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WESML – Wave Energy at the Shoals Marine Lab

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ABSTRACT / EXECUTIVE SUMMERY

This study investigates the feasibility of using technology to convert wave energy into usable electricity in the Gulf of Maine. The interest of this investigation is to provide electricity to the Shoals Marine Laboratory on Appledore Island, at the Isles of Shoals. Technologies have been evaluated, and site locations considered, with the goal of providing 5-10 kilowatts of power.

Many variables were considered such as bathymetry, wind directions and meteorological conditions. Data on the wave activity was collected at specific sites of interest for wave energy conversion devices. These data were correlated with NOAA station 44098, a wave data buoy at Jeffrey's Ledge, located 42 km east. The correlation factor was 1.03 ±0.21, which allowed historical data to be extrapolated to predict the historical wave conditions near the Shoals Marine Lab. It was calculated that Appledore Island most commonly experiences wave heights of 1 meter, wave periods of 5.5 seconds, and energy densities of 1-2kW per meter of wave crest, during the summer months.

Two viable wave energy devices were identified, for shallow-water and deep-water locations. A shallow surge-type device was investigated from Resolute Marine Energy in Boston, Massachusetts, while a deep buoy-type device was found from Ocean Power Technologies in New Jersey. Permitting for the devices was minimal within a short-term summer deployment.

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I. INTRODUCTION

Background Information

To reduce emissions and the effects that fossil fuel consumption has on global warming, a variety of renewable energy sources have been designed, tested, and implemented. Such renewable energy devices have resulted in the reduction of carbon footprints. Biomass, wind, solar, and hydropower are prominent renewable energy sources today. There is also a relatively new field of renewable energy focused on the marine environment. Marine renewable energy consists of tidal energy converters, offshore wind farms, and wave energy converters. Tidal energy is generated by turbines mounted on pilings, or floating platforms, in a tidal river. The strong tidal currents are used to spin the turbine and generate electricity. Offshore wind energy consists of mounting a wind turbine on some sort of floating platform and generating electricity from the wind. Wave energy uses the power that is generated by the sea and converts it to electrical energy. Since wave energy is a relatively new form of renewable energy there is a variety of wave energy conversion (WEC) devices that are at various stages of design, testing, and manufacturing.

The Shoals Marine Laboratory (SML) is interested in using wave energy conversion to generate electricity. The SML is a remote island-based laboratory run cooperatively by Cornell University and the University of New Hampshire. The SML is located on Appledore Island, within the Isles of Shoals, off the coast of New Hampshire and Maine. This island is completely independent from the mainland grid and is required to produce its own energy. Solar, wind, and diesel generators are currently used to power the island. The laboratory is seeking an additional 50kW of green energy to reduce diesel energy dependence, thereby lowering the amount of imported diesel. With additional renewable energy technologies at the island, the laboratory could expand their educational programs to include a wider array of research. With wave energy conversion device the SML will have a wide diversity of renewable energy sources at the island and this could set an example for future islands to convert to 100% green energy.

Figure 1: Shoals Marine Lab site map (www.sml.cornell.edu)

The SML maintains a power grid that includes a wind turbine on the north side of the island, solar panels on various buildings, diesel generators, and a battery bank that ties all devices together to store energy until it is needed. The current battery bank is located near the south side of the island, in the radar tower, as shown in Figure 1. A new battery bank has been planned for installation, in-line with Broad Cove near the fuel depot. The new battery bank has a large enough capacity for an additional renewable energy device to be installed and tied into the grid.

Goals

The main goal of this study was to determine the feasibility of installing a seasonal wave energy conversion device by exploring and resolving the following objectives:

1. Assess wave energy resources and potential location to install a wave energy conversion device
2. Investigate electrical connection to the SML electrical grid
3. Investigate environmental impacts and required permitting
4. Search and evaluate available wave energy conversion devices
5. Determine benefits and costs for viable wave energy conversion devices

Approach

The wave energy resource was characterized by measuring waves in three field experiments and correlating results with a nearby continuously operating wave measurement station. An appreciation of environmental concerns was obtained through a site visit and discussions with SML staff. Maine DEP was contacted regarding permitting requirements. Available WEC technology was determined by internet research, conference proceedings and personal contact. Two specific devices were identified as suitable, and their energy production, installation requirements and costs determined.

Primary locations were identified for the installation of a wave energy conversion device off the east coast of the island. The area near Broad Cove, east of Appledore Island, was chosen for study due to the strong wave activity and proximity to on-land infrastructure. Bathymetric data was used to identify areas of appropriate depth and uniform seafloor conditions. A shallow-water area was identified for a surge “flap” type device and a deep-water area identified for a heave “buoy” type device.

The eastern shore of Appledore Island receives the majority of wave activity during summer months, when the laboratory is operational. The prominent direction of swell was determined from historical data collected by NOAA station 44098 at

Jeffrey's Ledge. From these observations a location was identified where pressure measurements would be made to calculate the wave height and peak period. This gathered data was correlated to the historical data from the wave buoy at Jeffery's Ledge, from which it was confirmed that nearly 70% of swell waves come from the southeast.

Figure 2: Red circle represents potential area or interest to install a wave energy conversion device off of Broad Cove (www.sml.cornell.edu).

II. WAVE ENERGY ASSESSMENT AND SITING

In ocean engineering there are a number of methods for determining the sea surface elevation. Devices typically used for this process include accelerometers mounted to buoys, subsurface pressure sensors and mounted wave-staffs. Due to the high-costs associated with buoy-mounted accelerometers and the difficulties of mounting a wave staff in an ocean environment, the most viable data-collection method is to record subsurface pressure fluctuations (Swift, Wave Engineering Properties). Subsurface pressure measurements can be used to accurately quantify elevation changes as waves pass the point of measurement.

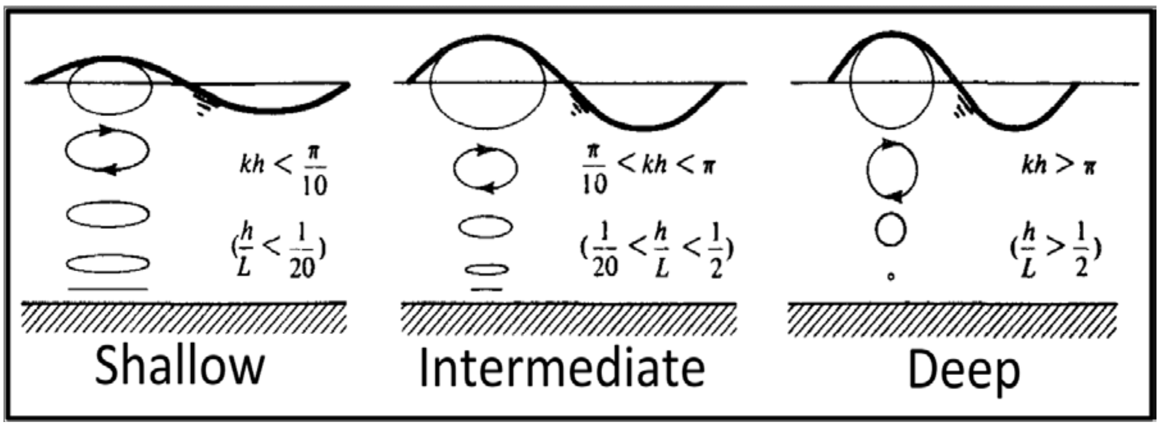

Figure 3: Schematic of how particles travel in the water column under different ocean conditions (Dean & Dalrymple, 1984).

Water particles oscillate in a particular manner when waves propagate across the surface. Certain criteria must be met when determining if the wave is considered a deep-water wave or a shallow water wave. In deep-water conditions, $\frac{h}{L} > \frac{1}{2}$, the mean water depth is greater than one half of the wavelength. In shallow water conditions, $\frac{h}{L} < \frac{1}{20}$, the mean water depth is less than one-twentieth of the wave length.

Linear Wave Theory

Linear Wave Theory, also known as Airy Wave Theory, produces a linearized description of the propagation of gravity waves on the surface of a fluid, in our instance, the ocean. This theory assumes an inviscid, incompressible, and irrotational flow. Linear Wave Theory was used to model the wave kinematics and dynamics of the random sea observed at Appledore Island. Linear wave theory models shallow water waves and deep-water waves to a high degree of accuracy, both of which are observed at Appledore Island. Linear wave theory used the following variables as defined: H as the significant wave height, k as the wave number, L as the wavelength, a as the wave amplitude, c as the wave phase velocity, η as surface elevation and h as the mean water depth, as shown in Figure 4.

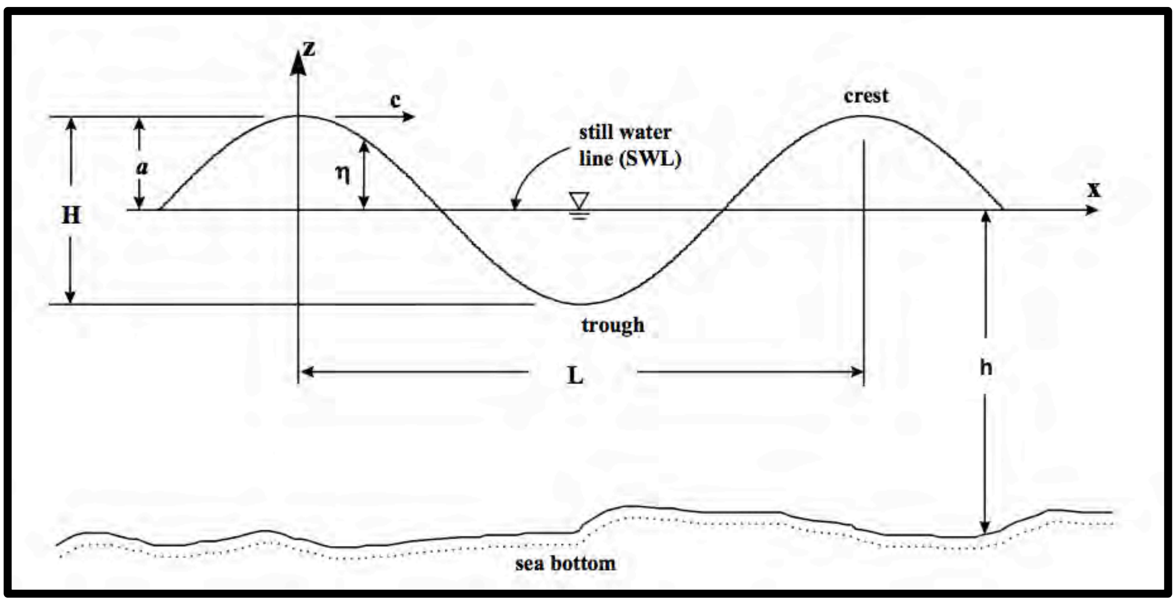

Figure 4: The general schematic of a sea. L is the wavelength, c is the wave celerity, h is the mean water depth, H is the significant wave height, a is the wave amplitude, η is the surface elevation (Dean and Dalrymple).

Linear wave theory is derived with a couple key assumptions about boundary conditions. First we assume that the amplitude of the waves on the surface is infinitesimal, so the surface can be modeled as a plane. Secondly, we can assume that the fluid flow is two-dimensional with the waves traveling in the x-direction. Finally we assume that the Coriolis and viscous effects can be neglected. With these three assumptions the surface elevation can be quantified.

$$\eta = a\sin(kx - \sigma t) \tag{1}$$

Here $\sigma = 2\pi f = \frac{2\pi}{T}$ and $= \frac{2\pi}{L}$, wave radian frequency is σ in radians per second, f is the wave frequency in Hertz (Hz), and T is the wave period which is the time it takes for two successive wave crests or troughs to pass a fixed point. Pressure changes with respect to wave frequency must be accounted for when determining the wave heights. The pressure response factor, K_p, is quantified by

$$K_p = \frac{\cosh(k(h+z))}{\cosh(kh)}. \tag{2}$$

The wave frequency and wave number are related to each other by the dispersion relation,

$$\sigma^2 = gk\tanh(kh), \tag{3}$$

where g is acceleration due to gravity. The dispersion relation can be simplified in two different ways: as a deep-water approximation and a shallow-water approximation. When the deep water criteria is met, the dispersion relation can be simplified to

$$\sigma^2 = gk. \tag{4}$$

When the shallow water criteria is met the dispersion relation can be simplified to

$$\sigma^2 = gk^2h. \tag{5}$$

Field Measurements of Waves

The ocean is often referred to as a random sea, which consists of a wide variety of wave types. It is generally known that ocean-waves have periods of 1 second or longer. There is also an effect from tides, which consist of longer period waves. Tidal periods can range anywhere from 12 to 12.4 hours. In New England the tidal cycles repeat every 12.4 hours. A tidal cycle is defined between points from high water to high water, or low water to low water (HOBO U20 Titanium Water Level Data Logger - U20-001-02-Ti, 2012).

$$\zeta = \frac{\frac{H}{2}gk}{\sigma^2}\frac{\cosh(k(h+z))}{\cosh(kh)}\sin(kx-\sigma t). \qquad (6)$$

The accuracy of the pressure readings at a certain depth could change due to horizontal displacement of the sensor from wave motion. To determine the magnitude of horizontal displacement equation 5 was used. To ensure that accurate pressure readings were recorded, the depth of the pressure sensor was computed using Equations 2 and 5. To capture waves as small as a 3 second period the pressure response factor K_p was set to 0.1 and the water depth, h, was set at 60 feet. Using these two parameters the depth at which the sensor should be placed was determined to be 17 feet. Deployment of the pressure sensor at a depth of 17 feet will result in accurate pressure readings for waves with a period of 3 seconds and larger.

Figure 5:Hobo Onset salt-water pressure sensor.

Figure 6: The pressure sensor attached to the computer connection device (HOBO U20 Titanium Water Level Data Logger - U20-001-02-Ti, 2012).

The pressure sensor that was used in the experiment to record pressure readings was a HOBO Onset Water Level Logger-Titanium shown in Figure 5. The pressure readings are taken through the hole on the left side of the device and the removable black cap on the right protects an optical output for a computer connection. The computer connection receiver is shown in Figure 6. This unit is a 100% closed system, removing the cap does not expose the system. There is a clear piece of plexiglass under the cap. This allows the device to communicate to the receiver via infrared optical sensors.

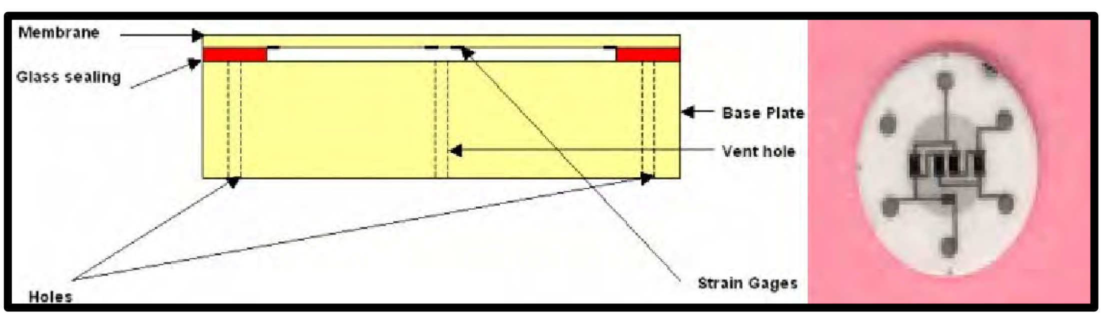

Figure 7: Shows the schematic of the ceramic pressure transducer (Left) and the strain gage mounted to the base (Right).

The sensor element consists of a ceramic pressure transducer, made up of several layers (see Figure 7). The first layer has a strain gage mounted on a titanium base plate followed by a glass membrane coating. A thermistor is attached to the top of the glass membrane. The thermistor will be used to perform a thermal compensation on the absolute pressure readings collected by the transducer. The back of the base plate consists of a conductor and resistors that make up the rest of the strain gage and thermistor circuit (Ceramic Pressure Sensors, CiTy Sensors SA, 2012). The measuring system contains programming that converts the output strain gage readings and thermistor readings into absolute pressure.

The basic schematic of the baseplate is shown in Figure 7. The base plate and transducer are connected to an onboard processor that controls the system. The sensor can be programmed to begin recording on a certain date and time, prior to deployment, by plugging the sensor into the computer. The absolute pressure readings are self-recorded onto the device and must be transferred to a computer using the infrared optical reader, as shown in Figure 6.

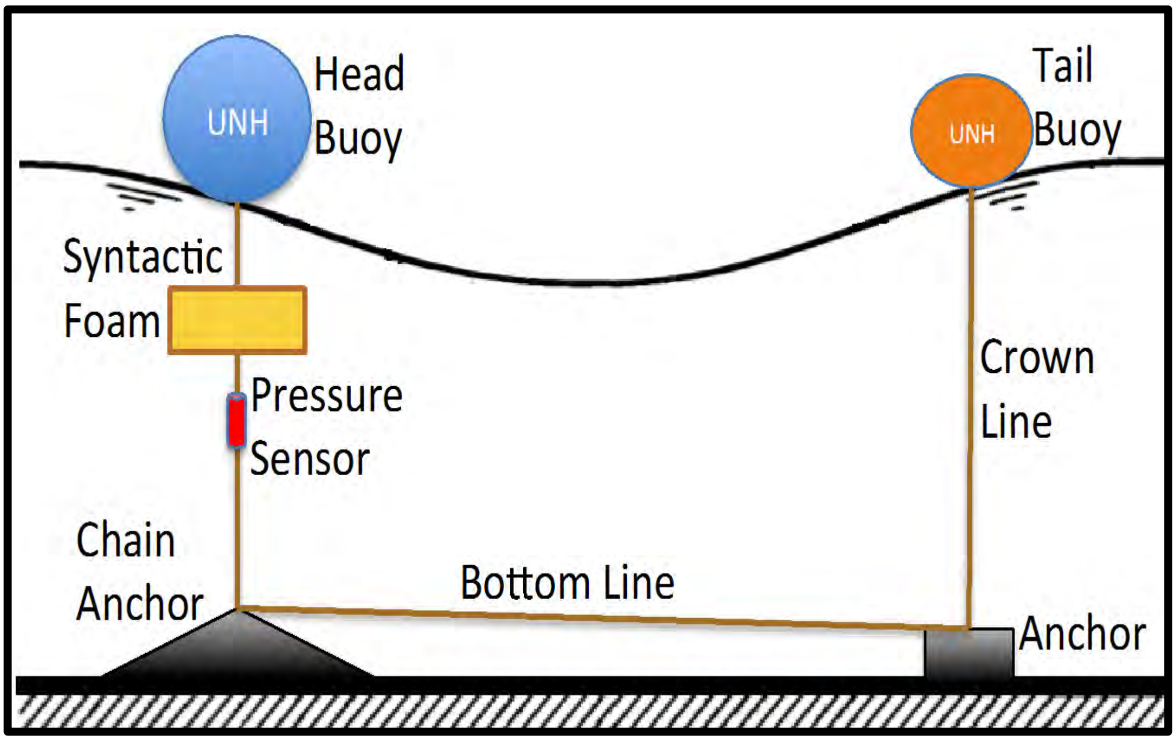

Figure 8: The experimental set up for the ocean deployment.

Subsurface pressure readings can be recorded using the HOBO Onset pressure sensor secured below the surface of the water, as shown in Figure 8. Pressure readings can be used to measure the surface elevation of the sea as a function of time and wave period. Due to the attenuation of pressure fluctuations with respect to depth it is important for the pressure sensor to be placed at a, pre-calculated, optimal depth. This depth will avoid excessive lateral-motion in order to retain a useful pressure response factor, corresponding to the recording frequency of the device (1 Hz).

Wave Data Analysis Procedure

An Energy spectral density (ESD) method was applied to analyze the pressure readings due to the fact that waves, in the sea, are composed of a wide range of frequencies. The raw spectral density needed to be corrected due to the change of pressure response factor at each frequency. The measured pressure spectral energy is corrected to the surface by dividing it by the pressure response factor squared at each frequency. Noise amplification occurs when waves are recorded with a wave frequency below the recording frequency of the device of 1Hz, as shown in Appendix A (pressure response factor plots). Therefore an increase in wave energy is seen at wave frequencies at 0.5 Hz or below. To prevent this problem the ESD was truncated where noise amplification occurs, which is the frequency that correlates to a pressure response factor of 0.1. The corrected ESD can then be used to calculate the significant wave height.

The recorded data set was separated into twenty-minute time series. This is necessary to factor out the tidal change that occurs. A twenty-minute period is short enough that little error is associated with the height differences in the tide. For one hour of data the time series must be separated into 3 data sets. Since the tide changes by approximately one foot per hour, each 20 minute period will only observe 0.33 foot change in tide, which is a small enough change in surface elevation that the tidal trend was factored out of the pressure measurements.

The de-trended 20-minute pressure data sets were put through a Fast Fourier Transform (FFT) to break down the oscillating pressure signal into constituent parts. The results of the FFT provided the pressure magnitude at each constituent frequency. The FFT was performed using the relation

$$P(t) = \sum_{k=1}^{\infty}(a_k \cos(2\pi\sigma_k t) + \mathrm{b_k}\sin(2\pi\sigma_k t)), \qquad (7)$$

where P(t) is the pressure magnitude at a given time, t is time, a is wave amplitude, and σ is the frequency. The FFT was performed using a MatLab script to autonomously analyze the pressure time series data, providing the Fast Fourier coefficients, a_k and b_k, for the pressure time series. An ensemble average was taken of all 20 minute pressure time series to produce an overall, pressure energy density spectrum. The ensemble average consisted of averaging each corresponding pressure reading at each frequency. A running average was then utilized to smooth out the energy spectral density curve (ESD).

The running-averaged ensemble ESD was then corrected for depth as a function of frequency using the pressure response factor. The wave number must be found first, with respect to each frequency. The wave number may be found using the full dispersion relation derived in Equation 3. Solving the dispersion relation in its transcendental form leads to the wave number, k. Matlab was used to solve the dispersion relation, which employs a Newton-Raphsen iteration algorithm.

