

PNNL-38730

# Harvesting Subsea Water Motion to Provide Clean Electrical Power

December 2025

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U.S. DEPARTMENT  
of **ENERGY**

Prepared for the U.S. Department of Energy  
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Pacific Northwest National Laboratory  
Richland, Washington 99354

# **Post Access Report**

**Harvesting Subsea Water Motion to Provide Clean Electrical Power**

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**Facility: Pacific Northwest National Laboratory (RFTS)**

**Facility point of contact: Ruth Branch**

**Date: December 15th, 2025**

## EXECUTIVE SUMMARY

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This TEAMER project had three main objectives related to characterizing the performance of a vortex-induced vibration (VIV) marine energy harvesting device called the Whatever Input To Torsion (WITT). The first was to characterize the motion of the WITT device as it vibrates on top of a pipe in a natural tidal flow. The second was to measure how much electricity the WITT device generates when it is deployed on top of a pipe that is secured to the seabed with a lander. The third objective was to measure how much electricity the WITT device generates in the same configuration but with a longer pipe. This TEAMER project succeeded in satisfying the first objective by measuring the motion of the WITT device with an inertial measurement unit (IMU) mounted in the WITT housing. The motion was described by examining changes in the acceleration, pitch, roll, and yaw, and displacement. The frequency of the motion was characterized using spectral analysis. The TEAMER project succeeded in reaching the second objective by measuring the power produced by the WITT. It is reported here as the average and maximum power in hourly intervals. WITT Energy decided to not have us pursue the third objective of testing a longer pipe because the first test was unexpectedly successful at having the system vibrate at the target frequency. A longer pipe would have resulted in a decreased frequency and therefore not have been a useful test. Based on these findings, the decision was made to keep the same pipe length for both tests and improve on other aspects of the test structure that had failed during the first test. The key finding of this TEAMER project is that the WITT is capable of generating electricity in moderate flow speeds when it is in a housing that is attached to a 2.5 m pipe and secured to the seabed by a lander. This report contains the first power values for a VIV instrument that generates electricity from a pendulum swinging at the top of a long pipe. The experiment demonstrated that the vibration frequency of the device varied with the tidal current speed, which changed throughout a given tidal cycle. This meant that the desired peak frequency was not sustained for more than one hour. The success of this TEAMER test provides evidence that continued research in the area of electricity generation from VIV holds promise as a source of marine energy for offshore applications. Future tests should focus on refining the pipe length equations and improving the power take off system of the WITT power electronics. In addition, experiments aimed at expanded testing and evaluation (e.g. longer than one month) are needed to measure the power production at higher tidal current speeds and test the system's durability.

## 1 INTRODUCTION TO THE PROJECT

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WITT Energy has developed a unique pendulum transmission system that allows motion along and around all three axes (Wickett *et al.*, 2019). It is a patented system that can produce in-situ power and can scale to larger sizes or be tuned for a range of environmental conditions. The goal of this project was to test the pendulum system as a subsea electricity generation device that harvests energy from vibrations caused by vortex shedding in a current. The WITT pendulum system was contained in a watertight housing and mounted on top of a long polyvinyl chloride (PVC) pipe that was secured to the seafloor with a lander (Fig. 1). The WITT/pipe/lander system was deployed in a tidal channel that experiences a range of tidal current speeds up to 2.8 m/s (Branch *et al.*, 2022a). As the tidal current passed the WITT/pipe/lander system, vortices were shed and the pipe and WITT vibrated. The vibrations caused the WITT pendulums to move and generate electricity. The tidal current speeds were monitored during the test.

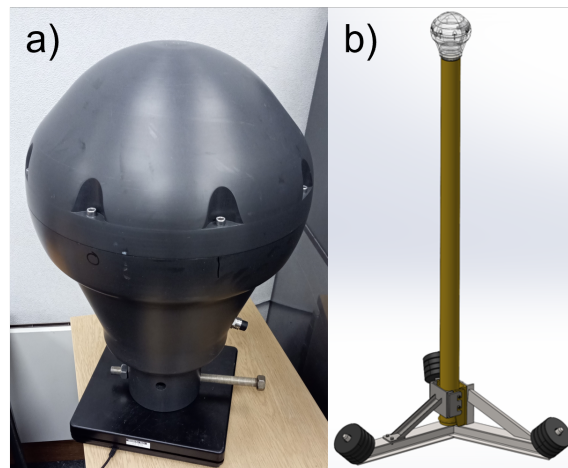


Figure 1: a) The WITT enclosure sitting on a scale b) diagram of the WITT on top of the pipe and lander. (From Branch *et al.* (2022a))

## 2 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS

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### 2.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED

WITT Energy

- Provide test article
- Troubleshoot instrument difficulties
- Assist in site selection
- Evaluate results and lead generation of the post access test report

## 2.2 NETWORK FACILITY RESPONSIBILITIES AND TASKS PERFORMED

- Provide numerical model output to WITT for test site selection
- Develop the test plan
- Cut PVC pipe
- Conduct testing
- Setup/breakdown
- Preprocess data
- Evaluate results

## 3 PROJECT OBJECTIVES

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The overall objective of this project was to test the WITT pendulum's electricity generation capabilities in a natural subsea environment where movement is caused by vortex shedding on a cylinder in a tidal current. This objective was reached by deploying the WITT device on top of a PVC pipe in the Sequim Bay channel. The specific objectives of the project were to:

- characterize the motion of the WITT device as it vibrated on top of a pipe in a natural tidal flow,
- measure how much electricity the WITT device generated over a range of flow velocities when it was deployed in a natural tidal channel on top of a pipe that was secured to the seabed with a lander,
- evaluate the effects of marine debris, sediment, and biofouling on the deployment with photos taken by the divers during the recovery to show if there were significant enough accumulations of marine debris, sediment, or biofouling on the lander or pipe to affect its motion
- compare the motion and electricity generation measured during these tests with previous tests and theory to forecast motion and electricity generation for other locations and currents.

The physical attributes investigated during this project were the current speeds in the Sequim Bay channel and the vibrational motion of the WITT on the end of a PVC pipe. PNNL supplied WITT Energy with numerical model output maps of the current velocities in the Sequim Bay channel to facilitate the choice of the test site. An initial micro-siting survey was conducted at the site chosen by the examination of the numerical model output. The micro-siting survey consisted of the deployment of an acoustic Doppler current profiler (ADCP) for two weeks to characterize the flow over a range of current speeds. The performance metric targeted by this TEAMER project was the amount of electricity produced at each current speed and how it was related to the motion of the WITT/pipe system.

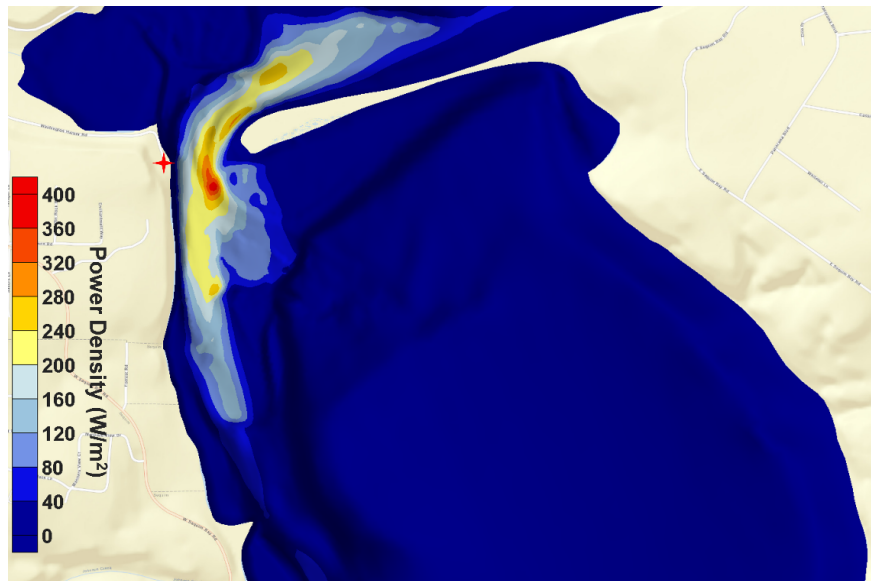


Figure 2: Modeled power density of the tidal currents in the channel near the PNNL-Sequim campus. The PNNL-Sequim location is shown as a red star at the mouth of Sequim Bay.

## 4 TEST FACILITY, EQUIPMENT, SOFTWARE, AND TECHNICAL EXPERTISE

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### PNNL Facilities

Testing occurred at and offshore of the PNNL-Sequim campus. The PNNL-Sequim facility is equipped with shoreline labs for equipment preparation and pre-deployment testing. PNNL-Sequim has a machine shop and staff available to cut the PVC pipe. PNNL-Sequim is located near the mouth of Sequim Bay where strong tidal currents occur. PNNL staff have modeled the tidal currents for the entire channel and the model output can be used for site selection (Fig. 2). The tidal currents have been measured in the channel several times with a PNNL owned acoustic Doppler current profiler (ADCP). The currents were highest on flood tide and reached a maximum of 2.82 m/s during the strongest flood tide (Fig. 3).

### PNNL Vessels and Dive Team

PNNL owns and operates two boats that are equipped with the necessary lifting capabilities and deck space to deploy the instruments (Fig. 4). PNNL MCRL has several certified divers and underwater radios for the deployment and recovery process.

## 5 TEST OR ANALYSIS ARTICLE DESCRIPTION

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The WITT pendulum system is a marine renewable energy (MRE) device that generates electricity from either wave or current induced motion. The sealed unit has two pendulums connected to a shaft that turns

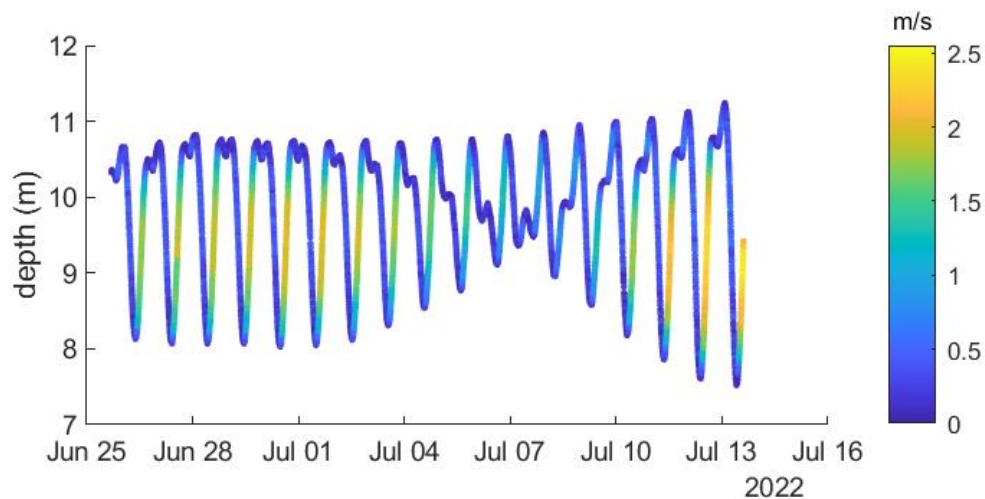


Figure 3: Tidal currents measured in the Sequim Bay channel by PNNL staff with a Nortek Eco ADCP.



Figure 4: PNNL boats that can be used for deployment of equipment in the tidal channel.

in one direction (Wickett et al., 2019). The output shaft drives a brushless motor and the generated electromotive force drives current to a battery charging circuit which contains a three-phase rectifier, DC/DC buck-boost converter, and battery charge controller. This circuit regulates input voltage of high impedance supplies or poorly regulated sources to optimize the converter's current to charge a battery. The charge controller can be programmed to operate in defined voltage regions for constant current, constant voltage, and float charging for multiple battery chemistries. As of now, the method of power conversion maximizes source current at the defined regulated input voltage. Input voltage and current generated from the motor along with its speed in RPMs is recorded to a data acquisition system.

The WITT is a unique patented device because it captures energy from six degrees of motion instead of just using up and down or side to side motion. The pendulums rotate around three axes and translate along three axes. For the test case proposed here, currents in a tidal channel adjacent to PNNL-Sequim will be used to generate motion and activate the WITT to harvest energy. When currents are used to generate motion, the WITT is mounted on top of a pipe and secured to the seabed with a three-legged lander. Vortices are shed as the current flows past the pipe. The vortices are shed in such a manner that they cause vibrations, and the vibrations are the movement that allows the WITT to harvest energy that can be stored. Energy harvested by the WITT is stored in an underwater rechargeable battery that can be connected to oceanographic instruments such as hydrophones.

The WITT configuration can be optimized for different site depths, current velocities, and instrument power requirements by changing the size of the WITT and the diameter and lengths of the pipe. Calculations are carried out pre-deployment to determine the WITT configuration for each site. The prototype tested in this project has a housing diameter of 0.33 m. The pipe diameter is 0.14 m and it is made of schedule 40 PVC.

The testing of the WITT as a subsea electricity generation device will further the field of current energy converters generating electricity from vortex induced vibration. Vortex induced vibration is an important field in MRE because electricity can be generated at current speeds that are lower than required by turbines (Branch et al., 2022b).

## **6 WORK PLAN**

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The work plan for this project consisted of site selection, instrument testing, and data management and processing. The site was chosen by first examining numerical model output and then measuring the tidal currents at the chosen site before deploying the instrument. The instrument testing consisted of two tests of the current energy converter. All the collected data was archived in a format that is useful for comparing the WITT motion to the electricity produced over the range of current speeds. The data processing is described in detail in section 6.6.

### **6.1 EXPERIMENTAL SETUP, DATA ACQUISITION SYSTEM, AND INSTRUMENTATION**

#### **Site Selection**

Numerical model output of the currents in the Sequim Bay channel were examined to choose a site that has the maximum velocity the WITT/pipe/lander system has been designed for. The maximum velocity



of the WITT/pipe/lander system is 1.92 m/s for a 3 m long pipe with a 350 kg lander. The maximum velocity was calculated based on an analysis of the drag forces and overturning moment. An ADCP was deployed to confirm the current speeds at the site are below the tolerance of the WITT/pipe/lander system. The ADCP deployment does not require divers. It was lowered from a boat and released a surface float at a pre-programmed date and time for recovery.

### **Field Testing**

The WITT pendulum system was mounted on top of a pipe that was secured to the seabed with a three-legged lander (Fig. 1). The WITT/pipe/lander system was deployed by a boat and divers during slack tide. The divers first assembled the lander and then secured the pipe with the WITT into the lander. The WITT/pipe/lander system remained in the field for at least two weeks to capture data over a full tidal cycle. The motion and electricity generation data from the WITT was recorded in a sealed data acquisition system that was secured on the seabed and connected by cable to the WITT.

PNNL owns and operates Nortek ADCPs that measures current speed and direction. An ADCP was configured to record water depth, current speed, and direction as it has on previous deployments (Fig. 3).

After the tidal cycle was complete, the WITT/pipe, data acquisition system, and ADCP were recovered by the divers. The data were examined to quantify the motion achieved over the range of current speeds and the electricity generated. The frequency of the motion was compared to the theoretical prediction to determine how well the theory was able to predict the motion. Improvements were made to the lander, WITT mounting, and ADCP measurement system before they were returned to the seabed for another full tidal cycle.

## **6.2 NUMERICAL MODEL DESCRIPTION**

Numerical model output were used to identify potential sites in the Sequim Bay channel. The Sequim Bay Operational Forecast System (SBOFS) was developed using the Finite Volume community Ocean Model (FVCOM) with an unstructured grid (*Chen et al.*, 2003). The model mesh contains 16,000 vertices and 31,000 triangular elements (Fig. 5). Ten uniform terrain-following sigma layers were used with open boundary conditions, sea surface boundary conditions, and river boundary conditions. Model outputs of water level, current speed, salinity, and temperature have been compared to data collected at the PNNL-Sequim dock. The model has been validated with water level and current speed data (*Wang*, 2022). The RMSE for both velocity and water level were less than 0.1 m/s and 0.1 m respectively.

## **6.3 TEST AND ANALYSIS MATRIX AND SCHEDULE**

### **Project Schedule**

Testing as specified in the above sections occurred over a period of a year following the planning and setup phase. The ADCP micro-siting survey occurred in June of 2024. The first VIV test occurred in September of 2024 and the second VIV test occurred in late February and early March of 2025.

