The VolturnUS 1:8 Floating Wind Turbine:
Design, Construction, Deployment, Testing, Retrieval, and Inspection of the First Grid-Connected Offshore Wind Turbine in US

DeepCwind Consortium National Research Program Final Project Report Vol. II

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Executive Summary

Volume II of the Final Report for the DeepCwind Consortium National Research Program funded by US Department of Energy Award Number: DE-EE0003278.001 summarizes the design, construction, deployment, testing, numerical model validation, retrieval, and post-deployment inspection of the VolturnUS 1:8-scale floating wind turbine prototype deployed off Castine, Maine on June 2nd, 2013. The 1:8 scale VolturnUS design served as a de-risking exercise for a commercial multi-MW VolturnUS design. The American Bureau of Shipping Guide for Building and Classing Floating Offshore Wind Turbine Installations was used to design the prototype. The same analysis methods, design methods, construction techniques, deployment methods, mooring, and anchoring planned for full-scale were used. A commercial 20kW grid-connected turbine was used and was the first offshore wind turbine in the US.

The Castine test site was selected based on metocean data which indicated that with a high probability, the desired 1:8 scale ABS design metocean conditions found farther offshore in the Gulf of Maine that would be experienced by a full-scale turbine. This was confirmed through a comparison of measured metocean data at the test site with far offshore data scaled by the appropriate factors. At 1:8 scale, this test site can produce with a high probability scale extreme wind/ wave events (e.g. 50-year return period) in a short period of time offering a unique venue for understanding floating turbine behavior in extreme events at near full-scale. Since the site and design have been selected carefully, this data can also be used to accurately predict the response of the commercial design as well as be used to validate coupled models at near full-scale and real ocean environment.

Since the experiment has been carefully crafted to match the scale system properties and environmental loads, the generated data can be used to predict and validate the behavior of a full-scale VolturnUS. This extensive data set has confirmed design calculations establishing confidence in the principles of the VolturnUS design methodology as well as the concrete hull and composite tower structural designs. The VolturnUS 1:8-scale floating turbine has been successfully subjected in service to scaled 50-year and 500-year extreme ABS design conditions. This experiment represents a major milestone in the design of the VolturnUS technology and floating turbines in general as few if any open water floating wind turbines have yet seen their extreme design conditions. Based on current observations, the 1:8-scale VolturnUS exhibits responses in line with coupled model design predictions and provides confidence moving forward with design and construction of a full-scale floating offshore wind turbines utilizing the VolturnUS platform technology. Numerical codes for offshore floating wind turbines have also been partially validated as part of this work providing another benchmark for development and understanding of floating wind turbines. Additional technical details may be found in several peer reviewed paper produced from this work. Please see references [36-39].

1. Introduction

This Volume summarizes the design, construction, deployment, testing, numerical model validation retrieval, and post-deployment inspection of the VolturnUS 1:8-scale floating wind turbine prototype deployed off Castine, Maine on June 2nd, 2013. This work begins with an overview of testing program objectives and requirements with an emphasis on those affecting the prototype design. The basis of design of the floating platform, mooring, and anchor systems including objectives of program and testing, site conditions, applicable design standards, and other requirements. Next the method for calculating design loads is presented for the support structure and turbine. With the design basis and method of load calculation discussed, the design is presented for the main components including dockside verification of hydrostatic and hydrodynamic characteristics. The report next provides a discussion of the construction and deployment of the VolturnUS 1:8 as well as a sample design performance data in ABS scaled operational and extreme sea states. Finally, an overview of the retrieval of the VolturnUS prototype after 18-months of testing is given along with post-deployment hull inspections.

2. Testing Program Overview

The commercial scale VolturnUS floating wind turbine platform design developed by the University of Maine uses innovations in materials, construction, and deployment technologies such as a concrete semi-submersible hull and a composite tower to reduce the costs of offshore wind. Due to limited use of these materials in floating offshore wind turbines, these novel characteristics require research and development prior to full-scale construction. An offshore model test at an intermediate scale (e.g. 1:8) can de-risk the development of a commercial scale VolturnUS system by providing properly scaled global motion data, allowing for implementation of full-scale structural materials, and demonstrating full-scale construction and deployment methods. Such a test requires careful treatment of the test site, scaling methods, model design, and construction to obtain meaningful data.

Model tests of offshore structures are routinely conducted in the offshore oil and gas sectors in wave basin facilities [1]. A basin model test offers a reduced risk and cost venue to accurately evaluate the floating system's dynamic characteristics. Scale model tests of wind turbines in a wave basin have been completed by several groups. These include Principal Power Inc. [2], Hydro Oil & Energy [3], WindSea AS[1], and the University of Maine [4]. These experiments aimed at validating dynamic global performance of various floating wind turbine platform types. These past efforts provide guidance for conducting scale model tests of floating wind turbines but do not include full-scale materials, construction methods, or deployment methods as part of the test.

Several intermediate scale wind turbines have been deployed or are in planning stages in the world although data is limited. There are currently four known intermediate scale testing efforts of floating wind turbines ongoing by commercial and public entities. Sway is conducting a 1:5 scale test of a spar design off Norway[2], Kyoto University deployed a 1:2 scale 100kW spar[3], a 1:4 scale testing program is planned by NORCOE in Norway[4],

[1] http://www.windsea.no
[2] http://www.sway.no/
[3] http://www.nawindpower.com/e107_plugins/content/content.php?content.12215

and there is planned scale testing by the Deepwind Consortium in Europe[5]. These programs indicate the interest in conducting intermediate scale tests prior to commercial scale projects as a step in the development process.

This testing program is a unique offshore Froude scale test program for an intermediate scale offshore wind turbine off the coast of Maine. This testing plan requires the selection of a suitable site to apply correctly scaled wind and wave loads, a commercial turbine to apply the primary wind forcing, thrust, an instrumentation system to collect environmental and structure data, and the inclusion of materials, design and construction methods representative of full-scale.

The prototype size, mass, and materials are based upon UMaine's full-scale semi-submersible design constructed of concrete with a light-weight composite tower. This full-scale design and its proposed deployment location off Monhegan Island, Maine are shown conceptually in Figure 1 below.

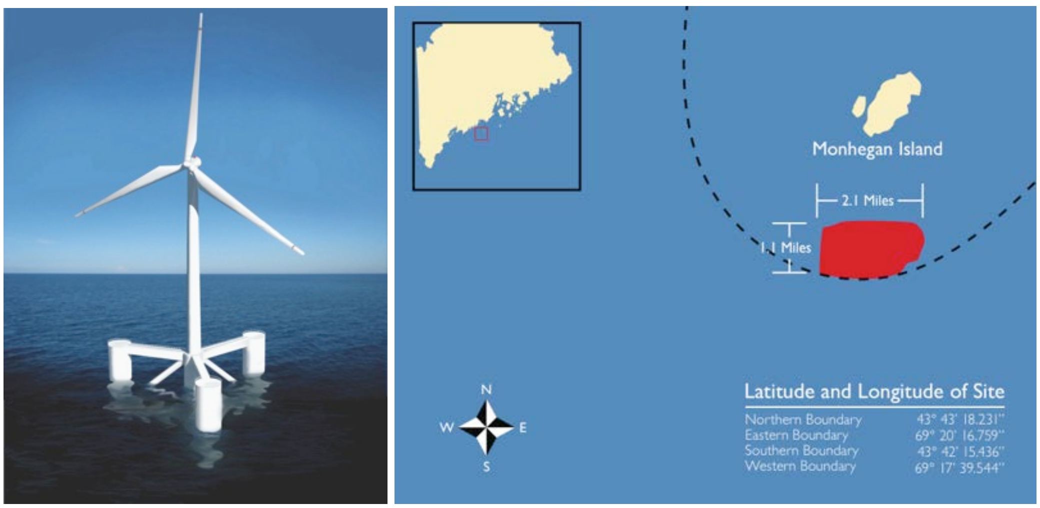

Figure 1 Full-scale 4-6MW VolturnUS and Proposed Deployment Site

The test program was performed near Castine Harbor, Maine as shown in Figure 2 and the model is a 1:8 geometric scale prototype of a 6MW turbine platform system to be deployed in the Gulf of Maine far offshore. The 1:8 model is shown in Figure 3. The turbine and platform were constructed onshore and towed to site fully outfitted to demonstrate full-scale construction and deployment methods. A comprehensive instrumentation package monitors key performance characteristics of the platform to verify the full-scale design and coupled modeling software.

The primary objectives of this testing effort are to:

1. Design, test, demonstrate, and validate the VolturnUS design including advanced material systems for floating wind turbines

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[4] http://www.norcowe.no/
[5] http://www.offshorewind.biz/2010/11/11/future-wind-turbines-go-offshore-%E2%80%93-deep-and-floating-denmark/

2. Collect wind turbine, floating platform, structural measurements, and environmental data to be used for validation of coupled aeroelastic/ hydrodynamic numerical models.
3. Develop deepwater offshore wind testing capabilities, procedures, and methods
4. Demonstrate floating offshore wind technology
5. Inform classification societies / design standards on floating wind turbine design

Figure 2 Project test site (courtesy, Google Maps, 2013)

Figure 3 Grid-connected VolturnUS 1:8 scale prototype

3. Summary of Design Requirements

This section summarizes the design requirements for the University of Maine 1:8 scale prototype concrete floating wind turbine with a composite tower designed, fabricated, and tested offshore in 2013. The prototype is approximately 1:8th scale of a full-scale 6MW VolturnUS design. The prototype turbine is a commercial 20kW design developed by Renewegy.

3.1 Scaling Laws

Froude-scale basin model testing techniques commonly used for offshore structures such as oil and gas and offshore vessels have been adapted for this testing program [1]. Particulars of Froude-scaled testing of floating wind turbines have been incorporated following previous work which prescribes maintaining the dominant wind turbine loading, thrust, perpendicular to the rotor plane [4][5]. Key scaling parameters are shown in **Table 1**. Unique challenges exist to maintain these parameters in an intermediate scale offshore test with competing requirements. For example, the site wind and wave conditions must occur with the correct magnitude, temporal characteristics, and joint occurrence. Similarly, a scale turbine is needed to apply the correct scaled thrust force. For the hull, the mass and dynamic characteristics must be scaled properly while also allowing of use of actual full-scale construction materials and deployment methods.

Table 1 Scaling factors employed for coupled wind/ wave model testing of floating wind turbines [4]

Parameter	**Scale Factor -Symbolic-**	**Scale Factor -1:8-**
Length (displacements, wave height)	λ	8
Area	λ^2	64
Volume	λ^3	512
Angle	1	1
Density	1	1
Mass	λ^3	512
Time (wave period)	$\lambda^{0.5}$	2.83
Frequency (turbine rpm)	$\lambda^{-0.5}$	0.35
Velocity (wind speed, current)	$\lambda^{0.5}$	2.83
Acceleration	1	1
Angular Velocity	$\lambda^{-0.5}$	0.35
Angular Acceleration	λ^{-1}	0.125
Force (waves, turbine thrust, current drag)	λ^3	512
Moment	λ^4	4096
Power	$\lambda^{3.5}$	1448
Young's Modulus	λ	8
Stress	λ	8
Mass Moment of Inertia	λ^5	32,768
Area Moment of Inertia	λ^4	4096

3.2 Site Selection

Castine, Mainer was selected after examining several other sheltered locations based on the following criteria: suitability of metocean (wind, wave, and current) conditions to achieve representative 1:8 scale far offshore environmental conditions, proximity to marine infrastructure, historical metocean data, geophysical suitability, and public support/ permitting. This section focuses on the environmental data used to justify the selection of the Castine site

Selection of a suitable test site for the offshore 1:8 Froude-scale model test requires careful treatment. The test site must generate the correct combinations of scaled winds and waves to simulate the behavior of the full-scale VolturnUS farther offshore. Full-scale design conditions for floating offshore wind turbines specified by the American Bureau of Shipping Guide for Building and Classing Floating Offshore Wind Turbine Installations were estimated from metocean data obtained far offshore Maine and represent the desired full-scale design environments [6]. With the desired environmental conditions in hand, the Castine site was confirmed through metocean data collection to produce close approximations of the desired scale conditions.

There exists over ten years of wind and wave buoy data at the proposed full-scale design deployment site off Monhegan Island, Maine [7] [8]. Data collected includes significant wave height and peak period, wave energy spectral parameters and ten-minute average wind speeds at 4m above sea level. Using this data, full-scale design load cases (DLCs) were developed for the Monhegan site. Several critical ABS DLCs are shown along with the desired 1:8 scale values in **Table 2**. DLC 1.2 is an operational type loading condition used for fatigue analysis. DLC 1.6 is an extreme turbine operating condition with an associated 50-year return period significant wave height concurrent with the operating wind speed. The table shows a DLC 1.6 case where the turbine is operating at peak thrust with a 50-year return period significant wave height and wave period associated with the rated wind speed. DLC 6.1 is another extreme case where the turbine is shut down and the unit is subjected to a larger 50-year significant wave height independent of wind speed. The last case shown is a station-keeping survival load case with a 500-year return period with the turbine parked. These four load cases have been found to control the design of the full-scale VolturnUS platform and were used to identify the proper test site.

Table 2 Full-scale (far offshore in the Gulf of Maine) and model scale metocean parameters for key ABS design load cases

<table>
<tr><th>ABS Design Load Cases (DLCs)</th><th>Required Metocean Design Parameter</th><th>Full Scale</th><th>1:8 Scale</th></tr>
<tr><td rowspan="2">DLC 1.2</td><td>Operational load case significant wave (m)</td><td>0-6.0</td><td>0-0.75</td></tr>
<tr><td>Associated wave period (s)</td><td>6.1-11.5</td><td>2.2-4.1</td></tr>
<tr><td rowspan="2">DLC 1.6</td><td>50-year significant wave height associated with turbine peak thrust (m)</td><td>8.0</td><td>1.0</td></tr>
<tr><td>Associated wave period (s)</td><td>12.7</td><td>4.5</td></tr>
<tr><td rowspan="3">DLC 6.1</td><td>50-year significant wave height (m)</td><td>10.2</td><td>1.3</td></tr>
<tr><td>Associated wave period (s)</td><td>14.1</td><td>5.0</td></tr>
<tr><td>50-year 10-minute wind speed at hub height (m/s)</td><td>40</td><td>14.1</td></tr>
<tr><td rowspan="3">Survival Load Cases (SLC)</td><td>500-year significant wave height (m)</td><td>12</td><td>1.5</td></tr>
<tr><td>Associated wave period (s)</td><td>15.3</td><td>5.4</td></tr>
<tr><td>500-year 10-minute wind speed at hub height (m/s)</td><td>45</td><td>15.9</td></tr>
</table>

Castine was selected after an analysis of data obtained from an instrumented metocean buoy deployed in the winter of 2011. The buoy data confirmed that the site could readily produce the desired ABS scaled metocean conditions. **Figure 4** shows a scatter plot of the measured peak period and significant wave height at Castine. Included in this figure are two trend lines. The blue trend line is a power law fit of the Castine data. The red trend line is a power law fit of the full-scale metocean conditions far offshore Maine scaled by the scale factors in Table 1 which represents the mean operational wave conditions required for DLC 1.2. 95% confidence intervals are also included for both trend lines. Also included on this figure are the peak periods and significant wave heights of DLC 1.6, 6.1, and the survival load case. Noting the overlap of the trend lines and scatterplot data, there is a good likelihood of experiencing the desired wave conditions at the site. In addition to the wave peak period and significant wave height joint occurrence, the correct wave spectrum shape is also highly desirable. **Figure 5** shows two images as an example of the wave spectral characteristics. The top image is a record of wave elevation over a one hour period with a significant wave height of 1.6m and a peak period of 5.2s. This is very close to the desired 500-year survival case. The bottom image shows the measured wave spectrum along with a superimposed scaled 500-year JONSWAP spectrum showing excellent agreement.