Since wavelength is dependent on the frequency of the waves, a wavelength and an associated wavenumber were computed for each frequency. Using the computed wavenumber at each frequency the pressure response factor, K_p, was computed at each frequency using the relation

$$K_p = \frac{\cosh(k(h+z))}{\cosh(kh)}, \tag{8}$$

where z is the depth at which the pressure readings were taken. The corrected spectrum for each frequency, $H(\sigma)$, was then computed using the relation

$$H(\sigma) = \frac{H(\sigma)_{uncorrected}}{(K_p(\sigma))^2}, \tag{9}$$

where $H(\sigma)_{uncorrected}$ is the raw spectrum. The corrected spectrum was then truncated at a frequency corresponding to a pressure response factor of 0.1, due to the inaccuracy of measurements below this value, which is a standard practice in ocean engineering.

The significant wave height, the average of the largest one third of the waves, was then computed using the corrected ESD by computing the zeroth spectral moment, m_0,

$$m_0 = \int_{\sigma_0}^{\sigma_n} H(\sigma)\, d\sigma, \tag{10}$$

where σ_0 is the first frequency point, and σ_n is the last frequency point. The significant wave height was then computed using the zeroth spectral moment and the relation

$$H_s = 4\sqrt{m_0}. \tag{11}$$

The computed significant wave height was then compared to the reported significant wave height measured at Jeffrey's Ledge to determine a correlation factor. The correlation factor was computed using the relation

$$C.F. = \frac{H_{S_{Appledore\ Island}}}{H_{S_{Jeffrey's\ Ledge}}}. \tag{12}$$

Field Experiments

Experiments were performed on four different occasions in 2012: September 27, November 30, December 1, and December 3. The locations of the field experiments are shown in Figure 9. Three out of the four data sets were reliable for use in further processing.

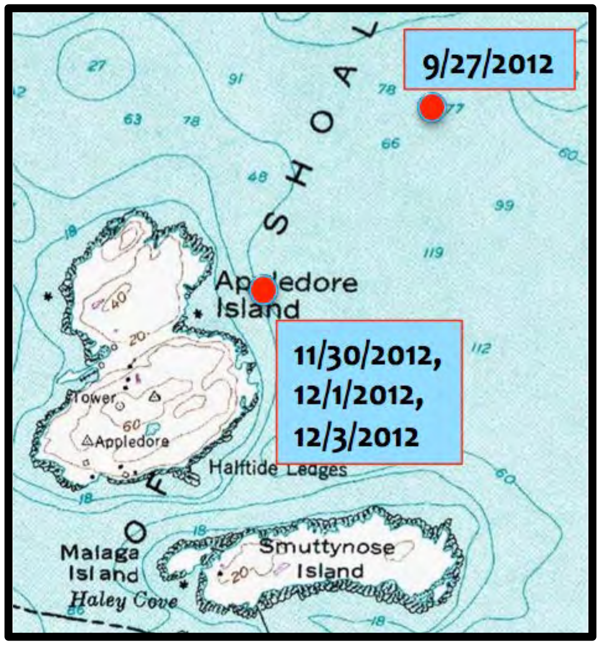

Figure 9: Map of Appledore Island and the ocean surrounding the island.
Showing the locations where the field experiments were performed (www.topoquest.com).

The data set gathered on September 27 was discarded due to a complication with the equipment during deployment. The main line for the pressure sensor was entangled with the main anchor causing the pressure sensor to sink to twice the depth expected. This technical problem set the pressure sensor at a depth that was too deep for accurate pressure measurements. As depth increases the pressure response factor decreases, data below a pressure response factor of 0.1 should be discarded because of noise amplification, which causes undesirable error. This allowed for great improvements in the deployment procedure for future experiments.

Experimental Results

Raw pressure readings were processed using the data analysis steps in a Matlab script to produce the energy density spectrums shown in Figure 10. The spectrums from the pressure readings taken at Appledore Island are presented alongside the corresponding energy density spectrum from Jeffrey's Ledge. From each test period it is noted that the computed spectrums at Appledore Island and the spectrum reported by the NOAA Jeffrey's Ledge buoy are very similar. The energy spectral density shows that the peak period is approximately equal at both locations, shown in Table 1, and the area under the curves are very close for both locations, shown in Figure 10.

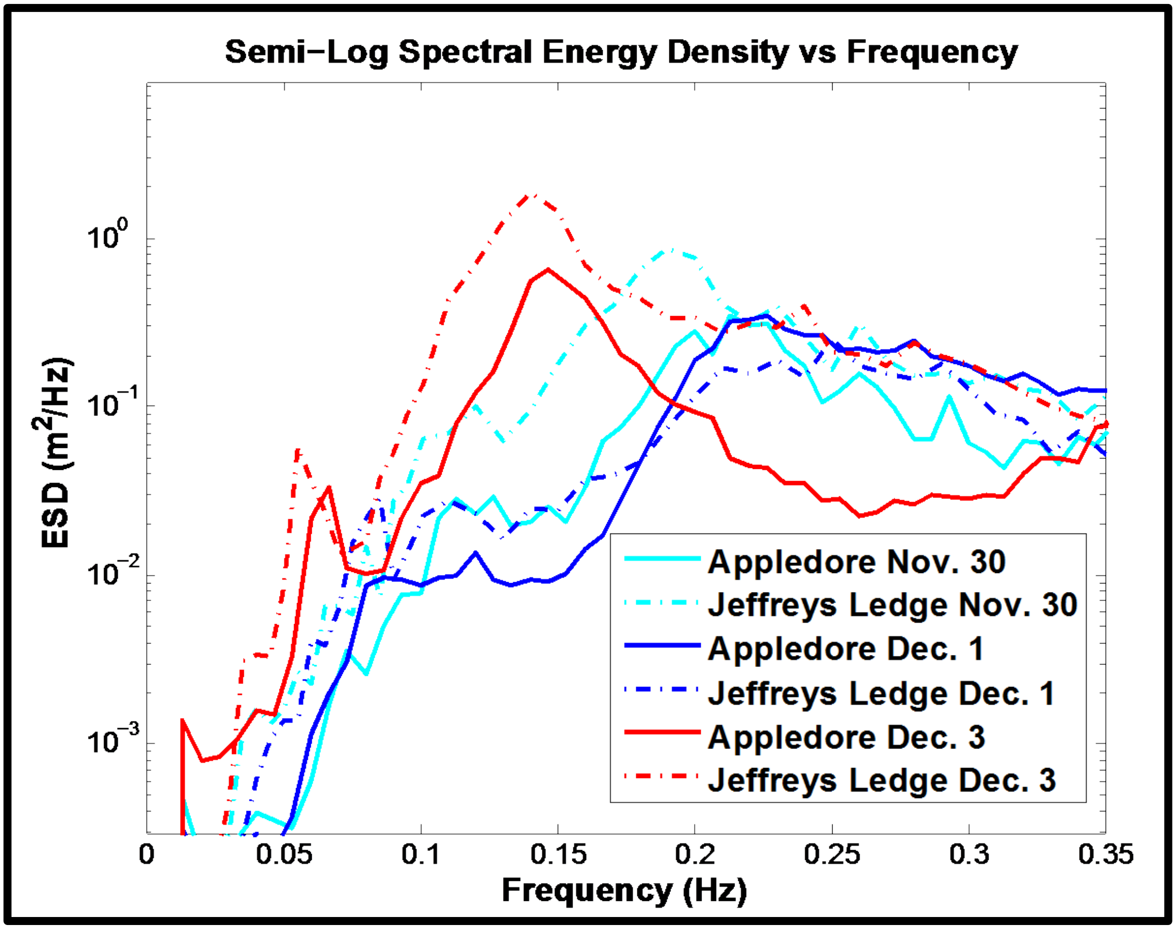

Figure 10: Energy Spectral Density computed for the three test dayss. Appledore results are shown with the solid lines. The correspondings energy spectral density plots for the correlated test period at the Jeffrey's Ledge Buoy is represented by the dashed lines.

Data Correlation

The energy density spectrum was used with Equation 10 and Equation 11 to compute the significant wave height. The computed significant wave heights are shown in Table 1. The significant wave height was computed for each data set and compared to data reported from Jeffrey's Ledge, to determine a correlation factor for each day measurements were taken, as shown in Table 1. The correlation factor from the three experiments was then averaged together to relate Appledore Island to the historic data from the Jeffrey's Ledge Buoy. The overall correlation factor was computed between the two locations by taking the average of each separate test period's correlation factor.

The average correlation factor was computed to be 1.03 ± 0.21. With such a strong correlation, the historical data recorded by NOAA from the Jeffrey's Ledge Buoy was used to project the wave environment at Appledore during the summer months, as shown in Figure 11.

Table 1: Significant wave height and peak wave period for Jeffrey's Ledge and Appledore Island during each test period. The location and dates mate with the spectral density plot in Figure 10.

Date	Location	Significant Wave Height [meters]	Peak Wave Period [seconds]
30-Nov	Appledore Island	0.9	4.55
	Jeffrey's Ledge	0.99	5
1-Dec	Appledore Island	0.97	4.5
	Jeffrey's Ledge	0.72	4.13
3-Dec	Appledore Island	0.95	6.73
	Jeffrey's Ledge	1.35	7.18

Statistics

The wave conditions at Appledore Island were compared to the wave conditions recorded by NOAA station 44098 at Jeffrey's Ledge. A correlation factor between the two locations was found based on significant wave height and peak wave period. The correlation factor allowed for all of the historical data recorded by NOAA, and the historical trends that are present in the Gulf of Maine, to be utilized in predicting the summer wave conditions at Appledore Island. Historical data for the summers of 2011, 2012, and 2013 were utilized in predicting the overall wave conditions at Appledore.

The correlation factor was used to predict the significant wave heights at Appledore Island by converting the historical significant wave heights reported by the NOAA Jeffrey's Ledge Buoy. With this relation a histogram of the percent occurrence of significant wave heights was plotted to observe the most common wave heights shown in Figure 11. This plot shows a breakdown of significant wave height in increments of 0.2 meters and the percent they occur during the summer months.

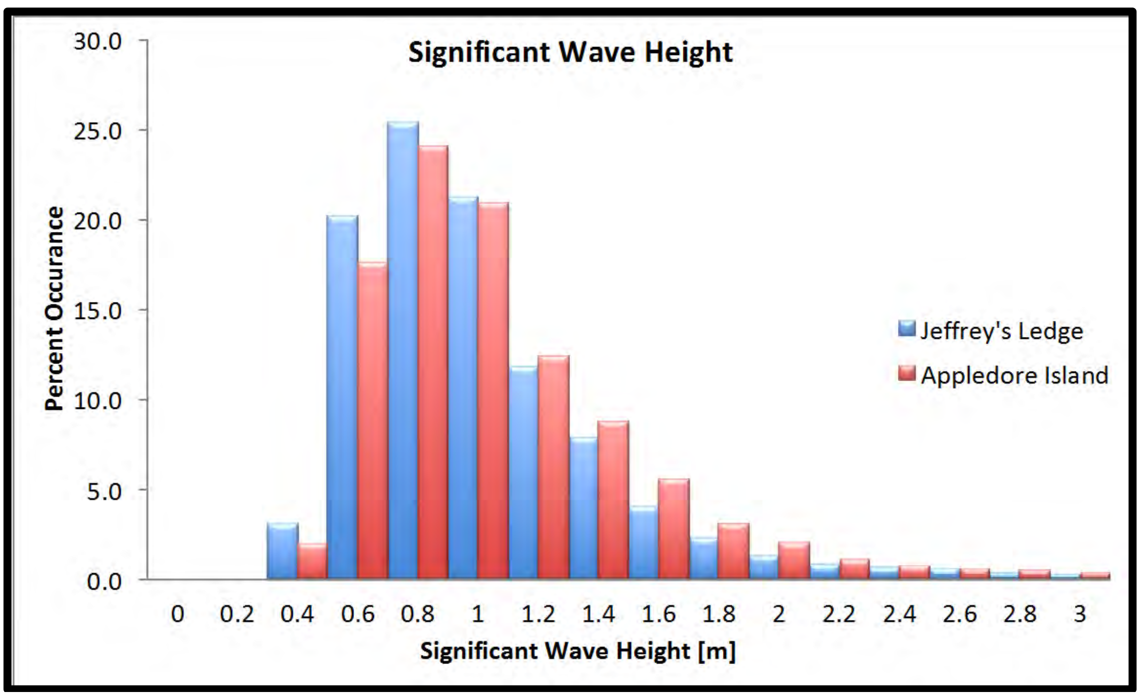

Figure 11: The significant wave height reported by the Jeffrey's Ledge Buoy for the summer month of 2009-2011,blue, and the projected significant wave height at Appledore Island, red. The x-axis represents the significant wave height in meters and the y-axis represents the percent occurance of each wave height.

The blue bars represent the reported significant wave heights from the Jeffrey's Ledge Buoy over the summer months of the last 3 years and the red bars represent the projected significant wave height at Appledore Island for summer conditions at Jeffrey's Ledge. From the histogram it appears that the east side of Appledore Island will most commonly see waves with significant wave heights on the order of magnitude between 0.6 and 1.0 meter. This range of wave heights will occur approximately 65% of the time.

Along with the significant wave height the average summer peak wave period was also computed for Jeffrey's Ledge from the historic data over the last three summers to be roughly 5.5 seconds. The team was able to use the peak period at Jeffrey's Ledge due to the strong correlation seen during experimentation between the two sites. Knowing the most common wave heights and periods allowed the team to inform wave energy conversion device vendors of the wave conditions at the site.

The team also predicted the maximum amount of obtainable power at the location using the projected significant wave heights. The power that is available at this location was computed with the relation

$$P = \frac{\rho g {H_s}^2}{8}. \tag{13}$$

This relation was used to determine the available power with respect to each significant wave height shown in Figure 11. A histogram of percent occurrence versus power per meter of crest was utilized to show the most common amount of power that is generated per meter of wave crest, as shown in Figure 12. This allowed for the team to determine how effective wave energy conversion devices could be at providing the desired power in this location.

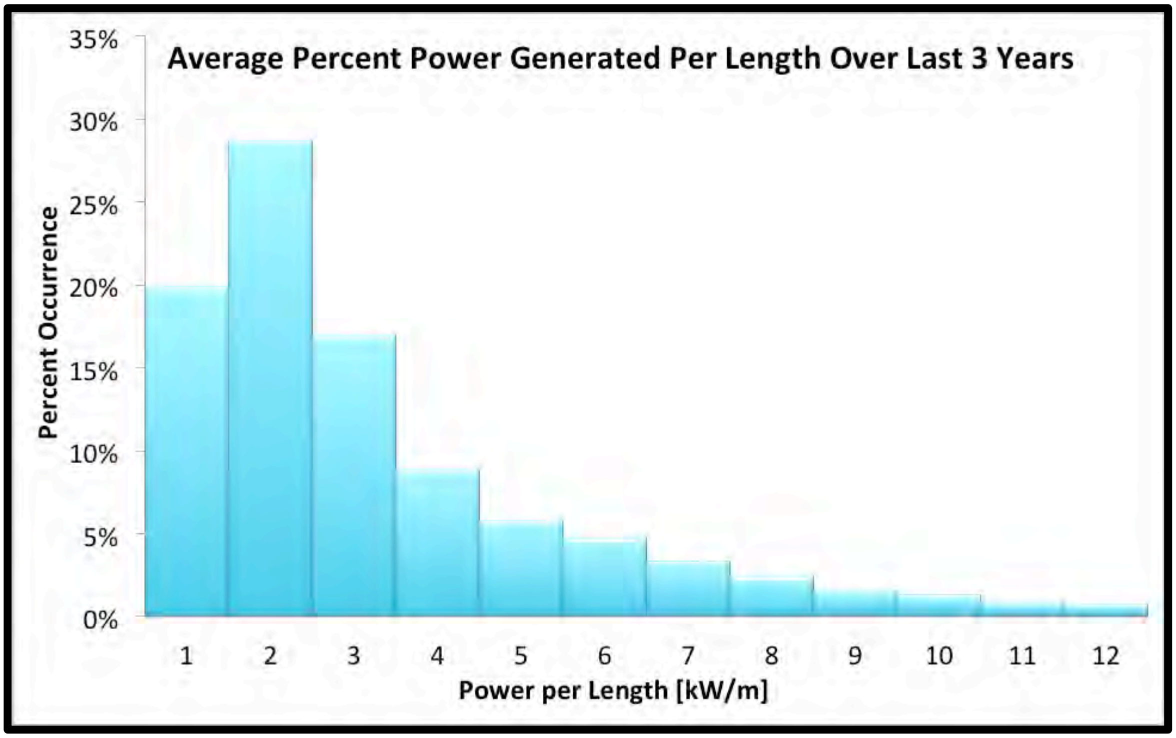

Figure 12: Power obtainable on the east cost of Appledore Island. The x-axis is power per crest length in kW/m and the y-axis is percent occurqance. It is most common to see 1-2 kilowatts per meter of crest.

Wind Data Analysis

Differences in wave conditions between Appledore and Jeffrey's Ledge are primarily caused by fetch and duration of wind interactions. When wind blows across the surface of the ocean, wind waves are created. The distance over which wind influences wave activity is known as fetch. There is a 42 km fetch between Appledore and Jeffrey's Ledge. When wind direction opposes the primary South-Southeast direction of oncoming waves, lower wave energy is reported at Appledore, correlation less than one. When wind direction aligns with the primary direction of oncoming waves, higher wave energy was reported at Appledore, correlation greater than one. This data is shown in Appendix C.

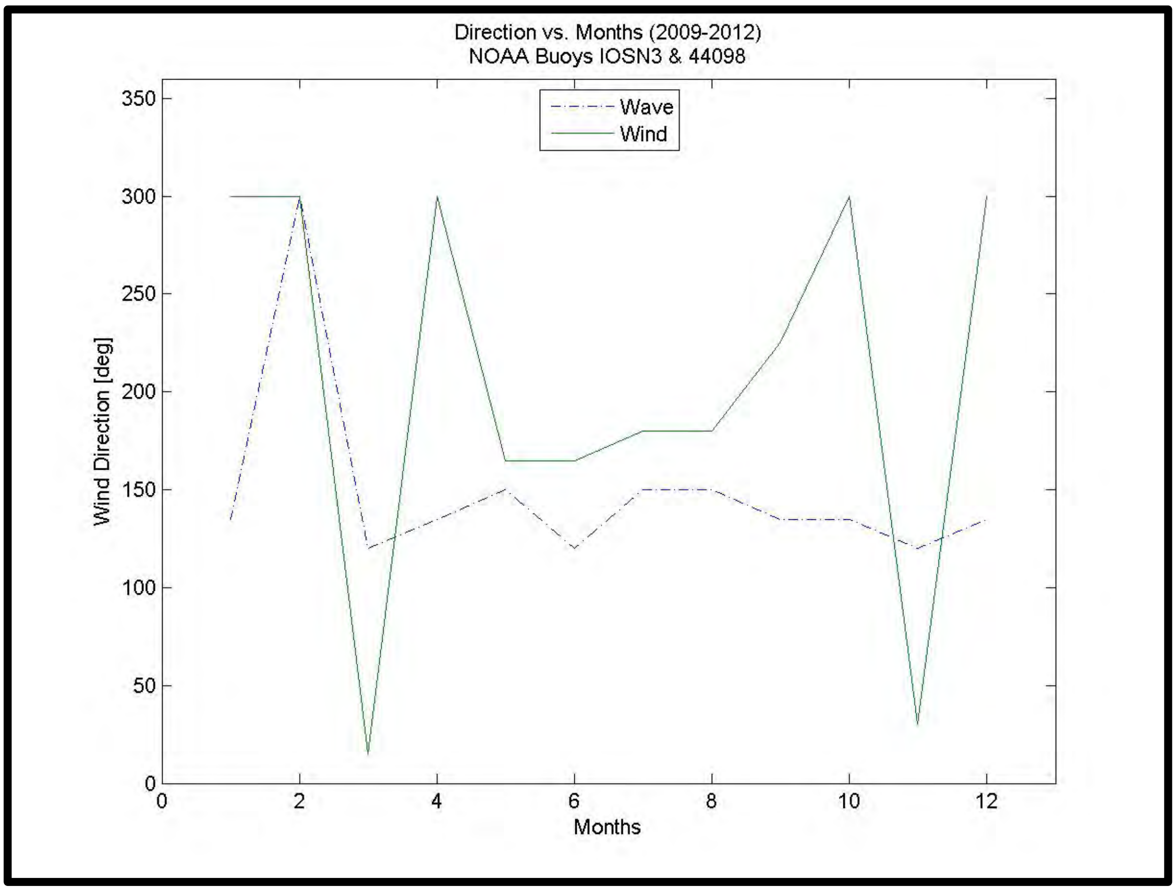

Figure 13: Wind direction from NOAA buoy IOSN3 on White Island vs. wave direction from NOAA buoy 44098 at Jeffrey's Ledge, for 2009-2012

The wind and wave data follow similar trends, Figure 13 shows the primary direction of wind at the Isles of Shoals and waves at Jeffrey's Ledge. The 50 nautical mile fetch between the two locations indicates that the waves will be larger at Appledore Island than at Jeffrey's Ledge from May to August. This plot only shows the most common wind and wave directions. The following figures show more in depth trends.

