PCCI
Marine and Environmental Engineering

Project 118: Final Final Report

Quarter Scale Testing of the Intelligent Mooring System for Floating Offshore Wind Platforms

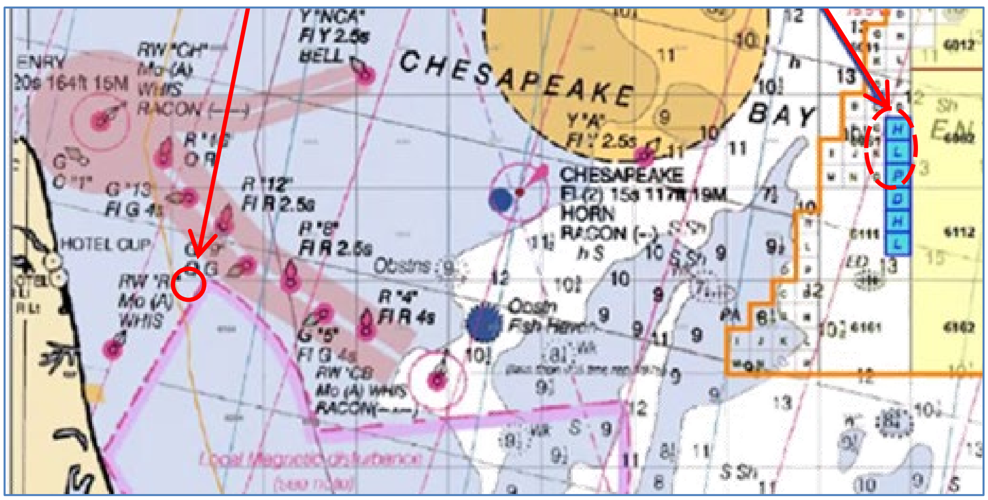
Prepared for:

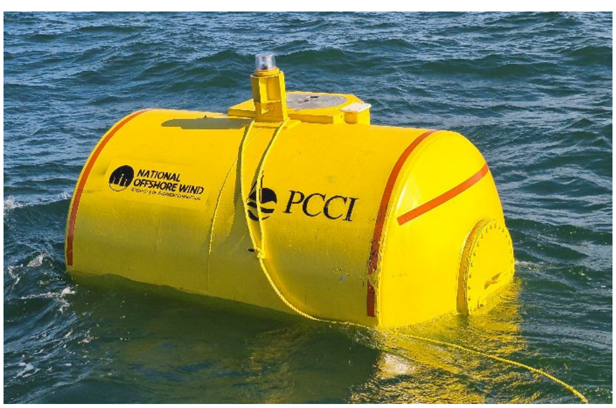
The National Offshore Wind Research and Development Consortium

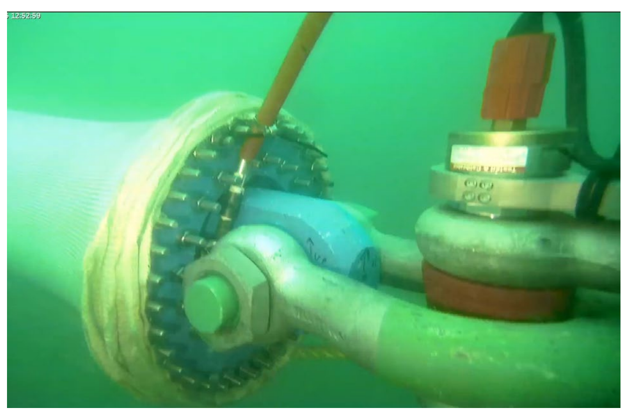
Stony Brook, New York

Program Managers: Kori Groenveld, Julian Fraize, Melanie Schultz

PCCI, Inc. 300 North Lee Street Suite 201, Alexandria, Virginia, 22314







NYSERDA Report 118 NYSERDA Contract 165430 September 2025

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

CDIP	Coastal Data Information Program
CENAO	Corps of Engineers Norfolk Area Office
DOE	US Dept. of Energy
ft	feet
IMS	Intelligent Mooring System
m	meter
MT	Metric Tonne (2205 lbs.)
NMFS	National Marine Fisheries Service
NOWRDC	National Offshore Wind Research & Development Consortium
PATON	Private Aid To Navigation
SNMREC	Southeast National Marine Renewable Energy Center
USACE	US Army Corps of Engineers
USCG	US Coast Guard
USN	US Navy
VOWTAP	Virginia Offshore Wind Technology Advancement Project
WETO	Wind Energy Technology Office
WETS	Wave Energy Test Site
4mE	Name for IMS device that is 4m long and on the East
2mW	Name for IMS device that is 2m long and on the West

1 Project Timeline and Key Conclusions

This report details activities performed by PCCI Inc. to simulate the effectiveness of the Intelligent Mooring System (IMS) and to plan and perform an at-sea test of a quarter-scale IMS unit. IMS units are a braided Dyneema sleeve with an internal bladder and steel padeyes on each end that could function as a pneumatic spring as part of the moorings for Floating Offshore Wind Turbines.

The objective of the proposed work was to advance the IMS to TRL 6 through close collaboration with U.S. floating offshore wind platform developer Ocergy, and 1/4-scale IMS at-sea testing in the U.S by PCCI. The project was awarded on 21 September 2021 and will complete on 30 September 2025. Key Dates are as follows:

Table 1. Key Dates for Project

21 Sep 2021	Project awarded, commence **Phase I**
08 Sep 2022	Coupled Modeling Report complete
2023	Develop budget & ConOps to test at alternate sites. Inventor builds two IMS units
15 Dec 2023	Notice to Proceed to **Phase II**, Planning for At-sea Test
March 2024	Develop ConOps & budget for At-sea test in Virginia Beach VA
May – Aug 2024	Write and Revise Biological Assessment for At-sea test
01 Oct 2024	NEPA and EFH Review Accepted
02 Oct 2024	Notice to Proceed to **Phase III**, At-Sea Test
18 Jun 2025	Data buoy installed, began collecting data.
25 Jul 2025	At-sea IMS units tensioned to 4.7 tons
18 Aug 2025	Data buoy comes ashore. Retrieved by PCCI 28 Aug.
30 Sep 2025	Draft Final Report Submitted

PCCI's conclusions are as follows:

1. Computer modeling indicates that an IMS system can reduce peak mooring loads by approximately six percent for floating wind platforms located in relatively shallow (60m) water depths.

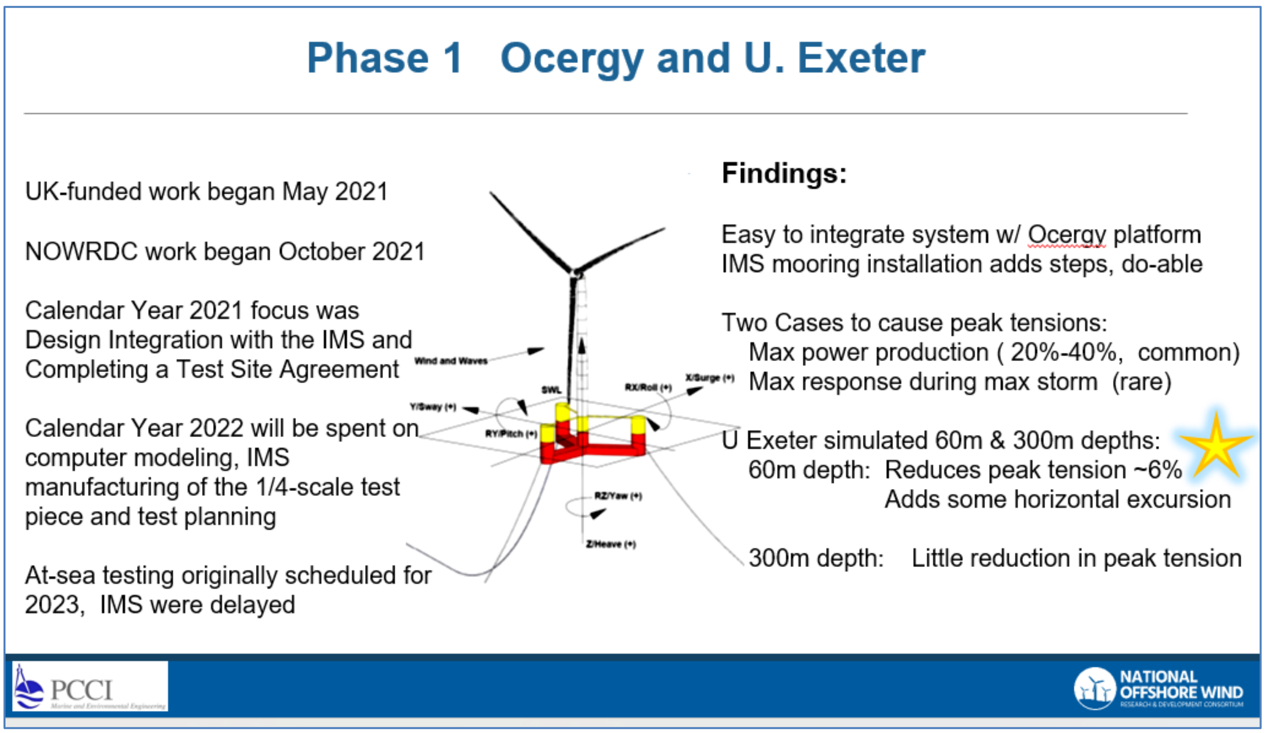
2. An at-sea test of two One-Quarter-Scale IMS units was performed for two months in the Atlantic Ocean. The IMS units experienced maximum tensions of 4.7 tonnes, ocean current of 2 – 3 knots, and wave heights often 1 to 3 meters. Three failures of air hoses were experienced during the two-month test. This failure is consistent with the vulnerability identified during Phase I. The instrumented test ended when the mooring's data buoy broke free after two months at sea. This failure is probably unrelated to the IMS units.

3. ABS performed an Approval-In-Principle review of the IMS. Their AIP roadmap letter lists various system vulnerabilities to be addressed during future full-size Detailed Design. Their recommendations are consistent with our findings during Phase I.

4. Based upon the air hose failures and ABS review, PCCI concludes that this project has demonstrated that the IMS has not achieved DoE Technology Readiness Level 6.

2 Phase I: Simulation of IMS Effectiveness

Phase 1 consisted of having Intelligent Mooring LTD. work with the University of Exeter and Ocergy Inc. to simulate the effectiveness of full-size IMS units. University of Exeter simulated the arrangement within *Visual Oraflex* hydrodynamic and wind-modeling software. The findings are summarized on this slide presented at the 2024 NOWRDC Symposium.



PCCI's team developed installation plans for full-size IMS units that are 20-30 meters in length. Installation is feasible but two possible vulnerabilities were noted:

1. The internal bladders are perceived as a vulnerability when handling the units on deck
2. The air hose that connects each IMS to the platform requires careful installation to prevent damage by crushing and flexure fatigue.

3 Phase II: Planning for At-Sea Test

During Phase II, our team performed two primary efforts.
PCCI engineers developed a design, budget, installation plan, and procurement of equipment to install the test mooring offshore of Virginia Beach Virginia. This mooring would have a battery-powered data buoy to collect tension and pressure data and send it to shore. PCCI's naval architect modified a steel buoy to hold pneumatic, electrical and communications systems for data acquisition. Details of this design and construction are presented in the next section.

Using PCCI's test-mooring design, biologists at Conshelf Associates prepared a Biological Evaluation for NEPA reviewers and other regulators such as the National Marine Fisheries Service. Our team developed the plan and permitting documents during spring 2024, submitted and revised them during summer 2024, and received NEPA/NMFS approval on 01 October 2024.

4 Phase III: At-Sea Testing

4.1 IMS Test Prototypes

The quarter-scale test was conducted on two IMS units attached in series and experiencing the same tension. An IMS functions as a pneumatic spring, with an internal bladder housed within a double-braided Dyneema sleeve. PCCI tested two IMS prototypes, one is nominally 2 meters long and the other is 4 meters. Each end has a padeye and 0.3m in diameter steel flange which acts as a fabric clamp and has threaded air ports. As the device extends, the diameter constricts, increasing the internal pressure. The load-extension curve for the device is non-linear, with greater stiffness at higher loads.

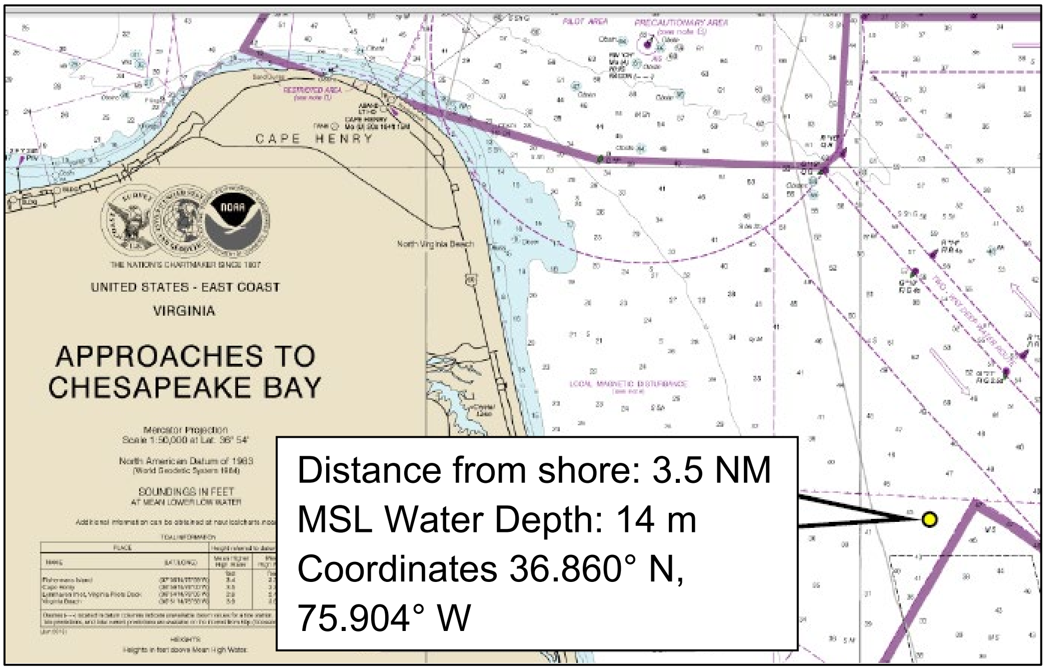
Figure 1. 2m and 4m IMS Test Devices

The IMS prototype units were bench-tested at a PCCI facility. Here, the devices were pressured to verify airtightness and were fit-checked with the air-fittings and shackles. Note, the 2m device is on the left, and 4m on the right.

