CalWave Open Water Demonstration

DE-EE0008097

Testing Report (Public Release)

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Executive Summary

The following summary is adapted based on the DOE news article including video link published on MARCH 28, 2022: CalWave Launches California's First Long-Term Wave Energy Project | Department of Energy

In September 2021, CalWave's xWave was tested during its first at-sea, long-duration wave energy pilot project, initially targeted for six month and extended to a total of 10 months. The launch edges the technology closer to providing grid-connected electricity for coastal communities worldwide. Wave energy is also a good complement to other renewable energy resources, such as wind and solar. When the sun sets and winds slow, waves keep moving at a steady pace through all four seasons. Combined, the three renewable resources could provide the grid with reliable power both day and night and year-round. On its own, wave energy could satisfy up to 34% of the United States' electricity needs. But the benefits extend beyond U.S. coastlines: Offshore, portable wave energy devices could help power the growing blue economy, including sensor-equipped sea drones that collect data on ocean ecosystems for marine research.

"Marine energy systems, like CalWave's xWave, are exciting not just because they can provide clean, carbon-free energy to coastal communities," said Yana Shininger, a technical project officer for the U.S. Department of Energy's Water Power Technologies Office (WPTO), which provided funding to CalWave to design, build, and test its proprietary technology. "From powering autonomous vehicles for ocean exploration to transforming salt water into fresh for remote island communities or disaster recovery situations, marine energy devices have a vast range of potential applications."

On Sept. 16, 2021, CalWave took that salty plunge: The company deployed its xWave prototype off the University of California San Diego's Scripps Institution of Oceanography research pier in San Diego, California. For ten months, the device rocked in the waves 1,800 feet—or about six football fields—off that pier. There, transformed the ocean's oscillating motion into electricity, which it then transported back to shore.

During severe weather events, CalWave's xWave has some tricks to weather even the most tumultuous storms. While many wave energy developers cloak their machines in heavy steel, the xWave design uses a far lighter, less expensive technique. Instead of floating on the ocean's surface, the xWave operates while submerged at different depths. When more destructive swells roll in, the xWave autonomously drops lower to avoid them. Operators can also remotely shut the device down to protect it during storms.

As a bonus, submerging the xWave keeps it hidden, ensuring beautiful ocean vistas stay that way.

In the San Diego sea trial, the xWave 'x1' was anchored at the test site and deployed close to the Scripps Pier. During this trial, CalWave collected data on how the xWave operates out at sea. But the team also collected information on how well marine energy devices cohabit with marine ecosystems. Collaborating with the Pacific Northwest National Laboratory's Triton Initiative—a project funded by WPTO to research environmental monitoring technologies and methods— the xWave was observed with a Boxfish 360 video camera and three different sound monitoring tools: Integral Consulting, Inc.'s noise spotter buoy, a drifting hydrophone, and three long-term, bottom-mounted hydrophones. Because wave energy is still so new, it's important that scientists collect data on machine-ecosystem interactions. Although only a few offshore deployments have collected this valuable information, existing data show that the risks for single devices are relatively low.

Researchers also need to monitor how the marine environment impacts their machines. Shifting sand and stones can collide with or get lodged in devices. CalWave will submit data on all these environmental interactions to an open-source, global, collaborative report to help ensure the safe adoption of robust marine energy technology worldwide.

This project received support from the U.S. Department of Energy's Water Power Technologies Office, the University of California San Diego Scripps Institution of Oceanography, the National Renewable Energy Laboratory, Sandia National Laboratories, DNV-GL, and the University of California Berkeley.

1. INTRODUCTION

This report was generated as part of the DOE-EERE 'Marine and Hydrokinetic Technology Development and Advancement' grant with project number DE-EE0008097. The objective of this project is to advance the Technology Readiness Level of the Wave Energy Converter (WEC) developed by CalWave Power Technologies Inc. (CalWave) through advanced numerical simulations, dynamic hardware tests, and ultimately a scaled open water demonstration deployment. In Budget Period 2, the key outcomes are deployment and operation of the demonstration unit at an open water site which replicates full scale ocean conditions, and performance and load measurements which are used to validate the high techno-economic performance of the full-scale device, as measured by the "Average Climate Capture Width per Characteristic Capital Expenditures" (ACE) metric defined for the Wave Energy Prize.

This report briefly describes the final system's design but, as a final test report, mainly focuses on the open water testing. For further description of the WEC system the reader is referred to CalWave's system content models.

Using a structured, systems engineering approach, CalWave has developed a submerged pressure differential type Wave Energy Converter (WEC) architecture called *XWave*. The single body device oscillates submerged, is positively buoyant, and moored to the sea floor. CalWave's device overcomes challenges that have faced the wave energy industry by integrating novel features such as advanced load management mechanisms via absorber variable geometry and submergence depth control.

CalWave's xWave WEC design addresses the fundamental challenge in wave energy conversion: the large differential between wave energy flux during typical conditions and rare but powerful storm conditions and extreme events which contribute little to annual energy production but dramatically increase structural costs and thus hinder cost competitive electricity production.

Conventionally, the conversion steps from ocean waves to device oscillations, to the power take-off dynamics, and ultimately to the electrical grid, has been approached as a series of discrete steps, each with their own challenges and solutions. This approach grafts itself well into traditional engineering domains and leverages established modeling techniques, design tools, and industrial processes. However, this segmented approach risks optimizing individual links in the power conversion chain, while creating new challenges and inefficiencies at the interface between the constituent parts.

In contrast, CalWave's approach is considering the entire chain of conversion steps as a single process with intrinsically connected requirements and optimization potential for performance and cost-efficient device design through synergies. With this approach, the limits of one step in the power conversion chain are critical to effectively control the next. Co-optimized WEC hulls, PTOs, and electrical export frameworks must be considered holistically, acknowledging the dynamic characteristics of their adjacent components, to efficiently work together.

CalWave worked together with Sandia National Lab (SNL) and the National Renewable Energy Lab (NREL) on the holistic WEC design, and detailed feedback from specialized partners on hull design, mooring and anchoring specification, and electrical grid interconnection.

2. WEC Testing Overview and Context

Testing Overview

The x1 demonstration device was primarily designed to evaluate full scale equivalent device operation and to validate the overall WEC concept with a first of its kind open water deployment and operation.

- To CalWave's knowledge the x1 was the first submerged pressure differential WEC utilizing a plurality of mooring tethers connected to multiple PTO units deployed in an open ocean environment at a larger size.
- CalWave's x1 system was successfully deployed and commissioned into operation on September 16th, 2021. The initial deployment duration of the x1 system was 6 months but due to the reliability and low maintenance cost for continued operation the deployment was extended to 10 months of operation lasting from September 16th, 2021 – July 18th, 2022.
- The x1 was operating in a 'Normal Operation' mode for 99.1% of the 10 months of deployed time.
- The x1 was fully functional at the time of retrieval in July 2022. If intended, the unit could have continued operation as no signs of degradation were identified.
- Deployment as well as recovery occurred in the timeframe of ~3-5 hours with support from UCSD, Scripps. Staging of the unit and final system commissioning occurred at the Driscoll's Boat Marina.
- Multiple environmental monitoring projects including acoustic noise measurements and anchor surveillance were conducted during the deployment months in collaboration with PNNL and Integral Consulting. Acoustic noise signals were far below thresholds and often non-identifiable.
- CalWave uploaded about 12 updated versions of the SCADA control code with improved controller and operating procedures. The updates were conducted via the data communication cable and a VPN. CalWave staff was not always physically present at San Diego for such operations.
- No major intervention occurred during the entire deployment time. Only minor maintenance such as swapping the sacrificial anodes and cleaning of an externally mounted camera occurred.
- For large portions of the testing, the x1 operated under fully autonomous control meaning that the main controller was responsible for choosing control coefficients, submergence depth control including tidal compensation, load management mechanism opening percentage, and other parameters autonomous 24/7.
- Two CoastScout wave buoys were deployed in immediate proximity to the WEC for high resolution wave elevation measurements and statistical data that was directly integrated into the WEC operational controller. An additional CDIP wave buoy provided additional data which increased the level of data quality and confidence in wave states measured.
- The unit was decommissioned, inspected, and cleaned in July 2022 and was subsequently transported back to the Bay Area for storage at CalWave's facilities.
- No personnel were injured during the entirety of the project; No major hardware was lost or damaged during the entirety of the project.

Figure 1: CalWave's xWave Technology deployed at Scripps, CA, operating fully submerged.

- Due to the inherent requirement to survive and withstand the often much larger sea states (than scaled equivalent sea states), most sub-components and assemblies had to be partially ‘overdesigned’ compared to a full-scale equivalent. Hence, WEC device characteristics such as the power rating of the export infrastructure and/or the individual PTO units cannot be seen as perfectly scaled.
- While the idea of choosing a ‘Scale’ for an open water deployment is somewhat arbitrary the approximate ‘Scale’ of the deployed unit was *1:5*.
- Primarily, the focus was on operating the machine efficiently for ‘mechanical power absorption’ to validate the WEC concept. The electrical backend as well as the rating of the WEC was mostly chosen to support all tests that CalWave wanted to evaluate during this first open water demonstration.

3. Deployment Location and Wave Resource

3.1 Deployment Location and Historical Metocean Analysis

CalWave evaluated multiple different deployment locations during BP1 of the project. Among the potential deployment locations was WETS - Hawaii, Galway Bay – Ireland, Scripps – California, Humboldt Bay – California, Jennette's Pier – North Carolina, and Puget Sound – Washington State. A thorough wave resource analysis as well as location/staging/vessel support/research support analysis was conducted.

Close collaboration with the UC San Diego Scripps Institution of Oceanography (SIO) evolved and it was ultimately decided to focus on Scripps as the deployment location for the demonstration device.

Scripps Institute of Oceanography is a world leading marine science and engineering institution located on the coast in La Jolla, California, just north of San Diego. Scripps operates many specialized marine science facilities, including Scripps Pier extending 300m into the bight north of Point La Jolla. CalWave's WEC was deployed approximately 550 meters off the Scripps Research Pier.

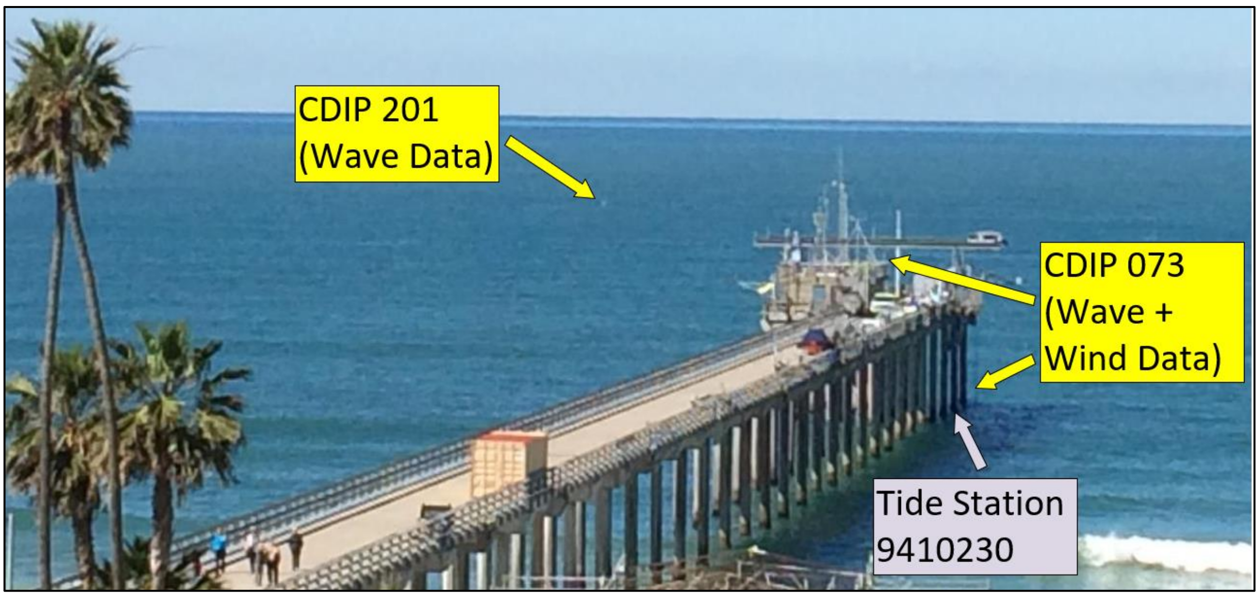

Figure 2: Scripps Pier, CDIP 201 buoy location close to deployment side as well as tide station on the pier. CalWave's onshore equipment was located in a small workshop at the end of the pier.

An umbilical cable was routed from the WEC back to the pier into a small workshop where CalWave's on shore power electronics and on shore SCADA equipment was located. The routing of the umbilical and the approximate location of the WEC relative to the pier is depicted in the Figure below.