With the wave characteristics at the site found to be acceptable, the turbine wind thrust and joint occurrence with significant wave height is discussed. Turbine thrust is the primary wind loading on the structure controlling operational global motions of floating wind turbines [4] [5]. This turbine thrust is associated with mean wave conditions based on the full-scale site metocean data. **Figure 6** shows a scatterplot of expected turbine thrust versus significant wave height shown in blue derived from the Castine buoy data. This was created by calculating turbine thrust based on measured wind. A power law fit with 95% confidence intervals shown with solid blue and dashed lines was made. Shown in red solid and dashed lines is the desired full-scale scaled turbine thrust for a given significant wave height and 95% confidence intervals based on the far offshore data and the full-scale 6MW turbine thrust versus wind speed relationship. This red line represents the operational ABS load case DLC 1.2. Also shown as a red diamond is DLC 1.6, which is an extreme load case. The data shows that the site consistently produces turbine thrusts with the correctly matched significant waves desired to simulate the controlling ABS DLCs. This is a distinct advantage as 50-year return period events can be witnessed fairly often making the intermediate scale test extremely useful from design perspective.

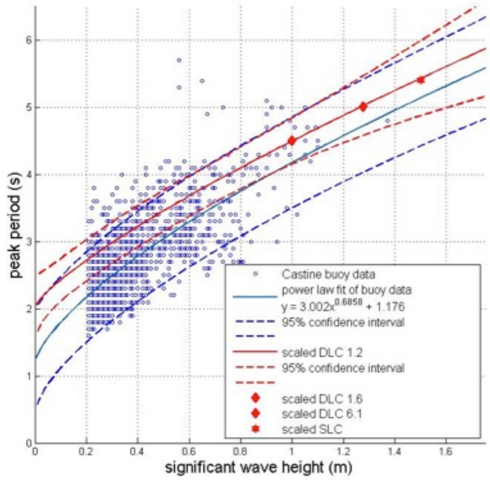


Figure 4 Measured (blue) and desired scaled (red) wave peak period v. significant wave height

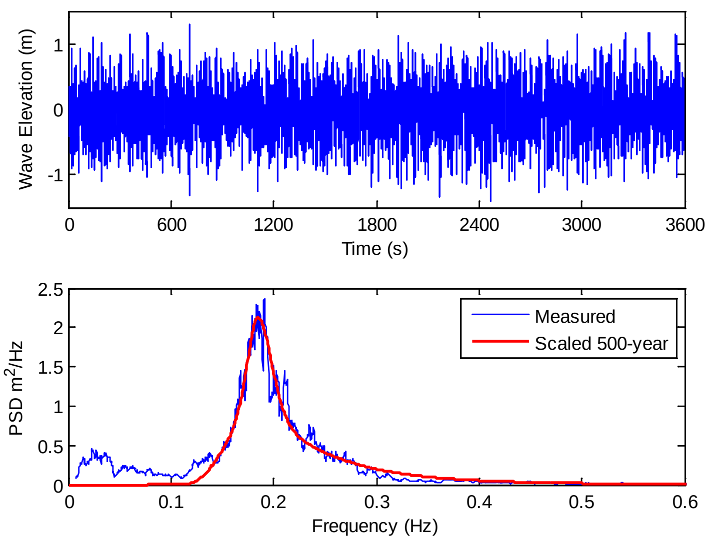


Figure 5 (top) Time series of wave elevation (bottom) measured wave spectra with far offshore Maine scaled 500-year wave spectrum

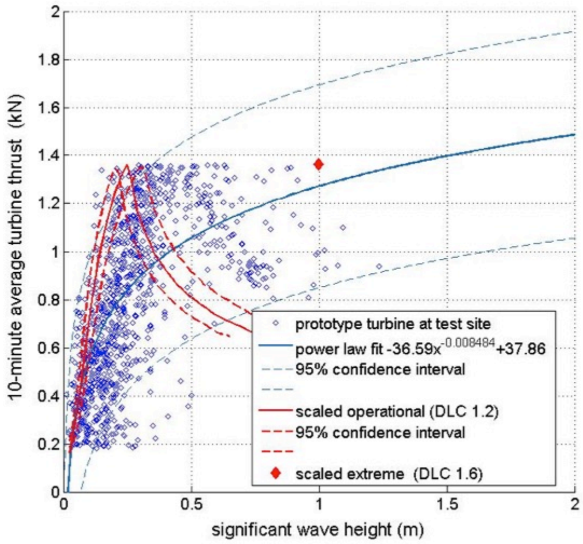


Figure 6 Measured (blue) and desired (Red) scaled 10 minute average turbine thrust v. significant wave height

This discussion of site selection is concluded with a similar comparison for 10-minute average wind speed versus significant wave height, useful for reproducing ABS DLC 6.1 and the survival load case which require the turbine to be parked and therefore only the drag load is applied to the turbine, tower, and platform. Again the desired scaled conditions are shown in red with a power law fit and 95% confidence intervals based on the far offshore data scaled by the appropriate scale factors and the actual Castine conditions are show in in blue with a power law fit. Again, there is good overlap between the desired and measured regions giving confidence the test site will produce the desired scaled conditions of the 1:8 VolturnUS scale prototype during the deployment period.

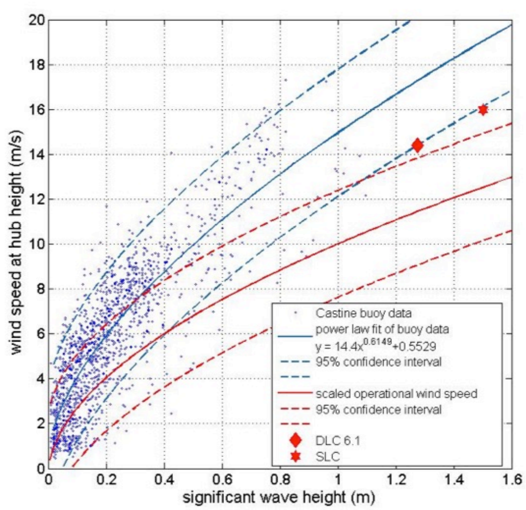


Figure 7 Expected (blue) and desired (red) scaled 10 minute average hub height wind speed v. significant wave height

3.3 Design Standards and Referenced Information

The following design standards were used in design of the VolturnUS 1:8 scale prototype. These are the same one as used for full-scale commercial scale VolturnUS project.

Primary Design Standards

1. ABS: Guide For Building And Classing Floating Offshore Wind Turbine Installations. American Bureau of Shipping. January, 2013. [6]
2. ABS: Guide for Building and Classing Bottom-founded Offshore Wind Turbine Installations. American Bureau of Shipping. July, 2014. [9]
3. ABS: Guide for Building and Classing Gravity-Bases Offshore LNG Terminals. . American Bureau of Shipping. November, 2010. [10]
4. ABS: Rules for Building and Classing Mobile Offshore Drilling Units (MODU), American Bureau of Shipping, January, 2012. [11]
5. ASCE 7-10: Design Loads for Buildings and Other Structures. American Society of Civil Engineers. 2010. [12]
6. API Recommended Practice 2SK: Design and Analysis of Station Keeping Systems for Floating Platforms Third Edition. The American Petroleum Institute, October 2005. [13]
7. DNV-OS-C501: Composite Components. October. 2010. [14]

Other Design Standards Considered for Additional Guidance

1. ABS: Guide for Building and Classing Floating Production Installations, American Bureau of Shipping, July 2009. [15]
2. ACI: Report on Floating and Float-in Concrete Structures Reported by ACI Committee 357, 2010. [16]
3. ACI, 318- 318-08: Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute, 2011. [17]
4. DNV-OS-J101: Design of Offshore Wind Turbine Structures [18]
5. DNV, DNV-OS-C502: Offshore Concrete Structures.[19]
6. DNV-OS-C101: Design of Offshore Steel Structures, General (LRFD Method), 2011. [20]
7. DNV-OS-J101: Design of Offshore Wind Turbine Structures, September, 2011. [21]
8. DNV-OS-J103: Design of Floating Wind Turbine Structures, June, 2013 [22]
9. GL 2012: IV: Rules and Guidelines Industrial Service: Part 2: Guideline for the Certification of Offshore Wind Turbines. Gemanischer Lloyd, 2012. [23]
10. IEC 61400-1: Wind turbines –. Part 1: Design requirements [24]
11. IEC 61400-3: Design requirements for offshore wind turbines. [25]
12. IEC 61400-x: Draft Standard for Floating Offshore Wind Turbines, International Electro technical Commission, Document 88/379/NP, 15 October 2010. [26]

13. IEEE 45-2002 – Recommended Practice for Electrical Installations on Shipboard, Institute of Electrical and Electronics Engineers, 9 October 2002. [27]
14. ISO 19901-1 Petroleum and Natural Gas Industries – Specific Requirements for Offshore Structures – Part 1: Metocean design and operating considerations. 2005. [28]
15. ASME: Reinforced Thermoset Plastic Corrosion-Resistant Equipment, American Society of Mechanical Engineers: RTP-1-2011, 2011. [29]
16. Rules for Classification of High Speed, Light Craft and Naval Surface Craft: Part 3 Chapter 4, Hull Structural Design, Fibre Composite and Sandwich Constructions, 2011. [30]

Design Software:

1. ANSYS AQWA,ANSYS, Inc. 2013. [31]
2. Jonkman, J. and Buhl, M., FAST User's Guide, National Renewable Energy Laboratory, Technical Report # NREL/EL-500-38230, August 2005. [32]
3. WAMIT software, WAMIT, Inc., version 6.3, Available from: http://www.wamit.com [33]

3.4 Wind Turbine

The turbine for the pilot scale is a Renewegy 20 kW wind turbine with active collective blade pitch control and is shown in Figure 8. Characteristics of the selected turbine are shown in Table 3.

Figure 8 Renewegy 20kW Turbine

Table 3 Renewegy 20kW Turbine Properties

Property	Renewegy VP20
Rated Power	20kW
Total Turbine Mass	479kg
RPM (1P)	100-110rpm (1.67-1.75Hz)
3P	300-330rpm (5.01-5.25Hz)
Free Wheel Wind Speed	2.5m/s
Cut-in Wind Speed	3.5m/s
Rated Wind Speed	15.8m/s
Cut-out Wind Speed	25.0m/s
Diameter	9.6m
Blade Length	4624mm

3.5 Turbine Aerodynamic Loads

The Renewegy VP20 turbine thrust versus wind speed as modeled in FAST is shown below in Figure 9. The actual turbine was de-rated to achieve the maximum scaled thrust produced by the 6MW turbine at 1/8th scale which occurs at about 1.35kN.

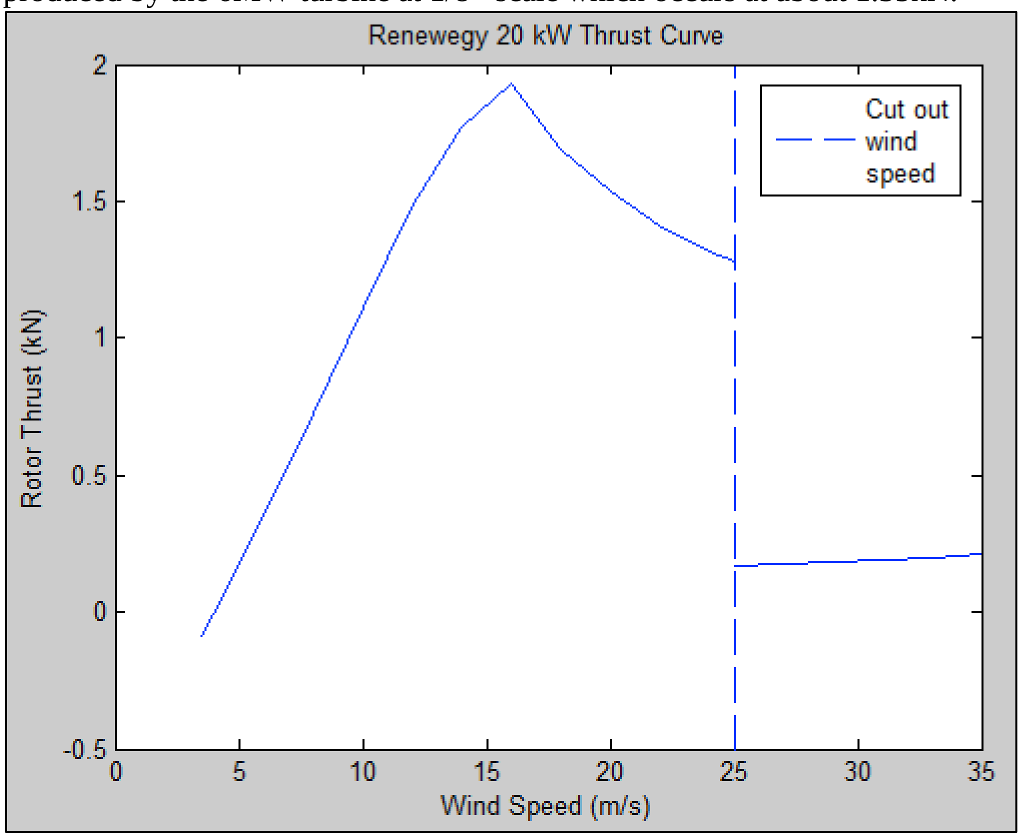


Figure 9 Renewegy 20kW Thrust Curve Estimated in FAST

3.6 Extreme Design Conditions

The prototype is designed to mimic a full-scale prototype. The 1:8-scale prototype will be structurally designed to resist environmental conditions at the Castine test-site with a probability of exceedance equivalent to typical offshore structures designed to

ABS Guide for Building and Classing Floating Offshore Wind Turbines. ABS requires a 50 year return period environmental conditions and assumes a 20 year design life. Using extreme value theory the percent chance of occurrence of this event during the lifetime of the structure is:

Probability of Occurrence = $P = 1-(1-1/T)^n = 1-(1-1/50)^{20} = 33.2\%$, where T is the return period and n is the design life.

For the prototype, up to ten deployments could occur and is this is taken as the design life of the structure. By solving the equation above and replacing n with 10 and P with 33.2%, one can estimate the required return period event required for the prototype to have the same chance of occurrence as a full-scale 20 year life structure.

$T = 1/(1-1(1-0.332)^{1/10}) = 25.2$.

Therefore, a 25 year return period was used in place of the 50 year for the ABS design conditions. Table 4 lists the extreme design metocean conditions at the test site made using buoy data. Table 5 lists the extreme waves and mean associated metocean conditions at the test site. Tide data collected from NOAA is shown in Table 6.

Table 4 Extreme Metocean Conditions at Castine Test Site

Return Period (years)	Significant Wave Height (m)	Mean Peak Period (s)	5 second Gust Wind Speed (m/s)	10-min Mean Wind Speed at 4m (m/s)
1	1.5	5.3	27.3	20.2
5	1.8	6.0	32.2	23.6
10	2.0	6.4	34.3	25.1
25	2.1	6.6	37.1	27.0
50	2.3	7.1	39.2	28.5
100	2.5	7.5	41.3	30.0
250	2.6	7.7	44.1	31.9

Table 5 Extreme Waves and Mean Associated Metocean Conditions at Test Site

Return Period (years)	EXTREME Significant Wave Height (m)	Peak Period (s)	JONSWAP Gamma	5 second Gust Wind Speed (m/s)	10-min Mean Wind Speed at 4m (m/s)*	Surface Current Speed (cm/s)
1	1.5	5.3	~2-3	25.4	24.2	0.21
5	1.8	6.0	~2-3	29.9	28.4	0.22
10	2.0	6.4	~2-3	32.9	31.2	0.22
25	2.1	6.6	~2-3	34.4	32.6	0.22
50	2.3	7.1	~2-3	37.4	35.4	0.23
100	2.5	7.5	~2-3	40.4	38.2	0.23
250	2.6	7.7	~2-3	41.9	39.6	0.23

Table 6 Tidal ranges

	Max (m)	Min (m)	Mean (m)	Range (m)	Standard Deviation
All Data	3.91	-0.660	1.64	4.57	1.55
High	3.91	2.57	3.17	1.34	0.279
Low	0.640	-0.660	0.118	1.30	0.286

3.7 Geophysical Data

Drag embedment anchors were utilized for the prototype as is planned for the full-scale design. Detailed bathymetric data exists from a study completed by University of New Hampshire Center for Coastal and Ocean Mapping Joint Hydrographic Center in the summer of 2008 [34]. Figure 10 shows the region where data is available. The information presented here served to aid in the design of the anchoring system.