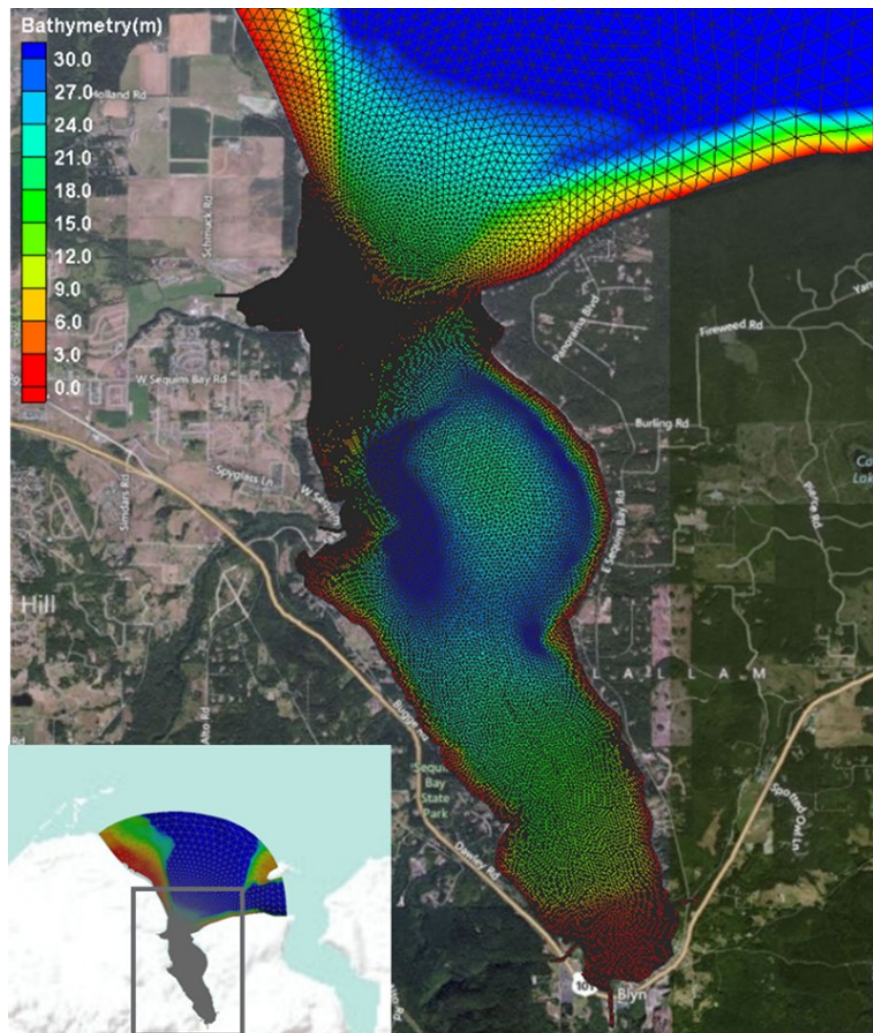


Figure 5: Sequim Bay model mesh showing the 16,000 vertices and 31,000 triangles. The mesh appears black where it has the highest resolution in the channel.

## 6.4 SAFETY

All work scope and funding was authorized by one or more responsible managers. All work activities conducted in laboratory or operations spaces were conducted under a project management office director approved electronic prep and risk (EPR) profile with the appropriate work planning and controls.

Hazards and risks associated with the work followed the requirements in hazard-specific work controls and were reviewed with the assistance of the PNNL Safety and Health representative, and/or PNNL subject matter experts (SMEs).

Standard controls to mitigate hazards were conducted in the following order:

- Elimination or substitution of hazards
- Enactment of engineered controls
- Performance of specified work practices and administrative controls
- Use of personal protective equipment

Determination of appropriate work controls relevant to the work performed are found in a PNNL Lab Assist document. A Lab Assist activity is a central document that includes work controls, applicable training, associated hazards, and approved lab spaces that all workers must review and acknowledge before performing work. All workers performing activities on this task were required to review hazards, mitigations, and engineering controls listed within the Lab Assist activity and completed trainings as appropriate prior to the onset of lab work.

## 6.5 Contingency Plans

There were risks associated with the work where issues could have prevented the researchers from completing the test objectives. The risks and mitigation/contingency are outlined in the table below:

| Risk                                                                                                             | Mitigation/Contingency                                                          |
|------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Weather conditions may prevent divers deploying or retrieving the unit on the planned dates with preferred tides | Request extension of performance period                                         |
| Unforeseen failure mode of apparatus (e.g., part corrosion causes leak)                                          | Consult with WITT Energy on a suitable repair or return unit and repeat testing |

Weather conditions, boat availability, and diver availability were issues during this TEAMER project and the CRADA was extended once. The main delay was due to the A-frame being broken on the boat that was needed to deploy the lander. The lander was deployed as soon as the boat was repaired and there was a suitable tide with good weather and available divers.

## 6.6 DATA MANAGEMENT, PROCESSING, AND ANALYSIS

### 6.6.1 DATA MANAGEMENT

- Deployment conditions and times were recorded in a field log. The log sheets were photographed and stored on MS OneDrive for backup and archival purposes.
- Current speed, water depth, ADCP tilt and associated timestamps recorded by the ADCP were stored on a PNNL computer and uploaded to MS OneDrive for backup and archival purposes.
- WITT housing motion, electricity generation, and associated timestamps recorded by the WITT DAQ were stored locally on a PNNL computer and uploaded to MS OneDrive in raw .csv format.
- The ADCP data and WITT motion data were uploaded to MHKDR.

### 6.6.2 DATA PROCESSING

#### ADCP Data

Two different ADCPs were used during the two tests. They both recorded the current speed and direction at multiple depths. They also recorded the timestamp, depth, temperature, and instrument tilt at the same times. The ADCPs were programmed to start at a chosen time. The Nortek Eco ADCP is sold in a format that only outputs current speeds at three depths but R. Branch manipulated the software to extract the data at more depths to give a more accurate view of the current profile. The second test used a Nortek Signature 1000 ADCP that automatically outputs current profile data in evenly spaced bins.

#### WITT Data

The WITT data acquisition system records the timestamp; acceleration in x, y, and z; gyro in x, y, and z; angle in x, y, and z; motor RPM, volts, and amps. The data acquisition began when the divers connected the underwater cable and stopped when the divers disconnected the cable. Ten minute averages were computed for some plotting and analysis purposes. The displacement of the WITT was calculated from the angle data. The motion in the x and y directions was calculated using the length of the pipe (L) and the angle of movement ( $\theta$ ).

$$m = L\sin(\theta) \quad (1)$$

The displacement was calculated with the approximation of two dimensional movement.

$$disp = \sqrt{m_x^2 + m_y^2} \quad (2)$$

**Time Alignment** The ADCP and WITT clocks were aligned and set prior to deployment.

### 6.6.3 DATA ANALYSIS

Ten minute averages of the WITT and ADCP data will be computed over the same time period for comparison purposes.

#### WITT Motion Analysis

The motion of the WITT on the pipe will be tracked and reported for the tests of the two pipe lengths over the range of current velocities tested. These results will assist future users of the WITT in their decisions of how to maximize the motion and therefore the power production given the current speeds at their locations. The WITT motion data (x, y, and z acceleration, gyro, and angle) will be plotted versus the current speed. The strongest tides will be examined with timeseries plots showing only twelve hours of data. Spectra will be calculated from ten minutes of displacement data and examined for their changes with current speed over the course of the tide. The peak and any secondary peak frequencies will be identified in the spectra. The peak frequency will be plotted as a timeseries for the test period along with the displacement and depth as functions of the current speed. The peak frequency will also be plotted versus the current speed and colored in one plot with the displacement and another plot with the voltage produced. These plots will enable us to determine which frequencies and current speeds resulted in the highest voltages.

The frequency of the vibration is controlled by the vortex shedding and the natural frequency of the pipe system. The vortex shedding frequency,  $f_s$ , is theoretically given by the Strouhal equation

$$f_s = 0.2 \frac{U}{d} \quad (3)$$

where  $U$  is the water current speed,  $d$  is the diameter of the pipe, and the Strouhal number is 0.2. This is a first order approach to understanding the shedding frequency that depends on assumptions such as a rigid structure and no shear. The natural frequency ( $f_n$ ) of the pipe system vibration is given by the equation for the first mode of transverse vibration of a fixed-free cantilever beam with 1-D deflection

$$f_n = \frac{k_n}{2\pi} \sqrt{EI/\rho AL^4} \quad (4)$$

where  $k_n$  is the mode constant,  $E$  is Young's modulus,  $I$  is the moment of inertia,  $\rho$  is the density,  $A$  is the cross-sectional area, and  $L$  is the pipe length. The first mode was calculated with  $k_n = 3.52$  (Rao and Yap, 1995). The moment of inertia was calculated assuming a hollow pipe with an inner diameter of 0.135 m and an outer diameter of 0.14. Added mass was not accounted for.

### WITT Power Production

The WITT power production was analyzed by examining the voltage and current produced as a function of the WITT movement and current speed. The power was calculated as the product of the voltage (V) times the electrical current (A). The plots of power versus current speed will inform future users of the WITT about which current speeds the WITT is capable of producing power at and help them choose their test site accordingly.

### IEC-200

The -200 standard, per its scope, is a systematic methodology for evaluating the power performance of tidal current energy converters (TECs) that produce electricity for utility scale and localized grids. The purpose of this test was to characterize how the converter, still in a prototype phase and to be tested under different hardware configurations, performs in a natural current environment. That is, the purpose of the testing was not to hold the converter at controlled setpoints for maximum energy harvesting and then at a rated power over many tidal cycles, as prescribed in the -200 specification; this testing represents work needed to establish operating points and parameters that may lead to the definition of a rated power and relative performance of different device configurations. For the purpose of reducing power capture to a

non-dimensional efficiency, the device area was defined as the combined swept area of the WITT enclosure and vertical pole, as these are the moving elements of the system. As the extent of motion during VIV will not be known a priori or consistent throughout the deployment, post-test analysis was conducted to obtain an average or representative value for swept area. Similar to the definition of area for traditional TECs, the area of the support frame will not be included in this calculation. Non-dimensional efficiency may then be defined as the electrical power produced by the system divided by the available power in the flow through an area equal to the projected area of the system. Inflow current speed was measured by a Nortek ADCP. Performance (i.e., efficiency) was reported as 10-minute averages.

## 7 PROJECT OUTCOMES

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### 7.1 RESULTS

#### 7.1.1 Modeling for Site Selection

The Sequim Bay model was used to identify a potential test site. Thirty-one potential sites were examined in the model output. They are shown as yellow dots on Figure 5 along with the location of a previous turbine test conducted by the University of Washington (*Bassett et al.*, 2025). Probability of exceedance curves and histograms of the current speeds were made for each site (not shown in this report) and the sites were evaluated based on their power density, depth, and angle difference between ebb and flood tidal flows. The angle difference between ebb and flood tidal flows was defined as the angle difference where an ideal asymmetry is 180 degrees.



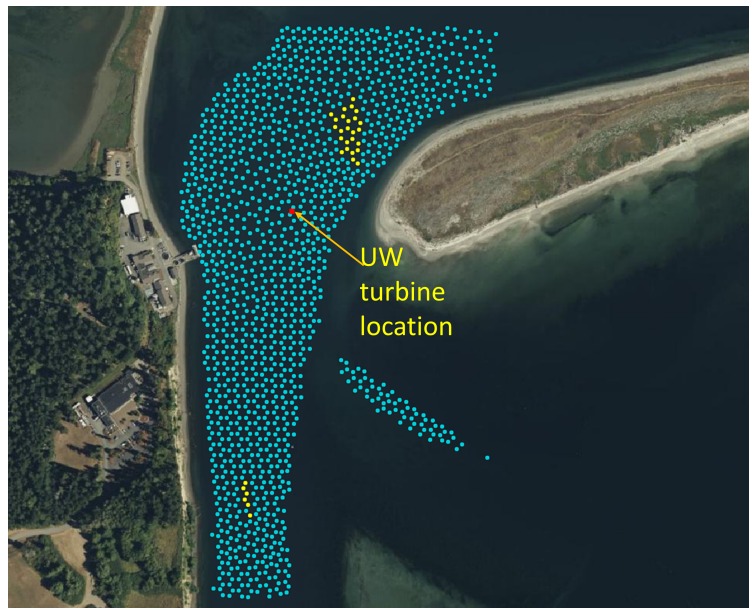


Figure 6: Sequim Bay model grid with the UW turbine site shown in red and potential tests sites shown as yellow.

A potential site was chosen from the southern grouping of points (Fig. 6). The angle difference between the ebb and flood tide directions at the potential site was not very different from the 2022 value (*Branch et al. (2022a)*). It was 0.21 degrees for the potential site and it had been 0.20 degrees at the 2022 site (Fig.7).

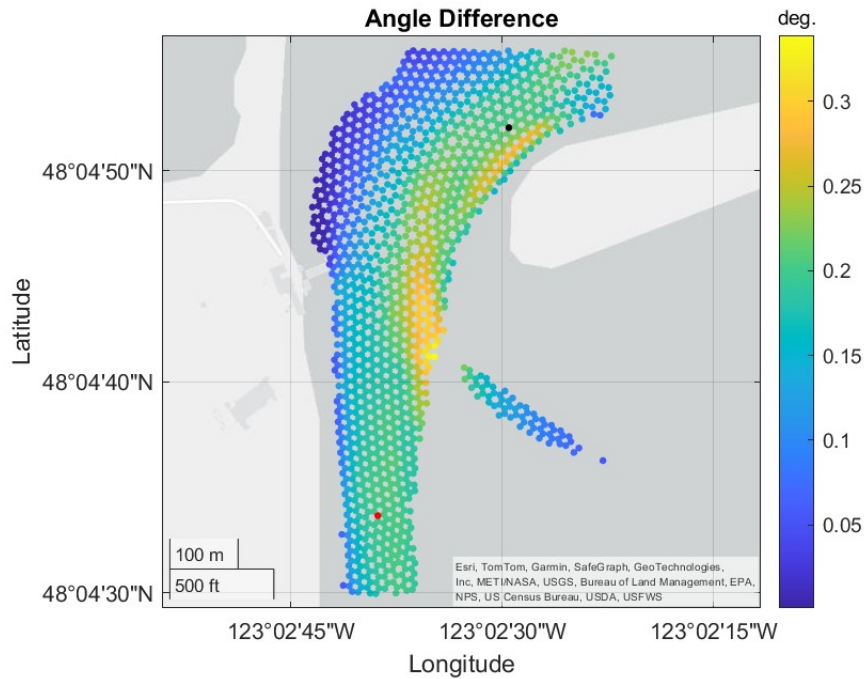


Figure 7: Sequim Bay model values for the angle difference. The black dot shows the location of the previous test (*Branch et al., 2022a*) and the red dot shows the potential site chosen for this project.

The histograms of the current speeds and probability of exceedance curves for the 2022 and potential site are shown in Figure 8. The probability that the current speed would be above 1 m/s at the 2022 site was 12%, but it increased slightly to 15% at the proposed 2024 site even though the maximum speeds were lower at that site.

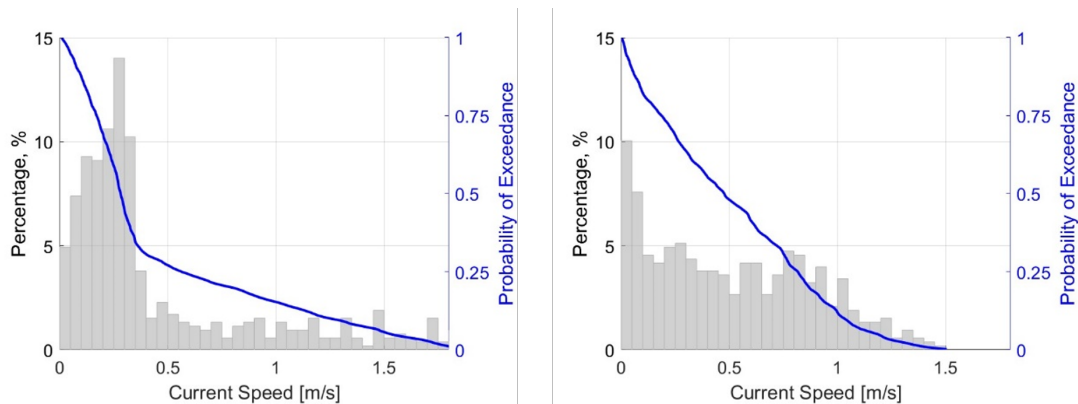


Figure 8: Histograms and probability of exceedance curves from the Sequim Bay model values for the 2022 site (left) and potential site (right)

A timeseries of the current speeds at the potential site is shown in Figure 9. The maximum modeled current



speed at the site during the model run time period was 1.51 m/s.