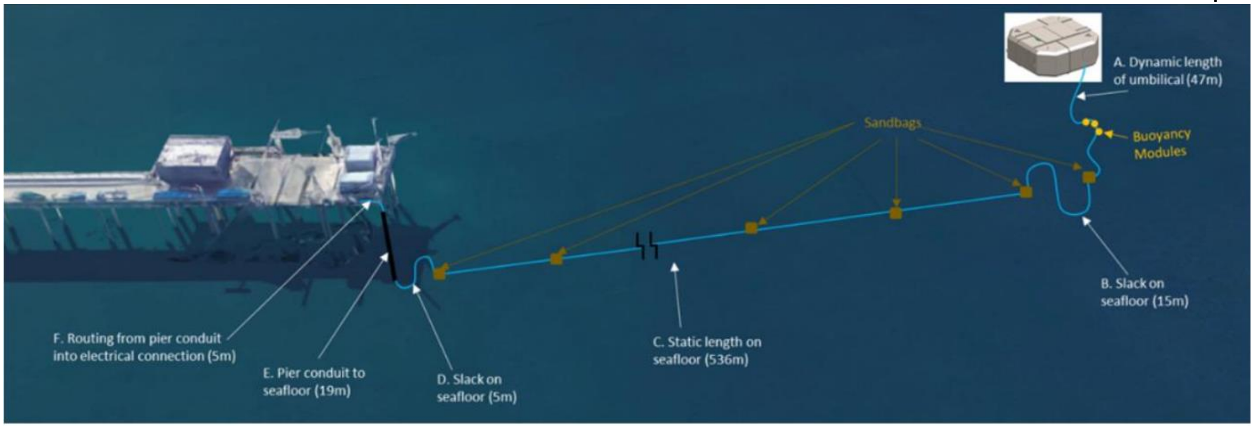

Figure 3: Approximately location of WEC with respect to the Scripps research pier.

The wave climate along the coast of La Jolla is among the most well characterized in the world, thanks to the immediate attention of leading oceanographers and engineers at Scripps Institution of Oceanography, especially the Coastal Data Information Program (CDIP). CDIP Station 201, "Scripps Nearshore", is the closest data source. 5 years of historical CDIP buoy data is available from the CDIP THREADDS server (https://cdip.ucsd.edu/m/products/?stn=201p1&param=waveHs). CalWave's data binning for sea states aligned with IEC 62600-100 for sea state definitions.

In addition to the CDIP buoy data, CalWave deployed two MarineLabs CoastScout buoys for high resolution data collection. A picture of the two buoys right before deployment is shown below. The two CoastScout buoys furthermore acted as additional ATON (Aids to Navigation) buoys.

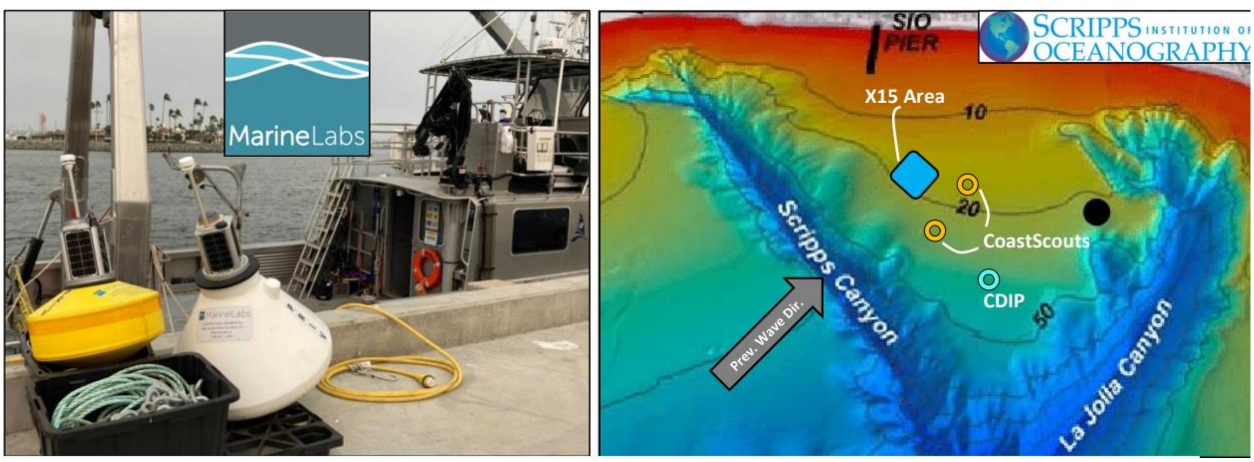

Figure 4: Left: Two CoastScout buoys by MarineLabs waiting for deployment at CalWave's deployment site. Right: Overview of wave buoys, deployment location, and CDIP location.

JPDs of the wave climate in each month are shown in the below Figure demonstrating considerable seasonal variability in wave conditions at the deployment site. Winter months (January-March & November-December) experience more long-period waves, with total energy spread over a larger period and wave height range. In contrast, summer months experience much more concentrated energy.

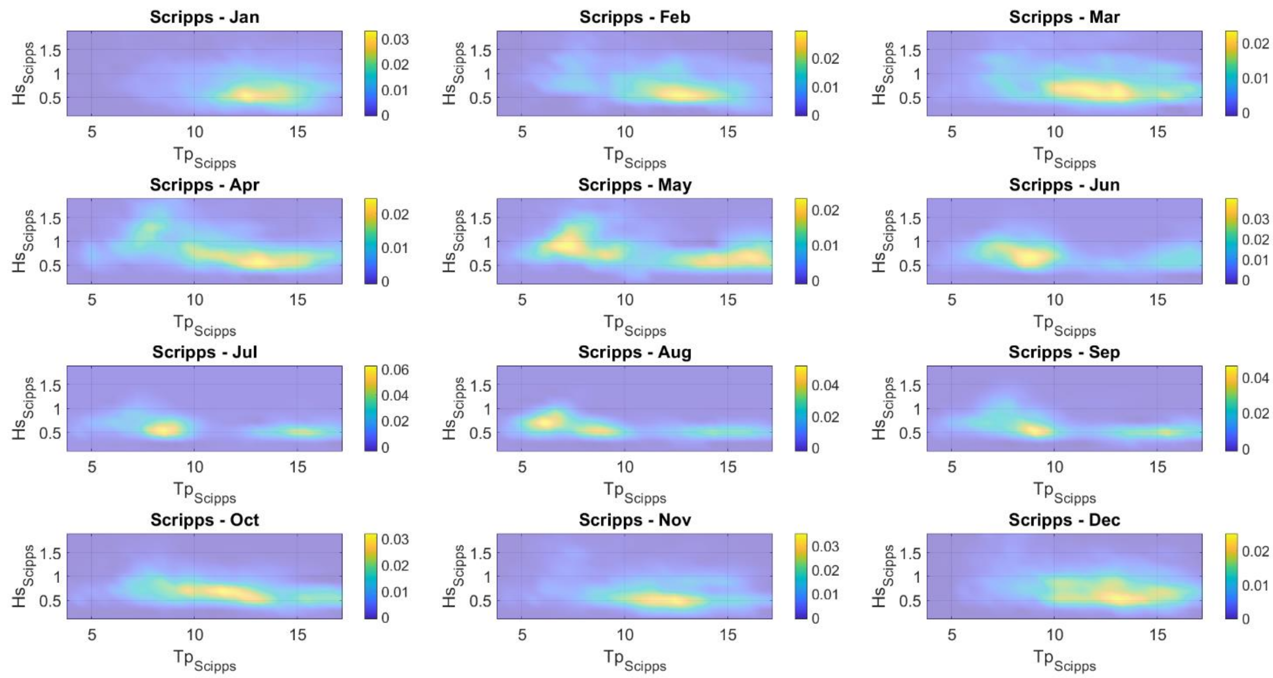

Figure 5: Scripps monthly occurrence JPDs based on 5 years of CDIP (CDIP 201) buoy data.

The average wave power over the year at Scripps is approximately 2.8 kW/m which renders this test site approximately 12 times less 'energetic' than PacWave South. When combining the monthly occurrence JPDs the following annual occurrence as well as energy contribution JPDs can be derived:

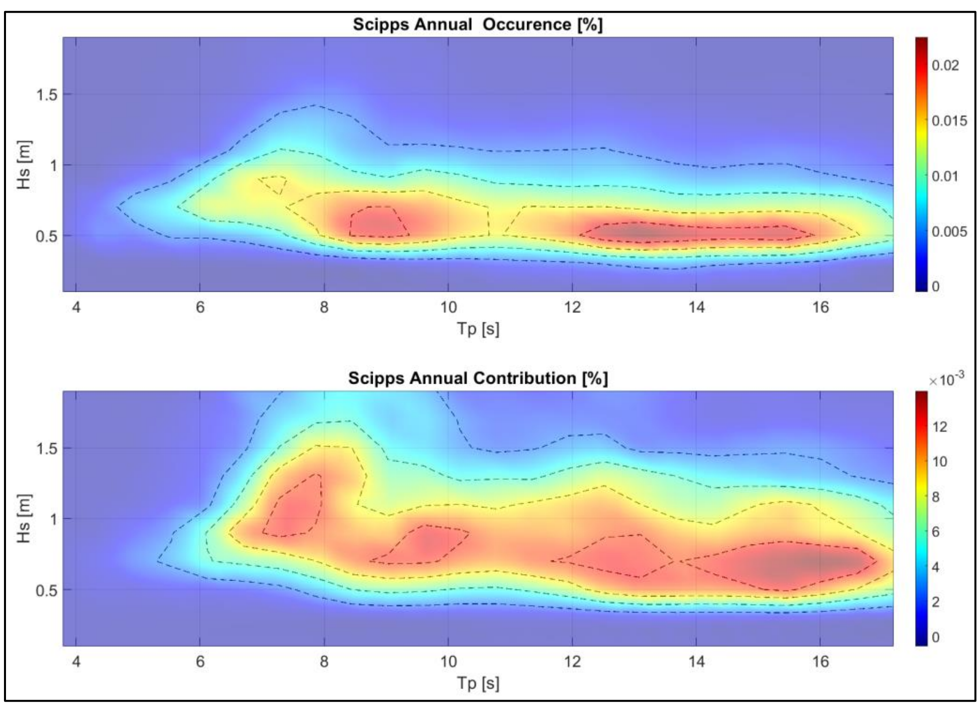

Figure 6: Annual occurrence and energy contribution JPDs based on CDIP 201 data.

The dominant wave direction at the deployment site is 285 Deg with the majority of all wave periods coming from the same direction. The incident wave direction at CDIP201 is predominately from the West-Northwest (285°). Short period wind-waves (Tp 3-6 seconds) can come from a broad 90° cone, though still generally from 285°. As the monthly breakdown of the wave directionality shows long period swells from storms out in the ocean with long periods above 12 seconds can reach the deployment site at an angle of ~245 Deg.

A similar picture is drawn when the directionality is compared against the significant wave height. All significant wave heights that occur at Scripps can be expected from ~285 – 290 Degree. The long swells from ~245 Degree usually entail lower significant wave heights below 1.6 m as the bottom plot shows. The device will be oriented towards the predominant 285° axis, and so the South Pacific storms wrapping around Point La Jolla represent an energetic off-axis load.

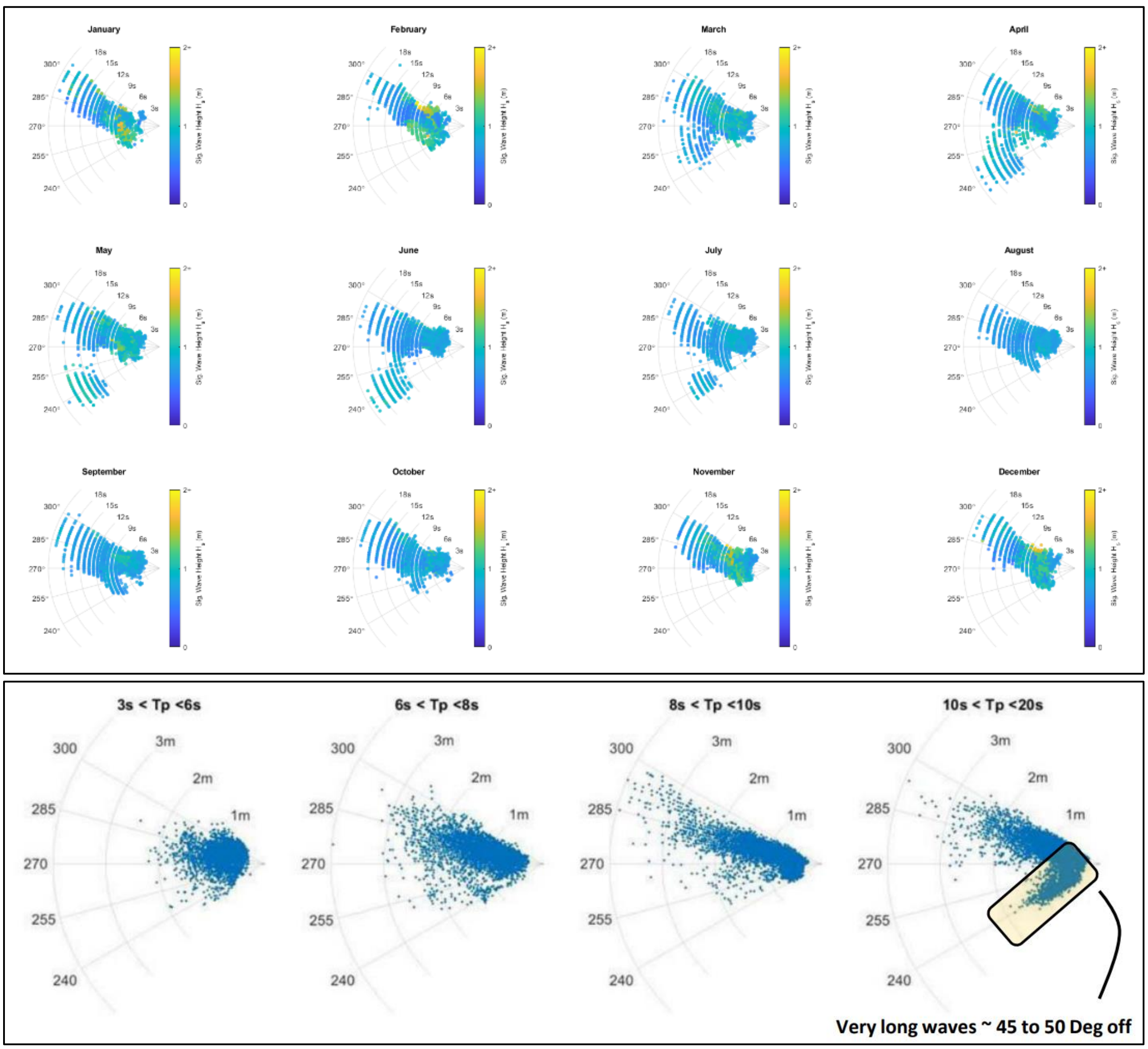

Figure 7: Scripps monthly wave directionality based on 10 years of CDIP (CDIP 201) buoy data.

