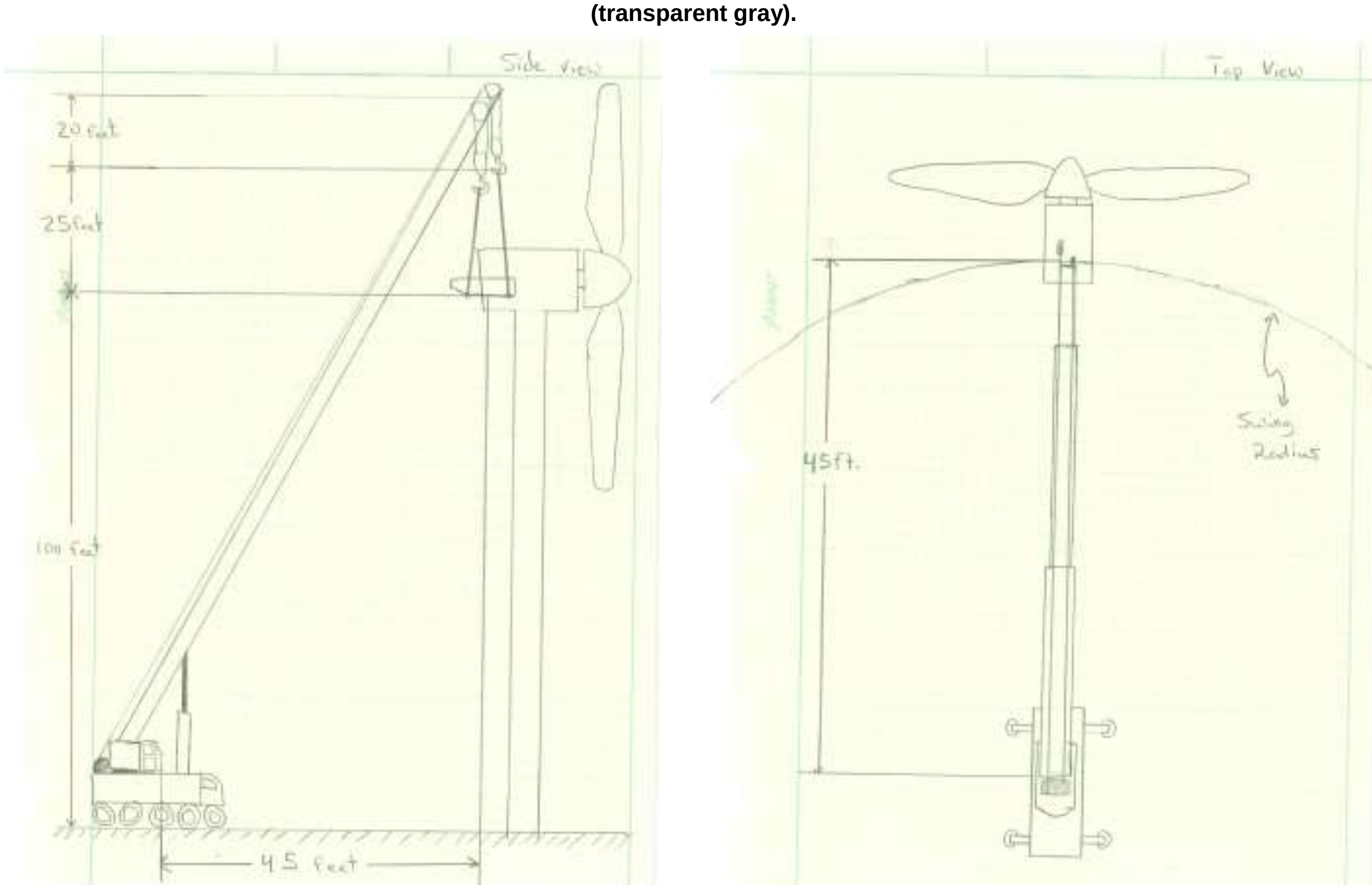


Figure 10 – Side and Top view of crane position relative to turbine with dimensions of distance from turbine, working height, and load height.