4.2 Test Site Description

The IMS test mooring was installed 3.5 nautical miles east of Virginia Beach. The location has a water depth of 47-ft (14.3 m), with a seabed composed of sand or mud & sand, per NOAA Chart 12208. Seabed samples were collected by verified by PCCI. The location is advantageous because it is outside of state waters and near enough to shore to be reasonably accessible. See Figure 2 for the nautical chart.

Figure 2. Site Location on Nautical Chart 12208



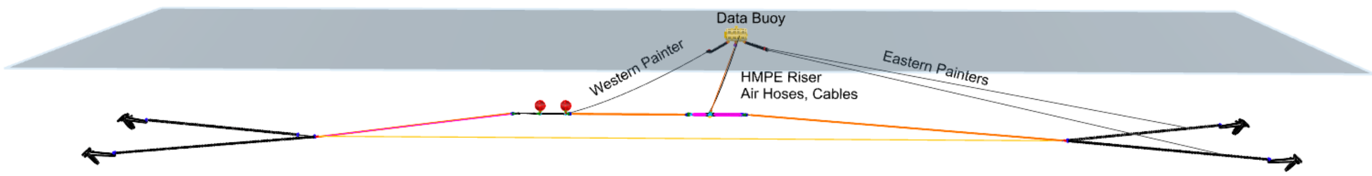
4.3 Test Mooring Design

4.3.1 Mooring Arrangement

The test mooring is a taut system spanning east to west. The IMS units are installed near the center of the mooring to a flounder plate. The plate also connects via a riser line to a nearby data buoy at the surface which collects and transmits data. The mooring is secured by four, 3000 lbs. anchors – two on each end. Each anchor has a shot (90-ft) of 2-inch stud-linked chain which join to form a bridle. The direct distance between each bridle connection is approximately 375-ft. See Figure 3 for a diagram of the mooring arrangement and Appendix A for a larger and more detailed diagram.

Figure 3. Perspective View Diagram of Test Mooring

Perspective view of the test mooring – looking north. This view is proportionately scaled. The IMS units are shown in magenta near the center of the mooring. The data buoy is yellow and near the center. The orange lines represent the HMPE rope. The 3000-lbs anchors and 2.0" chain is shown in black. The red spheres represent 2200-lbs lift bags.

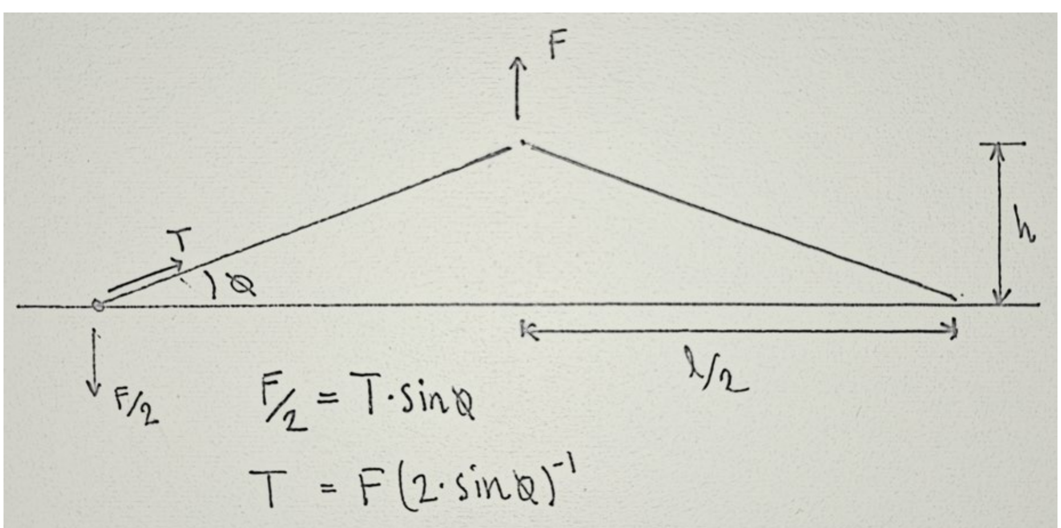


4.4.2 Principle of Mechanical Advantage

The mooring geometry was selected such that modest buoyant forces would create a much larger tension in the IMS units. With lift bags and IMS units roughly 30-ft above seabed, the theoretical mechanical advantage is about 3. However, since the mooring geometry does not form a perfect vertex, the installed mechanical advantage is approximately 2.6. Please see the Lessons Learned section for the As-built configuration and the as-measured mechanical advantage.

Figure 4. Diagram of Mooring Forces and Tensions

The diagram below shows the relationship between vertex height *h (*or, also related, the angle from horizontal, theta) and the line tension *T.* For a given buoyant force *F*, the tension is increased as the angle and vertex height decrease. The buoyant force in the test mooring is generated by the IMS units themselves, the liftbags, and the data buoy.



4.4.3 Data Buoy

The data buoy is meant to ride on the surface to capture wave forces and to house the data acquisition, electrical, and air systems. The buoy was modified from a steel tension-bar mooring spring buoy and is 10-ft x 6-ft diameter. The weight of the buoy is 4800 lbs. fully loaded.

The following components are onboard:

- Two independent Schneider Electric (Ayyeka) data acquisition units capable of storing and transmitting data over the wireless network. Each unit has its own loadshackle, pressure sensor, and battery bank.
- Two battery banks, each with five 12V 100Ah LiFePO4, marine batteries in parallel.
- Two 150 cubic foot steel air tanks.
- Aluminum hatch for accessing pressure control valves.
- 300-lbs of adjustable ballast weight.
- USCG approved navigation light and radar reflector.

Figure 5. Inside Data Buoy: Data Acquisition and Air Systems

Mounted inside the buoy are independent data acquisition, air, and electrical systems. The pressure sensors are internal and attach to 1/4inch air lines which run down to the IMS units. The loadshackles are mounted below the surface and transmit to the data buoy via 4-20 mA signal cables.

Figure 6. Inside Data Buoy: Battery Banks, Air Tanks, and Ballast

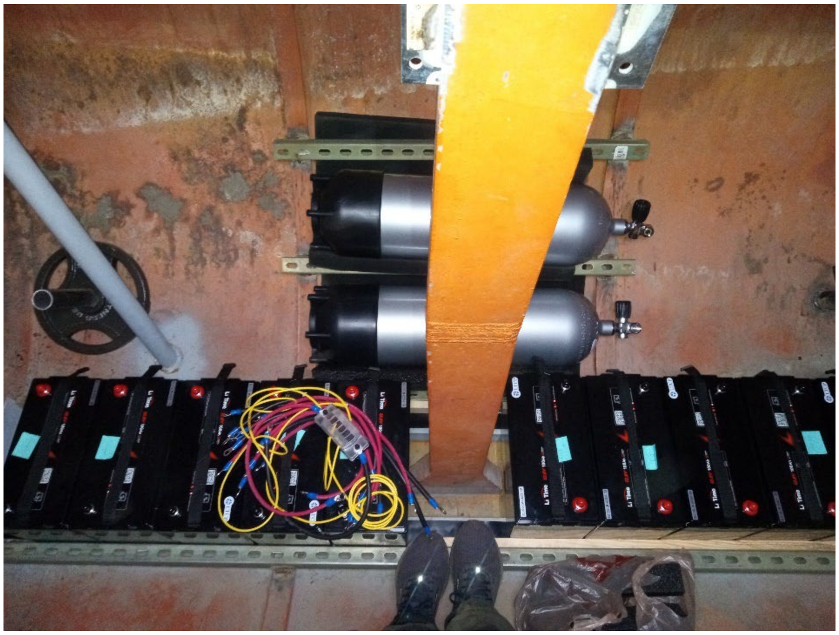


Figure 7. Floating Data Buoy

The hatch, light, and radar reflector are shown. The white panel is a plastic cover for a compartment containing cell network antennas.

4.5 Test Duration and Timeline

The load-shackle cables and air lines were connected and began logging data on June-18th. Thus, nine weeks of data have been recorded. Key dates of various events are listed below in Table 2. A more complete log of daily tasks is included in Appendix C and D.

Table 2. Key Dates for At-Sea Test

02 Oct 2024	Notice to Proceed to Phase III, At-Sea Test
Feb 18, 2025	Installed anchors from spud barge and pulled anchor chains with tug.
May 19-30	Nine dive days working on anchor chains, removing large slings, taking measurements.
June 9-16	Six dive days working on installing rigging and installing IMS units between anchor bridles.
June 17	Data buoy installed.
June 18	Load shackles and air lines connected, began collecting data.
July 22	Repaired air lines and increased IMS tension considerably.
July 25	Tightened the mooring and installed two 1000 kg buoyant liftbags, tension ~ 4.7 tonnes
July 26	Pressure loss in 4m IMS to ~10 psi , tension now ~ 4.0 tonnes
July 31 (0500)	Abrupt tension change from 4 tonnes to null or noise signal
July 31 (1900)	Pressure loss in 2m IMS to 3 psi
August 07	Pressure sensor on 4m IMS ceases to observe tidal fluctuation
August 19	Buoy is observed ashore at False Cape State Park, Virginia, 18 nm s of mooring site
August 29	Buoy returned to Cheatham Annex. Remainder of mooring remains on site.,

5 Environmental Conditions

5.1 Waves

Wave heights at the test site are well approximated using the nearby CDIP wave measurement buoys. Station 147 is about 10 NM away from the test site and has provided accurate wave forecasting for dive operations. Unfortunately, this buoy has been offline for the majority of July (Back online July-29). For July operations, Buoy 171 was used for forecasting, but is about 20 NM east of the test site and in much deeper water, thus experiencing slightly larger significant wave heights. See Figure 8 for monthly wave histories at each buoy.

Seasonally, wave conditions are most calm in the summer months, with waves rarely exceeding one meter. Larger waves are more probable during the hurricane season and winter storms. Therefore, the data captured since mid-June has been during the calm portion of the year. See Table 3 for the monthly wave height probability. Peak recorded tensions occur when currents are strong.

Table 3. Monthly Significant Wave Height Probability Distribution

Monthly significant wave height probability distributions at CDIP wave buoy 147. The data shows higher wave height probability for non-summer months. Each wave height bracket is 0.25 meters. This is based on five years of data.

Coastal Data Information Program Station 147 – UC San Diego (cdip.ucsd.edu)

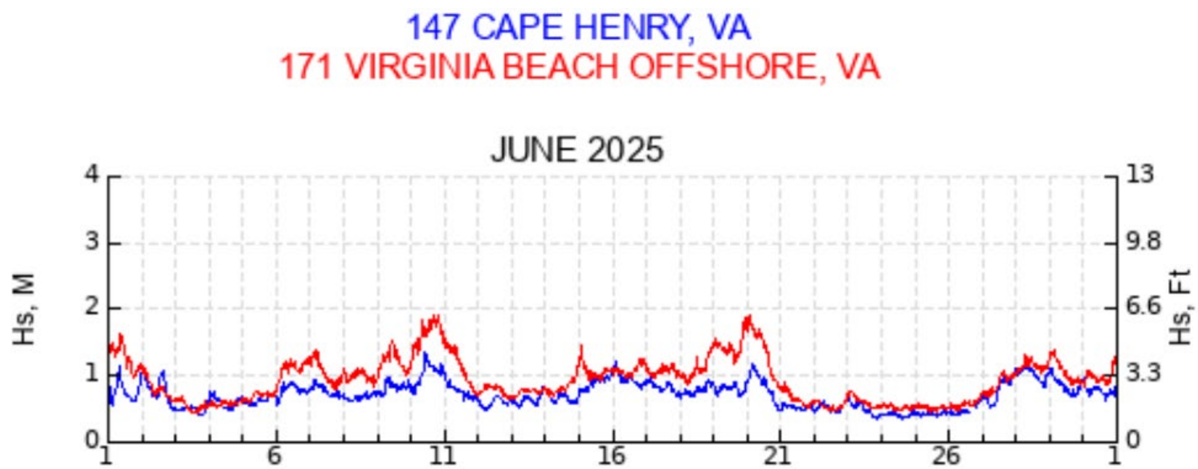
% Distribution		Month											
Hs (m)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.06	0.00
0.25	0.50	7.40	2.17	5.67	3.75	3.67	9.79	11.20	8.27	2.27	2.71	4.37	4.14
0.50	0.75	26.08	19.02	16.31	21.09	27.65	37.36	51.66	46.18	16.44	18.67	21.25	24.41
0.75	1.00	20.96	26.78	30.53	26.44	32.14	28.39	28.87	27.01	28.25	23.93	25.20	26.41
1.00	1.25	13.97	19.34	17.45	17.61	15.13	13.13	6.04	10.69	19.36	19.72	17.62	19.65
1.25	1.50	13.76	12.52	10.50	13.83	9.01	5.38	1.22	3.94	11.76	14.98	12.15	9.54
1.50	1.75	8.84	7.60	8.03	8.82	4.08	2.35	0.57	1.69	7.01	7.81	7.35	7.70
1.75	2.00	4.23	5.76	5.09	4.34	4.14	1.39	0.27	0.87	5.08	4.99	5.28	5.05
2.00	2.25	2.00	3.53	3.02	2.38	2.12	0.96	0.08	0.60	4.71	3.12	2.50	1.59
2.25	2.50	1.41	1.88	1.92	0.98	1.09	1.05	0.05	0.22	2.30	2.14	1.59	0.68
2.50	2.75	0.34	0.61	0.90	0.34	0.33	0.17	0.03	0.16	1.12	0.92	1.02	0.30
2.75	3.00	0.07	0.49	0.26	0.20	0.49	0.03	0.00	0.27	0.59	0.43	0.48	0.08
3.00	3.25	0.17	0.29	0.12	0.20	0.14	0.00	0.00	0.08	0.31	0.14	0.37	0.11
3.25	3.50	0.10	0.03	0.09	0.03	0.00	0.00	0.00	0.03	0.08	0.05	0.62	0.14
3.50	3.75	0.24	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.20	0.08	0.20	0.08
3.75	4.00	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.16	0.00	0.08
4.00	4.25	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.14	0.00	0.05
4.25	4.50	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.08	0.00	0.00
4.50	4.75	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.03	0.00	0.00
4.75	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00

