University College London Faculty of Engineering Sciences Department of Mechanical Engineering

Live Data Monitoring Platform – Coastal Buoy

MECH0073 Final Design Report

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Abstract

Coastal monitoring requires platforms that integrate underwater acoustic, motion, and environmental sensing at a cost and operational scale accessible to research groups. Existing low-cost buoys typically carry only low-bandwidth environmental channels, and commercially mature platforms are sealed and not modifiable for student or research use. This project converts an inherited passive instrument carrier into an integrated coastal monitoring prototype within a £2,500 hardware budget.

The realised buoy is a free-flooded HDPE-shell platform with closed-cell Plastazote LD45 buoyancy, a bolted aluminium tripod and mast carrying a daymark and navigation light, and two IP68 enclosures protecting the battery and electronics. Sensing comprises an Aquarian H2DM hydrophone captured through a HiFiBerry DAC+ADC Pro, a nine-axis inertial measurement unit (IMU) on an Arduino Nano 33 BLE Sense Rev 2, and a DS18B20 water-temperature probe. A Raspberry Pi 4 coordinates logging to a Samsung T9 solid-state drive and operates a 4G/LTE uplink through a PiTalk HAT; a 12 V, 10 Ah $LiFePO_4$ battery supplies a regulated 5 V rail and a duty-cycled navigation light. The data architecture retains raw sensor records locally while transmitting position, battery state, system health, and selected summaries over the cellular link when available.

Verification followed a staged ladder: bench commissioning of the sensing chain, controlled wave-tank assessment of buoyancy and stability, and a saltwater field deployment from a supported launch at Brighton on 1 May 2026. Hydrostatic predictions, the mass budget and centre of gravity, and free-flood thermal behaviour were validated to within the prototype tolerance band. The IMU peak-period recovery and end-to-end sensing pipeline integrity met their requirements; the hydrophone acquired ambient and event-driven recordings, but the analogue gain configuration does not yet bring low-level deep-sea ambient noise above the digitiser noise floor. GNSS field acquisition and LTE successfully maintained connectivity throughout field testing. The original 14-day continuous endurance target was reduced during integration to a duty-cycled, short-duration prototype envelope to remain within mass, packaging and handling limits.

The contribution is a defensible first-generation integrated prototype with quantified limitations, explicit closure routes, and a handover package that supports continuation by future cohorts.

Declarations

Declaration of Originality

i. **Use of AI**

I acknowledge the use of generative AI tools during this project. The specific tools and their roles were:

- **ChatGPT (OpenAI, GPT-5.4)**: assistance with structuring Python data-analysis scripts, interpreting error messages during software debugging, and reviewing the clarity of written passages.
- **Claude (Anthropic)**: assistance with consolidating supervisor feedback into actionable section structure, drafting comparative trade-off tables, and reviewing internal consistency of cross references and quantitative claims.

All engineering content, design decisions, analysis, code, and results are my own responsibility. AI tools were used in an assistive capacity and not as authors of substantive content; their suggestions were reviewed, edited, accepted, or rejected on the basis of my own engineering judgement. No AI tool was used to generate experimental data, to produce references, or to produce content presented as another author's work.

i. Sponsorship

No sponsorship has been received.

ii. Additional Funding

No additional funding has been received.

iii. Ethics

No ethical approval required.

iv. Continuation of Previous Projects

This project is not a continuation of a previous individual or group project carried out by one of the team members.

This project is not a continuation of an Industry project.

v. Continuation of Project

This project is structured with the intention of continuation in subsequent years.

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1. Project Definition and Requirements

1.1 Operating Context and Problem Definition

Coastal waters are difficult to monitor because they change quickly and are strongly affected by local conditions. Weather, tides, marine traffic, pollution, coastal infrastructure and ecological change can all alter the water environment over short time periods and small spatial scales. For researchers, this creates a need for monitoring platforms that can be deployed close to shore, collect useful data without constant supervision, and be recovered without relying on large vessels or expensive commercial systems.

Most low-cost coastal monitoring platforms focus on environmental variables such as temperature, salinity, dissolved oxygen, currents and waves. These measurements are important and align with the Essential Ocean Variables used by the Global Ocean Observing System to describe the state of the ocean. However, they do not capture the acoustic environment. Underwater sound can provide information about vessel activity, ambient noise, biological presence and marine mammal behaviour, which cannot be measured through conventional environmental sensors.

Adding acoustic monitoring changes the problem from a simple sensor buoy into a more demanding integrated system. A hydrophone produces far larger data volumes than temperature or motion sensors, so the buoy must be able to record continuously, store raw data locally and manage data transfer without losing the original record. It also makes the physical design more sensitive, because waterproofing, cable routing, electrical noise, vibration, hydrophone placement and serviceability can all affect the quality of the recorded data.

Existing low-cost platforms show that compact autonomous sensing is possible, but they are often limited to lower bandwidth environmental measurements. Commercial systems such as the Sofar Spotter provide a useful benchmark for packaging, telemetry and field usability, but they are closed products and are not intended to be modified freely between research tasks. This leaves a gap for a low-cost coastal buoy that is open, inspectable and adaptable, while still being realistic to build, deploy and validate within a student project.

Figure 1.1: Sofar Spotter Buoy (Sofar Ocean)

1.2 Stakeholders, Use Case and Scope

Primary users are academic researchers in coastal monitoring, marine acoustics, and environmental sensing: users who typically need adaptable platforms with raw data access and affordable enough for iterative development. Secondary users are future project teams who may extend the buoy as a teaching, testing, or research platform; for them, CAD files, wiring records, software setup notes, and operating procedures form part of the platform’s future usability and are treated as engineering deliverables in this project rather than as administrative extras.

The intended use case is short-to-medium duration deployment in sheltered nearshore waters. The buoy is to be transported to a coastal site, launched by a small, supervised team from a boat, monitored during deployment, and recovered after the test window. It is required to record hydrophone, motion, temperature, and position related data locally on the buoy itself, and to transmit selected data and health information regularly to the land over a cellular network. A central goal of this work is live remote monitoring: the primary users must be able to access the data in which the buoy is recording, including its sensor activity, health, and position, from land while a deployment is underway, rather than only after recovery. Local logging remains the primary data path and retains the full raw record onboard, while telemetry delivers this near-real-time awareness over an intermittent cellular link that is treated as a normal coastal operating condition rather than an exceptional one.
The development scope covers the buoy platform and its structural adaptations, the sensing subsystem, the embedded processing and logging arrangement, the battery-powered electrical system, data transmission, and the documentation handover.

Verification is kept to the level of evidence appropriate for a first-generation prototype. It consists of component checks, bench integration, still-water testing, wave-tank assessment[1], and finally field testing[2].
The only externally imposed constraint on the project is budget: an allowance of £500 per team member, giving £2,500 in total for the five-person team which must cover the structural, sensing, electrical, and communications components and other expenses. All other targets, including the internal performance objectives such as minimum operational endurance, are set out in the Product Design Specification in Section 1.3.

1.3 Product Design Specification

The Product Design Specification (PDS) consolidates the operating envelope, performance requirements, and exclusions established in Sections 1.1 and 1.2 into a specification level view that was used as the working baseline for design development and as the reference for compliance assessment. Table 1.1 summarises the headline requirements; the full PDS, with detailed numerical limits, priorities, and verification routes for every subsystem, is given in Appendix A.

The PDS is structured around three classes of requirement: operating envelope (the conditions the platform must function within), system requirements (what the platform must do), and constraints (how the design could be developed). Priority is recorded as Must, Should, Could, or Excluded. Must items were treated as binding design constraints, and verification routes for each are identified in Sections 3.6 through 3.8 (FEA, stability, and load checks) and Sections 6.3 and 6.4 (tank and field testing[3]).

Table 1.1: Headline Product Design Specification. Detailed requirements are given in Appendix A.

Area	Headline Requirement	Priority
Operating environment	Shallow coastal and sheltered nearshore water, sea state up to 4, sustained wind up to 15 m/s, current up to 0.5 m/s	Must
Physical envelope	Total unballasted mass ≤ 30 kg; loaded freeboard ≥ 50 mm	Must
Flotation	Free-flooded compartment with sealed buoyant core; positive buoyancy preserved on hull breach	Must

[1] Davide Grande, RA108558/1, "RA_tanks_v4.pdf", 2026
[2] Project team field-test record Brighton Field Test of Prototype, 2026

Sensing	Acoustics from hydrophone, sea-state estimates, and seawater temperature; hydrophone depth adjustable from 0.5 m to 3.0 m	Must
Power and endurance	continuous operation ≥ 14 days	Must
Environmental protection	IP68 enclosures; marine-grade materials for all saltwater hardware	Must
Deployment	Two-person deployment and recovery from supervised small craft; two-buoy mooring (surface plus sub-surface float)	Must
Cost and programme	Hardware budget ≤ £2,500; single academic year development cycle	Must

2. Design Drivers, Concept Selection and System Architecture

2.1 Requirements and Design Drivers

The PDS in Section 1.3 defines the targets the platform must satisfy. This section identifies the principal engineering requirements that follow those targets and uses them to justify the main architectural decisions taken in this work. The intent is to establish clear traceability, so that each decision derives from a stated requirement rather than from preference.

Four requirements govern design: (1) The hydrophone is the primary sensor and must operate continuously at 96 kHz and 32-bit resolution. (2) The complete raw record must be retained locally on the buoy. (3) Selected data must also be transmitted to shore, with remote access maintained throughout a deployment. (4) The platform must sustain a multi-day mission, for which 14 days is adopted as the governing figure. These requirements impose four demands on architecture.

1. High sustained data rate, determined by the acoustic sampling configuration and the requirement for uninterrupted recording.
2. Substantial local storage capacity, since several days of raw data must be retained onboard.
3. Requirement for genuine computing capability, in order to manage the file archive, prepare and transmit selected data, support remote access, and maintain operating state.
4. Significant energy demand, as continuous acquisition and active computation must be sustained for the full mission without intervention.

These demands cannot be resolved independently, as the platform is simultaneously bound by limits on mass and size. Deployment is carried out by two people from a small boat, with a manual lift limit of 25 kg per person and a total mass held at or below 50 kg. The mission therefore calls for a capable and energy-intensive payload, while the handling constraints cap the quantity of hardware, and the battery capacity, that the platform can accommodate.

2.2 Exploration of previous work

Figure 2.1 shows the three concepts analysed to identify industry standard design features as well as advantages and disadvantages of potential design features.

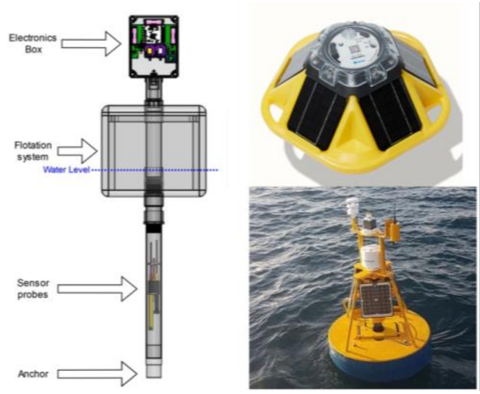

Figure 2.1: Concept 1 (left): Vertical buoy; Concept 2 (top right): Mini buoy; Concept 3 (bottom right): Top-mount buoy

One of the main advantages of concept 1 [1] is its simplicity as it uses inexpensive, off-the-shelf parts making future development and modularity viable. Although this is not a high priority, this is a design consideration which is important for this project as it will be handed over to a new group of engineers to develop further in the future. This design simplicity also keeps costs low ensuring that the project stays within budget constraints. One of the key disadvantages of this buoy is the algae growth on all submerged parts. Care should be taken to mitigate this in the final design by using anti-fouling coatings/features or at least note that regular cleaning/maintenance would be required. In addition to this, the buoy's durability may struggle in coastal waters as this has only been tested in a relatively still pond. Overall, the structure of the buoy is good with the anchor at the base, sensor probes just above and a flotation system keeping the water level well below the electronics. This will minimise the risk of the electronics becoming water damaged.

Concept 2 [2] provides a compact, lightweight and easily hand-deployable solution which is ideal for this project. It's cloud connectivity allowing real-time access to data via a simple-to-use dashboard is a key feature which this project should integrate. The buoy features a variety of sensors and this design could easily be adapted to be modular. A key point to note is that this buoy costs over £4,900 which is significantly more than the budget for this project so it may not be feasible to integrate some of the buoy's key features. In addition to this, the buoy is designed to be used in conjunction with many other buoys to span a large area to get more accurate data further adding to the cost. A single Sofar Spotter buoy would be largely ineffective in collecting accurate marine data. The use of solar panels is interesting as this is a sustainable source of power. However, the reliability of this power source will need to be assessed for expected deployment conditions. The visibility light is an important safety feature especially considering a buoy being developed for multi-day deployment and this will ensure that the buoy avoids impacting other vessels.

Concept 3 [3] is a strong long-term scientific monitoring buoy measuring a variety of coastal parameters. The size of it allows flexibility in usage as a variety of sensors can be integrated easily. The size and weight of it also allows a large battery to be integrated for long term deployment. However, the size and weight of this buoy are outside the constraints of this project. The top mount is a useful design feature making the buoy significantly more visible, allowing sensors and lights to be mounted on top as necessary for a modular design whilst also having a solar panel to recharge batteries when possible.

Overall, all three designs provide useful design direction in some key aspects but have drawbacks which must be mitigated over the course of this project. Concept 1 is an ideal starting point but its poor durability and regular maintenance makes it unsuitable as this project will be developed for long term ocean monitoring in future project iterations. The design may be suitable for coastal conditions over a short 14-day period but it is important to keep future project development in mind too. Concept 2 provides a strong reference for a compact, lightweight, hand-deployable design with a real-time dashboard but the high cost makes it difficult to translate directly into this project. Concept 3 has some great safety features and is clearly visible in an ocean environment but is ultimately too large and heavy for easy deployment and handling. Overall, whilst concept 1 and 3 provide inspiration for some design features, concept 2 is the most suitable design to develop towards over the course of this project. Improvements can be made to the cost, the modularity of sensors and accuracy of results in a single-buoy deployment scenario.

2.3 Benchmarking against a commercial platform (Sofar Spotter)

The Sofar Spotter buoy has dimensions 420 mm (width) x 310 mm (height) and a weight of 7.45 kg. This is well below the 50 kg safe handling limit previously outlined but provides insight into the lower-bound of what is possible for this type of buoy. The dimensions of the buoy designed over the course of this project should be less than 1m (width) x 0.5m (height). The lower cost will likely make it difficult to create a custom-fitted hull for the components used so the hull will be larger than the Sofar Spotter's but the small size does provide insight into what is possible.

It uses satellite as well as cellular connections depending on the location of the buoy to optimise connectivity in any region/environment. Although this is the safest way to maintain strong connectivity to the buoy, it may not be cost or space effective for this project. Since the buoy is only being deployed in coastal regions, cellular connection should be sufficient and any loss of connectivity should be temporary. Fail-safe GPS systems should be used regardless in the instance of total buoy failure to avoid losing the buoy out at sea.
The use of solar panels is an interesting design choice as power may be unreliable. A power assessment needs to be conducted in order to establish the feasibility of using solar energy to power the buoy. Some sensors and systems may require too much power for the solar panel to sustain power delivery over the 14-day deployment. In addition to this, cloudy weather which is so common in the UK may also make this less effective.

The use of a real-time dashboard is definitely something that should be integrated into the system design to allow the user to not only find failures quickly but also identify interesting points of data to investigate in real-time. Although that is the primary function of the dashboard, the dashboard should also be able to report battery levels and error warnings in case of system failure. The GPS location of the buoy should also be available to track it's movements and the data can be further improved this way using publicly available weather and wave data for the buoy's specific location.

The modular mooring system is also interesting as this allows the user to create a single or two-buoy system as necessary depending on the data being collected. This could be a useful feature for this project increasing modularity as the project develops and sensors are swapped out over future iterations. For some sensors such as the hydrophone, a two-buoy system may be optimal to avoid noise being created by the mooring under the primary sensing buoy. The mooring system used on the Sofar Spotter acknowledges a maximum working load of 1,780 N so this should be kept in mind when designing.
Table 2.1 summarises and quantifies these updated requirements based on the data available regarding the design of the Sofar Spotter buoy.