Manitowoc

Grove TMS9000E
Product Guide

Features

- 90 t (110 USt) capacity
- 11,2 m - 43,4 m (36 ft - 142 ft) five-section full power boom
- Patented TWIN-LOCK™ boom pinning system
- 10 m - 17 m (33 ft - 56 ft) bi-fold lattice swingaway extension
- Optional lattice insert extensions for a 72,2 m (237 ft) maximum tip height
- Tiltable superstructure cab
- Up to 21 300 kg (48,500 lb) counterweight with hydraulic removal system

Specifications

Superstructure

Boom

11,2 m - 43,4 m (37 ft - 142 ft) five-section, full power boom with TWIN-LOCK™ boom pinning system. Maximum tip height: 45,8 m (150 ft).

Boom nose

Five nylatron sheaves, mounted on heavy duty tapered roller bearings with removable pin-type rope guards. Quick reeve boom nose. Removable auxiliary boom nose with removable pin type rope guard.

Boom elevation

Single lift cylinder with safety valve provides boom angle from -3° to +82°.

Offsettable lattice extension

10 m - 17 m (33 ft - 56 ft) bi-fold lattice swingaway extension manual offset at 0°, 20°, and 40°. Maximum tip height: 63,1 m (207 ft).

*Optional offsettable lattice extension

10 m - 17 m (33 ft - 56 ft) bi-fold lattice swingaway extension hydraulically offset from 5° - 40°. Controlled from the crane cab.
Maximum tip height: 63,1 m (207 ft).

*Lattice extension

Two 5 m (16 ft) inserts for use with lattice swingaway extension to increase length up to 21,9 m (72 ft) or 26,8 m (88 ft).
Maximum tip height: 72,2 m (237 ft)

Load moment and anti-two block system

Load moment and anti-two block system with audio/visual warning and control lever lockout provides electronic display of boom angle, length, radius, tip height, relative load moment, maximum permissible load, load indication and warning of impending two-block condition.

Cab

All aluminum construction cab with acoustical lining is hydraulically tiltable to +20° and includes tinted safety glass, adjustable operator's seat with hydraulic suspension, sliding windows in side and cab rear, hinged front window with wiper, sun visor and window shade. Other features include diesel heater/defroster, armrest integrated crane controls, and ergonomically arranged instrumentation.

Crane control system

Full control of all crane movements using electrical control levers with automatic reset to zero. Controls are integrated with the LMI and engine management system by CAN-BUS. ECOS system with graphic display.

Swing

Two planetary gear boxes with axial piston fixed displacement motors. Infinitely variable to 1.7 rpm. Holding brake and service brake.

Counterweight

7258 kg (16,000 lb) consisting of various sections with hydraulic installation/removal system operated from the cab.
*Optional "Heavy Lift" counterweight package consisting of (2) 4636 kg (10,000 lb) sections in addition to standard, for a total of 16 329 kg (36,000 lb).
*Optional "XL" counterweight package consisting of (2) 1814 kg (4000 lb) and (2) 1021 kg (2250 lb) wing sections in addition to standard and "Heavy Lift" package, for a total of 21 999 kg (48,500 lb).

Hydraulic system

2 separate circuits, 1 axial piston variable displacement pump (load sensing) with electronic power limiting control and 1 gear pump for swing.
2 thermostatically controlled oil coolers keep oil at optimum operating temperature.
Tank capacity: 508 l (134 gal)

*Denotes optional equipment

Specifications

Superstructure continued

Hoist

Main and auxiliary hoists are powered by axial piston motor with planetary gear and brake. "Thumb-thumper" hoist drum rotation indicator alerts operator of hoist movement. Standard fifth wrap indication with shutoff.

Hoist line pull:
1st Layer: 10 034 kg (22,122 lb)
3rd Layer: 8466 kg (18,665 lb)
5th Layer: 7322 kg (16,142 lb)

Maximum line speed:
111 m/min (365 fpm)

Maximum permissible line pull:
7621 kg (15,700 lb) 34x7 Rotation Resistant
*Optional 7784 kg (17,160 lb) 35X7 Class
Rope diameter: 19 mm (3/4")

Rope length: 225 m (738 ft)
Casar Eurolift/Endurance Dyform
214 m (702 ft) 35X7 Flex-x

Maximum rope storage: 300 m (984 ft)

Carrier

Chassis

Triple box section, four-axle carrier, fabricated from high strength, low alloy steel with towing and tie-down lugs.