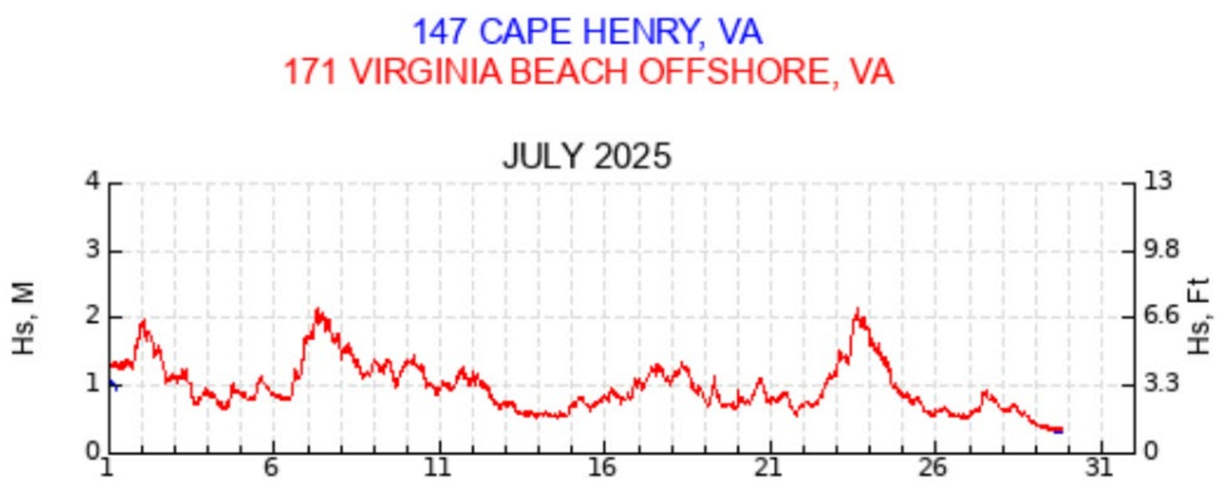
Based on hourly data of buoy 44099 from 2016, 19', 20', 21', 22'

Figure 8. S.Wave Heights for June and July at Nearby Stations

Significant wave height data for the months of June and July at station 147 (about 10 NM ENE of test site) and station 171 (about 20 NM E of test site)

Coastal Data Information Program Station 147 and 171 – UC San Diego (cdip.ucsd.edu)





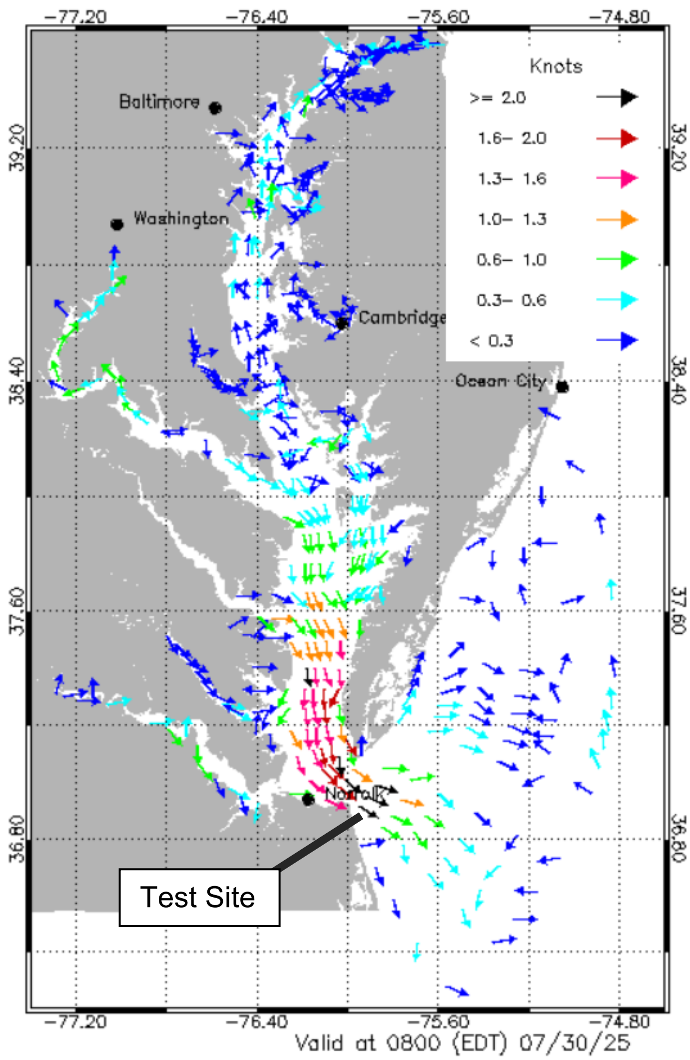
5.2 Currents

Near the test mooring, currents are challenging to predict due to the confluence of forces at the mouth of the Chesapeake Bay. These include semi-diurnal tides, outflow from the bay, and ocean currents. Unlike wave data, there are no sufficiently accurate forecasts or historical data sources nearby for reliable current speeds. The best available source is the shown in Figure 9, which provides a very coarse approximation. As shown, the mouth of the bay can experience strong ebbing currents near the test site. During dive operations, currents of approximately 3-knots were observed. Sensor data shows a strong influence of current forces acting on the mooring, showing increased tension over several hours.

Figure 9. Chesapeake Bay Operational Forecast System Currents

Surface currents and directions in the Chesapeake Bay. The currents near the mouth of the bay can be very strong, greater than 2-knots.

Chesapeake Bay OFS – NOAA (tidesandcurrents.noaa.gov)



6 Results and Observations of At-Sea Test

PCCI tested the 2- and 4-meter IMS units installed in the ocean environment for two months. Over this period the load shackles and pressure sensors were recording data. Sampling rates varied, were often at 1 Hertz. See Appendix B for a weekly presentation of this data. The following are notable events and observations during the test.

1) The IMS units were pressurized to 30-psi on June 18th. Divers tensioned the system using a lever-hoist on the seabed to achieve about 0.75 MT.

2) Strong currents on June 20th caused tensions to spike to 2.5 MT. After the strong currents, the new equilibrium position was less taut than before. Thus, some slack was introduced – likely from the heavy anchor chains being dragged into a straighter position.

3) The loadshackle connected to the 2m IMS lost signal 48-hours after installation – on June 20th. This was later found to be a faulty signal cable splice and was deemed unrepairable. The loadshackle attached to the 4m IMS is still in operation and functioning as expected. The tension is the same on both IMS units, so there is no loss in useful information with just one loadshackle.

4) For the next four weeks, static tensions remained somewhat low – around 0.2-MT, but remained pressurized throughout. Periodic strong currents would create peak tensions up to 1.2-MT in some cases.

5) On July 21st (see Figure 10), buoyancy was added to the subsurface buoys. This pulled additional slack from the bridle chains that caused the air lines to fail due the mooring geometry shifting.

6) On July 25th , the air lines were repaired and pressure was increased to 40-psi. Submerged lift-bags were increased the buoyancy to approximately 2 MT, and caused the IMS tensions to reach 4.75 MT. This event is shown on Figure 10.

7) The larger 4m IMS lost pressure abruptly on July 26th after experiencing a gradual decrease. The leak is at approximately 20-ft depth (~10 psi). As a result of this, the depressurized IMS provided extra length and less buoyancy, causing static tensions to decrease to about 3.75-MT.

8) During 01 to 03 August, the 2m IMS pressure slowly decreased to 34 psi, and then fully depressurized. The loadshackle records tension to often be 0 tonnes with occasional spikes to ~6 or ~13 tonnes.

9) During 04 to 18 August, the 4m IMS pressure shows gradual pressure variation from 10 to 14 to 11 psi, then an abrupt drop to 3 psi on 11 August.

10) On 19 August, waves at the site increased to 2 meter Hs significant waveheight. The data buoy breaks free from its four mooring lines, and washes ashore at False Cape Virginia State Park, as shown in Figure 11. PCCI arranged with park personnel to recover the buoy on 28 August and return it to US Navy Base Cheatham Annex on 29 August.

Figure 10 shows the week when the IMS units when experiencing the highest tension and inflation pressures. Note that on July 22nd, buoyancy was added to the system temporarily. Next, on July 25, two tonnes buoyancy was added after removing 4-ft of slack from the mooring, creating a 4.7 tonne tension load. The titles 4mE and 2mW indicate length (4 meter or 2 meter units) and east/west orientation. The 4m IMS depressurized on 26 July, lengthening the mooring slightly which reduced tension to 3.7 tonnes.

Figure 10. Loadshackle and Pressure Sensor Data – Maximum Tension - Week of July 21st

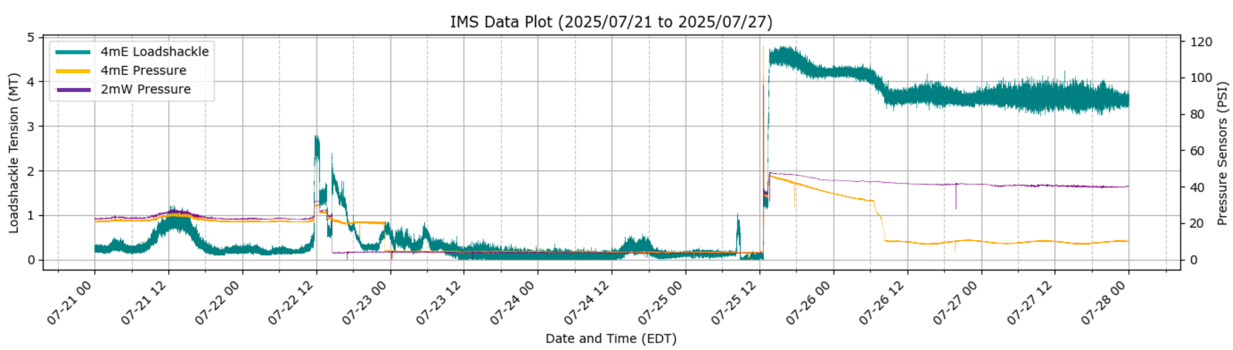


Figure 11. Location of Buoy and recovery location

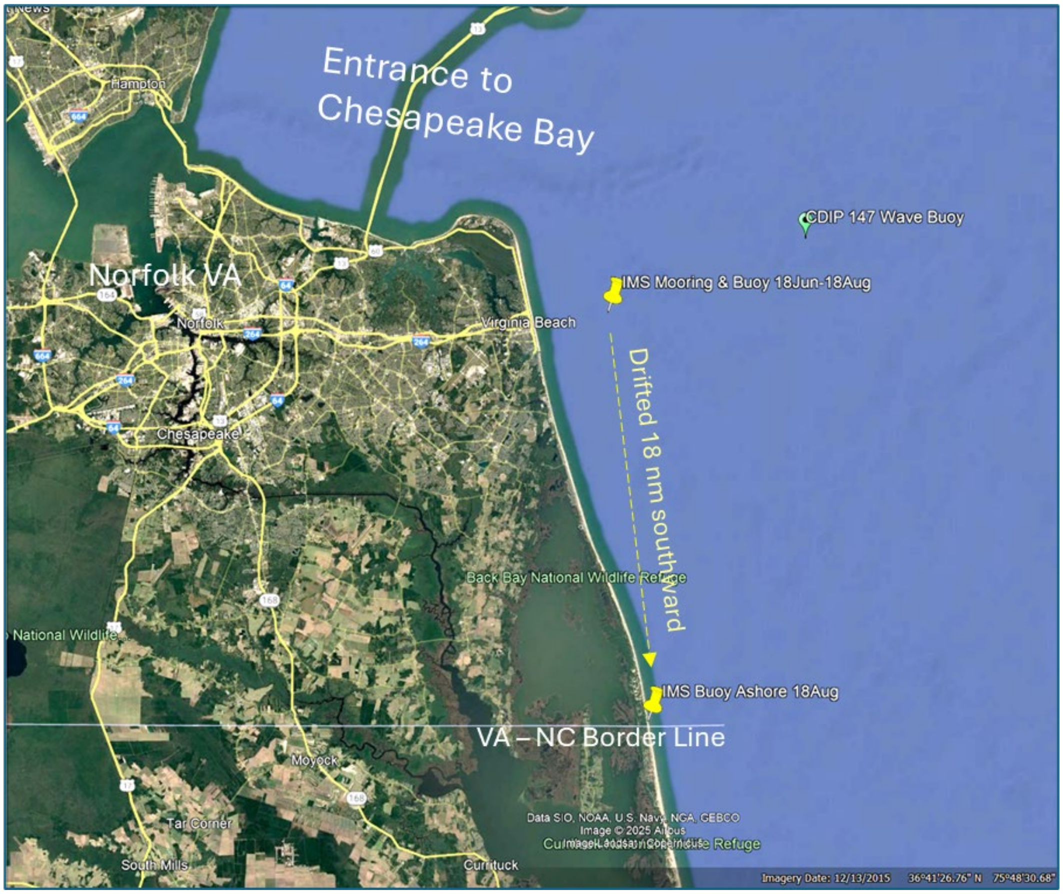


Figure 12. IMS Data Buoy ashore (L) and returned to USN Base Cheatham Annex (R)

7 Project Lessons Learned

This chapter provides the lessons learned during the project. We include lessons about obtaining the at-sea test permit, the unique “buoyant tension mooring system”, oceanographic currents, and the sensor failure modes experienced.

7.1 Obtaining Permits for At-Sea Test

Installation of the At-Sea mooring required PCCI and NOWRDC to obtain permission from the US Dept of Energy for NEPA, the US Army Corps of Engineers, US Coast Guard, and National Marine Fisheries Service.

PCCI had originally proposed to test the IMS at the pre-permitted Hawaii Wave Energy Test Site. The WETS has pre-installed seabed anchors, power and signal cables, and was pre-permitted to conduct tests of ocean mooring equipment. Due to project delays, the WETS site became unavailable, so PCCI considered performing the test at other sites such as the navy test range in Dania Beach, Florida, the Southeast National Marine Renewable Energy Center in Florida and at a Virginia Offshore Wind Technology Advancement Project (VOWTAP) research aliquot located 20 miles offshore of Virginia Beach VA. We determined that the deep seabed of SNMREC would require excess cost, and then elected to use the VOWTAP site, which is leased to Virginia from BOEM for the purpose of Offshore Wind research. Initial scoping requests with VOWTAP during late 2021 were taking an excessive time, so the VOWTAP rep counseled PCCI to install the mooring at a “normal” ocean location rather than at a “test” site.