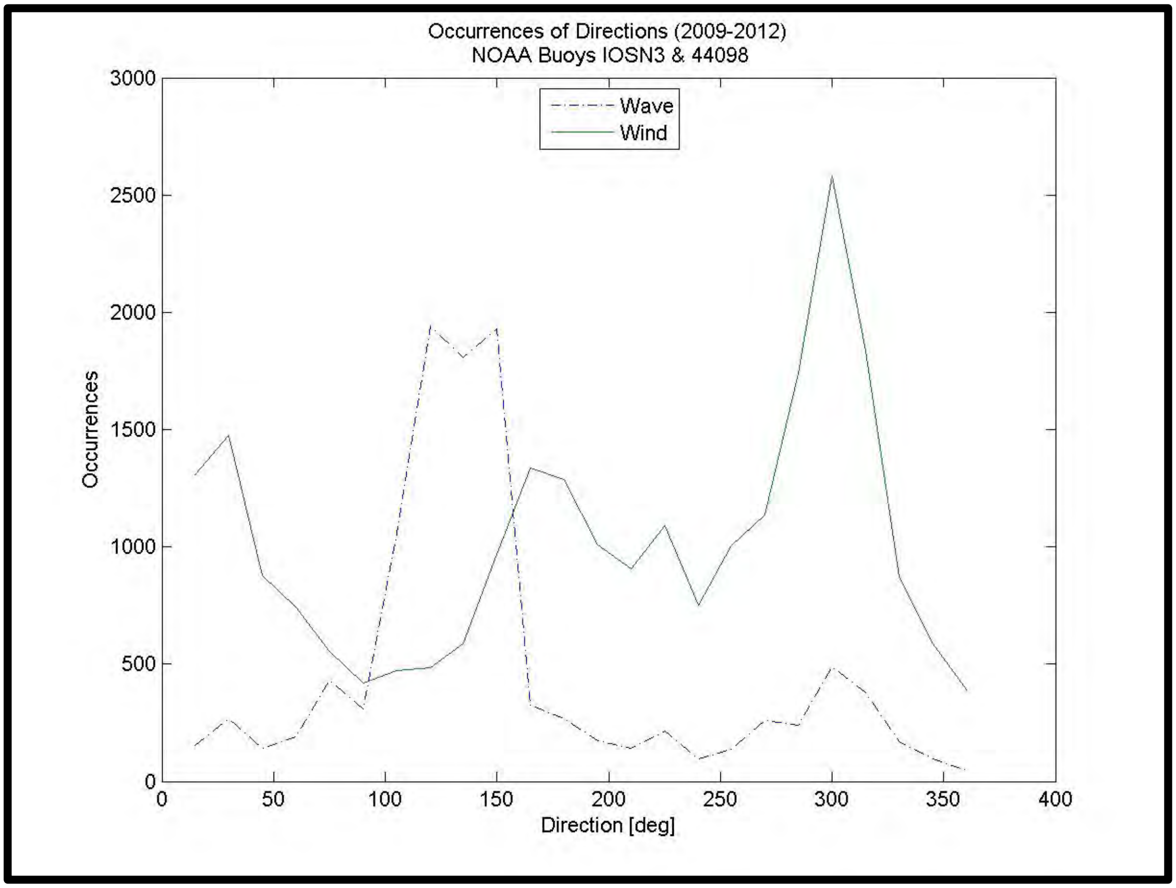

Figure 14: Number of occurrences of wind and wave directions taken every 15 degrees

As can be seen in Figure 14 above There is a strong correlation for the directions 180 to 360, corresponding to compass directions south, west, and north. The prominent wave direction throughout the summer is from the southeast direction, 110° to 150°. This trend is also shown in Figure 15 below

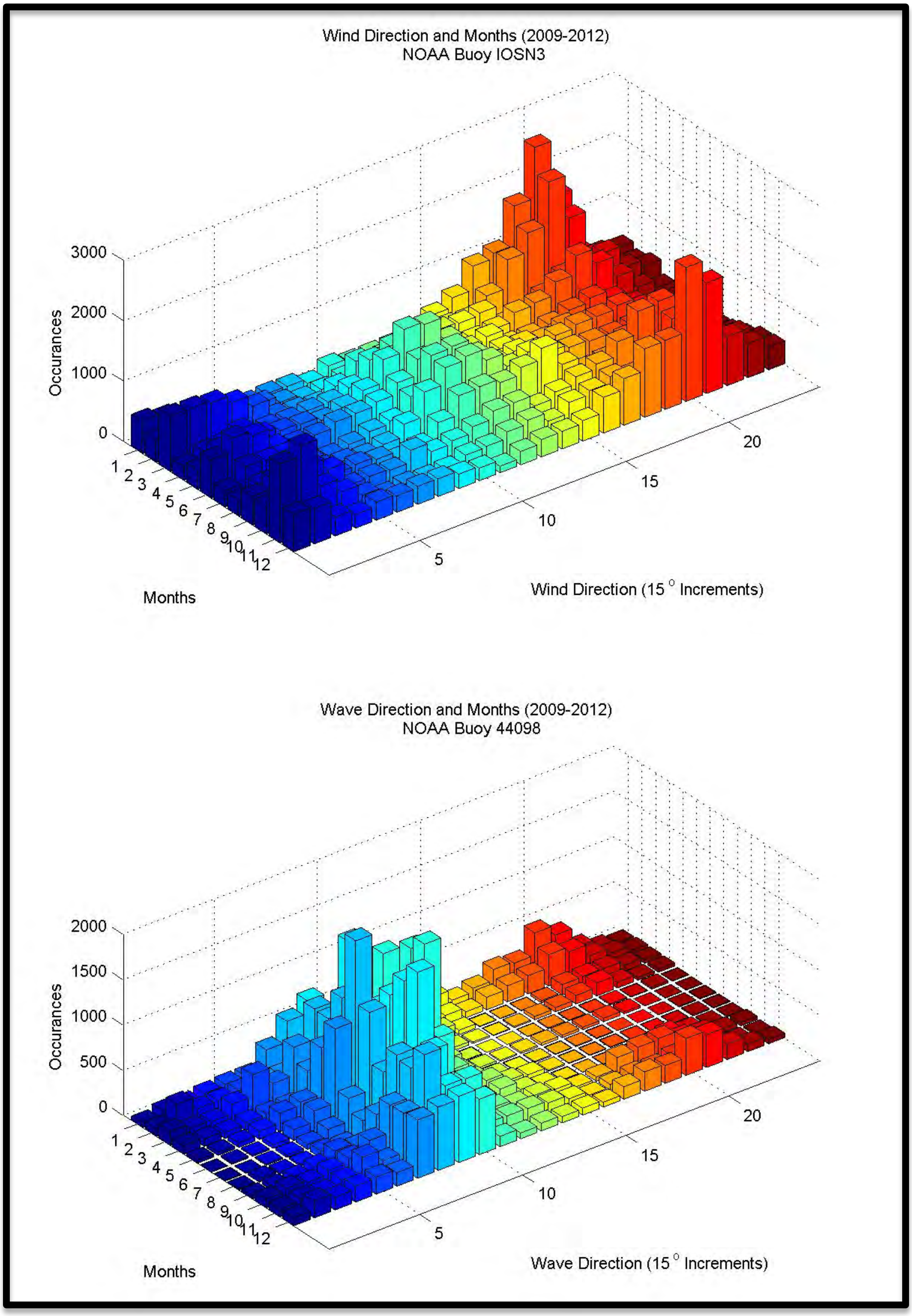

Figure 15: Wind direction vs months from 2009-2012 from NOAA buoy IOSN3. Wave direction vs months from 2009-2012 from NOAA buoy 44098

Throughout the year, and especially during the summer, most of the wave activity comes out of the southeast. The most common occurrences for wind and wave align around the 150° direction. This diverges, however, and wind is most likely to blow from directions closer to the west with waves from east. This means that for most of the summer wind will be opposing the wave direction and will be generating wave conditions that are smaller at Appledore Island than at Jeffrey's Ledge.

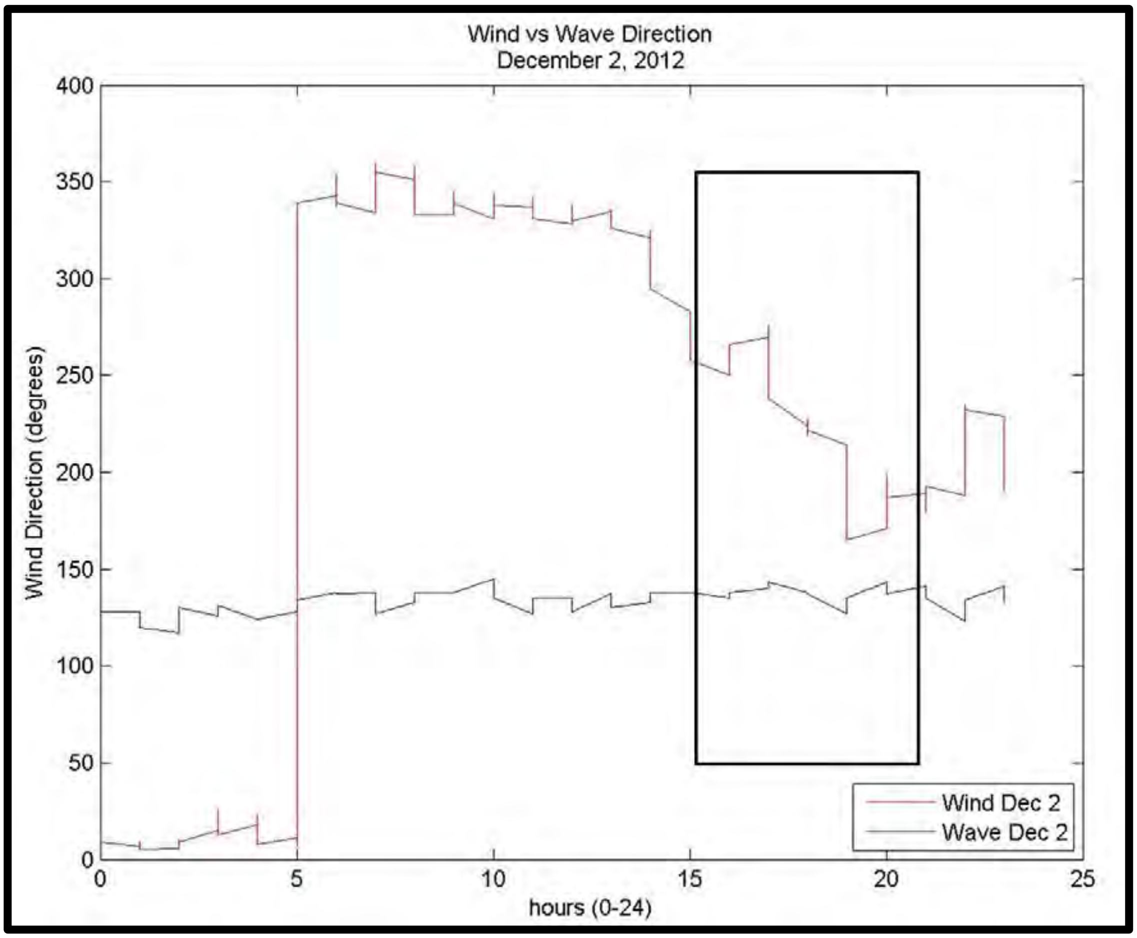

Figure 16: Wave direction at Jeffrey's Ledge and wind direction at Duck Island on December 2, 2012. The black square indicates the time period during which wave measurements were taken, between 1500 and 2100 hours, while correlation factor ranged from 0.88 to 0.92.

Wave direction is from the southeast while wind blows from the north-northeast for 10 hours prior to the time that measurements were taken. This 10 hours of wind energy opposing the primary wave direction is clearly the reason that the significant wave heights were lower at Appledore Island than at Jeffrey's Ledge. This reduction in wave heights caused a correlation factor less than one. The 40km fetch length between Appledore and Jeffrey's ledge and the opposing wind energy on December

2nd, are clearly the reason why lower wave heights were measured at Jeffrey's Ledge.

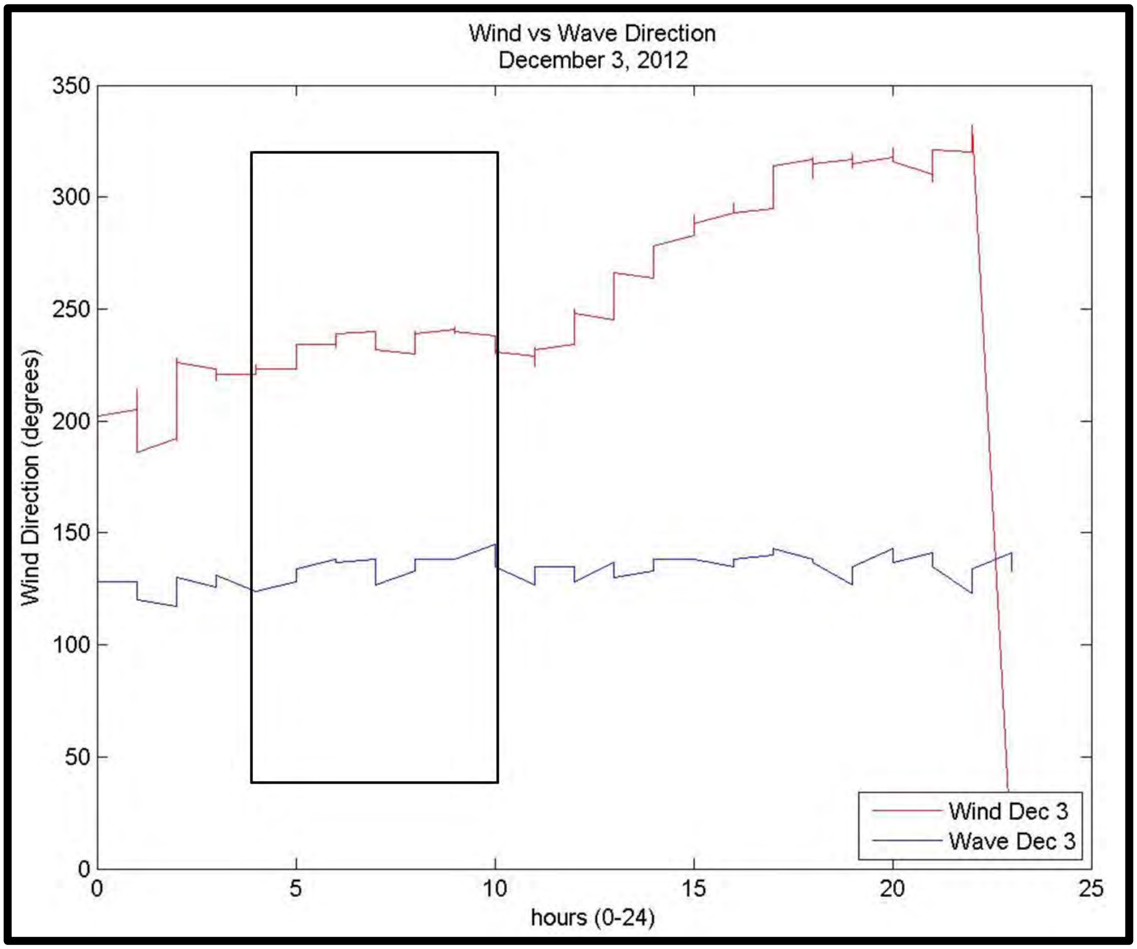

Figure 17: Wave direction at Jeffrey's Ledge and wind direction at Duck Island on December 2, 2012. Wave measurements were taken between 400 and 1000 hours, as indicated by the black square, with a correlation factor ranging from 1.21 to 1.25.

Prior to measurements, the wind at Duck Island was blowing from a prominently south-south-west direction from 1800 hours on December 2nd to 300 hours on December 3rd, as shown in the figures 16 and 17 above. This wind direction is approximately aligned with the south south-eastern wave direction measured at Jeffrey's Ledge on that day. Because the wind is nearly aligned with the wave direction for 9 hours the wave heights at Appledore Island were found to be greater than those found at Jeffrey's Ledge. This resulted in a correlation factor of approximately 1.23.

Site Bathymetry

It was important for the team to study the bathymetry, underwater sea floor elevations, to determine the best placement for a wave energy conversion device. Two types of locations were of interest: a shallow water site for a bottom-mounted device and a deep water site for an anchored buoy-type WEC. Initially the team worked closely with the Center for Coastal and Ocean Mapping (CCOM) to generate plots of the sea floor off the east coast of Appledore Island. Paul Johnson at CCOM helped generate a contour map of the bathymetry around the island from data that was gathered in the summer of 2010, using multi-beam sonar (Figure 18).

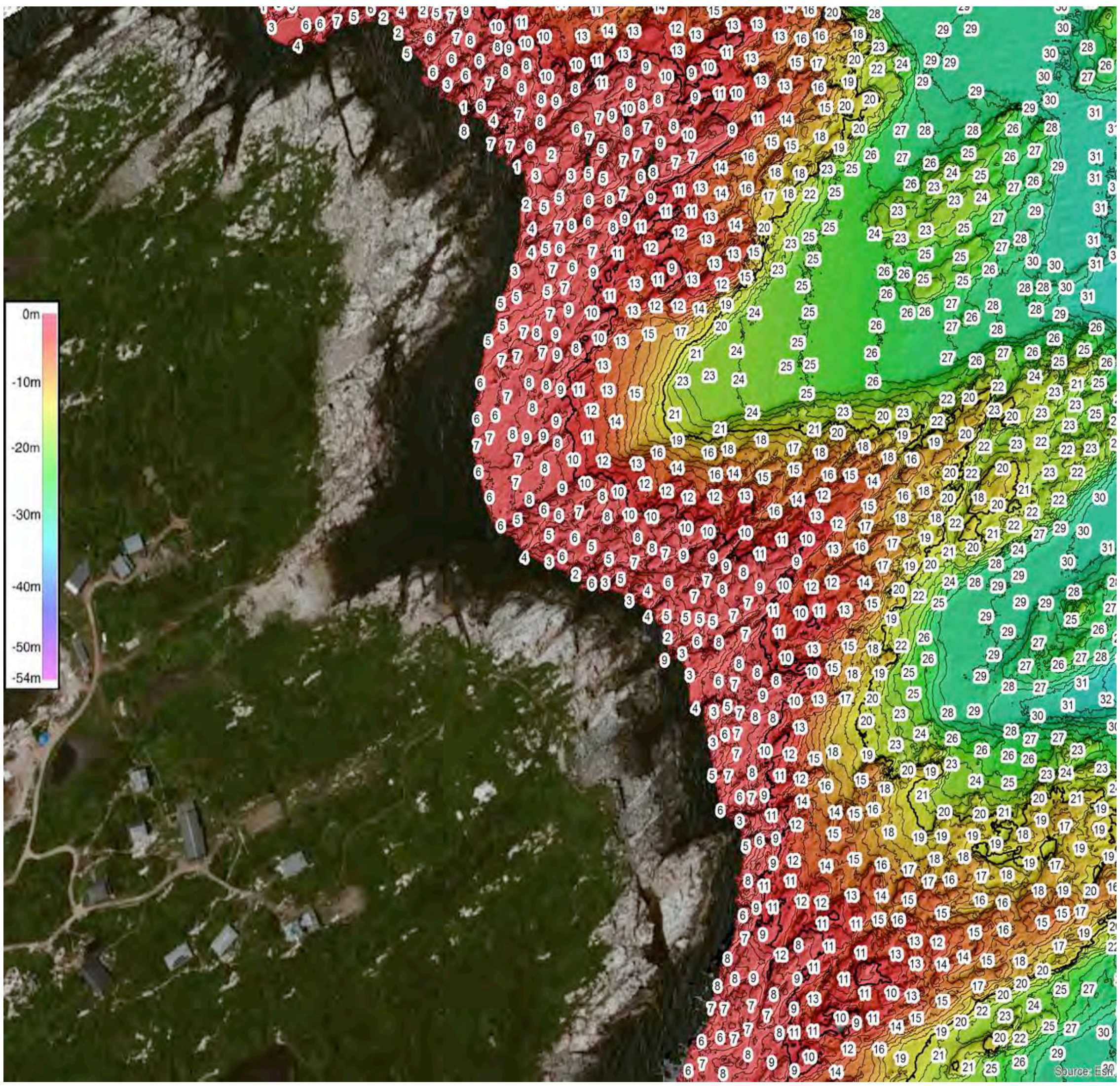

Figure 18: Bathymetry on the east coast of Appledore Island. The color bar shows the different depths of the seafloor and the black contour lines help indicate the different elevations. The depths are measured with respect to mean low water level.

The bathymetry around the east coast of the island shows that there may be a significant number of boulders near shore, and it appears to level out around 25 meters to a smooth, sandy bottom. The bathymetric plot has contour lines that are indicated at every meter of depth.

Using the contour lines it was easy to determine that the water depths near shore vary from 1 to 10 meters. The seafloor to the north and south of Broad Cove varies drastically, while the area immediately outside of Broad Cove has the least amount of variation from 6 to 9 meters. This area would be a key location to install a bottom-mounted flap-type WEC device. Since the seafloor varies so much in this area it is necessary to gain a better understanding of what type of rocks and elevations are actually present just outside of Broad Cove. This knowledge would help determine the best way to mount a wave flap.

The bathymetric map was used to understand the sea floor in the deep-water area as well. Figure 18 shows that the seafloor depth drops rapidly from 10 meters to 25 meters. At depths of 25 meters it appears that the seafloor is relatively smooth and could, presumably, consists of sand. This location fits the deep-water wave motion criteria and would therefore be an appropriate location for a wave buoy-type device.

Recommended Installation Location

Two wave energy conversion devices were considered for the Shoals Marine Lab. The first device was a bottom-mounted device. This device operates from the surge motion observed in the shallow water regime. The red rectangle on Figure 19 represents what appears to be the best location for a wave flap. Because of the highly variable seafloor depths, adjustable legs will be necessary on the platform of the device. A diver would be able to adjust the height of each leg during deployment to ensure the device is level. The red circle on Figure 19 represents the best location for a wave buoy.