Outrigger system

Four hydraulic telescoping, two-stage, double box beam outriggers with inverted jacks and integral holding valves. Quick release type outrigger floats 610 mm (24 in) diameter. Three position setting with fully extended, intermediate (50%) extended and fully retracted capacities. Outrigger monitoring system.

Maximum outrigger pad load: 49 442 kg (109,000 lb).

Outrigger controls

Located in the superstructure cab and on either side of carrier. Crane level indicators located at all stations. Auto leveling standard.

Engine- North America

Cummins ISX 11.9 six-cylinder, turbo-charged and after-cooled diesel engine. 11.9 L (729 in³) 336 kW (450 bhp) at 1800 rpm. Maximum torque 2102 Nm (1550 lb-ft) at 1400 rpm. 2010 "On Highway" EPA, CARB compliant.

Equipped with engine compression brake, audio-visual engine distress system and ether cold start aid.

Fuel Requirement: Maximum of 15 ppm sulfur content (Ultra Low Sulfur Diesel). Diesel exhaust fluid required.

Engine- Export

Cummins QSM 11 six cylinder, turbo charged and after-cooled diesel engine. 10.8 L (660 in³), 300 kW (402 bhp) at 1800 rpm. Maximum torque 1898 Nm (1400 lb-ft) at 1400 rpm. Tier III "Off-Highway" EPA, CARB and EU Stage IIIA compliant.

Equipped with engine compression brake, audio-visual engine distress system and ether cold start aid.

Fuel Requirement: Maximum of 5000 ppm sulfur content.

Fuel tank capacity

376 L (100 gal)

Transmission

Roadranger 11 speeds forward, 3 reverse, manual.

Steering

Front axles, single circuit, mechanical steering with hydraulic power assist. Turning radius: 13,7 m (45.1 ft).

Axles

Front: (2) beam-type steering axles, 2,12 m (83.4 in) track.
Rear: (2) single reduction drive axles, 1,89 m (74.5 in) track. Inter-axle differential locks.
Drive: 8 x 4 x 4.

*Denotes optional equipment

Specifications

Carrier continued

Brakes

S-cam, dual air split system operating on all wheels. Spring-applied, air released parking brake acting on rear axles. Air dryer.
ABS with traction control.

Suspension

Front: Walking beam with air bags and shock absorbers.
Rear: Walking beam with air bags and shock absorbers.

Tires

Front: 445/65R 22.5 tubeless, mounted on aluminum disc wheels.
Rear: 315/80R 22.5 tubeless, mounted on aluminum disc outer wheels, inner wheels steel.

Lights

Full lighting package including turn indicators, head, tail, brake, and hazard warning lights.
Meets FMVSS and CMVSS standards.

Cab

One man design, aluminum fabricated with acoustical lining and tinted safety glass throughout. Deluxe fabric covered seat with air adjustment. Complete driving controls and engine instrumentation including tilt telescope steering wheel, tachometer, speedometer, voltmeter, water temp., oil pressure, fuel level, air pressure gauge, engine high temp./low oil pressure A/V warning. Other standard items include hot water heater/defroster, electric windshield wash/wipe, fire extinguisher, seat belt and door lock.

Electrical system

Four maintenance-free batteries provide 24 V electrical system. Standard battery disconnect.

Maximum speed

105 kph (65 mph)

Gradeability (theoretical)

70%

Miscellaneous standard equipment

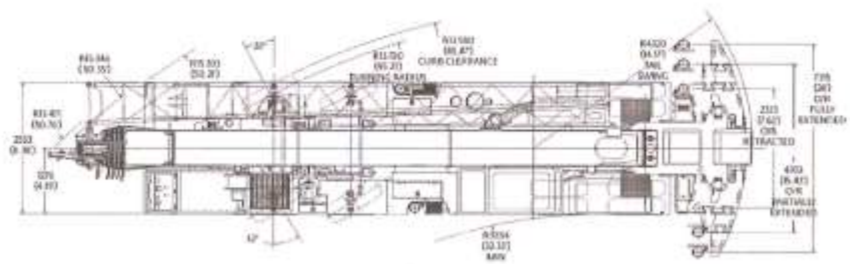
Aluminum fenders with rear storage compartments; dual rear view mirrors; electronic back-up alarm; sling/tool box; tire inflation kit; air cleaner restriction indicator; headache ball stowage; air conditioning; traction control; air horn; CraneSTAR asset management system.