Table 2.1: Summary of updated requirements based on benchmarked Sofar Spotter buoy

Spotter-derived principle	Spotter reference specification	Updated Buoy Requirement
Hand-deployable platform	Spotter buoy: 42 cm width × 31 cm height, 7.45 kg [4]	Buoy unit shall be ≤ 50 kg absolute max; max dimension 1m x 0.5m
Raw data stored locally	Spotter stores sensor data onboard and sends data via satellite/cellular [5]	Raw acoustic data shall be stored locally; ≥ 1 TB usable storage, ≥ 2 TB media compatibility desirable

Satellite + cellular resilience	Spotter supports Iridium SBD satellite and cellular [4]	Buoy shall use 4G LTE as primary telemetry
Dashboard and API access	Spotter streams to a dashboard and API; supports remote configuration and alerts [6]	Dashboard shall show position, battery %, storage %, last file time, uptime, firmware version; telemetry cadence default ≤ 10 min
Two-way remote control	Spotter supports remote configuration, alert thresholds, and firmware updates [6]	Buoy shall support two-way command of telemetry cadence, gain and alert thresholds
Field usability	Older Spotter specs list LEDs, grab handles, and recovery LED with ≥ 1 mile visibility [7]	Buoy shall include recording status, telemetry status, LEDs, grab handles, and recovery light visible ≥ 1 nautical mile
Pre-deployment self-test	Spotter-style field operation depends on simple deployment readiness	Buoy shall complete self-test in ≤ 5 min, checking battery, storage, telemetry, hydrophone detection, and recording write test
Modular sensor expansion	Spotter platform uses Smart Mooring and Bristlemouth-style modularity [6]	Auxiliary sensors shall be modular; failure/removal of any auxiliary sensor shall cause 0 loss of acoustic recording function
Subsurface cable/mooring robustness	Smart Mooring supports subsurface sensing and cable-based payload integration [6]	Hydrophone cable shall have strain relief, abrasion protection, and shall not carry main mooring load; mooring components shall have SF ≥ 3.0
Mooring depth suitability	Spotter buoy can be moored up to 50 m; platform page describes buoy + Smart Mooring fixed-point use up to 100 m depending configuration [6]	This buoy is expected to operate in 5–30 m water depth; mooring scope shall be adjustable across full range; watch circle target ≤ 2 × water depth
Motion affects data quality	Spotter is a wave-following buoy	Hydrophone mount shall keep mechanical/flow-noise contribution below in-band ambient noise; acquisition self-noise shall be ≥ 10 dB below lowest expected ambient
Data integrity and recovery	Spotter backs up sensor data locally and through cloud services [8]	Acoustic files shall have zero-sample gap target; file length ≤ 60 min; post-recovery manifest shall include start/end UTC, sample count and file size
Recovery assurance	Spotter has satellite/cellular tracking and recovery light	Buoy shall transmit emergency packet containing location, battery state, last acoustic file timestamp

2.4 Processing Architecture: Microcontroller Against a Single-Board Computer

The requirements in Section 2.1 determine the processing of hardware. The platform must sustain continuous 96 kHz, 32-bit acquisition and write the resulting stream to a multi-day local archive. It must also segment files for transmission, operate a cellular telemetry stack, and support remote access. These tasks exceed the memory, storage interface, and filesystem capability of a typical microcontroller. They are general-purpose computing functions, better served by a full operating system than by bare-metal firmware.

This points to a single-board computer (SBC) rather than a microcontroller as the primary processing unit. An SBC provides the high-speed storage interface, network stack, and managed filesystem that the mission requires, none of which a microcontroller offers natively.

An SBC is, however, poorly suited to deterministic low-rate acquisition, and it draws several watts continuously, against a small fraction of that for a microcontroller. The architecture therefore retains both device classes rather than choosing one. The SBC manages storage, telemetry, and scheduling, while a companion microcontroller handles deterministic acquisition of low-rate channels such as motion sensing. The detailed division of functions, and the specific devices selected, are set out in Section 4. The continuous power cost of the computing node is carried into the power architecture below.

2.5 Power Architecture: Energy Harvesting Against Onboard Battery

The power architecture follows from the energy demand. A continuous load of a few watts, sustained across the 14-day governing mission and including headroom for additional components, implies an energy requirement on the order of 1.3 kWh, equivalent to approaching 100 Wh per day. Two strategies were considered to meet it: onboard solar harvesting, as used by the Sofar Spotter platform in Section 2.2, and a large onboard battery.

Solar harvesting was rejected primarily on grounds of scale. The Spotter meets its energy demand on solar alone only because its load is small, pairing a battery of roughly 50 Wh and panels of around 10 W with an intermittent mission of order tens of watt-hours per day. The standard sizing estimate divides the daily demand by the peak sun hours and an efficiency factor of about 0.8 [9]. Southern England receives only 3 to 4 peak sun hours on an annual average [10], so replenishing a 100 Wh daily demand requires roughly 35 to 40 W of panel under favourable conditions. UK output is strongly seasonal, with winter generation falling to about a third of the summer figure [11], so remaining energy-positive through winter would demand an array on the order of 100 W. A panel of this rating occupies close to 1 m², whereas the expected concept design is a 1m diameter cylinder that is already committed to the mast, daymark, antenna, and enclosure. Therefore, the available area cannot accommodate an array of useful size. Solar harvesting would also add a charge controller, marine wiring, and additional deck penetrations, increasing cost, ingress risk, and failure modes.

A large onboard battery was therefore selected. The consequence is direct, as the required capacity adds mass and demands internal volume, which couples to packaging, centre of gravity, freeboard, and stability. This is where the 50 kg mass limit and the stability requirements of the PDS become binding, since extending endurance through capacity also raises mass and threatens the stability margin. The final battery sizing and the measured energy budget are reported in Section 4.

2.6 Concept selection summary

Taking inspiration from all three designs, the buoy consists of a cylindrical base with a tripod mount on top where safety features and other sensors can be mounted. The electricals will be safely stored inside the buoy and will transmit data back to a real-time dashboard via cellular connection. In order to improve the sustainability over the project life-cycle and also reduce cost, the hull from [12] will be used. This is a large hull with plenty of internal space for components and some sensor mounting spots already attached to the underside. Figure 2.2 shows the finalised concept design. The internals will be similar to the Sofar spotter as well as the general cylindrical buoy geometry but the mount design is taken from concept 3. Figure 2.3 outlines the key areas that this project will focus on investigating and implementing.

Figure 2.2: Finalised concept design

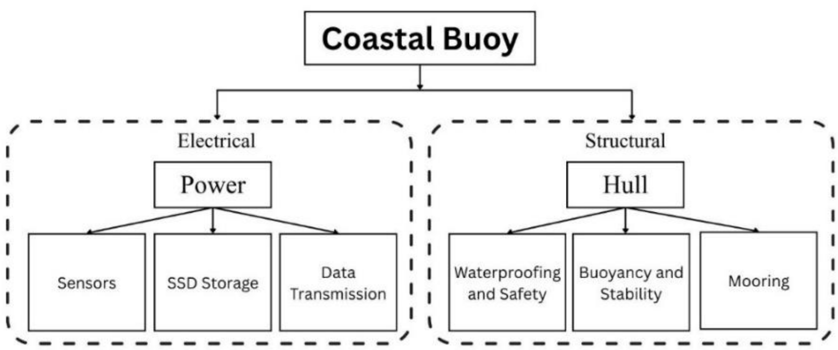

Figure 2.3: System block diagram

3. Mechanical Design and Hydrostatic/Structural Analysis

3.1 Mechanical Design Approach

Following the system level concept selection in Section 2, the mechanical design work focused on adapting the inherited buoy into a stable, serviceable and deployable sensing platform. The detailed requirements have already been defined in the Product Design Specification (PDS) located in Appendix A, so this section focuses on how those requirements can be achieved through the mechanical design process.

The main mechanical challenge was to integrate new sensing, electrical, visibility and deployment hardware without compromising the buoy's existing flotation and stability performance. The design therefore had to balance added functionality against mass growth, centre of gravity position, freeboard, structural robustness, acoustic measurement quality and ease of handling during deployment.

The mechanical strategy was to treat the buoy as a system of linked design decisions. Subsystem placement determined the mass distribution; mass distribution affected draft and stability; stability influenced ballast and battery placement; and testing observations informed later mechanical changes. Section 3 follows this sequence by first assessing the inherited platform, then defining the added mechanical architecture, before verifying the resulting design through mass, buoyancy, stability and load checks.

Table 3.1: Mechanical design logic used in Section 3.

Design concern	Role in Section 3
Existing platform	Establish what can be reused and what constraints it imposes
Added subsystems	Define where new hardware is placed and why
Mass distribution	Quantify total mass and centre of gravity
Buoyancy margin	Check draft and freeboard after integration
Stability	Assess upright behaviour and self-righting limitations
Structural loading	Check wind, mooring and handling loads
Iteration	Explain how testing and build issues changed the final design

3.2 Inherited Buoy Platform Assessment

The inherited buoy formed the main mechanical starting point for the project. Its value is that it already provides a proven flotation body, a wide circular waterplane and existing mounting interfaces that can be reused. This reduces the risk, cost and fabrication time associated with designing a new hull from scratch and allows the mechanical work to focus on improvements rather than basic buoyancy generation. The role of this section is not to justify the decision to reuse the hull, which was addressed during concept selection, but to define the physical constraints and opportunities that the platform introduces.

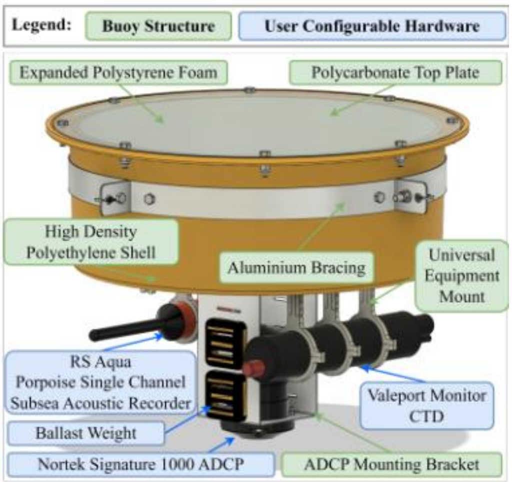

Figure 3.1: Annotated CAD diagram of inherited buoy.

The buoy consists of a wide circular HDPE body with an existing polycarbonate top plate, underside mounting points and removable hardware from the previous project. The wide base is mechanically useful as it provides a large waterplane area, improving the initial resistance to roll and pitch. This is important as the new design requires additional topside features to aid in identification and communication. Components discussed in Section 3.3, including the tripod, navigation light and mast all add mass above the waterline, raising the centre of gravity so their positioning will be considered carefully and is quantified in Section 3.5.

One of the key constraints in utilising this buoy, is that the hull body is free flooded. In the previous design, expanded polystyrene foam was placed inside the hull body to occupy part of the internal volume, reducing the amount of water that could enter the body and helping to preserve buoyancy. The previous configuration could tolerate this arrangement as the buoy acted mainly as a passive carrier for independently powered and independently sealed instruments, so it did not need to house a shared battery, control system or integrated data acquisition system. For the current design, sealing the whole buoy would not be a reliable approach due to existing bolt holes and potential leak paths. Therefore, the hull will be used as a protective outer structure while electrical components can be placed inside IP68 rated enclosures. These enclosures can be submerged underwater up to 1.5 metres for long durations of time with reduced ingress risk when assembled correctly [13] which is ideal for our use case and provides a certified waterproofing method rather than manually sealing the buoy.

A distinction was made between features that could be retained, features that could be repurposed and features that had to be replaced. The HDPE hull, polycarbonate top plate, underside mounting points and perimeter hardware were retained as they provided the main flotation structure. The original Acoustic Doppler Current Profiler (ADCP) bracket was also retained, not for ADCP deployment, but due to its existing slots which allowed ballast weights to be attached below the base of the buoy. The original Expanded Polystyrene (EPS) foam also would need to be replaced as it does not conform closely to the internal geometry and shed loose polystyrene beads during handling. The poor fit left voids that could fill with water, reducing its effective buoyancy contribution, while loose EPS fragments created an environmental contamination risk.
A full table identifying each feature from the previous buoy, whether it was retained, repurposed or removed can be found in Appendix B.

3.3 Mechanical Architecture and Subsystem Placement

This section defines the new mechanical architecture added to the inherited platform: which subsystems were introduced, where each was placed, and why. The driving principle was to add the new sensing, electrical, visibility, and deployment hardware without disturbing the inherited flotation behaviour or the existing structural load paths described in Section 3.2. The architecture is grouped by physical location topside, internal compartment, and below the hull, because location, more than function, controlled the mass distribution and design constraints.

Parts List			
Item	Qty	Part Number	Material
1	1	Enduramaxx 110 Chemical Storage Bund	Polyethylene, High Density
2	1	2-1-1 Nortek 1000 ADCP	Nortek 1000 ADCP
3	1	ADCP Bracket (2mm Aluminium 5083 Sheet Metal x 1 Pcs)	Aluminum 5083 87 Cold Formed
4	4	Recovery Bracing (2mm Aluminium 5083 Sheet Metal x 4 Pcs)	Steel
5	6	Universal Mount (Buoy Side) (10mm Nylon Waterjet Cutting x 6 Pcs)	Nylon 6
6	2	Waterproof box	----
7	4	Hanger	Stainless Steel AISI 430
8	2	DIN 439-2 - M8 x 1 Steel 6 Plain	Steel 6, Plain
9	1	Hanger v2(Mirror)	Stainless Steel AISI 430
10	1	DIN 439-2 - M8 x 1 Steel 6 Plain	Steel 6, Plain
11	1	Hanger v2(Mirror) (1)	Stainless Steel AISI 430
12	1	DIN 439-2 - M8 x 1 Steel 6 Plain	Steel 6, Plain
13	2	DIN 439-2 - M8 x 1.25 Steel 6 Plain	Steel 6, Plain
14	2	Hanger v2(Mirror) (2)	Stainless Steel AISI 430
15	2	DIN 439-2 - M8 x 1.25 Steel 6 Plain	Steel 6, Plain
16	1	Polycarbonate Cover	Polycarbonate, Clear
17	1	4G gps	Aluminum 7075
18	1	Flag base	----
19	1	HJN ASME B18.2.2 - 1-12 Steel Grade 2H Plain	Steel Grade 2H, Plain
20	3	New tripod	Aluminum
21	1	Cross base	Aluminum 7075
22	1	Cross	Acrylic, Clear

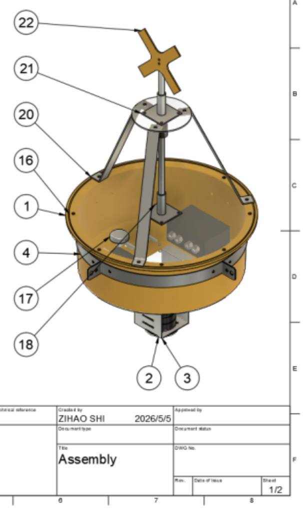

Figure 3.2: Annotated section view of the buoy showing the principal added subsystems and their vertical positions.

3.3.1 Topside Structure: Tripod, Mast and Cross Plate

A three-leg aluminium tripod (marked as 20 in Figure 3.2) was added above the inherited top plate to carry the visibility and tracking hardware clear of the water surface. The legs are arranged at 120° symmetry around the centre of the top plate (marked as 16 in Figure 3.2), converging at a circular acrylic cross plate the apex through which the central mast (marked as 21 in Figure 3.2) clamped. The tripod feet pass through the inherited top plate and the High-Density Polyethylene (HDPE) hull, so that wind, daymark, and mast-bending loads are reacted into the hull structure rather than the acrylic. The trade-off is an upward centre of gravity (CoG) shift, quantified in Section 3.5 and addressed by ballast in Section 3.6.

3.3.2 Visibility and Tracking Hardware: Daymark, Navigation Light, GPS Puck

A flat acrylic daymark in a cross profile (marked as 22 in Figure 3.2) is mounted at the top of the central mast, sized as the smallest visible profile compatible with the PDS visibility requirement to limit wind-drag area. A LED navigation light sits on a short stalk below the daymark, positioned as high as possible to maximise visibility to nearby vessels; its low mass (0.27 kg) makes the CoG penalty acceptable. The Global Navigation Satellite System (GNSS)/4G puck is bolted to the upper face of the polycarbonate top plate for a clear line of sky, with its cable routed to the inside of the hull into the electronics enclosure.

3.3.3 Internal Compartment: IP68 Enclosures, Foam, Hydrophone Routing

Two new IP68 enclosures sit on the base of the internal compartment, a smaller enclosure for the battery and a larger enclosure for the Raspberry Pi, Arduino, and 4G HAT, with full explanations in Section 4. They are positioned low to keep CoG down, separated radially to balance mass, and offset from the centre to leave clearance for topside cable runs.

As discussed in Section 3.2, the original EPS foam was not suitable for the updated design. We chose a closed cell Plastazote Low Density 45 kgm^{-3} (LD45) foam to fill the void around the enclosures. The foam is cut to fit the exact volume inside the hull and adds reserve buoyancy on top of the inherited flotation core, and being closed cell preserves these functions even though the compartment is free flooded by design (Section 3.2) and prevent any environmental contamination risk.