Based on VOWTAP’s advice, PCCI selected a site that would require the fewest possible agencies to review for permissions. The selected site was solely in federal, not state, waters located 3.5 nm east from the coast of Virginia. It was slightly north of a large US Navy Operating Area and was shoreward of the heavily trafficked USCG Vessel Traffic Separation Scheme serving the entrance to the busy Chesapeake Bay. Table 4 provides a narrative summary of PCCI’s permitting work

Table 4. PCCI's Permitting Timeline

Date	Description	Comments
Nov 2021 – Feb 2022	Request to use VOWTAP lease aliquots H, L or P located ~20 miles east of Virginia.	PCCI provided several technical replies to VOWTAP for BOEM to review. We then planned for a different seabed site 3.5 nm east of Viginia Beach, VA.
24 Feb 2022	Submit Buoy Permit Pre-Application NAO-2022-00508 to US Army Corps of Engineers Office CENAO	PCCI provided several promptings and technical replies to USACE during March and April. The requested site is outside of the regulated navigation area 165.501, restricted area 334.320 and danger zone 334.380. It has acceptable depth, suitable seabed, and is within cellphone range from shore.
26 April 2022	USACE reviewed the buoy description and location and held that the mooring qualified under Nationwide Permit 5_ Scientific Measurement, which does not require pre-construction notification.	CENAO's "408" reviewer at USACE determined that the test mooring location would not require a 408 permit. PCCI paused plans for At-sea Test while inventor built test units.
May – July 2024	Submission and revisions of "Biological Assessment" (later called an "Evaluation" prepared by subcontractor Conshelf Associates (CSA) and PCCI.	Note that a Biological "Evaluation" is used for "Informal NMFS Consultation". A Biological "Assessment" is used for "Major construction activities".
July – Aug 2024	NEPA review of Biological Evaluation performed by NOWRDC's staff expert from DOE Wind Energy Technology Office (WETO)	NMFS conducts an initial review and may request additional information. After receiving all requested info, they require 60 days to perform an "Informal Consultation".
August 2024	PCCI prepares EFH Consultation Worksheet using EFH Mapper software.	Performed on behalf of NOWRDC/DOE.
19 Sep 2024	DOE received a letter of concurrence (LOC; 09/19/2024) from NMFS.	NMFS concurred with DOE that "award activities may affect but are not likely to adversely affect ESA-listed species or critical habitat under their jurisdiction and that no take is anticipated or exempted."

		They made Conservation Recommendation (CR#1) to ground-truth the seabed to verify no essential fish habitat was present.
19 – 25 September	PCCI applied to USCG for a VMRC-ACOE buoy permit, this initiated the Joint Permit Application (JPA) process with federal and Virginia state agencies.	Once reminded that project was not in state waters and qualified under USACE Nationwide Permit 5, application devolved to much simpler USCG Private Aids to Navigation (PATON) permit
26 Sep 2024	PCCI provided CR#1 information to NMFS	PCCI provided a report by Berquist, the "Virginia Beach offshore sediment study" indicating that all soil samples taken near the vicinity of the proposed test site contain only sand and no gravel, rock, or shell substrates. This had been confirmed by a visual seabed inspection at the proposed test site during 2024.
27 Sep 2024	PCCI submitted PATON application to USCG	USCG approved PATON on 29 Oct 2024.
01 Oct 2024	DOE WETO obtains NMFS agreement, then signs NEPA Determination letter GFO-0008390-056, CID #GO8390	NMFS responded on 09/30/2024 confirming that the site investigation from 2024 coupled with the Berquist report adequately addresses CR #1.

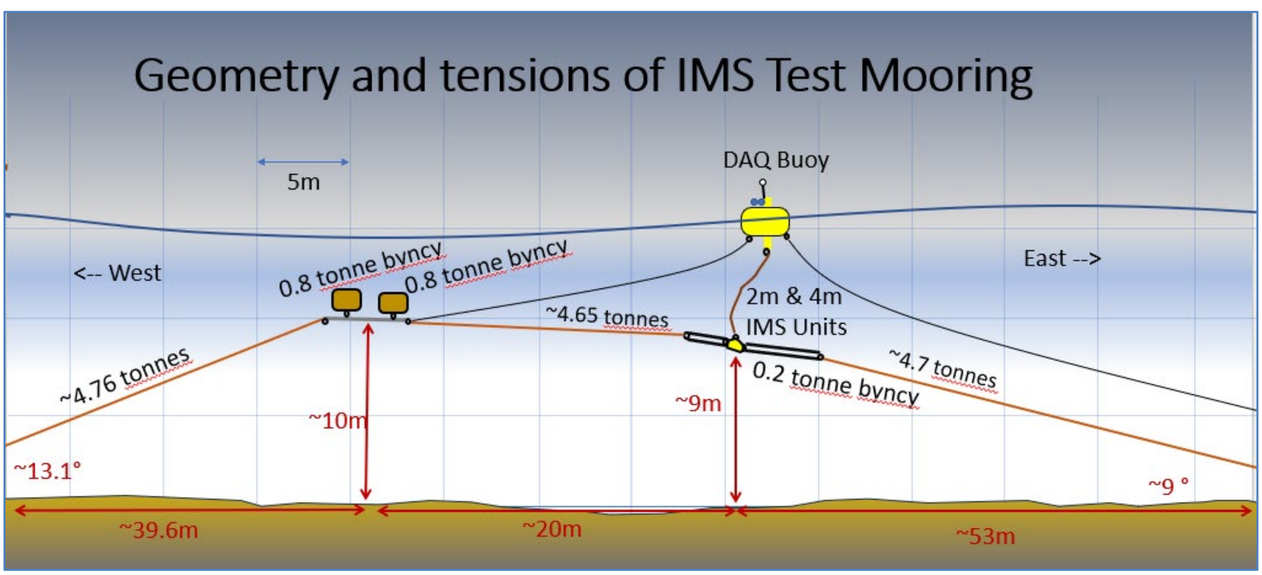
7.2 Design and Effectiveness of Buoyant-Tension Mooring System

The mooring's design intent was to use 3 tonnes of buoyancy to tension the IMS units with an average of 10 – 12 tonnes. This buoyancy was to be generated by two 58" diameter (1.47m) steel sphere buoys that could be controllably filled with water or air. Higher tensions would be caused by large waves lifting the data buoy to pull upward on the flounder plate, causing momentary peak loads of 20 tonnes.

Once on site, fast currents (> 1 kt) hindered the divers during installation, so we opted to install buoyancy using two 1000 kg buoyancy fabric pillow lift bags because they were simpler to control. Liftbags would also be less hazardous for mariners if they inadvertently surfaced. Once fully tensioned on 25 July 2025, the mooring assumed a shape that was generally trapezoidal as shown in Figure 13 below with forces from Figure 10. The two pressurized IMS units provide approximately 0.2 tonnes of net buoyancy, and we estimate that each lift bag (minus shackle, thimble and wire sling) furnished approximately 0.8 tonnes buoyancy.

Due to the fast currents, the heights shown in Figure 13 are estimates only and were not measured. Lines stretch as the tension increases, which affects the overall geometry. This figure includes our calculation that the buoyant force has lifted the chain bridles (not shown) 0.8 meters above the seabed. Each of the three ropes shown (west, middle and east) exert a consistent horizontal force of 4.64 tonnes.

Figure 13. Mooring geometry created a 2.6-to-1 tensile mechanical advantage



7.3 Unexpected Fast Currents at Mooring Site

PCCI investigated public information to estimate ocean currents when choosing a suitable site. We also looked at HF surface current radar, it seemed inconclusive because the site is outside the boundary of typically observed domains within the Chesapeake Bay, or near Chincoteague, or near North Carolina. Based on this review we concluded that currents were generally mild and that the “fast” currents would be nearer the entrance to Chesapeake Bay.

This conclusion was mistaken: fast tidal currents were present at the site, often faster than one knot. These strong currents caused two-thirds of on-site time to be unproductive for divers. This oversight and resulting poor productivity slowed installation of the mooring and caused cost overruns. Once the mooring was taut on 25 July, the data buoy riser line should have been shortened again to match, and the four signal cables and hoses re-secured. The overly-long riser line meant that the buoy did not create significant vertical excitation of the mooring, which had been the design intent to obtain larger variations of the mean tension. The overly-slack riser line also probably allowed the buoy to undergo excessive surge motions, leading to progressive failures of the sensor wires, air hoses, and eventually the buoy’s four mooring lines.

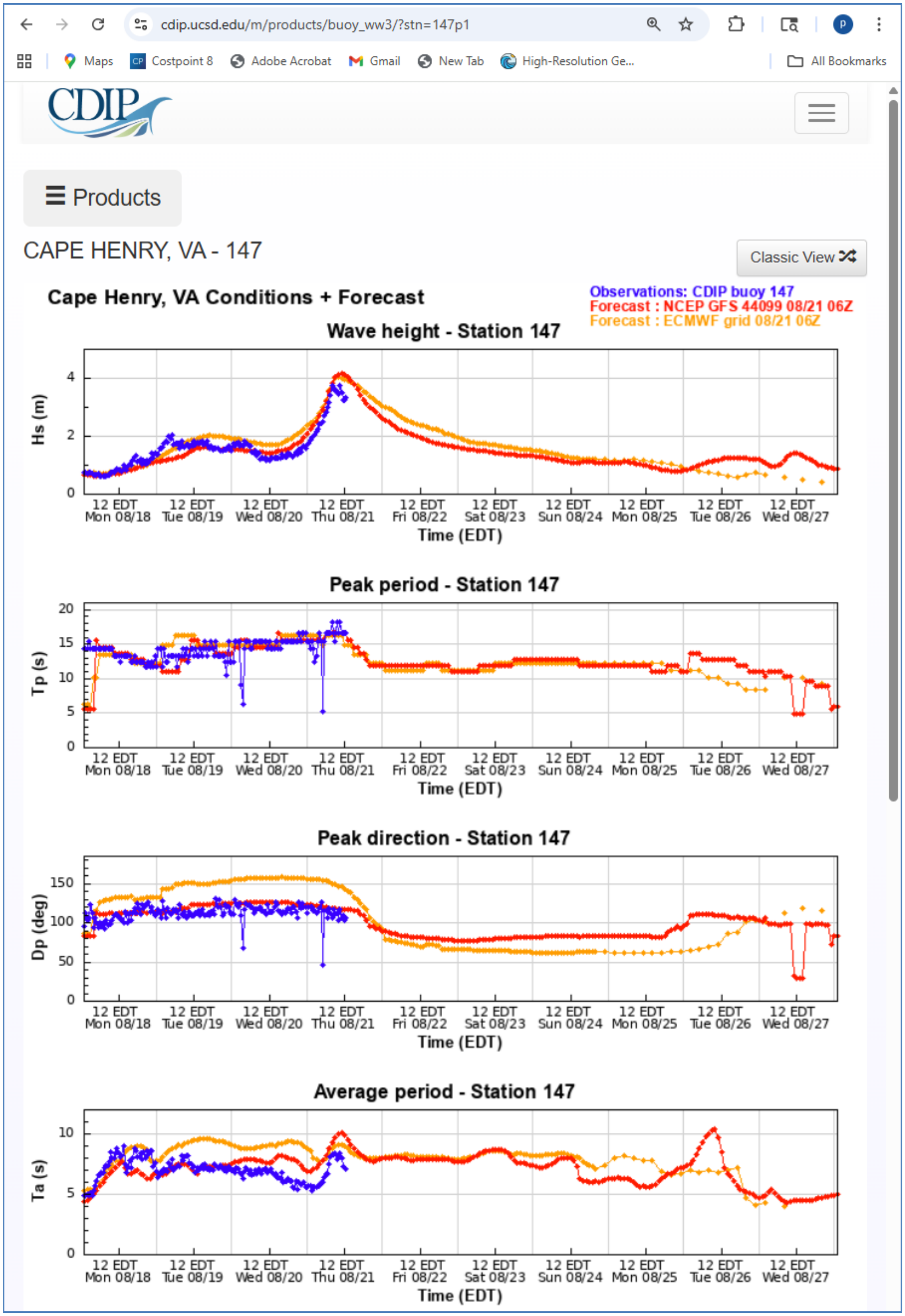
7.4 Sensor Cable Damage, Buoy Separation & Recovery

Section 5 lists the dates when the four sensor cables or hoses degraded and failed. The air pressures sensed at the 4m IMS indicate that the IMS mooring was experiencing significant current-induced motions during August 5th – August 11th., as can be observed in Appendix B.

The buoy eventually parted its 1.5” Dyneema riser line and its three 1” nylon mooring lines. The break(s) likely occurred early on August 19th, as waves built to significant wave heights of 2 meters, which implies that a few waves were 3.5m in height. See Figure 14. The buoy was first reported by a bicyclist riding from Corova Beach, North Carolina, about one-quarter mile north of the Virginia / North Carolina border on the afternoon of August 19th. The bicyclist reported this info to a friend, who informed PCCI via LinkedIn.

Staff at False Cape Virginia State Park helpfully used their beach excavator to move the buoy from the shoreline to their vehicle work area. PCCI then coordinated with them for us to retrieve the buoy via truck on August 28th.

Figure 14. Waveheight record caused by approach of Hurricane Erin.



8 Conclusions

Based on work performed PCCI and our team, we find:

1) Modeling performed by the University of Exeter with Ocergy suggests that the IMS can reduce Floating Offshore Wind Turbine peak mooring loads by approximately six percent, in 60m water depth. In 300m water depth the reduction is negligible

2) The IMS devices have successfully been installed and pressurized in their intended ocean environment. The IMS units successfully held pressure for more than five weeks. The first leaks that occurred were on the sensor air hoses and were repaired. Later leaks require investigation but the symptoms are consistent with leaks of the airhose again, and not the IMS unit.

3) The air lines represent a potential vulnerability of a fielded IMS mooring system. While the exact configuration of a full-scale device would likely differ, the device would need to incorporate a series of check valves to prevent depressurization in the event of air line failure. Further, automated valves would also be advised to increase the pressure remotely or to maintain a certain target pressure.

4) During the installation of the device, it was found that the location of the air ports were nearly interfering with the shackle ear. Later iterations of the flange component should incorporate more logical positions for the ports.