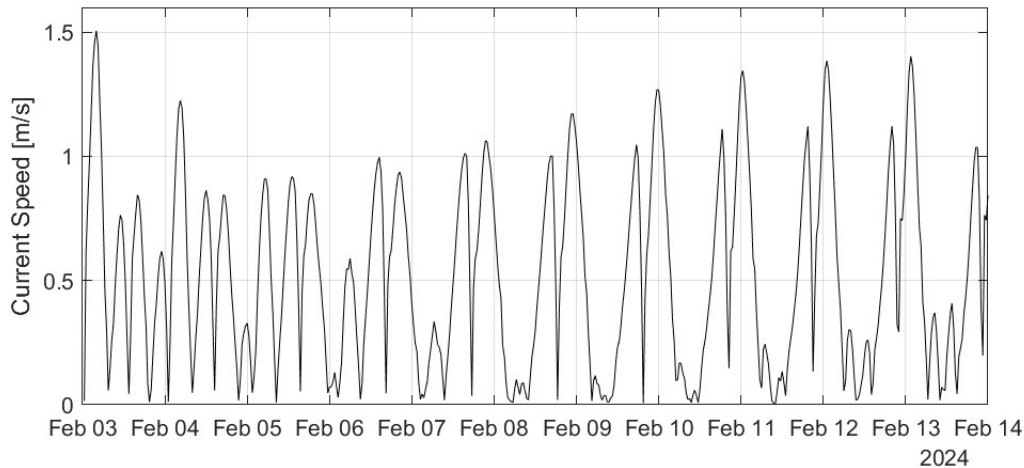


Figure 9: Timeseries of the modeled current speed at the potential test site.

### 7.1.2 Micro-siting Survey

A micro-siting survey was conducted at the potential test site by deploying a Nortek Eco ADCP. The Nortek Eco base configuration is an ADCP that floats above weights on the seafloor (Fig. 10).

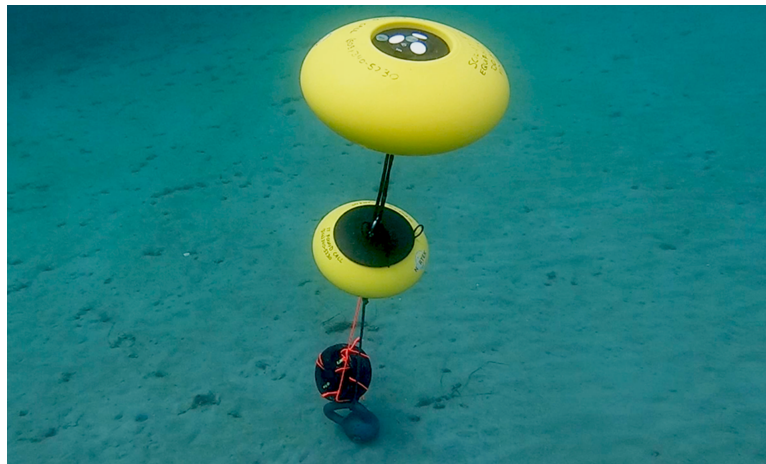


Figure 10: Subsurface buoy configuration that the Nortek Eco ADCP was deployed in at the proposed test site.

The Eco was deployed at the proposed test site (48.076 N, -123.0441 W) on 6/1/24. It was programmed to surface on 6/17/24. It did not surface at the correct time in the correct location. The recovery team saw the buoy several hundred meters away and recovered it. It had been dropped with two 45 lb. weights. Ninety pounds of anchor weight was not sufficient to hold it in the correct location.

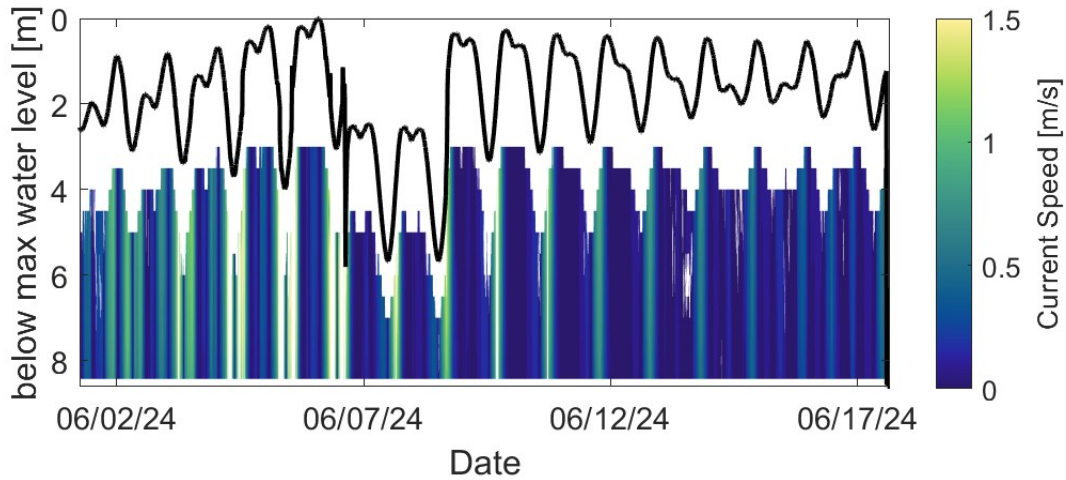


Figure 11: Nortek Eco ADCP data from the survey to assess the current speeds at the proposed test site.

The data from the survey show that the ADCP began to move during ebb tide on 6/4 (Fig. 11). It moved slightly on the flood and ebb tides of 6/5/24 and then moved significantly on the flood tide of 6/6/24. The current speed data after 6/4/24 are not at the test site and are not useful in characterizing the conditions at the site.

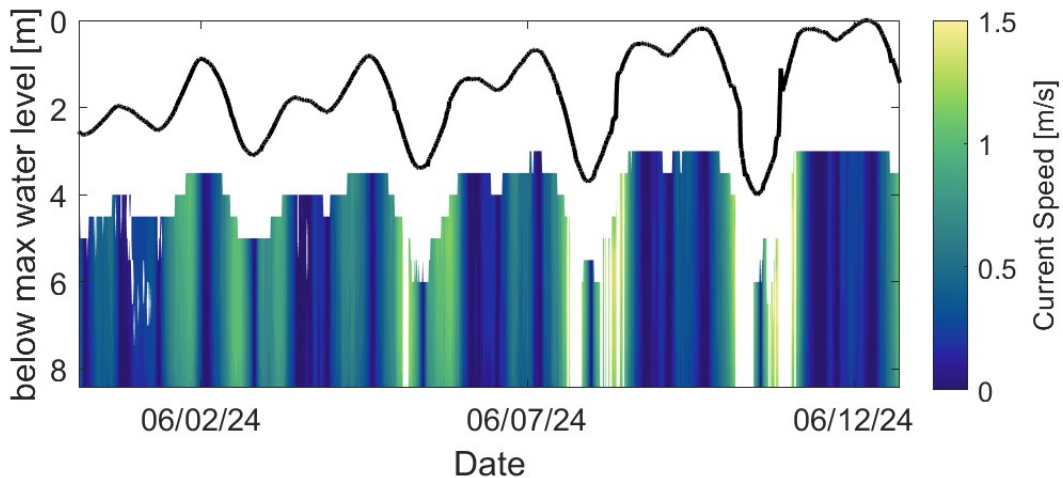


Figure 12: Nortek Eco ADCP data from the survey to assess the current speeds at the proposed test site.

The maximum speed that was measured at the test site was 1.33 m/s. The current speed was lower near the seabed than at the surface due to boundary layer effects. The white vertical lines in the current data shown in Fig. 12 indicate that the Eco could not measure the highest current speeds at the site. The Eco stops recording current speeds when it tilts more than a pre-programmed threshold on the line that it floats on above the weights. This dataset indicates that the highest current speed it can measure in this configuration is 1.33 m/s. Although we did not measure the actual maximum current speed at the potential test site, the

timeseries that we measured indicated it would not be significantly higher than 1.33 m/s because of the sinusoidal behavior of tidal current speeds (Fig. 13). We decided to proceed with the test at this location.

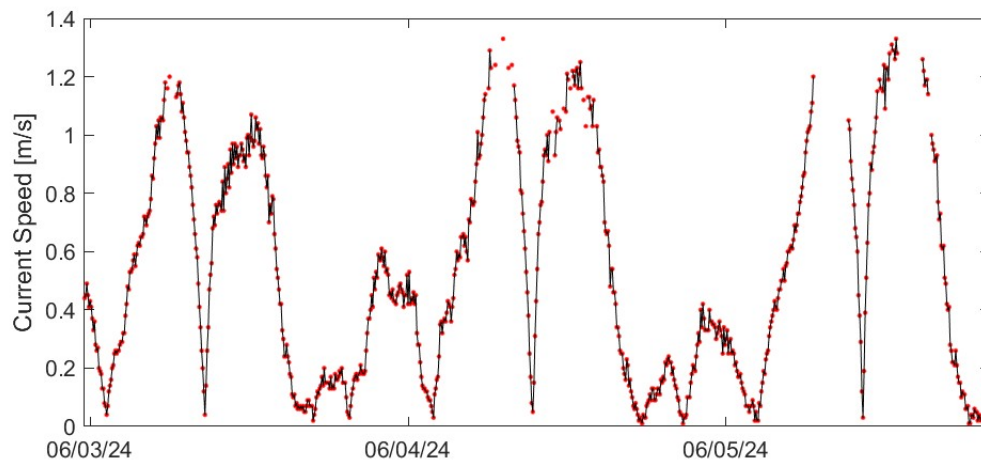


Figure 13: Timeseries of Nortek Eco ADCP data that shows the gaps in the data at higher current speeds.

### 7.1.3 Pipe Length Calculations

The natural frequency of a 0.14 m pendulum is 1.3 Hz but the WITT transmission system has been found to be the most efficient when the vibration frequency is 1.2 Hz. Previous research had used OrcaFlex to model the WITT/pipe system and had determined the pipe should be 3.5 meters long to cause vibrations at 1.2 Hz at the pendulums. When the WITT/pipe system was deployed it primarily vibrated at 0.65 Hz (Fig. 14). One goal of this work was to choose a different pipe length to force the pipe to vibrate closer to 1.2 Hz. Calculations based on equation 4 determined that a 2.5 m pipe should be used to achieve vibrations at 1.2 Hz (Fig. 14).

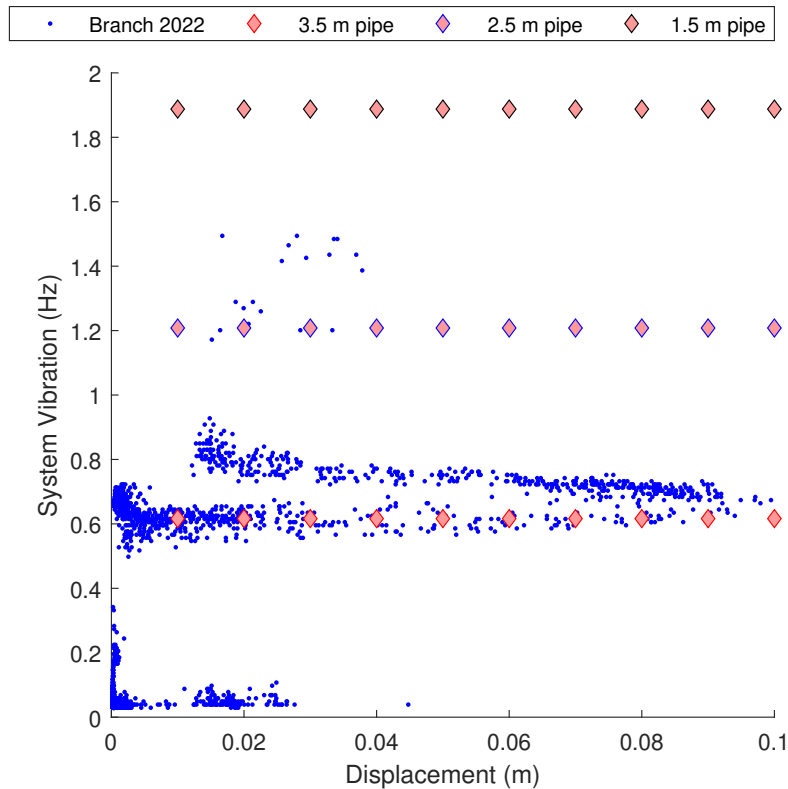


Figure 14: Response of the 2022 WITT deployment of a 3.5 m pipe (blue dots) and the theoretical response (1-D in deflection and 1st mode) of an undamped-seawater-immersed cantilever cylinder.

#### 7.1.4 Test 1

The first test of the WITT VIV system began on 9/10/24 as the lander and instruments were placed on the seabed. The instruments were set to record data for two weeks, but the instruments were not recovered until 10/8/24 because of diver and tide schedules. The test used a pipe length of 2.5 m as measured from the top of the lander to the top of the pipe. Four instruments and two data acquisition housings were attached to the lander (Fig. 15). The instruments were an Nortek Vector ADV, Nortek Eco ADCP head, IMU, and Go Pro. The data housings were for the ADV data and the WITT data.



Figure 15: Test article on land prior to the first deployment.

The lander and instruments were put in the water 9/9/24. Photos taken by the divers are shown in Figures 16 and 17.



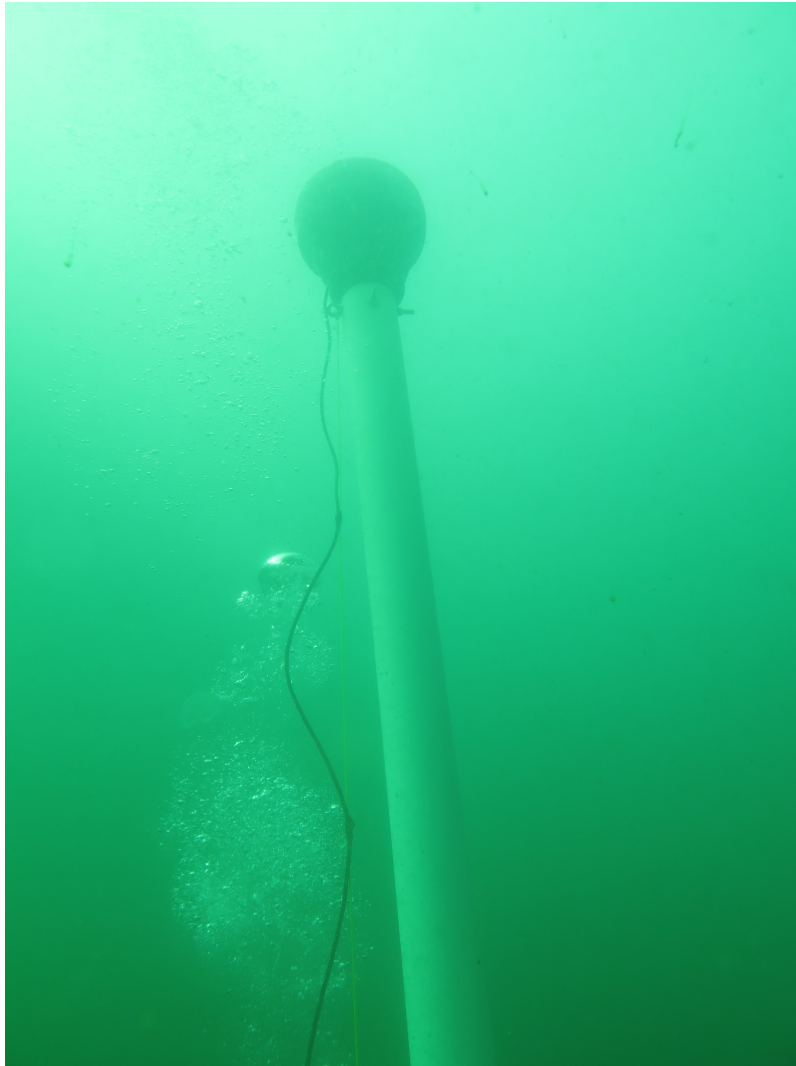


Figure 16: WITT on the end of the pipe at the start of Test 1.