Another useful perspective on wave direction and peak period is by monthly variation. The off-axis 240° waves can come in any month. The largest waves, above 2m Hs, come from the West-Northwest axis, and only in the “shoulder” testing months of April/May and October/November.

The ocean currents at Scripps are relatively benign with average speeds of 10 – 20 cm/s. Nevertheless, these current estimates were additionally used during the design phase of the umbilical and the safety mooring line. Offset loads on the submerged absorber body were ever so slightly compensated via asymmetric pre-tension of the mooring lines.

Tidal compensation, however, is utterly important for safe and efficient operation of the WEC. The mean tide at Scripps is about +/- 0.6 meter. CalWave developed an autonomous tidal compensation controller into the SCADA system that ensured that the WEC kept its relative submergence depth with respect to the water surface at the desired setpoint despite the changing tide. Current and past tide levels can conveniently be reviewed on NOAAs tide prediction website for La Jolla, CA under https://tidesandcurrents.noaa.gov/noaatidepredictions.html?id=9410230&legacy=1 .

The National Ocean Service has maintained a water level station (#9410230) directly on Scripps Pier, 800m east of the deployment location, since 1924. This station is an excellent reference for water levels during CalWave’s demonstration. The datums at station 9410230 report a Mean Tide Range of 1.126 meters, with a typical daily water level variation of 1.624 meters (the “Great Diurnal Range”). (Note, “water levels” include tides as well as storm surge and other localized phenomena).

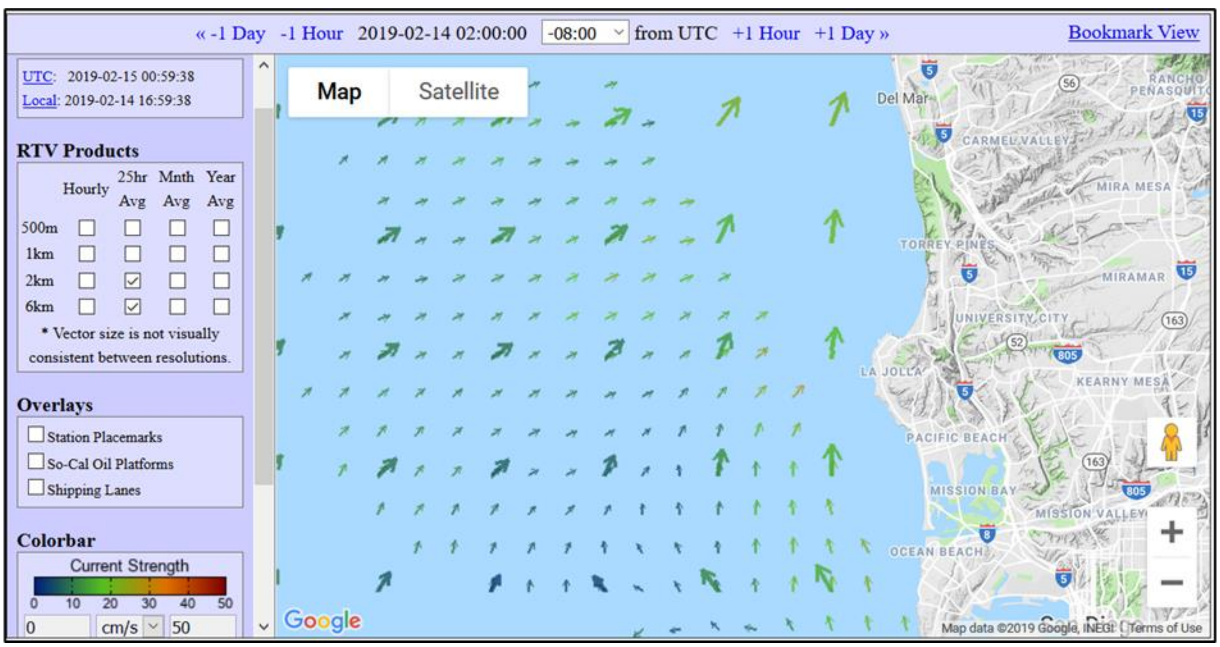

Figure 8: Screen shot of the HFRNet surface current model forecasts from CORDC.

In addition to historic and real-time water level observations, NOAA publishes tide predictions up to a year in advance.

Surface current measurements are not directly available at the deployment site. However, near real-time estimates are derived from a network of shore-based high-frequency radar installations (HFRNet) maintained by the Coastal Observing Research and Development Center (CORDC) at UCSD. These surface current predictions are available at several time and spatial resolutions; a representative screen shot from the HFRNet webpage is shown in above Figure.

NOAA's Center for Operational Ocean Products and Services (CO-OPS) publish current predictions for many "virtual stations" around active ports and harbors, including San Diego Bay. The closest station is PCT0026, ~ 1km west of Point Loma Light and 22 km south of the CalWave's deployment area. Nevertheless, the currents at Point Loma are rather mild, with a peak of ~50 cm/s; a representative plot of the surface currents is shown in the Figure below. CO-OPS publish annual predictions of surface currents.

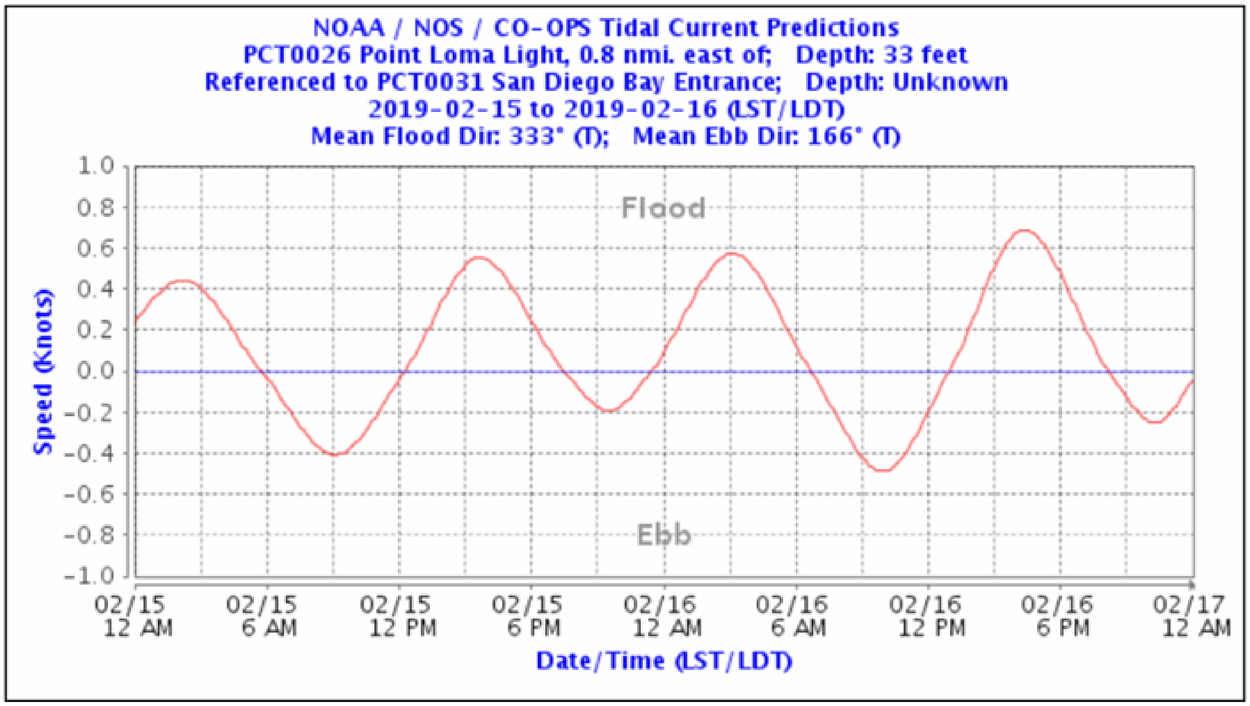

Figure 9: Surface current projects at "virtual station" PCT0026, 22km south of the deployment area.

3.2 Metocean Analysis of Deployment months and Scaling Analysis

During the main deployment month from October 2021 to July 2022 the following significant wave heights were recorded.

The majority of the time significant wave heights below 1 m Hs were recorded with a more consistent, higher level of significant wave heights around 1m Hs during the month of March to June. The high wave elevation resolution of the CoastScout buoys allowed accurate measurement of the maximum occurring wave height in each half of an hour bin.

The average wave direction was measured via the CDIP as well as the CoastScout buoys and is shown in the figure below. As expected, the main incident wave direction of ~285 Deg is quite consistent over the deployment month. An average deviation of +/- 20 degrees occurs frequently. Few storms with off axis wave direction down to ~240 Deg were encountered that lasted only for a few hours.

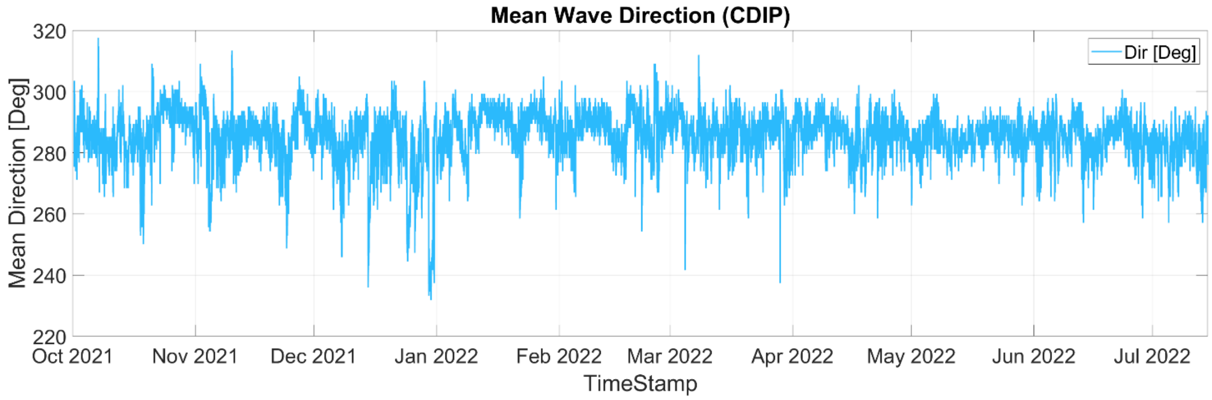

Figure 10: Mean wave direction [Deg] over the months of deployment at Scripps.

When occurrences of sea states are accumulated over all months, the total occurrence JPD can be derived. As before, the PacWave South wave contour at an assumed scale of 1:5 is added to the plot as well as the unscaled WETS contour. The comparison clearly shows that the majority of the sea states encountered lie outside of the relevant range for a 1:5 scale PacWave comparison. However, it can also be seen that a deployment at WETS would have been even more disadvantageous with respect to scaling opportunities.

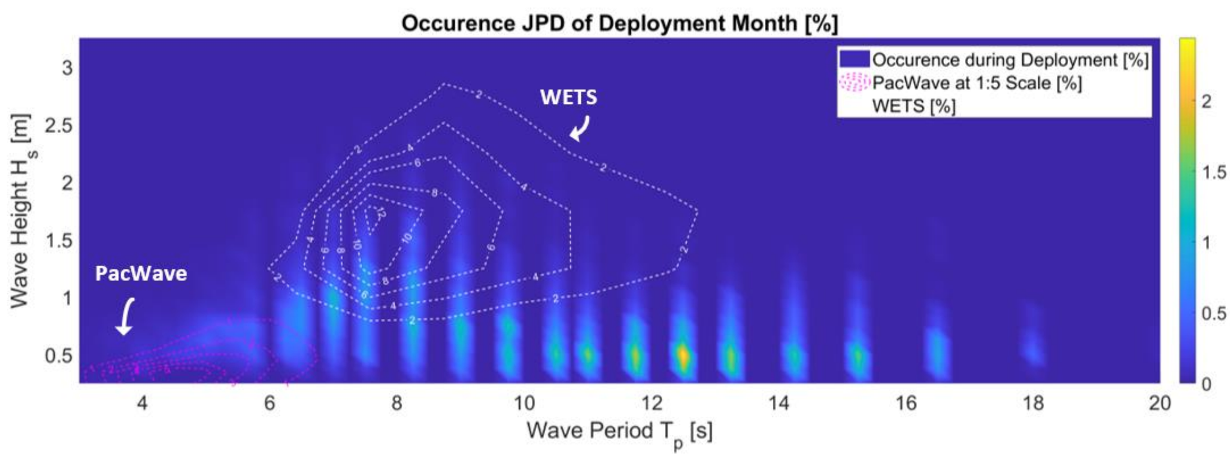

Figure 11: Occurrence JPD of all deployment months at Scripps. The PacWave South JPD at a 1:5 scale as well as an unscaled WETS contour was added to the JPD for comparison.