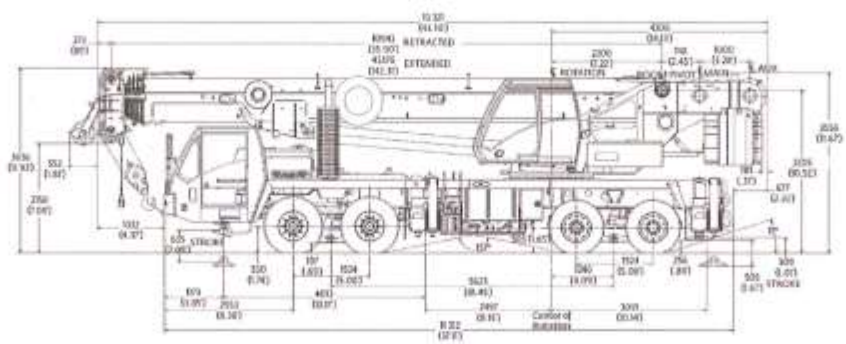
*Optional equipment

- Auxiliary Lighting and Convenience Package: Includes amber strobe light for superstructure and carrier cab, and boom mounted aircraft warning light (fully wired)
- Dual boom base mounted floodlights
- Hook blocks
- Pintle hook (rear)
- Trailing Boom Package
- Aluminum outrigger pads
- Counterweight packages
- Tow cable
- Wind speed indicator
- Winterfront radiator cover
- Additional storage
- Counterweight slings
- Cross axle differential locks
- 360° house lock

*Denotes optional equipment

Dimensions



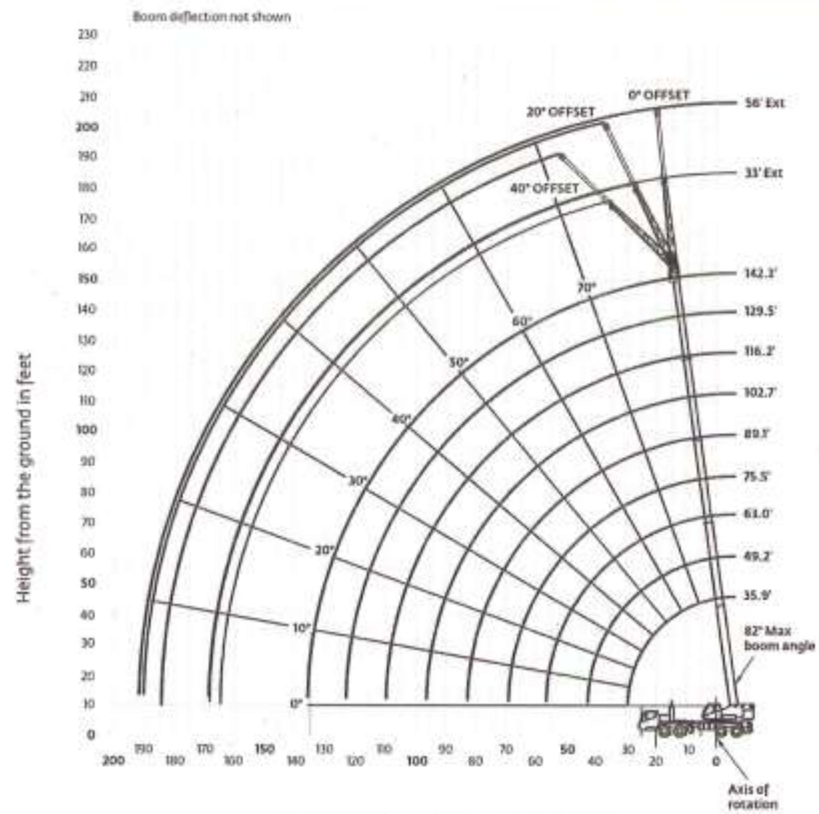


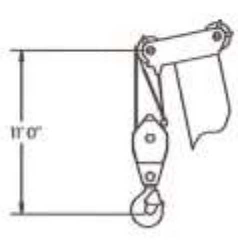
Dimensions shown in mm (ft)

Working range

Main boom and manual extension

36 ft - 142 ft main boom and manual lattice extension





Dimensions area for largest Grove furnished hookblock and headache ball, with anti-two block activated.