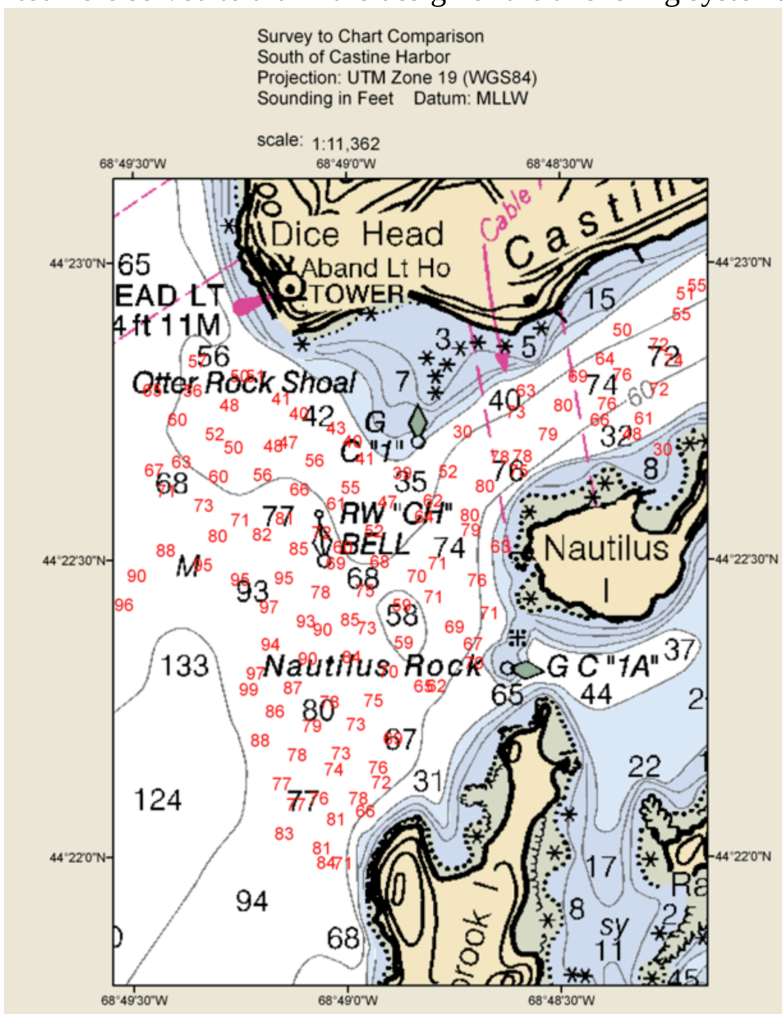


Figure 10: Chart (13309) comparison for western edge of survey (Ito etal, 2008)

Figure 11 illustrates surficial deposits for the Castine and Sears Island area of Belfast & Penobscot Bays. The seafloor is comprised of soft, fine-grained (silt and clay) sediments (illustrated in blue) of variable thickness with bedrock outcropping (illustrated) around island and land masses. The fine-grained sediment areas would be optimal for drag anchors. The area south of Sears Island is primarily gravel, similar to the beach deposits located on the island. Brothers et al. (2010) have shown that the fine-grained sediments within Belfast Bay (between Belfast and Sears Island) is comprised of a complex of pockmarks, or massive depressions associated with historical fluid escape (usually gas) that have been mapped to be as large as 40 m deep and 300m in diameter [35].

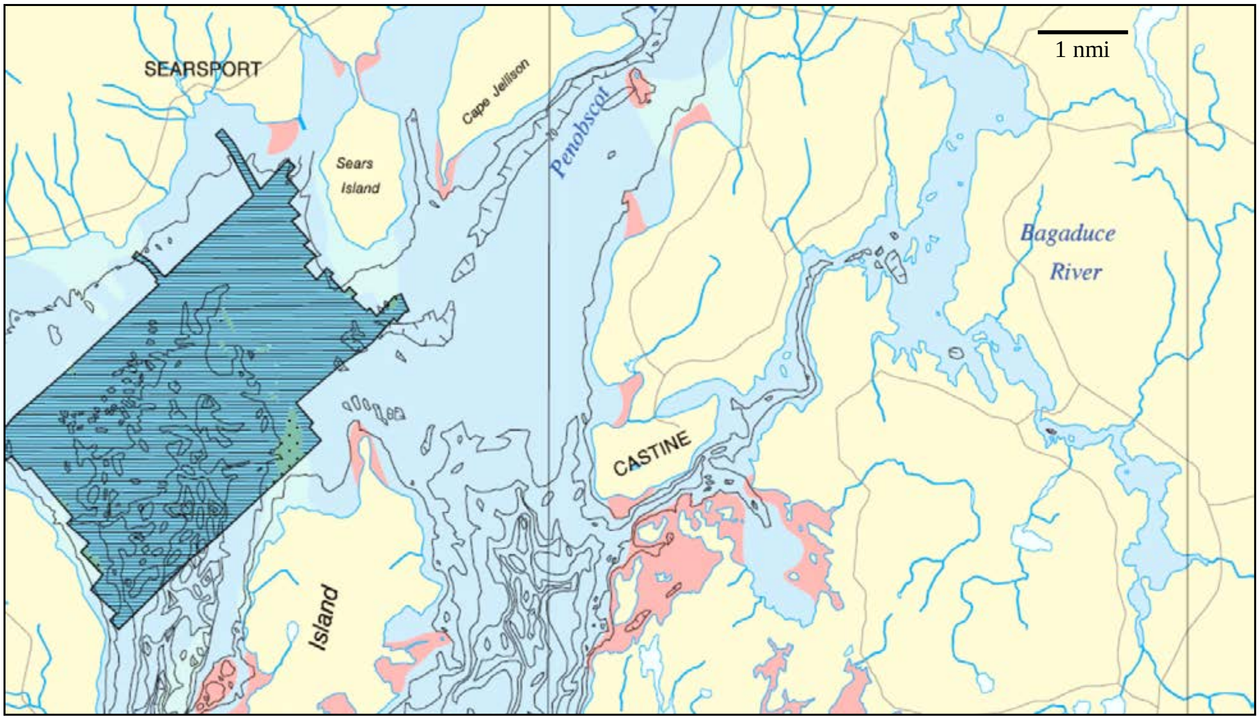


Figure 11 Castine area surficial sediments

Note: The figure above illustrates predominantly fine-grained sediment (blue), rock (red) and gravel (green) (Barnhardt et al. 1996a). The dark gridded area shows the location of an extensive pockmark (deep seafloor depressions) study involving sub-bottom and bathymetric profiling.

4. Load Analysis Methods

4.1 Design Load Cases

The following load cases were be taken into account per ABS Guide for Building and Classing Floating Offshore Wind Turbine Installations section 5-2 to design the hull, moorings, anchors, tower, and to check the adequacy of the turbine itself. Load factors of safety are dependent on the type of loading per ABS.

1. Power production (DLC 1.2-1.6)
2. Power production plus occurrence of faults (DLC 2.1-2.4)
3. Start up (DLC 3.1-3.3)
4. Normal shut down (DLC 4.1-4.3)
5. Emergency shutdown (DLC 5.1)
6. Parked (standing still or idling) (DLC 6.1-6.4)
7. Parked and fault conditions (DLC 7.1-7.2)
8. Temporary (Load-out, transportation, installation, maintenance and repair) (DLC 8.2-8.3)
    a. The platform was be checked for the following conditions including those described in ABS

i. All construction/ assembly loads both on the individual component and sub-assembly level
ii. Tow out loads based on tow plan and tow route environmental conditions.

The turbine, tower, equipment, hull, mooring, and anchors were designed following the ABS design load cases and guidance.

4.2 Turbine and Tower Design Load Calculations

Turbine and tower loads were calculated in FAST coupled aerodynamic/ hydrodynamic software [40] using multiple long duration time domain simulations of the fully coupled wind, wave, and current loads. This software has been validated against 1:50 scale tank testing data (Please see Volume I)

4.3 Hull Structural Design Load Calculations

Hull loads following the load cases from ABS were calculated in the following manner:

1. Wind loading from the turbine is applied in a quasi-static manner per ABS with an amplification factor to account for dynamic wind effects based on FAST coupled modeling and tank testing data. The turbine, tower, and hull wind loads will be included in this way. Turbine loads will be calculated using information in section 4.2.

2. Wave pressures and accelerations/ inertial loads are calculated using WAMMIT wave diffraction analysis software for discrete phase angles of the wave considered.

3. Hydrostatic forces are calculated based on WAMMIT predicted dynamic displacements for each phase angle and the mean displacements due to wind and self-weight.

4. All loads from 1-3 are imported into a quasi-static finite element model and the member loads will be determined.

5. Waves considered include ABS load cases as well as those recommended in the ABS Design Wave Approach outlined in ABS MODU 3-2-A2. Peak waves in a sea state defined by Hs and Tp will be considered

6. Slamming loads, tow out loads, and construction loads are considered separately and analyzed using specific models recommended by DNV, ABS and others.

7. Local connection loads are addressed with sub-assembly finite element models including global effects

4.4 Composite Component Development, Testing and Implementation

The VolturnUS 1:8 utilized composite materials in its construction of the light-weight composite tower system. A light-weight composite tower can offer overall system cost savings by reducing the overall center of gravity of the floating system and thereby resulting in floating foundation weight reductions. A 1:8 scale version of a full-scale tower designed, fabricated, and structurally tested at the University of Maine prior to erection on the VolturnUS floating foundation. A detailed overview of the 1:8 scale composite tower analysis, design and testing is provided in a peer reviewed journal paper [44]. Figure 12 shows the structural testing of the 1:8 scale tower using a servo-hydraulic loading actuator to apply horizontal load at the tower top to simulate wind turbine inertial and aerodynamic loads. The tower is cantilevered horizontally and fixed at the tower base. The testing helped to confirm the natural frequency, bending stiffness, and its ability to withstand proof loading and ensure suitability for use for the project.

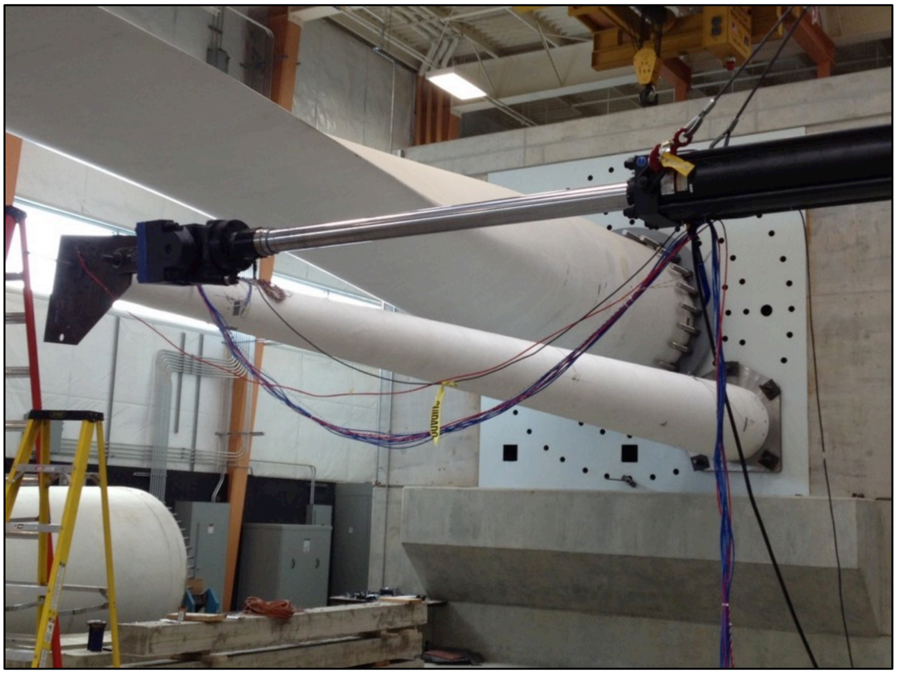


Figure 12. Tower loading configuration.

5. VolturnUS 1:8 Design

This section of the report outlines key features of the VolturnUS 1:8 prototype main components. APPENDIX A Design Drawings provides a drawing package which describe the overall system. The VolturnUS 1:8 prototype was designed to be constructed, assembled, and deployed using similar materials and techniques as the full-scale design, which can be fully constructed and assembled dockside. After assembly, the entire structure is towed at a shallow transit draft with standard tug boats for mooring and electrical umbilical hook up at its final installation site. **Table 7** lists the gross properties of the model and the full-scale system. The properties compare well with the target scale values derived from the full-scale properties. Some dissimilitude exists due to the competing goals of the test program. A commercial pitch regulated 20kW turbine modified to produce 12kW was used for the test. At this reduced power, the turbine applies the desired peak scaled thrust force at the rated wind speed. The power and rotor diameter are not perfectly scaled but were acceptable for the test given that the thrust load is the primary wind turbine forcing on the platform. The platform uses three catenary chain moorings anchored to the sea bed with drag embedment anchors. The water depth is close to the target full-scale system.

The concrete hull design, composite tower design, mooring, anchors and construction process replicate the full-scale system. The concrete hull is constructed of fifteen concrete members and representative of the full-scale design and construction process. The connections, thicknesses, and reinforcements of the concrete hull are scaled. The 1:8

scale model can be fully dismantled into components for shipping over the road on a truck. The 1:8 composite tower is constructed of the same reinforcements and resins as a full-scale tower. Both the tower and concrete hull underwent structural qualification testing to confirm structural designs prior to fabrication. The assembly of the hull, tower, and turbine all took place on land at the Cianbro Modular Manufacturing Facility in Brewer, Maine. **Figure 13** shows the completed unit.

Table 7 General properties of the 1:8 scale and full-scale systems

Parameter	**VolturnUS 1:8**	**VolturnUS Full-Scale**
Draft	2.9 m	20m
Hub Height	12.2 m	100m
Rotor Diameter	9.6 m	152m
Rated Power	12 kW	6MW
Peak Thrust Load	1.37kN	700kN
Hull Material	Concrete	Concrete
Tower Material	Composite	Composite
Water Depth	15-27m	100m
Number of Mooring Lines	3 x catenary chain	3 x catenary chain
Anchors	Drag Anchor	Drag Anchor

Figure 13 1:8 model outfitted and ready for deployment

6. Construction

The VolturnUS 1:8 prototype was designed to be constructed, assembled, and deployed using similar techniques as the full-scale 6MW. This provides a unique opportunity to learn about these important and very expensive activities at near full-scale. The full-scale VolturnUS system is designed to be fully constructed and assembled dockside which minimizes heavy equipment operations at sea. After assembly, the entire structure can be towed at a shallow 9m draft with standard tug boats for mooring and electrical umbilical hook up at its final installation site. This is a significant advantage over other floating turbine platform types as it greatly reduces at sea construction costs and heavy offshore equipment. In addition, in the event of needed major repairs to the turbine, the entire unit can be disconnected from its mooring and electrical umbilical and towed back to shore further reducing operation and maintenance costs.