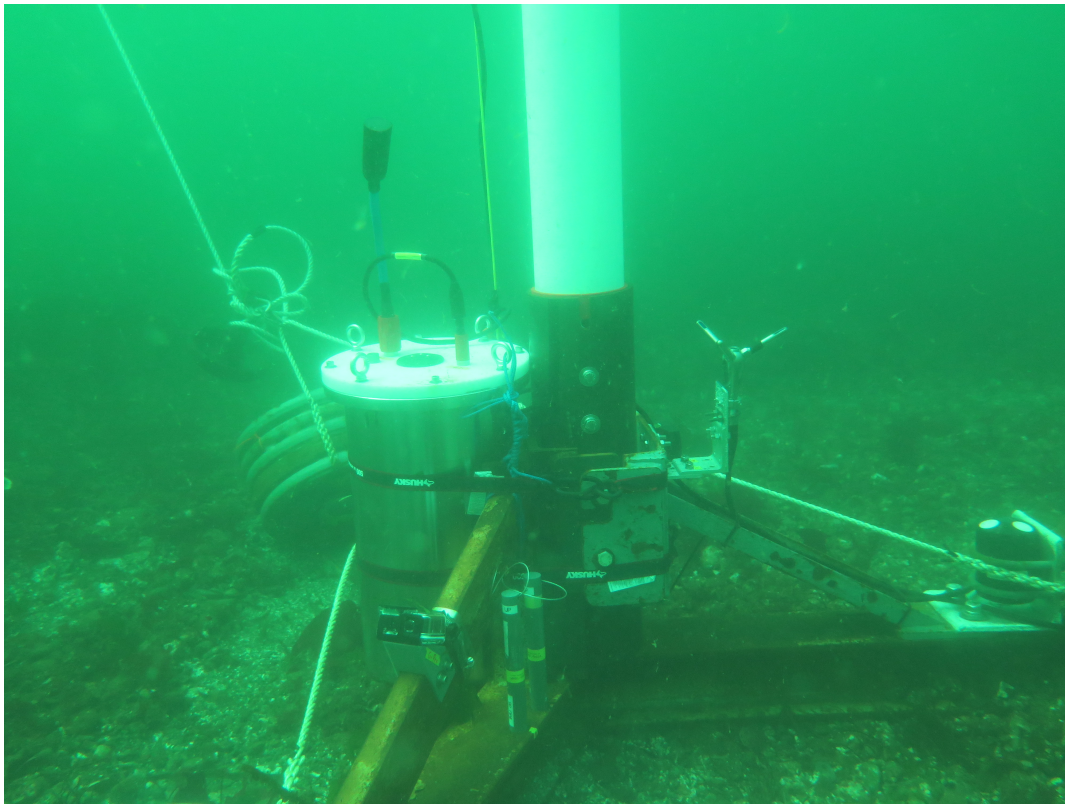


Figure 17: Instruments on the lander at the start of Test 1. Flood tide flow was from right to left in the photo.

NOAA predicted that the tidal range and therefore the current speeds would increase and peak on 9/15 and 9/24 (Fig. 18).

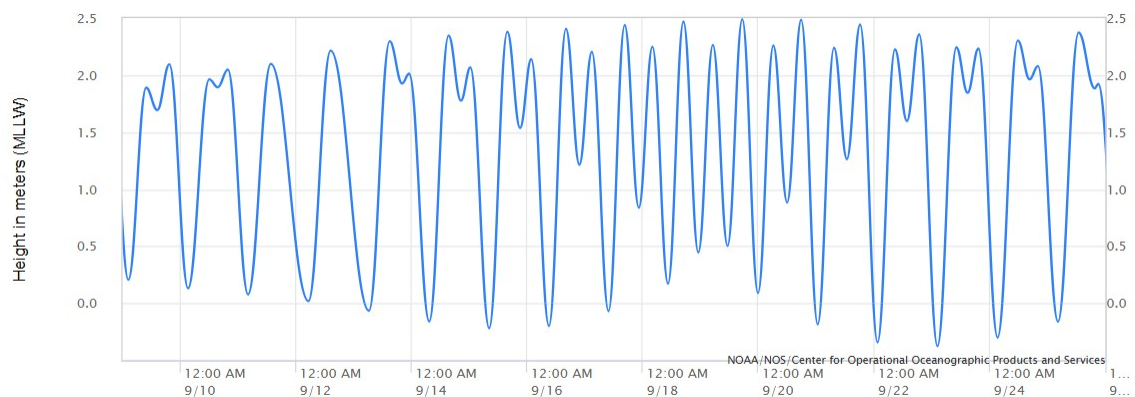


Figure 18: NOAA predicted water levels at nearby site 9444555.

On 10/8/24 the pipe with the WITT, the WITT data housing, ADV and its housing, ADCP, IMU, and Go Pro



were recovered from the seafloor. The lander and weights were left on the seafloor for a future test. The Go Pro was borrowed from another project and could not be programmed to delay the start of the recording. It therefore did not collect video during the strongest current speeds, but the video it did collect is very helpful for communication purposes. It shows a crab crawling on the unit and a fish swimming near the pipe. It also recorded sound and therefore documents how quiet the WITT VIV system is. The Go Pro video showed kelp accumulation on the pipe and lander (Fig. 19).



Figure 19: Snapshot from the Go Pro video of the test article during Test 1.

The divers noticed a strange smell when they recovered the instruments and did not know which instrument it was coming from. The ADCP was not too covered with biofouling (Fig. 20), but upon further inspection it was noted that it had flooded and the data were not recoverable.



Figure 20: Nortek Eco after Test 1.

The ADV was therefore the only source of current speed data. The ADV only measures current speed at a single point instead of giving a vertical profile of water speeds in the water column. The maximum current speed measured by the ADV was 1.1 m/s (Fig. 21), but this represents a burst of turbulence rather than a sustained current speed that is interacting with the pipe. It is also the speed at the depth of the ADV head which is close to the seabed and not a good representation of the current speed at the height of the WITT. The current speed at the height of the WITT would be higher because the boundary layer reduces the current speed near the seabed. The data were averaged in 10-minute subsections and shown in Figure 21. The maximum 10-minute average of the current speeds was 1.10 m/s. The ADV was only a backup instrument and therefore not the originally intended measure of current speed. It was mounted close enough to the pipe that the ebb tide data may have been corrupted as the ADV was in the wake of the pipe (Fig. 17).

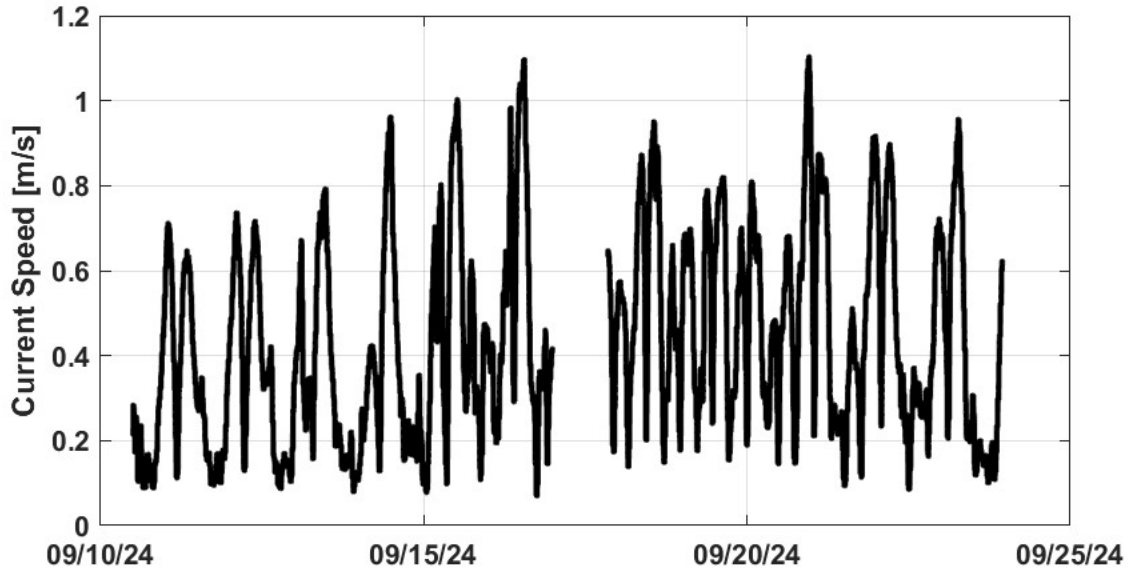


Figure 21: ADV current speed data from Test 1. The data gap on 9/17 is from partial file corruption.

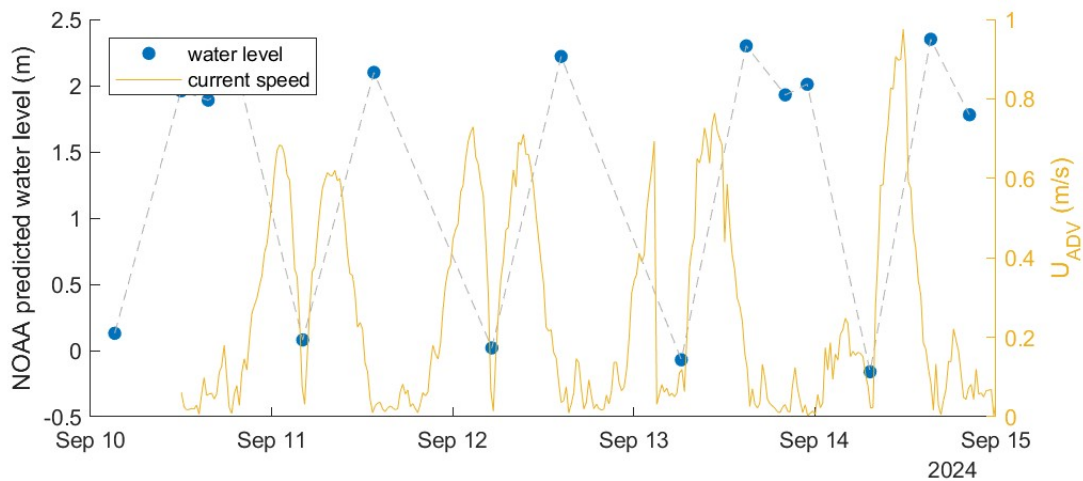


Figure 22: Timeseries of the NOAA predicted high and low tide water levels and current speed as measured by the ADV

The current speeds measured by the ADV were highest near the end of ebb tide and in the middle of flood tide (Fig. 22).

The WITT pendulum/electronics system connected the gear box to a generator, rectifier, DC/DC converter, and lastly the battery (Fig. 23). The power take off system managed the energy harvesting by controlling the voltage and current cut-ins. In Test 1, the voltage cut-in was set to high (8 V) and the current was set to

high (1.25 A). The power produced by the WITT was measured before and after the DC/DC converter.

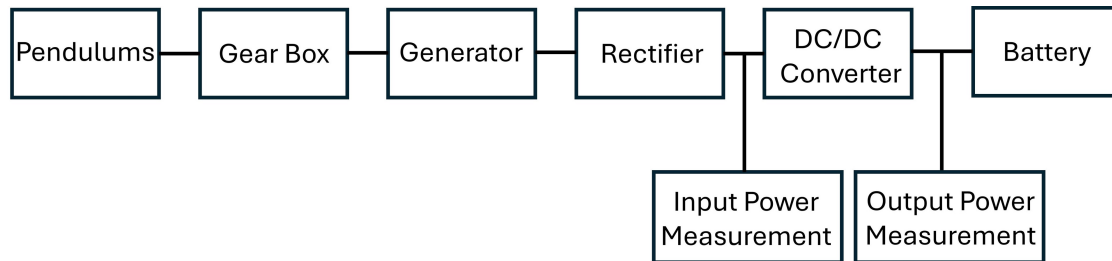


Figure 23: Block diagram of the WITT power electronics.

The WITT generated power from 9/10/24 until 9/13/24. It stopped generating power on 9/13/24 because a wire snapped. The maximum hourly average power it measured during this time period was 1.46 W before the DC/DC converter and 1.26 W after the DC/DC converter (Fig. 24). The maximum instantaneous power it measured was 30.75 W before the DC/DC converter and 27.68 W after the DC/DC converter (Fig. 25).

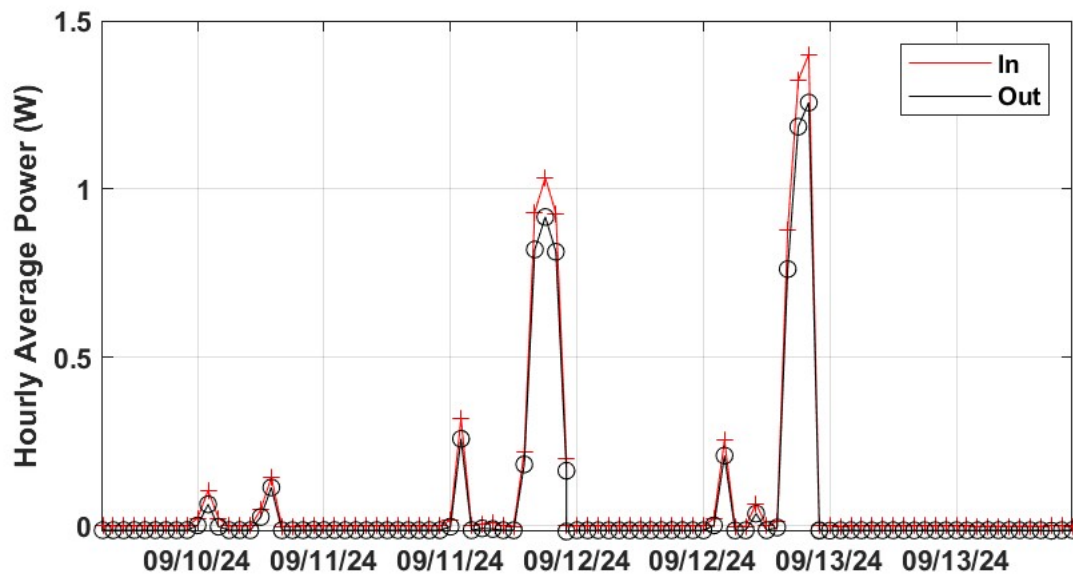


Figure 24: Test 1: Hourly average power values measured before the DC/DC converter (In) and after the DC/DC converter (Out).

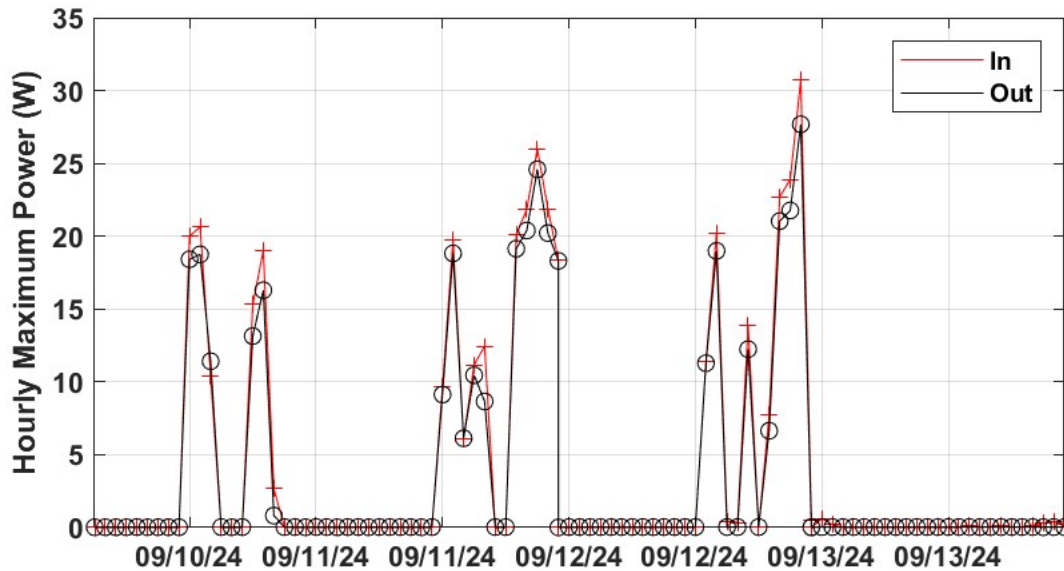


Figure 25: Test 1: Maximum power values measured before the DC/DC converter (In) and after the DC/DC converter (Out).

The timeseries of the power generation and current speed indicate that power was not generated at the times of the highest current speed, but as the current speed was speeding up or slowing down (Fig. 26). The current speeds showed groups of double peaks where the first high current speed in a group was during ebb tide and the second was during flood tide. The highest hourly average power values occurred at the end of flood tide as the current was slowing down as is typical for mixed-semidiurnal tides. As previously discussed, the ADV current speeds are not representative of the flow across the length of the pipe. It was only meant as a backup instrument and its measurements were most likely contaminated by wake from the pipe during ebb tide because of its position on the lander (Fig. 17). It also did not measure the current speed at the height of the WITT, which is the relevant current speed for this project. The current speed at the height of the WITT would have been higher than the current speed at the ADV location because of the boundary layer. Any results of Test 1 that involve the ADV measurements should not be trusted as the best possible measurements.

The WITT produces the most power when the pipe hits a resonant motion, and the pipe may have hit resonance most effectively near the end of flood tide. Spectra of the displacement show frequencies between 0.75 and 1 Hz and stronger energy during flood tide than ebb tide (Fig. 27). The spectra were calculated using the Pwelch method for 10 minutes of data with 1024 points and 512 points of overlap. The sampling frequency was 8 Hz. The largest displacement values were measured during flood tide when the frequency of vibration was near 0.8 Hz (Fig. 28). The IMU data were analyzed to relate the motion of the WITT to the power production. The maximum power produced was more strongly correlated with the displacement than the average power produced and neither were strongly correlated with the frequency of vibration (Fig. 29).