3.3.4 Below Hull Hardware: Hydrophone Tether Eyebolts

Eyebolts (marked as 7,9,11,14 in Figure 3.2) were added through the bottom of the hull as anchor points for the hydrophone tether. The hydrophone hangs from one of these eyebolts on a rope of selectable length, which sets the hydrophone's deployed depth below the buoy: changing the rope length changes the depth without disturbing the sensor itself or the cable routing. There will be up to 10 eyebolts for modularity purpose.

3.4 Materials, Manufacturing and Corrosion Strategy

Material and manufacturing choices reflect the prototype scope: simple geometries fabricated using university workshop equipment, bolted modular assembly, and a deliberate trade between mass, corrosion resistance, and manufacturability. The principal materials are HDPE (reused shell), polycarbonate (top plate), closed-cell Plastazote LD45 (foam), Aluminium 5083 (bracing) and Aluminium (Al) 7075 (tripod elements), 316L stainless fasteners and submerged hardware, and an acrylic daymark cross. Al 7075 reduces topside mass at the cost of requiring inspection between deployments rather than being marine-grade; this is acceptable for a prototype and identified for replacement with Al 5083 for unattended long-duration use. Galvanic protection between mixed metals at submerged interfaces is provided through sacrificial zinc consideration at fastener locations and isolation washers where dissimilar metals would otherwise be in continuous contact under seawater. A full material selection table can be found in Appendix C.

3.5 Mass Budget and Centre of Gravity

The subsystems discussed in Sections 3.3 and 3.4 introduce additional mass above, within and below the inherited hull. This made the mass budget a design control tool rather than only a final accounting exercise. Total mass affects draft and freeboard, while the vertical centre of gravity affects the stability margin calculated in Section 3.7.

Brendon's previous tested configuration had a total mass of 37.1 kg including 8 kg of ballast, giving an approximate unballasted tested configuration mass of 29.1 kg. A centre of gravity height was not explicitly reported; instead, the previous study characterised stability through an inclining test, giving GM values of 0.26 m and 0.27 m, equivalent to an average GM/D of approximately 33 percent.

Each component was individually weighed, and vertical positions were measured from a datum at the base of the buoy shell (z = 0).

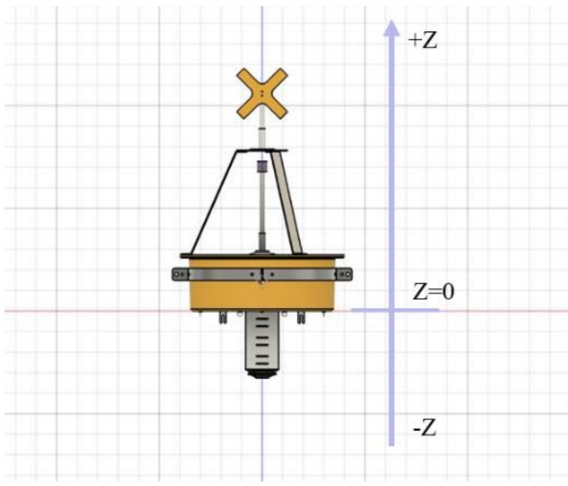

Figure 3.3: Base of buoy chosen as datum position.

The centre of gravity was calculated using:

$$z_{CG} = \frac{\Sigma m_i z_i}{\Sigma m_i} \qquad (Eq. 1)$$

Table 3.2: Summarises the mass budget grouped by subsystem; full per-component breakdown is given in Appendix D.

Subsystem	Mass (kg)	Effective z (m)	Moment (kg·m)	Notes
Tripod assembly (legs, mast, cross, light)	2.31	0.580	1.340	Above waterline — raises CoG
Shell + top plate + ring + sensor mounts	11.38	0.162	1.838	Dominant mass component
Foam (Plastazote LD45, 45 kg/m³)	3.50	0.125	0.438	Internal buoyancy
Battery + IP68 enclosures + electronics	2.99	0.070	0.209	Deliberately mounted low
Mooring fittings (ropes, eyebolts, shackles)	2.21	0.045	0.100	At base level
GPS puck	0.10	0.250	0.025	Top plate
ADCP bracket	0.64	−0.200	−0.128	Below shell base
Subtotal — no ballast	23.13	—	3.821	
Ballast (6 × 2 kg, max config)	12.00	−0.200	−2.400	On ADCP bracket
Total — max ballast	35.13	—	1.421	

Table 3.3: Calculated centre of gravity for both configurations.

Configuration	Total mass m (kg)	Σmz (kg·m)	z_{CG} (m above shell base)
No ballast	23.13	3.821	0.165
Max ballast (12 kg)	35.13	1.421	0.041

The final unballasted prototype mass is approximately 23 kg and a centre of gravity 0.165 m above the shell base, remaining below the PDS target of 30 kg. The tripod assembly makes the largest positive vertical moment contribution because it is mounted high above the hull, so its effect on stability had to be countered by low mounted mass. Adding 12 kg of removable ballast increases the total mass to ~35 kg but lowers the centre of gravity to 0.041 m above the shell base. This 12.4 cm reduction validated the design decision to retain and the inherited ADCP bracket.

The calculated centre of gravity is used in the following buoyancy, freeboard and stability checks. The mass budget shows that the design challenge was not only whether the buoy could carry the added payload, but whether the added mass could be positioned without allowing the topside visibility structure to dominate the stability behaviour.

3.6 Buoyancy, Draft and Freeboard

The mass budget in Section 3.5 defines the total weight that the buoy must support. The purpose of the buoyancy check is to determine whether the inherited hull, replacement foam and sealed enclosures provide enough displacement to maintain the required freeboard in both the unballasted and ballasted configurations.

As the hull is free flooded, water can enter and leave the main body during operation. The buoyancy calculation therefore does not assume trapped air inside the hull. Instead, the useful buoyant volume is taken from the closed cell Plastazote foam and sealed IP68 enclosures, which exclude water from the internal volume. The total available buoyant volume is:

$$V_{buoyant} = V_{foam} + V_{IP68\ boxes} = 0.0795 + 0.006 = 0.0855\ m^3 \qquad (Eq. 2)$$

At floating equilibrium, the displaced water volume required to support the mass is:

$$V_{required} = \frac{m}{\rho_w} \qquad (Eq. 3)$$

where m is the prototype mass, ρ_w is the density of salt water ($1025\ kgm^{-3}$). Draft was then estimated by dividing the required displaced volume by the measured waterplane area of the buoy. The detailed calculation steps and geometry assumptions are provided in Appendix E, while the resulting draft, freeboard and reserve buoyancy values are summarised in Table 3.4.

Table 3.4: Equilibrium flotation results.

Quantity	No Ballast	Max Ballast	Notes
Total mass m (kg)	23.13	35.13	Measured
Displaced volume V_{disp} (m^3)	0.02256	0.03427	Based on saltwater density
Buoyancy used (% of $V_{buoyant}$)	26.4%	40.1%	Large reserve margin
Predicted draft (cm of shell below water)	5.9	8.9	Estimated from waterplane area
Freeboard (cm of shell above water)	19.1	16.1	>60% shell above waterline. Above PDS requirement
Reserve buoyancy (kg supportable)	≈ 64	≈ 52	Additional payload capacity

The buoyancy check shows that the final configuration is not operating close to its flotation limit. Even with 12 kg of removable ballast installed, only 40.1% of the available buoyant volume is required to support the prototype mass, leaving approximately 52 kg of additional supportable mass in theory. This margin should not be treated as usable payload capacity, since additional mass would also affect stability, handling and the PDS requirement for two-person deployment.

3.7 Stability and Self-Righting Assessment

The buoyancy assessment in Section 3.6 confirmed that the prototype retained sufficient freeboard in both the unballasted and ballasted configurations. The next step was to assess whether the same configurations were stable once the added topside structure, electronics and removable ballast were included. This assessment uses the centre of gravity values from Section 3.5 and the predicted draft values from Section 3.6.
Brendon's previous tank testing provides a useful reference for the inherited platform. The previous tested configuration had a diameter of 0.8 m and a mass of 37.1 kg, with measured metacentric heights of 0.26 m and 0.27 m. This gave an average GM to diameter ratio of approximately 33%. However, the current prototype has a different mass distribution due to modifications, so the stability assessment was recalculated for the modified configuration.

The assessment is split into two parts. First, small angle stability is evaluated using metacentric height, which determines whether the buoy produces a restoring moment for small roll and pitch disturbances. Second, large angle stability is assessed using the righting arm curve, which is required because positive metacentric height alone does not prove that the buoy will recover from complete inversion.

3.7.1 Small Angle Stability

The PDS requires GM to remain above 0.15 m in all configurations, so both the no ballast and maximum ballast cases were assessed.
The metacentric height was calculated from the centre of buoyancy height, KB, the metacentric radius, BM and the centre of gravity height, KG:

$$GM = KB + BM - KG \qquad (Eq. 4)$$

KG was calculated in Section 3.5, KB can be taken as half the predicted draft calculated in Section 3.6 and BM was calculated from the circular waterplane geometry and displaced volume. As the hull is free flooded, the internal cavity was not treated as trapped air. Any empty internal space can fill with water and therefore does not provide useful buoyancy. The buoyancy model therefore only counts the volumes that exclude water, mainly the closed cell foam, sealed IP68 enclosures and solid structure.
For this first order small angle calculation, the buoyant waterplane was approximated as a circular footprint of radius 0.35 m. The metacentric radius was calculated using:

$$BM = \frac{I_{wp}}{V_{disp}} = \frac{\frac{\pi r^4}{4}}{V_{disp}} \qquad (Eq.5)$$

where I_{wp} is the second moment of area of the waterplane and V_{disp} is the displaced volume from Section 3.6. Full working and assumptions are provided in Appendix F, while the main results are summarised in Table 3.5.

Table 3.5: Small angle stability results.

Quantity	No Ballast	Max Ballast	Notes
KG (m)	0.165	0.041	From Section 3.6
KB (m)	0.0293	0.0445	= h_{sub} / 2
BM = I / V_{disp} (m)	0.522	0.344	Dominated by wide waterplane
GM (m)	0.386	0.348	Both comfortably stable
Stability assessment	Stable	Stable	GM >> 0.15 m threshold

Both configurations are stable in the upright small angle condition, and both GM values exceed the PDS threshold of 0.15 m, confirming that the buoy generates a restoring moment after small disturbances.
The result also shows that the buoy's small angle stability is dominated by its wide circular waterplane rather than by ballast alone. Although adding 12 kg of ballast lowers KG, it also increases the displaced volume, which reduces BM. This is why the calculated $GM$is slightly lower in the maximum ballast case. The ballast is still valuable, but its main benefit is not increasing small angle GM. Its main benefit is improving resistance to large angle overturning, which is assessed in Section 3.7.2.

3.7.2 Large Angle Stability and Self Righting

Metacentric height alone does not determine whether the buoy will recover from a large disturbance or from complete inversion. Large angle stability was therefore assessed using the righting arm, GZ, across heel angles from 0° to 180°.

The righting arm represents horizontal separation between the line of action of buoyancy and the line of action of weight. A positive GZ produces a restoring moment toward the upright position, while a negative GZ produces a capsizing tendency. For this analysis, a numerical voxel model of the buoy was constructed treating the foam-filled shell as a buoyant cylinder (D = 0.70 m, H = 0.25 m) discretised into ~16,000 volume elements. For each heel angle θ from 0° to 180° in 5° steps, the waterline was solved iteratively to balance buoyancy against weight, and the centroid of the submerged volume B(θ) was computed. The righting arm GZ(θ) is the horizontal offset between the line of action of buoyancy through B and the line of action of gravity through G. Methodology and assumptions are provided in Appendix G.

Three configurations were assessed. The first was the no ballast configuration. The second was the design ballast configuration, with 12 kg of removable ballast mounted on the retained ADCP bracket at $z = -0.20\ m$. The third was an extended ballast case, where the same 12 kg ballast mass was placed lower at $z = -0.40\ m$. The extended case was included to test[1] whether increasing the ballast lever arm alone could produce full self-righting.

Table 3.6: Large angle stability and self-righting summary.

Configuration	Range of stability	Peak GZ	GZ at 180°
No ballast	0° – 78°	108 mm @ 30°	−11.4 mm
Ballast at z = −0.20 m	0° – 133°	161 mm @ 45°	−7.3 mm
Extended bracket (z = −0.40 m)	0° – 149°	209 mm @ 50°	−7.3 mm

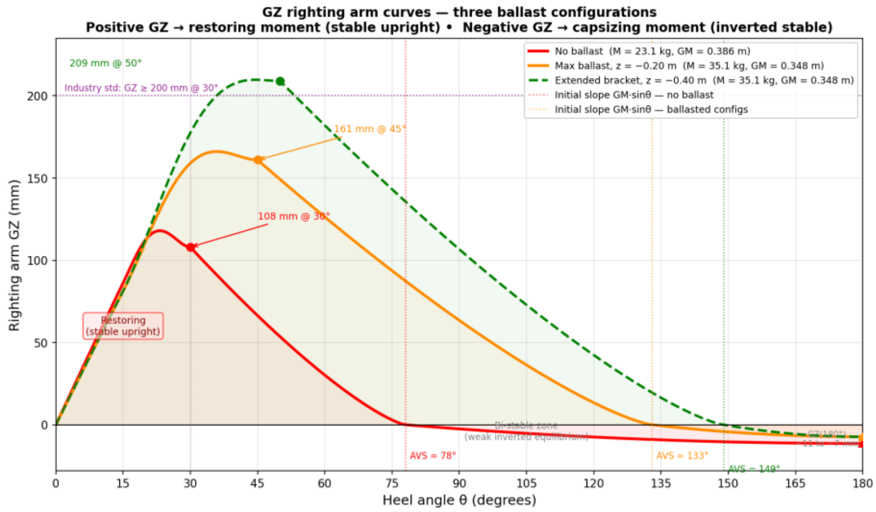

Figure 3.4: GZ righting arm curves for three ballast configurations.

The analysis shows that ballast substantially improves large angle stability but does not produce self-righting from inversion. Adding 12 kg of ballast at the design position increases the range of positive stability from 78° to 133°, meaning the buoy becomes much harder to capsize. Lowering the same ballast further increases this range to 149° showing that a longer ballast lever arm improves resistance to overturning.
However, all three configurations remain bi-stable because GZ becomes negative before 180°. This means that if the buoy is forced into a fully inverted position, it can remain inverted rather than automatically returning upright. The limitation is mainly caused by the broad flat upper geometry, which creates a stable inverted condition once the buoy is completely overturned. This agrees with tank observations that will be discussed further in Section 6, where the buoy was placed upside down in a wave tank[4] and it did not consistently recover by itself. Self-righting was only achieved once the buoy was given a small initial heel angle, supporting the conclusion that the flat upper geometry creates a stable inverted condition.

The design implication is that the current ballast system is suitable as it provides a wide range of positive stability (0° to 133°), meaning the buoy would need to be driven through a large heel angle before it becomes unstable from its normal condition. A domed or curved upper surface would likely improve the design by removing the stable inverted condition and this has been identified as a future modification which will be implemented for the prototype review.

3.8 Wind, Structural, and Mooring Load Checks

3.8.1 Wind heeling check

The tripod, mast, daymark, navigation light, and GPS/4G puck were all added above the waterline in this project, and each one contributes both projected area and a moment arm about the waterline. The same architectural choices that improved visibility, communications, and IALA compliance therefore introduced a wind heeling penalty that did not exist on the inherited buoy (Appendix B). The wind heeling check confirms that this penalty

[4] Davide Grande, RA108558/1, "RA_tanks_v4.pdf", 2026

stays inside the restoring capacity quantified in Section 3.7 and identifies the wind speed at which that envelope is exhausted. Wind loading was therefore checked treating the wind as a steady horizontal force:

$$F_{wind} = \frac{1}{2} C_d \rho_{air} A v^2 \qquad (Eq.6)$$

$$M_{heel} = F_{wind} h_c \qquad (Eq.7)$$

where C_d is the drag coefficient, ρ_{air} is air density, A is projected windage area, v is wind speed and $h_c$is the effective height of the windage centroid above the waterline.

The limiting wind speed is defined as the point when the wind heeling moment equals the peak righting moment from the GZ curve in Section 3.7:

$$F_{wind} \cdot h_c = m \cdot g \cdot GZ_{max} \qquad (Eq.8)$$

Solving for v gives a closed form expression for the wind speed at the stability boundary. Component areas and the h_c calculation are tabulated in Appendix H; $C_d = 1.2$ was taken as a conservative value for the mixed mast, plate and cylinder geometry presented to the wind.