Additionally, there are some sea states that reached into the contour regions of PacWave rendering the opportunity to assess some wave states for performance of the WEC at an idealized 1:5 scale. Hence, the Scripps test site represented the best opportunity to test a scaled device.

4. X1 SYSTEM

Using a structured, systems engineering approach, CalWave has developed a submerged pressure differential type WEC, *XWave*. This device is shown in Figure 12. The single body device oscillates submerged, is positively buoyant, and moored to the sea floor. CalWave's device overcomes challenges that have faced the wave energy industry by integrating novel features such as advanced load management mechanisms via absorber variable geometry and submergence depth control.

Figure 12: X1's prismatic absorber body during a lifting operation.

CalWave's *X1* combines multiple unique features distinguishing it from other device designs:

- **Multiple degrees-of-freedom for high power absorption and load distribution:** Although most WEC devices oscillate in more than a single degree of freedom (DoF), energy is often only absorbed from a single DoF. However, absorption can a) be significantly increased and b) evened out on the wave period time scale by utilizing more than a single DoF in the absorption process. CalWave's absorber and mooring design is derived from a kinematic modal optimization allowing for true energy extraction in multiple degrees of freedom (Surge, Sway, Heave, Pitch, Roll) which allows for high wave power conversion efficiencies as well as a lower peak-to-average power absorption. The device's multiple tethered topology controls multiple degrees of freedom separately, further optimizing operations in different bandwidth-limited wave states. Although kinematic control of the device follows cable driven parallel robot approaches which are well understood, optimization of these mechanisms in correlation with an impedance matching approximation for hydrodynamic device control forms an innovative device approach in the field of wave energy conversion.
- **Load distribution among multiple Power Takeoff units:** Multiple, independently controlled PTO units facilitate kinematic control. Electrical power is aggregated on a shared DC voltage bus, thus reducing the dynamic fluctuations before export via a single grid-interfacing inverter.

- **Wave Load Management and hydrodynamic tuning via geometry and depth control:** As part of CalWave's holistic device design which supplements the PTO control strategy, a wave load management mechanism via adjustable absorber geometry was integrated from the beginning of the technology development. Complementary to the submerged operation of the device this unique ability to alter geometry between sea states and specifically for severe/extreme wave states effectively reduces the primary wave-to-structure excitation loads, analogous to pitch/yaw control of wind turbines.

5. x1 IOM&D Activities at Scripps

This section focuses on the Installation and Operations of the open water demonstration to be conducted in collaboration with University of California, San Diego (UCSD) near the Scripps Institution of Oceanography (SIO) pier. All operations were coordinated with University of California, San Diego (UCSD) Scripps Institution of Oceanography (SIO) staff as well as local vessel operators and marine operations contractors.

Adjustments to sequences for the preset operations can be made in the field with the use of Management of Change (MOC) process. The respective management personnel must be contacted and contribute to determining a safe and effective method of performing operations. The current and weather conditions must be deemed favorable before starting operations.

Before the start of any operations, all vessels and individuals involved hold operational procedure review and safety meetings to prepare for upcoming operations. All equipment is checked at this time and the equipment verified for availability for upcoming operations. Additionally, Hazard Identification (HAZID) reviews are conducted with relevant parties in advance of any planned operation, in order to provide adequate time to address any raised concerns.

The vessel captain and CalWave representatives approve any deviations that become unavoidable in the field during the installation process. VHF working channels are identified at pre-operation briefings.

5.1 General Safety Guidelines

Operational procedures were written in part to provide for a safe and efficient operation. Before operations began, the vessel operator and CalWave staff held a Hazard Identification (HAZID) meeting to review the entire job, following these step-by-step procedures. As the site owner, SIO staff were invited to attend all safety and operational briefings, regardless of the inclusion of SIO staff or vessels in the operations.
In addition to CalWave and any vessel operator safety guidelines, all operations were conducted consistent with SIO rules and regulations.

The following safety issues were addressed during safety meetings:

- Hand awareness.
- Proper personal protective equipment (PPE) required.
- Unsafe conditions will be reported and will be corrected.
- Employees will identify and correct the unsafe acts of coworkers.
- All incidents, injuries, and illnesses, regardless of how minor, will be reported immediately.
- All employees must be aware of their appropriate muster list assignment.
- All tools must be stored and maintained when not in use.

- Fingers, arms, and legs must be kept clear of all pinch points.
- Proper tag lines will be used to position and control loads.
- Proper lifting techniques must be used when manually moving loads.
- All personnel are required to wear a full body harness any time they are working at height and whenever specified by the vessel captain.
- Good housekeeping increases the safety of any job. Work areas must be kept free of trip, slip, or fall hazards.
- Employees must inspect all lifesaving equipment upon arrival and prior to departure of the vessel. All discrepancies are to be reported to the vessel captain.
- Proper eye protection will be used during welding and cutting operations.
- Lightning and other adverse weather conditions must be taken into consideration, and operations must be suspended when meteorological or sea conditions pose a danger to personnel working aboard vessels.
- Contingency plans of the vessel will be followed to prevent pollution events should a hydraulic hose break or other equipment failures pose a danger to the environment.
- Provisions for adequate communication between vessel crews, and pier side staff must be present to ensure coordination of all parties in their assigned duties. SIO recommended one designated radio channel to be selected and reserved for use by the parties involved in the marine operation.
- Crew fatigue factors must be considered. The crew will be adequately sized to offer ample rest periods on long duration jobs by rotation of crewmembers.
- Consideration of extremely hot or cold weather conditions must be made and crewmembers rotated in work assignments to keep exposure to excess environmental factors within tolerable limits. This is essential in preventing cases of heat exhaustion or hypothermia.
- In the event that variance from these written procedures becomes necessary, all supervisory personnel are to be made aware of the change and agree with the new procedure.

The safety of personnel and the environment are the first considerations during any operation. No personnel were injured during the entire project.

5.2 Project Location

The specific area for the WEC deployment was approximately 540 meters from the Scripps Institution of Oceanography (SIO) pier, at a heading of 276.9 (SEE).

5.3 Shore Side Monitoring and Control Station

Shore side monitoring and control occurred at the Ellen Browning Scripps Memorial Pier, operated by SIO. For the duration of the test period, CalWave entered into a lease agreement with UCSD and had 24-hr access to the pier facilities.

Figure 13: SIO Pier

Figure 14: Instrumentation Shed - inside

Transit Routes

The contracted vessels transited to the test site along the agreed transit routes as determined by vessel mobilization location and operations being performed. For transit operations involving equipment under tow, contingency planning for towline failure was included in operational planning and hazard identification, including considerations for spare towline and/or additional line handling vessel.

A list of transit routes to site is provided below.

Table 1: Transit Routes.

Vessel	Route	Distance (nm)
BW1	1 - SIO pier to Test Site	0.3
BW1, R/V Beyster	2 – Driscoll Mission Bay to Test Site	8.9
R/V Beyster	3 - Pont Loma to Test Site	16.5
R/V Beyster	4 – Point Loma to Driscoll Mission Bay	10.1
DB San Diego, Katherine	5 – National City to Test Site	22.2

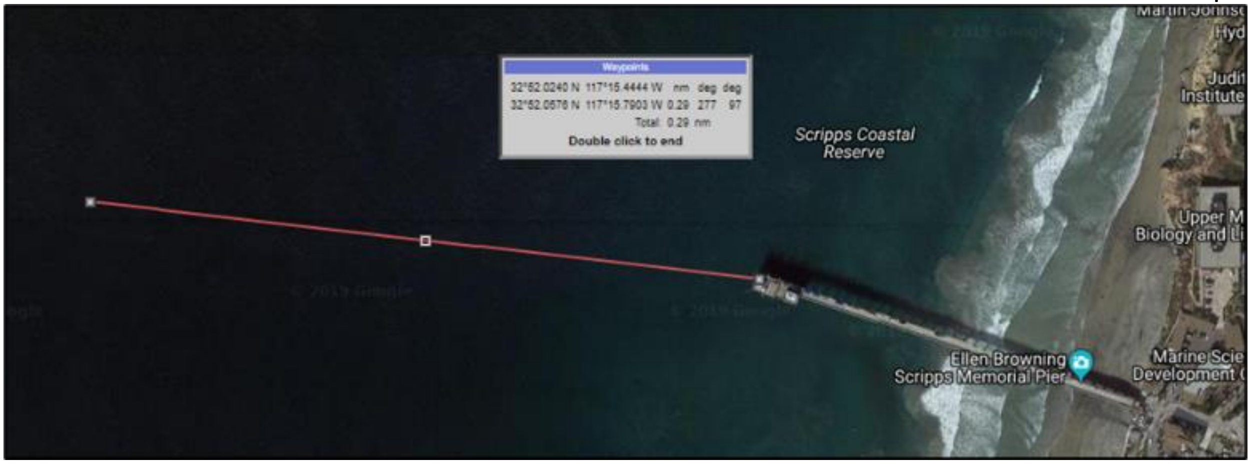

Figure 15: Transit Route 1: SIO Pier to Test Site.

Figure 16: Transit Route 4: Point Loma to Driscoll Mission Bay

Figure 17: Transit Route 5: National City to Test Site

5.4 Vessels & Operators

Support Vessel: R/V Beyster

The research vessel Bob and Betty Beyster (R/V Beyster) is a purpose-built coastal research vessel designed for efficient operations offshore in Southern California. The Beyster is owned and operated by Scripps Institution of Oceanography (SIO). This is the primary vessel used during the test period.

Figure 18: R/V Beyster.

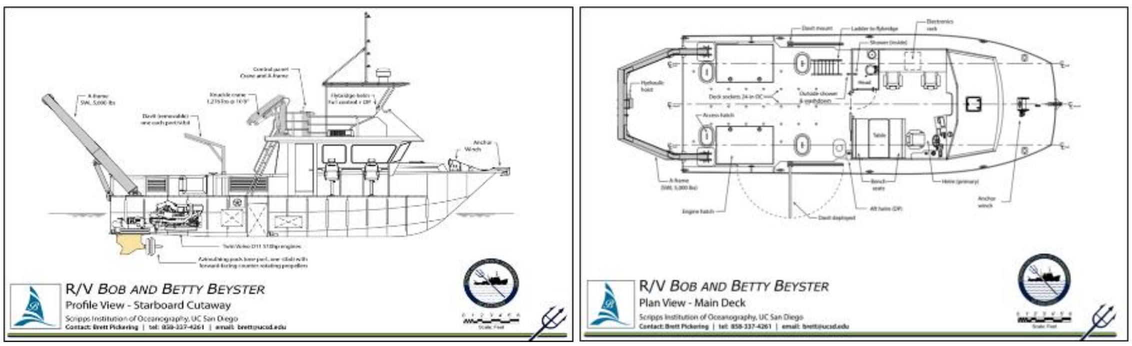

Figure 19 R/V Beyster -Starboard Cutaway & Main Deck Plan View

Vessel Specification	
Length	42-ft
Beam	16-ft
Freeboard	3-ft
Stern A-frame Capacity	2.5 tons
Stbd Knuckle Crane Capacity	660-lbs, 17-ft reach
Dynamic Positioning System	DPS
Deck Space	192-sqft
Max Speed	38-kts
Cruising Speed	25-kts

Figure 20 R/V Beyster Vessel Specifications

Vessel Operators

The primary vessels used in this project were owned and operated by UCSD Scripps Institution of Oceanography (SIO).

Dive Services Providers

For non-commercial diving UCSD research divers were used. However, use of the UCSD research divers was limited to inspections, seafloor surveys and similar low-risk, non-complex diving.

5.5 Project Operations

5.5.1 Anchor Site Survey

The survey consisted of identifying the specific anchor locations, including verifying, and obtaining evidence (photographs and video) of seafloor conditions between and around anchor locations. It was important to orient the anchors such that the prevailing wave direction is in between anchors and ensure the anchors are appropriately spaced. Additionally, seafloor surface samples are required in order to perform geotechnical lab analysis to validate against previous geotechnical analysis performed near the proposed site and support detailed design of the anchor blocks.

The anchor grid has been defined from review of available seafloor data reports and GIS tools. This location was chosen because of the sandy benthic profile with no apparent obstructions and the shallow slope. The available seafloor data indicated an anchor spread with approximately 1 m of depth variation resulting in a slope of less than 5 degrees from any anchor point to the center of the grid.

At target depth, each diver is allocated a maximum of 40 min bottom time without the need for decompression (a safety stop is required). Multiple dives at this depth are allowed with adequate surface interval time. It is anticipated that a team of two divers can accomplish the survey by performing multiple dives.

Mobilization: Anchor Survey & Marking

These procedures were written in anticipation of using a small dive support vessel. The vessel was mobilized with all the necessary equipment to complete the scope of work and deployed from SIO pier.

Table 2: Equipment List: Anchor Survey & Marking

OWNER	DESCRIPTION	SIZE	QTY
19’ Boston Whaler (BW-1)			
UCSD	Dive Support Equipment		1
UCSD	Weighted downline		1
UCSD	Underwater camera/video system	Sony a6500	1
UCSD	Backup underwater video system	GoPro	1
CalWave	Sealable bags for collecting seafloor sand	Minimum 1.56L (95in^3)	1
CalWave	Sealable bags for collecting seafloor sand	Minimum 0.42L (25in^3)	3
SIO Pier			
UCSD	Lift rigging to support vessel deployment & recovery		1

Operations Sequence: Anchor Survey & Marking

The following sequence details the work performed for the anchor survey operation. Planned downtime per dive was 10 to 15 minutes. Brief surface intervals are required between dives adhering to no-decompression constraints as determined by dive computers and validated with dive charts.