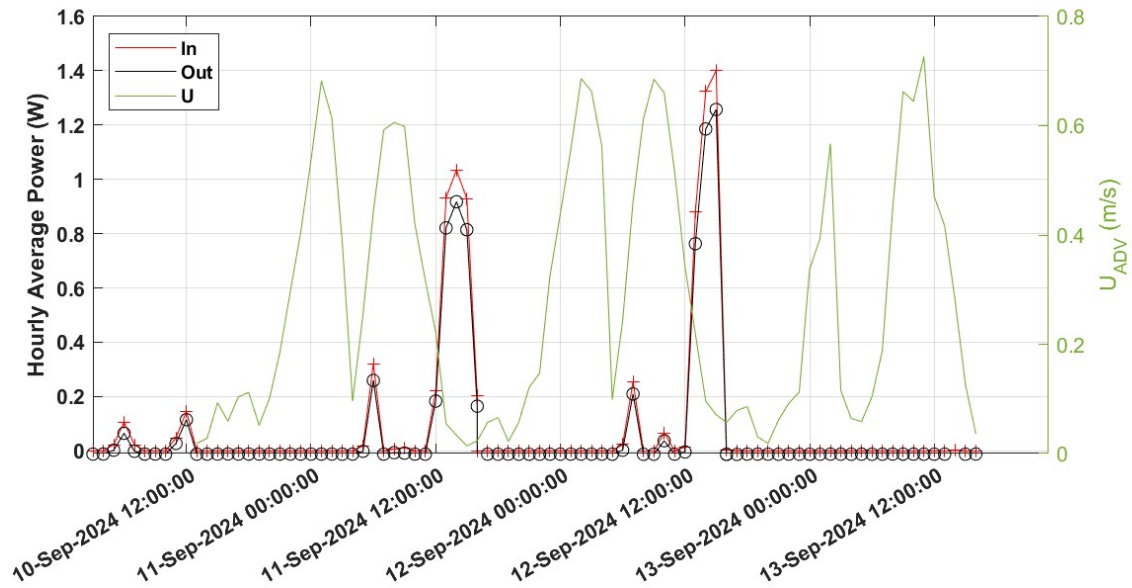


Figure 26: Timeseries of the hourly average of the power generated and the current speed.

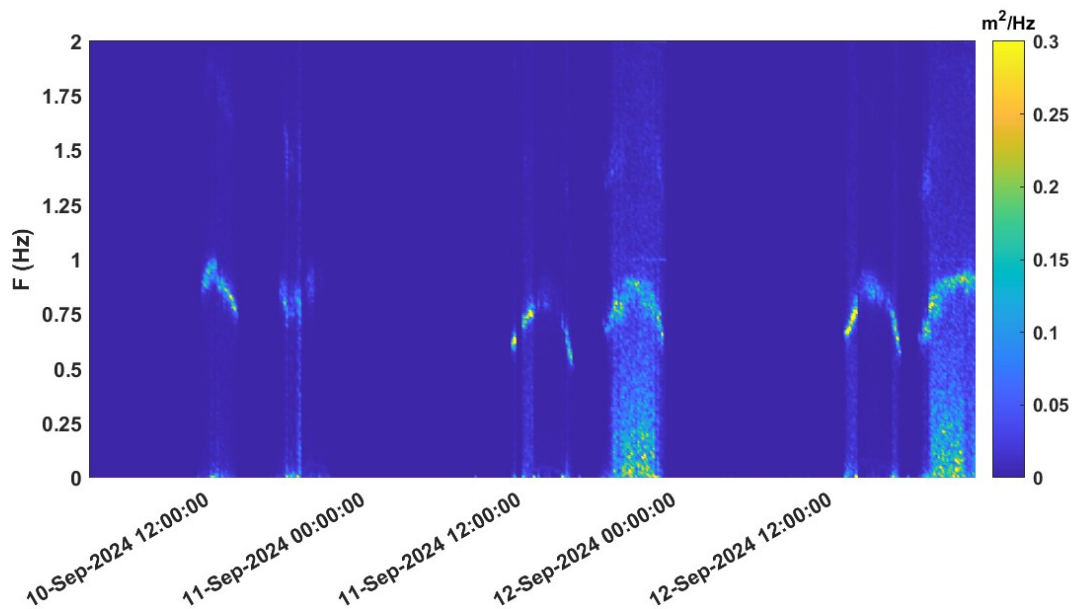


Figure 27: Spectra of the WITT displacement.



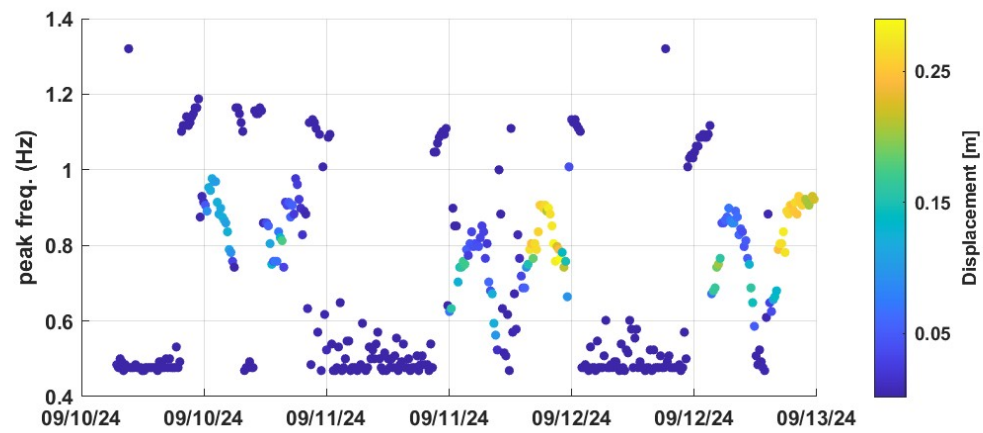


Figure 28: Timeseries of the peak frequency ( $>0.46$  Hz) and RMS of the displacement as measured by the IMU.

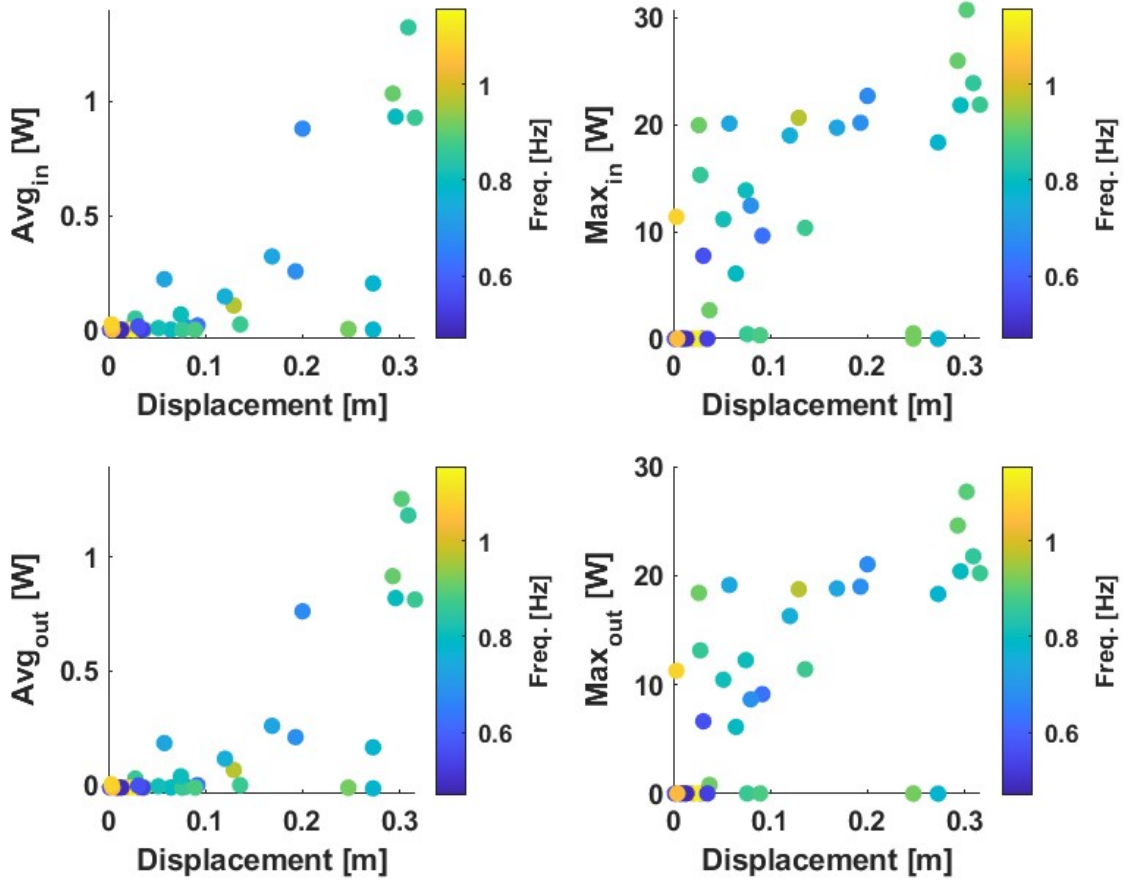


Figure 29: Power produced as a function of the RMS of the displacement and frequency of vibration.

A non-dimensional efficiency was calculated as

$$E = \frac{P_{produced}}{P_{theory}} \quad (5)$$

where  $P_{produced}$  is the electrical power produced by the system and  $P_{theory}$  is the available power in the flow through an area equal to the area swept by the pipe and the WITT housing. The area swept by the pipe and WITT housing was calculated as the area of the pipe plus the approximate area of the WITT housing that faced the flow. The area of the pipe facing the flow was calculated as  $2.5 \times 0.14 = 0.35 \text{ m}^2$ . The area of the WITT housing facing the flow was approximated as a circle with diameter of 0.33 m ( $0.09 \text{ m}^2$ ). The total area was therefore  $0.44 \text{ m}^2$ . The theoretical power was calculated as

$$P_{theory} = \frac{1}{2} \rho u^3 A \quad (6)$$

where  $\rho$  is the density of seawater,  $u$  is the current speed, and  $A$  is the swept area. Efficiency values were unable to be calculated utilizing the ADV measurements.

### 7.1.5 Test 2

The WITT, pipe, and WITT data acquisition housing were attached to the lander on Feb 25, 2025. A new pipe was used for Test 2 because the pipe from Test 1 had been sitting outside for several months and we were concerned about its structural integrity. The new pipe was cut to the same dimensions as the pipe used in Test 1. Although the test plan said two pipe lengths would be tested, we decided to test the same pipe length because the ADCP had failed during Test 1 and the WITT had failed after a couple of days. A shim had also broken loose during Test 1 so the connection between the pipe and the lander was re-engineered before Test 2. During Test 2, a Nortek Signature1000 ADCP and a Nortek Vector ADV were deployed next to the WITT lander on a Sea Spider lander. They were mounted on their own lander to prevent them being influenced by the vibration of the WITT lander or the wake from the pipe. The test was planned for two weeks, but due to diver and boat scheduling issues, the instruments were recovered later on March 24. The ADCP acquired data until its battery died on March 13, the intended end-date of the test. The Sea Spider lander was deployed with 430 pounds of steel to weigh it down.

The WITT power take-off system was slightly adjusted between Test 1 and Test 2. The potentiometer settings were changed in order to allow power to be harvested from less energetic pendulum swings. In Test 1, the voltage cut-in was set to high (8 V) and the current was also set to high (1.25 A). This meant that when the voltage exceeded 8 V we started pulling all of the current available from the system up to 1.25 A. Because of this setting, the pendulums built up a significant amount of swing before any power was pulled to slow them down. Unfortunately, this more aggressive swinging caused the pendulums to clip the wiring and short the motor, seizing the gearbox. To avoid this problem in Test 2, the voltage cut-in was lowered to 4 V and the current was set to the middle (1 A). This allowed the system to start producing power and reduce the kinetic energy of the pendulum motion. The WITT produced power for the entire intended measurement period of Test 2 and was still producing power when it was retrieved. The motion of the WITT may have been influenced by the swing of the pendulums and the power draw. This has been measured previously when the WITT was used as a wave energy converter (*Branch et al.*, 2024).

The ADCP was configured to ping continuously at 1 Hz in low power mode, with a depth bin size of 0.5 m and a 15 m range. The ADV was configured to run on a duty cycle, collecting 5 minutes of data at 32 Hz every 20 minutes. The IMU was recording orientation (in the form of quaternions), acceleration, and angular velocity at 10 Hz.

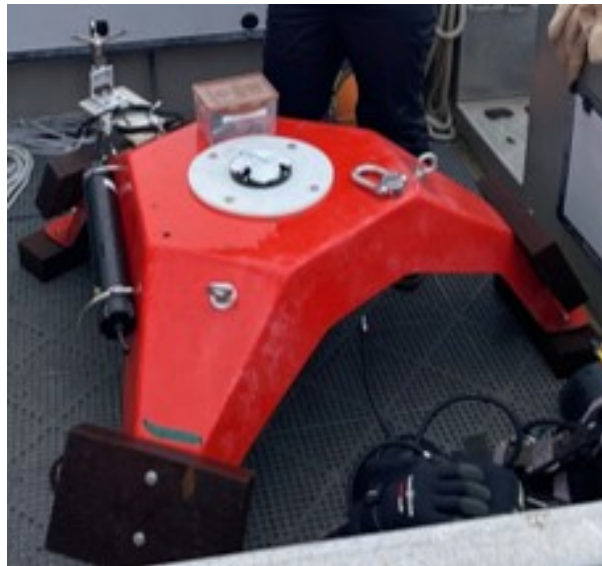


Figure 30: Sea Spider tripod with the ADV and ADCP prior to deployment for Test 2.

Spring tides occurred during the first days of Test 2, between Feb 26 and Mar 2, where maximum water speed reached 1.8 m/s (Fig. 31).

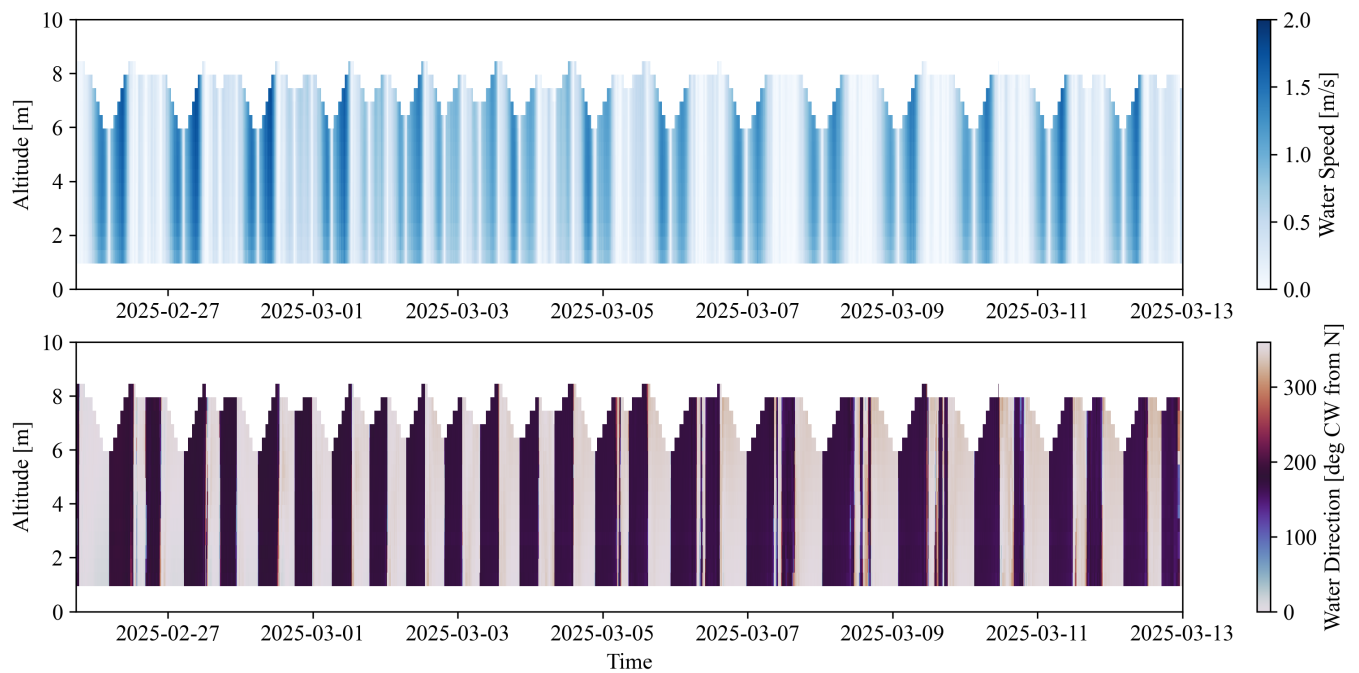


Figure 31: Magnitude and direction of horizontal water velocity during Test 2.