Figure 3.5 breaks the total project area down by component. The shell freeboard is the single largest contributor by area at 0.134 m^2 (no ballast), accounting for approximately 47% of the total windage. However, it sits low against the waterline, so its contribution to the heeling moment is small. The cross/daymark is the second largest contributor by area but dominates the heeling moment arm, because its mounting position approximately 0.99m above the waterline gives it the largest $A \times h$ product of any component.

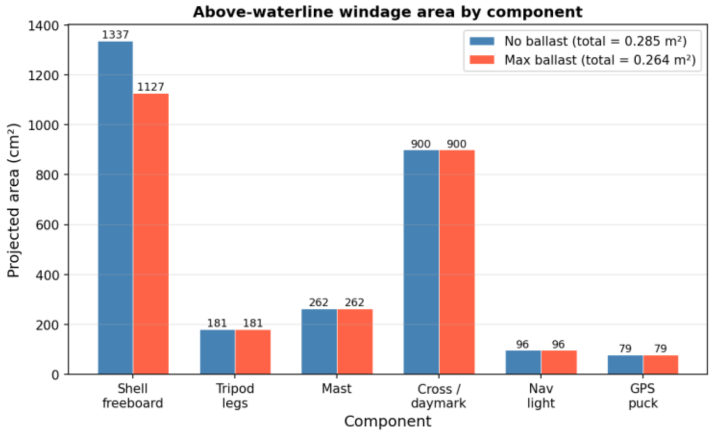

Figure 3.5: Projected windage area by component. The cross/daymark is the single largest contributor despite its compact size, due to its elevated position giving it the largest moment arm.

The static stability limit is reached when the wind heeling moment equals the peak restoring moment, and the corresponding limiting wind speeds are shown in Table 3.7.

Table 3.7: Wind heeling stability limit.

Configuration	Peak GZ	Limiting wind speed	Beaufort equivalent	Assessment
No ballast	108 mm at 30°	15.9 m/s	Beaufort 7, near gale	Pass for controlled testing[1]
Maximum ballast	161 mm at 45°	24.7 m/s	Beaufort 10, storm	Pass for controlled testing[1]

The wind analysis shows that the unballasted buoy can resist steady winds up to approximately **15.9 m/s**, while the maximum-ballast configuration increases this to approximately **24.7 m/s** before the wind heeling moment exceeds the peak restoring moment. These values are above the expected wind conditions for controlled coastal prototype deployment. The tripod and daymark therefore introduce a real windage penalty, but the resulting heeling moment remains within the stability envelope of the buoy.

3.8.2 Structural check (Finite Element Analysis)

The purpose of Finite element analysis (FEA) is to identify the critical stress location in the topside structure and to size the safety margin at that location, not to certify the platform for long-duration operational service. FEA was carried out on the principal new load-bearing components — the aluminium tripod leg, the HDPE top plate (inherited), and the acrylic cross plate at the tripod apex, to confirm that the bolted topside structure can carry its self weight without yielding or excessive deformation.

The combined mass of the topside hardware, mast, daymark, navigation light, cross plate, and fasteners, is approximately 5 kg. By symmetry, this load divides equally between the three tripod legs, giving 5/3 kg ≈ 16.35 N applied vertically at the upper bolt hole of each leg. The same total 5 kg load is applied to the cross plate at its central mast hole. Wind heeling moment is included in this analysis.

The tripod leg was analysed as a single aluminium 7075 flat bar with the lower bolt hole fixed (representing its connection to the inherited hull) and the 16.35 N load applied at the upper bolt hole. The peak von Mises stress is 96.5 MPa at the lower bolt hole, giving a static safety factor of approximately 5.2× against the 7075 yield strength of ≈ 503 MPa. A maximum principal stress cross-check at the same location gives 113 MPa (safety factor 4.5×). The two criteria agree on the critical location and give safety factors of similar magnitude, which provides confidence that the result is not a numerical artefact. The lower bolt hole is therefore identified as the principal stress concentration in the topside structure and the joint requiring the most inspection attention before deployment.

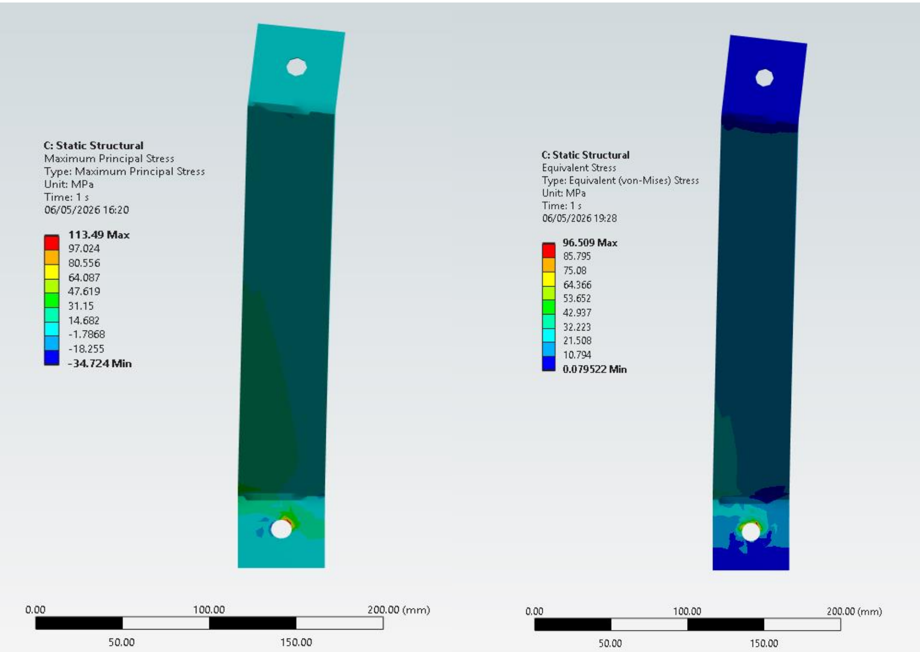

Figure 3.6: FEA results of the tripod leg, maximum principal stress & von-Mises stress.

Top plate and cross plate (secondary components). The inherited 5 mm polycarbonate top plate carries a peak von-Mises stress of 0.66 MPa at the inner tripod bolt circle, giving a static safety factor of approximately 90× against the polycarbonate yield strength of ≈ 62 MPa. The 5 mm acrylic cross plate with a yield strength of ≈ 70 MPa at the tripod apex carries a peak maximum principal stress of 1.22 MPa at the three outer bolt holes (safety factor ≈ 57×). Both plates therefore carry stresses two orders of magnitude below yield and are not strength critical components, their structural role is to maintain alignment between the tripod legs and the mast, not to react the load directly. The load path runs through the aluminium tripod legs into the inherited hull, as intended by the design.

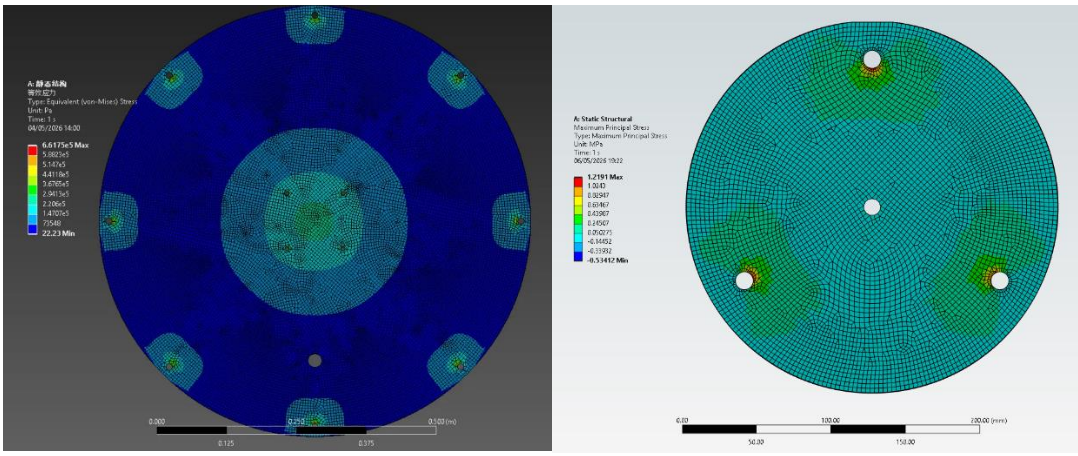

Figure 3.7: FEA results of the inherited top plate (left) and the added cross plate (right).

Limitations of the analysis. The FEA captures the dominant static load paths under self weight but does not include several effects that would matter for an operational deployment. Inertial loads from wave induced motion are not modelled, given the leg's modest static margin. Fatigue from cyclic wave loading is not analysed and is the most plausible long term failure driver, with the tripod leg's lower bolt hole as the location most exposed. Fastener pre load and contact behaviour at the bolted interfaces are not modelled, the bolt holes are treated as fixed/loaded supports. For these reasons, the structural analysis is interpreted as a prototype-level verification rather than certification for long duration offshore service. The design is considered suitable for controlled prototype testing[1] provided that the lower tripod bolt holes are inspected for paint integrity and bolt torque before each deployment. Any future operational version should include wave load cases, fatigue analysis.

3.8.3 Mooring & Handling load check

The buoy is intended for controlled coastal testing with tethered deployment and recovery. Mooring and handling loads are relevant because they can introduce horizontal force at the gunwale, local bearing on the structural fasteners, and overturning moments around the centre of buoyancy. The principal interfaces affected are the inherited underside ADCP bracket, the lifting/recovery padeyes, the shackles and rope hardware, the tripod-to-hull bolted connection, and the hydrophone tether eyebolts on the hull underside. The assessment in this section is a qualitative interface check using the quasi-static load magnitudes derived. It confirms that the design has accounted for each interface and identifies the dominant load case for each, but it does not constitute a full offshore mooring-system design. Such a design would additionally require dynamic snatch load analysis, fatigue assessment, and certified mooring hardware specification, none of which are in this project's scope.

Table 3.8: Mooring and handling interface check.

Interface	Dominant load case	Magnitude (≈)	Design control	Outcome
Recovery / lifting padeyes	Two person manual lifting	170 N per padeye	Bolted through reinforced perimeter; M6 A4 shear capacity ≈ 5 kN per bolt	Safety factor > 25× under nominal lift
Tether / mooring line attachment	Quasi static wind + current drag	50 N horizontal	Same M6 A4 bolted attachment; tether deployed from controlled vessel	Safety factor > 100× quasi static
Ballast attachment	Static weight + wave induced acceleration	12 kg static + ~30% inertial	Symmetric attachment using inherited bracket;	Within inherited bracket's existing capacity

(ADCP bracket)			pre deployment torque check	
Tripod to hull bolted joint	Wind drag on daymark + mast transferred through tripod legs into HDPE hull	96 MPa peak at lower leg bolt hole (Section 3.8.2)	M6 A4 with penny washers to spread bearing load in HDPE; pre deployment inspection	Adequate static margin; HDPE creep/bearing flagged as the critical long-term concern
Hydrophone tether eyebolt	Hydrophone weight + cable drag	< 10 N	A4 stainless through-bolted in HDPE; rope rather than cable carries the suspended weight	Loads negligible relative to fastener and HDPE bearing capacity

3.9 Mechanical Iterations and Final Configuration Summary

This section closes the chapter by assessing the design against the mechanical PDS targets defined in Appendix A.

Table 3.9: Mechanical PDS Compliance Summary

PDS requirement	Target	Achieved	Status	Justification or evidence
Total mass	≤ 30 kg unballasted	23.13 kg	**Met**	Section 3.5; supports two person manual deployment.
Freeboard	> 50% of shell above water	76% (no ballast), 64% (ballasted)	**Met**	Section 3.6; both configurations comfortably above target.
Initial stability (GM)	≥ 0.15 m	0.386 m / 0.348 m	**Met**	Section 3.7.1; both configurations >2× target.
Self-righting from full inversion	Buoy returns to upright unaided	Stable in all three ballast configurations	**Not met**	Section 3.7.2; flat top plate creates stable inverted equilibrium. Mitigated by 133° angle of vanishing stability so inversion is hydrodynamically unlikely; full closure proposed as domed top plate in Appendix J.
Wind survivability	Pass for controlled deployment	15.9 m/s (no ballast), 24.7 m/s (ballasted)	**Met**	Section 3.8.1; both configurations exceed expected coastal conditions.
Structural margin (topside)	Safety factor > 2× at critical location	5.2× at tripod leg lower bolt hole	**Met**	Section 3.8.2; FEA verified.
Modular ballast attachment	Ballast configurable without disassembly	6 × 2 kg removable weights on ADCP bracket	**Met**	Section 3.3, 3.9; uses inherited geometry.

The final mechanical design meets all PDS targets except full self-righting from inversion. The decision to record this as not met rather than partially met is deliberate. The mitigation is the 133° angle of vanishing stability achieved by the ballasted configuration, which makes full inversion hydrodynamically unlikely under any sea state in scope for this project. The proper engineering closure for this limitation is a domed upper surface, identified in Appendix J, as a high priority refinement.

4. Electrical, Sensing, Power and Data Architecture

This section aims to outline the total system architecture and calculates the required power, storage and cellular connectivity for the buoy to operate effectively. A schematic of this is available in Appendix I. The key components are the Aquarian H2DM hydrophone, the Raspberry Pi 4B as the main computer and the Arduino Nano 33 BLE Sense Rev 2 as an Inertial Measurement Unit (IMU). The DS18B20 temperature probe also supports the acoustic measurements, since water temperature sets the local speed of sound and therefore informs the interpretation of the hydrophone data. This is because of the hydrophone sensitivity and sound propagation varying heavily at different temperatures.

4.1 Component Selection Rationale

The selection of the electrical architecture was driven by the practical design constraints of the buoy; where each component satisfies at least one of the main system needs. This includes reliable local data storage, acoustic capture, and recoverable nearshore telemetry.

4.1.1 Power source and navigation light switching

The 12 V, 10 Ah $LiFePO_4$ battery was selected as a prototype-scale energy source. A 12 V system voltage is compatible with the navigation light branch and gives a suitable input to the 5 V regulator. The 10 Ah capacity also keeps the battery mass and enclosure size within the handling limits of the buoy. $LiFePO_4$ was preferred over lead acid for its higher usable energy per unit mass, and over higher-energy lithium-ion chemistries for its greater chemical stability, which is better suited to a sealed marine prototype. [14][15].

The navigation light was kept on a separate 12 V branch instead of being powered through the 5 V compute rail. This keeps the light's load off the Raspberry Pi supply and reduces the risk of a voltage dip on the processor when the light switches on. The light is an LED unit because low current draw and long service life are both important on a small battery powered buoy. Switching is handled by a D4184 MOSFET load switch module, allowing the Raspberry Pi or a timing circuit to duty-cycle the light without carrying the lamp current through the Pi. A MOSFET switch was preferred to a relay because it has no mechanical contacts, makes no switching noise and is better suited to repeated flashing. The module format also made the prototype easier to wire and package.

4.1.2 Compute and data orchestration

The Raspberry Pi 4b provides native USB support for the SSD and the companion microcontroller, GPIO header access for the audio HAT, enough processing margin to run audio capture, file organisation and telemetry scripts together. The trade-off is higher power consumption than a bare microcontroller. That penalty was accepted because the project needed fast development, mature software tooling and a straightforward route for recovering files after deployment.

4.1.3 Sensing chain: acoustic, motion and temperature

The sensing chain combines acoustic, motion and temperature measurements, but the acoustic path is the most demanding part because it carries the highest data rate and is most sensitive to electrical noise. The Aquarian H2DM was selected because it provides an affordable analogue hydrophone with a built-in buffer preamplifier, a known sensitivity of (-) 172 dB re 1 V/µPa, and a cable arrangement that can be suspended below the hull without needing a proprietary logger [16]. The signal is captured by the HiFiBerry DAC+ADC Pro, which mounts directly on the Raspberry Pi GPIO header and appears to Linux as a standard audio device, allowing the team to use normal audio capture tools rather than writing a custom driver [17]. The HiFiBerry board uses the Texas Instruments PCM1863 audio ADC family, which supports high sample rate audio capture, programmable gain and a quoted dynamic range suitable for proving the logging chain [18]. The design capture setting is 192 kHz at 24 bit, single channel, giving margin above the H2DM response band while keeping file sizes manageable for local SSD storage. The hydrophone is suspended approximately 3 m below the buoy on a cable, with the cable routed away from digital electronics to reduce conducted noise. The limitation is gain headroom for quiet ambient sound. Using the H2DM sensitivity, a very quiet ambient level of about 35 dB re 1 $\mu Pa^2/Hz$ at 1 kHz, near the lower bound of the Wenz ocean-noise curves, corresponds to a hydrophone output of roughly 0.14 $\mu V/\sqrt{Hz}$. [19]. This output sits close to, or below, the digitiser's input noise floor. The present chain is therefore adequate for demonstrating capture, storage, and moderate-to-loud events, but not for quiet ambient measurement. Resolving quiet ambient would require an external low-noise preamplifier, characterised on the bench. The closure route is an external gain stage of approximately 30 dB, with low enough input referred noise to lift quiet hydrophone signals above the digitiser noise floor while preserving headroom for larger transients.