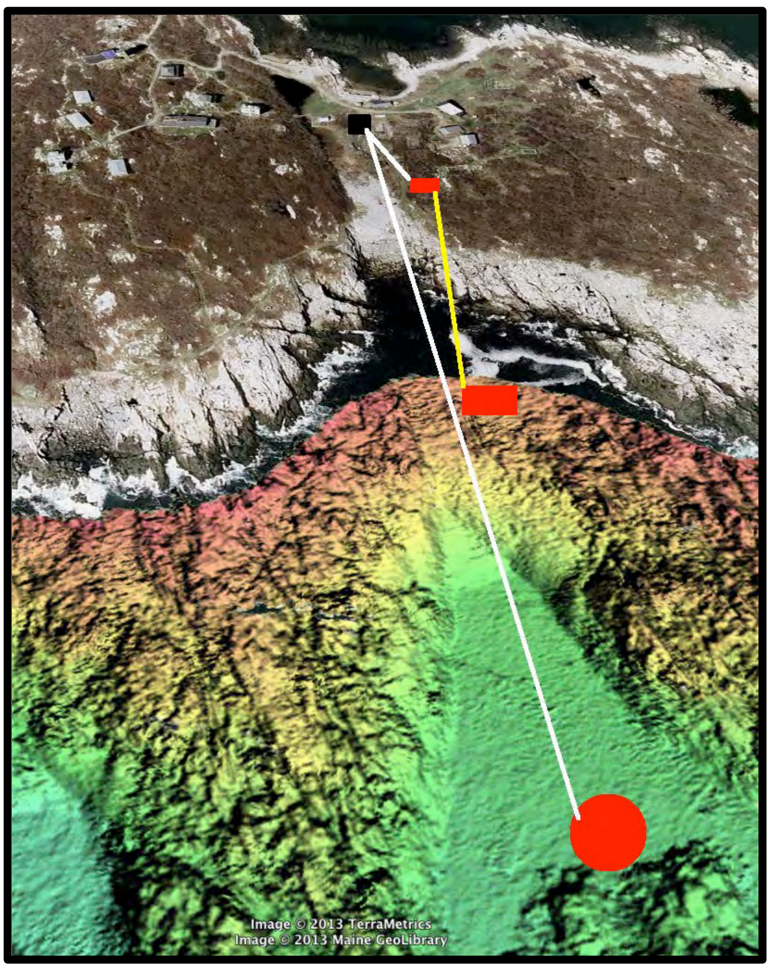

Figure 19: Map of bathymetry off the east coast of Appledore Island. The black square represents the new battery bank location, the red square represents an onsite utilities building, the red rectangle represents a potential location for a wave flap, the red circle represents a potential location for a wave buoy, the white line represents power cables, and the yellow line represents a hydraulic cable.

III. ELECTRICAL CONNECTION

Power Transmission to Shore

The power that is generated from the device needs to be transferred to shore from the deployment location to the battery bank. The routing of electricity was discussed with respect to a shallow-water device and a deep-water device.

The bottom–mounted, shallow water option could generate electricity on-site or pump hydraulic fluid to shore for conversion to electricity. Since the specific flap-type device discussed in section VI used the second method, the hydraulic fluid approach is discussed here. To transfer the working fluid from the device location to the onshore generator, a route must be planned for the hydraulic piping. A strategic route will need to be planned through the surf and intertidal zones. This piping could either be braced to the seabed at intervals with heavy weights or drilled and pinned into the sea floor, to minimize movement and abrasion of the piping against rock and ledge. The piping will run approximately 200m up to land where it will feed through an induction generator. The generator will be installed in a weather tight enclosure that is mounted a short distance inland. The enclosure will also be required to house all necessary controls and data acquisition systems. The main power electric transmission line will run approximately 200m from the control shed to the new battery bank. The power transmission line could either be a high voltage, three-phase line with a step down to 48V DC at the battery bank or low voltage, high amperage DC cable with a step down at the utility building.

A deep-water wave buoy device generating electricity would require a submarine high voltage power transmission line. The submarine cable would have two parts: a static cable and a dynamic cable. The static cable would run from the shore through the intertidal and surf zones. Beyond the breaker waves there would be an underwater connecter to mate the static cable to the dynamic cable. The dynamic cable, which can handle a great deal of movement, will run from the sea floor to the wave buoy. The dynamic cable will then have another underwater connecter to mate the cable to the wave buoy as shown in Figure 20 (5).

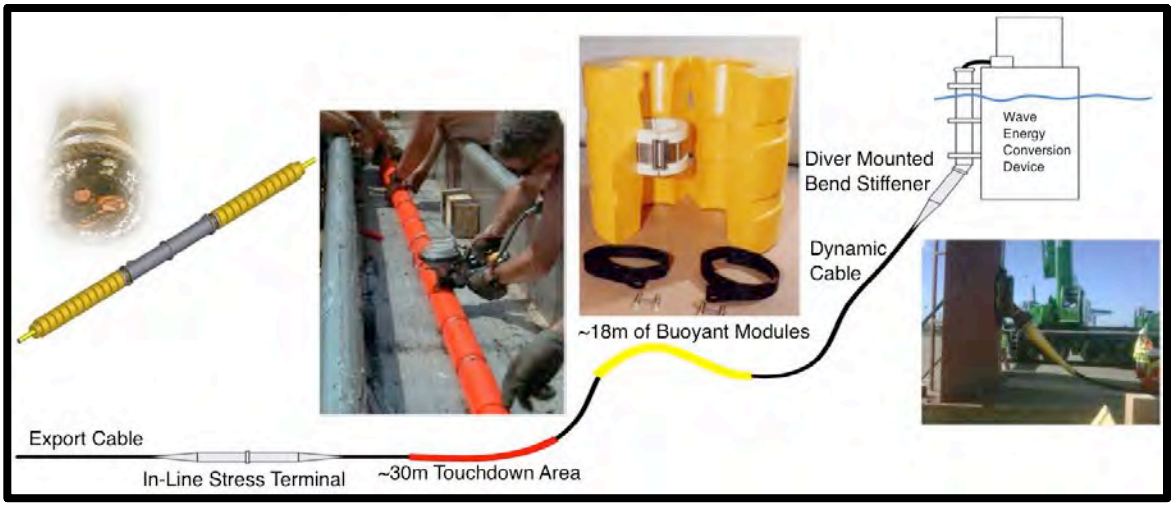

Figure 20: Power transmission line that would be used for a wave buoy (macartney.com).

The hydraulic line, from the flap-device, and the power transmission cable, from the buoy-device, would travel through the intertidal zone. This area of the transmission and hydraulic cable could be difficult to install and keep intact. This area of the seafloor is very non-uniform and consists of numerous boulders. The bathymetry study shows that the seafloor can change anywhere from 1 meter to 10 meters in a very short stretch. It may be necessary to install frames onto the boulders to elevate the cable or hydraulic line, and allow it to run at a relatively constant slope. The cable or hydraulic line would need to be installed in a conduit to protect the line from breaking due to the strong particle motion in this region, and there is a concern for larger boulders and debris going across the line and cutting or breaking it. With the extra protection of a conduit there would be less concern of the line being damaged.

Battery Bank Connection

Whether electric power comes directly from the device or from an onshore generator, both systems would connect to the battery bank in a similar manner to the wind turbine. Figure 21 represents the electrical schematic of the windmill to the battery bank (6). As shown, there is a fuse disconnect that would be similarly required to connect the wave energy conversion device to the grid and disconnect it at any time. The power transmitted through the cable is conditioned; changing the power from alternating current to direct current. The wave energy converter would also go through a similar charge controller to convert the AC power produced by the generator to DC power, which is connected to the 48V DC battery bank.

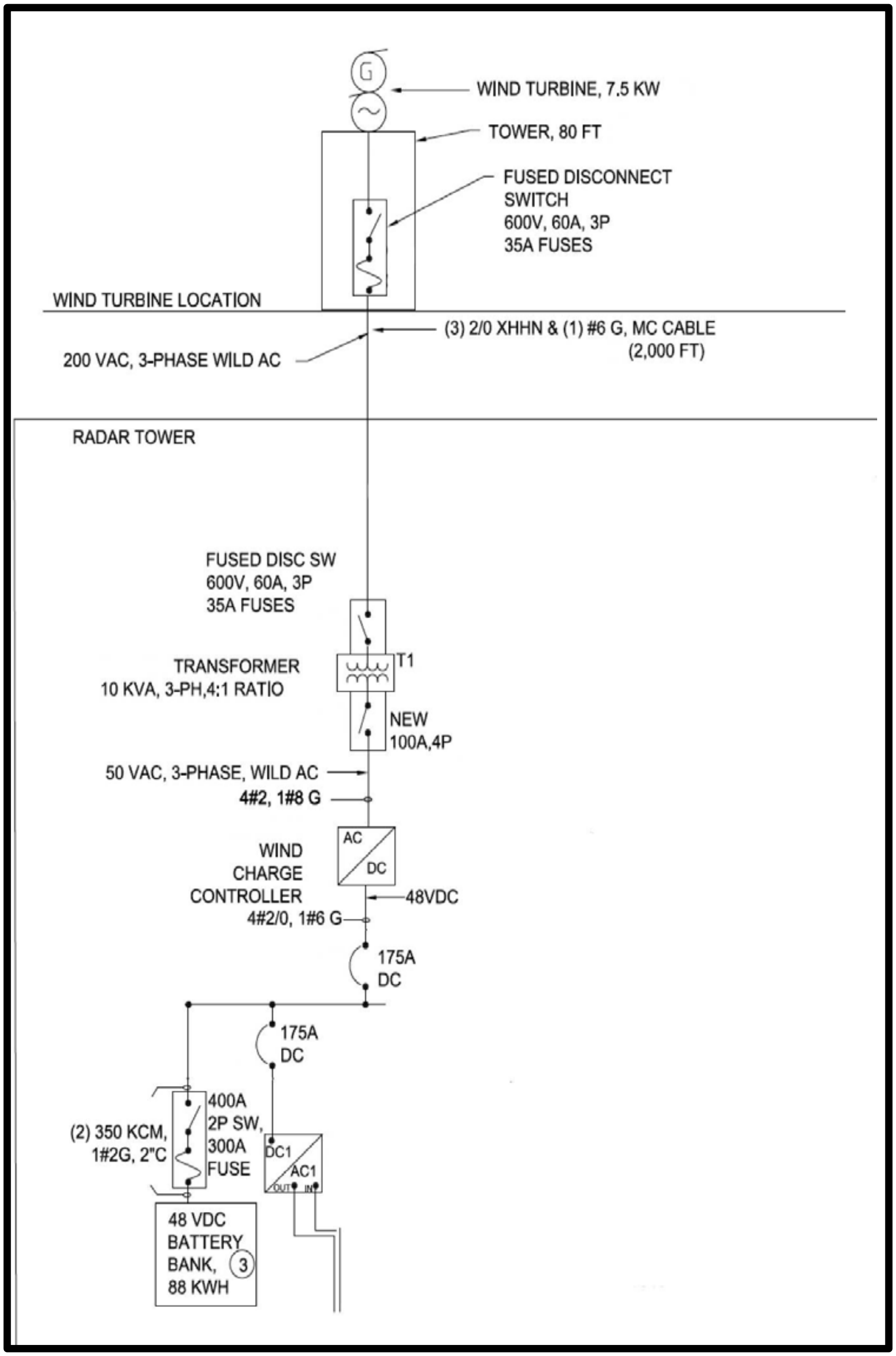

Figure 21: Electrical schematic of the wind turbine connected to the battery bank (6).

IV. ENVIRONMENTAL IMPACTS AND PERMITTING

Environmental Concerns

There are a number of environmental concerns for installing a wave energy conversion device at Appledore Island including the disruption of bird nesting, fish migration, and intertidal zone ecology. It is especially important that the installation of a wave energy conversion device will not affect the biology around and at the SML because the laboratory primarily studies these ecosystems. There is a concern that an electrical cable running through the water could produce electro-magnetic waves and repel fish and smaller ocean creatures away from this location as well as kill off plants. The power generation would likely be small such that electro-magnetic waves are not a significant concern. Installing a power transmission line or hydraulic cable would require strategic placement though the intertidal zone to ensure that bird nesting grounds, seaweed, and plants are not disturbed. The lines can be mounted so that they will not snag or warp. The consideration of fishermen will also need to be taken into account since this area is heavily fished, and we can not install a device in the area where lobster men deploy traps.

The Nature of Seasonal Deployment

The Isles of Shoal Marine Lab is only operational during the summer months so there is no need for a device to be deployed over the winter. The device would be deployed in the ocean off the east coast of the island in April, and removed at the end of the season in September. It is beneficial for the marine lab to have the device in the water a fraction of the year to reduce the required permitting and legal procedures. Winter is a period of high wave activity, so removal of the device will reduce the potential for damage in oversized wave conditions. The seas tend to be more severe during the winter months and when storms roll through significant wave heights up to 20 feet are not uncommon. These waves have the tendency to bridge the lowest part of the island.

Required Permitting

Permitting is required to install a permanent wave conversion device at Appledore Island. This area of Maine falls under the National Resource Protection Act (NRPA) (7), and is monitored by the Maine Department of Environmental Protection (DEP). This act is designed to protect the sea, land, and animals along the coast of Maine. If there is going to be something placed in coastal waters for seven months or more, a year-long permit is required.

A permit would be required to install a mooring system for a wave buoy or for mounting a platform on the seafloor. Along with this permit, if there is a power transmission cable installed on the sea floor, there needs to be a permit for this as well. All installations need to be marked. This is especially important for bottom-mounted devices that may not be visible from the surface. Permitting for either of these devices and the transmission line is exempt if the equipment is not in the water more the seven consecutive months in a year. Since the SML only plans to operate this device during the summer months, permitting should not be an issue as long as the SML installs and removes the device and equipment at the beginning and end of the operating period. It is recommended that the SML applies for the mooring permit, DEP rule chapter 305, and Section 9 Permit by Rule (Utility Crossing) just to be safe in case the device remains in the water for more than 7 months (8).

Appledore Island is also known for having a large amount of bird nesting along the coastline and fish migration patterns through the waters surrounding the island. Because of these two conditions, the Maine DEP requires Timing of Action Approval (9) for both the Department of Inland Fisheries and Wildlife and the Department of Marine Resources (10). These are two applications that can be found on the Maine DEP website and need to be filled out before work begins. Submission should be early so that there is sufficient time for the Maine DEP to approve the work.

V. WAVE ENERGY TECHNOLOGIES

Classifications:

Wave Energy Conversion (WEC) technology is in its infancy and many devices are under development, which are able to convert wave motion into electrical energy. Devices fall into three main categories: shore mounted, near shore, and deep water. Two main categories of WEC technology were investigated for this feasibility study, devices that intercept surge-motion of shallow water waves and devices that intercept heave-motion of deep-water waves. Wave height and peak period are the contributing factors in wave energy conversion.

In one common wave energy conversion concept, buoys use the vertical oscillating heave-motion of surface waves to create relative motion between a float component and a stationary spar component. The relative linear motion is converted into rotary motion inside the spar, then into electricity using a rack and pinion system and an induction generator. A buoy device must be placed at depths of 20-60 meters for exposure to the heave motion of deep-water waves.

A small seabed-mounted bottom-hinged wave energy converter, also known as a surge-device, “flap” or “paddle”, absorbs the surge motion of shallow-water waves. Shallow water waves are present when mean water depth is much smaller than the average wavelength of incident waves. The shoaling effect forces water particles at shallow depths to assume an elliptical path, which surges laterally with a high density of energy. A surge device must be placed at depths of 6-10 meters to be exposed to the surge-motion of shallow water waves. The paddle moves with the surge, and forces a rotary pump to drive hydraulic fluid from the device through hydraulic piping to an induction generator on land. The system is closed and uses a biodegradable hydraulic fluid. The electrical energy from the generator is then transformed from high-voltage AC to low voltage DC and fed into the battery bank.

Power Estimations

Wave energy devices come in many shapes and sizes. It was important for the team to determine size of devices that could to capture the desired power from the wave conditions at the site. A plot was created that relates the amount of obtainable power to the capture efficiency of a wave energy conversion device. The Shoals Marine Lab has a goal to reduce their diesel energy use from 12.5kW to approximately 6.25 kW. The plot below was used to compare the incident wave power to the attainable power of commercially available devices, using the capture efficiencies published by the device vendors. The plot was generated for the most common wave conditions at Appledore Island, 1 meter significant wave height and a 5.5 second peak period. Assuming a typical efficiency of 40% a 6 meter wide device would need to be installed to supply the island with 10 kW of power.

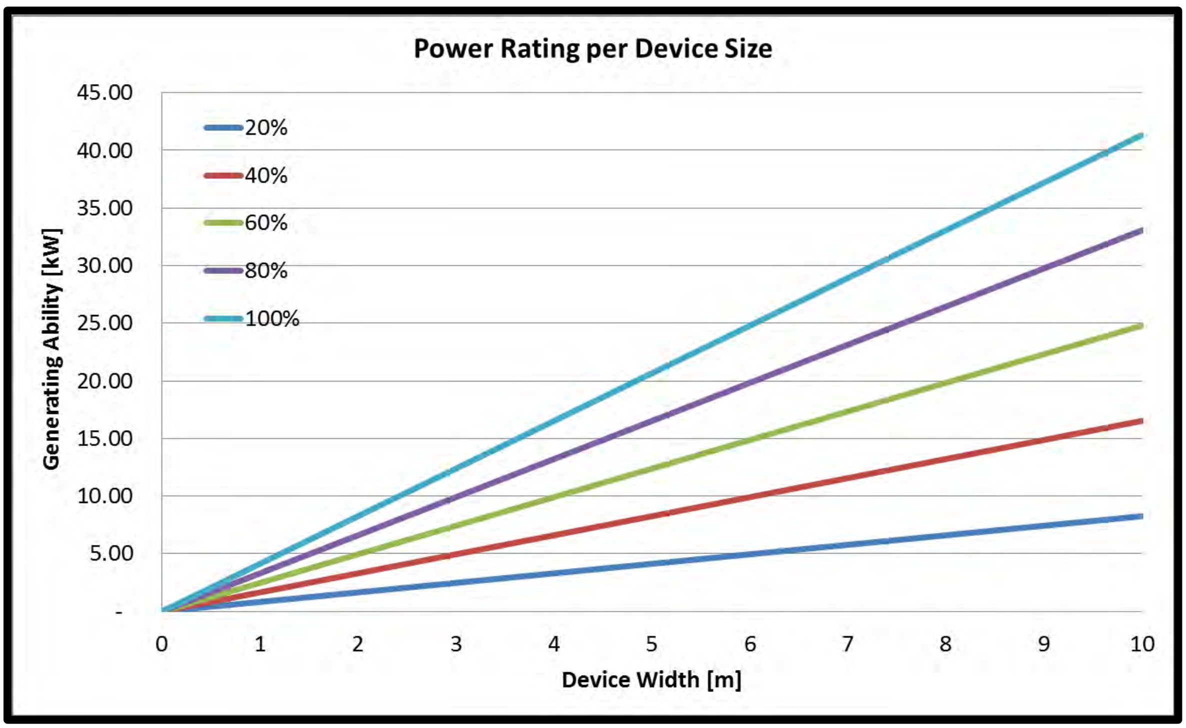

Figure 22: Reference plot to determine the approximent size of a device going of the maximum obtainable power at Appledore Island, the device generation ability, and the width of the device.

VI. SPECIFIC SYSTEM BENEFITS AND COSTS

Benefits

The use of wave energy converters at Appledore Island would provide the Shoals Marine Lab with continuous renewable energy from ocean waves. Since SML is not operational during the winter, a device would be seasonally deployed in the spring and removed in the fall. Seasonal deployment could prolong the life of a machine by protecting it from damaging winter storms. An installation could provide pertinent information for wave energy research regarding effective mooring systems along rocky east-coast shorelines, effective electrical connectivity to a remote island grid, and performance statistics of wave energy converters in an eastern US wave environment. It would also provide an opportunity to determine the modularity of wave energy conversion technology.

RME Surge WEC

Resolute Marine Energy Inc. (RME) is an ocean renewable energy company, located in Boston Massachusetts, whose goal is to build small-scale wave-driven power solutions in the range of 1-10kW (10). RME has built a surge WEC device which was able to capture approximately 40% of the incident wave activity, during ocean-trials in Duck, North Carolina (11). The SurgeWEC consists of a bottom-hinged flap that is 5m wide and 3.5m tall, connected to a hydraulic rotary pump shown in Figure 23.

Figure 23: RME SurgeWEC (www.resolutemarine.com)

The wave data, gathered in December at Appledore Island, was sent to RME to be analyzed using their predictive software. The results showed that the SurgeWEC device would generate 1.5-2kW of energy in the wave environment at Appledore (13). Using a simple comparison of size to energy output

$$\mathbf{W_{required}} = \mathbf{W_{actual}} * \frac{\mathbf{E_{required}}}{\mathbf{E_{actual}}}, \tag{13}$$

it was estimated that a single device must be 30 meters wide to produce the desired 10kW of energy. This could also be accomplished with an array of 5m-wide devices of the current design. An array of six SurgeWEC devices at Appledore Island would provide the Shoals Marine Lab with an average of 10kW of renewable wave energy; as long as the average wave conditions consist of a significant wave height of 1 meter and peak wave periods of 5.5 seconds. The peak generating capacity could be well above 10kW, depending on the wave activity.

The cost of installation was determined with help from the engineers at RME, who provided insight into the equipment and procedures necessary to install their device. Components included hydraulic piping, electric cabling, an induction generator, a hydraulic motor, a utility building and contracted services. Obtaining the bill of materials allowed the team to communicate with vendors and determine the cost of each component for the installation. The total cost of equipment and services to install a single device is approximately $200,000, as shown in Table 2. The total cost does not include the price of the wave flap because this information was not disclosed, but a rough price could be estimated at $500,000. Therefore an array of six devices would cost approximately $5 million.

OPT Wave Buoy

Ocean Power Technologies (OPT) is a leading renewable energy solutions company, located in Pennington, New Jersey. The Mark 3 Power Buoy is presently their flagship device, producing an average power of 150kW, shown in Figure 24. The spar of the buoy extends 35 meters below the surface, to a large heave plate, that maintains the relatively stationary position of the spar, which is anchored with a three-point mooring system. The float is 11m in diameter. Efficiencies have a range of 30-45% and the output is high-voltage AC (10). Using the above relation, the Mark 3 Power Buoy would have to be scaled down to a width of 5 meters, as shown in Figure 22, to produce the desired output of 10kW.

Figure 24: OPT wave buoy (www.oceanpowertechnologies.com)

OPT has developed two other devices that are more suitable for Appledore. The Autonomous Power Buoy (APB) is available in three variations with 10, 35 and 350-Watt outputs. The APB models have a low generating capacity and would be most suitable for trickle charging the battery bank. A trickle charge would ensure that the battery bank maintains a continuous charge from wave activity throughout the summer. The ideal buoy from OPT is the 40kW Power Buoy (PB-40), which was rated for the large wave conditions seen in Santona, Spain, and would produce approximately 10kW of energy in the conditions at Appledore (13).