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Load charts
Main boom

36 ft - 142 ft Fixed lengths | 48,500 lb | 100% 24 ft 0 in | 360°

Pounds (thousands)

Feet	35.9'	49.2'	63.0'	75.5'	89.1'	102.7'	116.2'	129.5'	142.3'
8	*220,000								
9	*185000								
10	165,000	138,000	130,500	91,000	83,000				
12	151,000	138,000	129,500	91,000	83,000				
15	131,500	127,500	122,500	91,000	83,000	60,350			
20	105,500	105,500	101,000	99,400	81,500	60,350	44,500	33,450	
25	83,600	85,750	84,300	84,550	73,500	56,750	44,500	33,450	26,700
30		70,150	70,600	70,250	65,600	50,100	44,250	33,450	26,700
35		58,050	58,600	57,850	59,350	44,700	40,100	33,450	26,700
40		48,050	48,950	48,250	49,550	40,150	36,250	32,850	26,700
45			41,600	43,050	42,250	36,350	32,400	30,050	26,700
50			37,000	37,450	36,600	32,650	29,550	27,550	25,550
55			27,450	32,650	31,950	30,250	27,050	25,300	24,300
60				28,700	27,950	28,200	24,900	23,150	22,350
65				25,350	24,700	25,400	23,000	20,550	20,750
70					22,100	22,700	21,200	20,000	19,300
75					20,850	20,400	19,500	18,600	18,000
80					19,300	18,450	18,400	16,650	16,100
85						16,700	16,750	15,550	15,100
90						15,250	15,600	14,300	14,150
95						11,500	14,250	13,400	13,300
100							11,050	12,700	12,150
105							11,000	11,950	11,250
110								11,000	10,400
115								10,100	9570
120								9360	8780
125									8070
130									7420
135									4330
140									

*Requires special equipment

36 ft - 142 ft Fixed lengths | 44,000 lb | 100% 24 ft 0 in | 360°

Pounds (thousands)

Feet	35.9'	49.2'	63.0'	75.5'	89.1'	102.7'	116.2'	129.5'	142.3'
10	165,000	138,000	130,500	91,000	83,000				
12	151,000	138,000	129,500	91,000	83,000				
15	131,500	127,500	122,500	91,000	83,000	60,350			
20	105,500	105,500	101,000	99,400	81,500	60,350	44,500	33,450	
25	82,900	84,900	83,600	84,550	73,500	56,750	44,500	33,450	26,700
30		68,050	68,650	68,200	65,600	50,100	44,250	33,450	26,700
35		56,000	56,450	55,700	57,050	44,700	40,300	33,450	26,700
40		46,500	47,100	47,450	47,700	40,150	36,250	32,850	26,700
45			40,300	41,500	40,650	36,350	32,400	30,050	26,700
50			35,600	35,550	34,700	32,650	29,550	27,550	25,350
55			27,450	30,800	30,050	30,250	27,050	25,300	24,300
60				27,000	26,250	27,000	24,900	23,350	22,350
65				23,850	23,550	23,850	22,350	21,550	20,750
70					22,050	21,300	20,700	20,000	19,300
75					19,800	19,100	19,400	18,050	18,000
80					17,900	17,250	17,500	16,150	16,300
85						15,650	15,950	15,050	15,300
90						14,250	14,550	14,200	13,800
95						11,500	13,250	13,150	12,550
100							12,150	12,050	11,450
105							11,300	11,050	10,450
110								10,750	9570
115								9310	8760
120								8990	8060
125									7330
130									6720
135									4980
140									

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Load charts

Main boom

36 ft - 142 ft Fixed lengths | 26,000 lb | 100% 24 ft 0 in | 360°

Pounds (thousands)