Motion sensing is provided by the Arduino Nano 33 BLE Sense Rev2, which combines a microcontroller and inertial sensors on one compact board and streams time stamped frames to the Raspberry Pi over USB serial [20]. Water temperature is measured using a DS18B20 waterproof probe on the 1-Wire bus. Its stated accuracy of ±0.5 °C over the relevant range is sufficient for environmental context alongside the acoustic record [21].

4.1.4 Communications, position and local storage

The PiTalk 4G/LTE HAT was selected because the buoy is intended for nearshore operation, where cellular coverage is a reasonable design assumption. Satellite communication would add module cost, antenna constraints, subscription burden and integration risk that are not justified for this prototype stage. The combined GNSS/4G puck reduces the number of external penetrations because one sky-facing antenna assembly supports both position and cellular operation. GNSS position is provided by the puck mounted above the polycarbonate top plate, connected to the PiTalk HAT and accessed over the cellular modem NMEA interface. Topside mounting is used to improve sky view and cellular access while keeping the modem and compute electronics inside the protected enclosure, with the cable passing through a dedicated gland. Position data support deployment tracking, recovery and metadata, while the cellular link is used for health and status information rather than for transferring the full raw data archive.

The Samsung T9 SSD, a 1TB portable storage was selected because continuous hydrophone recording can generate tens of gigabytes per day, depending on the final capture format. An SSD provides the capacity, sustained write performance and mechanical robustness needed for this duty more convincingly than relying only on a microSD card. The SSD is therefore the primary data archive. Telemetry is used for health and post-processed data, while the raw acoustic and motion records remain local until the buoy is recovered.

4.2 Architecture and Layer Responsibilities

The electrical, sensing, power and data architecture is organised in four functional layers, shown in Figure 4.1 A sensing layer acquires hydrophone, inertial measurement unit (IMU), temperature and Global Navigation Satellite System (GNSS) derived position data. An embedded layer timestamps and logs the data, organises files, manages the solid-state drive (SSD), and operates the cellular link. A power layer provides regulated 5 V and 12 V rails from a 12 V/10 Ah $LiFePO_4$ battery and switches the navigation light through a MOSFET module so the light duty cycle is independent of the compute load. A communications layer handles 4G/LTE telemetry, GNSS, and the dashboard interface.

The four-layer split shown in Figure 4.1 reflects how the system was built and debugged. Each layer could be verified independently on the bench before being integrated, hence that a commissioning fault could be localised to sensing, embedded acquisition, power distribution or communications rather than treated as a whole-system failure.

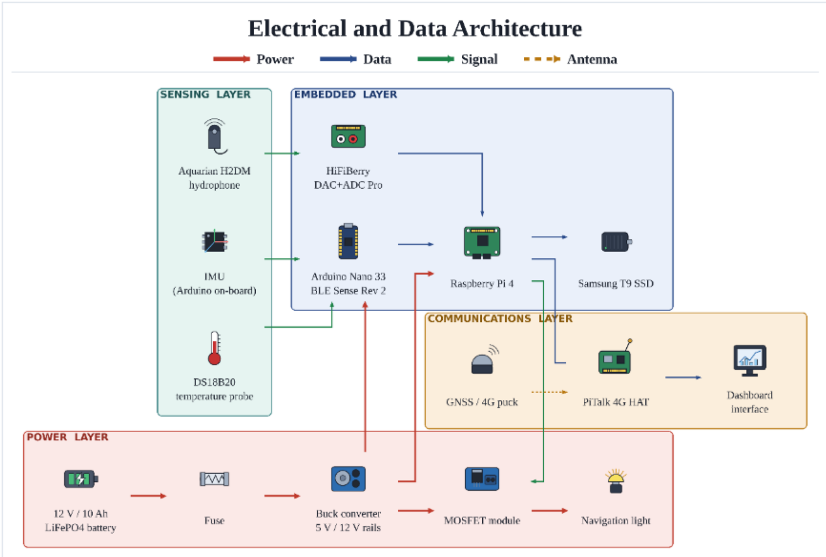

Figure 4.1: Electrical and data architecture block diagram. Power flows from the battery through regulation to the compute and sensing loads; data flows from the sensors through the embedded layer to local SSD storage and selected cellular telemetry.

4.3 Local Storage and Data Flow

Local storage is provided by a Samsung T9 USB-C SSD attached to the Raspberry Pi. The SSD is sized by the hydrophone data files, since the acoustic channel is the only implemented sensor that is likely to generate gigabyte-scale daily files. The design calculation is based on the capture format rather than on an assumed uplink capacity. For pulse-code modulation audio, the uncompressed data rate is:

$$Data\ Rate = f_s b N_{ch} \qquad (Eq. 9)$$

where $f_s = Sample\ rate,\ b = bit\ depth\ (bytes), N_{ch} = Channel\ count$

Table 4.1 summarises the data storage case being assumed for calculations.

Table 4.1: Acoustic data storage size calculations.

Capture case	Rate	Daily volume	Use in design
96 kHz, 24-bit, stereo file	576 kB s^{-1}	49.8 GB day^{-1}	Conservative case if the audio stack records two channels.

Raw hydrophone files and raw IMU logs remain on the SSD for recovery after deployment. The cellular link is used to transmit data and also for operational awareness, not as the main archive. This keeps the scientific record independent of moment-to-moment network quality and avoids tying the success of a deployment to live bulk transfer.

The telemetry data rate is not fixed. It depends on what data the software sends, how often it sends it, and how the modem handles connection failures and retries. At a 10 min cadence, 144 check-ins are attempted per day. A balance between upload frequency and upload size needs to be reached through practical testing but this should certainly be in under 30-minute intervals to avoid the system trying to upload exceptionally large amounts of data.

4.4 Telemetry: 4G/LTE, Dashboard and GNSS

The PiTalk 4G/LTE HAT [13, 15] provides the cellular modem path and the GNSS position route. LTE was selected over satellite backhaul because the prototype is intended for sheltered nearshore use within UK cellular

coverage. Satellite communication remains a future option, but it adds module cost, integration effort, antenna constraints and recurring data cost that are not justified for the present prototype scope.
The intended transmitted data package comprises of:

- battery percentage
- SSD free-space percentage and last successful write timestamp;
- real-time data updates for hydrophone, temperature, GNSS and IMU data

The dashboard is therefore part of the operating interface, not a replacement for the recovered data archive. Its purpose is to let the team see whether the buoy is alive, recording, communicating and located where expected. If the LTE link drops out, local acquisition should continue and the dashboard should show the loss of remote visibility once communication is restored.

4.5 Power Distribution and Design-Stage Endurance Logic

The 12 V/10 Ah $LiFePO_4$ pack supplies a 12 V rail for the navigation light and a buck-regulated 5 V rail for the Raspberry Pi and its peripherals. The buck converter is sized from the Pi-side peak demand. The Raspberry Pi 4 specification calls for a 5 V, 3 A supply; this sets the minimum regulator and wiring requirement before additional USB peripherals and modem transients are considered.

The navigation light is switched through a D4184 MOSFET module from the 12 V rail. The light is duty-cycled at the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) special-mark flash code (yellow, group flash), so that the light load does not pass through the compute rail and does not contribute to compute brownout risk. The adopted flash code is F-Y(5s).

Table 4.2 outlines the theoretical power requirements based on each component's datasheet specification. Some components are accounted for through the component they are plugged into such as the HiFiBerry in the case of the hydrophone. As per this, a 12V power supply is required for the system to operate.

Table 4.2: Theoretical power requirement.

Component	Theoretical Voltage (V)	Theoretical Maximum Current (A)	Theoretical Average Power (W)
Raspberry Pi 4b	5.1	3	4.5
HiFiBerry DAC + ADC Pro	5	0.1	0.4
PiTalk LTE HAT	5	1.7	1.5
DS18B20	3-5.5	0.0015	0.004
LED light	12	0.225	2.7
Total Peak (worst case scenario)	5V (12V directly from battery for LED)	4.8A (+0.225A for LED directly to battery)	9.154 W

To conserve power, the LED will be duty-cycled and only kept on for 4 hours at night when it is most needed. This results in a daily energy consumption of 165.7 Wh. The battery is only able to supply a total of 120 Wh allowing the system to run for approximately 17 hours in normal operating conditions. This is sufficient for a prototype as a proof of concept, but future iterations will need to be developed to allow the prototype to operate for longer periods of time to reach the goal of 14-day deployment. This is feasible by duty-cycling the compute electronics rather than continuously turned on, and a larger battery or optimisation of expensive solar or other power generation systems which would be outside the constraints of this project.

5. Prototype and Deployment

5.1 Prototype

The realised prototype is the integrated outcome of the design described in Section 3 & 4. The inherited HDPE hull and polycarbonate top plate were retained as the flotation basis (Section 3.2), with the new tripod, mast, daymark, navigation light, GPS/4G puck, electronics and battery enclosures, foam fill, and hydrophone tether all added on top of and inside this base platform. All connections are bolted (M5/M6 A4 stainless), no welded or adhesive structural joints exist in the added assembly, and every subsystem can be removed for inspection or replacement without dismantling the rest of the buoy. The above water structure carries the daymark, light, and GPS/4G puck at the top of the central mast, supported by the three-leg aluminium tripod and the acrylic cross plate at its apex. The hull underside carries the inherited ADCP bracket (which retains the ballast modules) and the new hydrophone tether eyebolts. The inherited internal compartment houses the two new IP68 enclosures, one for the $LiFePO_4$ battery and another for the Raspberry Pi, Arduino, sensor breakout, and 4G HAT. These are surrounded by closed cell Plastazote foam that adds reserve buoyancy. The compartment is free flooded by design, with the IP68 enclosures providing a barrier between seawater and the electronics.

Figure 5.1: Front elevation of the completed prototype, full assembly including tripod, mast, daymark, navigation light, and GPS/4G puck above the inherited hull

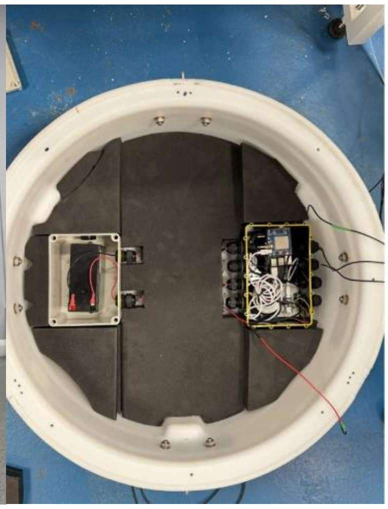

Figure 5.2: Internal layout, top-down view of the open compartment showing the battery enclosure, electronics enclosure, and Plastazote foam fill in the inherited hull.

5.2 Mooring methods

The buoy's behaviour on station, drift, motion, and the dynamic loads transmitted into the platform, is set by the mooring arrangement rather than the buoy itself. Two configurations were considered: a single point catenary mooring and a two-buoy mooring. This section reviews each and identifies the selection.

Single-point catenary mooring. A single seabed anchor connects to the surface buoy through a chain with deliberate slack that absorbs wave motion through its own weight (Figure 5.3). It is the standard arrangement for small coastal data buoys in shallow water under modest loading. Two-buoy mooring. Additional subsurface floatation may be required for smaller buoyancy buoy applications where the floatation may not be adequate to support the mooring weight (Figure 5.4). Extra floatation can also free motion for wave measurement applications or offer additional resistance to horizontal loading.

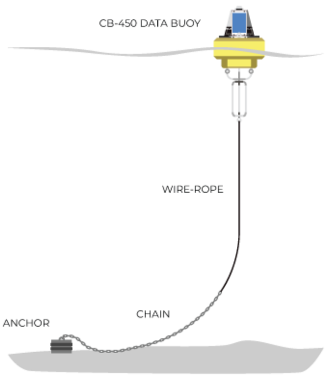

Figure 5.3: Schematic of a single-point catenary mooring

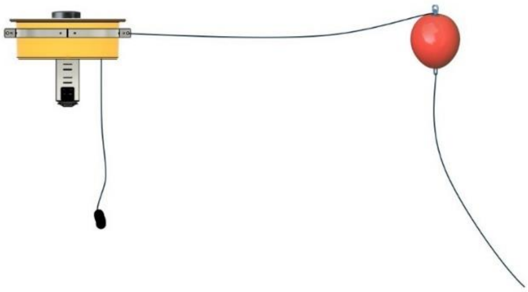

Figure 5.4: Schematic of a two-buoy mooring

A Single-point catenary mooring attached to the primary buoy was found to interact with the sensor payload during bench rehearsal: a vertical mooring line beneath the buoy obstructs the ADCP downward field of view, and a taut line near the hydrophone introduces vibration noise and acoustic reflections that contaminate the recorded data. The resolution adopted a two-buoy mooring that clears the ADCP field of view, isolating the hydrophone from mooring-line vibration.

6. Testing and Validation

Following physical integration of the buoy, testing was used to verify whether the prototype could operate as a complete coastal monitoring system. Validation began with individual component checks, before progressing to controlled wave tank testing[5] and a coastal deployment at Brighton[6] on 1 May 2026. This staged approach allowed faults in waterproofing, sensing, power, communication and data handling to be identified before the prototype was exposed to more realistic operating conditions.

The section therefore presents the evidence gathered from component testing, wave tank testing and field deployment, and explains how these results informed the final prototype configuration and remaining design limitations.

Table 6.1: Test sessions and conditions.

Session	Location	Configuration	Conditions	Quantities measured
Wave tank	UCL fluids Lab	Ballast added, daymark removed, freshwater	Still-water reference and controlled wave conditions	Freeboard, draught, internal temperature, IMU dynamic response, acoustic noise floor
Field deployment	Brighton	Unballasted, ADCP bracket and sensor mounts removed, saltwater	Calm to moderate, 10–12 °C ambient	Integrated operation, field freeboard, acoustics, sensor and telemetry behaviour

[5] Davide Grande, RA108558/1, “RA_tanks_v4.pdf”, 2026

[6] Project team field-test record Brighton Field Test of Prototype

6.1 Component and Subsystem Verification

Before the full buoy was tested, the main components were checked individually to reduce the risk of a system level failure during deployment. These tests covered waterproof enclosures, cable glands, power usage, sensor calibration, data storage and processing system.

6.1.1 Subsystem Validation

All eight subsystems met their activation criteria, several with large margins. The Raspberry Pi booted to a working state in 40 s, against a 60 s target. The DS18B20 agreed with a reference thermometer to within 0.1 °C, well inside its 0.5 °C requirement. The Samsung T9 sustained a write speed of 226 MB/s, far above the rate required to record the 96 kHz, 32-bit acoustic stream, so storage bandwidth is not a limiting factor. Three findings emerged during testing. They did not block progress to the tank stage, but each was recorded for follow-up as outlined in Table 6.2.

Table 6.2: System validation

HiFiBerry and H2DM hydrophone capture format	The HiFiBerry DAC+ADC Pro supports sampling up to 192 kHz, but the driver chain restricts the bit depth to 16 or 32-bit, with 24-bit not available in the recording path. The sample rate was not fixed and was set deliberately rather than maximised. 96 kHz was chosen because the acoustic content of interest is well within the resulting bandwidth, and a higher rate would only inflate the data volume for no useful gain. The hydrophone is also a single-channel source, so the recorded second channel duplicates the first, and 32-bit depth carries far more dynamic range than the hydrophone noise floor needs. Recording in this format produces about 66 GB per day. A software change to mono, and to a lower bit depth where the driver allows, reduces this to roughly 25 GB per day with no loss of useful acoustic information.
IMU logging rate	The BMI270 inertial sensor is logged at the host at about 10 Hz. Wind-driven coastal waves typically have peak periods of roughly 1 to 10 s, corresponding to frequencies of about 0.1 to 1 Hz, with longer swell extending to 12 s or more [22][23]. Logging at 10 Hz therefore samples the dominant wave band at roughly ten to a hundred times its frequency, which is well above the rate needed to resolve it. This keeps the data volume and processing load low while still capturing the wave behaviour the buoy is designed to measure.
LTE modem recovery	The PiTalk LTE HAT, which is based on the Quectel EG25-G LTE Cat 4 module, requires a physical power-key (PWRKEY) press to power up and re-register on the network after a complete power-off. For an unattended deployment this is a single point of failure, because the link cannot recover on its own after a power interruption. An automatic press circuit — a transistor or relay driven by a host GPIO pin to emulate the PWRKEY pulse — is identified as the fix and is recorded in the future work list.