Estimated anchor points were calculated using the Great Circle Calculator, written by Ed Williams, with Earth Model WGS84/NAD83/GRS80. Conversions between datum sets have been calculated using the Earth Point calculator. Datum sets are provided with an accuracy of approximately 0.182 meters. Current assumptions for mooring geometry accounts for up to 1 meter of offset per anchor. It was anticipated for the Anchor Survey operation to take 3-4 hours to complete.

Setup & Methodology

While mobilizing equipment, a safety briefing was conducted, and the operations plan was reviewed by all parties. The vessel was mobilized on the pier and deployed using the pier crane. All parties boarded the vessel by way of chain ladder from pier.

At each anchor location, the GPS coordinates and depths were validated by shipboard GPS and annotated. A downline was deployed at each site to provide visual reference on seafloor. Divers were then deployed. Divers obtained video evidence of seafloor conditions and sediment samples at each site.

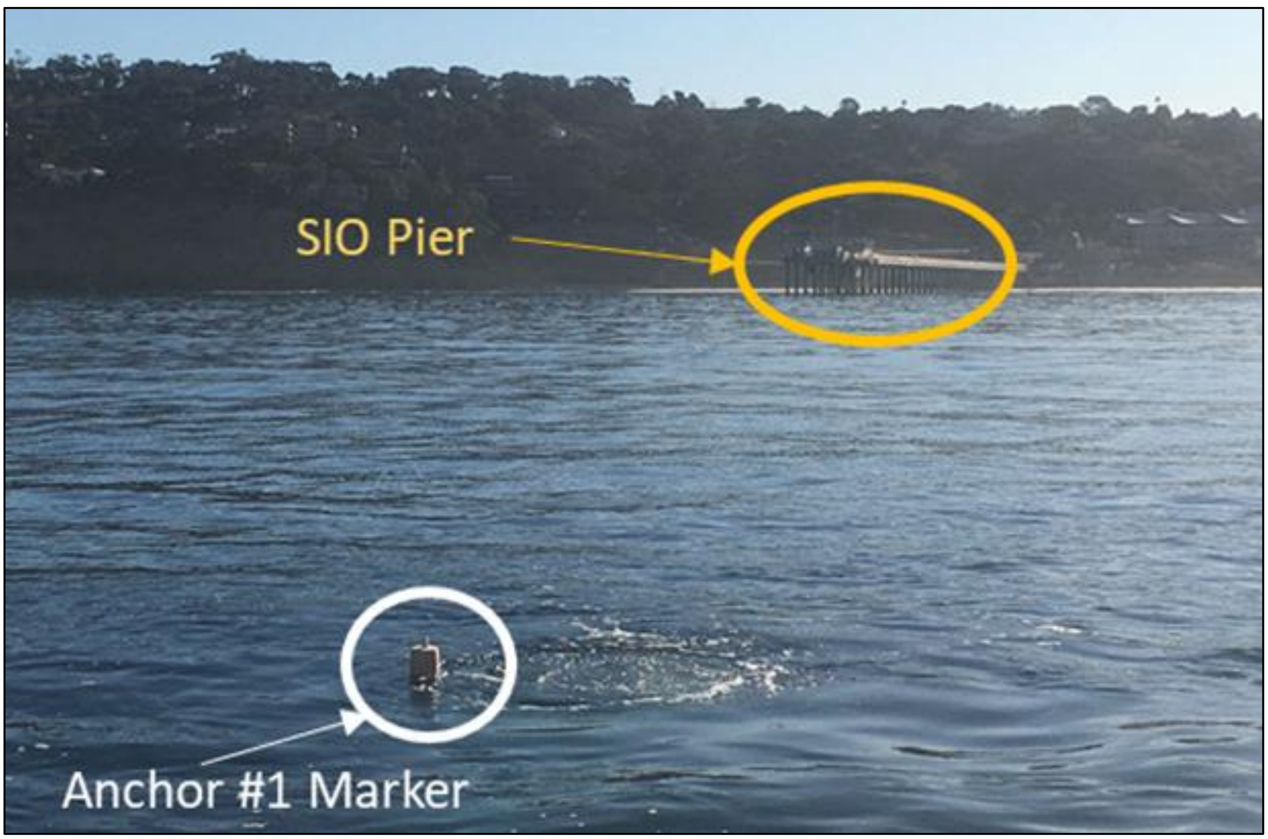

Figure 21 Visual Reference of Anchor Point #1 Distance to SIO Pier

Timings

Mobilization and pre-briefing commenced at dive shed at approximately 07:00am. Vessel arrived on-site at 08:40am and departed site approximately 10:45am.

Seafloor samples were delivered to SCST labs in San Diego. Results from the sediment analysis was included in the detailed design of the anchor. Below are photographs of the vessel GPS at each anchor point, indicating time of arrival at site, GPS coordinates and depth.

Anchor points 1-3 were surveyed at locations accurate to within the margin of error in the vessel GPS. Anchor point 4 is believed to have also been surveyed accurately, however due to a glare on the vessel GPS the photograph had to be retaken after deploying the downline and it is believed that the difference between Target and Survey is due to the drift of the vessel in the time between deploying the downline and retaking the photograph.

As the survey was completed on a rising tide, the target depth for the anchor points needed to be corrected for the tide at time of survey. The below figure shows the approximate tide at the Scripps Pier tide station at time of survey for each anchor.

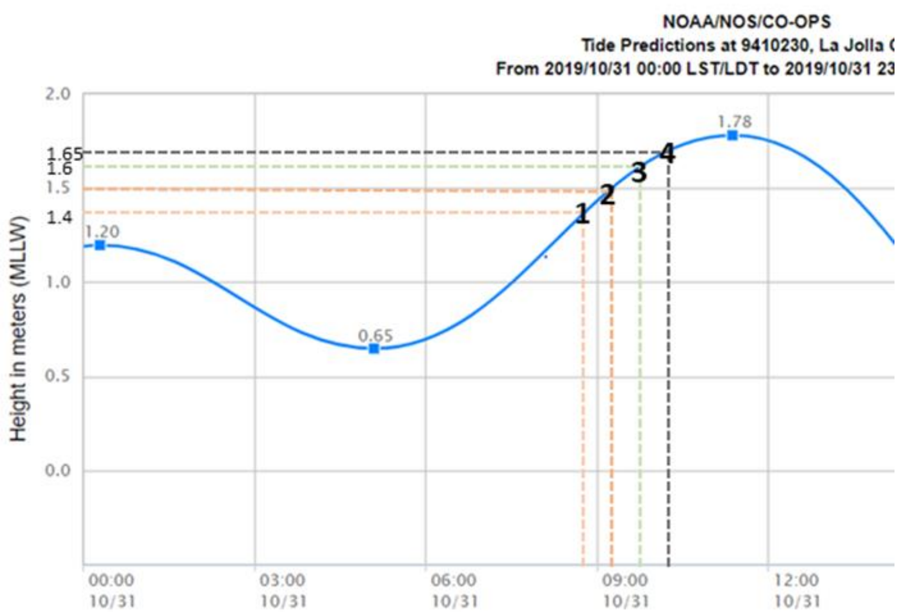

Figure: 22 Tides at time of survey.

On average the surveyed depth was ~1 ft deeper than anticipated, which is well within an acceptable limit. Equally as important as actual depth at anchor is the differential in depth between anchor points. A target was set to find a suitable anchor location with a slope of less than 5%. However, as presented below, the actual depths surveyed slightly exceed this target (5.3%). This has been reviewed and determined to be an acceptable deviation. All anchor sites were free of debris, obstructions, or macrobenthos.

The anchor installation vessel mobilized was brought to the test site. For each successive anchor placement, the ROV Pilot intended to deploy the ROV to locate the marked anchor position, while the anchor center padeye was rigged for deployment. A line (anticipated ¾" nylon three strand) is connected to the off-center lift hoist ring secondary attachment point which will be passed to the R/V Beyster to be used as a tag line to ensure anchor orientation and position and upon successful anchor deployment left in place connected to a marker buoy. The anchor was then lifted over the side and lowered over the pre-marked anchor position, with communication coordinated between the ROV Pilot and Crane Operator.

5.5.2 Umbilical Lay

During initial deployment of the umbilical, prior to the WEC deployment, the connector was capped, wrapped in plastic, and secured to the strain termination. The strain termination was then secured to anchor #2, allowing for the umbilical connector end to be recovered by divers during WEC deployment operations. During this initial deployment, and any subsequent period when the umbilical is deployed and not connected to the WEC, the seafloor configuration would be as pictured below.

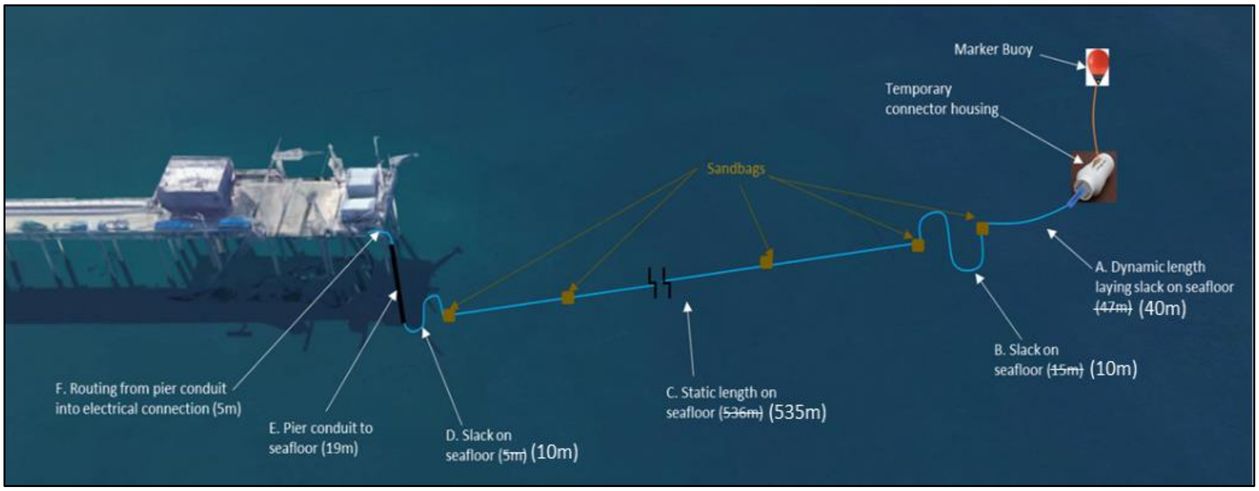

Figure 23: Umbilical Lay Location; WEC not Deployed.

Mobilization: Umbilical Cable Installation

Mobilization primarily occurred at R/V Beyster home port in Point Loma, with the umbilical transfer to the vessel occurring at Driscolls Mission Bay Marina.

In order to prepare the umbilical for deployment, the wooden drum provided by the manufacturer (with strain termination facing out) was transferred to a reel stand. The cable was spooled out in its entirety in order to be re-spooled with the strain termination on the inside of the drum and the un-terminated end facing outwards. The strain termination was secured to the inner wall of the drum and the cable was wrapped around the drum by hand, under tension, to ensure alignment of wraps along the base. During this operation, one individual fed the cable on-to the drum, and another ensures wrap alignment and tension.

The spooling was stopped as per the marking table to allow markings and abrasion protection to be placed on the cable to allow for visual verification of adherence to lay table during deployment. Additionally, several places near the ends of the cable were marked with colored tape to indicate other critical locations (e.g., placement of weights and buoyancy elements). Any time the deployment drum was stopped, care was taken to ensure constant tension is reapplied prior to restarting the spooling process.

The umbilical cable on the wooden drum weights approximately 775 kgs, the reel stands weights approximately 942 kgs. Therefore, the total weight of the umbilical on the reel stand is 1,716 kgs. It was initially anticipated that a shore crane at MARFAC would be used to transfer the umbilical and reel stand to the stern deck of the R/V Beyster. However, due to logistical efficiency it was instead determined to transit the R/V Beyster from her home point to Driscolls Mission Bay Marina the evening prior to deployment and use the marina crane to transfer the umbilical to the vessel. This allowed for the R/V Beyster to tie up overnight at Driscolls and depart pre-dawn on the day of the operation.

During the deployment the A-frame crane was used with the assistance of a block to deploy the cable. The apparent weight of the suspended umbilical cable was calculated to be approximately 13 kgs in the shallow water near the pier, gradually progressing to 21 kgs at maximum depth, near the test site. In order to allow one crew member (Crew #1) to maintain focus on paying out the cable with constant tension, a second crew member (Crew #2) spools the cable off the reel, feeding to Crew #1. Due to risk of drum inertia, an additional crew member will be on deck to assist with handling the wooden drum. Additionally, a Prusik knot was tied to the cable, with crew sliding the know along the cable as it is deployed. This was provided as a safety mechanism to prevent the cable from deploying uncontrolled.