The semi-submersible concrete hull was constructed at the University of Maine Advanced Structures and Composites Center in the winter of 2013. The concrete members represent at scale the connections, thicknesses, and reinforcements of the full-scale systems. The only difference from the full-scale system is that the 1:8 scale unit can be fully dismantled for shipping over the road on a truck. The 1:8 tower is constructed of the same reinforcements and resins as full-scale tower. Both the tower and concrete hull underwent structural qualification testing to confirm structural designs prior to fabrication. The assembly of the hull, tower, and turbine all took place on land at the Cianbro Modular Manufacturing Facility in Brewer, Maine. Figure 14 through Figure 25 show the VolturnUS hull at various stages of construction.

Figure 14 Concrete Formwork for VolturnUS Center Column and Bottom Beam Slabs

Figure 15 Bottom Beams Form Work in Place

Figure 16 Bottom Beams Cast, Radial Columns Poured

Figure 17 Compression Struts Cast Separately

Figure 18 Compression Struts Installed

Figure 19 Top Beams Inserted and Painting Complete

Figure 20 Installation of Tower at Cianbro Facility in Brewer

Figure 21 Installation of Turbine

Figure 22 Completed Unit

Figure 23 Unit Installed in Water for Dockside Testing

Figure 24 Drag Anchors being lowered into water

Figure 25 Anchor Deployment Vessel

7. Dockside Verification Testing

Several tests were completed to confirm the models hydrostatic and hydrodynamic characteristics dockside prior to deployment [. As a confirmation of the static stability characteristics of the 1:8 scale model, a fully assembled unmoored heave and pitch hydrostatic static stiffness test was completed using known weights dockside prior to deployment. The results are shown in **Figure 26** and are compared to the estimated response. The testing confirmed the expected properties of the model. The heave measured has some variability due to local waves created by wind and small craft nearby.

This issue was not experienced in the pitch stiffness test. As a confirmation of the dynamic characteristics of the model, a combined heave/pitch decay test was completed using a crane pulling and then releasing from one of the outside columns. Onboard instrumentation measured pitch and heave and corrected for angular displacement. **Figure 27** shows a power spectral density plot created using the free decay data. The pitch and heave natural frequencies matched the estimated scaled values.

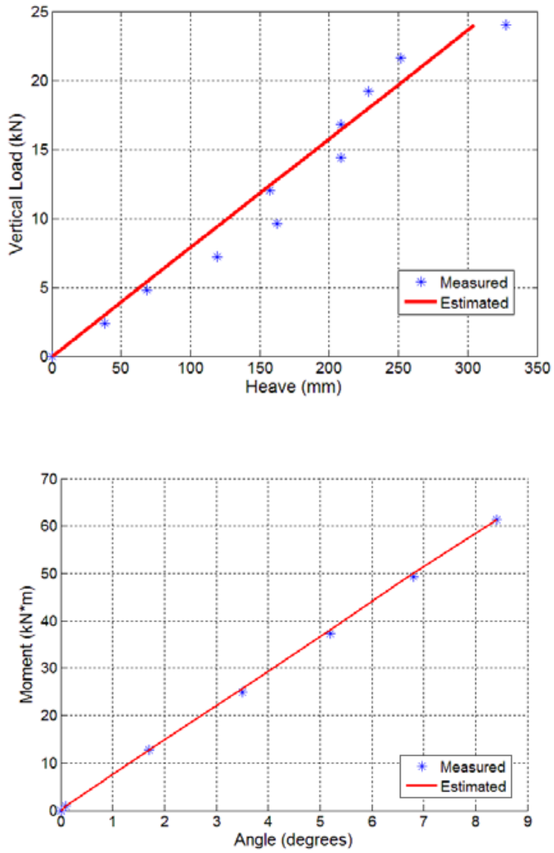


Figure 26 Hydrostatic heave (top) and pitch incline (bottom) testing.

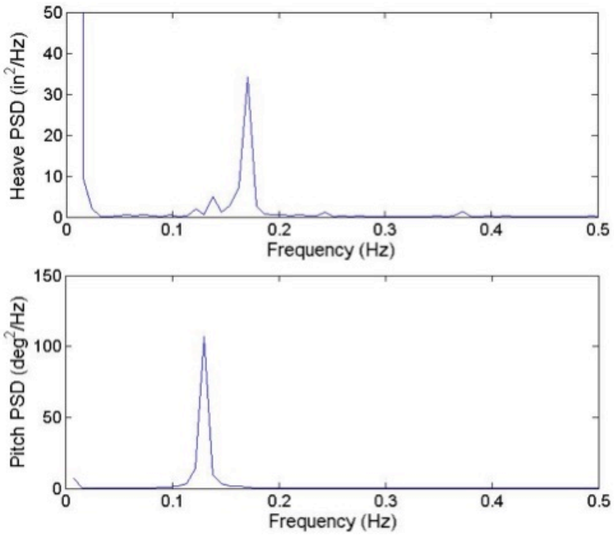
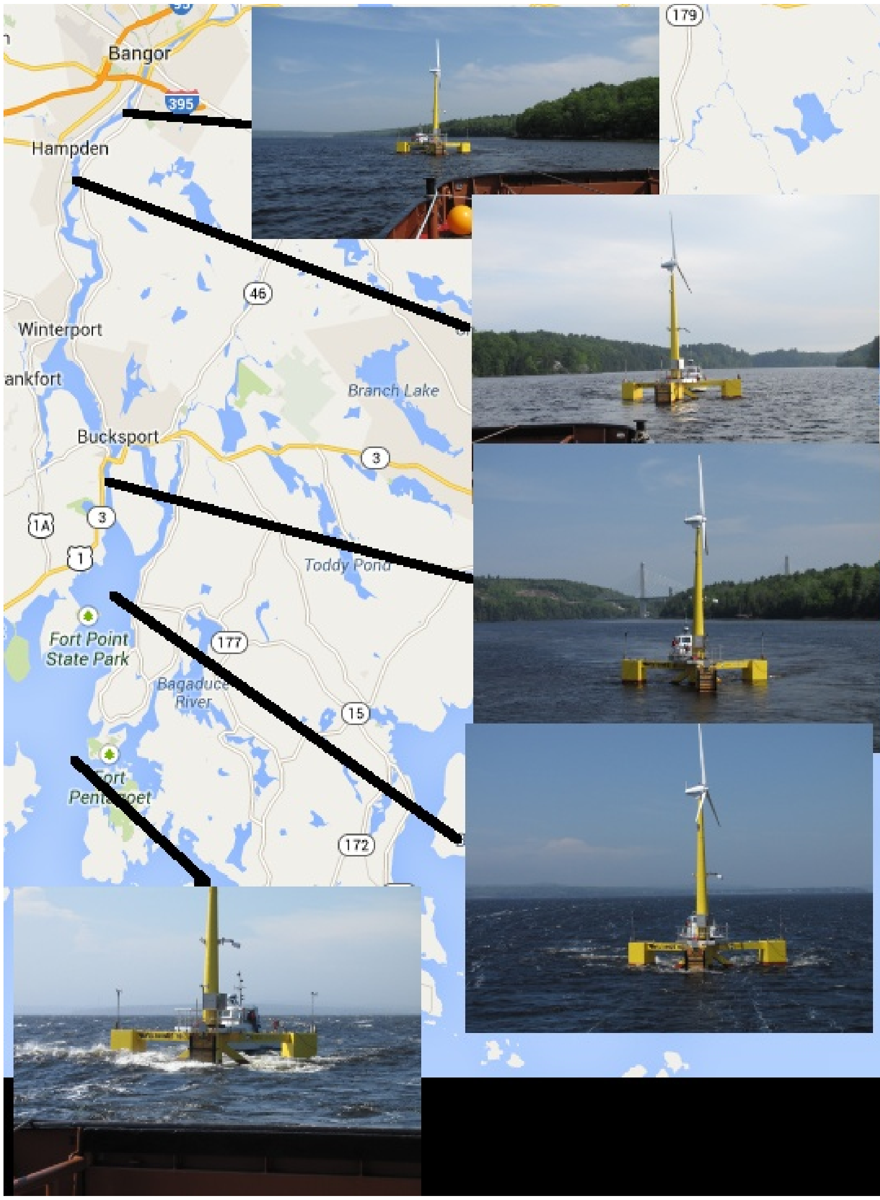


Figure 27 Power spectral density plots heave (top) and pitch angle (bottom)

Figure 28 Incline Testing Dockside

8. Deployment

The deployment of the prototype took place on June 2nd, 2013. The tow route was from Brewer, Maine down the Penobscot River to Castine, Maine was approximately 50km (28nm), and took about 11.5 hours. This route is shown in Figure 29. The entire unit, fully assembled was towed with a single tug boat and an assistance vessel in such a fashion as to replicate the tow configuration employed in the deployment of a full-scale VolturnUS. An image of the VolturnUS being towed is shown in Figure 30. The tow-out, which was to occur at 3.7km per hour, was expected to produce a tow line tension of 36kN in still water. During the actual tow-out at 3.7km per hour seen at point one, the line tension measured with an onboard load cell. Towards the end of the tow, the model encountered waves approximately 1.5m in height (equivalent to 12m full-scale). Despite this, the tow-out occurred without incident providing additional evidence that the tow-out procedures for the VolturnUS system are sufficiently robust. Upon arrival in Castine, the unit was hooked to preinstalled chain moorings connected to preset drag anchors. Table 8 provides measured tow line tension of the unit during the tow.



(1) High tide near Brewer. Tidal currents are nearly slack. No waves, no wind.

(2) Near Hampden Maine. Waves are choppy with light winds. Outgoing tide.

(3) Just south of the Bucksport bridge. Light winds. Outgoing tide.

(4) Upper Penobscot bay, waves and wind rising.

(5) Approaching anchorage point Hs ~1.-1.5m. High winds.

Figure 29 VolturnUS Tow Route

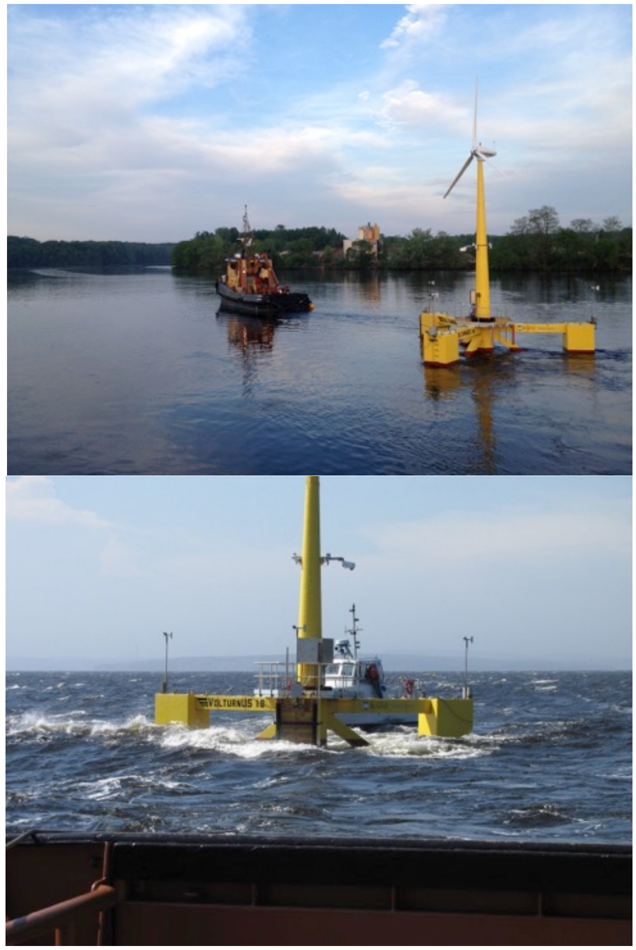


Figure 30 Images of (top) towing of VolturnUS in the Penobscot River and (bottom) towing of VolturnUS through 1.5m waves in Penobscot Bay

Table 8 Cable tension during tow

Location	Tow Line Tension (lbf)					Tow Line Tension (KN)				
	Mean	STD	Max	Min	COV	Mean	STD	Max	Min	COV
1	8254	389	9906	6651	0.05	36.7	1.7	44.1	29.6	0.0
2	7814	464	9512	5793	0.06	34.8	2.1	42.3	25.8	0.0
3	7670	489	9465	5793	0.06	34.1	2.2	42.1	25.8	0.0
4	8162	2052	20568	1705	0.25	36.3	9.1	91.5	7.6	0.0
5	3066	4364	21556	-430	1.42	13.6	19.4	95.9	-1.9	0.0

9. System Performance and Numerical Model Validation

9.1 Sample Test Results: Operational and Extreme Seas

Installed testing results are presented in this section as well as an overview of the onboard instrumentation systems. Figure 31 outlines the types and locations of sensors onboard the model, as well as the remote sensors. Data collected include wind speed and direction, wave height, wind turbine power and rotor speed, platform angular position, platform translational and rotational accelerations, tower loads, platform loads and mooring line loads. Sample rates vary depending on the instrument and range from 10 to over 60Hz depending on purpose. For example accelerometers are sampled at 60Hz while turbine power output is 10Hz. In total, over 60 channels of data are being collected from the floating wind turbine. Also shown are the labels for the three legs of the platform as well as the coordinate system utilized for expressing the acceleration results. Further, an instrumented buoy provides a separate wave height measurement, wind speed, atmospheric, and current profiles from the surface to the seafloor. This comprehensive set of data permits careful comparisons between predicted performance and measured performance, and as noted earlier, can also be used to accurately predict performance for a full-scale 6MW VolturnUS floating wind turbine located farther offshore.