Table 6.3: Bench test results.

Subsystem	Test	Criterion	Result	Notes
Raspberry Pi 4B	Boot to working state (SSH)	< 60s	40s	Boots reliably to a working state
HiFiBerry DAC+ADC Pro	Driver load and enumeration	Device visible	Achieved	No device-tree overlay required
Aquarian H2dM	Sustained recording	Clean 15-minute file	Achieved	No glitches or dropouts
Arduino Nano 33 BLE Sense Rev 2	IMU stream	>10Hz logged	10 Hz	Sensor internal rate = 104Hz

DS18B20	Enumeration and read	±0.5°C of reference	±0.1°C	Settles to the reference within a few seconds of immersion as the metal probe reaches thermal equilibrium
GNSS module	Cold-start fix	3D fix < 2 min	90s	9 of 14 satellites used
PiTalk LTE HAT	Registration and ping	Successful ping	Achieved	power key re-registration required in complete reboot
Samsung T9 SSD	Mount and sustained read / write	Sustained write > 0.77MB/s (continuous 96 kHz, 32-bit stereo rate)	226 MB/s	Far in excess of the required rate

6.1.2 Power and Endurance

In all three tests, the system was powered from a portable 5 V battery rather than from the 12 V $LiFePO_4$ pack. The buck converter that steps 12 V down to 5 V forms part of a custom PCB designed later in the project, which could not be used in the tests because of its long manufacturing and shipping lead time. The final prototype will use this PCB, which both tidies the wiring and integrates the buck converter, allowing the buoy to run from the 12 V battery. The measurements reported here are therefore taken on the 5 V rail directly, and the 12 V battery figures are projected forward to that final configuration.

The power consumption was measured at the bench using an FNB58 USB-C digital multimeter on the 5 V rail, supplied from the portable battery. A continuous session of 17.4 minutes was logged and instantaneous power across the duration is shown in Figure 6.1. The navigation light was not part of this session. It was characterised separately and draws an almost constant 0.225 A at 12 V, so it is added to the energy budget as a fixed load rather than measured here.

The key result is that active recording draws essentially the same power as idle. Mean power during active recording was 4.27 W, against 4.38 W at idle. This is because the hydrophone capture and the SSD writes are handled by direct memory access and place little additional load on the processor. The practical consequence is that the cost of recording is the base cost of keeping the Raspberry Pi and its peripherals running. Reducing power therefore depends on managing the base load through duty cycling or sleep states, not on recording less.

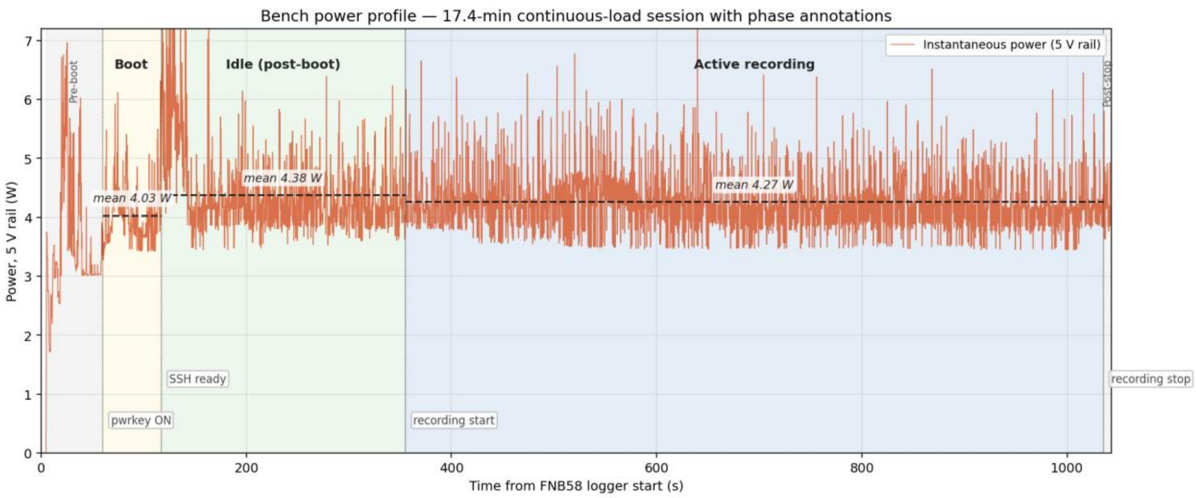

Figure 6.1: Instantaneous power on the Raspberry Pi 5 V rail across a 17.4-minute continuous-load bench session, recorded with an FNB58 in-line data-logger. Phase means are 4.03 W during boot, 4.38 W at idle, and 4.27 W during active recording

To refer the measured 5 V load to the 12 V battery in the final configuration, a buck-converter efficiency of 90% is assumed. On this basis the 4.27 W at 5 V corresponds to about 4.74 W at the 12 V battery, or 395 mA. The navigation light adds 12 V × 0.225 A for 4 hours per day, which is 10.8 Wh per day. Under continuous recording, the total daily energy demand is therefore approximately 124.7 Wh per day.

The intended battery is a 12 V, 10 Ah $LiFePO_4$ pack, storing 120 Wh. Against a continuous demand of 124.7 Wh per day, this gives an endurance of about 0.96 days, or roughly 23 hours. This is below the multi-day targets, and it was a deliberate outcome since the battery pack was kept small for cost, size, and easy two-person handling during prototype testing, and the architecture is designed to scale to a larger battery without any change to the electronics or software.

To show this, the same measured load is projected onto larger battery options and onto a duty-cycled operating mode. Duty cycling here means recording for 10 minutes in each hour rather than continuously, which lowers the daily demand to about 29.8 Wh per day. The projections are summarised in Table 6.4.

Table 6.4: Endurance projection summary.

Scenario	Battery	Duty cycle	Wh / day	Days
As-built prototype, continuous	12 V × 10 Ah (120 Wh)	Continuous + 4 h/d LED	124.6	0.96
As-built, duty cycle	12 V × 10 Ah	10 min/h + 4 h/d LED	29.8	4.03
3x battery of as-built prototype, duty cycle	3 × 12 V × 10 Ah (30 Ah)	10 min/h + 4 h/d LED	29.8	12.09
Full-scale, continuous	12 V × 150 Ah (single)	Continuous + 4 h/d LED	124.6	14.44
Full-scale, duty-cycled	12 V × 150 Ah (single)	10 min/h + 4 h/d LED	29.8	60.4

6.1.3 Waterproof testing

The first component level validation focused on the waterproof performance of the IP68 electronics enclosure. Two leakage paths were considered: water entering through the top cover seal and water entering through the cable glands.

To isolate the top cover seal, the enclosure was closed with the cable gland openings plugged, removing cable gland leakage as a variable. The box was then submerged for 15 minutes and inspected for water ingress. The test initially failed. Inspection showed that the lid screws had been over tightened, damaging the sealing interface and preventing the gasket from compressing evenly. This showed that the enclosure performance depended not only on the IP rating of the box, but also on how consistently it was assembled. To control this, a torque screwdriver was purchased and used whenever the enclosure was sealed. This tool will also be included in the project handover so future users can reproduce the same consistent sealing procedure rather than relying on judgement when tightening the screws.

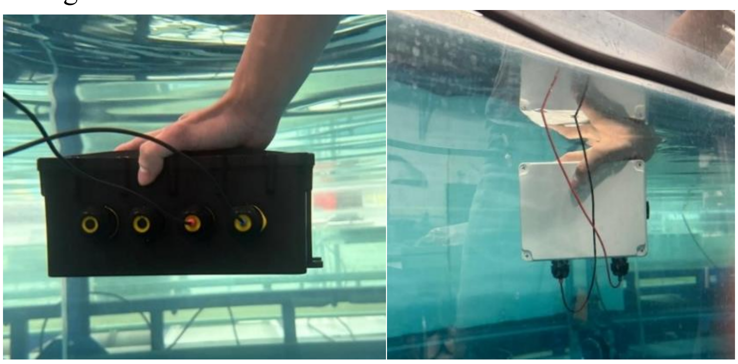

Figure 6.2: IP68 submersion test for water ingress

A second waterproofing test was then carried out with cables routed through the cable glands as shown in Figure 6.2. This test also failed initially, but for a different reason. The cables were too small for the gland sealing range, so even when the gland nut was fully tightened, the rubber seal could not compress properly around the cable. This left a leakage path into the enclosure. The solution was to build up the cable diameter at the sealing location using heat shrink until the cable sat within the required gland range as shown in Figure 6.3. Once this was done, the gland compressed properly and the enclosure was retested without further water ingress. The cable was also tugged and moved during the test to check that the gland seal remained watertight. This was an important integration lesson because the cable gland could only be considered waterproof once the cable diameter matched the gland specification.

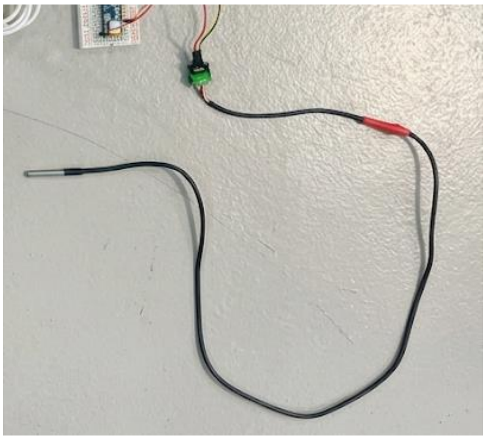

Figure 6.3: Heat shrink (red) applied to temperature probe cable.

6.1.4 Internal Foam Replacement

The switch from EPS foam to Plastazote LD45 was introduced earlier in the report, but the testing and design iterations behind this change are explained here. During handling and early water testing, the original foam was found to shed polystyrene beads. This created a contamination risk because loose beads could escape into the water if the buoy was damaged, opened or repeatedly deployed.

The first mitigation was to wrap the foam in cling film. This reduced the amount of loose material released during handling, but it was not considered a reliable final solution. The original foam still fitted poorly within the buoy shell, leaving gaps around internal components and the cling film could tear or degrade during repeated use. This meant the underlying issue had only been contained rather than solved. The foam was therefore replaced with a bespoke cut closed cell Plastazote foam that fitted the internal geometry more closely and did not shed beads. The change also made the prototype more suitable for repeated testing because the foam could be installed and removed without breaking apart.

This test showed that the foam selection was not just a buoyancy decision, but also an environmental and integration decision. The final foam choice reduced contamination risk while improving the fit and reliability of the internal layout.

6.2 Controlled Wave Tank Testing

The second stage of testing was carried out in the UCL fluids laboratory to test the fully integrated buoy under controlled wave conditions[7] before coastal deployment. Unlike the component tests, this stage tested how the buoy behaved as one integrated system. The daymark was removed for this test because its height prevented the

[7] Davide Grande, RA108558/1, “RA_tanks_v4.pdf”, 2026

buoy from being lowered into the tank without fouling the fixed ceiling structures. The test examined four main areas: hydrostatic flotation and stability, internal thermal behaviour under load, inertial response to regular waves and the acoustic noise floor of the recording system. The full test plan for wave tank testing can be found in Appendix M.

Figure 6.4: Snapshot of wave tank testing.

6.2.1 Stability and Self-Righting Behaviour

The buoy remained stable during wave excitation and did not approach the heel angles required for loss of positive stability predicted in Section 3.7.2. This supported the earlier stability analysis, which showed that the buoy had a large range of positive righting arm before becoming unstable from its normal upright condition.

A self-righting check was also carried out by placing the buoy in an inverted position. As predicted in Section 3.7.2, the buoy did not consistently recover from complete inversion by itself. Recovery was only achieved once a small initial heel angle was introduced. This test confirmed that a domed or curved upper surface should be developed in future to improve recovery from complete inversion.

6.2.2 Effect of External Floats

As seen in Figure 6.4, for one iteration of our buoy, a series of yellow fish floats were utilised around the perimeter of the buoy. These were a great mechanical addition as they provided extra buoyancy and more stability. However, the wave tank exposed a problem we overlooked. During wave motion, the floats repeatedly contacted the buoy shell and water surface, creating unwanted noise.

This was a critical issue because the buoy includes hydrophone measurements so any noise generated by the buoy itself could contaminate the acoustic data. Although the floats improved mechanical performance, the purpose of the buoy is to collect reliable marine data, therefore, the floats were removed from the final configuration.

6.2.3 Internal Thermal Response

The internal temperature of the electronics enclosure inside the IP68 waterproof box was monitored during the tank session to confirm that the sealed enclosure did not overheat while the system ran under load. This is a concern in operation, as the enclosure is closed and the heat generated by the Raspberry Pi, SSD, and LTE hardware must pass out through the enclosure wall into the surrounding water rather than being vented to air.

Two temperatures are of interest, and they behave differently. The Raspberry Pi system-on-chip (SoC) ran at about 60 °C throughout the session, holding a steady level with roughly 21 °C of headroom below its 80 °C throttling threshold, as shown in Figure 6.5. The chip therefore operated comfortably within its safe range under continuous load.

The air inside the sealed IP68 box, measured by the Arduino's built-in HS3003 sensor, stayed much cooler. Submerged in the tank, it fell from 26 °C and settled at about 22 °C, against about 32 °C when the same enclosure was run in air. This difference reflects the effectiveness of the free-flooded hull in managing heat. Water fills the hull and surrounds the enclosure, drawing heat through the enclosure wall far more effectively than air does, so immersion assists cooling rather than trapping it. Both temperatures reached a steady value rather than climbing without limit, which is the behaviour required for sustained operation.

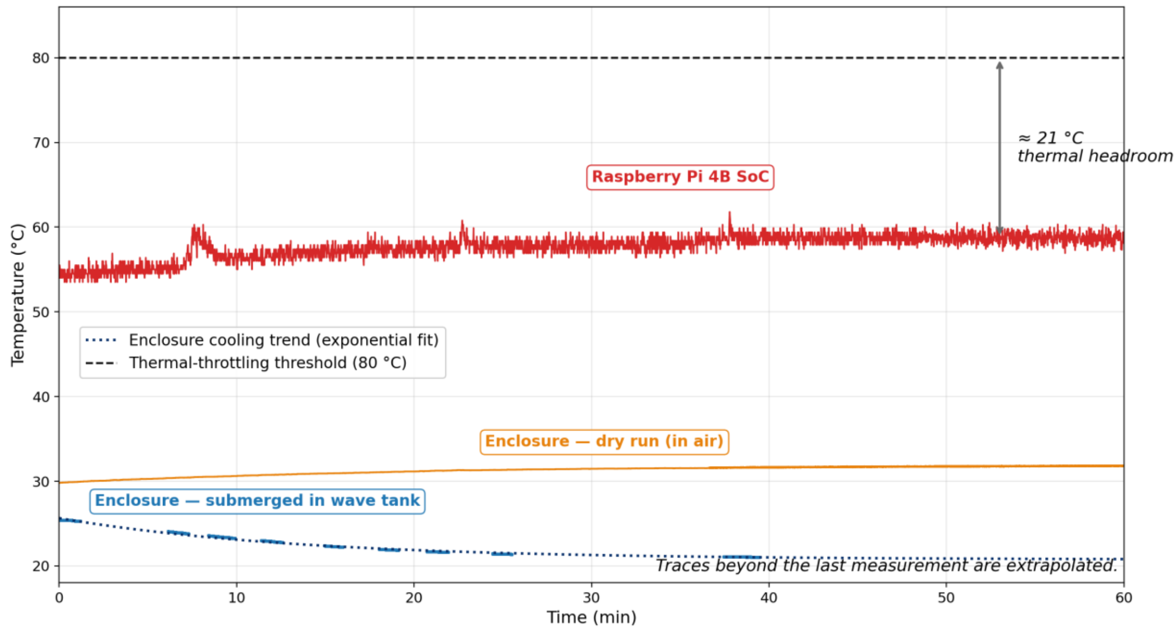

Figure 6.5: Thermal behaviour over a one-hour deployment: Pi 4B SoC temperature (red), enclosure temperature in air (orange) and submerged in the wave tank (blue), relative to the 80 °C throttling threshold. Segments past the last recorded sample are extrapolated.

6.2.4 IMU dynamic response

The IMU was tested in the tank to assess the accuracy with which the buoy's own motion can estimate the wave. The buoy was driven through 10 conditions: a still-water reference and 9 regular wave conditions, spanning commanded frequencies of 0.55 to 1.70 Hz and amplitudes of 0.027 to 0.080 m. The BMI270 was logged at about 10 Hz, each record was trimmed to the duration of its steady section, and a Welch power spectral density (PSD) identified the dominant frequency and its signal-to-noise ratio. The supporting analysis is given in Appendix K.