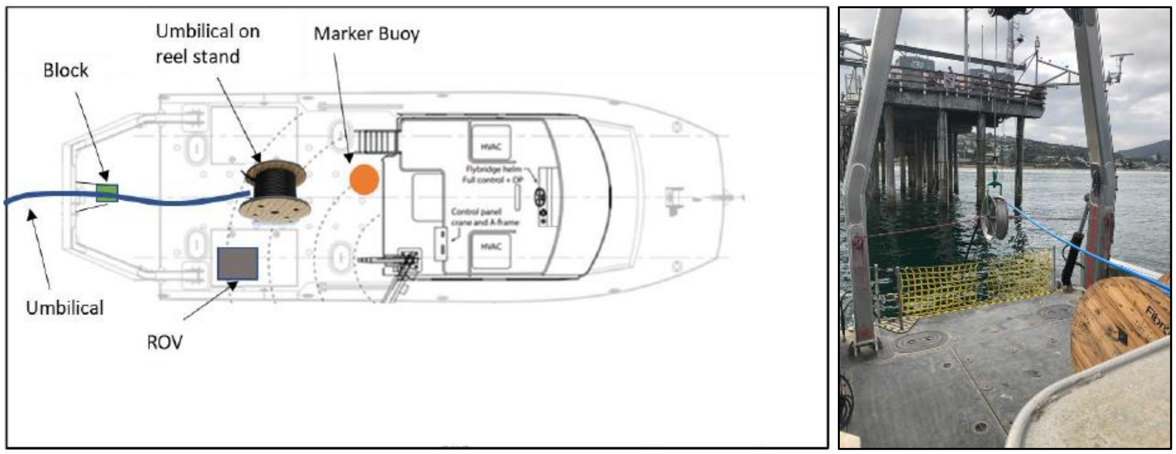

Figure 24: R/V Beyster Deck Layout.

Results

The cable lay operation was executed as planned. Points of note are that the deployment angle is possible to roughly approximate viewing from the deck. It was briefly discussed to deploy a drop camera to understand lay angles more accurately, but decided the value added from that would not outweigh the complexity and risk of additional equipment in the water. The use of the prussic on the cable while being deployed was helpful but does take effort to manage. Additionally, it is important to note that this cable is relatively small and therefore manageable by hand and with the deployment equipment used, a larger or armored cable would be more appropriate to deploy with a mechanical spooler.

Figure 25: Left: RV Beyster with loaded umbilical reel. Right: RV Beyster during spool out of the umbilical.

Timings

Step #	Activity	Est Hours	Act Hours	Diff
T	Transit to SIO Pier (16.5nm @ 10kts)	1.5	1.5	0.0
1	Secure unterminated end of umbilical to SIO pier with spooler on vessel (transferring to/from pier to Beyster)	3.0	2.0	-1.0
2	Transit to test site via lay table	1.5	1.5	0.0
3	Secure WEC end of umbilical to marker buoy & deploy	2.0	1.0	-1.0
T	Transit to home port	1.0	1.0	0.0
	Total Time Estimate (hrs.)	**9.0**	**7.0**	**-2.0**
	Total Time On-Site (excluding transit to/from site)	**6.5**	**4.5**	**-2.0**

5.5.3 WEC Installation and Commissioning

In preparation for WEC installation (and during transportation), the mooring belts were wrapped under and around the hull and secured to the top of the hull with standard lift/tie off hardware. Connection hardware for the PTO Mooring Belt is suitable for connection with standard marine shackles.

Securing the PTO Mooring Belt in this configuration allowed vessel crew access to disconnect the belt from the attachment point for connection with the mooring lines.

The towline was connected to both the vessel (R/V Beyster) and the WEC with a single V-bridal. The V bridals is connected to the tow vessel, passed through the tow shackle (1-1/2” galvanized Crosby shackle, which has a sufficient working load limit of tons) and secured back to a second fastening point on the tow vessel. This configuration allowed for quick adjustment of tow length by paying out or pulling in one end of the tow line, which additionally allowed the wear point on the tow line to be periodically adjusted.

This bridal configuration resulted in an approximate 11° uplift angle at tow point connection, well below the 30° allowable based on tow point design. This geometry is shown for the WEC below.

This tow length is variable depending on weather conditions and vessel traffic, but was roughly 4 times the vessel length, exceeding the recommended minimum 2-3x vessel length towing. The tow was initially established in a significantly shorter configuration while inside the marina and lengthened once outside the marina area. Additionally, a drogue was attached to the trailing end of the WEC to assist with lateral stability during tow. A small safety observation vessel accompanied the R/V Beyster for the duration of the tow.

Once arriving at the test site, the R/V Beyster was positioned windward to allow for station keeping of the WEC during the installation process. CalWave staff transferred from the tow vessel to the WEC to de-rig the mooring belts in preparation for making mooring line connections. The dive team secured their vessel to the marker buoy attached to the smaller clump weight. A diver swam to the WEC and was passed down the rigged shackle and swivel for the mooring line connection to anchor. The diver cleared the WEC, and the remaining mooring line and associated hardware was over boarded, allowing the diver to bring the shackle to the anchor and make the connection. This process was repeated for the remaining mooring lines in sequence 3->4->1->2 therefore securing the leeward side of the WEC first while the R/V Beyster maintained the WEC position at the center of the mooring grid. An additional line and lift bag was available should additional force be needed to bring the shackle to the anchor (by lashing the line to the shackle and through the anchor swivel and inflating the lift bag). With an additional line used to support the weight of the cable, the diver held the strain termination in position while staff onboard the WEC connected the strain relief and mated the electrical connector after verifying dead both on the pier and via Wi-Fi communication to the WEC. Staff onboard the WEC then handed down each of the three umbilical buoyancy modules for the diver to secure to the mooring line at the pre-marked locations. Lastly, the safety line was connected between the marker buoy and the WEC.

At this point, the dive team departed the site and CalWave staff transferred back to the R/V Beyster, which remained on station while the electrical connection was made at the pier and the WEC completed functional and submergence checks. Once all tests were completed successfully, the R/V Beyster departed the site.

Demobilization: WEC Installation & Commissioning

Demobilization shall occur at each vessel’s home port, depending on storage locations of any CalWave owned equipment. Any requirements for lifting equipment, including recovering the line handling vessel to SIO pier will be coordinated in advance with all parties (this section to be updated once equipment and material are further defined). Once control of the WEC is verified as transferred to the SCADA system at the SIO pier, the WEC Operator on-board the R/V Beyster will remain hands-off WEC controls. UCSD will be informed when all vessels have departed the site.

Results

The WEC installation and commissioning was executed as planned. Points of note are that the shape of the WEC and the single point tow arrangement did give the WEC some lateral movement and drag during tow; the drogue was quite helpful with lateral stability but did add to the drag. The shallow freeboard did lead to the WEC nosing under when the tow vessel exceeded roughly five knots, even with the uplift angle on the tow line. For towing the next larger scale WEC in potentially rougher sea conditions a more sophisticated towing arrangement will be preferred.

Figure 26: WEC Arrival at Test Site & Functional Checks.

5.5.4 WEC Inspection & Maintenance

For the first month of deployment, the WEC was continuously monitored from the CalWave shore-based operations station as commissioning and system tests were undertaken.

Periodic system checks at the beginning of each deployment month were be executed to ensure SCADA communication was working, all sensors were responsive and in range, active control of PTO units were available, load management via geometry control was functional and device submergence depth change capabilities were ensured. These tests were executed as a standard test routine and manually started. This ensures that the wave environment is suited for execution of the standard test protocol.

From then on, the WEC was monitored periodically by the CalWave on-call duty manager, with automated alarm functionality (e.g., alarms audible/viewable from cell phone or another mobile device). Periodic dive inspections were performed by UCSD based on their availability and alignment with other diving operations in the area.

Inspection Checklist

The SCADA continuously monitored critical parameters while the WEC was in operation. Additionally, CalWave maintained logs to identify any trends that could have been of concern.

The following points were visually inspected on a regular basis by UCSD divers.

- Hull structural damage, biofouling, or corrosion
- Mooring twists, kinks, biofouling, or signs of damage
- Navigation lights in place
- Umbilical cable connection, Lazy S configuration, and touchdown points at WEC and SIO pier
- Evidence of marine mammal interaction
- Anchor evidence of dragging, biofouling, corrosion, and structural integrity

- All connection hardware

Results

Dive inspection operations were conducted periodically by UCSD dive team based on availability and as requested by CalWave. The site was inspected more than what was necessary due to the nature of an early-stage pilot demonstration project, and the proximity and flexibility of the UCSD dive team.

Very little corrosion was identified during these inspections. Bio growth was more significant though it is important to note that all moving parts were largely self-cleaning and marine growth on static areas did not have noticeable impact on WEC operations. The marine growth was much more prominent on stainless steel surfaces compared to painted surfaces. We also found that the anodes on the mooring line elements were somewhat undersized and had to be replaced during the deployment, while the anodes for the hull structure were somewhat oversized and less than half consumed during the deployment period.

5.5.5 WEC Environmental Monitoring

CalWave collaborated with the PNNL Triton initiative as well as with Integral Consulting on different environmental monitoring aspects. The Triton Initiative targets to reduce barriers to testing marine energy devices by researching and developing monitoring technologies and methods to understand potential environmental impacts.

A 360-degree underwater camera was deployed on a lander close to the anchor to characterize artificial reef and fish aggregating effects around the x1 WEC. The lander was deployed in La Jolla from a small boat using a davit on a sandy bottom at around 20 m of water depth, off the Scripps Institution of Oceanography's. The system was deployed three times a day for three consecutive days. Results of this assessment can be reviewed in depth in the following paper:

> Hemery, Lenaïg G., Mackereth, Kailan F., Gunn, Cailene M., and Pablo, Edward B.. Use of a 360-Degree Underwater Camera to Characterize Artificial Reef and Fish Aggregating Effects around Marine Energy Devices. Switzerland: N. p., 2022. Web. doi:10.3390/jmse10050555.

Integral Consulting furthermore deployed the NoiseSpotter. To characterize wave energy converter (WEC) sounds relative to ambient, environmental, and anthropogenic sounds, the Integral team deployed the NoiseSpotter® (DE-EE0007822; Raghukumar et al., 2020) near an operational pilot-scale WEC, developed by CalWave Power Technologies Inc in November 2021. The NoiseSpotter® is comprised of a compact array of three acoustic particle motion sensors that measure acoustic pressure and the three-dimensional particle velocity vector associated with the propagation of an acoustic wave in real-time. The results of the deployment can be reviewed in the following paper:

> Raghukumar, K.; Chang, G.; Spada, F.; Petcovic, D.; Boerner, T. (2022). Acoustic Characterization around the CalWave Wave Energy Converter [Presentation]. Presented at UMERC+METS 2022 Conference, Portland, Oregon, US.

5.6 Decommissioning and Site Remediation

Recovery & Decommissioning occurred in the reverse sequence of Installation & Commissioning. Once all CalWave owned equipment is removed from the test site, UCSD divers performed inspections to verify if any further site remediation is required.

The following activities were performed as part of the site decommissioning

Action
CalWave Team Arrive in San Diego
Prep site at Driscolls
Recover WEC
Umbilical Prep & Pre-Dive
Recover Umbilical, ATON Buoy, & CoastScout Buoys, including Anchors
Prep for Transport
Load Out, CalWave Team Depart San Diego

5.6.1 WEC Recovery

The recovery of the WEC was conducted based on the previously provided operational planning, but in reverse sequence. Upon arrival at site, the WEC Operator on board the tow vessel established Wi-Fi connection to the WEC and opened the umbilical contactor. Once staff at the pier station acknowledged the contactor opened inside the WEC, the umbilical breaker was opened at the pier ensuring the cable was isolated at both ends.

CalWave staff then transferred to the WEC, routed the tow line through the tow shackle and cleaned the top surface of marine growth to allow for a safe and functional space to secure the mooring hardware to the for towing. The dive team launched the small boat from the pier, tied up to the marker buoy and sequentially disconnected the mooring lines at the midline (H-bracket) connection point, allowing the synthetic mooring lines to fall to the seafloor. As the dive team disconnected each mooring, CalWave staff lifted the hardware onto the WEC and fastened to the lift points. Upon disconnecting all mooring lines, CalWave staff disconnected the umbilical cable, placed dust covers on both connectors and passed the strain termination to a diver to be placed on an anchor and tied to a buoy for future recovery. At this point, the safety line was disconnected, drogue deployed and CalWave staff recovered to the R/V Beyster, which was now rigged for towing. The dive team recovered the remaining synthetic mooring lines, inspected the seafloor area to ensure no equipment or foreign objects were left behind, and caught up with the R/V Beyster to act as a safety observer vessel during the tow.

Towing of the WEC proceeded at approximately 4 knots. Upon nearing the harbor entrance, the tow was shortened, and drogue recovered. For the final approach to the recovery slip, the small boat tied a tag line to the WEC to allow both vessels to work together in controlling lateral motion during tow while bringing the WEC into the slip.

5.6.2 Umbilical & Marker/Wave Data Buoy Recovery

After the WEC was recovered, the umbilical was prepared for recovery. This involved demobilizing the R/V Beyster from her towing configuration and loading on the umbilical reel stand with drum and a motorized spooler. At SIO pier, the umbilical cable was physically removed from the shore station and lowered through the conduit onto the seafloor, with divers under the pier supporting. Additionally, a jet pump was needed to extract the section of umbilical cable nearest to the pier from the sand. It was found that the cable was buried under approximately 3 meters of sand near the foot of the pier, but only for the first 50 meters of linear distance from the pier, afterward only minimal sand covered the cable.

For the umbilical recovery, the R/V Beyster arrived on site and recovered the strain termination tied to the buoy at the anchor it was attached to. The cable was brought on board, routed through the block on the stern A-frame, wrapped 2-3 revolutions around the motorized spooler and affixed to the wall of the drum. The R/V Beyster then proceed slowly astern while one crewmember operated the motorized winch, a second crewmember cleaned marine growth from the cable as it passed between the motorized spooler and wooden drum, and a third crewmember manually spooled the wooden drum.