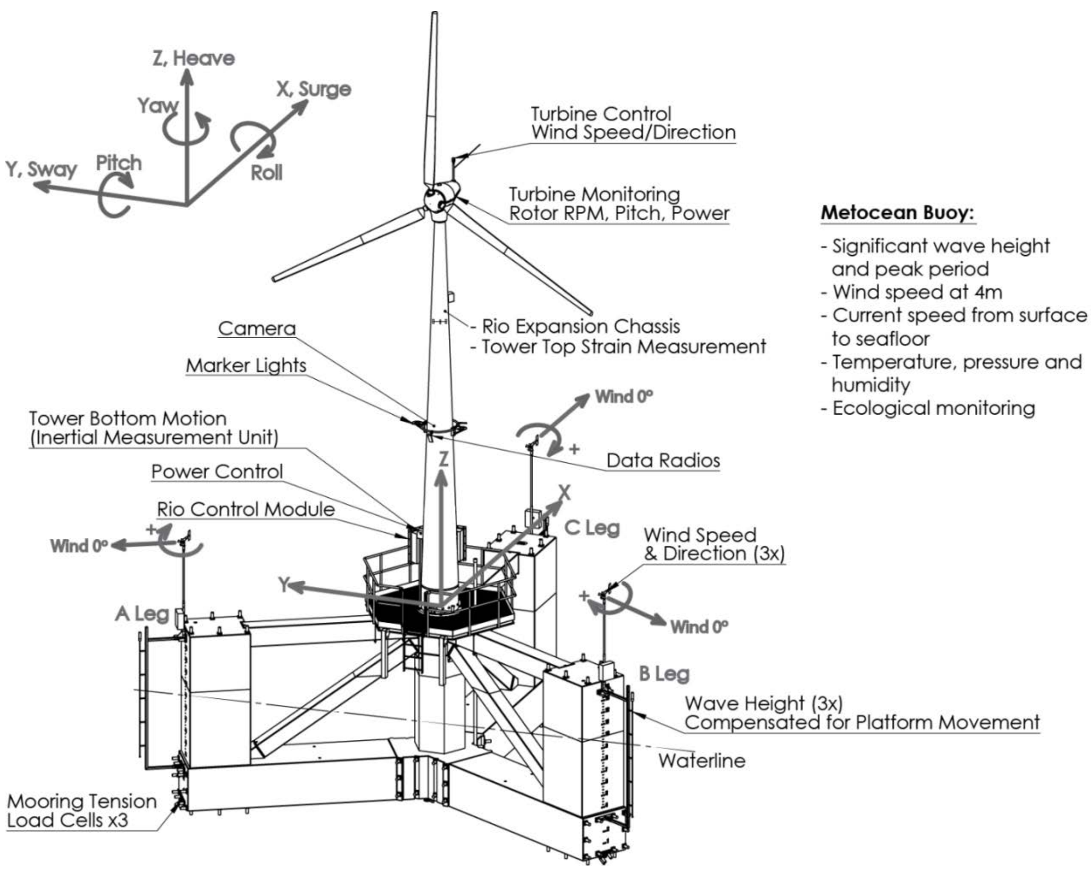


Figure 31 Instrumentation systems

A Fourier analysis of select data from the tower bottom inertial measurement unit is now presented for an operational type event (i.e. DLC 1.2) where the turbine was producing power in a sea state of 0.52m which is equivalent to a 4.2m full-scale significant wave height. Table 2 discusses the desired 1:8 scale wind and wave combinations needed to produce the ABS DLCs. Data considered herein include angular rotations for which a Fourier analysis is performed to demonstrate that the data sets are capturing the expected motion behavior of the VolturnUS floating wind turbine system. The results are shown in Figure 32. As depicted in the figures, the expected behavior observed includes slowly-varying motions associated primarily with second-order difference-frequency wave diffraction forces exciting the platform at its resonant pitch frequency of 0.12Hz, motion in the wave energy frequency range of approximately 0.15-1.0Hz, and wind turbine excitation. With regard to the wind turbine excitations observed, specifically the once-per-revolution (1P) turbine excitation of 1.67-1.75Hz (100-110rpm) is present.

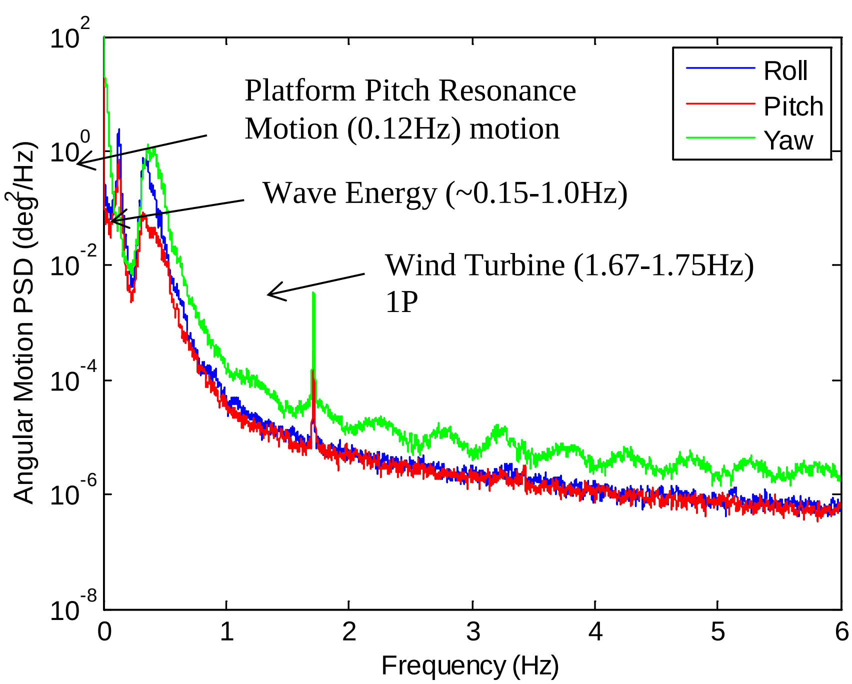


Figure 32 Power spectral density plots of bottom tower angular motions

During this testing campaign several storm events occurred that produced the desired extreme scaled conditions required by the ABS. This near full-scale test offers a unique opportunity to understand floating turbine behavior when exercised to design limits. In this section, one such event, occurring on November 1st 2013 is discussed. On this day the model experienced a scaled DLC 1.6 which considers the turbine operating at rated wind speed, applying the peak overturning moment to the platform while experiencing 50-year waves. The maximum recorded values of this scaled DLC 1.6 on Nov. 1, 2013 are shown in Table 9. The maximum recorded wave height and peak thrust of the turbine were within 3% of desired DLC 1.6 scaled conditions. Also shown is the predicted behavior from a coupled aeroelastic/ hydrodynamic simulation of the full-scale system subjected to ABS DLC 1.6. The floating platform performed markedly well and exhibited accelerations very close to the predicted results used for design of the full-scale system. Direct comparisons of the scale model test data to the numerical models of the full-scale system produce favorable results, indicate good agreement and give confidence for full-scale implementation. These favorable direct comparisons of the model to full-scale predictions also indicate that the model test program is performing as intended. Figure 33 shows the prototype in this extreme environment.

Table 9 Comparison of measured and predicted loads for scaled and full-scale ABS DLC 1.6 50-year extreme conditions

Parameter	1:8 Scale (Full-Scale)		
	VolturnUS Data	FAST Simulation	% Difference
Maximum Wave Height (m)	2.69 (21.5)	2.64 (21.1)	1.9%
Maximum Turbine Thrust (kN)	1.4 (717)	1.37 (700)	2.2%
Maximum Accelerations at the Tower Base (g)	0.165 (0.165)	0.177 (0.177)	-6.8%
Maximum Platform Pitch Angle (degrees)	5.91 (5.91)	5.81 (5.81)	1.7%

Figure 33 VolturnUS 1:8 subjected to scaled extreme 50-year design conditions of ABS DLC 1.6 on November 1st, 2013

9.2 Sample Verification of Numerical Model

Comparisons between results of numerical modeling software FAST [40] and experimental performance data collected are now presented. FAST is a coupled aeroelastic and hydrodynamic model for simulation floating wind turbine global performance and has been validated through comparisons with tank testing data (see Volume I). The date of the event used for model correlation was November 27th, 2013, 12:51:54 PM to 1:51:58 PM. The mean and maximum wind speeds were 15.4m/s and 23.6m/s, respectively. The significant wave height was 1.6m. The peak period was 5.2s and the maximum wave height was 2.6m which is equivalent to a scaled 500-year event for the 6MW VolturnUS. The simulated time was one hour. To facilitate comparison between the data and model, a custom version of FAST was utilized that computes wave diffraction forces from a measured wave elevation time series record collected during this event. The standard version of FAST can only simulate regular waves or random waves based on a user defined spectra. Wind speed and direction were also input directly. This approach allowed for a reasonable modeling approximation of the measured environment and followed the work of Coulling et al. [41]. Another modification of the standard FAST model is the inclusion of a quadratic viscous drag damping model that was tuned using free-decay test data. Figure 34 shows comparison between the data and FAST for the tower base sway acceleration. The model results compares well with the measured performance capturing the maximum amplitude and frequency of the acceleration. Similarly, tower base roll acceleration is shown in Figure 35 again confirming the ability of the numerical code to accurately predict the peak performance of the VolturnUS system. Table 10 lists maximum recorded values for select variables. The FAST model compares well with measured performance and further improvements are expected as a more refined study is underway. Differences seen between the data and model are due to several factors. These factors include:

- Uncertainty in the measured wave environment. The three wave staffs measure water level changes about 1.07m from the outside face of the radial column. The water level recordings are corrected for platform vertical and angular motions using accelerometer data on the hull to predict the wave elevation at the platform center. Given the close proximity of the wave staffs to structure, the water level at the wave staff is affected by the distortion of the wave field by the presence of the hull. This distortion will affect the water level at the wave staff and hence the measurement of wave elevation. The model uses these measurements directly for input of the wave elevation. Therefore this uncertainty affects both the wave measurement itself and inputs/the predictions of the model itself.
- Uncertainty in the measured wind speed. There are three wind speed measurement devices on the model. Each device is mounted about 3.8m above the water surface on one of the radial columns. This hub height of the turbine above the water level is 12.2m. The difference in elevation between the turbine rotor center and the wind speed measurement is 8.5m. Assuming a power law wind shear model and an exponent of 0.14 per ABS, this could result in a 17.7% difference in the wind at hub height as compared to the sensor height. However, given the inherent uncertainty in extrapolation of wind speed and the lack of data to validate a wind shear power law models, the direct wind speeds at 3.8m were used for these model comparisons. Once, again the model uses the wind time series directly as input which introduces further differences between the test data and model comparisons.
- Uncertainty in instrumentation measurements. Environmental, accelerometers, turbine instrumentation, and load measurement devices all have inherent uncertainty. These uncertainties have been minimized to the extent possible but do introduce further uncertainty in the data and input for the models.
- Assumptions of turbine control logic. The turbine is a commercial machine and its internal control system logic was proprietary and not available for the project. A turbine model was created in FAST that closely matches the Renewegy turbine publically

available aerodynamic performance. Several assumptions were made in an effort to develop a controller that would reproduce the expected wind turbine power, thrust, and blade pitch behavior. These assumptions will lead to differences between the model and physical turbine.

- Uncertainty in mooring line geometry. The mooring lines installed have considerable line lengths (greater than 600ft). It is possible that the laid length of chain is not a straight line from the touchdown point to the anchor. The line may arc or zig-zag. The chain path may have been distorted during installation or during tidal and storm events. It is difficult if not impossible to inspect the chain on the sea floor because it is embedded in the mud. This non-linear path could alter the mooring restoring force. The numerical models assume that the mooring line remains in a vertical pane defined by the touch down point, the as-built anchor location, and the water surface.
- Modeling limitations. FAST currently does not include 2nd order wave forcing. Although these effects are expected to be small, they do present another difference between the test and the model. Further, FAST utilizes a potential flow model (WAMIT). This may not be completely valid for the fairly large wave environments considered here. Drag forces, neglected by a potential flow models, may become somewhat significant. The model also assumes uni-directional long crested waves. This is not completely true for a real ocean environment where there is wave energy in multiple directions and short-crested waves are present.

Further investigations of these uncertainties and expansion of the numerical models to include additional physics is underway but is beyond the scope of this dissertation. Despite these testing uncertainties and modeling limitations, the model and data compare well indicating the suitability of the testing methodology to produce usable data for model validation.

Table 10 Comparison of peak values calculated using FAST and those measured on Nov. 27, 2013

Variable	**Units**	**Data**	**FAST**	**% Diff.**
Blade Pitch Angle	deg.	31.7	29.7	6%
Tower Base Sway Acceleration	g	0.121	0.116	4%
Tower Base Heave Acceleration	g	0.102	0.091	10%
Platform Roll Acceleration	rad/s^2	0.119	0.108	9%

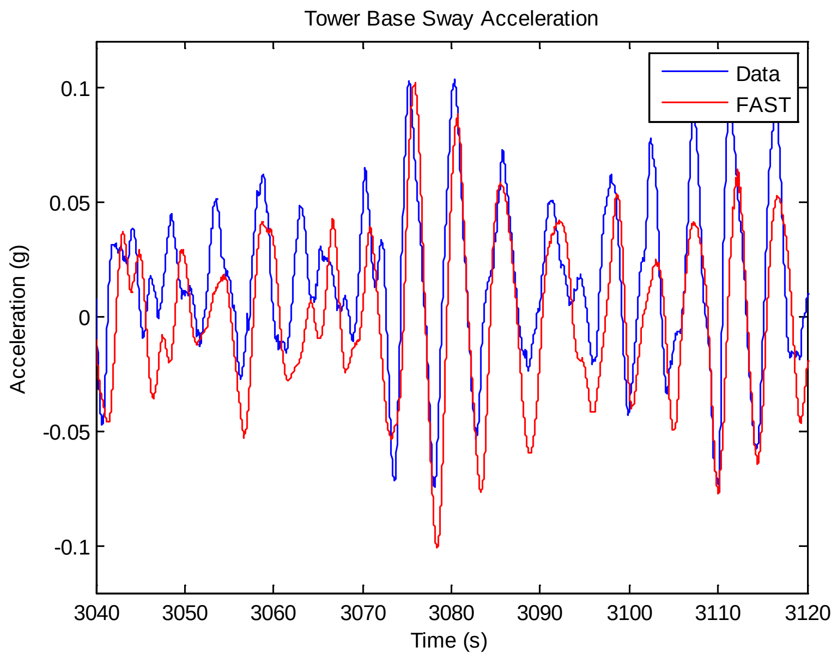


Figure 34 Comparison of tower base sway acceleration predicted by numerical modeling in FAST and model test data collected at Castine on Nov. 27, 2013

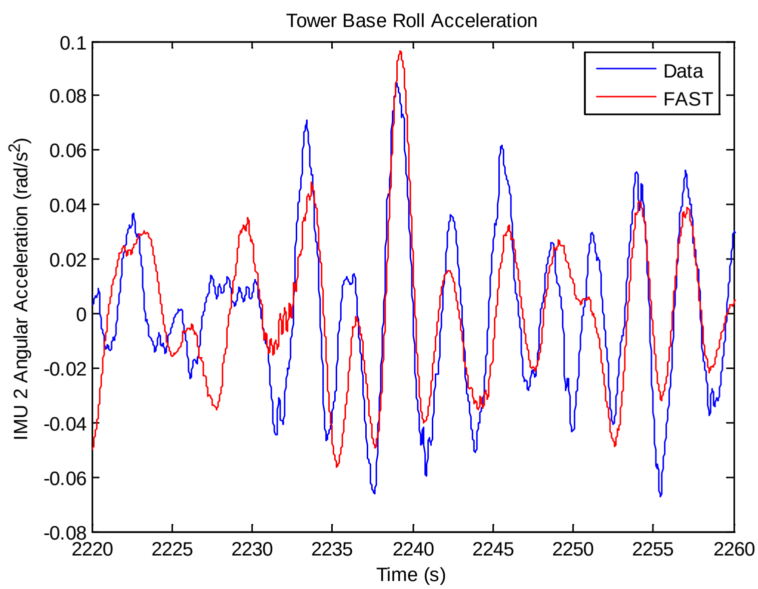


Figure 35 Comparison of tower base roll acceleration predicted by numerical modeling in FAST and model test data collected at Castine on Nov. 27, 2013

10. Decommissioning and Recovery

The successful decommissioning and recovery of the VolturnUS 1:8 took place on November 4th, 2014 at 8:30am after 18-months of testing. Once testing was complete, the entire prototype was towed completely assembled with a single tugboat following the tow route shown in Figure 36 using the Maine Maritime Academy *Pentagoet* tugboat. The route started from the testing site off of Castine, Maine and ended at the Mack Point Marine Intermodal Cargo Terminal in Searsport, Maine where the unit was removed from the water with a crane. The length of the tow was approximately 5.5 nautical miles and the entire tow took approximately 4hours. Measurements were made during the operation to confirm tow-out recovery methods and load predictions. The tow was completed successfully with no incidents and demonstrated recovery methods for a full-scale 6MW system. Measurements of marine growth, corrosion, and structural health were also completed to assess the robustness of hull system's materials and design.