5) The American Bureau of Shipping performed an Approval-In-Principle review and issued an AIP Certificate. Their AIP Roadmap Letter notes possible failure modes and requires resubmission during a future detail design phase.

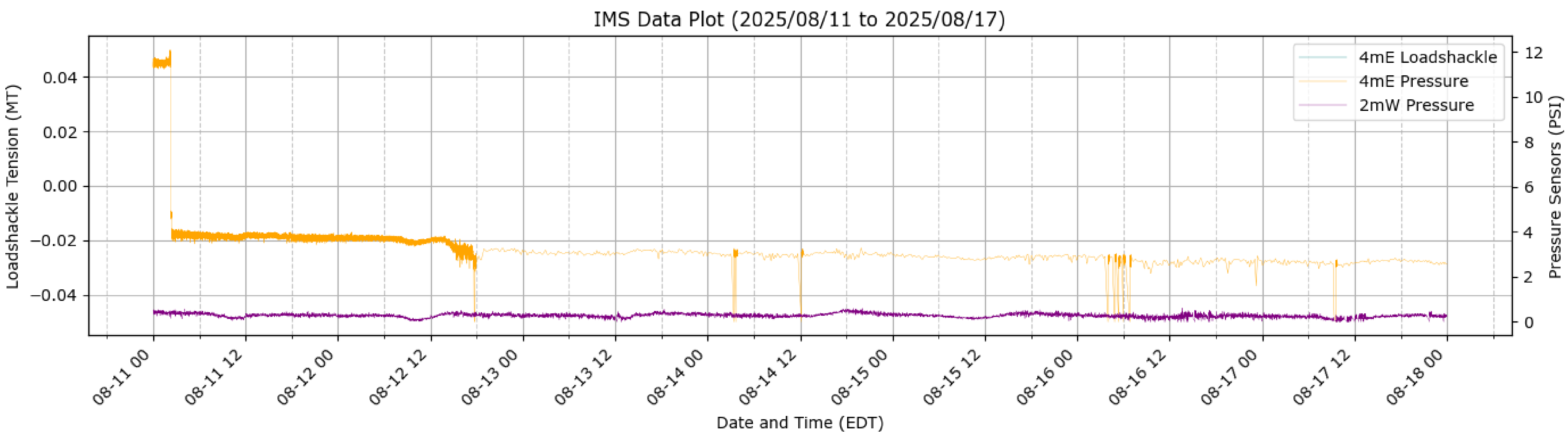
6) Based upon the air hose failures and ABS review, PCCI concludes that this project has demonstrated that the IMS has not achieved DoE Technology Readiness Level 6.

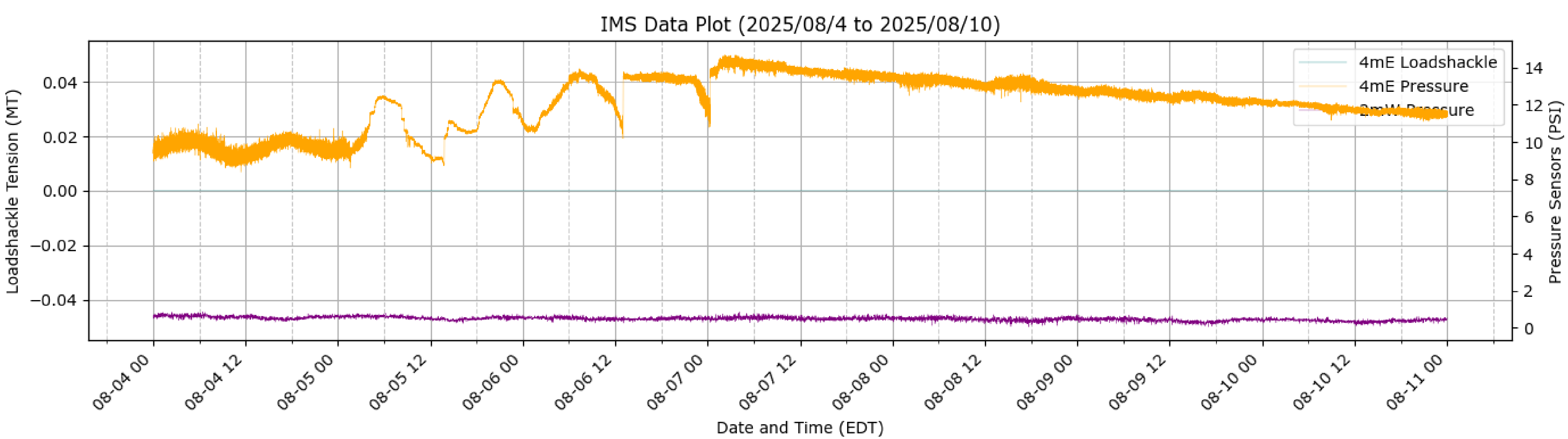
Appendix A. Mooring Diagrams

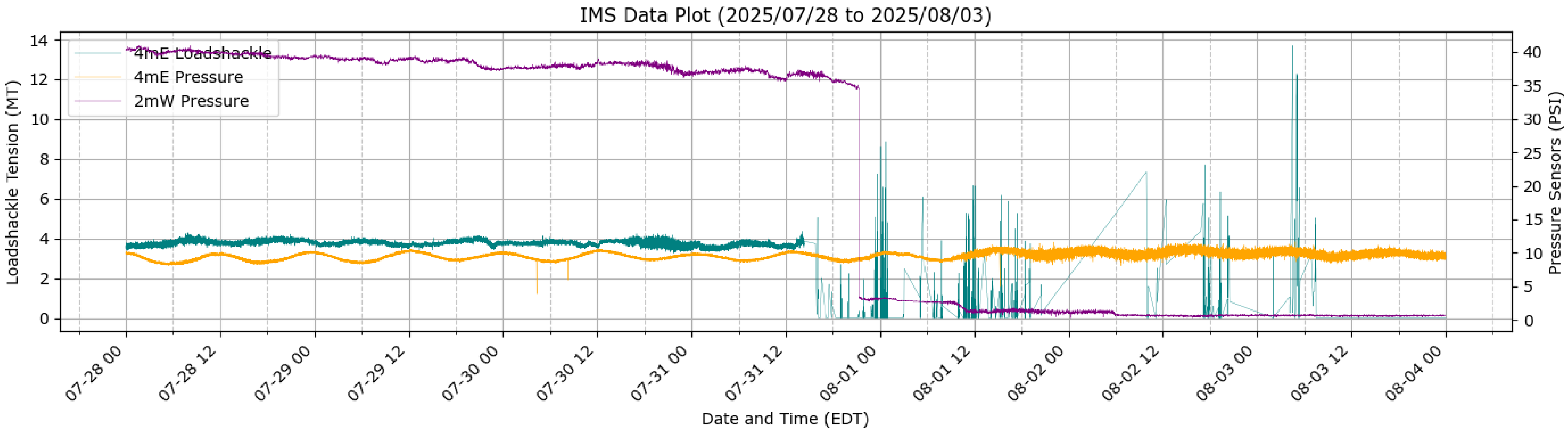

10' Wire Rope Sling
Center HMPE, 51 ft
12' Wire Rope Sling

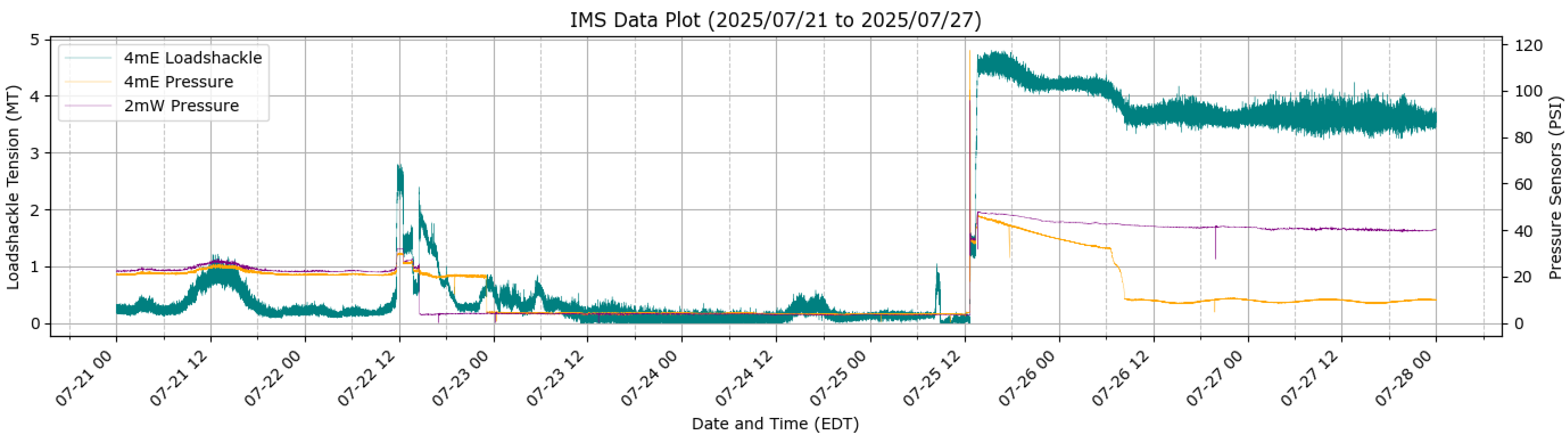

100 ft
10 ft
N
2200 lbs Lift Bags
2.5" HMPE Rope
IMS Units
2" Studlink Chain
58" Diam. Buoys
1.5" Nylon

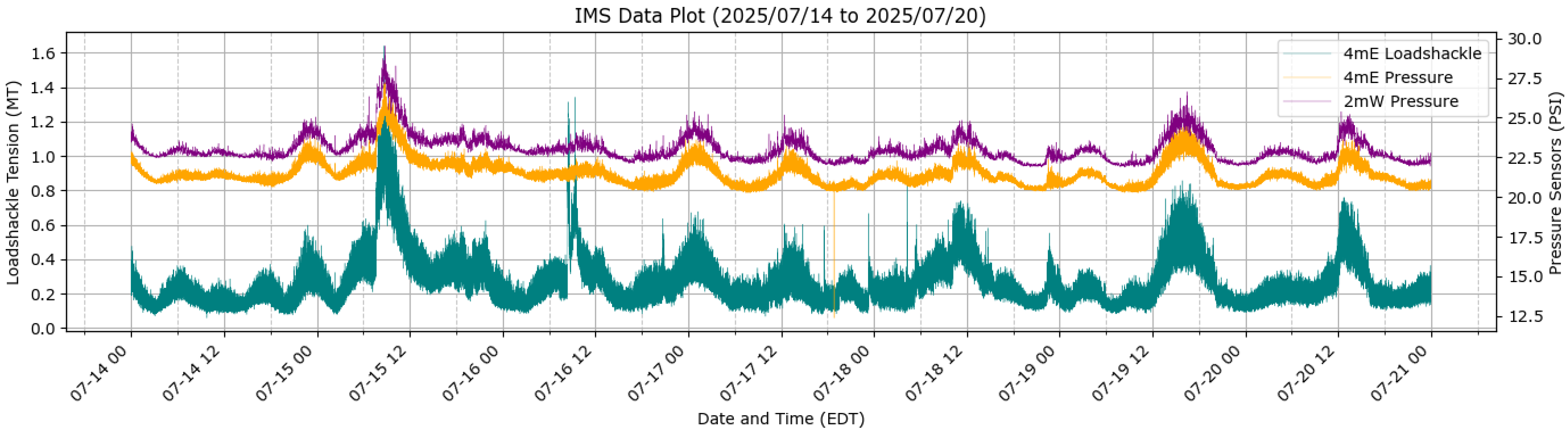
Appendix B. Weekly Sensor Data

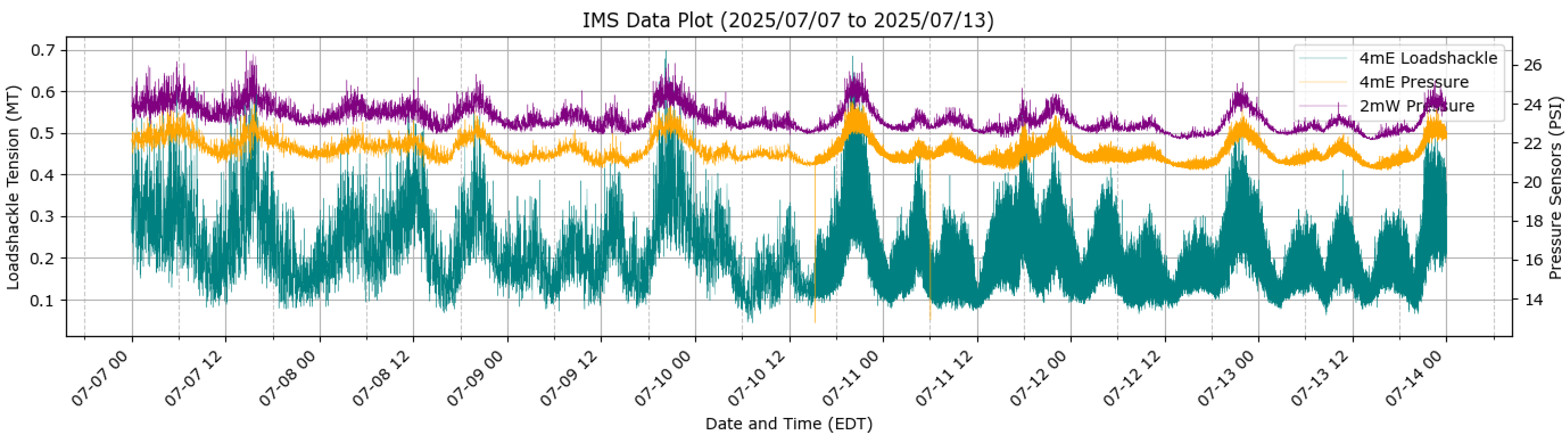

IMS Data Plot (2025/08/11 to 2025/08/17)
4mE Loadshackle
4mE Pressure
2mW Pressure
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
08-11 00
08-11 12
08-12 00
08-12 12
08-13 00
08-13 12
08-14 00
08-14 12
08-15 00
08-15 12
08-16 00
08-16 12
08-17 00
08-17 12
08-18 00