Feet	35.9'	49.2'	63.0'	75.5'	89.1'	102.7'	116.2'	129.5'	142.3'
10	165,000	138,000	130,500	111,000	83,000				
12	151,000	138,000	129,500	111,000	83,000				
15	128,500	127,500	122,500	111,000	83,000	60,150			
20	95,750	97,750	98,300	97,600	81,500	60,150	44,500	33,450	
25	72,700	74,650	75,250	74,750	73,500	56,750	44,500	33,450	26,700
30		58,850	59,100	59,700	59,750	50,100	44,250	33,450	26,700
35		46,850	47,850	47,700	46,800	44,700	40,300	33,450	26,700
40		37,500	38,650	38,500	37,050	38,750	36,250	32,850	26,700
45			32,100	31,950	31,900	32,000	30,300	30,050	26,700
50			27,150	27,100	27,850	27,050	27,350	25,900	25,950
55			21,850	24,250	24,050	23,250	23,550	23,350	22,700
60				21,300	20,950	21,250	20,500	20,350	19,700
65				18,750	18,450	18,700	18,300	17,850	17,200
70					16,400	16,600	16,200	15,900	15,250
75					14,750	14,950	14,550	14,350	13,500
80					13,350	13,400	13,000	12,600	11,950
85						12,050	11,650	11,250	10,600
90						10,900	10,500	10,100	9470
95						7430	9480	9070	8450
100							8580	8170	7550
105							7770	7360	6740
110								6640	6020
115								6000	5380
120								5400	4750
125									4260
130									3770
135									3330
140									

36 ft - 142 ft Fixed lengths | 11,000 lb | 100% 24 ft 0 in | 360°

Pounds (thousands)

Feet	35.9'	49.2'	63.0'	75.5'	89.1'	102.7'	116.2'	129.5'	142.3'
10	164,000	138,000	130,500	111,000	83,000				
12	147,000	138,000	129,500	111,000	83,000				
15	120,500	123,000	121,000	111,000	83,000	60,150			
20	84,900	80,900	87,500	86,750	81,500	60,150	44,500	33,450	
25	61,950	63,550	63,850	65,650	64,500	56,750	44,500	33,450	26,700
30		46,400	47,550	47,400	46,400	45,400	44,250	33,450	26,700
35		35,500	36,500	36,350	37,300	36,350	35,850	33,450	26,700
40		28,300	29,250	30,400	30,000	30,000	29,500	29,350	26,700
45			24,100	25,000	24,650	24,950	24,500	23,950	23,200
50			20,000	20,900	20,850	20,800	20,350	19,900	19,150
55			15,200	17,750	17,650	17,650	17,200	16,750	16,000
60				15,300	15,250	15,250	14,800	14,350	12,700
65				13,250	13,200	13,200	12,800	12,350	11,700
70					11,500	11,500	11,100	10,700	10,050
75					10,300	10,300	9730	9310	8660
80					8920	8930	8530	8110	7470
85						7890	7500	7080	6450
90						7000	6600	6190	5560
95						3750	5800	5400	4770
100							5120	4700	4080
105							4400	4090	3470
110								3530	2910
115								3040	2420
120								2580	1970
125									1500
130									1100
135									
140									

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Load charts
Main boom

36 ft - 142 ft Fixed lengths | 0 lb | 100% 24 ft 0 in | 360°

Pounds (thousands)

Feet	36.9'	49.2'	63.0'	75.5'	89.1'	102.7'	116.2'	129.5'	142.3'
10	158,500	138,000	130,500	111,000	83,000				
12	141,500	138,000	129,500	111,000	83,000				
15	110,000	112,000	111,500	111,000	83,000	60,150			
20	75,800	77,850	78,200	78,900	79,000	60,150	44,500	33,450	
25	48,000	50,650	51,950	51,750	50,650	49,800	44,500	33,450	26,700
30		35,900	37,100	38,400	37,950	37,550	37,210	33,450	26,700
35		26,450	27,850	28,900	28,850	28,850	28,300	27,750	26,700
40		20,350	21,800	22,900	22,550	22,950	22,050	21,500	20,700
45			17,200	18,200	18,150	18,150	17,700	17,150	16,400
50			14,150	15,050	13,000	15,000	14,350	14,100	13,350
55			10,000	12,950	12,500	12,500	12,300	11,650	10,950
60				10,600	10,550	10,550	10,150	9710	9030
65				9040	8880	8980	8570	8040	7470
70					7670	7670	7260	6840	6150
75					6570	6560	6160	5740	5060
80					5620	5620	5210	4820	4170
85						4820	4420	4030	3370
90						4120	3720	3310	2680
95						3050	3100	2690	2070
100							2560	2150	1510
105							2070	1670	1050
110								1240	
115									
120									