The maximum current speed at the height of the WITT was 1.63 m/s (Fig. 32).

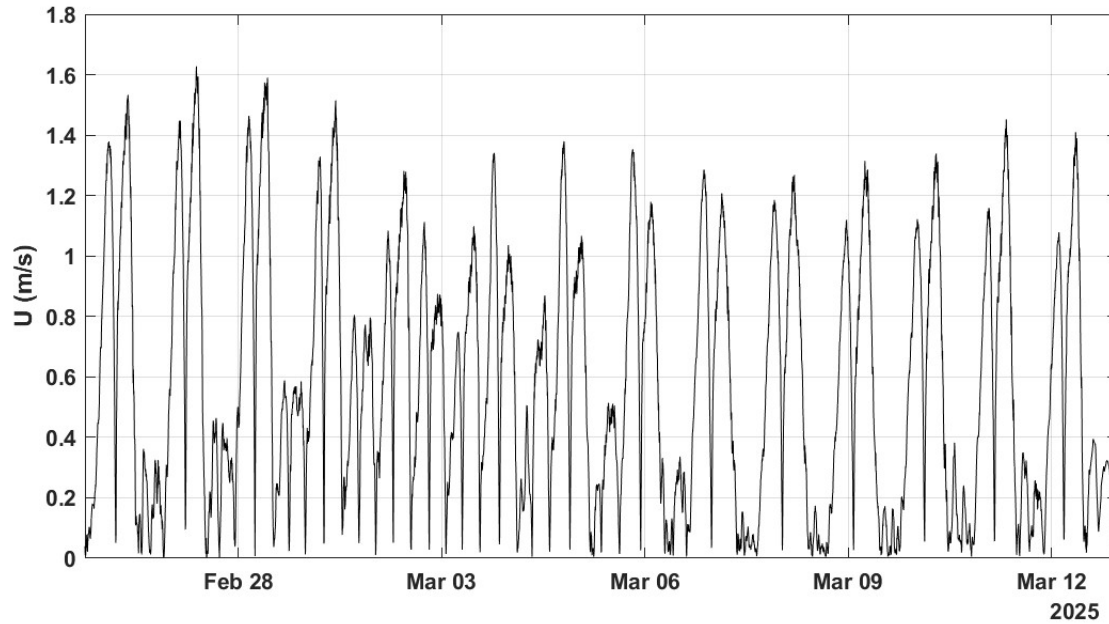


Figure 32: Magnitude of the current speed at the WITT height during Test 2.

The tides during the test were a high tide followed by a slightly lower tide, high tide again, and then a much lower low tide (Fig. 33). The higher current speeds occurred during the larger tidal exchanges with ebb preceding flood.

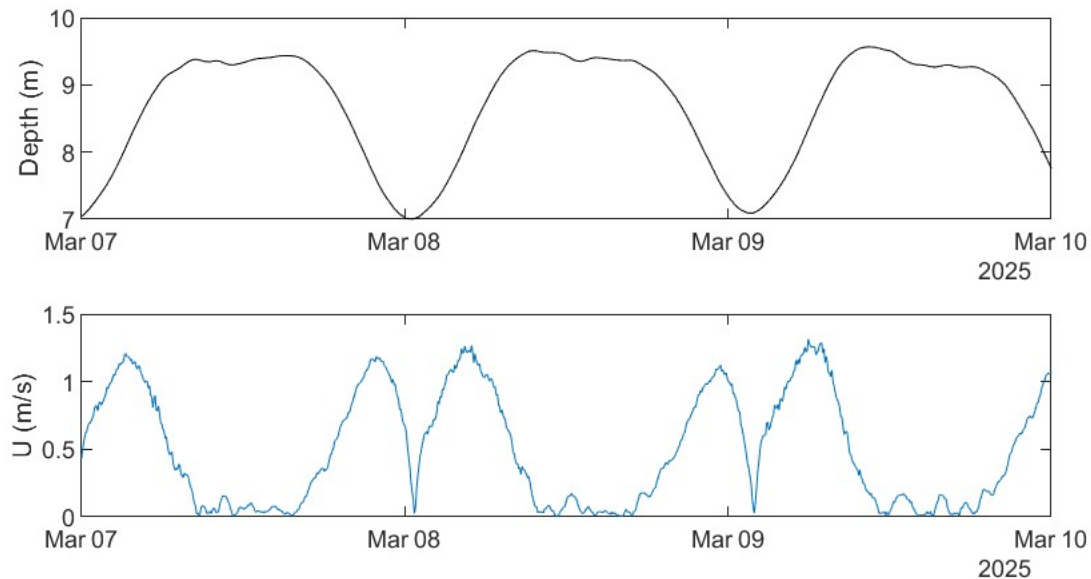


Figure 33: Water depth and current magnitude 2.85 m above the seabed from 3/7/25-3/10/25 during Test 2.

The hourly average power generation changed constantly during the test as the tidal current speeds accelerated and decelerated (Figs. 34 and 35). The hourly average power values decreased to near zero after March 15th (Fig. 34). The displacement decreased at the same time (Fig. 36), but there is no known reason for the decrease. The tidal range was increasing again over those dates which should have increased the movement and power production but it did not (Fig. 37). The most likely reason for decreased movement and power production would have been kelp fouling but the divers did not report seeing large amounts of kelp when they recovered the system.



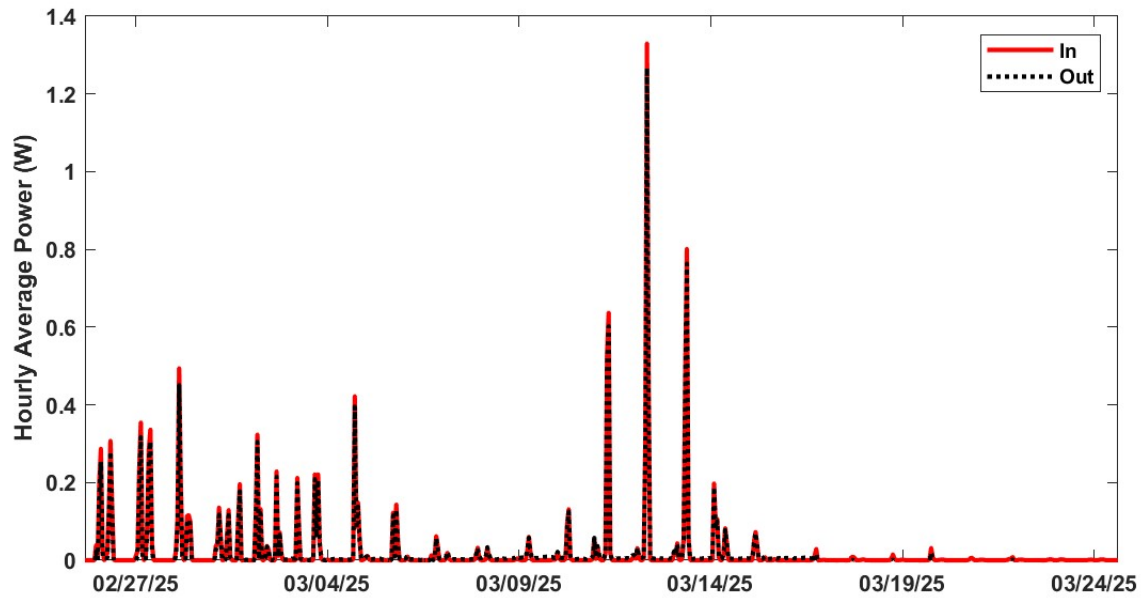


Figure 34: Hourly average power produced by the WITT during Test 2.

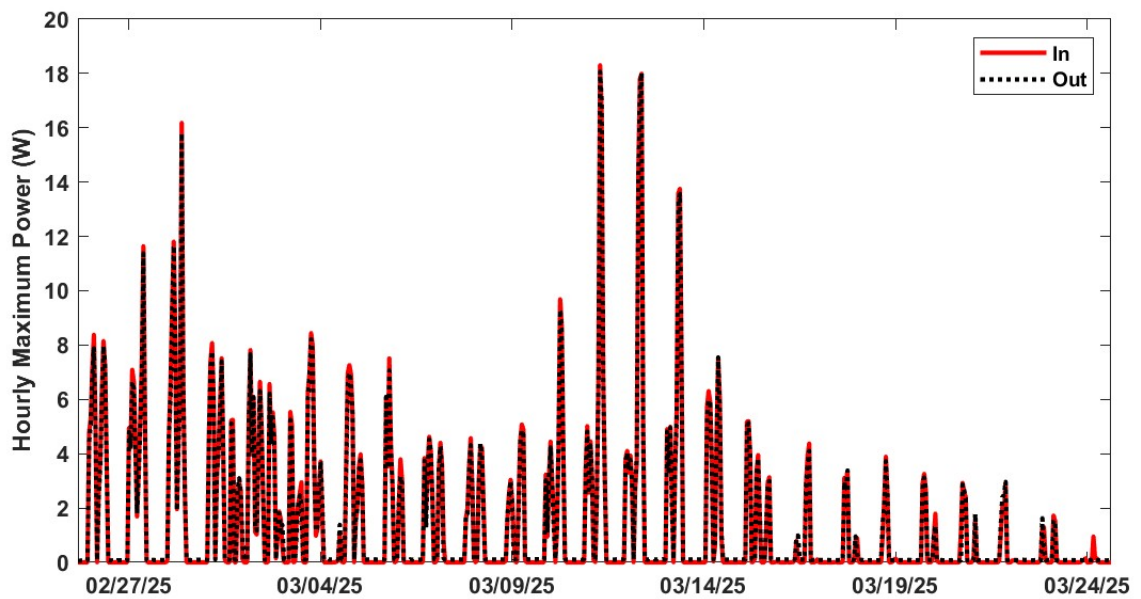


Figure 35: Hourly maximum power produced by the WITT during Test 2.

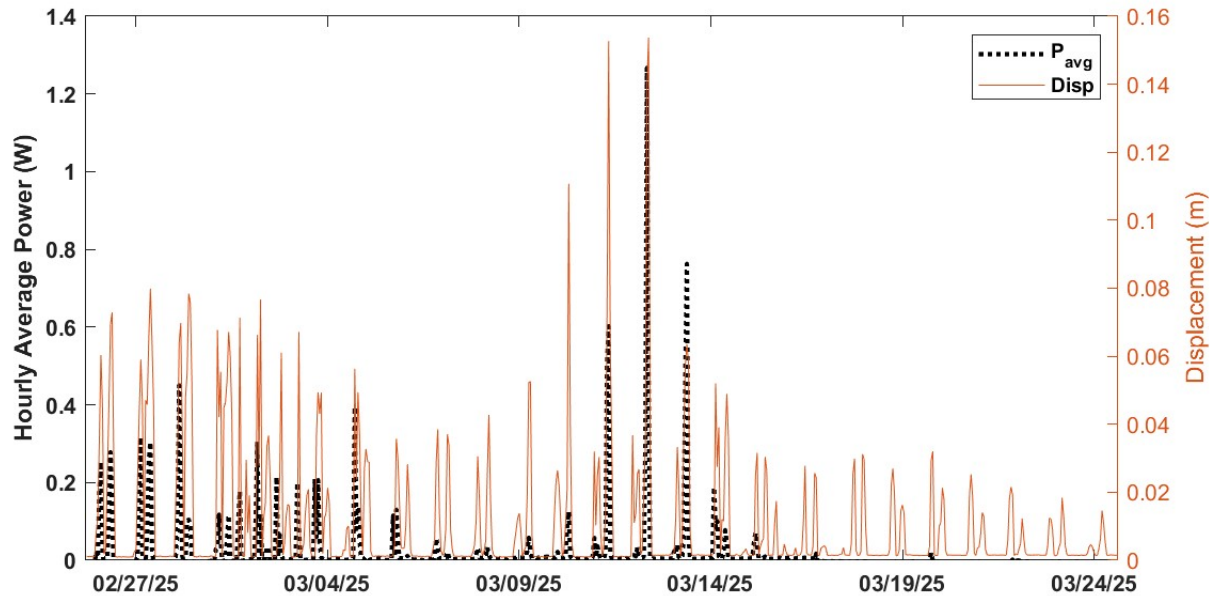


Figure 36: Timeseries of the hourly average power produced and the displacement of the WITT on top of the pipe.

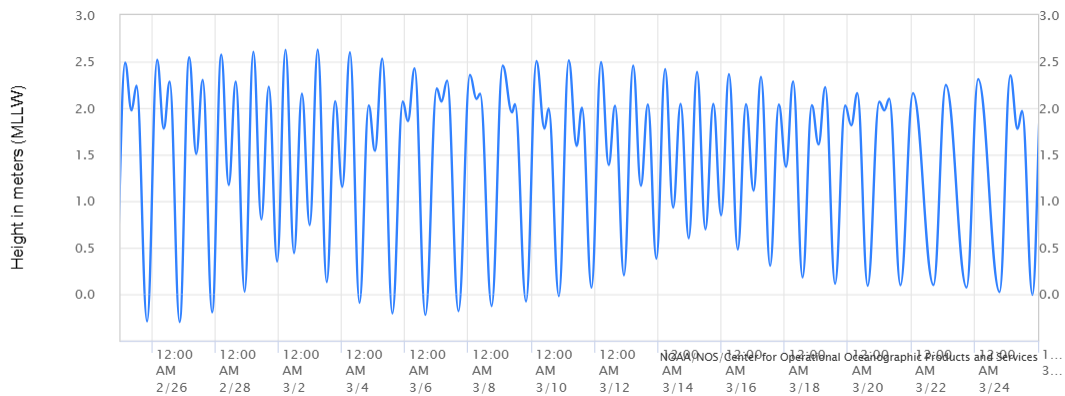


Figure 37: NOAA prediction of the tidal height during Test 2.

The average and maximum power values increased with the RMS displacement of the WITT on top of the pipe (Fig. 38).

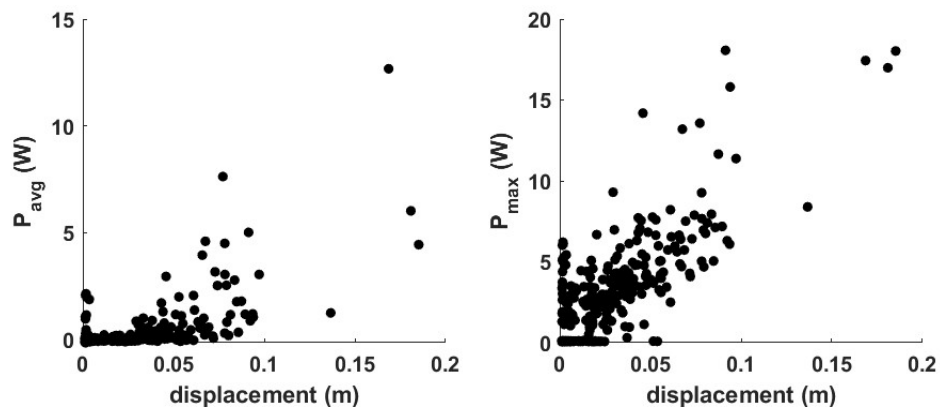


Figure 38: Hourly average (left) and maximum (right) power produced by the WITT as a function of the RMS displacement during Test 2.

Because the instruments were retrieved two weeks later than originally planned, the ADCP was not recording current speeds for the entire time that the WITT produced power. It did record the current speeds during the two highest peak of the power production on 3/11/25 and 3/12/25 (Fig. 39).