Price estimates were provided for both buoys, by Nick Caruso, the Director of Business Development at OPT. The PB-40 would cost $5,000,000 to purchase from OPT. The APB-350 would cost $700,000 to purchase. Both buoys will require submarine power cables and contracted services for installation and removal. The power cable will cost approximately $600,000 per mile and the contracted services to install the buoy will cost $200,000. All the prices required to install an OPT wave device are shown in Table 3. At this time, to install 10kW WEC device, it is estimated that to purchase and installation a WEC device it would roughly cost 6 million dollars.

Table 2: Materials and labor break down for the Resolute Marine Energy wave flap.

Cost Analysis (for a 2 kW system)			
Material	**Cost**		**Subtotals**
Wave Flap			
Hydraulic Piping			**$ 7,500.00**
1-inch Hydraulic Piping (per. ft.)	15	$	
Length of Hydraulic Piping	500	ft	
Total Cost of Hydraulic Piping	7,500	$	
Pipe Fittings			**$ 240.00**
Hydraulic Piping Fittings(per fitting)	60	$	
Number of Fittings	4		
Total Cost of Hydrolic Fittings	240	$	
Electric Cable			
Electric Cable (per ft.)	189	$	**$ 94,696.97**
Length of Electric Cable	500	ft	
Total Cost of Electric Cable	94,697	$	
Motor, Generator, Inverter			**$ 14,000.00**
Hydraulic Motor (2.5 hp)	1,000	$	
Induction Generator (Output 2kW)	10,000	$	
Inverter	3,000	$	
Contracted Services			**$ 10,200.00**
Crane (per day)	1,500	$	
Transportation & Boom Truck (per hr)	200	$	
Transportation & Boom Truck (Boston-Newcastle '6 hrs.') (Moores)	1,200	$	
Riverside & Pickering Barge - Ken Anderson			
R&P barge; 4 crew members; 12 hrs; crane on land and on barge	5,500	$	
Tugboat	3,500	$	
Dive Team			**$ 50,000.00**
Mobilization and Base Installation	50,000		
Shed and Accessories			**$ 4,583.11**
Prefab Shed (8ft x 16ft)	3,879	$	
Prefab Shed (8ft x 8ft) $2659/shed x2sheds	5,318	$	
WIFI Outdoor AP Kit (per 90m)	317	$	
Distance from Battery Bank to Shed	200	m	
Total for WIFI	704	$	
Total Cost			**$ 181,220.08**

Table 3: The cost for purchasing a wave buoy from OPT

OPT Buoys	
PB - 40	$ 5,000,000.00
ATB - 350	$ 700,000.00
Power Cable	
Cost of cable per mile	$ 600,000.00
Instalation Costs	
Permitting, Moring, Environmental Impacts, etc.	$ 200,000.00
Total Cost	
PB - 40 System	**$ 5,500,000.00**
ATB - 350 System	**$ 1,080,000.00**

Deployment

Wave-flaps and wave-buoys would be deployed in a similar manner. For safe deployment the weather should be fair, with wave heights smaller than 1m. First the device would be placed on a barge using a crane and transported from Portsmouth Harbor to Appledore Island. The barge should have a crane onboard. Large ballasted floats would be secured to the device and the onboard crane would be used to lift the device off the barge and place the device in the water. Once the device is floating in the water the device would be towed into position. When the device is in position the ballasted floats would be used to lower the device into the proper position.

The flap-type device would be floated to a shallow water position and lowered to the seafloor. The Surge device must be secured to a rigid platform at depths of 6-10 meters and held down using heavy weights. The seafloor at these depths is relatively non-uniform, as described in Bathymetry, Section II. Consequently the legs of the platform should be adjustable to allow a dive team to level the platform upon installation. A hydraulic line would then run from the device to shore where it would tie into the hydraulic motor coupled to the induction generator. An electrical cable would then be run from the generator to the battery bank and tied into the battery bank.

A buoy device would be brought out to Appledore Island in the same manner as a wave flap. The buoy would be placed into the water by a crane located on the barge.

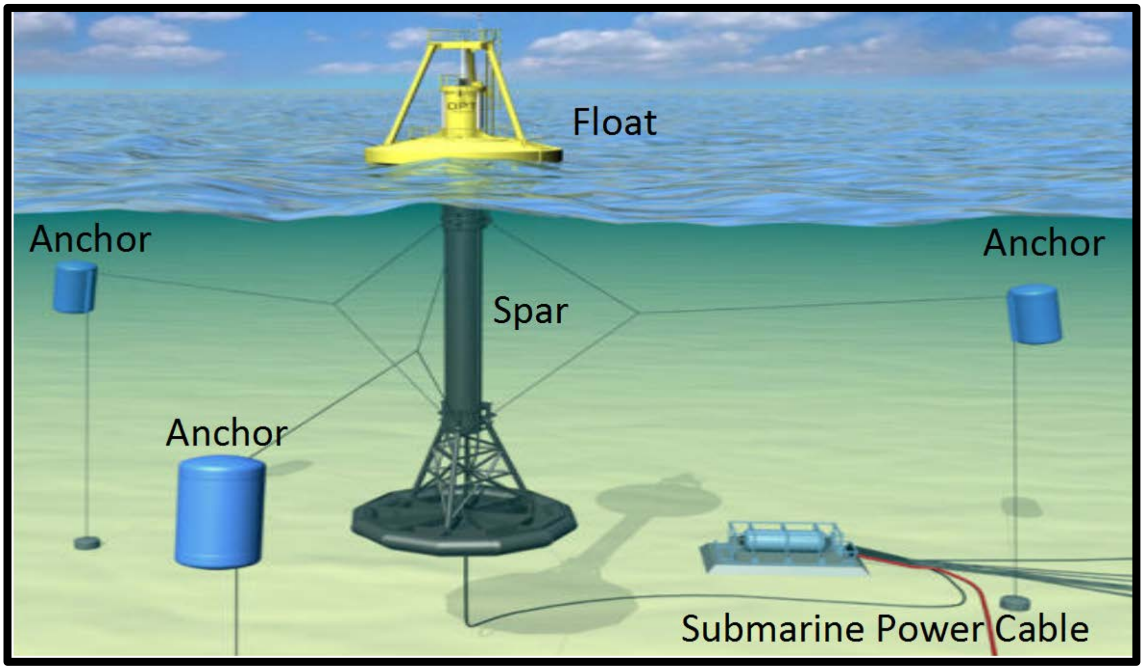

Figure 25: OPT wave buoy installation schematic (www.oceanpowertechnologies.com)

The 40kW Power Buoy would be deployed at a depth of 49 meters of water due to the draft of the spar, while a 350W Autonomous Power Buoy would be deployed at 18 meters of water due to the draft of the spar. The buoys would be towed into position and secured to the seafloor using a three point mooring system. The three point mooring system is shown in Figure 25. This mooring system is used to allow the spar to move freely within a controlled area. A submarine power cable would be used to route the electrical energy from the buoy, shown in Figure 25, to the battery bank on land.

When seasonally removed in the fall, the procedure would be the exact opposite of installation. Again the weather and wave conditions should be fair. The mooring systems would be dismantled and lift bags would be attached to the device to bring it to the surface. Once at the surface the device could be towed by boat to the dock at Appledore Island, where a crane would be used to lift it onto shore. Once the device is on shore the device should be placed in a location and winterized for storage through the winter. Removal and storage would be significantly simplified if a boat launch were available at Appledore Island. The devices could be towed in and out of the water using a submersible trailer and large floats, as shown in Figure 26. Additionally the surge device would require a dismantling and removal of hydraulic piping, while the buoy would require dismantling and removal of submarine electrical cabling.

Figure 26: Deployment of a SurgeWEC device at the U.S. Army Corps of Engineers field research station in Duck, North Carolina on December 1, 2012. An Army surplus Ligher Amphibious Re-Supply Cargo (LARC) was used to tow the SurgeWEC into position. Moving the SurgeWEC from the beach to its final location took approximately 10 minutes (14).

Preferred Device

Both devices require similar amounts of funding to purchase and install. An array of surge-type flap devices and a buoy-type device would require approximately $5 million. The mooring system for a flap device would require a significant amount of labor to install. Additionally the shallow water environment is much more dangerous for an ocean-going device than a deep water environment. The buoy device would be much easier to install and does not have the risk of being damaged by moving boulders or other harmful objects.

VII. CONCLUSION AND RECOMMENDATIONS

The team has deemed that it is technically feasible for the Isles of Shoal Marine Lab to use wave energy conversion to generate electricity on Appledore Island. A wave energy conversion device could be installed off the east coast of the island in the area near Broad Cove. The 40kW Power Buoy (PB-40) from Ocean Power Technologies is a potential wave energy conversion device for this application. The SurgeWEC wave-flap device from Resolute Marine Energy is another potential device, which must be installed in an array of six devices.

Suitable locations in this area have been found for a shallow water wave flap device and a deep water wave buoy. Measurements during field experiments were correlated with the wave-data buoy at Jeffrey's Ledge (Station 44098), providing a prediction of the summer wave conditions at Appledore. An analysis of wind activity at the sight, along with the wave data, indicated that wave heights at Appledore will typically be larger than those at Jeffrey's Ledge. Bathymetry was also studied and two ideal locations were found for a wave buoy and a wave flap.

Since the industry and technology of wave energy conversion is relatively new, the devices are still fairly expensive to build and there are not a lot to choose from. The primary challenge in the installation of a wave energy converter is acquiring funding for the project. Approximately $5 million dollars is necessary to purchase and install the PB-40 or the SurgeWEC, which would provide around 10kW of electricity to the island. If only a fraction of this funding is available then a single wave-flap or a smaller wave-buoy could be purchased and installed to provide a trickle charge to the battery bank which powers the island.

The addition of a wave energy conversion device would diversify the renewable energy portfolio on the island. This device could benefit the educational renewable-energy programs at the Shoals Marine Lab, allowing students not only to experience the wind and solar contributions but to learn more about the up-and-coming wave energy solutions that are being developed. This educational benefit would offset the monetary cost of installation, having a positive impact on ocean renewable energy research at UNH and Cornell.

Future Direction of the Project

The next step for the project could be to perform an extensive survey of the seafloor off the east coast of Appledore Island to examine the typical seafloor conditions and predict the transportation of sediment and boulders. Pressure measurements should continue to be made on an annual basis at Appledore Island, to generate a historical data set for the Shoals Marine Lab. In this way the correlation, between Appledore and the historical data from Jeffrey's Ledge, can be made more accurate over time.

Device companies should be contacted who are willing to test their devices at the island. Appledore Island could be used as a local grid-connected wave conversion test site. The seasonal nature of the deployment site could attract developers who wish to perform ocean-testing. Such a device could be applied to a live load over a summer-long test period. Not only would this provide the island with more renewable energy but it would provide important performance statistics for the for the ocean renewable energy industry. Alternatively, a search could be performed for funding opportunities to purchase and install a permanent device.

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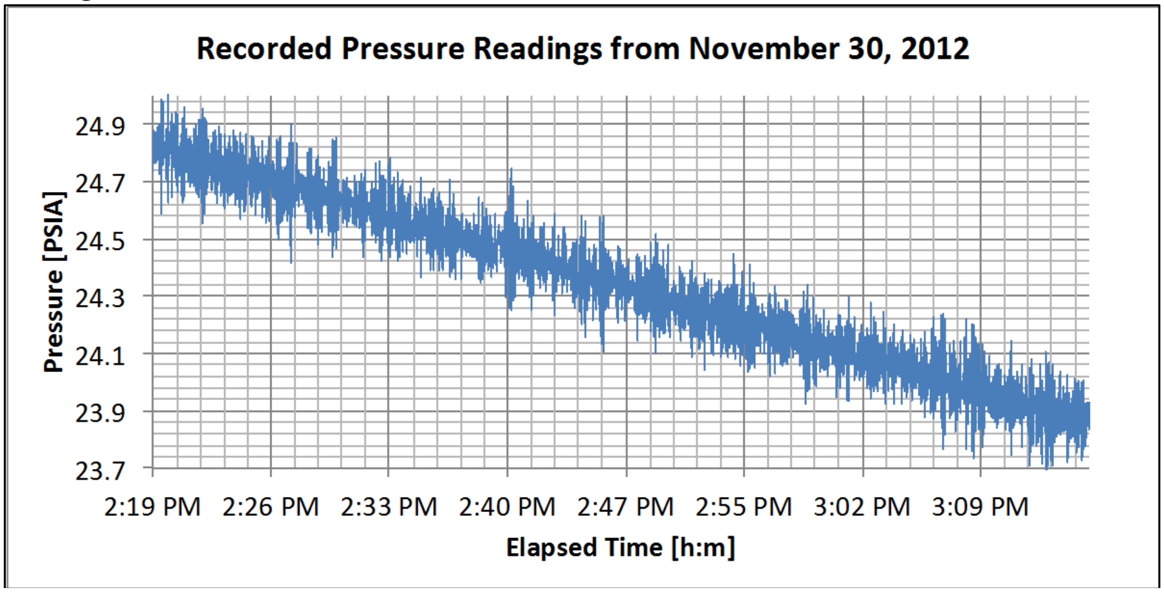
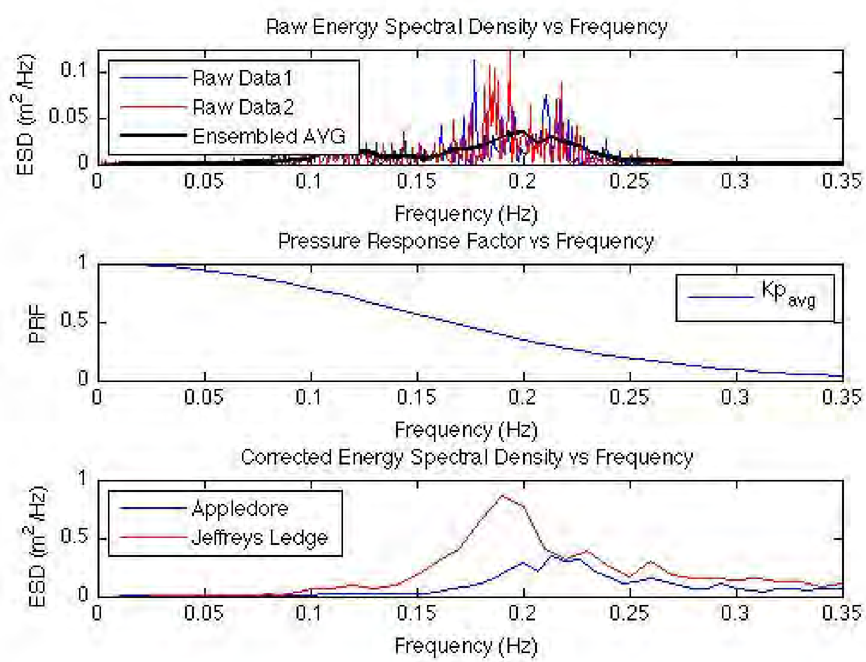
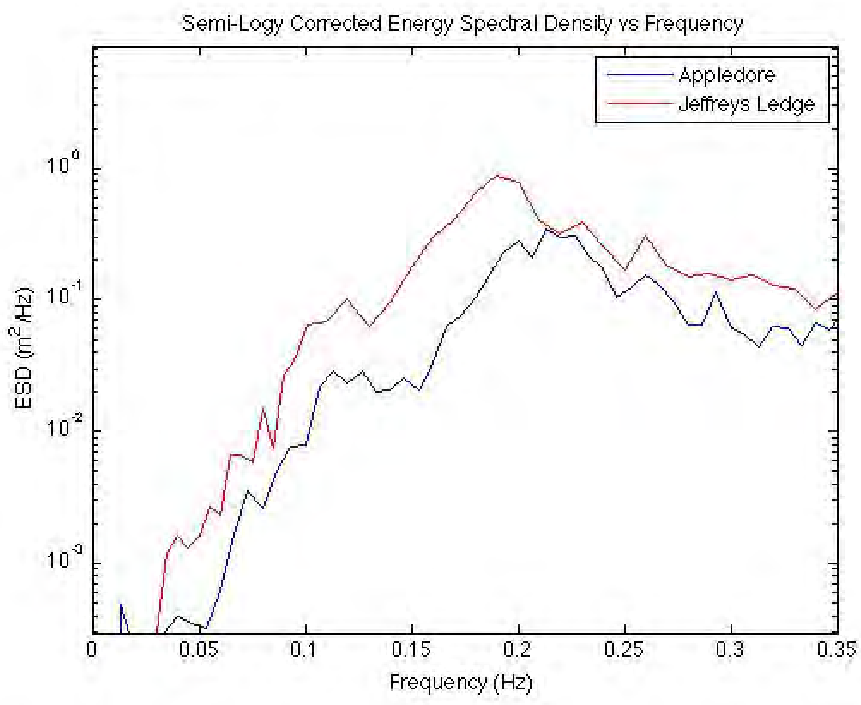
IX. APPENDIXES

Appendix A: Data Processing

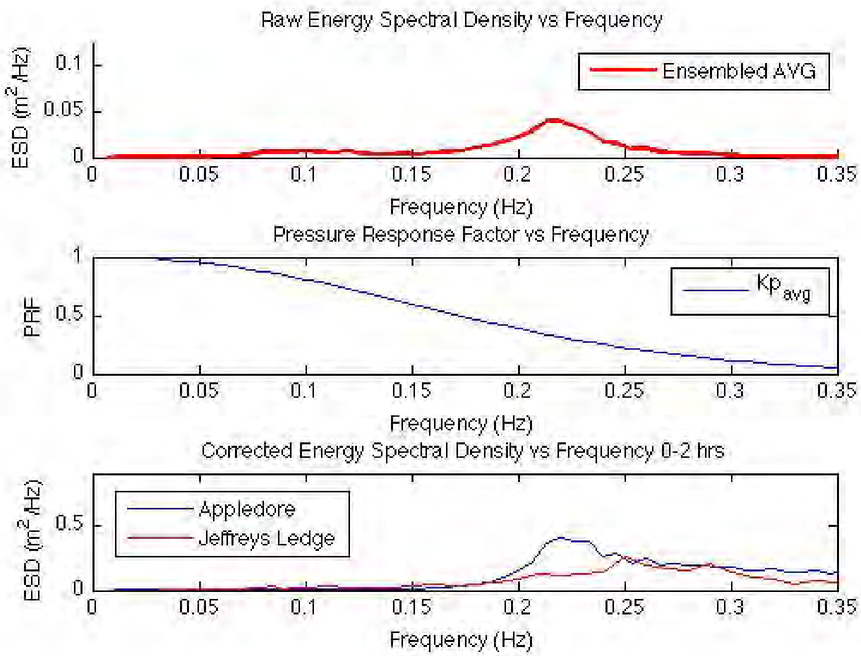
A.1: Figures from November 30, 2012

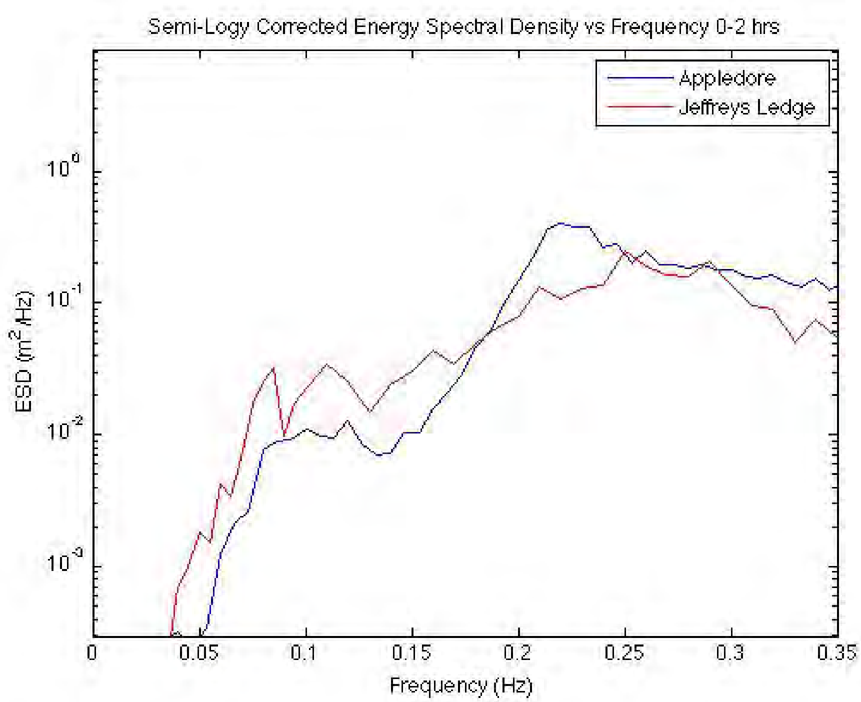


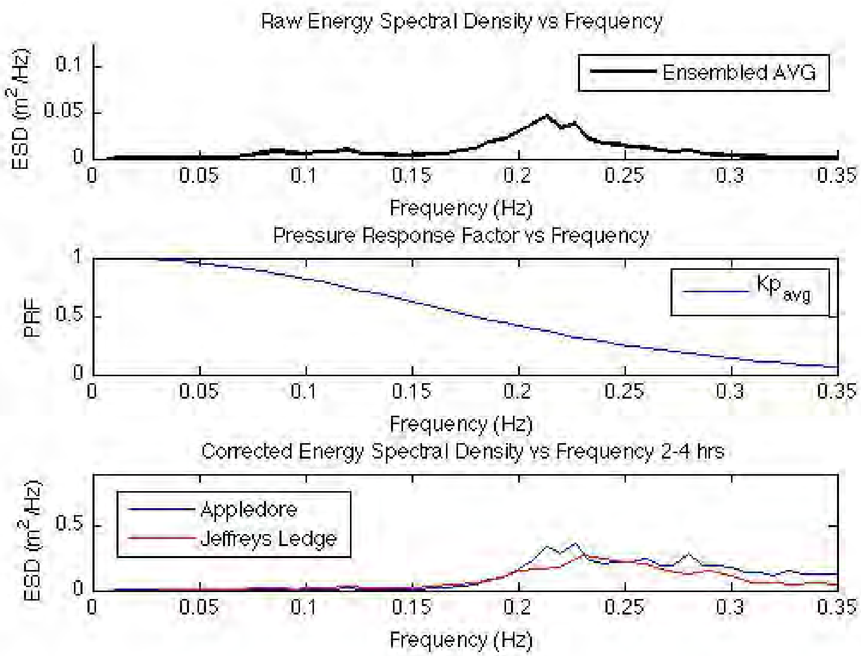


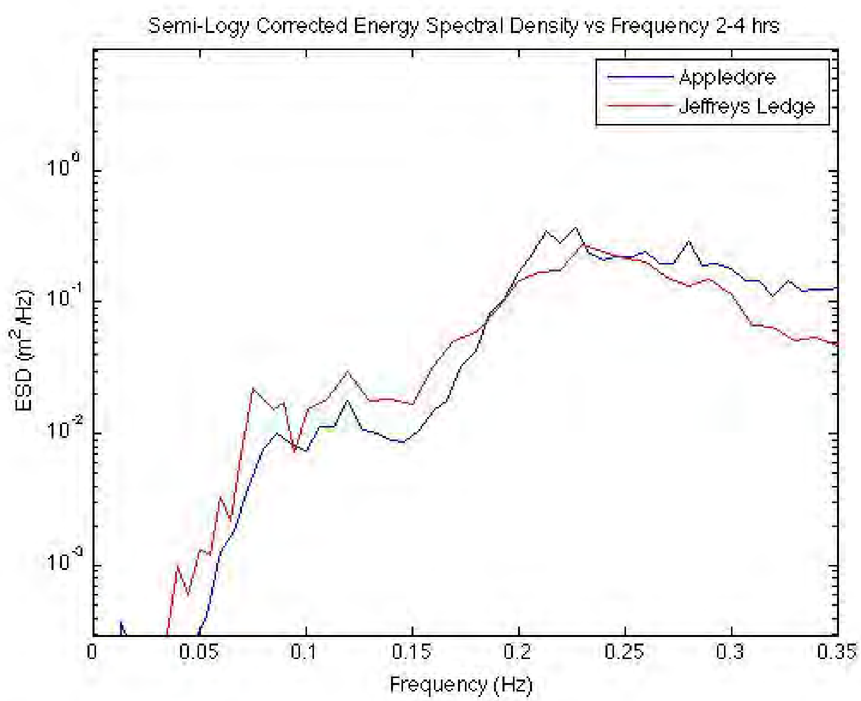

Semi-Logy Corrected Energy Spectral Density vs Frequency
Appledore
Jeffreys Ledge
ESD (m^2/Hz)
10^0
10^-1
10^-2
10^-3
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Frequency (Hz)