The principal result is that the buoy recovers wave frequency accurately but does not yet resolve wave height. The two outcomes are governed by different aspects of the measurement, as set out below. Frequency is recovered reliably, as all 9 wave conditions produced a distinct spectral peak near the commanded frequency, tracking the 1:1 line within 11% (mean error 4.7%), with signal-to-noise ratios of 24.9 to 48.2 dB against a 10 dB detection threshold. The detected peak falls slightly below the commanded value at the higher frequencies. This arises in part because the spectrum is evaluated only at discrete frequency intervals, about 0.04 Hz apart at the 10 Hz logging rate, so a peak can be located only to the nearest interval rather than at its exact frequency. The remainder reflects a physical reduction in the buoy's response above its heave resonance, where the structure no longer follows the wave. The buoy is therefore a credible instrument for identifying the dominant wave period, which is the more useful sea-state quantity for most monitoring purposes.

Wave height is not yet recovered reliably, as it presents a fundamentally more demanding measurement. Heave amplitude is inferred from IMU vertical acceleration through $x = \frac{a}{(2\pi f)^2}$, a double integration in which the frequency error enters the displacement doubled: $\frac{\delta x}{x} = \frac{\delta a}{a} + \frac{2\delta f}{f}$. Frequency is recovered as the location of a

sharp spectral peak, which is robust to noise, whereas amplitude depends on the magnitude of that peak after this noise-sensitive integration, which is not. Random accelerometer noise alone would produce only millimetre-scale displacement uncertainty, but in practice the estimate is dominated by gravity leakage from pitch and roll, mounting misalignment, and integration drift. These effects are most damaging at the lower frequencies, where the true acceleration of a given heave is small and is therefore most readily corrupted.
The measured response is nonetheless physically consistent: the ratio of measured to commanded heave peaks near 1 Hz and falls toward zero at higher frequencies (Figure 6.6, right), in agreement with the predicted heave resonance of approximately 1.2 to 1.7 Hz (Appendix K). This confirms that the response represents genuine buoy motion rather than measurement noise.

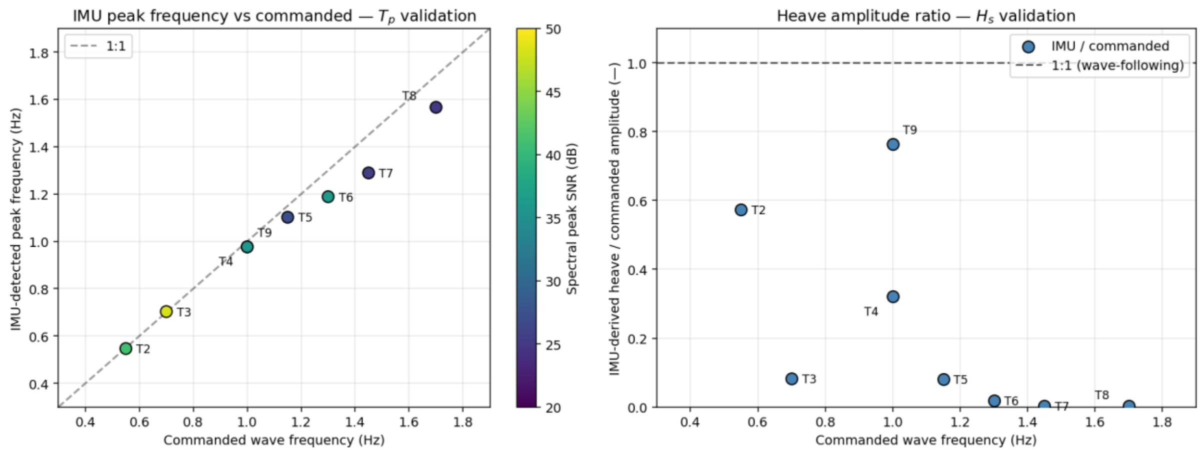

Figure 6.6: IMU frequency and amplitude against the tank reference (still water). Left: detected vs commanded peak frequency for the nine wave conditions, marker colour by spectral-peak SNR ratio; Right: heave amplitude ratio against commanded frequency, absolute heave is uncalibrated.

Three factors nonetheless prevent the height figures from being treated as calibrated, (i) the absence of an independent reference for the local wave height at the buoy, (ii) the noise sensitivity of the acceleration to displacement conversion, (iii) and the use of a fixed mean-gravity projection that does not track pitch and roll. The heave figures should therefore be interpreted as a relative response indicator rather than a calibrated measurement. Calibration would require an external amplitude reference, such as a wave gauge or calibrated side-view video, a six-position accelerometer calibration, and an orientation-tracking filter. These steps are recorded in the future-work list.

6.2.5 Hydrophone Acoustic Response

The hydrophone was recorded under the same nine tank conditions as the inertial tests: a stationary still-water reference and eight regular wave conditions from 0.55 to 1.70 Hz at amplitudes of 0.027 to 0.080 m. The objective was not to record the waves as sound, but to determine whether the motion of the platform introduces any signature into the acoustic data, which governs whether genuine environmental sound could subsequently be distinguished from the buoy's own behaviour.

The controlled wave conditions produced no detectable acoustic signature. The hydrophone recorded only the self-noise of its own chain, which was not distinguishable between still water and the strongest wave condition, as shown by three independent observations.
First, the recorded spectrum is invariant to the wave condition. Above approximately 1 kHz every condition coincides with the still-water reference (Figure 6.7, left), and the level between 5 and 40 kHz remains at −151.7 dBFS/Hz across all nine conditions, varying by less than 0.05 dB. A level that holds constant while the wave amplitude varies by an order of magnitude is a property of the instrument rather than a measurement of the

environment. Second, no additional energy appears at lower frequencies (Table 6.5). The level under waves is at or below the reference in every band, and at the strongest condition, where the buoy moved approximately ten times as much as in still water, no increase in level was observed. Third, the spectrogram of that strongest condition (Figure 6.7, right) is stationary over the full 120 s, exhibiting no transients and no energy at the 1 Hz drive frequency or its harmonics. A recording that had captured the waves would show such energy.

*Table 6.5: **Hydrophone level by frequency band across the nine tank conditions.***

Band	Variation between conditions (dB)	Mean level relative to still water (dB)
2 ~ 12 Hz	3.9	-1.1
12 ~ 100 Hz	0.9	-0.3
0.1~1 kHz	1.0	0.4
1 ~ 10 kHz	0.1	0.0
10 ~ 40 kHz	0.0	0.0

Variation between conditions and mean level relative to the stationary still-water reference. Values are negative or zero in every band, confirming no rise under wave forcing.
This outcome is consistent with established acoustic theory. At these frequencies the waves are far smaller than an acoustic wavelength: a 2 Hz sound wave in water has a wavelength on the order of 750 m, far exceeding the tank dimensions. A disturbance this much smaller than a wavelength radiates negligible propagating sound, so the wave-induced pressure remains a local, near-surface effect below 2 Hz rather than travelling sound, and lies outside the hydrophone's calibrated band. The mechanisms that would generate audible sound, breaking crests and air bubbles, did not occur at these small amplitudes. The yellow float ring surrounding the buoy in Figure 6.4 splashed audibly in air as the buoy heaved, but produced no measurable rise in the underwater record, consistent with the low recording gain identified below and the limited transmission of near-surface splash into the water column.

This low gain is the principal limitation identified by the test, and the corrective measure is well defined. For representative coastal ambient, the hydrophone produces only about 0.8 to 8 µV in a 1 Hz band, which lies at or below the converter's own noise of a few microvolts, so the quiet signal is lost within the noise floor of the chain. The HiFiBerry ADC’s input gain can be raised as an immediate first step, but its range is limited and it does not add a low. An additional fix could be an external low-noise preamplifier ahead of the converter, providing 40 to 60 dB of gain to lift quiet ambient sound clear of the floor. The gain must be applied before the converter, since gain introduced afterwards amplifies signal and noise equally and confers no benefit. With this preamplifier and a pistonphone calibration to establish absolute sound pressure level, the chain would be capable of quantitative acoustic measurement.

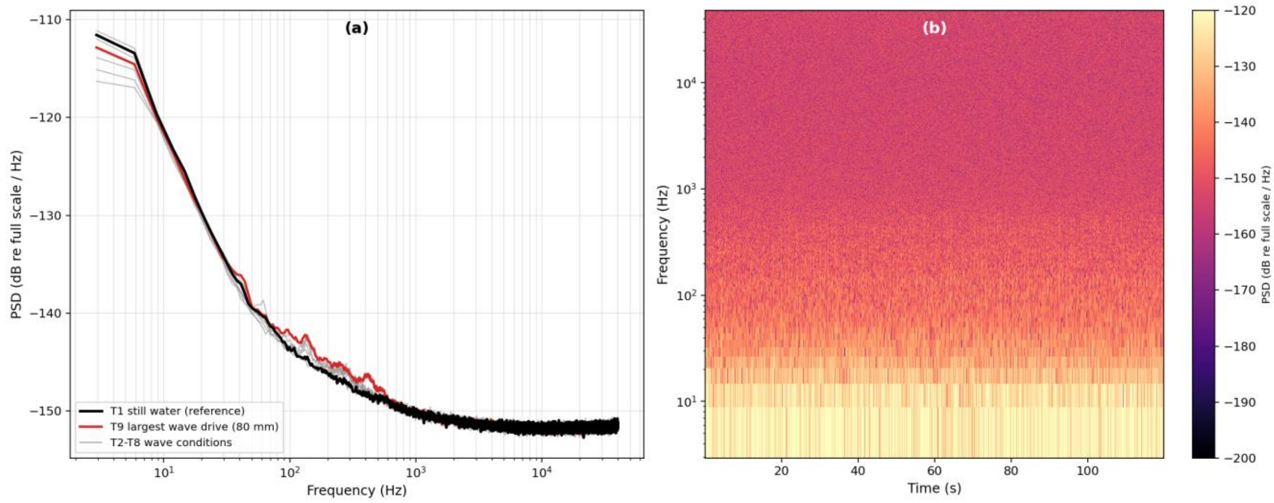

Figure 6.7: Wave-tank hydrophone analysis. (a) Power spectral density (PSD) for all nine conditions (b) Spectrogram of the strongest condition (0.08m), stationary over the full record with no harmonics of the drive frequency

6.3 Field Deployment Results

The final verification stage was a saltwater deployment in open coastal water at Brighton[8] on 1 May 2026. This tested the integrated prototype as a whole, after the bench and tank stages had verified the subsystems in isolation. The test window ran for approximately two hours, set by boat hire availability and the project budget rather than by any constraint of the prototype itself.

6.3.1 Deployment and recovery

Two operators deployed and recovered the buoy from a small boat. Both operations went without incident (Figure 6.8). The buoy was deployed unballasted. It floated upright and held positive freeboard throughout the window, which is consistent with the unballasted flotation prediction in Section 3.6. After recovery the team opened both enclosures and inspected them for water ingress. None was found at either the battery or electronics enclosure. The two-hour window was enough to exercise every subsystem in realistic conditions but too short to test endurance, which is carried forward to Section 7.2 as future work.

Figure 6.8: Field deployment from a supported small craft at Brighton on 1 May 2026. The buoy is being lowered unballasted, and floated upright with positive freeboard throughout the two-hour window.

6.3.2 Acoustic response

The tank test identified low recording gain as the main limitation, with quiet ambient sound lost in the converter noise floor. The field deployment validated the corrective measure: with the gain change in place, the chain captured cleanly to the SSD and the dashboard resolved discrete events such as a vessel passage and surf clearly

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[8] Project team field-test record Brighton Field Test of Prototype

above the background. The acoustic event view, spectral density view, and full deployment spectrograms are given in Appendix P.

6.3.3 GNSS position

A GNSS position fix was acquired at sea, which confirms the position route end to end in the field. The PiTalk modem reported a 3D fix on 8 satellites with HDOP 0.9 (Excellent) at the deployment position of 50.80817°N, 0.12405°W. The dashboard recorded 0 m drift across the 2 h window, and the live battery state held at 91% (12.61 V) throughout. The fix supports deployment tracking, recovery, and position metadata for the recorded data, which were the design roles set out in Section 4.1.4. Figure 6.9 shows the overview view used by the team on land during the deployment.

6.3.4 LTE telemetry and dashboard

The 4G/LTE uplink was established at sea, and the dashboard updated live throughout the deployment. The team could see the buoy's position, battery state, storage state, and recording status from land while the buoy was on station. This met the central objective of live remote monitoring set out in Section 1.2, rather than the data being available only after recovery. The telemetry layer reported 99.9% upload delivery across the window, with 52 files acknowledged by the backend and 0 files pending in the replay queue at recovery. The primary radio link operated at RSSI of −72 dBm and SNR of 11.2 dB on a 30 s cadence (Figure 6.10), which is well inside the link-quality margin needed for reliable JSON-payload telemetry. The dashboard's gap detector logged no dropouts greater than one cadence interval during the two-hour window. The live dashboard views recorded during the deployment, namely overview, telemetry, system health, environment, alerts, hydrophone summary, soundscape, daily events, acoustic events, sound levels, spectral density, recording effort, location and map, files, and historical data, are included in Appendix P as the operating evidence for live remote monitoring.

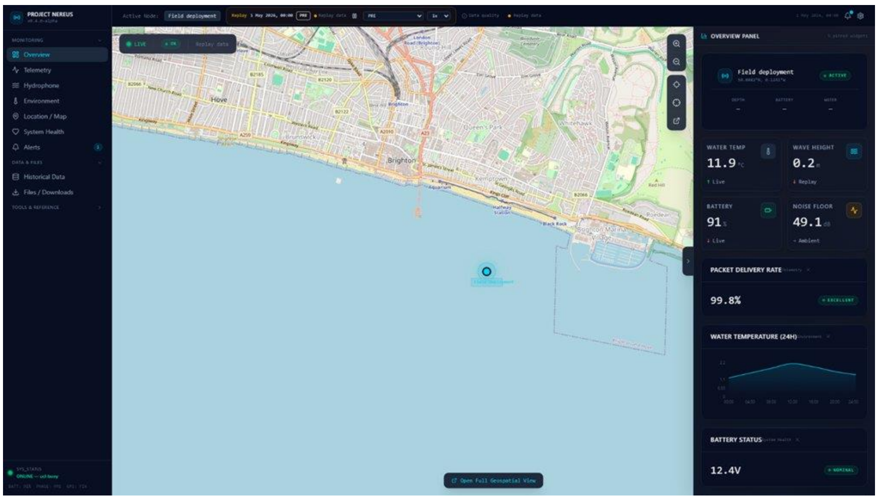

Figure 6.9: Live overview dashboard during the Brighton field deployment. The map shows the buoy on station. The right-hand panel reports water temperature (11.9 °C), battery (91%), packet delivery rate (99.8%).

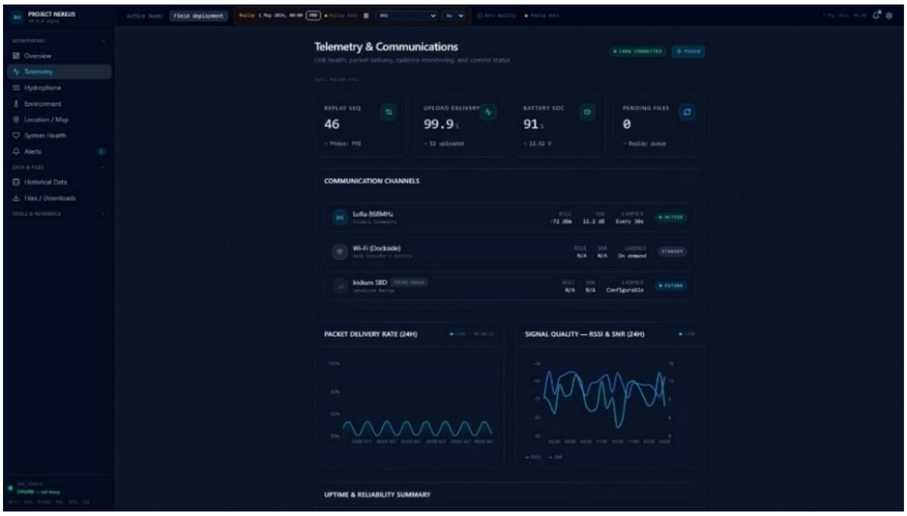

Figure 6.10: Telemetry and communications dashboard during the Brighton field deployment.

6.4 Design Changes Resulting from Testing

Each stage of testing produced observations that fed back into the prototype design. This section consolidates those changes in one place, so that the influence of testing on the final configuration can be assessed without re reading the individual test sections. The changes are grouped by the test stage that triggered them.