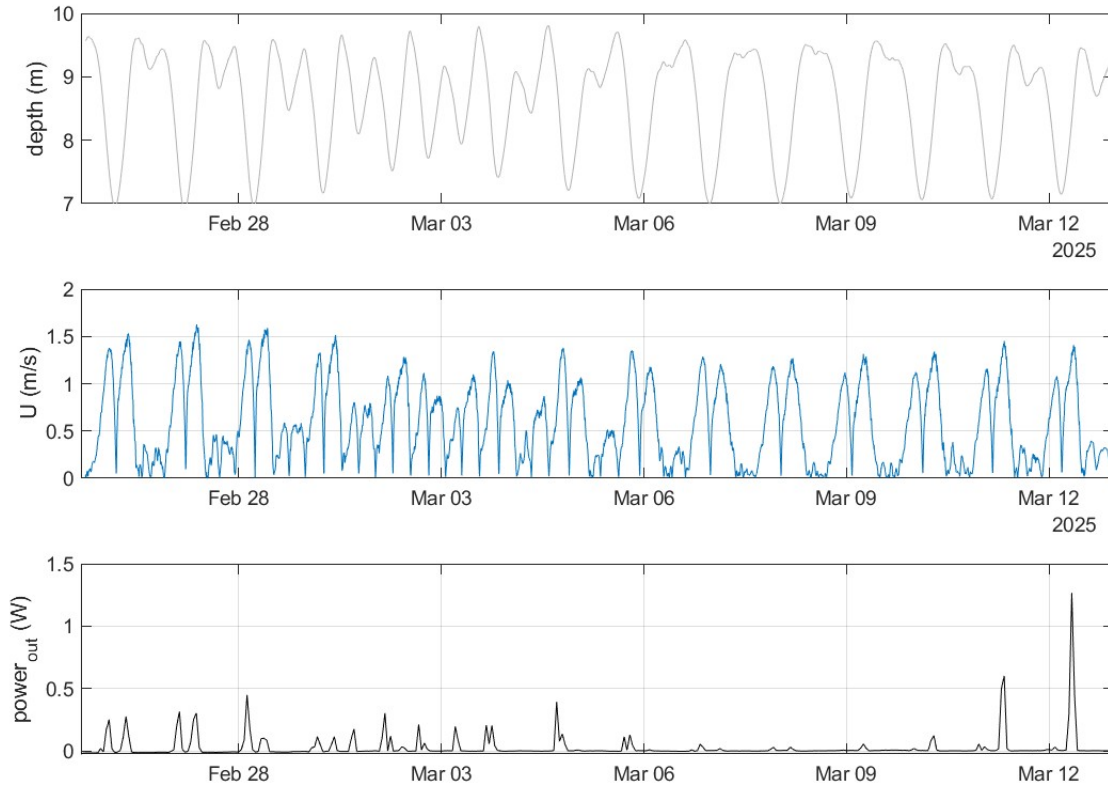


Figure 39: Timeseries of the water depth, current speed at the WITT height, and hourly average WITT power produced during the time period of Test 2 when the ADCP was recording.

Plots of the average and maximum power generated by the WITT versus the current speed as measured by the ADCP show a stronger correlation with current speed for the maximum power than the average power (Fig. 40). The average power values indicate that a pattern of increasing value with current speed may emerge for current speeds above 1 m/s, but tests at higher current speeds would be needed to verify that. The average power values for current speeds between 0.5 and 1 m/s were not significantly lower than those for current speeds between 1 and 1.6 m/s.

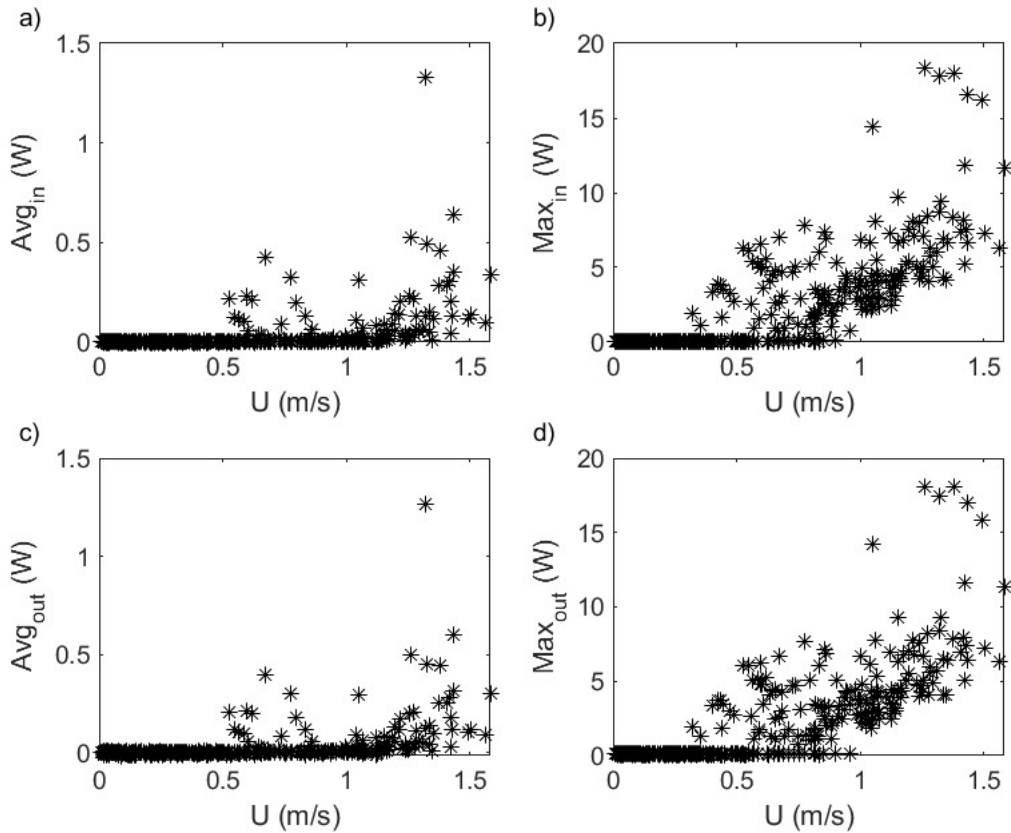


Figure 40: WITT power production as a function of current speed as measured by the ADCP at the WITT height. a) The hourly average power that went into the DC/DC converter, b) the maximum hourly power that went into the DC/DC generator c) the hourly average power as measured after the DC/DC converter and d) the maximum power measured after the DC/DC converter.

The WITT movement was characterized by examining data from an IMU mounted in the WITT housing at the top of the pipe. The angle data shows there was a change in the angles halfway through Test 2 and the magnitude of the angular vibrations was reduced after that (Fig. 41). This occurred at the same time as high tidal current speeds. The Sea Spider moved during Test 2 and was found touching the lander at the end of the test. The shift in the IMU angles may have occurred as the Sea Spider bumped into it, changing the orientation of the equipment. The Y and Z angular data appear to have more noise in their signals after 3/16/25. The acceleration signals also appear to have more noise in their signals after 3/16/25 (Fig. 42).

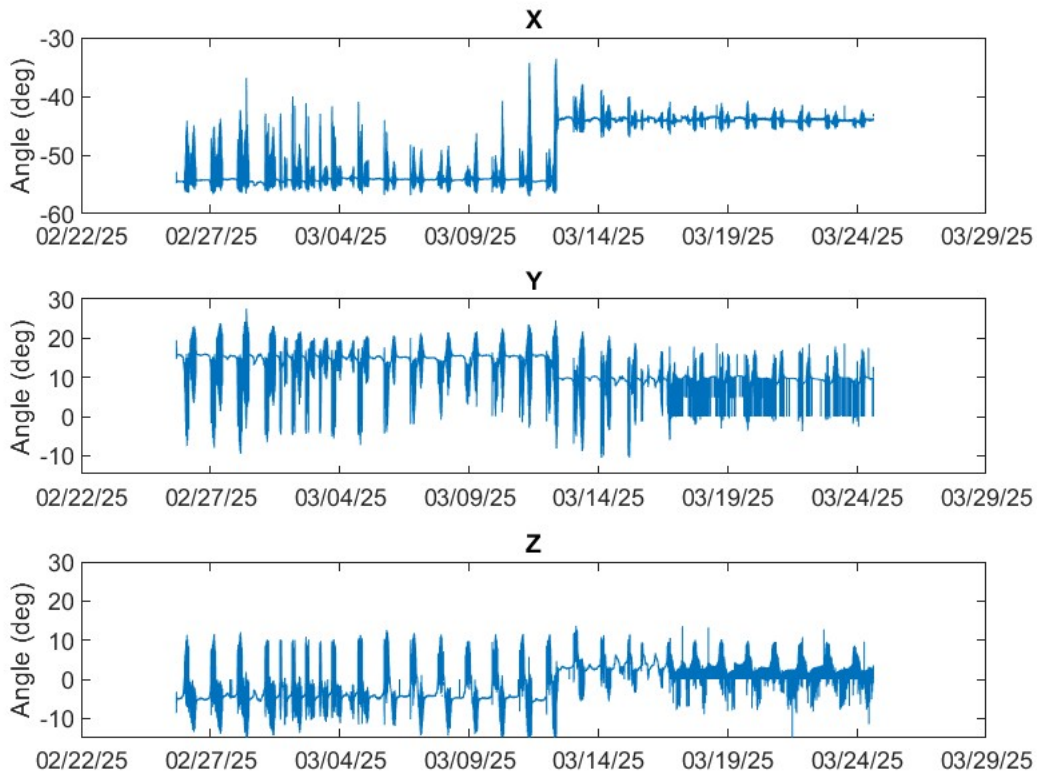


Figure 41: Timeseries of the angles measured by the IMU in the WITT housing on top of the pipe during Test 2.

Reduced accelerations were measured after 3/16/25, but the tidal exchange was predicted to be much lower over that time period so the current speeds and WITT motion may have been reduced (Fig. 43).

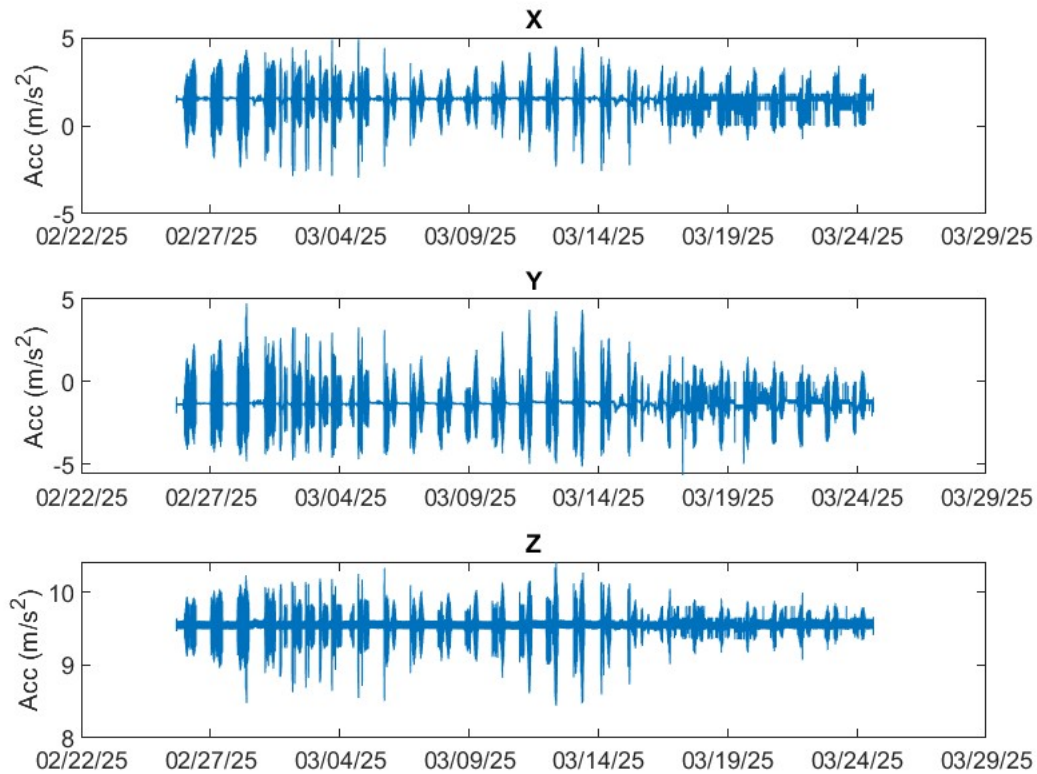


Figure 42: Timeseries of the acceleration measured by the IMU in the WITT housing on top of the pipe.

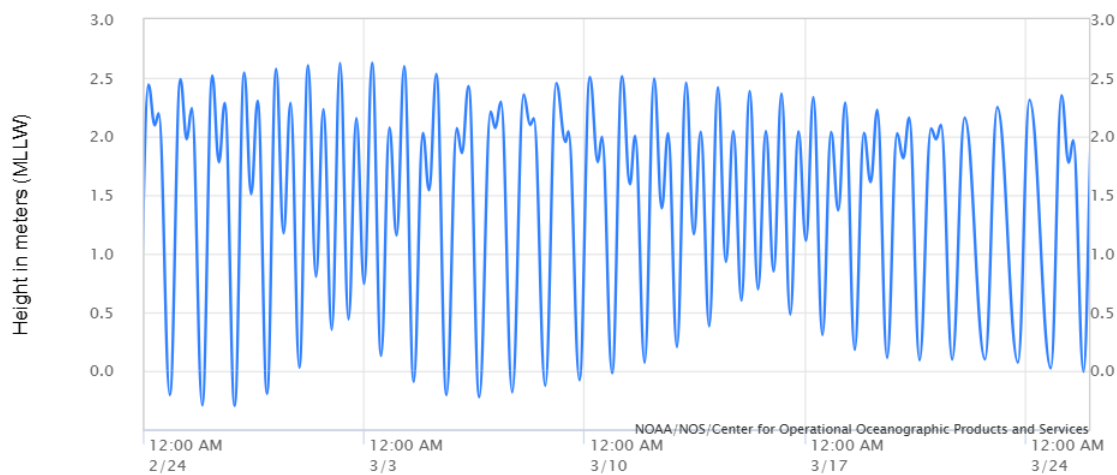


Figure 43: Timeseries of the NOAA predicted tidal height at nearby station 9444555.



The frequency of vibration was calculated from the data of the IMU that was mounted in the WITT housing at the top of the pipe. The WITT housing showed the strongest vibrational energy around 0.5 Hz, but it also had higher modes of vibration around 1 and 1.5 Hz (Fig. 44).

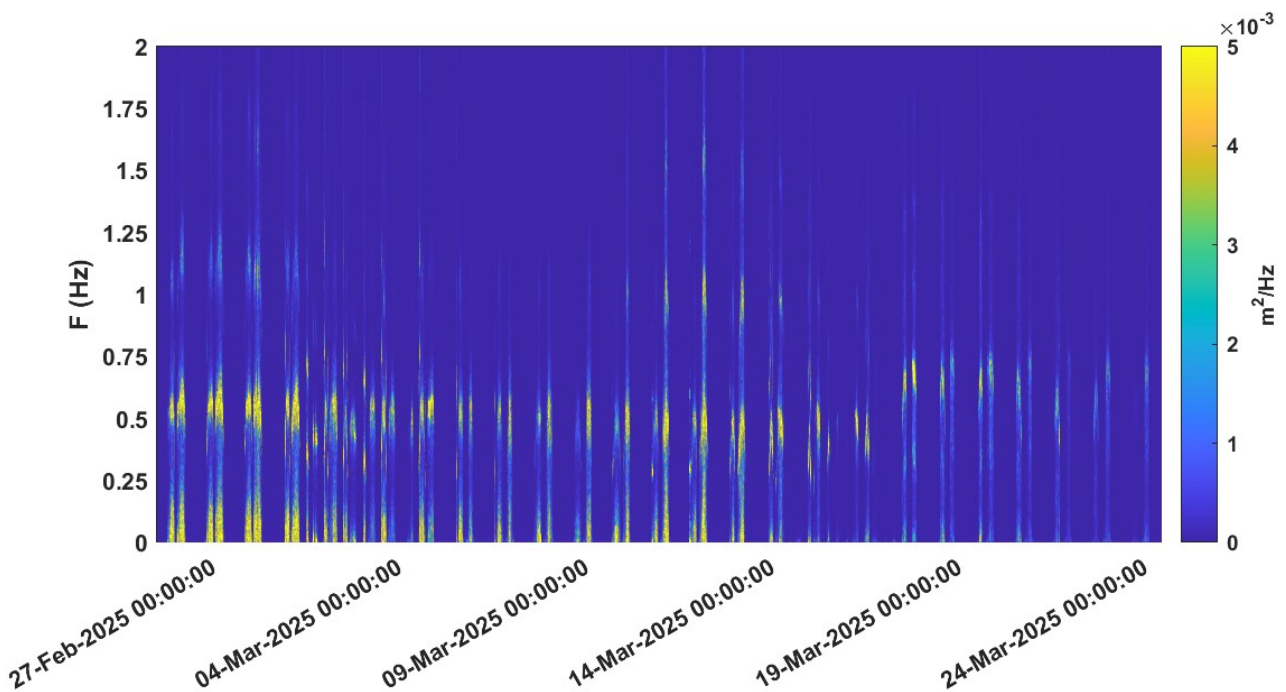


Figure 44: Timeseries of the frequency of the vibration as measured by an IMU in the WITT housing.

The peak frequency of vibration did occasionally hit the desired 1.2 Hz, but it did not stay at that frequency for long and more energy was present at the lower frequency harmonic (Figs. 44 & 45).