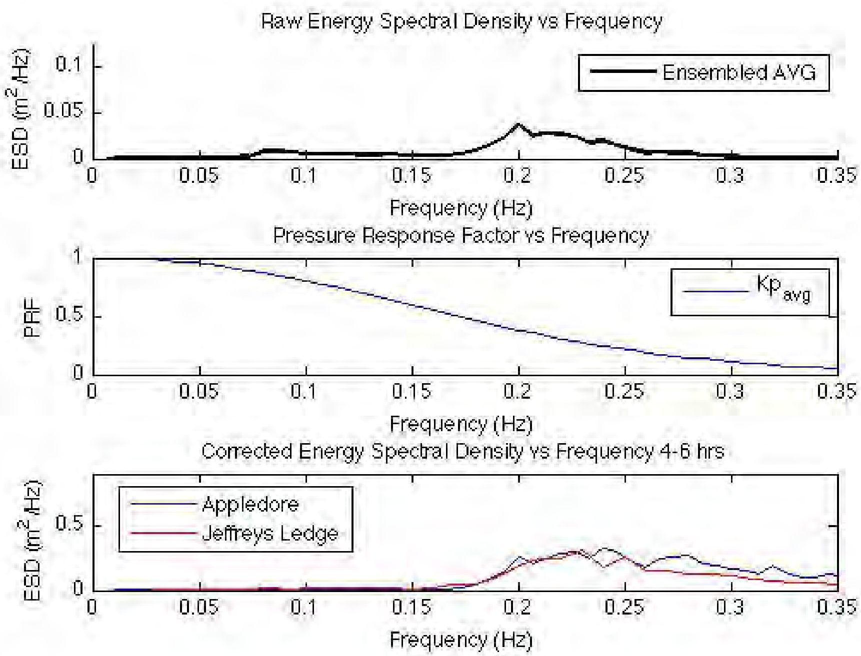
Appendix A.2: Figures from December 1, 2012

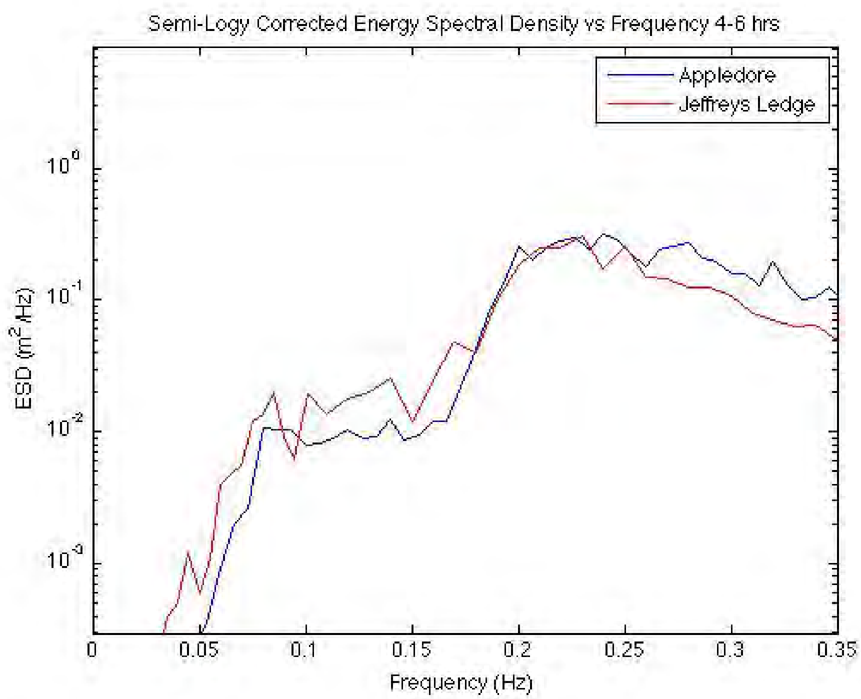




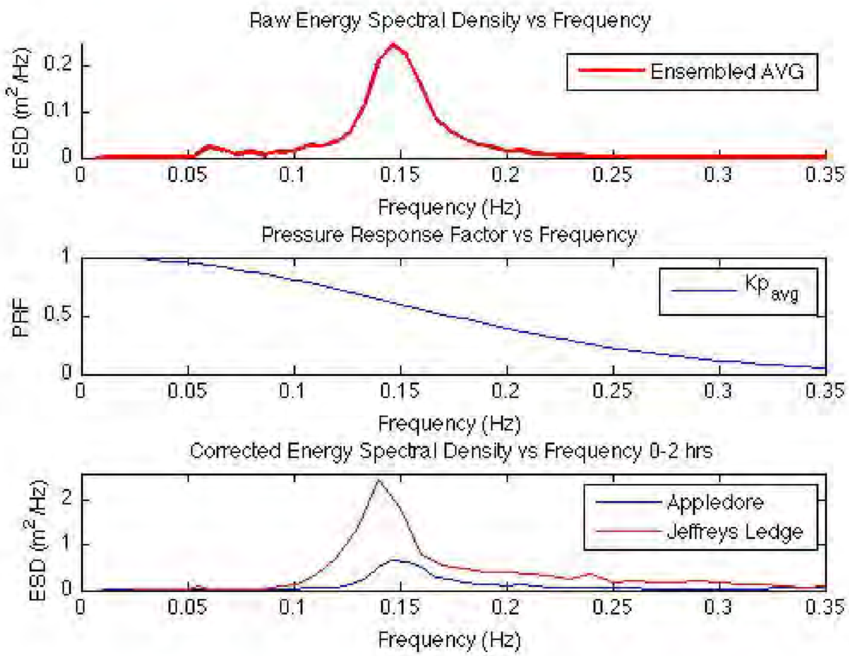

Raw Energy Spectral Density vs Frequency
Ensembled AVG
ESD (m2 /Hz)
Frequency (Hz)
Pressure Response Factor vs Frequency
Kpavg
PRF
Frequency (Hz)
Corrected Energy Spectral Density vs Frequency 2-4 hrs
Appledore
Jeffreys Ledge
ESD (m2 /Hz)
Frequency (Hz)

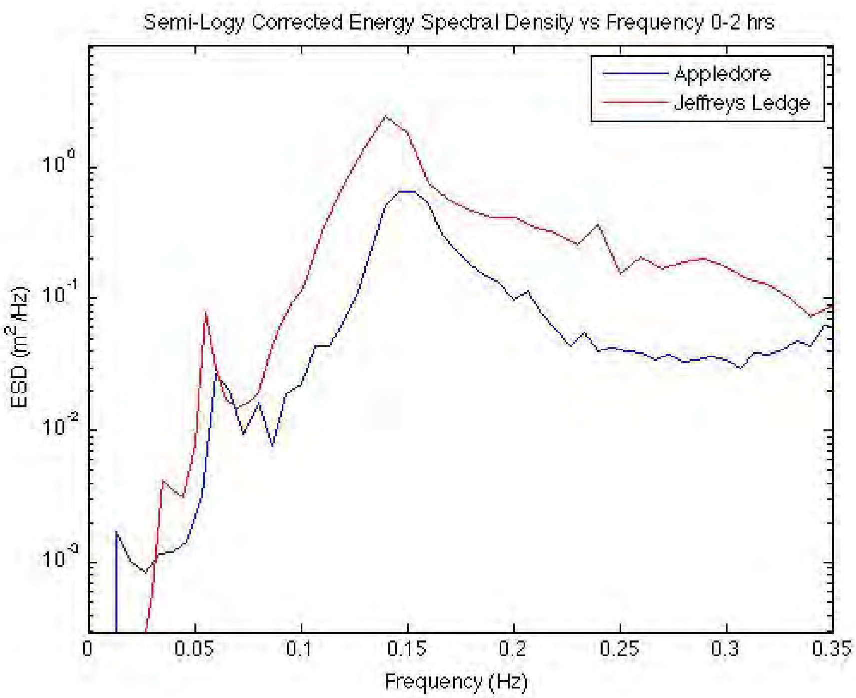

Semi-Logy Corrected Energy Spectral Density vs Frequency 2-4 hrs
Appledore
Jeffreys Ledge
ESD (m2 /Hz)
Frequency (Hz)

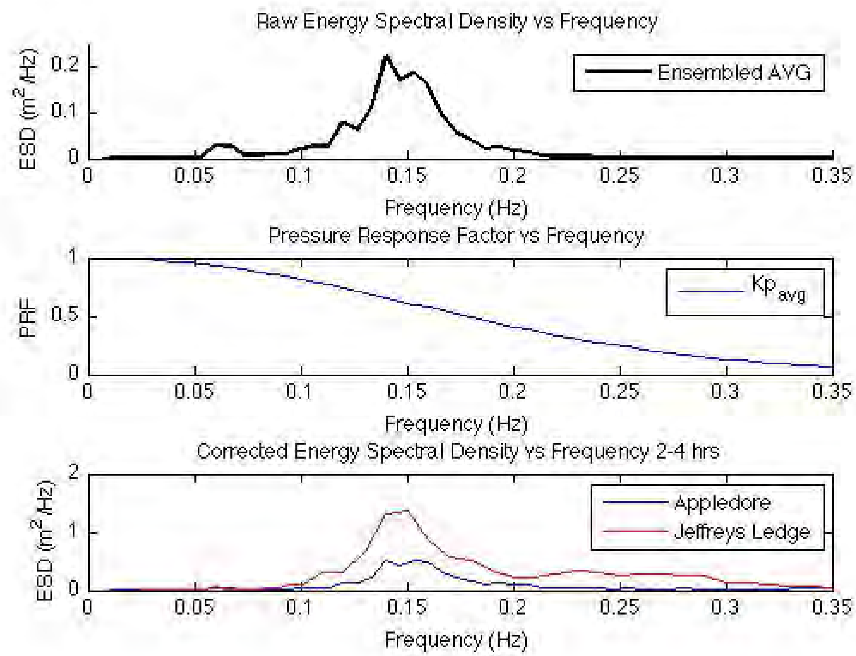

Raw Energy Spectral Density vs Frequency
Ensembled AVG
ESD (m^2 /Hz)
Frequency (Hz)
Pressure Response Factor vs Frequency
Kp_avg
PRF
Frequency (Hz)
Corrected Energy Spectral Density vs Frequency 4-6 hrs
Appledore
Jeffreys Ledge
ESD (m^2 /Hz)
Frequency (Hz)

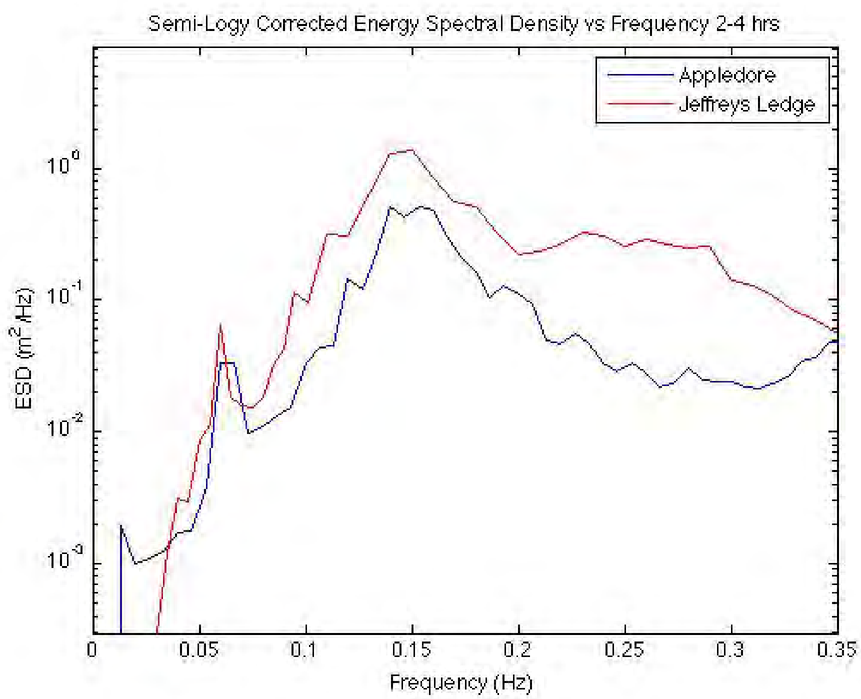

Semi-Logy Corrected Energy Spectral Density vs Frequency 4-6 hrs
Appledore
Jeffreys Ledge
ESD (m^2 /Hz)
Frequency (Hz)

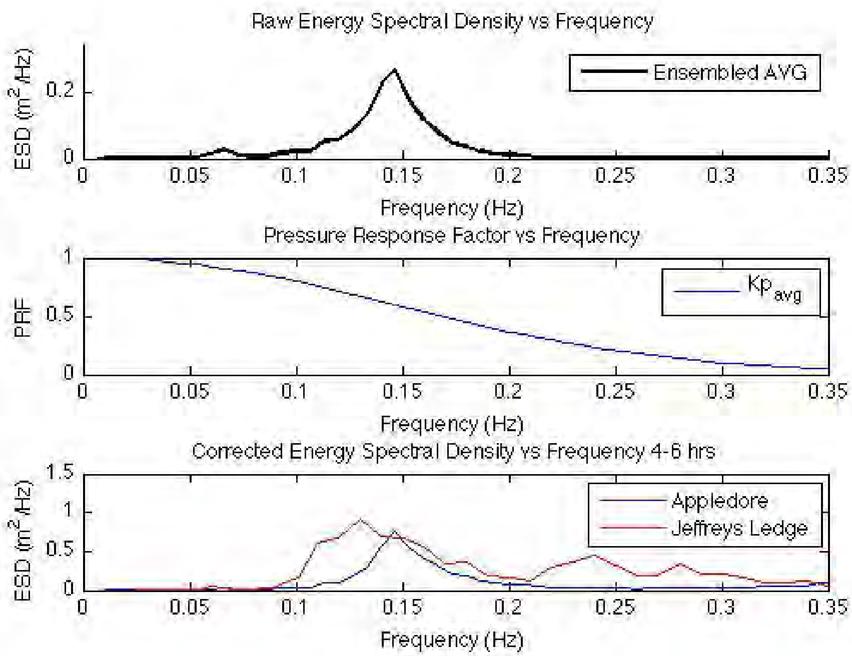
Appendix A.3: Figures from December 3, 2012

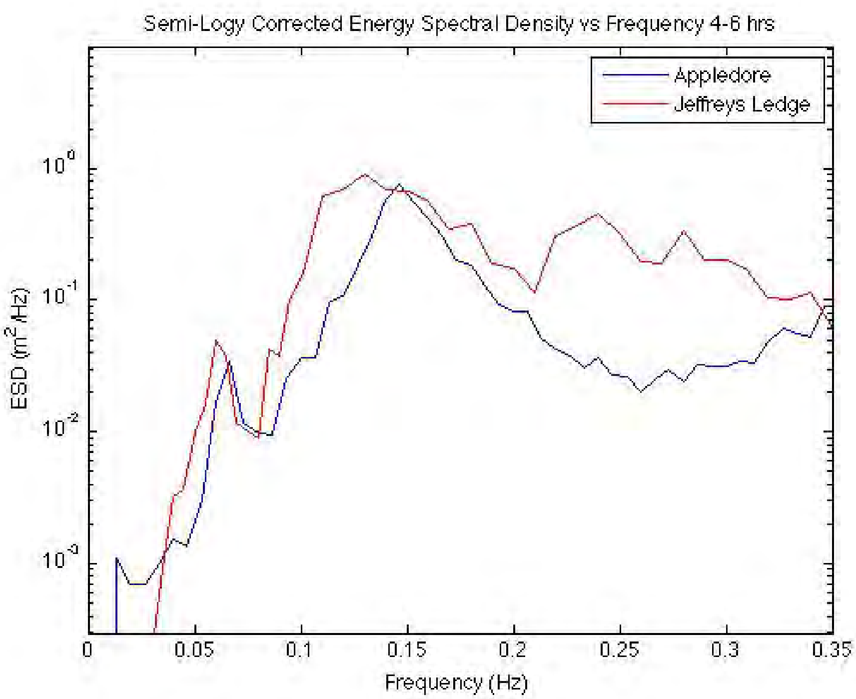





Raw Energy Spectral Density vs Frequency
ESD (m2 /Hz)
Ensembled AVG
Frequency (Hz)
Pressure Response Factor vs Frequency
PRF
Kpavg
Frequency (Hz)
Corrected Energy Spectral Density vs Frequency 2-4 hrs
ESD (m2 /Hz)
Appledore
Jeffreys Ledge
Frequency (Hz)


Semi-Logy Corrected Energy Spectral Density vs Frequency 2-4 hrs
ESD (m2 /Hz)
Appledore
Jeffreys Ledge
Frequency (Hz)

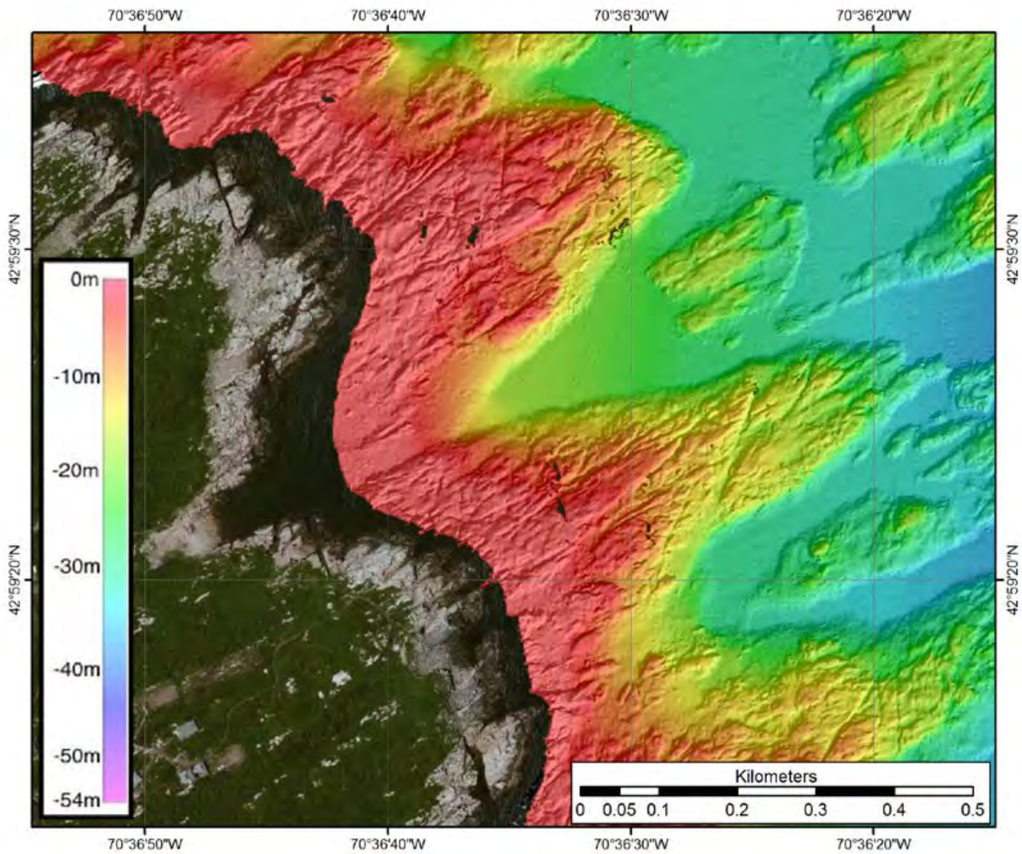

Raw Energy Spectral Density vs Frequency
ESD (m^2/Hz)
Ensembled AVG
Frequency (Hz)
Pressure Response Factor vs Frequency
PRF
Kp_avg
Frequency (Hz)
Corrected Energy Spectral Density vs Frequency 4-6 hrs
ESD (m^2/Hz)
Appledore
Jeffreys Ledge
Frequency (Hz)