Load handling

11,2 m - 43,4 m (33 ft - 56 ft) folding boom extension (luffing or manual)

	298 kg (657 lb) hook block	
	Without	With
*33 ft extension (erected)	2994 kg (6600 lb)	4899 kg (10,800 lb)
*56 ft extension (erected)	5579 kg (12,300 lb)	8754 kg (19,300 lb)

*Reduction of main boom capacities

When lifting over main boom nose with 11,2 m or 43,4 m (33 ft or 56 ft) extension erected, the outriggers must be fully extended or 50% extended (4,7 m [15 ft 5 in] spread)

NOTE: All load handling devices and boom attachments are considered part of the load and suitable allowances MUST BE MADE for their combined weights. Weights are for Grove furnished equipment.

Auxiliary boom nose	60 kg (133 lb)

Hook blocks and headache balls:	
73 t (80 Ust), 5-sheave	730 kg (1609 lb) +
55 t (60 USt), 5-sheave	581 kg (1281 lb) +
36,3 t (40 Ust), 3-sheave	462 kg (1019 lb) +
22,7 t (25 Ust), 1-sheave	298 kg (657 lb) +
7,5 t (8,3 Ust), overhaul ball	161 kg (355 lb) +

+ Refer to rating plate for actual weight.

When lifting over extension and/or jib combinations, deduct total weight of all load handling devices reeved over main boom nose directly from swingaway or jib capacity.

Hoists	Cable specs	Permissible line pulls	Nominal cable length
Main and auxiliary	19 mm (3/4 in) Caser Eurolift Rotation Resistant Min. breaking strength 35 690 kg (78,683 lb)	7138 kg (15,736 lb)	225 m (738 ft)
Main and auxiliary	19 mm (3/4 in) Endurance Dyform 34 LR Rotation Resistant. Left Lang Lay Min. Breaking Strength 36 287 kg (80,000 lb)	7138 kg (15,736 lb)	225 m (738 ft)
Main and auxiliary	19 mm (3/4 in) 35x7 Class Rotation Resistant Min. breaking strength 38 918 kg (85,800 lb)	7784 kg (17,160 lb)	(214 m) 702 ft

The approximate weight of 19 mm (3/4 in) wire rope is 2.2 kg/m (1.5 lb/ft)

Hoist performance

Wire rope layer	Hoist line pools	Drum rope capacity m (ft)	
	Available kg (lb)*	Layer	Total
1	10 034 kg (22,122 lb)	33,5 m (109.95 ft)	33,5 m (109.95 ft)
2	9184 kg (20,247 lb)	36,6 m (120.14 ft)	70,1 m (230.09 ft)
3	8466 kg (18,665 lb)	39,7 m (130.32 ft)	109,9 m (360.41 ft)
4	7853 kg (17,312 lb)	42,8 m (140.50 ft)	152,7 m (500.91 ft)
5	7321 kg (16,142 lb)	45,9 m (150.68 ft)	198,6 m (651.59 ft)
6	6858 kg (15,120 lb)	49,0 m (160.87 ft)	247,6 m (812.46 ft)

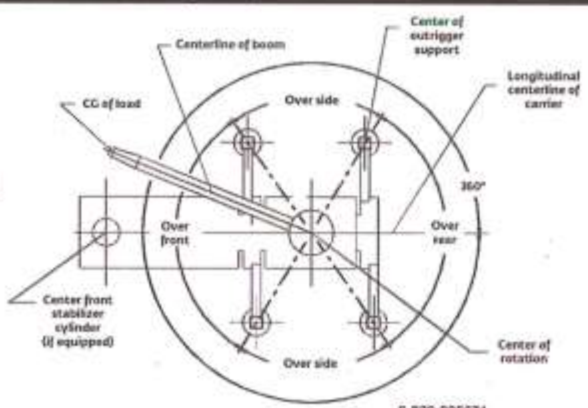
*Max lifting capacity

19 mm Casar Eurolift: 7138 kg (15,736 lb)

19 mm 35x7 Class: 7784 kg (17,160 lb)

Working area diagram

Bold lines determine the limiting position of any load for operation within working areas indicated.



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The individual crane's load chart, operating instructions and other instructional plates must be read and understood prior to operating the crane.