Once the umbilical cable was on board, the marker buoy and two wave data buoys and anchors were recovered and the R/V Beyster proceeded back to home port for demobilization.

Figure 27: Recovery operation of the umbilical on the RV Beyster with CalWave staff.

6 x1 System Performance

The x1 was deployed for a total of 7106 hours. During that time, the x1 was operational and in 'Normal Operation' state for 7043 hours, leading to an availability of 99.11%.

The x1 was brought into a 'Commissioning Mode' that allowed for SCADA updates over the umbilical data connection for about 0.49% of the deployed time, accumulating for ~34 hours. The x1 spent ~24 hours in an idle 'Hold On' position waiting for a human to approve continuing operation. Such idle durations could have been entirely removed by autonomously going into 'Norm Operation' state again. However, it was decided that a manual system check via the online web browser-based SCADA interface should be executed before the device was allowed again to go into normal operation.

CalWave's WEC was available throughout all main storm events and any failures that occurred were not correlated with storm/extreme wave events. This has proven the effectiveness of CalWave's load management using the geometry and submergence depth control.

6.1 Reliability, Maintainability, Availability

Reliability, maintainability, and availability were selected as key metrics for assessing the system performance baseline. Reliability is defined as the probability that a working asset will continue working for a set period. An asset that can operate without failure for a long period of time will have high reliability. For this deployment, reliability is assessed by calculating the mean time to failure (MTTF), which is the operational time divided by the number of failures.

Maintainability is defined as the time and resources it takes to repair an asset that is not functioning. An asset that is quick and inexpensive to fix when it breaks will have high maintainability. For this deployment, maintainability is assessed by calculating the mean time to repair (MTTR), which is the down time divided by the number of failures. Availability assesses the probability that an asset is currently operational. Having a high MTTF and a low MTTR aid in having high availability. Availability is calculated as the percentage of scheduled working time that an asset is properly operational.

WEC in Operation

For the purposes of assessing reliability, maintainability, and availability of the entire WEC system, the WEC is defined to be operational when the WEC is fully capable of transmitting power back to shore. This means that the PTO and especially electric machine systems are working properly. It also means that there is no interruption or issue with the umbilical, or WEC and shoreside switchgears. This is equivalent to the WEC SCADA system running in its Normal Operation mode, as the aforementioned aspects are all requirements to be in this state. Note that the WEC can and did have more minor aspects fail and still meet this definition of operational.

The WEC was deployed for a total of 7106 hours. During that time, it was operational for 7043 hours, leading to an availability of 99.11%. This resulted in a MTTF of 293.45 hours, and MTTR of 2.58 hours.

The MTTF for hardware only faults exceeded 10 months and there was no unplanned recovery of the system for the entire test duration.

The x1 achieved a very high availability over the entire deployment for an initial prototype. Additionally, the failures that were encountered were quickly solved and lead to high maintainability. While the MTTF and thus reliability may be seen as having some room for improvement, the majority of non-operational instances of the x1 were due to controller reboots to correct software issues. These reboots are both very quick and low cost and could be reduced with future improvements to the SCADA system.

It is however worth noting that the x1 did not experience any failures during the deployment that required physical recovery and repair of internal components of the WEC. While this suggests high reliability of the physical WEC systems, the time and cost to repair any such failures is likely to be much higher than the above reported MTTR.

Individual subsystems listed below experienced issues/failures although they did not occur to the degree of affecting device operation.

Sacrificial Anodes

Sacrificial Anodes were one of the few items on which maintenance was conducted during the deployment. While the sacrificial anodes on the hull were sized well and did not deteriorate by recovery, the fairlead anodes needed to be replaced twice while the hatch and H-Bracket anodes needed to be replaced once. Anode replacement was a maintenance operation that was performed by divers. It did not require taking the system out of operation and instead calm days with deep WEC submergence depth were targeted. An example fairlead anode that required replacement is shown in Figure 28. Sacrificial anodes serve as one of the first layers of protection against corrosion and it is important for the life of the WEC to replace them before they are completely corroded out. In future deployments, the anode size could be increased and more of the bare metal surfaces coated to reduce the required frequency of anode replacement.

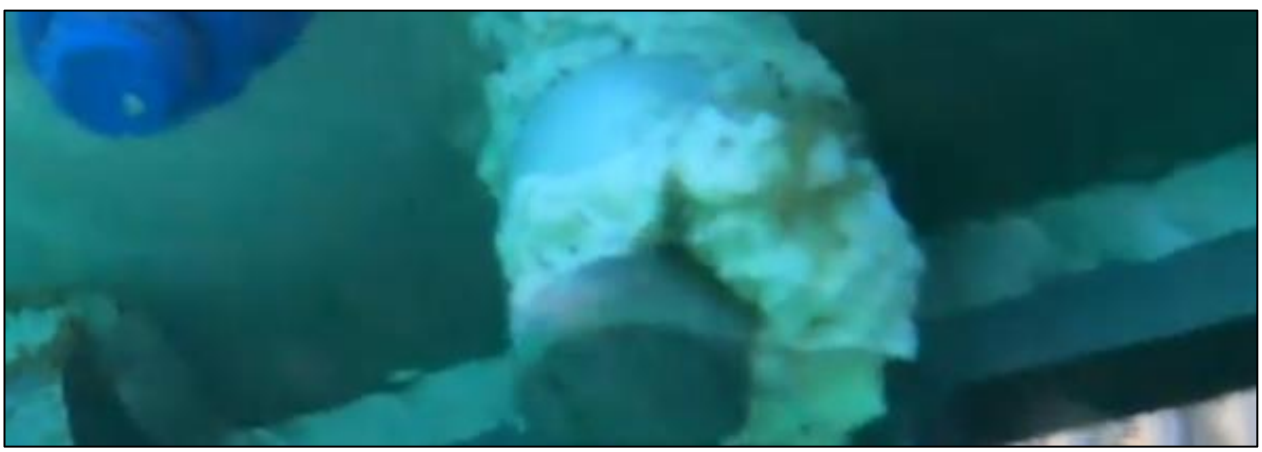

Figure 28: Corroded fairlead anode.

Underwater camera

Another maintenance item was the single exposed underwater camera, shown in Figure 29. Over time, the camera became covered with bio growth, obstructing the field of view. The camera was maintained by having divers perform a quick cleaning during routine inspections. For future deployments where dive inspections may be less frequent, a mechanical wiper system could help to keep the camera face from being obstructed.

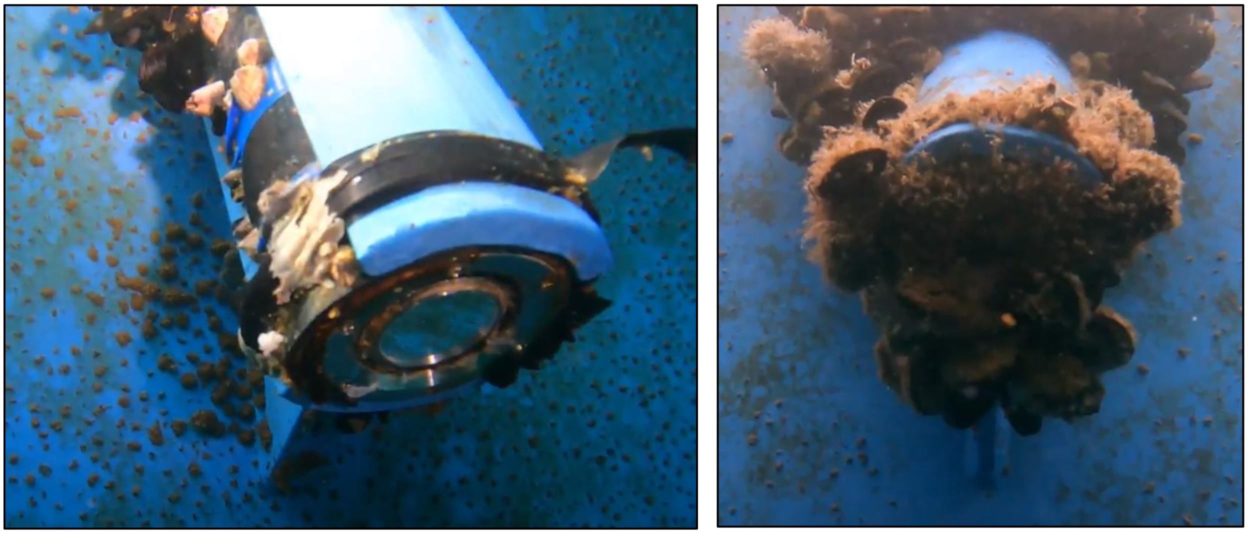

Figure 29: Underwater camera showing different stages of bio growth.

6.2 Controlled Operation

Testing data binned according to IEC standards is provided along with this submission in the Testing Content Model excel sheets. A total of 10 sheets for 10 months covering the deployment period includes information about PTO Loads, mechanical power at various stages of the conversion chain, electrical import and export power, capture length as well as the spectral breakdown of the wave spectrum in each half of an hour reporting period.

The x1 system operated with great satisfaction in the expected loads and kinematic (displacement and speed) bounds. The PTO as well as the main SCADA controller successfully executed CalWave's control strategies and equally important, enabled safe and controllable operation. The x1 did what it was commanded to do with respect to the following control aspects:

Submergence Depth and Load Management

The Holistic Control system in the x1 used the submergence depth as an additional mean to control the wave loads exerted onto the device. Based on a combination of sensor inputs the controller can autonomously choose a submergence depth in which the device can operate in an expected load range suitable for all systems onboard.

PTO torque control including minimum and maximum line tension controller

The x1 SCADA system in combination with the well-tuned and tested PTO system performed extremely well with respect to torque tracking and control execution. Minimum and maximum line tension controllers were working as expected and minimum line tension was reduced by about 20% in the last 2 months of operation.

The following plot shows an example of a 15-minute normal operation window during December 25th, 2021. The torque setpoint and the actual measured torque overlap and show the tracking capabilities of the PTO system and controller in a time-resolved fashion:

The plots below show the normalized torque measured/setpoint over the entire deployment duration:

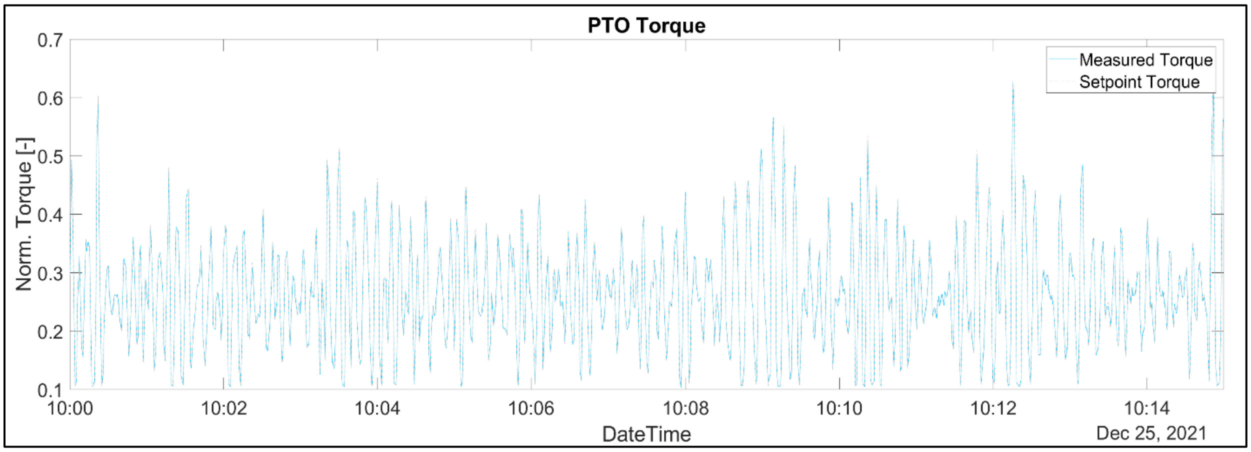

Figure 30: Time resolved torque tracking for a 15 minute snipped during December 25th 2021. Excellent torque tracking is observed.

To gain a better picture of the tracking capabilities over a large frequency spectrum the FFT of both the setpoint and the actual signal is compared in the plot below. The FFT covers one day of operation (December 25th) and again shows the great tracking capabilities over a very large torque tracking range.

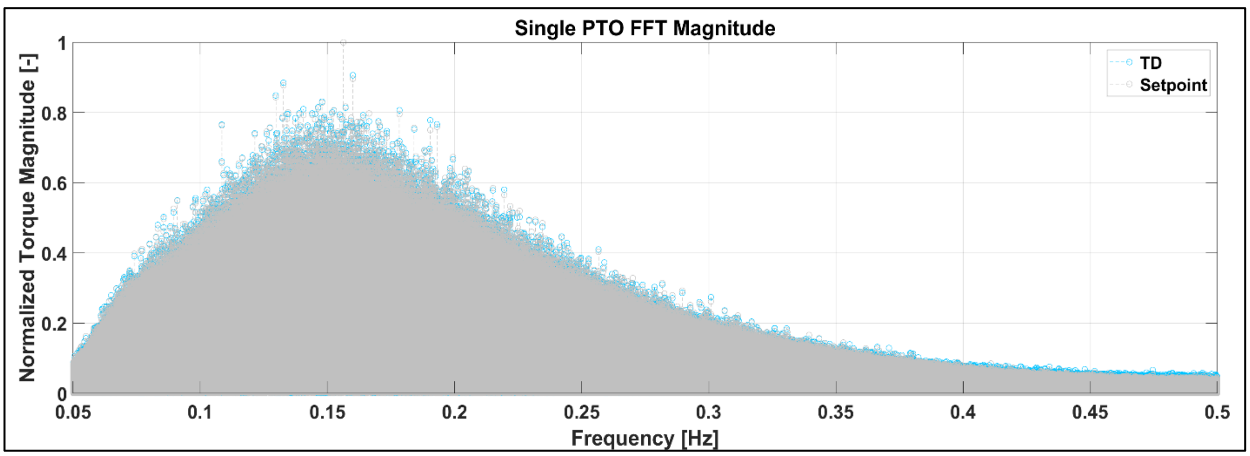

Figure 31: Frequency domain magnitude for the 4th week of December. Good torque tracking of the magnitude over a very broad frequency range is observed.