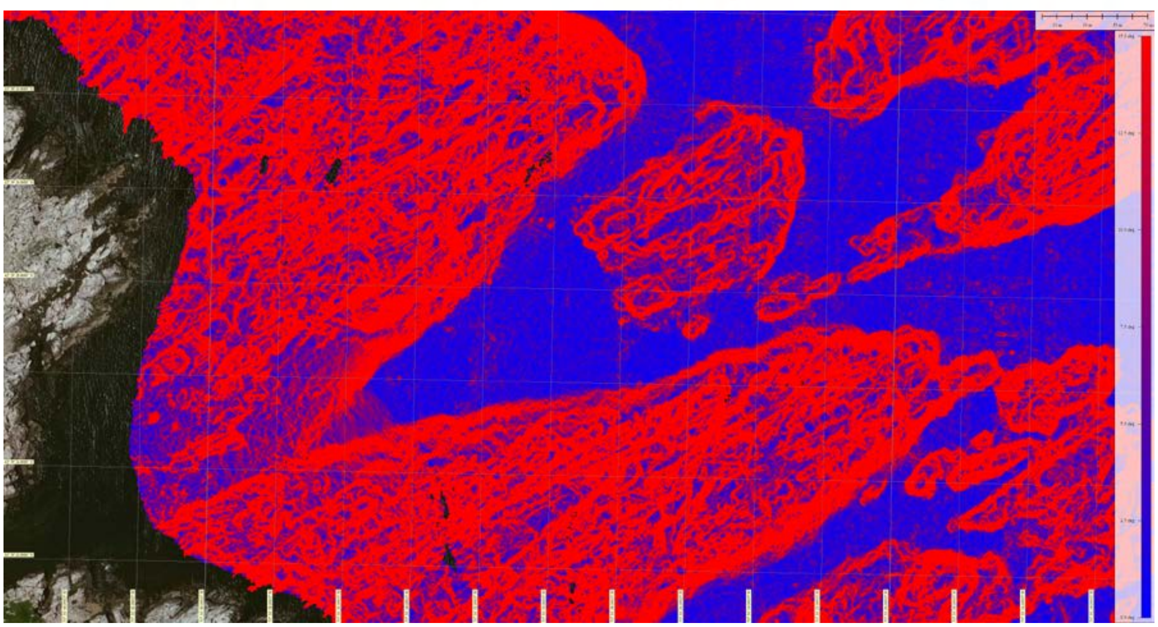

Semi-Logy Corrected Energy Spectral Density vs Frequency 4-6 hrs
ESD (m^2/Hz)
Appledore
Jeffreys Ledge
Frequency (Hz)

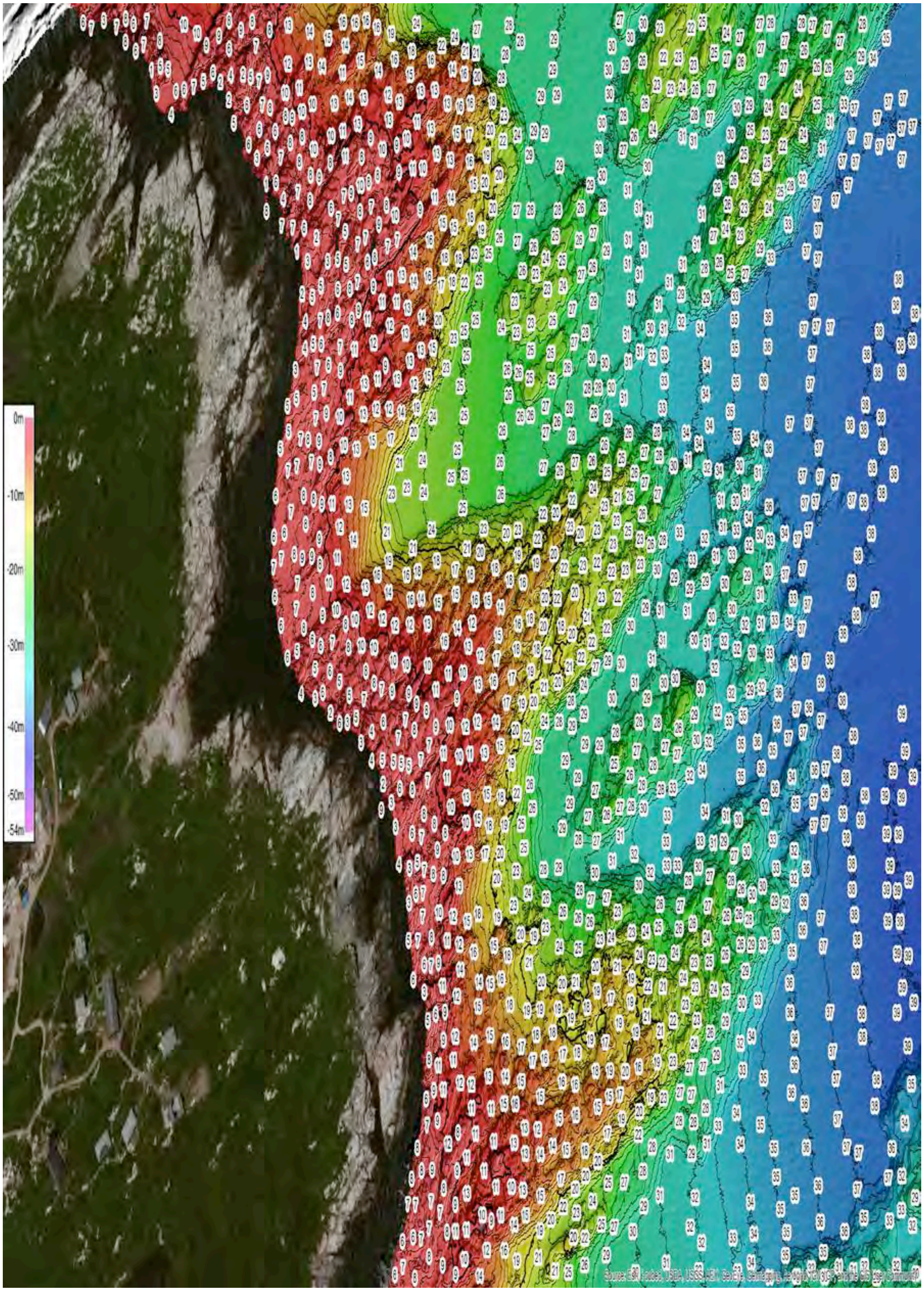
Appendix B: Wave Data and Conditions for Each Experiment

Date	Time	Location	Peak Peariod [Seconds]	Significant Wave Height [Feet]	Correlation Factor Between Significant Wave Height	Swell Direction [Deg]	Wave Direction [Deg]	Wind Direction [Deg]	Wind Speed [m/s]
1-Dec-12	2100-2300	Jeffrey's Ledge	4.4	2.3	1.25	98	71		
		Appledore Island	4.5	3.2				360	8.8
December 1-2, 2012	2300-0100	Jeffrey's Ledge	4	2.36	1.21	113	72		
		Appledore Island	4.5	3.15				360	8.2
2-Dec-12	0100-0300	Jeffrey's Ledge	4	2.4	1.21	119	60		
		Appledore Island	4.5	3.17				360	8.2
3-Dec-12	1000-1200	Jeffrey's Ledge	7.14	4.7	0.88	127	145		
		Appledore Island	6.7	3.12				230	8.8
3-Dec-12	1200-1400	Jeffrey's Ledge	6.7	4.5	0.84	137	135		
		Appledore Island	6.7	3.01				250	8.8
3-Dec-12	1400-1600	Jeffrey's Ledge	7.7	4.07	0.92	138	133		
		Appledore Island	6.8	3.2				280	10.8
30-Nov-12	1900-2000	Jeffrey's Ledge	5	3.25			24		
		Appledore Island(Sensor1)	4.55	2.96	0.91			13	3.2
		Appledore Island(Sensor2)	4.55	3.33	1.02				
27-Sep-12	2000-2200	Jeffrey's Ledge	4.55	2.7	1.6		33		
		Appledore Island	5.3	4.36				113	4.3

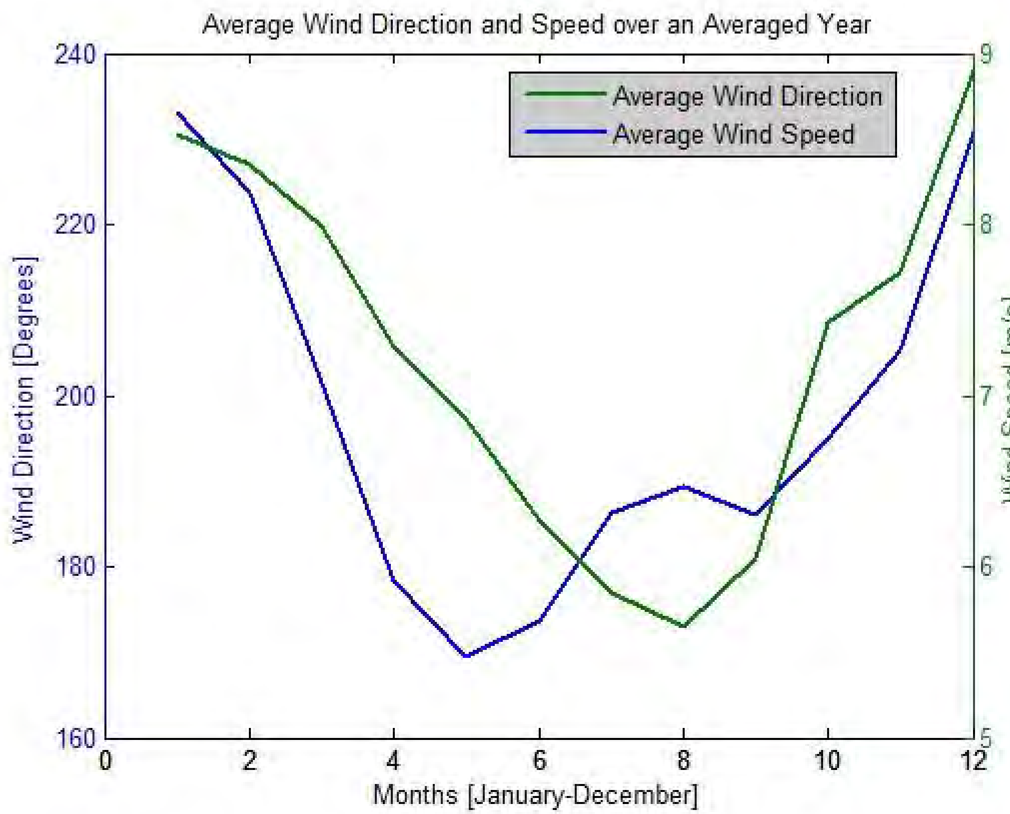
Appendix C: Bathymetry



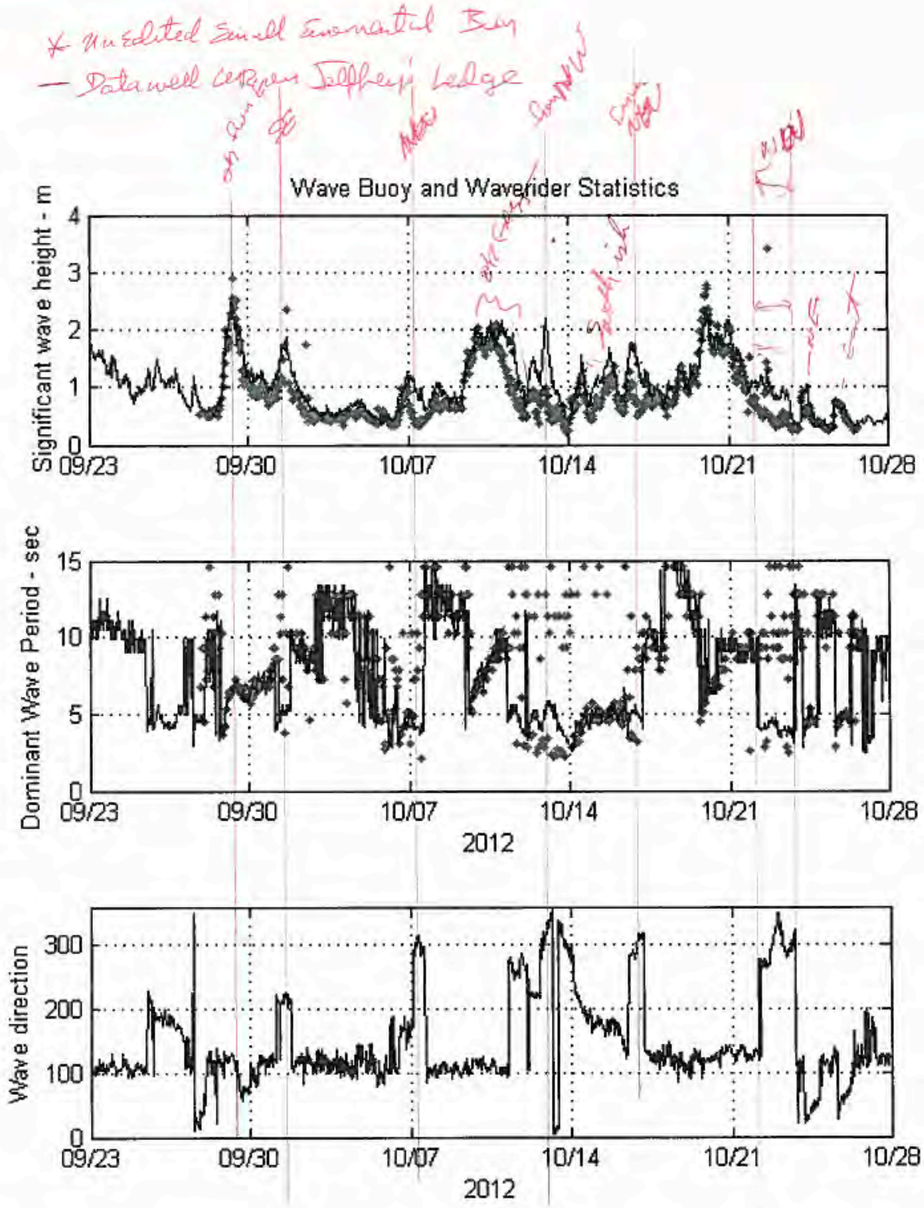



0m
-10m
-20m
-30m
-40m
-50m
-54m

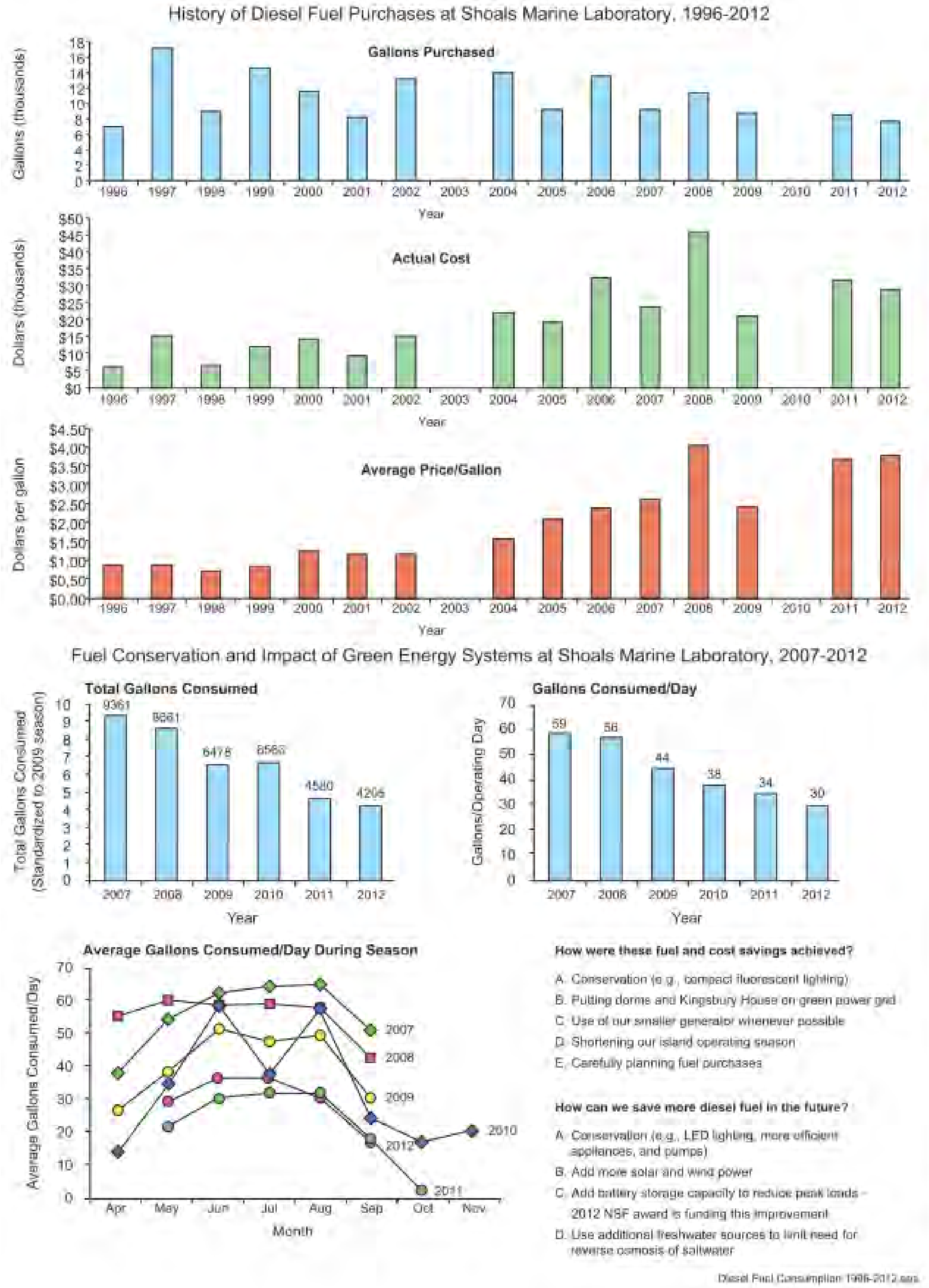
Appendix D: Appledore Island Wind Conditions



Appendix E: Jim Irish Wave Statistics Data



Appendix F: Appledore Island Fuel Usage



Appendix G: Equipment Available at Shoals Marine Lab:

Provided by Ross B Hansen, Assistant Director for Island and Coastal Operations

1. 16' x 20' Barge
2. Case 580 Super M with extend-a-hoe backhoe
3. John Deere 3340 tractor
4. (2) John Deere 4 x 6 Gators
5. 50' Research vessel with a knuckle crane and "A" Frame. http://www.sml.cornell.edu/sml_welcomekingsbury.html
6. 36' Research vessel.
7. 27' Research vessel
8. 21' Parker
9. (3) 15' Achilles boats (Zodiac style boats)
10. (1) 17' Boston Whaler.
11. 1 ton diesel truck with dump body.
12. High Tide pier on Appledore to unload heavy gear (tide dependent).
13. 20' x 25' Floating dock and gangway to access island on any tide.
14. 3 ton lifting crane at UNH pier in Newcastle
15. Toyota forklift at UNH pier in Newcastle
16. Various Lifting straps and chains

Appendix H: Project Budget

Expenses	
Travel	
Challenger ½ Day	$404
Subtotal	$404
Labor	
Skilled labor	$0
Subtotal	$0
Project Materials & Equipment	
HOBO Onset Water Level Logger - Titanium	$595
Subsurface Float	$0
Rope	$0
Marker Buoys	$0
Mooring materials	$0
Subtotal	$595
Total	$999
Revenue	
Sources of Funding	**Funds to Date**
Dept. Mechanical Engineering.	$450
UNH - Ocean Projects	$2,000
Grants - Government	$0
Total	$2,450

Appendix I: Hobo Onset Pressure Sensor Specifications

onset HOBO Data Loggers

CALIBRATION CERTIFICATE

LOGGER SERIAL NUMBER: 10214888
CALIBRATION RESULT: PASSED

Report Number	10214888_09_10_12_59
Certification Date	9/10/2012
Logger Type	HOBO Water Level Logger
Water Level Range	0 to 31 m (0 to 100 ft)
Logger Part Number	U20-001-02
Logger Status	New
Full Scale Pressure Range	0 to 400 kPa (0 to 58 psi)
Calibrated Range	69 to 400 kPa (10 to 58 psi), 0 to 40° C

Onset Computer Corporation certifies that the pressure accuracy of the data logger listed above has been observed to be within its published pressure specifications. Onset Computer's calibrated reference instruments are traceable to NIST, and certification files are maintained at Onset Computer's corporate headquarters in Bourne, MA.