The decommissioning of the VolturnUS 1:8 illustrates the advantageous ability for recovery and repair of the full-scale floating VolturnUS wind turbine concept. Fixed bottom turbines and deep draft floating wind turbines require expensive vessels/operations at sea for installation, maintenance, and recovery. The VolturnUS floating turbine can be easily disconnected from its moorings and electrical export cable and then towed to shore with a single tug boat. This process was exemplified through the VolturnUS 1:8 prototype recovery operation. The three chain catenary moorings were disconnected and secured with a marker buoy. Similarly the electrical export cable was disconnected and held on station. With the unit free from its moorings, a single tug boat towed the unit to Searsport, Maine. An aerial image of the VolturnUS being towed is shown in Figure 37 depicts the tow-out configuration. Upon arrival in Searsport, the entire system was lifted and placed onto the dock. The unit was then taken apart completely in the dry further illustrating how floating offshore wind turbines can minimize at sea operations and reduce the cost of offshore wind. Figure 38 shows the VolturnUS 1:8 unit ready for lifting in Searsport.

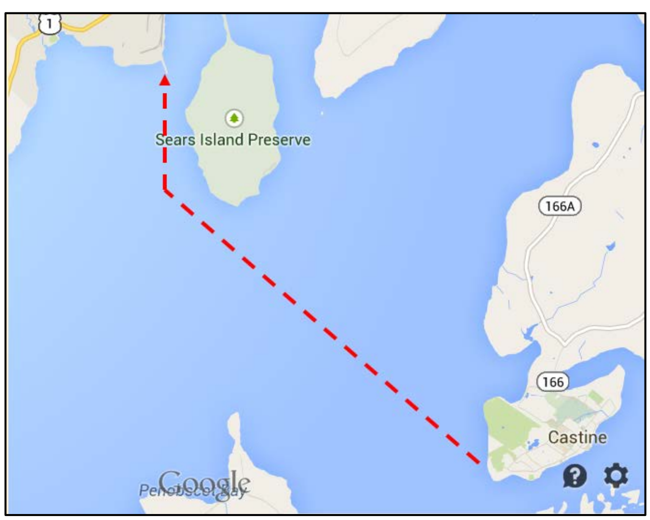


Figure 36 VolturnUS Tow Route

Figure 37 VolturnUS 1:8 Recovery Tow Configuration

Figure 38 Crane Ready to Pick VolturnUS 1:8 at Searsport, ME

Measurements of tow speed and tow line tension were made during the recovery operation to further verify analytical predictions. Tow line tension was measured using a load cell in-line with the tow line. Calculations for the predicted tow-line force were made following DNV-RP-C205 (2010). Table 11 shows thirteen measurements of tow speed and average tow-line tension. The measurements are compared to analytical predictions made using DNV guidance, the actual hull geometry and the measured tow speed. The predicted line tensions compare well with the measured tensions. The analytical prediction is on average 10% larger than the measured load indicating the analytical assumptions are producing a conservative estimate of the tow-line loads. A 12% coefficient of variation was calculated for the ratio of predicted to measured load. Several factors could have affected the current speed and tow line load measurements which may have contributed to the deviation. These include current speed and tow-line force measurement uncertainty, variation in current speed with depth, and the presence of a vessel wake disrupting the flow around the submerged body. Despite the practical challenges in making field measurements during a real tow operation, the measured tensions compares well and the predicted tensions are slightly conservative giving confidence in the analytical tools and methods used for the towing operation.

Table 11 Measured and Predicted Towline Tensions

Test No.	Tow Speed (m/s)	Measured Load (kN)	Predicted Load (kN)	Predicted / Measured
1	1.22	32.9	30.5	93%
2	1.35	31.6	37.9	120%
3	1.39	31.6	39.8	126%
4	1.35	32.0	37.8	118%
5	1.28	33.4	33.6	101%
6	1.24	33.8	31.6	94%
7	1.38	32.9	39.2	119%
8	1.34	31.8	36.9	116%
9	1.40	33.4	40.5	121%
10	1.40	34.5	40.5	117%
11	1.22	33.4	30.8	92%
12	1.25	34.9	32.3	93%
13	1.41	33.4	41.2	124%
			Average	**110%**
			Coefficient of Variation	**12%**

11. Hull Inspections

Once the VolturnUS 1:8 platform was safely in the dry, the hull was inspected to determine marine growth rates, damage to the concrete hull including cracking or spalling, steel corrosion rates, and post-tensioning losses. This data provides insights on the durability of the systems and will help inform future full-scale design efforts.

Marine growth was recorded for different parts of the hull. An anti-fouling paint was used on the hull below the waterline to minimize growth. The coating did a fairly good job preventing growth on the hull. Along member corners, connections and horizontal surfaces, significant accumulations up to 5.4cm were observed and consisted mostly of mussels and sea weed. In the most densely covered areas, only about 20% of the surface area was covered with marine growth. Uncoated components such as the mooring chains were completely covered for the first 5m of length below the mooring fairlead. Thickness of marine growth of the mooring chains was measured up to 6.5cm. The wet density of this growth was measured to be approximately 725kg/m^3. This data provides key measurements for the Gulf of Maine which can be used later for full-scale design efforts.

Figure 39 Marine Growth on the VolturnUS 1:8 Hull

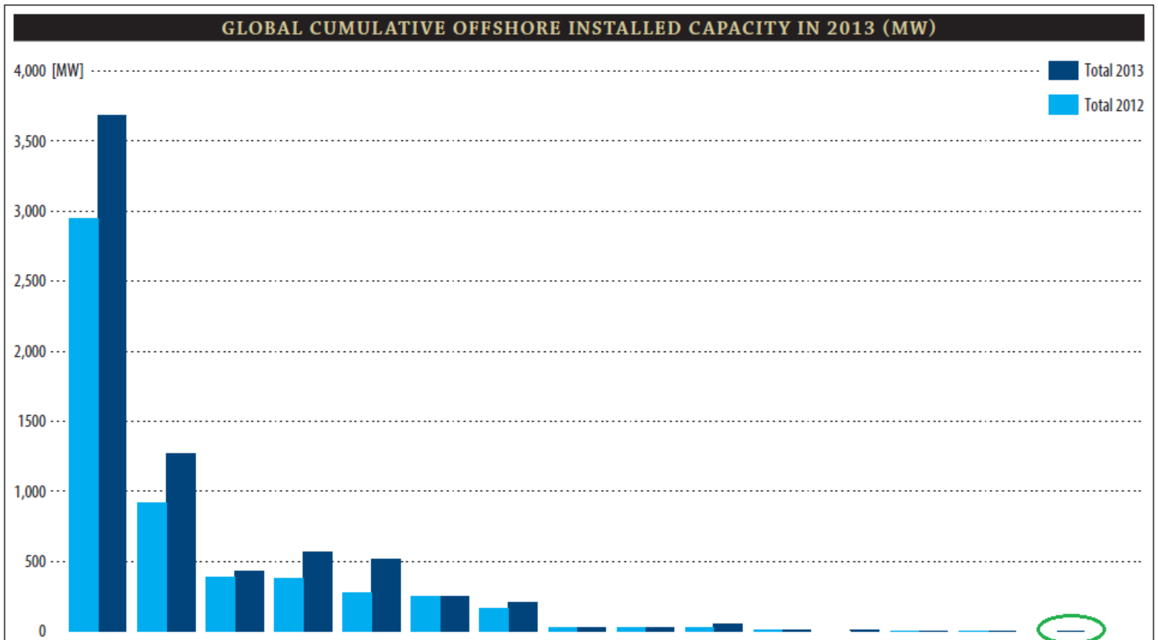
Following removal of the marine growth, the hull was dismantled and a full structural inspection for each member was conducted to assess the concrete durability, member connections and steel reinforcement. The concrete hull had not experienced any damage during its deployment and investigations did not reveal any signs of cracking or spalling. No wear on the concrete was noted giving confidence that the concrete mix proportions and structural design performed as intended. Corrosion of steel reinforcement was not observed giving confidence in the corrosion protection methods implemented which included epoxy coatings and grease. Accessible steel reinforcement was measured for corrosion and showed little to no measurable amount of corrosions after 18-months. Lift-off tests for the stressing steel were also completed to determine losses due to concrete shrinkage, creep, steel relaxation, and steel anchorage losses. Steel losses were under the design estimated losses indicating conservatism in the design methodology. Member-to-member connections also appeared to have endured the testing program with no damage or wear again giving confidence in the materials and design methods implemented. This inspection gives confidence that the material systems, corrosion protection, and design methods provide sufficient robustness. Following this inspection the unit was returned to the University of Maine.

12. Conclusions

A unique offshore intermediate-scale model testing approach has been developed and successfully produced scale global performance data as well as demonstrated the full-scale design, advanced materials, construction techniques, and deployment methods for a floating wind turbine foundation called VolturnUS developed by the University of Maine. Scale model test techniques developed for wave basins were adapted for this offshore test. The Castine test site was selected to readily produce scale ABS design metocean conditions found farther offshore in the Gulf of Maine that would be experienced by a full-scale turbine. This was confirmed through a comparison of measured metocean data at the test site with far offshore data scaled by the appropriate factors. At 1:8 scale, this test site reliably produces scale extreme wind/ wave events (e.g. 50-year return period) in a short period of time offering a unique venue for understanding floating turbine behavior in extreme events at near full-scale. The 1:8 scale model was designed, constructed using full-scale structural materials, arrangements, and methods while maintaining desired hydrostatic and dynamic characteristics confirmed through dockside testing. A commercial grid-connected turbine was used and modified to apply the desired scaled dominant wind forcing, thrust. A scale mooring system consisting of chain catenaries and drag anchors was implemented.

Since the experiment has been carefully crafted to match the scale system properties and environmental loads, the generated data can be used to predict the behavior of a full-scale 6MW VolturnUS. This extensive data set has confirmed design calculations establishing confidence in the principles of the VolturnUS design methodology as well as the concrete hull and composite tower structural designs. The VolturnUS 1:8-scale floating turbine has been successfully subjected in service to scaled 50-year extreme ABS design conditions. This experiment represents a major milestone in the design of the VolturnUS technology and floating turbines in general as few if any open water floating wind turbine has yet seen its extreme design conditions. Based on current observations, the 1:8-scale VolturnUS exhibits responses in line with coupled model design predictions and provides confidence moving forward with design and construction of a full-scale floating offshore wind turbines utilizing the VolturnUS platform technology. Numerical codes for offshore floating wind turbines have also been partially validated as part of this work providing another benchmark for development and understanding of floating wind turbines. Numerical models of the physical model show good agreement.

The prototype was successfully recovered after 18-months of testing offshore marking the successful conclusion of the test program. VolturnUS, developed by the University of Maine, was at the time, the only grid-connected offshore wind turbine in the US as evidenced by the Global Wind Energy Council Report in 2014 as shown in Figure 40 [42]. The prototype is a 1:8 Froude scale model of a planned 6MW full-scale design to be deployed far offshore Maine near Monhegan Island. The model test serves to de-risk the deployment of the full-scale turbine and was installed offshore Castine, Maine in June, 2013. The VolturnUS design utilizes innovations in materials, construction, and deployment technologies such as a concrete semi-submersible hull and an advanced composite tower to reduce the costs of offshore wind turbines. The model was designed to replicate the geometry, materials, construction, tow-out and anchoring methods which will be used at full scale. A comprehensive instrumentation package monitors key performance characteristics of the platform to verify the design assumptions and coupled modeling software. Data collected during the testing confirm the methodology used to design the test program including site selection, scaling laws, instrumentation list, and demonstrating full-scale construction materials and deployment methods.



	UK	Denmark	PR China	Belgium	Germany	Netherlands	Sweden	Finland	Ireland	Japan	Korea	Spain	Norway	Portugal	US	Total
Total 2012	2,947.9	921.1	389.6	379.5	280.3	246.8	163.7	26.3	25.2	25.3	5.0	0.0	2.3	2.0	0.02	**5,415.0**
New 2013	733.0	349.5	39.0	192.0	240.0	0.0	48.0	0.0	0.0	24.4	0.0	5.0	0.0	0.0	0.0	**1,630.9**
Total 2013	3,680.9	1,270.6	428.6	571.5	520.3	246.8	211.7	26.3	25.2	49.7	5.0	5.0	2.3	2.0	0.02	**7,045.9**

Source: GWEC

Figure 40 Global Installed Offshore Wind Capacity

The results of this effort were detailed in four peer reviewed papers developed for this project. A concise summary of these papers and key conclusions are presented below:

1. Design conditions for full-scale floating offshore wind turbines were presented in the paper titled “Gulf of Maine Extreme Wave and Wind Design Parameters for Offshore Wind Turbines”, Journal of Ocean Engineering by Anthony Viselli, George Forristall, Bryan Pearce, and Habib Dagher [39]. Design parameters needed for the development of full-scale floating wind turbines in the Gulf of Maine using Gulf of Maine buoy data were estimated including the 50 year significant wave height, wind speed, and gust factors for five sites. These design values serve as the basis for full-scale design efforts and for selecting the model test site for the model test. This publication represents the first time buoy measurements have used to make estimates of extreme waves and winds in the Gulf of Maine.
2. An overview of the testing effort was presented in the paper titled “VolturnUS 1:8 - Design And Testing Of The First Grid-Connected Offshore Wind Turbine in the USA” by Anthony Viselli, Habib Dagher, and Andrew Goupee. This paper was presented at Society of Naval Architects and Marine Engineers’ (SNAME) 19th Offshore Symposium in February, 2014 and won the “Best Paper” award at the symposium [43].

3. The publication “Model Test of a 1:8 Scale Floating Wind Turbine Offshore in the Gulf of Maine” by Anthony Viselli, Andrew Goupee, and Habib Dagher published by the Journal of Offshore Mechanics and Artic Engineering on May 1st, 2014 and also presented at the 33rd Offshore Mechanics and Artic Engineering Conference in San Francisco, California in June, 2014 [37]. A suitable test was identified that produced the desired 1:8 scaled conditions and was confirmed through buoy measurements and testing of the VolturnUS 1:8 model. Test results were used to validate coupled models and the prototype was exercised in ABS equivalent scaled conditions. These data confirm the suitability of the model testing methodology. The effort also allowed for de-risking full-scale commercial project.
4. The publication “Design and Model Confirmation of the Intermediate Scale VolturnUS Floating Wind Turbine Subjected to its Extreme Design Conditions Offshore Maine” by Anthony Viselli, Andrew Goupee, Habib Dagher, and Christopher Allen was published by Wiley Wind Energy Journal and presented at the American Wind Energy Association Windpower Conference in Las Vegas on May 7th, 2014 [38]. First, the paper presented numerical model comparisons with test data that confirmed the ability of the models to predict turbine behavior, platform motions, mooring line tensions using as built geometry and direct environmental inputs. This comparison confirms the suitability of the testing methodology to generate useful data for validation of numerical models. While this model correlation study has been able to draw positive conclusions regarding the performance of the numerical software tools FAST and AQWA, there are several pieces of additional work that have not been covered. These include additional environments included in the correlation study, methods of refining environmental input conditions used in the analysis, expanding the capabilities of FAST in an attempt to refine the agreement between the measured data and predictions (e.g., refined aerodynamics, addition of slow-drift forces, permitting the use of realistic short-crested seas in the hydrodynamic load calculations, etc). In the winter of 2013-2014 this prototype witnessed the equivalent of 50-year to 500-year return period storms exercising it to the limits prescribed by design standards, offering a unique look at behavior of a floating turbine subjected to extreme design conditions. The test data shows that the VolturnUS platform was successfully exercised in service under operational, extreme, and survival load cases similar to those put forth by the ABS Guide [1]. Measured responses of VolturnUS 1:8 confirm the design ability to successfully withstand these ABS conditions. The experiment further provides unique operational data on the behavior of floating wind turbine platforms exercised to these ABS design limits. Operational, 50-year to 500-year scale conditions were witnessed, recorded, and compared with expected full-scale response. Because the VolturnUS 1:8 model was properly scaled, the test site carefully selected to produce scaled conditions, and the turbine properly matched to

provide the correct thrust, the performance could be compared to a 6MW full-scale unit subjected to comparable ABS conditions far offshore Maine.