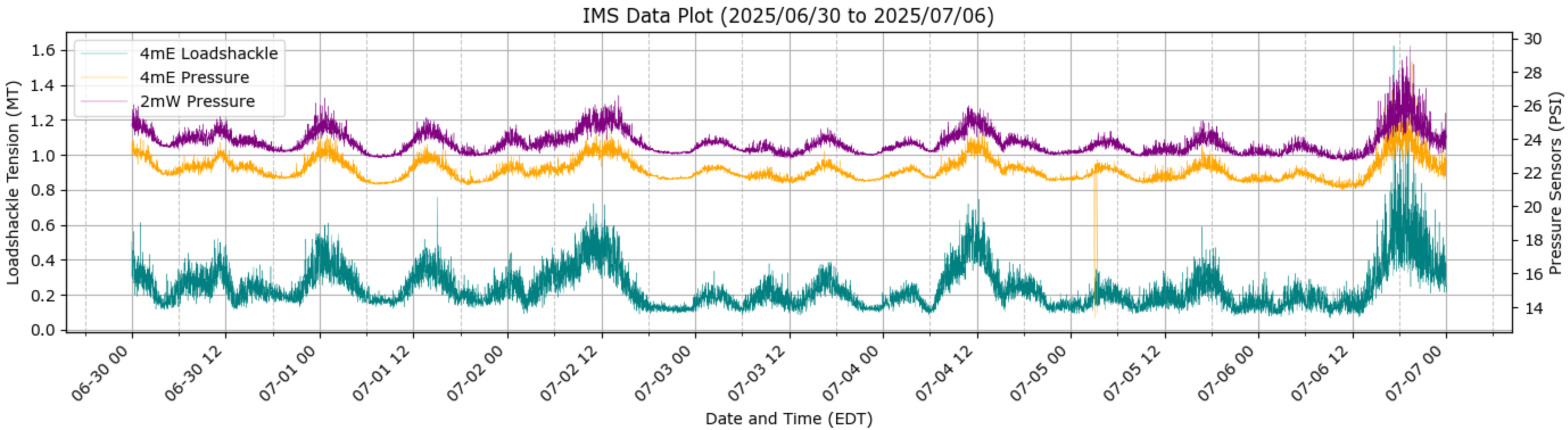

IMS Data Plot (2025/08/4 to 2025/08/10)
4mE Loadshackle
4mE Pressure
2mW Pressure
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
08-04 00
08-04 12
08-05 00
08-05 12
08-06 00
08-06 12
08-07 00
08-07 12
08-08 00
08-08 12
08-09 00
08-09 12
08-10 00
08-10 12
08-11 00

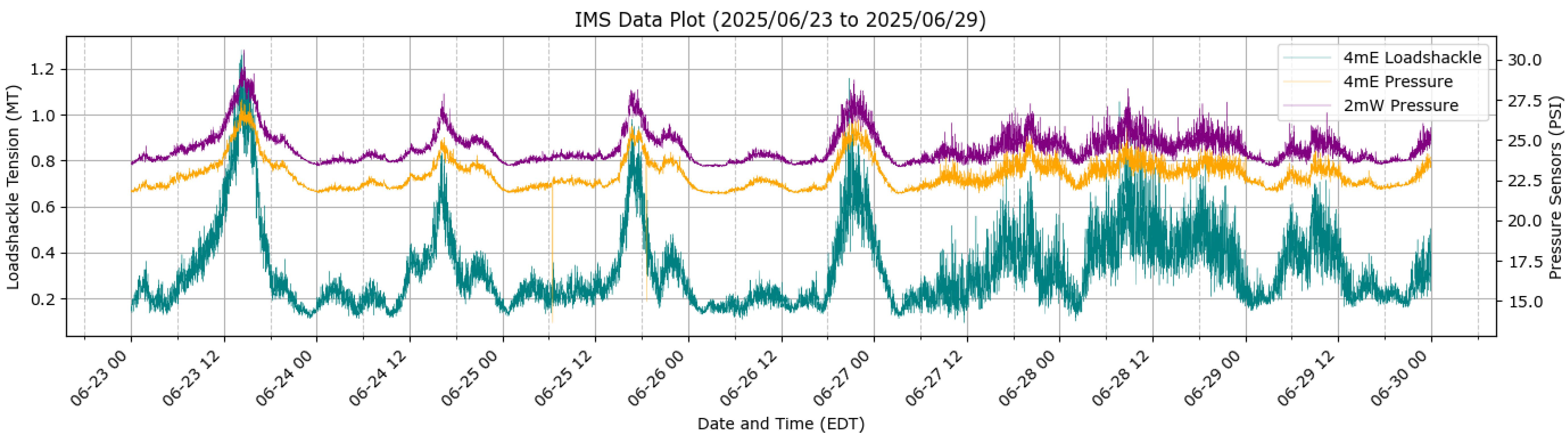

IMS Data Plot (2025/07/28 to 2025/08/03)
4mE Loadshackle
4mE Pressure
2mW Pressure
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
07-28 00
07-28 12
07-29 00
07-29 12
07-30 00
07-30 12
07-31 00
07-31 12
08-01 00
08-01 12
08-02 00
08-02 12
08-03 00
08-03 12
08-04 00

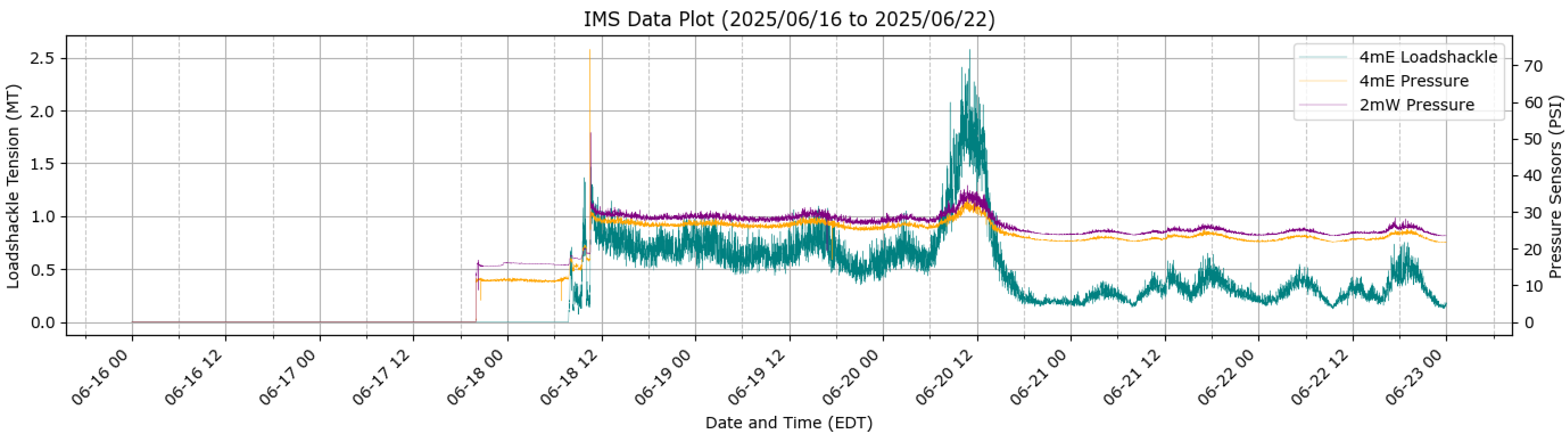

IMS Data Plot (2025/07/21 to 2025/07/27)
4mE Loadshackle
4mE Pressure
2mW Pressure
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
07-21 00
07-21 12
07-22 00
07-22 12
07-23 00
07-23 12
07-24 00
07-24 12
07-25 00
07-25 12
07-26 00
07-26 12
07-27 00
07-27 12
07-28 00


IMS Data Plot (2025/07/14 to 2025/07/20)
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
4mE Loadshackle
4mE Pressure
2mW Pressure


IMS Data Plot (2025/07/07 to 2025/07/13)
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
4mE Loadshackle
4mE Pressure
2mW Pressure


IMS Data Plot (2025/06/30 to 2025/07/06)
4mE Loadshackle
4mE Pressure
2mW Pressure
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
06-30 00
06-30 12
07-01 00
07-01 12
07-02 00
07-02 12
07-03 00
07-03 12
07-04 00
07-04 12
07-05 00
07-05 12
07-06 00
07-06 12
07-07 00


IMS Data Plot (2025/06/23 to 2025/06/29)
4mE Loadshackle
4mE Pressure
2mW Pressure
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
06-23 00
06-23 12
06-24 00
06-24 12
06-25 00
06-25 12
06-26 00
06-26 12
06-27 00
06-27 12
06-28 00
06-28 12
06-29 00
06-29 12
06-30 00


IMS Data Plot (2025/06/16 to 2025/06/22)
Loadshackle Tension (MT)
Pressure Sensors (PSI)
Date and Time (EDT)
4mE Loadshackle
4mE Pressure
2mW Pressure
2.5
2.0
1.5
1.0
0.5
0.0
70
60
50
40
30
20
10
0
06-16 00
06-16 12
06-17 00
06-17 12
06-18 00
06-18 12
06-19 00
06-19 12
06-20 00
06-20 12
06-21 00
06-21 12
06-22 00
06-22 12
06-23 00

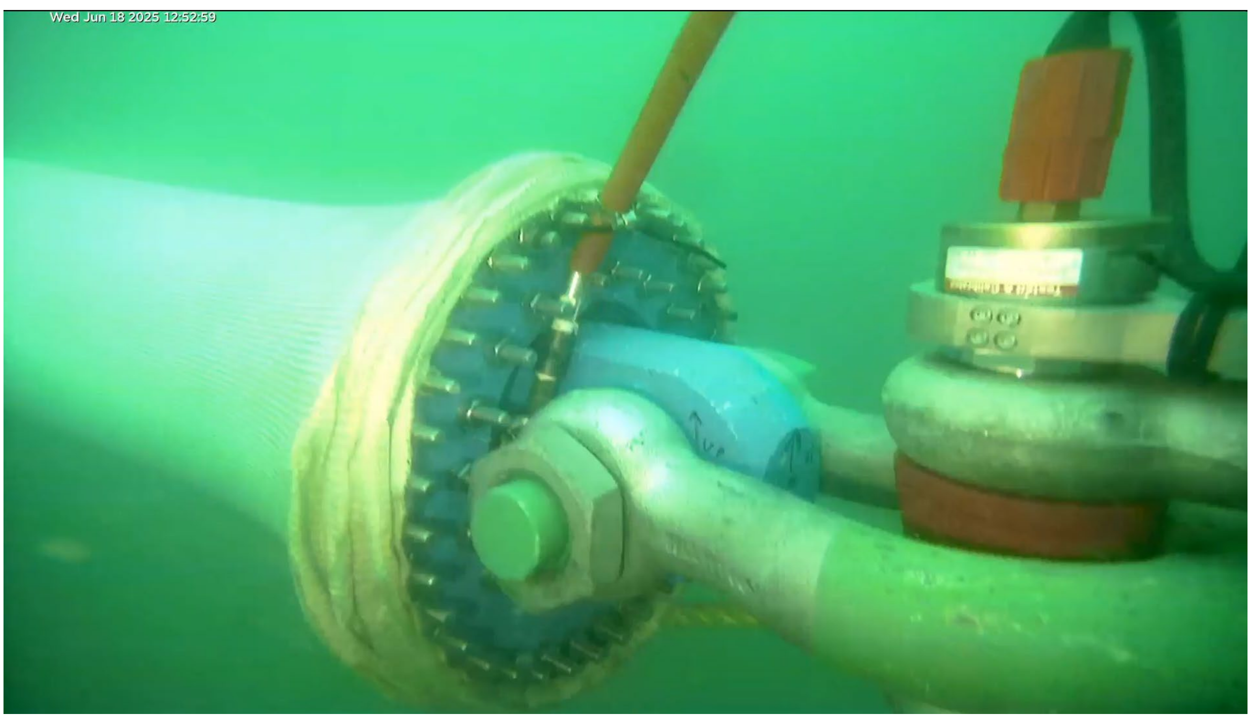
Appendix C. Log of Installation Activities

Tuesday, February 18, 2025	Installed anchors and anchor chains with spud barge and pedestal crane. Pulled the anchors along bridle path with tug Emmy Lou.
Thursday, May 8, 2025	Spliced sensor cables at Norfolk yard, tested loadshackles, pressure sensors, data acquisition.
Friday, May 9, 2025	Conducted a walkthrough of segment connections at warehouse and strategized with the dive team.
Monday, May 19, 2025	Anchor and chains were located at each end. Eastern side was brought together and shackled using lever hoist. Bridles were marked with Buoys. Extra 60' steel wire slings were recovered to the dive warehouse.
Tuesday, May 20, 2025	Completed shackling the chain bridles together. Both the east and west bridles marked with A5 Buoys.
Wednesday, May 21, 2025	Weather Day, no diving, performed tasks at diver warehouse.
Thursday, May 22, 2025	Tug Emmy Lou traveled to site intending to do another pull on the anchor chains. Too difficult for them to navigate and retrieve pull-wire on open ocean.
Friday, May 23, 2025	Dive vessel was used to pull bridles into a V-shape. Attempted to take distance measurement but current much too strong.
Tuesday, May 27, 2025	Waves larger than predicted, headed back just after arriving.
Wednesday, May 28, 2025	Weather Day, no diving.
Thursday, May 29, 2025	Large waves jumbled the chain bridles, pulled with dive vessel again. Added 10' wire sling to NW leg to straighten.
Friday, May 30, 2025	Installed guide-line between bridles and performed multiple measurements
	Dive vessel unavailable following week
Friday, June 6, 2025	No diving, spliced western segment of HMPE
Monday, June 9, 2025	Attached air fittings and tested lifting configurations. Attempted to run segments along guide-line, but currents became too strong later.
Tuesday, June 10, 2025	No diving due to large waves forecasted. Spent half day flaking lines, making all shackled connections possible and strategizing for easy deployment following day.
Wednesday, June 11, 2025	The longest section of HMPE was installed onto the guide-line and shackled to the eastern bridle. Lightning in the afternoon stopped diving.