Test Equipment and Procedures

Pressure Regulator and Calibrator: TE1-9947 (Calibrated on 03/01/2012)
Environmental Chamber: TE1-10026
Onset Calibration Software: D-9420
Onset Calibration Procedure: D-9124
Range of Applied Pressures: 69 to 400 kPa (10 to 58 psi)
Range of Applied Temperature: 0-40 °C (Nominal)

Test Data

Pressure (psia)	
Applied	Observed
22.500	22.519
37.500	37.535
57.500	57.522

Results

Specified Absolute Pressure Accuracy: PASSED

Typical: ± 0.1 %FS, ± 0.40 kPa (± 0.06 psi)

Maximum: ± 0.3 %FS, ± 1.20 kPa (± 0.17 psi)

Test Performed By: IA

D-9568-F

Onset Computer Corporation 470 MacArthur Blvd. Bourne, MA 02532 USA
Tel: 508-759-9500 Fax: 508-759-9100 Web: www.onsetcomp.com Email: sales@onsetcomp.com

Appendix J: Matlab Wave Data Processing Code

Contents

Analysis of December 3 Deployment at Pressure Sensor 2

```
close all
clear all
clc
```

Load Measured Wave Data

```
load wave.mat
```

Load Jeffrey's Ledge Data

```
load 'Jeffreys_Ledge_Matlab.txt'
JeffreysLedgeFreq = Jeffreys_Ledge_Matlab(:,1);
JeffreysLedge = Jeffreys_Ledge_Matlab(:,2);

WVHT_m = 1.43;                  % Significant Wave Height in Meters
WVHT_ft = WVHT_m * 3.28084;     % Significant Wave Height in Feet
WVHT_JeffreysLedge_ft = WVHT_ft % Average Significant Wave Height in Feet
```

```
WVHT_JeffreysLedge_ft =

    4.6916
```

Convert Measured Pressure Data

```
wave = wave-14.75;              %abs psi to gage psi
wave = wave .* 6894.75729;      %psi to pa
ro = 1030;                      %density of sea water mg/m3
g = 9.81;                       %gravity m/s
wave = wave ./ (ro * g);        %meters of head
```

Parameters

```
rate = 1;                       % sample rate of 1 Hz
depth = 64 * 0.3048;            %64ft, depth of the water
num_sections = 8;               % number of sections used to ensemble average
```

Hour 1

1 X 20 Minute Data Set Analysis
%% Acquiring Raw Section Data Plot

```
    % the mean depth of the instrument
    % This calls a program to find the raw pressure spectrum

press1 = wave(1:1200)';
z_press1 = -mean(press1);
[Guu_press1,f_press1] = Guu_calc(press1,rate);

% This calls another function which sections the data...
% into a number of sections, finds the spectra and emsembles
[Guu_ensemble1,f_ensemble1] = section_data(press1,rate,num_sections);

% Acquiring the Wave Number for Each Frequency
    % Gets the period
    % This loop finds all the wave lengths,...
    % by using the dispersionr elation function
T_1 = 1./f_ensemble1;
for i = 1:length(T_1)
    L_1(i) = dispersion(T_1(i),depth);
end

% Finds the wave number
k_1 = 2*pi./L_1;

% Acquiring the Plot for the Pressure Response Factor
    % Calculates the pressure response factor
clear i
kp1 = k_factor(k_1,z_press1,depth);

% Acquiring the Corrected Wave Spectrum
    % Calculates the corrected spectrum, taking into account kp
clear i
for i = 1:length(kp1);
    Guu_disp1(i) = Guu_ensemble1(i)/((kp1(i))^2);
end

% 2 X 20 Minute Data Set Analysis %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Acquiring Raw Section Data Plot
    % loads second pressure data (20 minutes worth)
    % the mean depth of the instrument
    % This calls a program to find the raw pressure spectrum
press2 = wave(1201:2400)';
z_press2 = -mean(press2);
[Guu_press2,f_press2] = Guu_calc(press2,rate);

% This calls another function which sections the data into...
% a number of sections, finds the spectra and emsembles
[Guu_ensemble2,f_ensemble2] = section_data(press2,rate,num_sections);

% Acquiring the Wave Number for Each Frequency
    % Gets the period
    % This loop finds all the wave lengths,...
    % by using the dispersionr elation function
T_2 = 1./f_ensemble2;
for i = 1:length(T_2)
    L_2(i) = dispersion(T_2(i),depth);
end
```

```
% Finds the wave number

k_2 = 2*pi./L_2;
% Acquiring the Wave Number for Each Frequency
    % Calculates the pressure response factor
clear i
kp2 = k_factor(k_2,z_press2,depth);

% Acquiring the Corrected Wave Spectrum
    % Calculates the corrected spectrum, taking into account kp
clear i
for i = 1:length(kp2);
    Guu_disp2(i) = Guu_ensemble2(i)/((kp2(i))^2);
end

% 3 X 20 Minute Data Set Analysis %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Acquiring Raw Section Data Plot
    % loads second pressure data (20 minutes worth)
    % the mean depth of the instrument
    % This calls a program to find the raw pressure spectrum
press3 = wave(2401:3600)';
z_press3 = -mean(press3);
[Guu_press3,f_press3] = Guu_calc(press3,rate);

% This calls another function which sections the data into...
% a number of sections, finds the spectra and emsembles
[Guu_ensemble3,f_ensemble3] = section_data(press3,rate,num_sections);

% Acquiring the Wave Number for Each Frequency
    % Gets the period
    % This loop finds all the wave lengths,...
    % by using the dispersionr elation function
T_3 = 1./f_ensemble3;
for i = 1:length(T_3)
    L_3(i) = dispersion(T_3(i),depth);
end

% Wave Number Total
    % Finds the wave number
k_3 = 2*pi./L_3;

% Acquiring the Wave Number for Each Frequency
    % Calculates the pressure response factor
clear i
kp3 = k_factor(k_3,z_press3,depth);

% Acquiring the Corrected Wave Spectrum
    % Calculates the corrected spectrum, taking into account kp
clear i
for i = 1:length(kp3);
    Guu_disp3(i) = Guu_ensemble3(i)/((kp3(i))^2);
end
```

Hour 2

4 X 20 Minute Data Set Analysis
%% Acquiring Raw Section Data Plot

```
    % the mean depth of the instrument
    % This calls a program to find the raw pressure spectrum
press4 = wave(3601:4800)';
z_press4 = -mean(press4);
[Guu_press4,f_press4] = Guu_calc(press4,rate);

% This calls another function which sections the data into...
% a number of sections, finds the spectra and emsembles
[Guu_ensemble4,f_ensemble4] = section_data(press4,rate,num_sections);

% Acquiring the Wave Number for Each Frequency
    % Gets the period
    % This loop finds all the wave lengths,...
    % by using the dispersionr elation function
T_4 = 1./f_ensemble4;
for i = 1:length(T_4)
    L_4(i) = dispersion(T_4(i),depth);
end

% Finds the wave number
k_4 = 2*pi./L_4;

% Acquiring the Plot for the Pressure Response Factor
    % Calculates the pressure response factor
clear i
kp4 = k_factor(k_4,z_press4,depth);

% Acquiring the Corrected Wave Spectrum
    % Calculates the corrected spectrum, taking into account kp
clear i
for i = 1:length(kp4);
    Guu_disp4(i) = Guu_ensemble4(i)/((kp4(i))^2);
end

% 5 X 20 Minute Data Set Analysis %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Acquiring Raw Section Data Plot
    % loads second pressure data (20 minutes worth)
    % the mean depth of the instrument
    % This calls a program to find the raw pressure spectrum
press5 = wave(4801:6000)';
z_press5 = -mean(press5);
[Guu_press5,f_press5] = Guu_calc(press5,rate);

% This calls another function which sections the data into...
% a number of sections, finds the spectra and emsembles
[Guu_ensemble5,f_ensemble5] = section_data(press5,rate,num_sections);

% Acquiring the Wave Number for Each Frequency
    % Gets the period
    % This loop finds all the wave lengths,...
    % by using the dispersionr elation function
T_5 = 1./f_ensemble5;
for i = 1:length(T_5)
    L_5(i) = dispersion(T_5(i),depth);
end
```

```
% Finds the wave number
k_5 = 2*pi./L_5;

% Acquiring the Wave Number for Each Frequency
    % Calculates the pressure response factor
clear i
kp5 = k_factor(k_5,z_press5,depth);

% Acquiring the Corrected Wave Spectrum
    % Calculates the corrected spectrum, taking into account kp
clear i
for i = 1:length(kp5);
    Guu_disp5(i) = Guu_ensemble5(i)/((kp5(i))^2);
end

% 6 X 20 Minute Data Set Analysis %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Acquiring Raw Section Data Plot
    % loads second pressure data (20 minutes worth)
    % the mean depth of the instrument
    % This calls a program to find the raw pressure spectrum
press6 = wave(6001:7200)';
z_press6 = -mean(press6);
[Guu_press6,f_press6] = Guu_calc(press6,rate);

% This calls another function which sections the data into...
% a number of sections, finds the spectra and emsembles
[Guu_ensemble6,f_ensemble6] = section_data(press6,rate,num_sections);

% Acquiring the Wave Number for Each Frequency
    % Gets the period
    % This loop finds all the wave lengths,...
    % by using the dispersionr elation function
T_6 = 1./f_ensemble6;
for i = 1:length(T_6)
    L_6(i) = dispersion(T_6(i),depth);
end

% Wave Number Total
    % Finds the wave number
k_6 = 2*pi./L_6;

% Acquiring the Wave Number for Each Frequency
    % Calculates the pressure response factor
clear i
kp6 = k_factor(k_6,z_press6,depth);

% Acquiring the Corrected Wave Spectrum
    % Calculates the corrected spectrum, taking into account kp
clear i
for i = 1:length(kp6);
    Guu_disp6(i) = Guu_ensemble6(i)/((kp6(i))^2);
end
```

Ensembling & Average Data Sets

```
kpAVG = (kp1 + kp2 + kp3 + kp4 + kp5 + kp6) ./ 6;

pressAVG = (press1 + press2 + press3 + press4 + press5 + press6) ./ 6;

Guu_ensembleAVG = (Guu_ensemble1 + Guu_ensemble2 + Guu_ensemble3 +...
    Guu_ensemble4 + Guu_ensemble5 + Guu_ensemble6) ./ 6;
Guu_pressAVG = (Guu_press1 + Guu_press2 + Guu_press3 + Guu_press4 +...
    Guu_press5 + Guu_press6) ./ 6;
Guu_dispAVG = ((Guu_disp1 + Guu_disp2 + Guu_disp3 + Guu_disp4 +...
    Guu_disp5 + Guu_disp6)) ./ 6;

f_ensembleAVG = (f_ensemble1 + f_ensemble2  + f_ensemble3 +...
    f_ensemble4 + f_ensemble5 + f_ensemble6) ./ 6;
f_pressAVG = (f_press1 + f_press2 + f_press3 + f_press4 +...
    f_press5 + f_press6) ./ 6;
```

Plot Ensembled Averaged, Pressure Response Factor, Corrected Spectrum

Plots the raw and ensembled data of the wave sprectra

```
figure(1)
subplot(3,1,1);
plot(f_pressAVG, Guu_pressAVG, 'B')
hold on,
plot(f_ensembleAVG, Guu_ensembleAVG, 'R', 'LineWidth', 2)
ylim([0 0.25])
xlim([0 0.35])  %.65
title('Raw Energy Spectral Density vs Frequency')
xlabel('Frequency (Hz)')
ylabel('ESD (m^2/Hz)')
legend('Ensembled AVG')

% Plots the pressure response factor
subplot(3,1,2);
plot(f_ensembleAVG, kpAVG)
xlim([0 0.35])  %.65
title('Pressure Response Factor vs Frequency')
xlabel('Frequency (Hz)')
ylabel('PRF')
legend('Kp_{avg}')

% Plots the new corrected wave spectrum
subplot(3,1,3);
plot(f_ensembleAVG, Guu_dispAVG)
hold on
plot(JeffreysLedgeFreq, JeffreysLedge, 'R')
legend('Appledore','Jeffreys Ledge')
ylim([0 2.6])
xlim([0 0.35])
title('Corrected Energy Spectral Density vs Frequency 0-2 hrs')
xlabel('Frequency (Hz)')
ylabel('ESD (m^2/Hz)')
```

Semilog Plot

Plots the new corrected wave spectrum

```
figure(2)
semilogy(f_ensembleAVG, Guu_dispAVG)
hold on
semilogy(JeffreysLedgeFreq, JeffreysLedge, 'R')
legend('Appledore','Jeffreys Ledge')
legend('Appledore','Jeffreys Ledge')
ylim([0.0002967 8.449])
xlim([0 0.35])
title('Semi-Logy Corrected Energy Spectral Density vs Frequency 0-2 hrs')
xlabel('Frequency (Hz)')
ylabel('ESD (m^2/Hz)')
```

Wave Analysis Using Spectral Density Plots Jeffreys Ledge

```
m0 = trapz(JeffreysLedge(2:45));      %Area under curve
m1 = trapz(JeffreysLedge(2:45)) * (JeffreysLedgeFreq(45)-...
    JeffreysLedgeFreq(2))^2;
m2 = trapz(JeffreysLedge(2:45)) * (JeffreysLedgeFreq(45)-...
    JeffreysLedgeFreq(2));
m01 = trapz(JeffreysLedge(2:45)) / (JeffreysLedgeFreq(45)-...
    JeffreysLedgeFreq(2));
Tm = sqrt(m0/m2);
T01 = m0/m1;
T10 = m01/m0;

%Significant Wave Height
Hm0 = sqrt(4.*(sqrt(m0)));
```

Correlation Calculation

```
CF = Hm / Hm0;
```

Display Results

```
disp('~~~~~~~Results from Spectral Plots~~~~~~~')
disp('Jeffreys Ledge')
Hm0

disp('Appledore Island')
Hm

disp('Correlation Factor')
CF
```

Wave Analysis Using Spectral Density Plots Appledore Island

```
m = trapz(Guu_dispAVG(5:60)); %Area under curve ft^2
Hm = sqrt(4.*(sqrt(m)));                    %Significant Wave Height
WVHT_Appledore_ft = Hm

correlation_factor = WVHT_Appledore_ft / WVHT_JeffreysLedge_ft
```

Contents


```
function [Guu_ensemble,f_ensemble] = section_data(data,rate,num_section);
```

Section the data and ensemble average

David W. Fredriksson Fall 2001 - OE810

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Sectioning the Data

```
n = length(data);
L = n/num_section;  %length of each section


j =1;
k = 1;
for i=1:L:n
   zac_set(j,:)=data(1,i:j*L);
   k = 1;
   j = j+1;
end

size(zac_set);

%for i =1:(num_section+(num_section-1))
%   mean_set = mean(zac_set(i))
%   zac_set(i) = zac_set(i)-mean_set;
%end
%clear i

%zac_set(1,:)
zac_set = zac_set;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
Input argument "data" is undefined.

Error in ==> section_data at 9
n = length(data);
```

Change over to frequency domain for section and

Ensemble average

```
for i = 1:(num_section)
   [Guu_set(i,:),fset] = Guu_calc(zac_set(i,:),rate);
end

Guu_set;
Guu_ensemble = mean(Guu_set);
f_ensemble = fset;
```

Contents


```
function L = dispersion(T,h);
```

Solve the wave dispersion relation

function L = disp(T,h); T = period, h = depth

David W. Fredriksson 12/14/00

Converted from c-code dated 2/26/92

```
g = 9.81;
error = 0.01;

i    = 1;
lo    = (g*T^2)/(2*pi);
l     = lo;
x     = (2*pi*h)/l;
tan_h  = tanh(x);
a    = (2*pi*h)/(l*l);
b     = cosh(x);
c    = 1/(b*b);
f_prime = (l/lo) + (a*c);
f    = (l/lo) - tan_h;

while (abs(f)>error)
   x    = (2*pi*h)/l;
   tan_h = tanh(x);
   a    = (2*pi*h)/(l*l);
 b     = cosh(x);
   c    = 1/(b*b);
   f    = (l/lo) - tan_h;
   f_prime = (l/lo) + (a*c);
   i = i+1;
   l = l - f/f_prime;
end

L = l;
```

Contents


```
function [kp] = k_factor(k,z,h)
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

This function calculates the pressure response

factor when measuring waves with a pressure sensor

D.W. Fredriksson Fall 2001 for OE810

kp is the pressure response factor

k is the wave number

z is the depth of the instrument

h is the depth at the site

```
for i = 1:length(k)
   kp(i) = (cosh(k(i)*(z+h)))/cosh(k(i)*h);
end
```

Contents


```
function [Guu,f] = Guu_calc(data,rate)
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

This function calculates the fft

function [Guu,f] = Guu_calc(data,rate)

```
% Removes the linear trend or mean value.

t2 = detrend(data);
%n2 = length(data);
n2 = max(size(data));
%n2= 512;
%n2= 1024;
%n2 = 4096;
%n2 = 8192;
%n2=16384;

%w = blackman(n2);
%t2 = t2.*w;


% Take the FFT to identify discrete frequency components.

y2 = fft(t2,n2);

% The Power spectral density, a measurement of the energy at
% various frequencies.

Guu = 2*y2.* conj(y2)/(rate*n2);%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Formation of the frequency axis using "rate" Hz (sampling rate)

f = rate*(1:n2)/n2;
%f2= 1/f2;

b1 = round(length(Guu)/2);
b2 = round(length(f)/2);

Guu = Guu(1:b1);
f = f(1:b2);

%box = 50;
%j = 1;
%i = (1:box:450);
%for k = 1:450;
%    f(j) = mean(f(k:k+box));
%    Guu(j) = mean(Guu(k:k+box));
%    j = j + 1;
%     k = k + 1;
%end
%clear i
```

Appendix K: Matlab Wind and Wave Direction Processing Code

```
% Code to correlate wind and wave directions
% on December 2 and 3, 2012
% Wind from NOAA NBDC IOSN3, Wave from NOAA NBDC 44098
% Paul Madea
% April 25, 2012
close all; clear all; clc;

dec=xlsread('wind2012.xlsx',6);
d3wind=dec(:,1:2);
d3wave=dec(:,3:4);
d2wind=dec(:,5:6);
d2wave=dec(:,7:8);

fig=1;
fig=figure(fig);
plot(d2wind(:,1),d2wind(:,2),'r')
hold on
plot(d3wave(:,1),d3wave(:,2),'b')
title({'Wind vs Wave Direction';'December 2, 2012'})
xlabel('hours (0-24)')
ylabel('Wind Direction (degrees)')
legend('Wind Dec 2','Wave Dec 2','location','southeast')
saveas(fig,'Dec2_WindvsWave.jpg');

fig=fig+1;
fig=figure(fig);
plot(d3wind(:,1),d3wind(:,2),'r')
hold on
plot(d3wave(:,1),d3wave(:,2),'-b')
title({'Wind vs Wave Direction';'December 3, 2012'})
xlabel('hours (0-24)')
ylabel('Wind Direction (degrees)')
legend('Wind Dec 3','Wave Dec 3','location','southeast')
saveas(fig,'Dec3_WindvsWave.jpg');

function WaveDirections
% Code to delineate wave direction
% David Kurtz & Paul Madea
% Wave Data from Jeffreys Ledge buoy 44098
% Wind Data from Duck Island buoy IOSN3
% 2009, 2010, 2011, 2012

% Initializing
clc; close all; clear all
months=1:12;
m=24;
a=0;
b=360;
h=(b-a)/m;
degrees = [h:h:b];

% WAVE 2009-2012
wa9=xlsread('wave2009.xlsx');
```

```
wa10=xlsread('wave2009.xlsx');
wa11=xlsread('wave2011.xlsx');
wa12=xlsread('wave2012.xlsx');
wave9 = [wa9(:,2),wa9(:,9)];
wave10 = [wa10(:,2),wa10(:,9)];
wave11 = [wa11(:,2),wa11(:,9)];
wave12 = [wa12(:,2),wa12(:,9)];
WAVE =
stats(m,h,wave9)+stats(m,h,wave10)+stats(m,h,wave11)+stats(m,h,wave12);
meanwavemo = common(h,WAVE);
meanwavedir = commonDIR(WAVE);

% WIND 2009-2012
wi9=xlsread('wind2009.xlsx');
wi10=xlsread('wind2010.xlsx');
wi11=xlsread('wind2011.xlsx');
wi12=xlsread('wind2012.xlsx');
wind9 = [wi9(:,2),wi9(:,6)];
wind10 = [wi10(:,2),wi10(:,6)];
wind11 = [wi11(:,2),wi11(:,6)];
wind12 = [wi12(:,2),wi12(:,6)];
WIND =
stats(m,h,wind9)+stats(m,h,wind10)+stats(m,h,wind11)+stats(m,h,wind12);
meanwindmo = common(h,WIND);
meanwinddir = commonDIR(WIND);

% PLOTTING
fig=1;
H1 = figure(fig);
plot(months,meanwavemo,'-.',months,meanwindmo)
axis([0 13 0 360])
legend('Wave','Wind','location','north')
xlabel('Months')
ylabel('Wind Direction [deg]')
title({'Direction vs. Months (2009-2012)';'NOAA Buoys IOSN3 & 44098'})
% saveas(H1,'dir_month.jpg');

fig=fig+1;
H2 = figure(fig);
plot(degrees,meanwavedir,'-.',degrees,meanwinddir)
legend('Wave','Wind','location','north')
xlabel('Direction [deg]')
ylabel('Occurrences')
title({'Occurrences of Directions (2009-2012)';' NOAA Buoys IOSN3 &
44098'})
% saveas(H2,'Occurrence_dir.jpg')

fig=fig+1;
H3 = figure(fig);
bar3(WAVE)
xlabel(['Wave Direction (',num2str(h),'^o Increments)'])
ylabel('Months')
zlabel('Occurances')
title({'Wave Direction and Months (2009-2012)';'NOAA Buoy 44098'})
% saveas(H3,'WAVE_dir_month.jpg')
```

```
fig=fig+1;
H4 = figure(fig);
bar3(WIND)
xlabel(['Wind Direction (',num2str(h),'^o Increments)'])
ylabel('Months')
zlabel('Occurances')
title({'Wind Direction and Months (2009-2012)';'NOAA Buoy IOSN3'})
% saveas(H4,'WIND_dir_month.jpg')

    function matrix = stats(m,h,data)
        matrix = zeros(12,m);
        for j=1:12
            for i = 1:length(data)
                if data(i,1) == j
                    for dir = 1:m
                        if data(i,2) >= h*(dir-1) && data(i,2) < h*dir
                            matrix(j,dir) = matrix(j,dir) + 1;
                        end
                    end
                end
            end
        end
    end
    function B = common(h,MATRIX)
        [row,col]=size(MATRIX);
        B = zeros(row,1);
        for i = 1:row
            [occurrences,B(i)] = max(MATRIX(i,:));
        end
        B=h*B;
    end
    function BB = commonDIR(MATRIX)
        [row,col]=size(MATRIX);
        BB = zeros(col,1);
        for i = 1:col
            BB(i) = max(MATRIX(:,i));
        end
    end
end
```