LIFTING EQUIPMENT AND ACCESSORIES INFORMATION - List the type and SWL of equipment used.

1. Crane with auxiliary hook and adequate working height
2. Rigging
    a. Three 30-foot-slings with each having at least a 1000 lbs. rating in a choker configuration.
    b. 3/8 inch haul rope for positioning with at least a 1000 lb. rating
    c. Progress-capture-pulley with at least a 1000 lb. rating
    d. Triple-action locking carabiner with at least a 1000 lb. rating
    e. 3 shackles each rated for at least 1000 lbs.
    f. Haul bag large enough to fit nacelle mounting plate inside and have at least a 1000 lb. rating
3. PPE (hard hats, safety glasses, gloves, high visibility vests, fall protection equipment)
4. Tagline
5. Radios, as deemed necessary by liftmaster
6. Miscellaneous
    a. Camera
    b. Anemometer
    c. Lightning detection system

DEBRIEF AND LESSONS LEARNED - Did the lifting operation go as planned or are changes to the lift plan required?

SIGNATURES / APPROVAL		
Lift Plan Preparer– Andrew Scholbrock	Signature:	Date:
Liftmaster – Don Baker	Signature:	Date:
EHS POC – Don Young	Signature:	Date:

APPENDIX F: DAILY PRE-TEST CHECKLIST

Daily Checklist
The following items will be reviewed daily by the Test Controller or delegate, with all personnel on site prior to any activities :

Task	Comments
PRE-TESTING	
1. Review weather forecast with SWiFT Site Supervisor to confirm conditions will be within safe operating limits for equipment and personnel.	
2. Review roles and responsibilities with personnel and confirm adequate qualifications are met.	
3. Review current test objective(s) and list of activities for the day and confirm completion of specific checklists for those activities. (see additional checklists)	
4. Review and address any safety concerns and highlight significant hazards for day's work activities.	
5. Verify that all required and optional PPE has been issued and is functioning correctly.	
POST-TESTING	
6. At end of daily operations, review activities with personnel and note any areas of improvement	
7. Confirm all equipment is put into a safe storage mode.	
8. Notify SWiFT Site Manager that operations have ceased for the day.	

APPENDIX G: TEST MATRIX

Test Bins

The test bins for Phase I of the experiment are shown in Table 1, categorized by atmospheric inflow, wind turbine operating region, and yaw offset angle. Sufficient statistical data will be collected in Phase I to calibrate the FLORIS model and build a look-up table for the Phase II controller. The test matrix is also designed to match up with experimental data that is being gathered from the DOE GE 1.5 turbine located at the National Wind Technology Center. This will enable comparative analysis at two different turbine scales and locations.

Table 10 Target test matrix characterized by turbine operating region, inflow conditions and yaw offset angle.

Operating Region / Atmospheric inflow	Region 2	Region 2/3 transition	Region 3
Stable	Yaw offset angle -25˚,0 ˚,12.5 ˚,18 ˚,25 ˚	Yaw offset angle 0 ˚,25 ˚	Yaw offset angle 0 ˚
Neutral	Yaw offset angle -25˚,0 ˚,12.5 ˚,18 ˚,25 ˚	Yaw offset angle 0 ˚,25 ˚	Yaw offset angle 0 ˚
Convective	Yaw offset angle -25˚,0 ˚,12.5 ˚,18 ˚,25 ˚	Yaw offset angle 0 ˚,25 ˚	Yaw offset angle 0 ˚

Prioritization of Test Cases

The operational status of the SWiFT site along with the historical atmospheric trends during the experimental campaign will drive the prioritization of the test cases. In the initial portion of the experimental campaign, the SWiFT site will be shifting from commissioning to attended mode and eventually unattended mode. In attended mode, SWiFT personnel are required to be on site while the turbine is operating. This means that the ability to operate the turbine and collect data will be greatly reduced outside of normal working hours. The historical atmospheric trends at the site characterized by month, day, and hour will also be considered to prioritize test cases that may occur less frequently than others. To comply with safety mitigation plans, the turbine will be operated in low (<15 degree) yaw misalignments until sufficient loads data from the blades and tower can be analyzed and compared against simulations. After review and approval, larger yaw angles can be implemented, always with a turbine operator present.

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