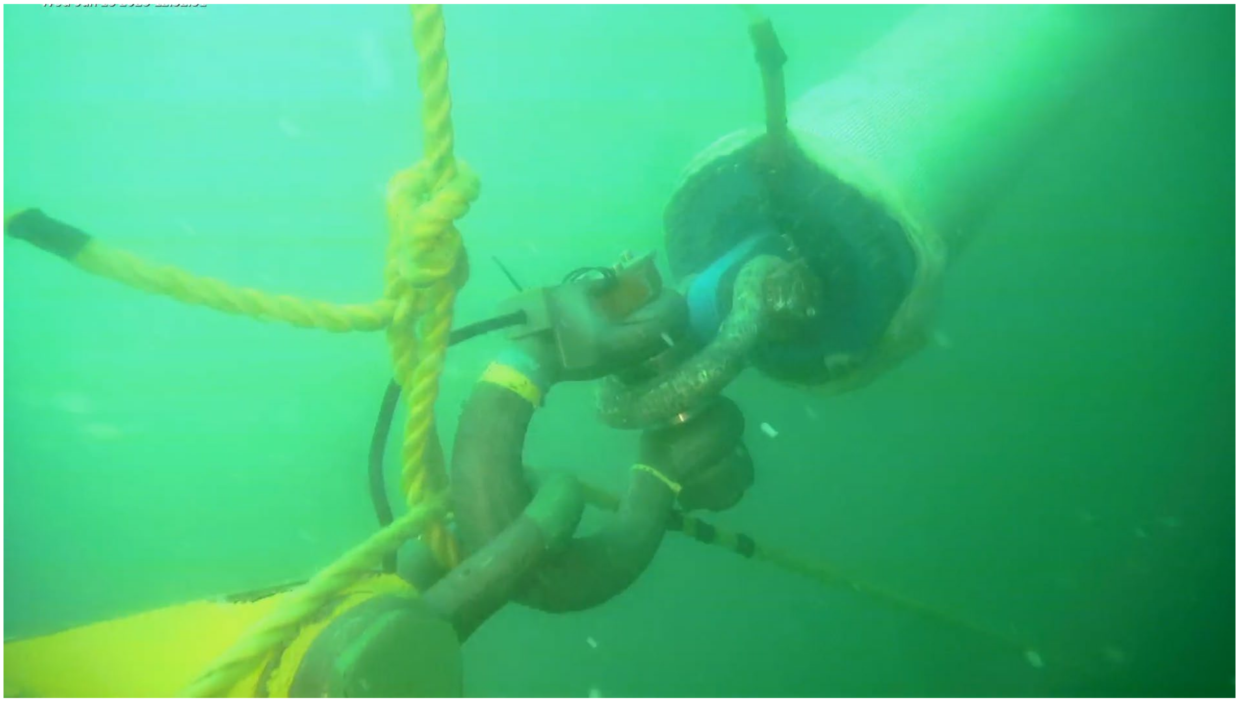
Thursday, June 12, 2025	Connected western HMPE segment, then travelled east, paying out slings and central HMPE segment. Lowered each IMS, and the flounder plate individually using onboard davit.
Friday, June 13, 2025	Launched and towed 58" steel sphere buoys to site. Flooded buoys and then attached to the mooring on seafloor. Inflated buoys, which pulled out slack. Resubmerged the buoys before incoming storm.
Monday, June 16, 2025	IMS units filled to 30 PSI, 10' slack is removed from sling segment near 2m IMS. Sphere buoys inflated ~10 ft off bottom.
Tuesday, June 17, 2025	Data buoy launched using shore-based crane. Tanks opened, buoy light attached. Mooring chains installed in sheltered inlet. Shackled in Data buoy riser, submerged the sphere buoys. Removed another 4ft of slack. Attached three painter lines to the mooring. Ran sensor cables and air lines to the data buoy and fastened umbilical to the riser line. Initialized the data loggers through hatch and inspected internal pressure readings.
Wednesday, June 18, 2025	Removed another 5' of slack from system using lever hoist. IMS pressure increased to 35 psi. All cotter pins secured on shackles. Air hoses and sensor cables reconfigured to provide strain relief and add protection near flounder plate. Painter chain slack was secured. Performed diver inspection.
Tuesday, July 22, 2025	System tension was increased by inflating sphere buoys. Attempts made to re-submerge the buoys to pull slack were made difficult by strong currents and increasing waves.
Friday, July 25, 2025	Sphere buoys were submerged, disconnected, and secured back to chain bridles. Pillow-type lift bags were installed in place of the sphere buoys. 5-ft of slack was removed from system. Air lines were repaired and IMS pressurized to 40-psi each. Lift bags were filled to full capacity, generating 4.75 MT of tension.

Appendix D. Dive Inspection Photos

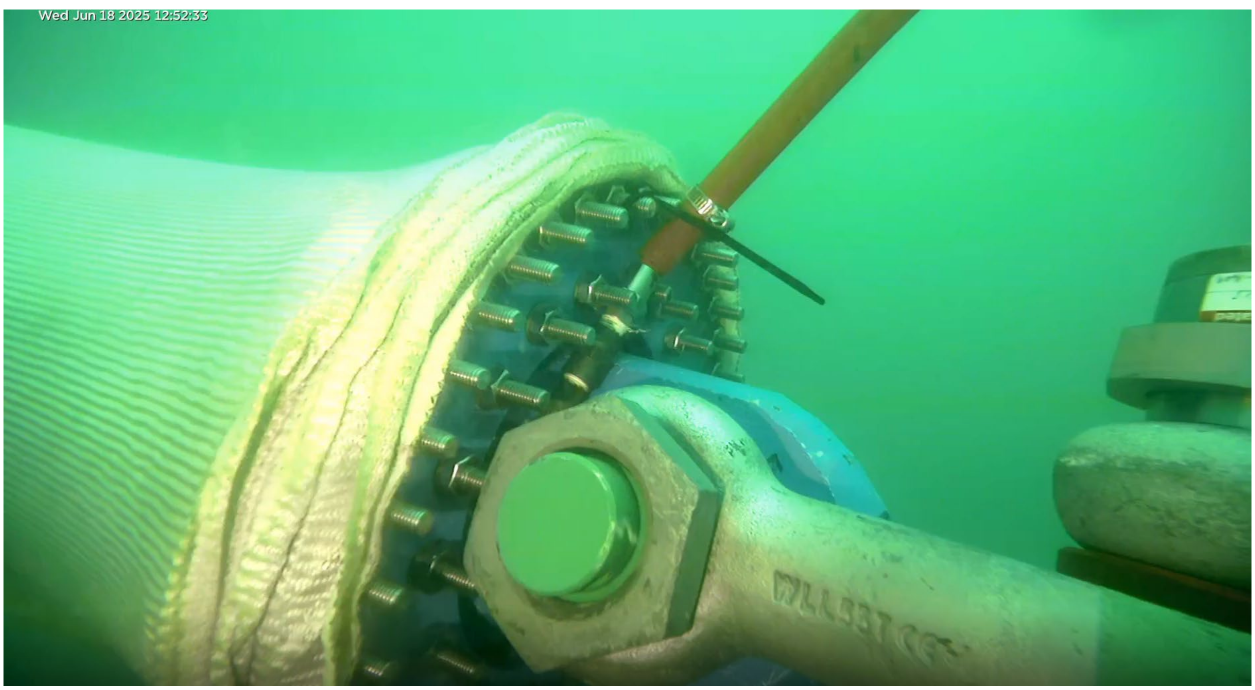
4m IMS end flange (without air connection) with 2” and 2” wide jaw shackles connected to 2.5” HMPE thimble.



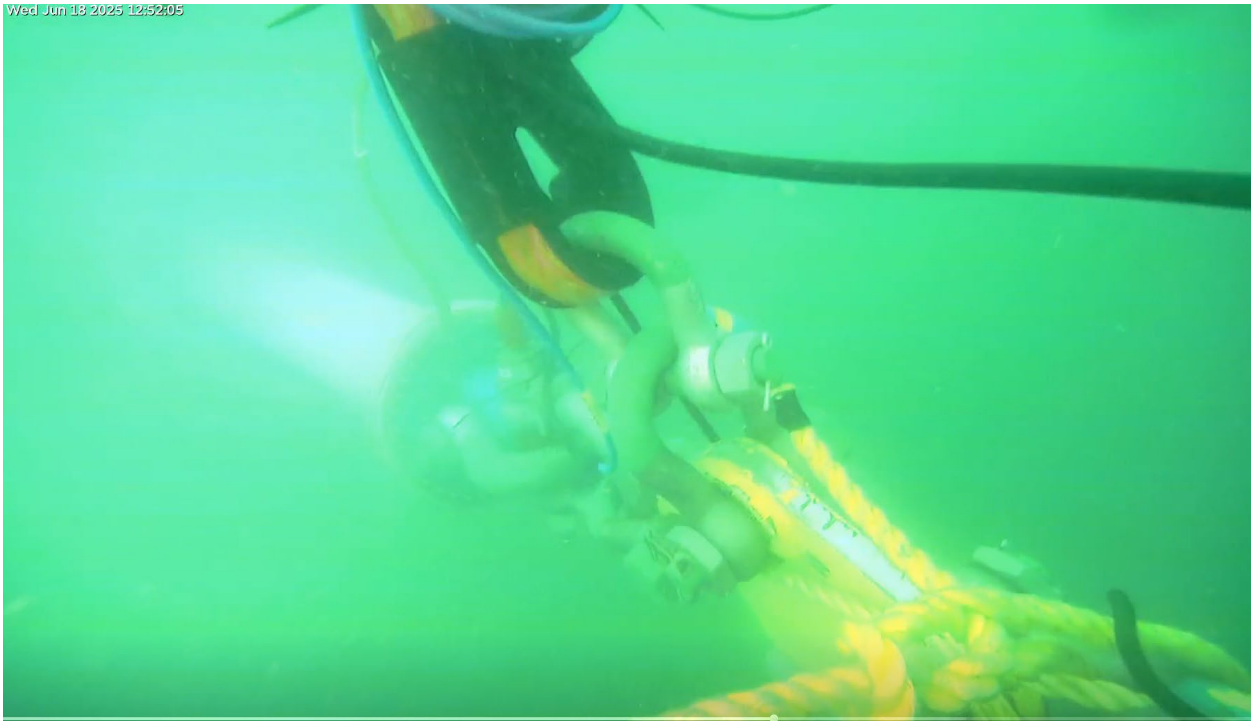
4m IMS flange with 1/4inch air fitting, attached to 2” shackle, and loadshackle.



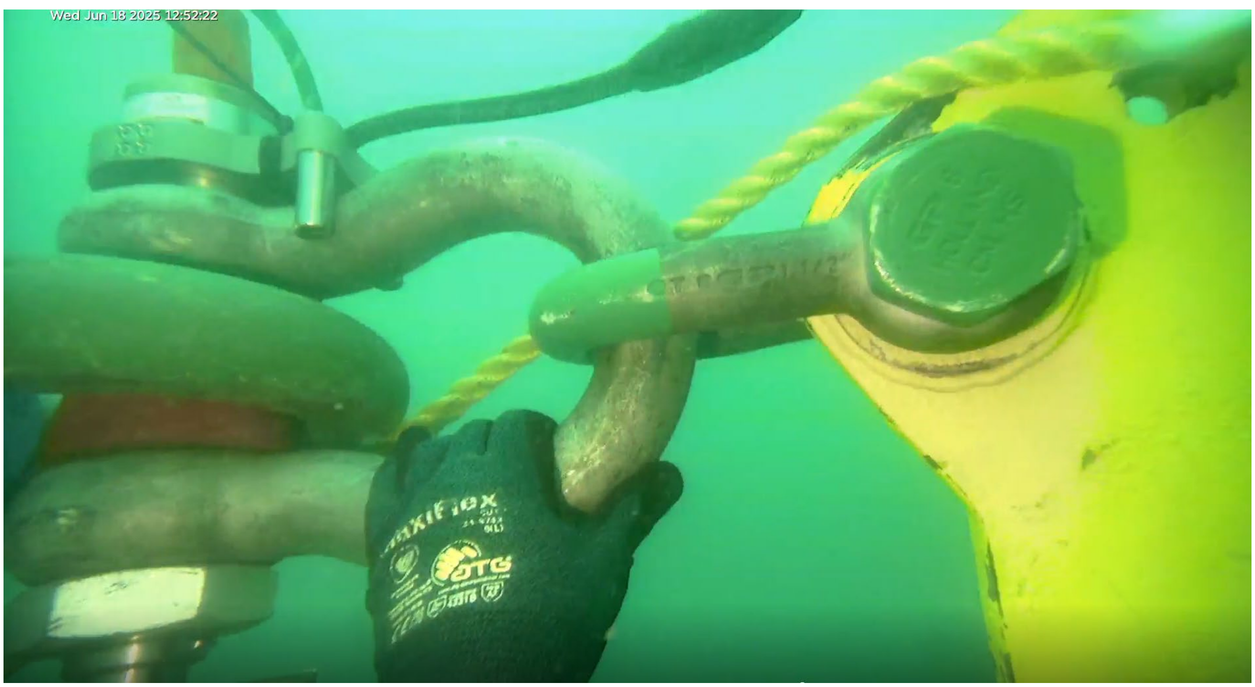
2m IMS and flange with 1/4inch air fitting, attached to 1.5” shackle, loadshackle, and corner of flounder plate.



Another view of the 4m IMS showing tight connection with air port and shackle ear.



Viewing ESE, showing 4m IMS in background, flounder plate, and riser line thimble on top.



View of flounder plate on right, attached to a loadshackle, and the 4m IMS on the left.

Appendix E. December 2024 Presentation Slides

Quarter-Scale Testing of the Intelligent Mooring System for Floating Offshore Wind

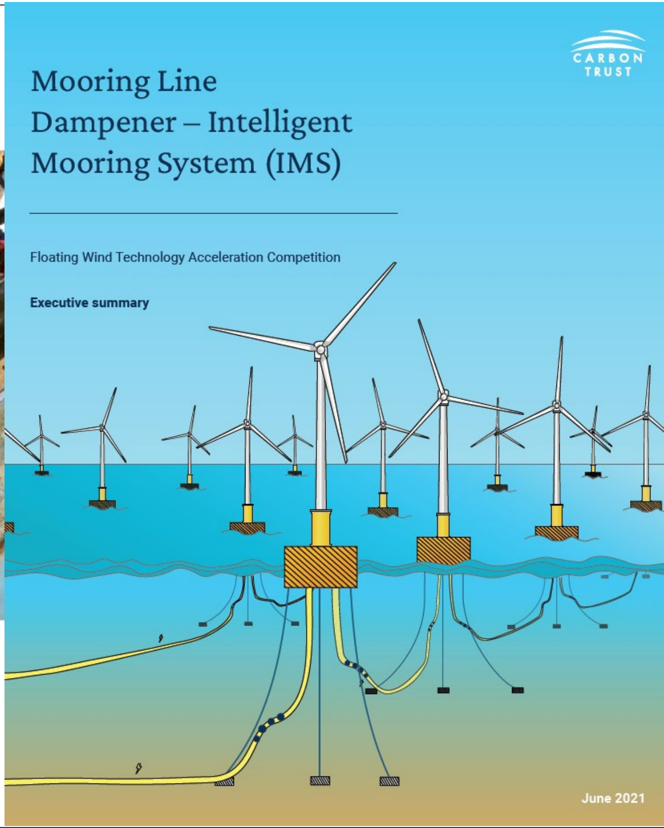
Goal:

Reduce peak and fatigue FOWT mooring loads to reduce LCOE

At shallower FOWT sites (to 100-m depth), conventional mooring systems can be challenged by anchor line snap-loads resulting from high wave regimes.