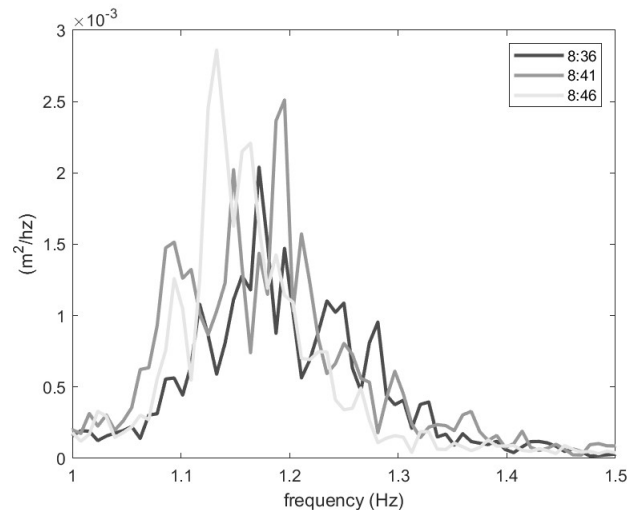


Figure 45: Example spectra from 2/26/25 of the WITT displacement over a 10-minute period.

A timeseries of the peak frequency colored by the RMS displacement does not show the same pattern seen during Test 1 of the largest displacement values during flood tide when the frequency of vibration was near 0.8 Hz. Only four time periods showed displacement values above 0.1 m and they were not associated with a specific phase of the tide (Fig. 46).

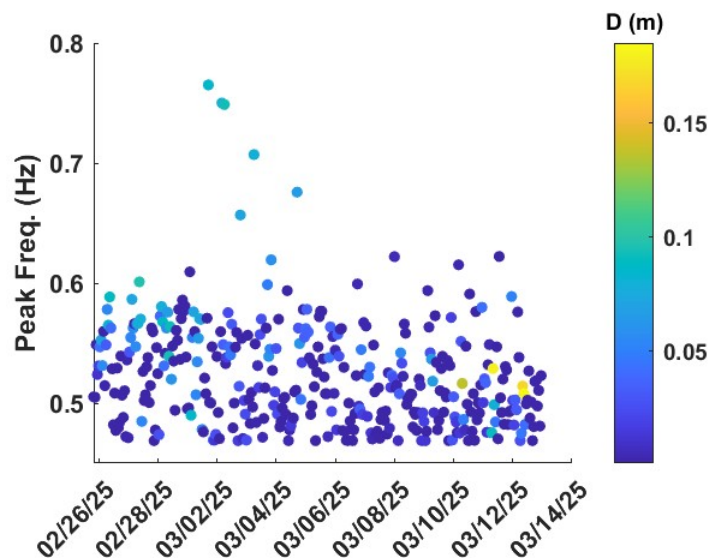


Figure 46: Timeseries of the peak frequency (>0.46 Hz) and RMS of the displacement as measured by the IMU during Test 2.

Power production increased with displacement and was not strongly correlated with vibration frequency during Test 2 (Fig. 47). The maximum displacement was 0.15 m, which was lower than the maximum dis-

placement measured during Test 1. This is most likely due to a change in the engineering of the connection between the pipe and the lander. During Test 1, a shim that had been between the pipe and the lander was not there when the pipe was retrieved at the end of the test. This means that there was space between the pipe and the lander connection. A new pipe/lander connection was engineered for Test 2 and the pipe was therefore held more tightly to the lander with no space between the pipe and lander. This resulted in smaller displacements and therefore lower power production.

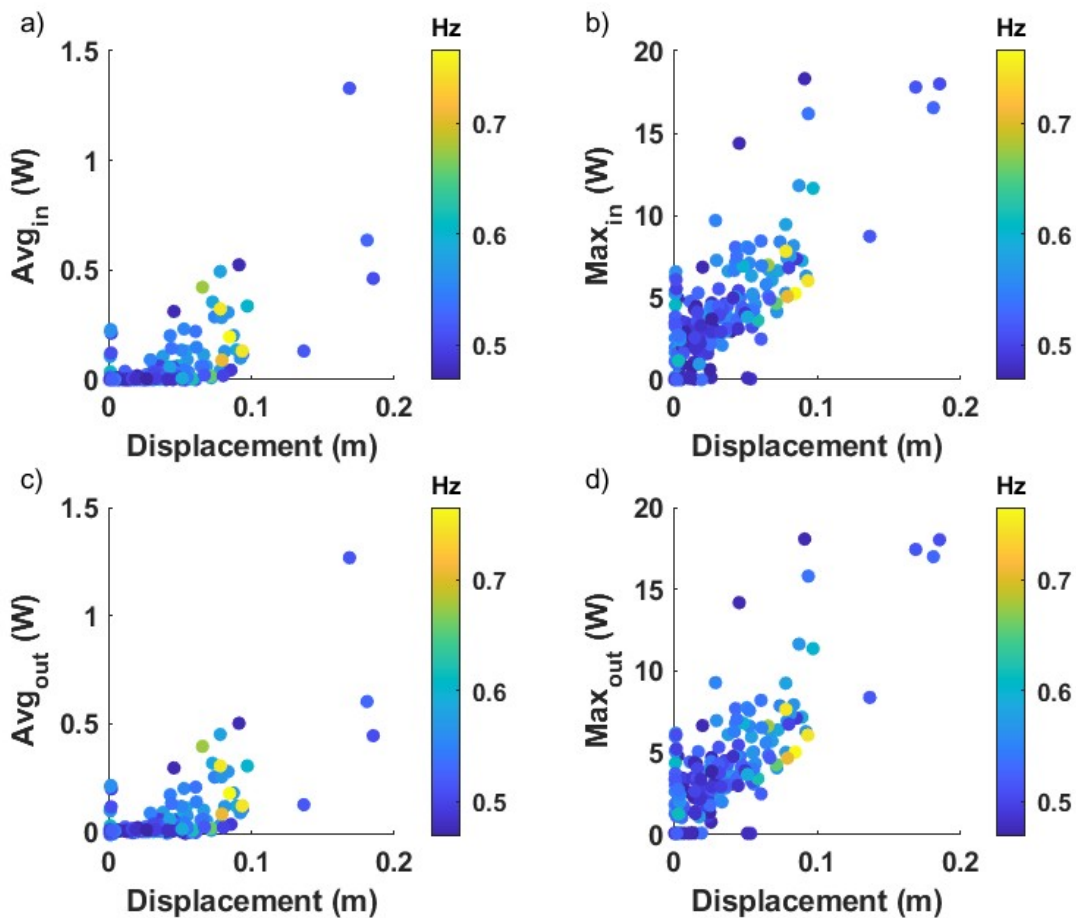


Figure 47: Power produced by the WITT as a function of the RMS of the displacement and vibration frequency.

Power production increased with current speed and displacement (Fig. 48).

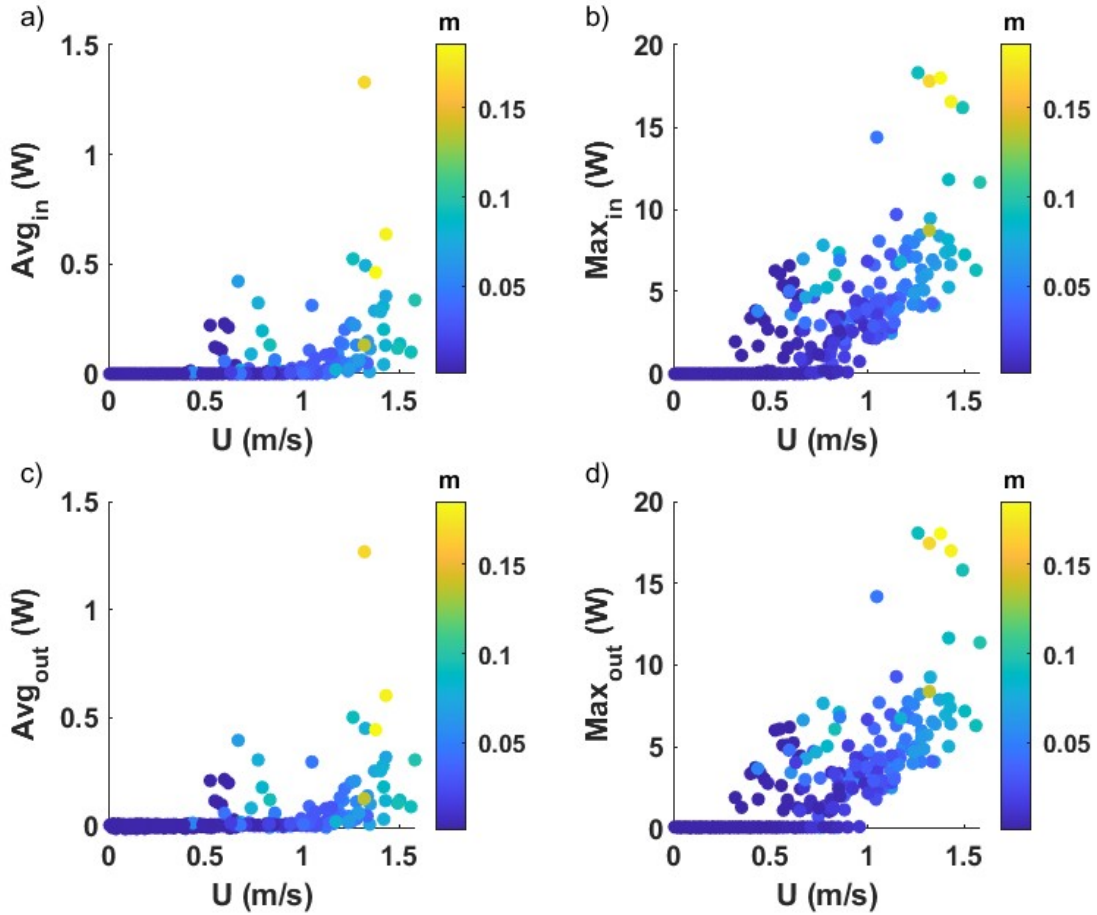


Figure 48: Power produced by the WITT as a function of the current speed and RMS of the displacement.

Efficiency was calculated using equation 5 with the average power as  $P_{produced}$ . The efficiency calculated using the average power as  $P_{produced}$  is mostly below 0.005 (Fig. 49). The higher values at current speeds below 0.5 m/s do not represent a useful efficiency because the instrument does not generate significant amounts of power below 0.5 m/s.

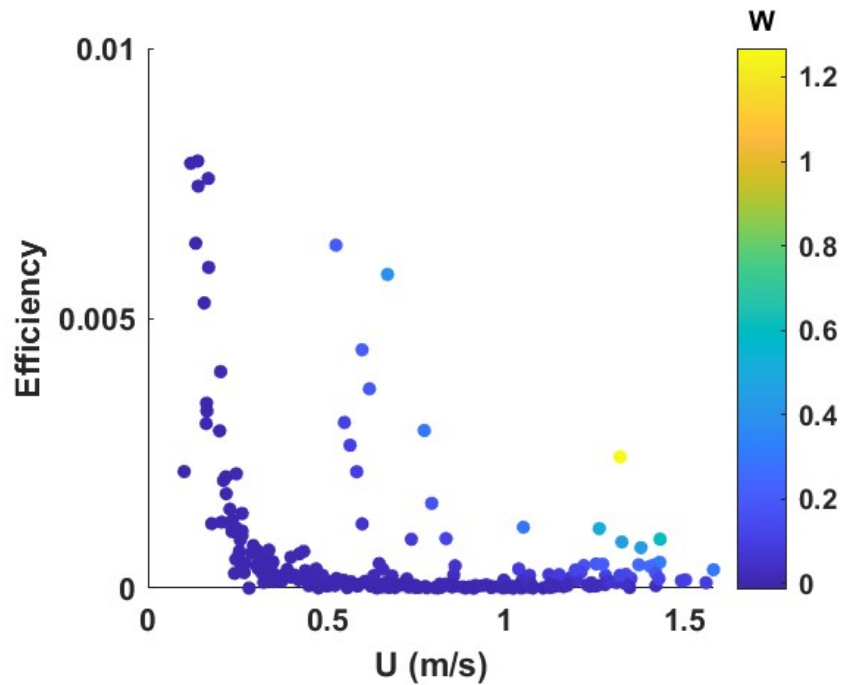


Figure 49: Efficiency as calculated with the average power produced during a one hour period. The colors represent the average power generated.

#### 7.1.6 Biofouling

The sea spider and instruments were recovered off of the lander on 3/24/25 at the end of Test 2. The pipe, sea spider, and data housing had some noticeable biofouling, but it did not appear to the divers that there was enough to interfere with the operation of the systems (Figs. 50, 51, 52).



Figure 50: Photo of the pipe as the divers recovered it on 3/24/25 at the end of Test 2.



Figure 51: Biofouling on the Sea Spider on 3/24/25 at the end of Test 2.





Figure 52: Biofouling on the WITT data acquisition housing on 3/24/25 at the end of Test 2.

The lander was left on the seabed on 3/24/25 because of diver/tide scheduling issues. It was retrieved on 6/17/25 and had been on the seabed since 9/9/24. Figure 53 shows the amount of biofouling that had accumulated on the lander over the nine month period.



Figure 53: Biofouling on the lander when it was recovered 6/17/25.



## **7.2 LESSONS LEARNED AND TEST PLAN DEVIATION**

Several lessons were learned with respect to project planning, safety procedures, sensors, and general efficiency and time management.

### **7.2.1 Project Planning**

Scheduling challenges were encountered when the boat we planned to use broke and we did not have a replacement. We had to wait several months for it to be repaired. This delayed our project. We also encountered challenges in boat and diver availability. The second test was two weeks longer than expected because of diver availability and we should have programmed the ADCP to collect data for a month instead of two weeks in case of delays. Next time we will assume that there will be recovery delays and plan accordingly.

### **7.2.2 Safety Procedures**

The PNNL dive team reported an unusual smell when they recovered the ADCP. This smell was an indication that the ADCP seal had been compromised and the ADCP had flooded. This could have been a potentially hazardous situation. We should have immediately quarantined it. We also did not immediately notice that we could hear the water sloshing inside the ADCP when we gently shook it. Next time we will examine sensors very carefully when we bring them to the surface and make sure that there are no signs they have flooded.

### **7.2.3 Sensors**

The most important lesson learned during this test was to have redundant measurements of key metrics. We would have not had any current speed measurements from Test 1 if we had not deployed an ADV and an ADCP because the ADCP failed. Several lessons were learned during this TEAMER with regards to current speed measurements with Nortek ADCPs. The first lesson was that we should use even more weight than we think we need for the anchor on the Nortek Eco. We used two forty-five pound weights and it still dragged the anchor. The second lesson learned was that the Nortek Eco ADCP only measures current speeds up to approximately 1.5 m/s when deployed in the configuration that it is sold in. It was configured to float over a line with weights to anchor it. Above 1.5 m/s the line tilted too much to measure the current speed. After that experience, the Eco was mounted on the lander for Test 1, upon recovery was discovered broken. The third time we wanted to measure current speed we used a much more expensive ADCP (Nortek Signature 1000) that was deployed in a sea spider lander. Mounting current measurement devices on their own lander instead of on the WITT lander was a better idea because of the vibration issues and possible wake issued of the current measurement device being in the wake of the pipe during one phase of the tide.

The second important lesson that we learned during this project was to increase the weight on anything you attempt to secure to the seafloor in an area with strong currents. The Eco ADCP, Sea Spider lander, and WITT lander all moved under the strong currents.

### **7.2.4 General efficiency and time management**

We struggled a bit with the tide/diver/boat schedules. We needed the R/V Strait Science to deploy and recover the lander and it was out of commission for several months. The R/V Resilience will eliminate this

challenge once it is operational. For Test 2, we were only planning for a two week test but ended up with a 4 week test because of diver/boat scheduling issues. We could have programmed the ADCP to record for 4 weeks instead of 2 weeks, but that was not the original plan.

### 7.2.5 Test Plan Deviation

The main deviation from the test plan was that we only tested one pipe length instead of two. The failure of the WITT during Test 1 after a short time period meant that we did not get to test the full range of current speeds that we wanted to test with the 2.5 m pipe length. The highest current speeds would have occurred on 9/15/24 and 9/23/24 (Fig. 18) and the WITT was not working at that time. A smaller deviation from the test plan is that the ADCP failed during Test 1 so we will not be uploading current speed data to MHKDR for Test 1.

## 8 CONCLUSIONS AND RECOMMENDATIONS

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This TEAMER project was a success in that it conducted two field tests of a new tidal current energy device. The first test was successful in measuring the device generating a maximum hourly power of 1.3 watts. The second test was successful in measuring the power produced for 28 days and the device was still generating power when we retrieved it. The major conclusion reached by this project was that vortex induced vibration can be used for power generation. The power generation was found to be more strongly correlated with the magnitude of the displacement than the frequency of the motion. Future work is needed to improve the power electronics, further refine the pipe length equations to maximize the displacement, extend the time in the water to test the reliability, and quantify the influence of turbulence on the pipe motion and therefore the power production.

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