Overall, during this example month with sea states entailing a medium intensity, common speeds reach about 50-60% of the peak speed over the entire operation. The utilization of the available machine speed envelope is hence quite good.

Tidal compensation

For devices such as the x1, proper tidal compensation controller is required. Especially for submerged operating device in which no hydrostatic restoring force exists (the device's buoyancy is fully defined at the point of full submergence) a change in the mean water level via tides does not lead to any 'natural' change of pre-tension on the PTO units/tethers. Hence, an autonomous tidal compensation system was implemented using a combination of hydrostatic pressures measured from pressure sensors, as well as tidal information obtained from nearby tide measurements stations.

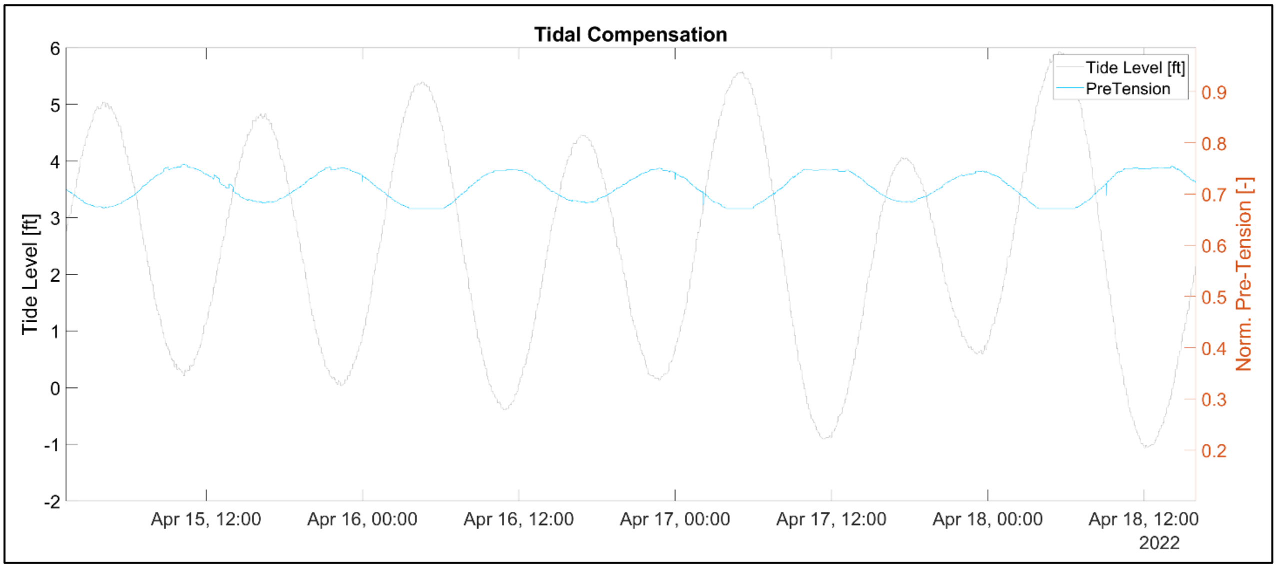

Figure 32: Tidal compensation via pre-tension adjustment for a three-day window in April.

Accurate tidal compensation is more important for smaller (demonstration) devices than for larger WECs as they are envisioned for the next deployment of the xWave technology e.g., at PacWave. However, accurate tidal compensation must be well designed in the control code of submergence setpoints to ensure that submergence depth is properly reached by the device.

6.3 SURVIVABILITY

The survivability of the x1 architecture was demonstrated during this deployment. The largest wave environment the x1 encountered occurred in mid-October 2021, as shown in Figure 33.

A significant wave height (Hs) of 3.17 m was recorded, which corresponds to 15.9 m Hs waves at full scale. This is a larger Hs than the 14.4 m 100-year return wave at PacWave. The maximum individual wave height recorded by the deployed Coast Scout wave measurement buoy was 4.98 m.

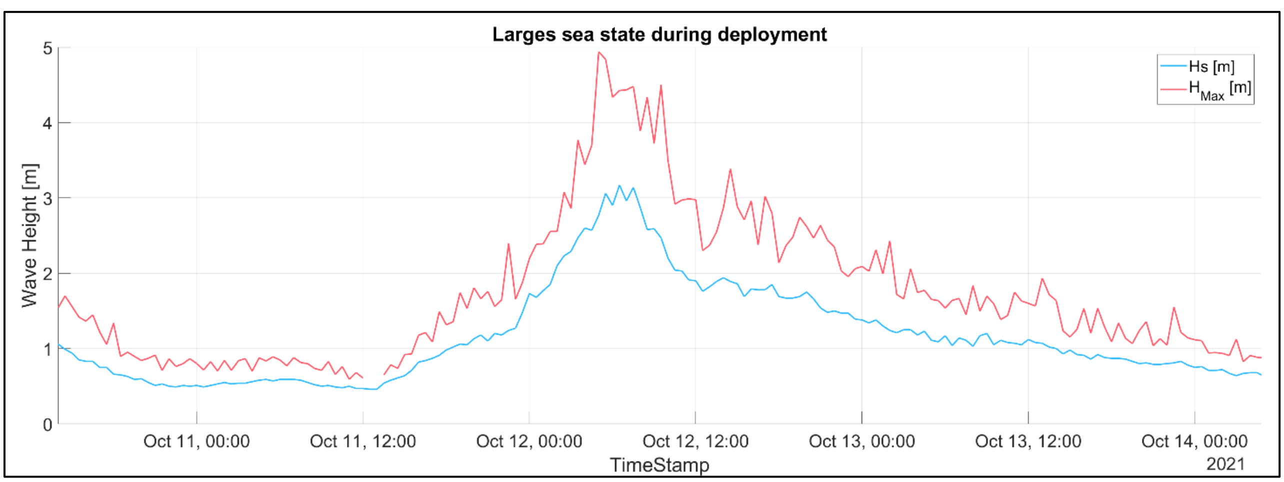

Figure 33: Recorded significant wave height at deployment site, October 2021.

There might be limitations on how survivability is evaluated at a scaled deployment with respect to structural loads. However, the comparison of the deployed WEC behavior including displacement of absorber body and PTO stroke, as well as measured loads on the PTO systems can to an extent be seen as a good indicated on how a larger system would respond.

The storm lasted multiple hours during which the x1 was able to maintain loads within acceptable limits and even continue to operate and generate power during this storm.

This validates the effectiveness of operating depth control, the load management mechanism, and PTO detuning at maintaining loads within acceptable/designed limits. Multiple other storm events occurred during the deployment time resulting in instantaneous wave elevations that exceeded 4 meters (correlating to 20 meters full scale wave events).

CalWave's load management mechanisms were extremely valuable during these storm events and significantly contributed to safe operation. The device continued operation in 'Normal Operation' mode and while being significantly larger, torque and speed values stayed within the predicted and accepted range!

7 Lessons Learned

The success of this deployment highlights the extensive planning and design methodology that went into building the x1. Nevertheless, as CalWave's first open ocean deployment of the x1, this project concluded with a host of valuable lessons learned. Design lessons learned include those related to biofouling, camera and pressure sensor design, backup power for onshore communication systems, and delicate component protection.

Biofouling

For this multiple month deployment, biofouling was anticipated, and the blue and white anti-biofouling paint was used to protect against biofouling. Note that the blue paint was professionally applied while the white was detailing paint that was applied over the blue (and therefore not in contact with the underlying primer). This is the reason a lot of the white paint did not last through the deployment. Nevertheless, the blue antifouling paint was found to be extremely effective at preventing biofouling as can be seen in the recovery pictures below.

However, the anti-biofouling paint was only applied to the mild steel surfaces of the hull. Everything that was not coated with the anti-biofouling paint that was within ~10m of the surface experienced significant biofouling in the form of mussels and barnacles by recovery. This included stainless steel PTO components, painted steel slewing bearings for the fairleads, brass nuts for the hull access hatches, and the polyurethane belts. This biofouling is shown on the hull access hatches.

Future long-term deployments will use camera systems with wipers to monitor biogrowth on key locations and functional items. Contrary to that, biogrowth on hull panels do not pose a threat to operation and performance per-se and hence, visual inspection using ROVs in long time intervals might be appropriate. Due to the simple shape and flat absorber hull panels, robotic (magnetic) systems that can support general cleaning of biogrowth can potentially be deployed.

The mussels found and grew on every little exposed bolt head or nut. It also appeared that the biofouling accelerated towards the end of the deployment. This could be due to general accelerated growth in the warmer summer months. It could also be that once components started to foul, the existing fouling itself provided new and thus increased surface area for biofouling to grow on.

It is notable that components that were regularly exercised, such as parts of the PTO belt, did not experience the same level of biofouling. This demonstrates that regular sliding contact between surfaces is effective at preventing biofouling. In future designs, exposed stainless steel components should also be coated with anti-biofouling paint where biofouling is undesired even if the anti-corrosion primer isn't as necessary.

The entrapped water chambers experienced quite different bio growth, especially those with added foam buoyancy pieces. The water chambers had openings on both the top and the bottom to allow water to flow in and out of them. However, due to the relative size of the holes compared to the size of the chamber itself, the environment inside them was likely more stagnant than the dynamic environment outside the WEC. Although there wasn't as much biofouling that was growing on the surfaces, there was an abundance of this algae that appeared to be growing untethered inside the chambers. These algae also served as an environment for shrimp and crabs. At certain portions of the chamber that did not see any flow, a dirt like substance accumulated that had clams in it. The growing algae were likely very close to neutrally buoyant and are not expected to have affected device performance. However, they did need to be cleared out on recovery.

Figure 34: Growth of algae inside entrapped water chamber.

Camera and Pressure Sensors

As noted in the previous sections, overtime, the underwater camera field of view became obstructed by biofouling. This could be remedied by having an active wiper that could clean the camera face of any smaller fouling and prevent larger growths. Alternatively, some kind of anti-biofouling cover that could be actuated off of the camera face when the camera is activated could also be an option.

For the hull pressure sensors that failed one after another, biofouling was a potential but unconfirmed cause. Due to the shape of the sensors, the pressure detecting membrane is not easily accessible and likely difficult to clean in the same manner as proposed for the underwater camera above. The type of sensor chosen for this deployment is more likely simply not well suited for longer term deployments, and alternative products should be investigated.

Power for Onshore Communication Systems

At the beginning of the deployment, onshore communication systems were powered simply from a wall outlet. These communication systems, namely the monitoring computer and ethernet extenders were set up such that they could be accessed remotely and did not require a person onsite to manage them. However, there was an instance where power issues with the grid caused these communication systems to trip and need to be restarted. Although the x1 device itself was still able to operate autonomously, for the period that the communication was down, we lost situational awareness of the WEC controller as well as the ability to communicate and thus update control parameters even though shore power had been restored. This led to the addition of an uninterruptible power supply (UPS) between the wall outlet and communication hardware. This would keep the communication equipment running smoothly in the event of short-term grid irregularities.

Wi-Fi Antenna Protection

In hindsight, the design and location of the Wi-Fi antenna, shown in Figure 35, was rather delicate. Damage to the antenna was avoided during installation and commissioning of the x1. However, during recovery, the antenna experienced some trauma that caused its plastic shell cover to break. The inclusion of some form of physical cage that would still allow the antenna to function while also protecting it from mild impacts should be a feature included in future designs. This applies to any delicate components that are exposed on the surface of the hull.

Figure 35: Wi-Fi antenna installed on deployed x1.

8. NEXT STEPS

Based on the successful demonstration of the xWave technology and the encouraging results on WEC behavior and performance, CalWave will continue the development of the technology towards higher TRL and TPL levels. The above lessons learned will be integrated into the device design as part of the risk mitigation process.

CalWave will evolve the technology via:

1) **FOA 1837 - PTO Control Co-Design**
   CalWave will strongly couple the PTO design, the WEC absorber/geometry design as well as the Holistic Control strategies (submergence depth control, geometry control, PTO and drivetrain control). Using state of the art tools such as the wecopttool developed by Sandia National Laboratories CalWave will evaluate tradeoffs and synergies between design parameter to optimize electrical power extraction over the entire lifetime and range of sea states the xWave technology will encounter. This project will significantly increase the TPL level of the xWave.

2) **FOA 2080 – CalWave Design for PacWave**
   CalWave is working on evolving the xWave technology towards a WEC design ready to be built and deployed at the PacWave South test site. All relevant project aspects such as risk management, grid interconnection, IEC accredited testing, environmental compliance, anchor and mooring design, and IOM&D planning will be covered to prepare for deployment at PacWave.

3) **FOA 2415 – CalWave xWave at PacWave**
   Under this award CalWave will build, deploy, and operate a scaled-up version of the xWave technology at PacWave South. With an envisioned deployed duration of 2 years and grid connection to the local utility grid, this project will push the xWave technology towards high TRL levels.