5. Lastly, although not explicitly published, the test program also allowed for an ecological monitoring/ permitting procedures to be developed in the State of Maine for floating offshore wind turbines and also help to de-risk a full-scale demonstration project.

These accomplishments highlight the usefulness of an intermediate scale testing approach in the early stages of a new technology development program for novel floating onshore wind foundation and other renewable energy technologies.

13. Acknowledgements

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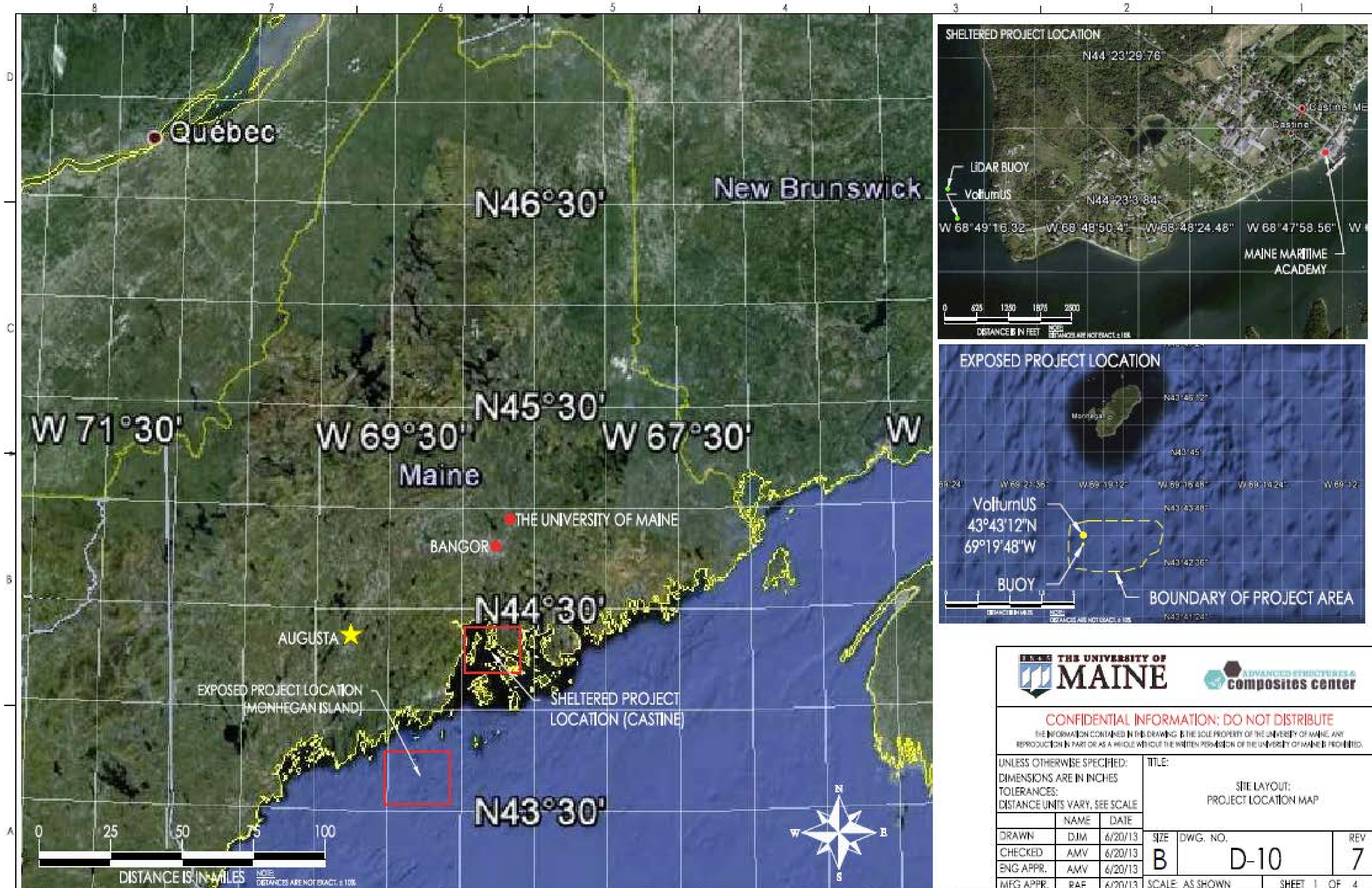
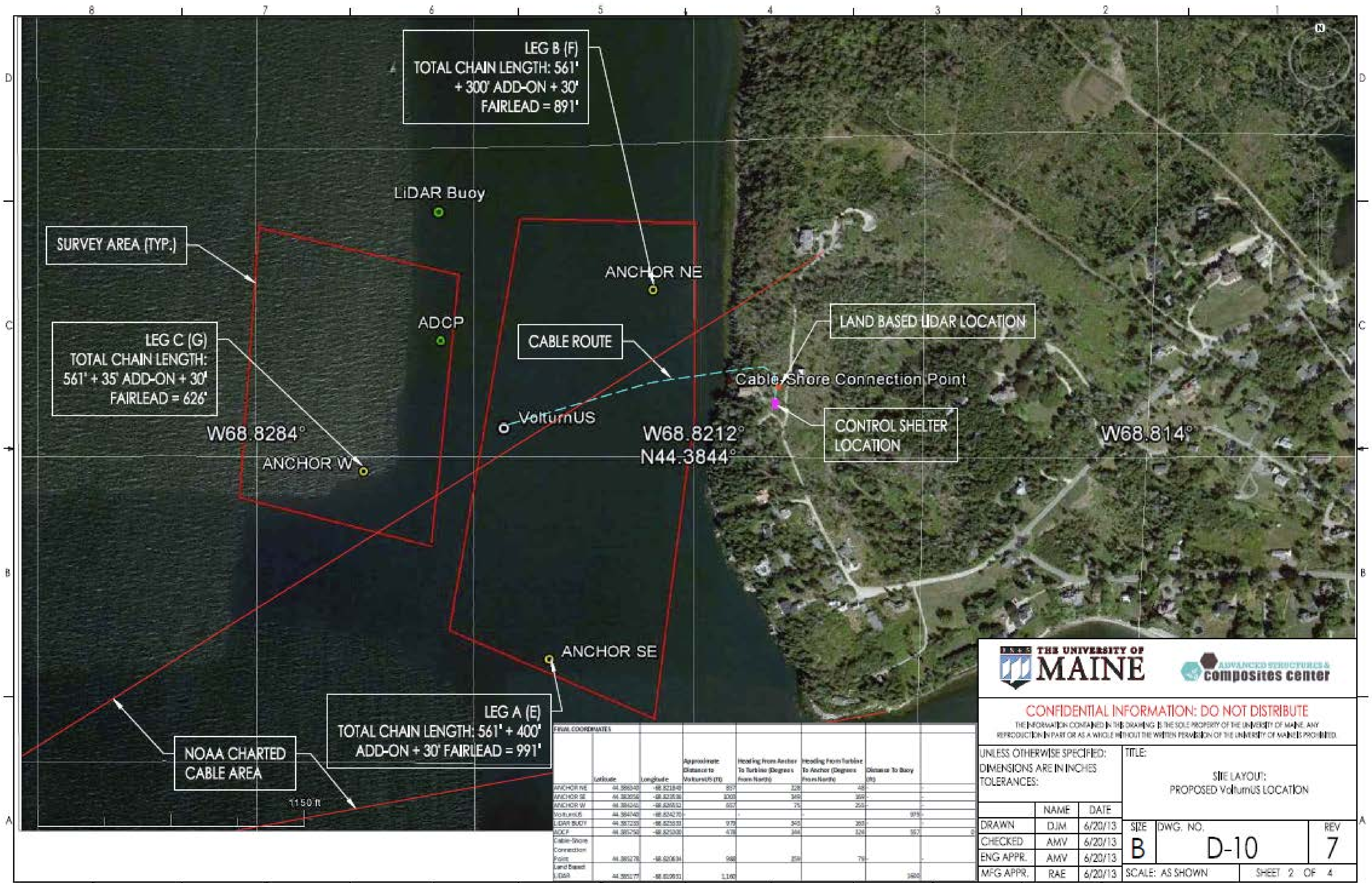
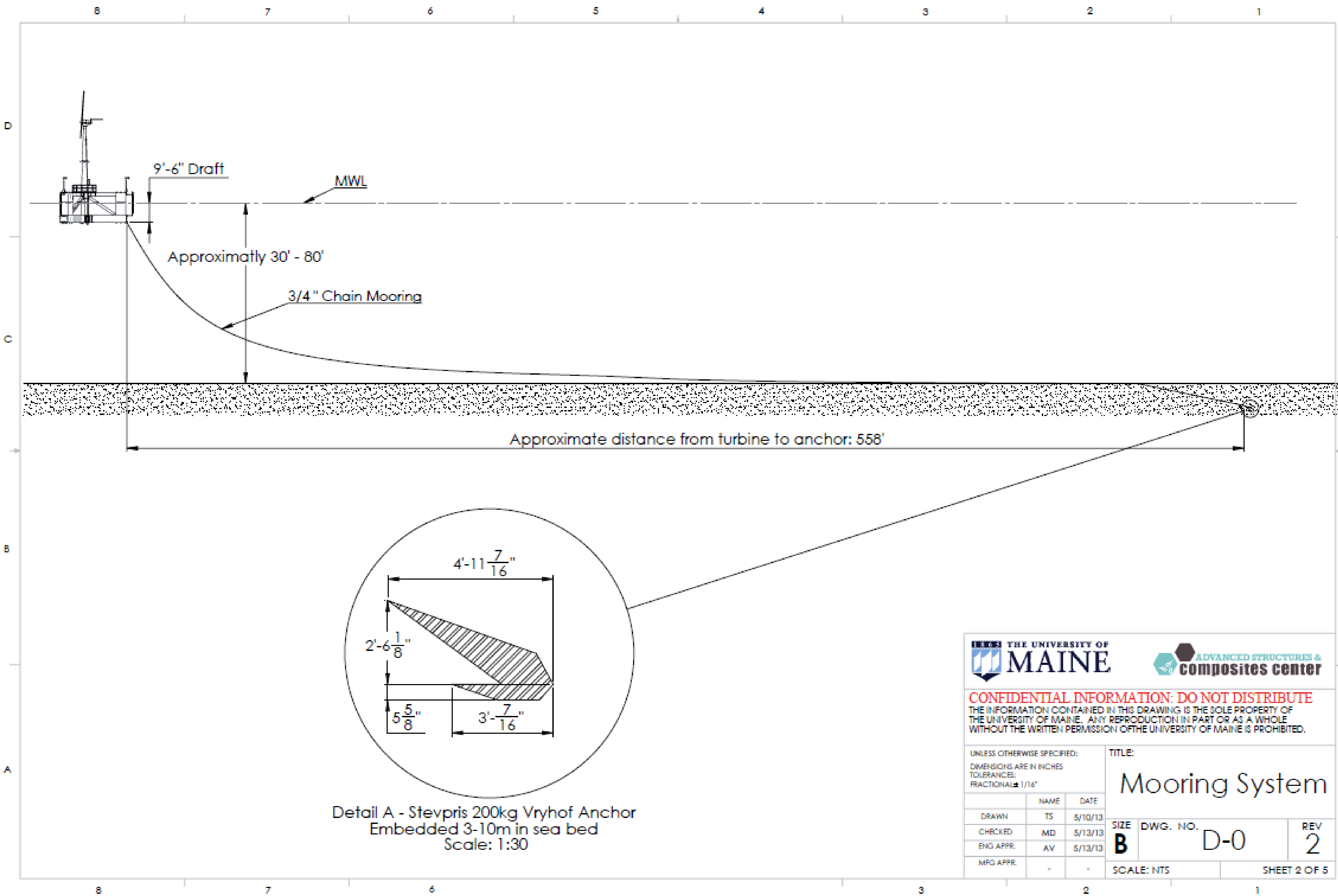
APPENDIX A: Design Drawings





FINAL COORDINATES

	Latitude	Longitude	Approximate Distance to VolturnUS (ft)	Heading From Anchor To Turbine (Degrees From North)	Heading From Turbine To Anchor (Degrees From North)	Distance To Buoy (ft)	
ANCHOR NE	44.386040	-68.821840	857	228	48	-	-
ANCHOR SE	44.382050	-68.823530	1003	349	169	-	-
ANCHOR W	44.384240	-68.826550	657	75	255	-	-
VolturnUS	44.384740	-68.824270	-	-	-	975	-
LIDAR BUOY	44.387230	-68.825530	979	345	165	-	-
ADCP	44.385750	-68.825030	478	344	324	557	0
Cable-Shore Connection Point	44.385270	-68.820634	988	259	79	-	-
Land Based LIDAR	44.385177	-68.819651	1,160			1600	