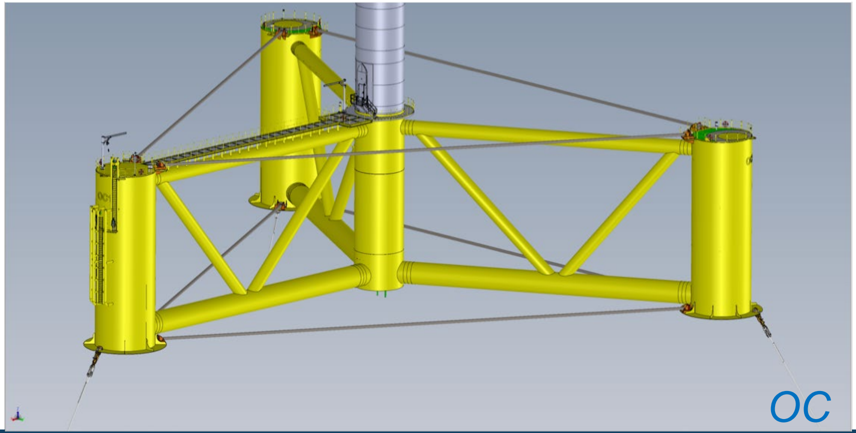
Mooring system costs are proportional to the peak loads, i.e those loads that occur infrequently from extreme environmental conditions

Moorings represent 10 to 15% of the total CAPEX costs



Team & Scope & 3 Phases

Phase 1 - USD 172K:
Integrate IMS with 15 MW platform
Phase 2 - USD 214K:
Plan & Permit at-sea test
Phase 3 - USD 443K:
Perform at-sea test



PCCI Marine and Environmental Engineering — Prime Contractor to NOWRDC, design review and installation oversight.

IM — Component and system design, fabrication

University of Exeter — Modeling and laboratory testing

OCERGY Sustainable Offshore Solutions — OCG-Wind floating platform integration with the IMS

Phase 1 Ocergy and U. Exeter

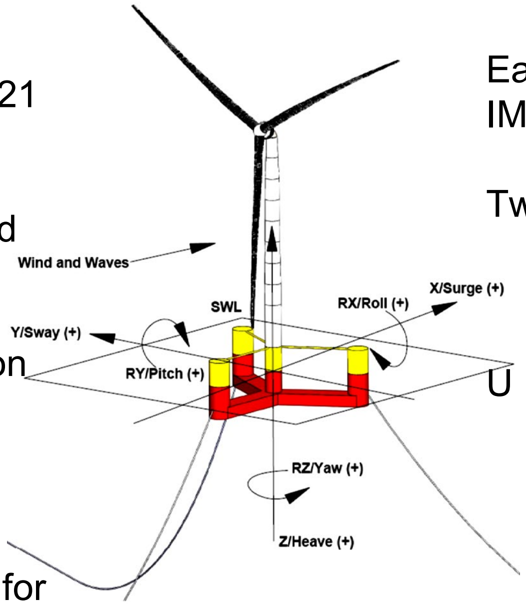
UK-funded work began May 2021

NOWRDC work began October 2021

Calendar Year 2021 focus was Design Integration with the IMS and Completing a Test Site Agreement

Calendar Year 2022 will be spent on computer modeling, IMS manufacturing of the 1/4-scale test piece and test planning

At-sea testing originally scheduled for 2023, IMS were delayed



Findings:

Easy to integrate system w/ Ocergy platform
IMS mooring installation adds steps, do-able

Two Cases to cause peak tensions:
- Max power production (20%-40%, common)
- Max response during max storm (rare)

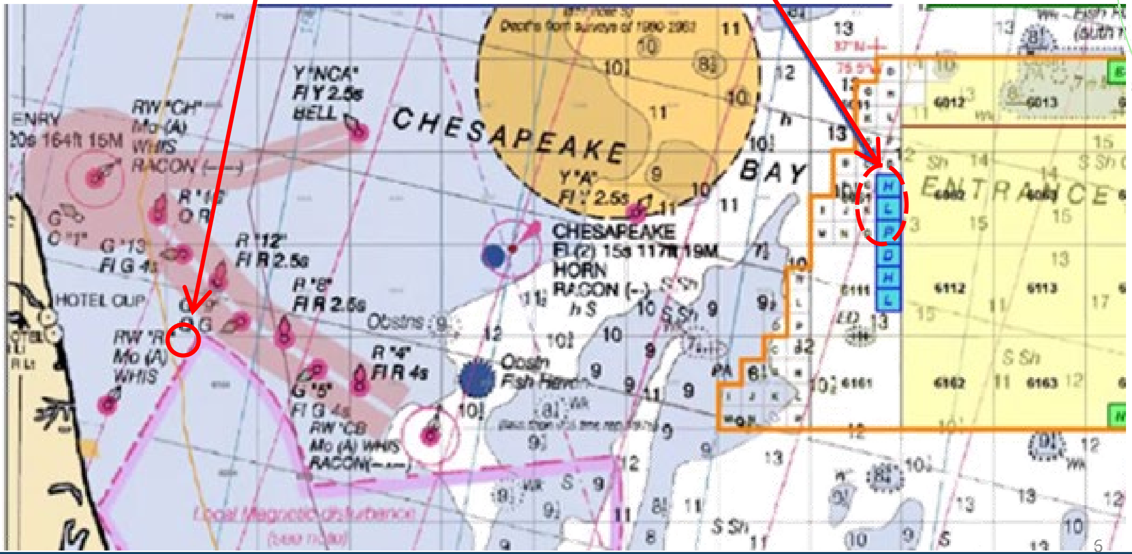
U Exeter simulated 60m & 300m depths:
- 60m depth: Reduces peak tension ~6%
  Adds some horizontal excursion
- 300m depth: Little reduction in peak tension

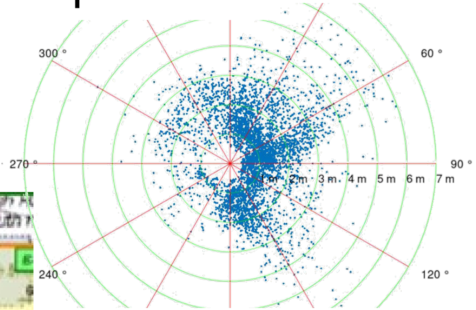
Phase 2 Planning & Permitting: VA instead of HI-WETS

<u>Test Goal</u>: Reliability test ! Reduce risk for first adopters

Approved Request:
NAO-2022-00508
Federal waters

First request: VA /
BOEM Offshore wind
research Lease





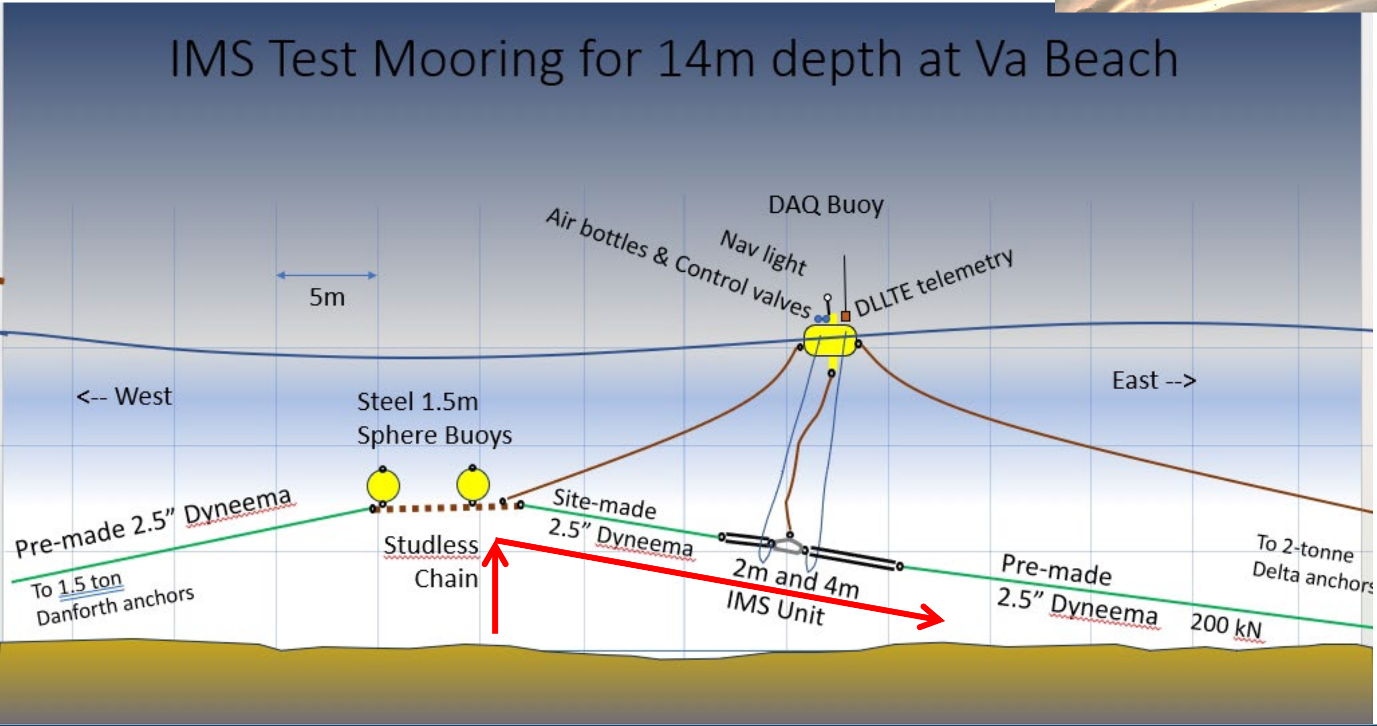
Hawaii Wave Energy Test Site - busy

Virginia Beach, VA instead of windward Oahu, HI (Less travel time)

Moored buoy with vector amplification instead of moored barge. (Less risk)

Two Units

Phase 2 Plan At-sea Test



Two 30 cm dia IMS units, in series: 2m long, 4m long .

Four x 1.5-ton anchors, two x 1.5-ton sphere buoys, 2.5" dyneema line

Predict ~10 tons taut, 20 tons storm

Install 2024 – early 2025.

Crane barge.

Tug sets anchors 20 tons each, dive team assemble and tighten mooring.

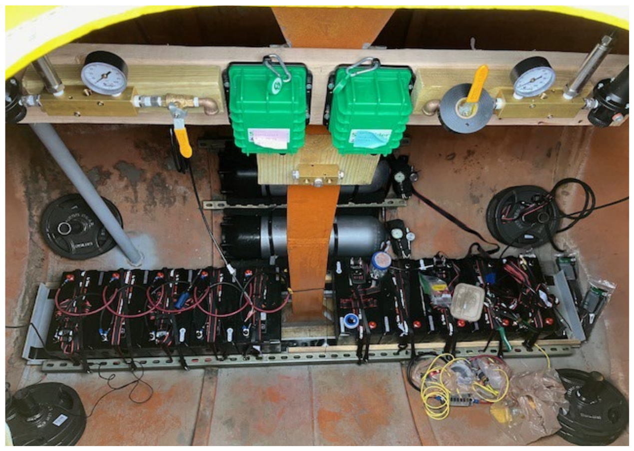
PCCI Marine and Environmental Engineering

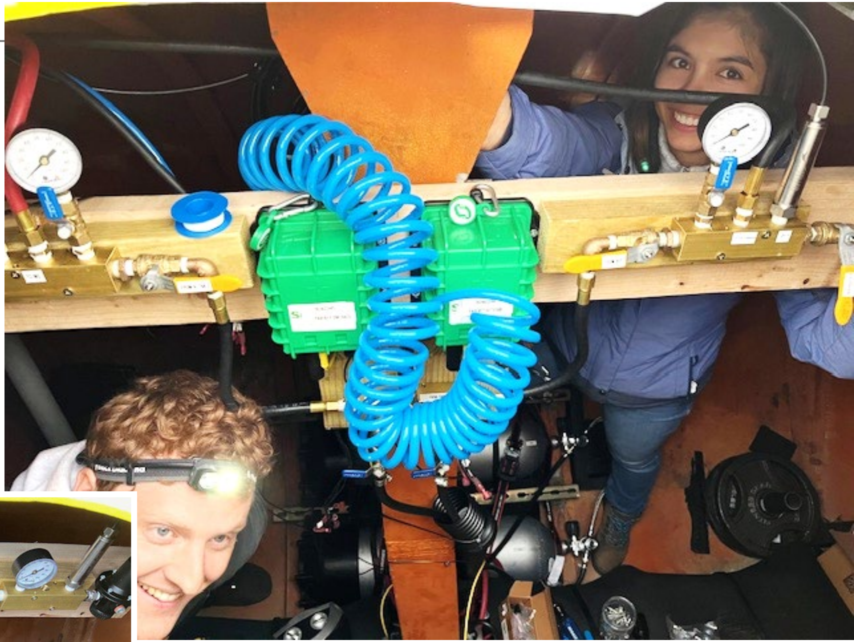
NATIONAL OFFSHORE WIND RESEARCH & DEVELOPMENT CONSORTIUM

Phase 3 Install the Test Mooring Dec - Jan

6'dia x 10' buoy from USN

Added hatch, padeyes, ladder, mooring light, thru-hull conduit





Two data systems: Log IMS internal pressure, tension, data logger, 4G modem, air bottles

Phase 3 Remaining Tasks 2025

- Conduct ¼ scale at-sea test
- Prepare Summary Report
- Evaluate data, inspect both IMS units
- ABS perform product design assessment and certification
- Write Market Engagement Report
- Submit Final Report