9'-6" Draft
MWL
Approximatly 30' - 80'
3/4 " Chain Mooring
Approximate distance from turbine to anchor: 558'
4'-11 7/16"
2'-6 1/8"
5 5/8"
3'- 7/16"
Detail A - Stevpris 200kg Vryhof Anchor
Embedded 3-10m in sea bed
Scale: 1:30
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CONFIDENTIAL INFORMATION: DO NOT DISTRIBUTE
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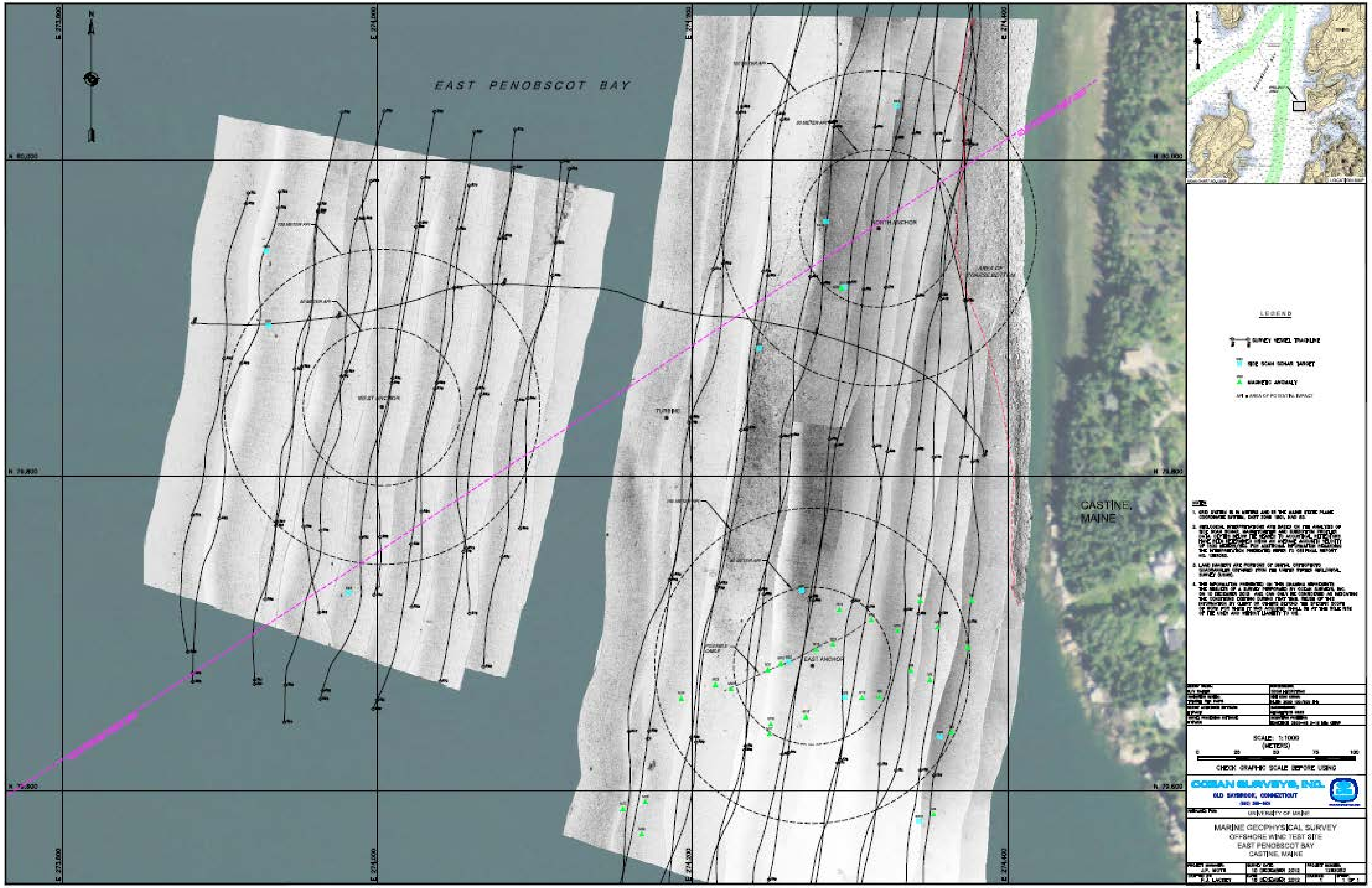
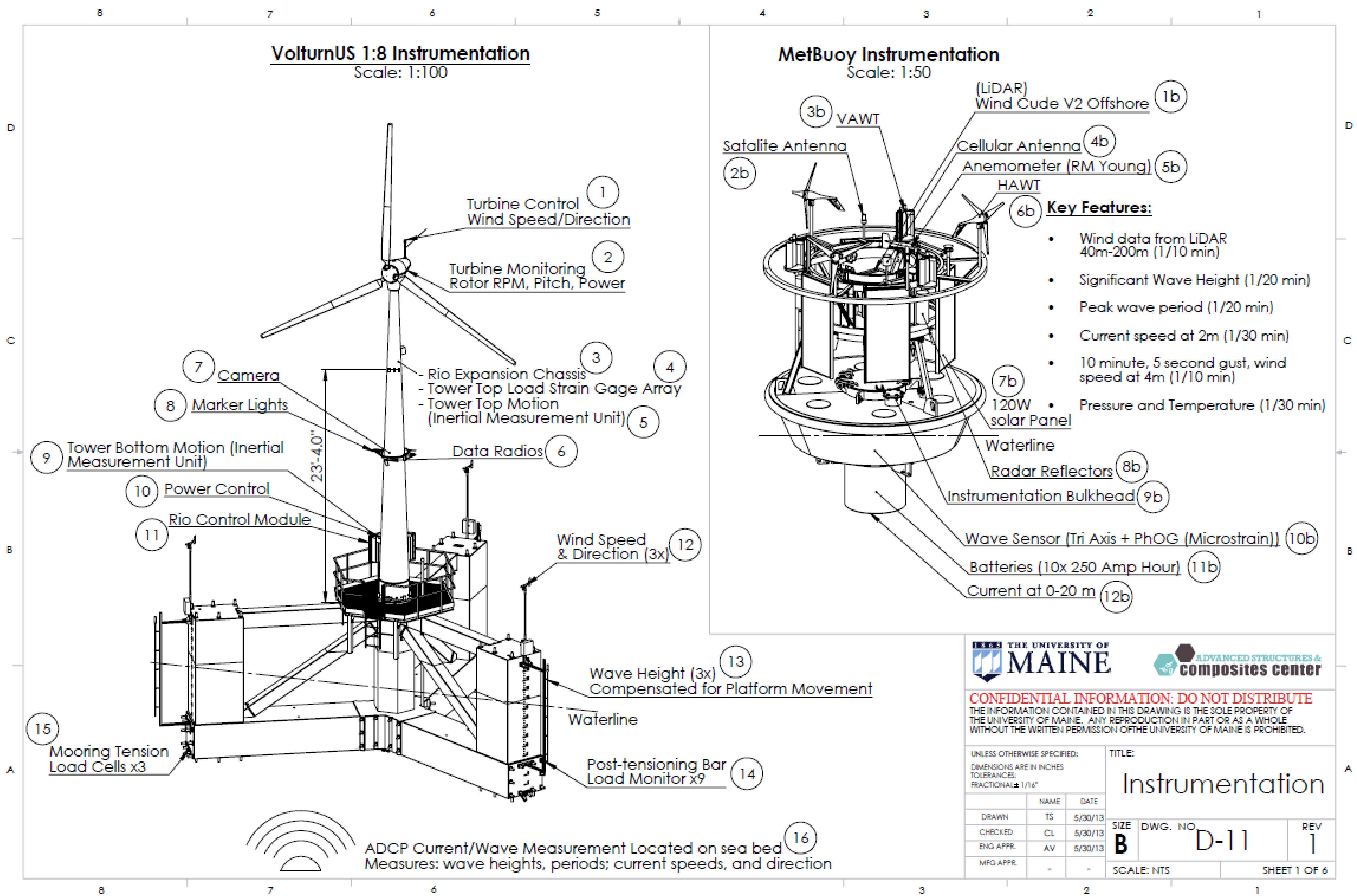
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL± 1/16"
NAME
DATE
DRAWN TS 5/10/13
CHECKED MD 5/13/13
ENG APPR. AV 5/13/13
MFG APPR.
TITLE:
Mooring System
SIZE B
DWG. NO. D-0
REV 2
SCALE: NTS
SHEET 2 OF 5



S-11 SITE INVESTIGATION


VolturnUS 1:8 Instrumentation
Scale: 1:100
1 Turbine Control
Wind Speed/Direction
2 Turbine Monitoring
Rotor RPM, Pitch, Power
3 - Rio Expansion Chassis
4 - Tower Top Load Strain Gage Array
- Tower Top Motion
5 (Inertial Measurement Unit)
6 Data Radios
7 Camera
8 Marker Lights
9 Tower Bottom Motion (Inertial
Measurement Unit)
10 Power Control
11 Rio Control Module
12 Wind Speed
& Direction (3x)
13 Wave Height (3x)
Compensated for Platform Movement
Waterline
14 Post-tensioning Bar
Load Monitor x9
15 Mooring Tension
Load Cells x3
23'-4.0"
16 ADCP Current/Wave Measurement Located on sea bed
Measures: wave heights, periods; current speeds, and direction
MetBuoy Instrumentation
Scale: 1:50
1b (LiDAR)
Wind Cude V2 Offshore
3b VAWT
2b Satalite Antenna
4b Cellular Antenna
5b Anemometer (RM Young)
6b HAWT
Key Features:
• Wind data from LiDAR
40m-200m (1/10 min)
• Significant Wave Height (1/20 min)
• Peak wave period (1/20 min)
• Current speed at 2m (1/30 min)
• 10 minute, 5 second gust, wind
speed at 4m (1/10 min)
• Pressure and Temperature (1/30 min)
7b 120W
solar Panel
Waterline
8b Radar Reflectors
9b Instrumentation Bulkhead
10b Wave Sensor (Tri Axis + PhOG (Microstrain))
11b Batteries (10x 250 Amp Hour)
12b Current at 0-20 m
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FRACTIONAL ± 1/16"
NAME DATE
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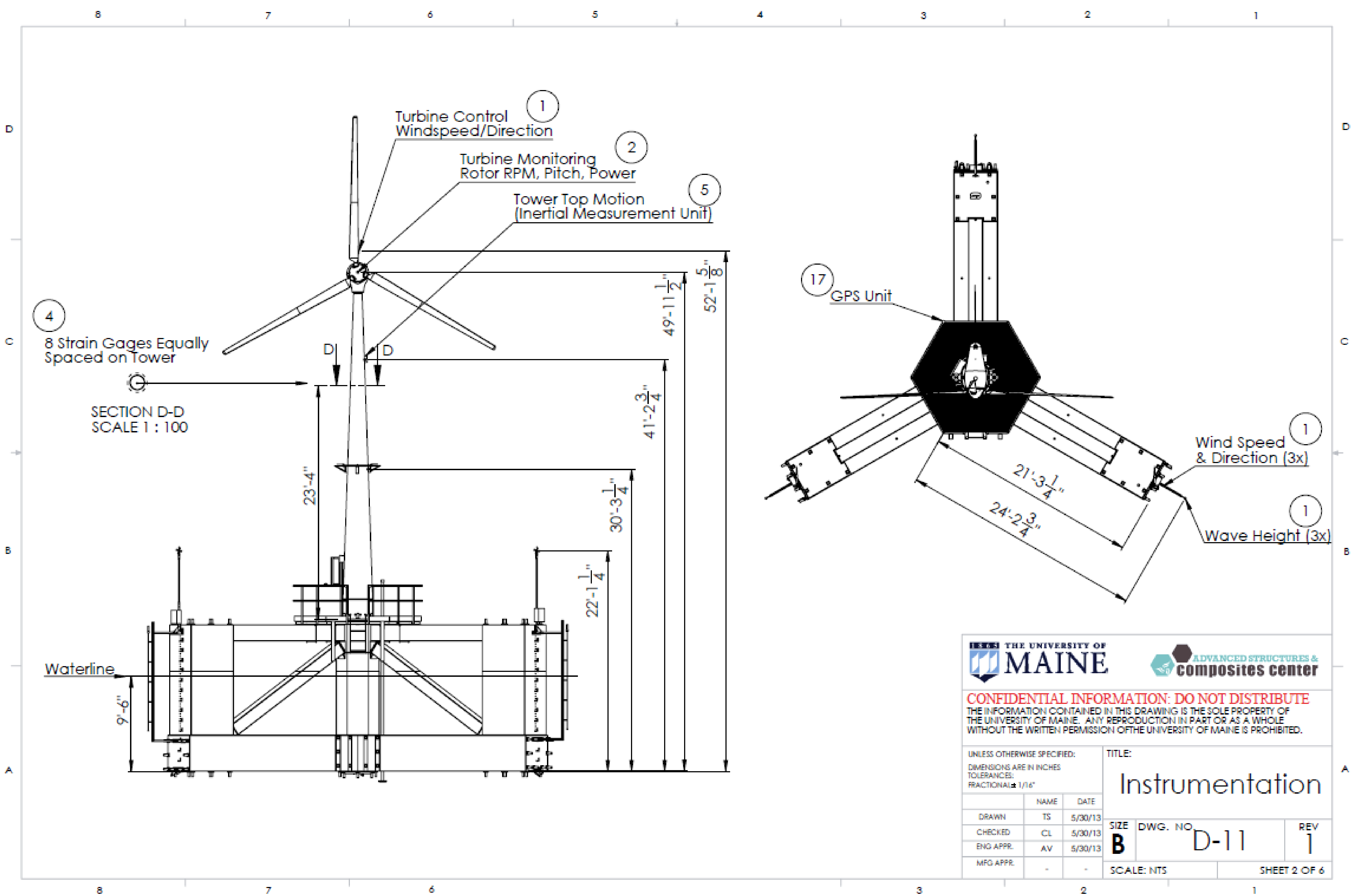
CHECKED CL 5/30/13
ENG APPR. AV 5/30/13
MFG APPR. - -
TITLE:
Instrumentation
SIZE B
DWG. NO. D-11
REV 1
SCALE: NTS
SHEET 1 OF 6


Turbine Control
Windspeed/Direction
Turbine Monitoring
Rotor RPM, Pitch, Power
Tower Top Motion
(Inertial Measurement Unit)
8 Strain Gages Equally
Spaced on Tower
SECTION D-D
SCALE 1 : 100
Waterline
9'-6"
23'-4"
22'-1 1/4"
30'-3 1/4"
41'-2 3/4"
49'-11 1/2"
52'-1 5/8"
GPS Unit
Wind Speed
& Direction (3x)
Wave Height (3x)
21'-3 1/4"
24'-2 3/4"
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Instrumentation
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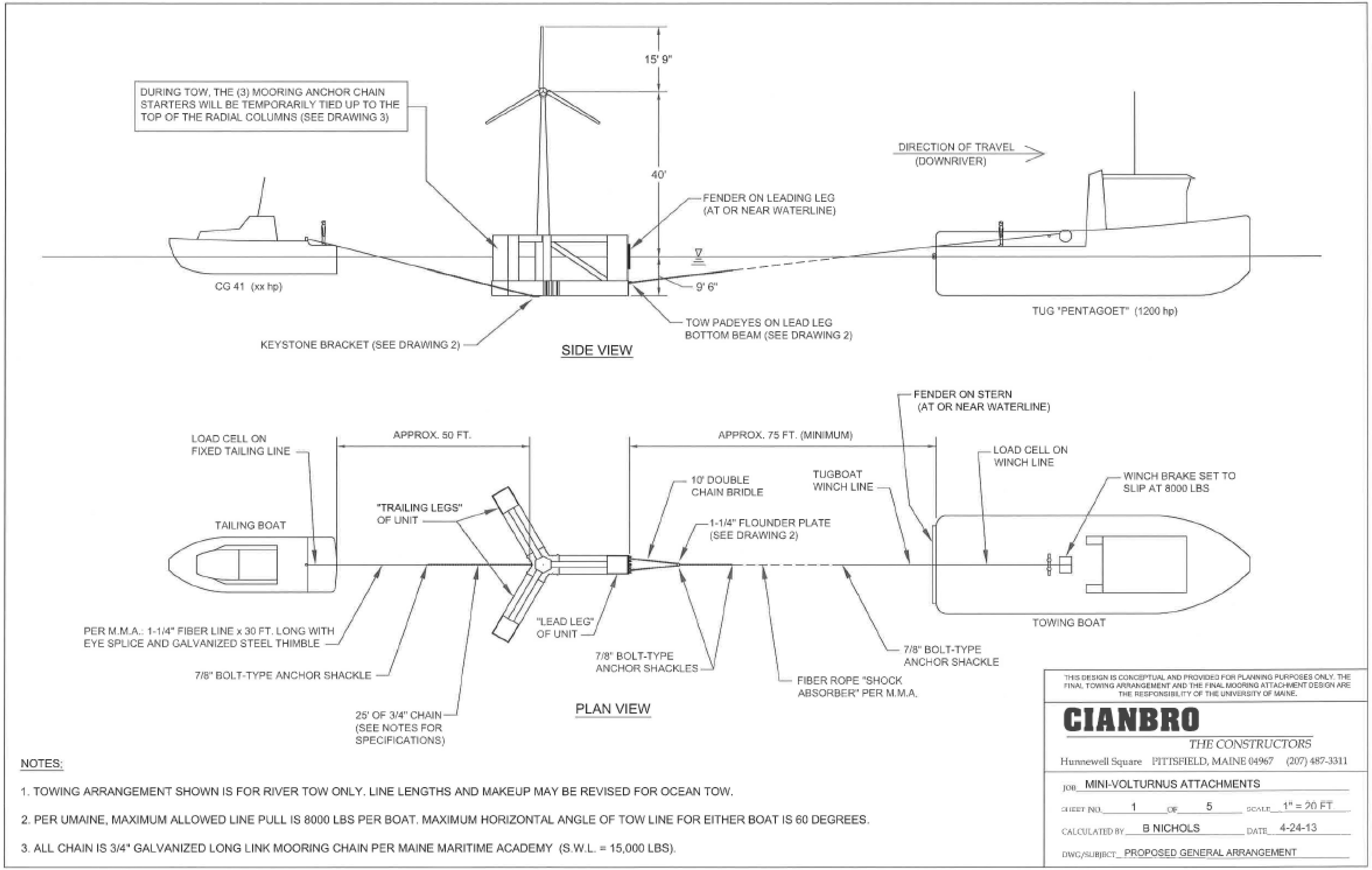
SHEET 2 OF 6



S-10 TOW OUT (CIANBRO)