Table 6.6: Design changes triggered by each stage of testing.

	Trigger (test observation)	Design change	Section reference
Bench and component testing			
6.4.1	Original EPS foam shed polystyrene beads during handling, conformed poorly to the internal geometry, and created environmental contamination risk.	EPS foam replaced with bespoke cut Plastazote LD45 closed cell foam. Improves geometric fit, eliminates bead shedding, and supports repeated handling.	6.1, 3.3
6.4.2	IP68 lid screws were over tightened during early waterproof testing, damaging the sealing interface and causing the first submersion test to fail.	Torque screwdriver purchased and added to the standard assembly procedure. The tool is included in the project handover so future users can reproduce a consistent seal.	6.1
6.4.3	Cable diameters were below the gland sealing range, so the gland could not compress fully around the cable. Caused the second waterproof test to fail.	Heat shrink applied to cables at the sealing location to build the outer diameter up to the gland specification. Validated by retest with no further ingress.	6.1
6.4.4	HiFiBerry DAC+ADC Pro driver path restricts bit depth to 16 or 32 bit (no 24 bit available), and the H2DM is a single channel source so the second channel is duplicated. Default configuration produces ~66 GB/day.	Recording format moved to mono and to the lowest bit depth permitted by the driver path. Data volume reduced to ~25 GB/day with no loss of useful acoustic content.	6.1
6.4.5	Quectel EC25 LTE modem requires a manual power key press to re register after a full power off, creating a single point of failure for unattended deployment.	Limitation accepted for the prototype; the auto press circuit is recorded as a high priority future work item rather than implemented in scope.	6.1, Appendix J (future work)
Wave tank testing			
6.4.6	External yellow fish floats added in an earlier iteration improved buoyancy and acted as bumpers, but generated mechanical contact noise against the	External floats removed from the final configuration. The acoustic measurement requirement took priority over the marginal mechanical benefit.	6.2

	buoy shell under wave motion that contaminated the hydrophone record.		
6.4.7	The buoy did not consistently self-right from complete inversion. Recovery was only achieved once a small initial heel angle was introduced, confirming the behaviour predicted by the GZ analysis.	No mechanical change implemented in the prototype scope. A domed or curved upper surface is recorded as a high priority future modification.	6.2, 3.7.2, Appendix J
Field deployment			
6.4.8	Continuous ambient sound and the support boat signature sat at or below the converter noise floor in open water, reproducing the gain limitation already observed on the bench and in the tank.	The field deployment confirmed that the chain captured discrete events such as vessel passage and surf, but quiet continuous ambient sound remained gain limited. This agrees with the tank result and confirms the need for an external low noise preamplifier before quantitative acoustic monitoring	6.3, Appendix J

The pattern across the eight items reflects the staged verification ladder: bench testing revealed integration issues that could be closed inside the prototype scope through procedure, material, or configuration changes; tank testing revealed behaviours that needed mechanical decisions (float removal, future self righting); field testing reproduced the gain limitation already known from the tank and confirmed it as the principal closure item for the next iteration. No new failure mode emerged in the field that had not already been observed in the laboratory, which is the result the staged approach was designed to produce.

6.5 Requirements Validation Summary

This section maps the verified performance of the prototype against the Product Design Specification of Table 1.1, with the full specification in Appendix A. Each requirement is graded with one of four outcomes.

- ‘Met’: the requirement was demonstrated.
- ‘Partial’: it was demonstrated in part, with a quantified route to closure.
- ‘Reduced scope’: it was deliberately rescoped for the prototype, with a validated path back to the original target.
- ‘Deferred’: it was not exercised and is routed to future work.

Table 6.7 records the outcome for each headline requirement, and the paragraph that follows links these to the primary objectives of the project.

Table 6.7: PDS compliance summary against the headline requirements of Table 1.1.

PDS area	Headline requirement	Evidence	Status
Operating envelope and physical platform			
A.1 / A.2	Operate in coastal water up to sea state 4, sustained wind 15 m/s, unballasted mass ≤ 30 kg.	Field deployment in coastal water (Section 6.3); wind heeling analysis confirms 15.9 m/s limit unballasted, 24.7 m/s ballasted (Section 3.8.1); final mass 23.13 kg (Section 3.5).	**Met**
A.2	Hull freeboard ≥ 50 mm at maximum ballast, draft ≤ 350 mm.	Calculated freeboard 161 mm and draft 89 mm at maximum ballast (Section 3.6); positive freeboard sustained throughout 2 hour field window (Section 6.3).	**Met**
Structural and flotation			
A.3	Topside primary structure safety factor ≥ 3 against yield under self weight.	FEA gives 5.2× safety factor at the lower tripod leg bolt hole (Section 3.8.2). Mounting interfaces achieve 90× and 57× safety factors.	**Met**
A.4	Reserve buoyancy ≥ 50% of fully loaded platform mass; positive buoyancy preserved on hull breach.	Reserve buoyancy 52 kg supportable at maximum ballast (Section 3.6); free flood hull architecture means single hull breach cannot cause sinking (Section 3.2).	**Met**

PDS area	Headline requirement	Evidence	Status
A.4	Positive righting moment for heel angles up to 60°.	GZ analysis (Section 3.7.2): angle of vanishing stability 78° unballasted and 133° ballasted. Tank test confirmed no approach to instability under wave excitation (Section 6.2).	**Met**
A.4	Self-righting from full inversion (Could grade).	Stable in all configurations; the buoy does not self-right unaided. Tank test confirmed this behaviour (Section 6.2).	**Deferred**
Sensing			
A.5	Hydrophone capture, frequency response 10 Hz to 50 kHz, recorded with adequate dynamic range.	Capture chain verified at bench (Section 6.1), tank (Section 6.2), and field (Section 6.3). Discrete events resolved clearly; continuous ambient is gain limited. Closure route via external preamplifier is defined and quantified.	**Partial**
A.5	Buoy motion measurement, 3 axis acceleration and angular rate at ≥ 50 Hz.	BMI270 IMU logged at ~10 Hz, which oversamples the 0.1 to 1 Hz coastal wave band by 10× to 100× (Section 6.1). The 50 Hz target was therefore reduced to a tested ~10 Hz; wave frequency is recovered within 11% across all 9 tank conditions (Section 6.2).	**Reduced scope**
A.5	Wave height resolution from IMU.	Frequency is recovered reliably; absolute heave amplitude is uncalibrated and shows the expected resonance shape only. Calibration route documented (six position calibration, external amplitude reference, orientation filter).	**Partial**
A.5	Seawater temperature ± 1 °C accuracy.	DS18B20 agreed with reference thermometer to within 0.1 °C, well inside the ± 1 °C requirement (Section 6.1).	**Met**
Compute, logging, and communications			
A.6	Continuous audio capture, parallel logging, concurrent telemetry on primary compute.	Active recording draws within 0.1 W of idle load, confirming no compute bottleneck (Section 6.1). Storage write rate 226 MB/s, far above the acoustic stream rate.	**Met**
A.6	Local storage ≥ 500 GB; raw data held locally.	1TB storage - Samsung T9 SSD acquired; supporting > 20 days continuous recording on board (Section 6.1, 6.4.4).	**Met**
A.6	4G LTE telemetry for health and status data.	Uplink established at sea; live dashboard updated during field deployment (Section 6.3).	**Met**
A.6	GNSS position fix at ≥ 1 Hz with clear sky.	Position fix acquired at sea and confirmed end to end (Section 6.3).	**Met**
Power			
A.7	Continuous operation endurance ≥ 24.	Bench measurement gives continuous endurance of approximately 23 hours on the 120 Wh pack (Section 6.1), deliberately reduced scope.	**Reduced scope**
A.7	Battery overcharge and undervoltage protection.	Integral to selected $LiFePO_4$ pack per component data sheet.	**Met**
Environmental protection and deployment			
A.8	Electronics enclosure IP68, verified by 24 hour submersion.	Submersion test passed on second iteration after the torque procedure was introduced (6.4.2) and the cable diameters built up (6.4.3). Field deployment showed no ingress on opening (Section 6.3).	**Met**
A.9	Two person deployment from a small craft, deployment and recovery each ≤ 30 minutes.	Demonstrated at Brighton[9] (Section 6.3); both operations completed without incident.	**Met**

[9] Project team field-test record Brighton Field Test of Prototype

PDS area	Headline requirement	Evidence	Status
Cost			
A.10	Hardware budget ≤ £2,500.	Bill of materials confirms total below budget (Appendix O).	**Met**
A.10	Inherited platform reuse where adequate.	Hull, top plate, bracing ring, and ADCP bracket all retained (Section 3.3).	**Met**
Endurance and long term performance			
A.1	Extended deployment duration up to 14 days unattended	Not exercised in scope. Bench projection supports the 14 day target with a higher capacity battery or hybrid energy source, but no extended deployment was carried out.	**Deferred**

The four governing requirements map onto these outcomes directly. Continuous acoustic capture with the full raw record held locally was demonstrated, so the data path objective is met. Quiet ambient sensitivity is the single open performance gap, reported as partial with a defined closure route. Live remote monitoring was achieved, since both the GNSS fix and the LTE dashboard worked at sea. The multi-day mission is the deliberate reduced-scope item. The 14-day requirement was not met at prototype scale, at about one day continuous, because the battery was kept small for cost and safe two-person handling. Table 6.4 shows a validated route to the target through battery capacity alone, with no change to electronics or software. The duty-cycled prototype reaches about four days, a threefold battery about twelve, and a full-scale battery the fourteen-day stretch. In short, the prototype meets its flotation, structural, protection, deployment, and cost requirements, partly meets sensing with a quantified path to closure, and meets remote monitoring in the field, while endurance is rescoped with a validated route to the full target.

7. Handover and Future Development

7.1 Handover Plan

A structured handover package was produced to allow the prototype to be inspected and developed by a future project team. This is important as the buoy was designed with the intention of it being built upon and developed rather than a single use prototype. The handover package will be provided on a USB drive as a project archive, supported by the project GitHub repository for software continuation.

The USB contains all relevant information required to reproduce the physical build, operate and deploy the buoy safely and continue development. This includes the final report and appendices, CAD files, manufacturing drawings, bill of materials, wiring diagrams, sensor and battery datasheets, Raspberry Pi and Arduino code, deployment scripts, raw and processed test data, risk assessments, operating checklists and future work notes. The intention is that a future team can understand not only the final design, but also the decisions, limitations and test evidence behind it. The handover therefore acts as both a project archive and a continuation plan.

7.2 Future Work

The future work has been prioritised around closing the main limitations identified during testing, rather than redesigning the whole buoy architecture. The full future work register is provided in Appendix J and is also included in the handover package, so that the next team can distinguish between urgent validation tasks and longer-term design improvements.

Reaching the 14-day deployment target deferred from the PDS (Section 1.3) will require either a higher-capacity battery or a hybrid power system combining a smaller battery with energy harvesting from solar, wave, or wind. Either option significantly increases the mass and volume budget of the platform: the present 120 Wh battery would need to grow by roughly an order of magnitude to support 14 days at the current consumption profile, and adding a solar array introduces new above-water area, fixings, and cabling. The resulting changes propagate into mass, centre-of-gravity, stability, and deployment handling, and may require a full hull redesign rather than incremental modification. The most realistic path is therefore a coordinated study that treats power, hull geometry, and stability as a single design problem, with safe two-person deployment retained as a binding constraint.

A second high-value upgrade is hybrid 4G plus satellite connectivity, replacing the current cellular-only telemetry. The 4G link offers higher bandwidth and lower latency where coverage exists but is unavailable beyond a few kilometres offshore, while a satellite link such as Iridium SBD or Swarm M138 provides continuous low-bandwidth coverage anywhere at sea. Combining the two with a simple link-selection rule (prefer cellular when available, fall back to satellite otherwise) would minimise communication downtime and remove the single biggest gap in the current deployment envelope. The same hybrid link also improves recovery resilience: a buoy that drifts out of cellular range under fault conditions remains trackable on the satellite channel, which is impossible with the present configuration.

8. Conclusion

This project started with an inherited passive instrument carrier and a budget of £2,500. The goal was to turn it into a coastal buoy that records underwater sound, tracks its own motion, and measures water temperature. It also had to keep the full raw recording on board and send its status and position back to shore. Those needs drove the main design choices. Computing ran on a single-board computer instead of a microcontroller. Power came from an onboard battery, not from energy harvesting. The hull was built as a free-flooded HDPE shell packed with closed-cell foam.

The finished buoy meets its core aims. The evidence came from three test stages. These were a bench build, a wave-tank session, and a saltwater deployment at Brighton on 1 May 2026. Acoustic capture ran for the full field window and wrote every raw file to the onboard SSD with no dropouts. The 4G uplink held at sea, and the dashboard showed live position and status from land. Hydrostatic predictions matched the build, as did the mass budget, the centre of gravity, and the thermal behaviour of the flooded hull. All of these sat within the prototype tolerance band. Two people launched and recovered the buoy from a small boat without trouble. This confirmed the handling limit behind its size and weight.

Not every requirement was fully met, and the report is direct about this. The hydrophone gain is too low to lift faint deep-ocean sound clear of the noise floor. This is the main open gap, and it has a defined fix. Wave height from the IMU is not yet calibrated, though wave frequency is recovered well. Endurance was rescoped for the prototype, with a route back to the original figure through battery capacity alone. The 14-day target and self-righting from full inversion were never tested. Both now sit in future work. Every open item carries a way to close it.

The outcome is a working first-generation platform rather than a finished product. A low-cost, modifiable buoy can carry a demanding acoustic payload next to motion and temperature sensing, and do it on a student budget. Much of the value lies in what is left behind. The design decisions, the test results, and the limitations are written down for the next team. The handover package gathers them in one place, so future work can start from a known position.

Several clear tasks remain. The hydrophone gain gap needs closing. Wave height needs calibrating against a trusted reference. Longer endurance means treating power, hull shape, and stability together rather than one at a time. With that work done, the platform can serve as a repeatable tool for coastal acoustic monitoring.

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10. Appendix

Appendix A: Product Design Specification

This appendix provides the detailed Product Design Specification (PDS) supporting the summary PDS in Section 1.3. Each row gives a quantified requirement, the priority (Must, Should, Could), and the verification route. Numerical values are stated for every parameter where a value was used in design or verification; values marked "to be determined" remained open at the prototype stage and are flagged in Future Work.

A.1 Operating Envelope

Requirement	Value	Priority	Verification
Deployment environment	Shallow coastal and sheltered nearshore water	Must	Design intent
Sea state envelope	Up to sea state 4 (significant wave height up to 2.5 m)	Must	Design assumption
Wind speed envelope (sustained)	Up to 15 m/s	Must	Load analysis, Section 3.8.1
Current speed envelope	Up to 0.5 m/s	Must	Load analysis, Section 3.8.3
Water depth	5 m to 30 m	Should	Design assumption
Operating air temperature	0 °C to 35 °C	Must	Component derating
Operating seawater temperature	4 °C to 25 °C	Must	Component derating
Short-campaign deployment duration	Up to 24 hours unattended	Must	Field test, Section 6.4
Extended deployment duration (future)	Up to 14 days unattended	Should	Future work, Section 7
Storm survival	Not required above sea state 4	Excluded	Out of scope

A.2 Physical Envelope

Requirement	Value	Priority	Verification
Maximum unballasted mass	≤ 30 kg	Must	Mass budget, Section 3.5
Maximum ballasted mass	≤ 50 kg	Must	Mass budget, Section 3.5
Maximum overall diameter	≤ 1.0 m	Must	CAD, build inspection
Maximum overall height (hull to topmost feature)	≤ 2.0 m	Must	CAD, build inspection
Hull freeboard, loaded	≥ 50 mm at maximum ballast	Must	Tank test, Section 6.3

Hull draft, loaded	≤ 350 mm at maximum ballast	Must	Tank test, Section 6.3

A.3 Structural Requirements

Requirement	Value	Priority	Verification
Topside primary structure static safety factor	≥ 3.0 against yield under self-weight load case	Must	FEA, Section 3.8.2
Topside primary structure deformation under self-weight	≤ 5 % of leg length at apex	Should	FEA, Section 3.8.2
Hull-level mounting interfaces (polycarbonate top plate, acrylic cross plate) static safety factor	≥ 10 against yield under self-weight load case	Must	FEA, Section 3.8.2
Padeye and lifting attachment static safety factor	≥ 5 against fastener shear under nominal lift (two-person)	Must	Hand calculation, Section 3.8.3
Mooring tether attachment quasi-static safety factor	≥ 10 against fastener shear under combined wind plus current drag	Must	Hand calculation, Section 3.8.3
Structural fasteners	M5 and M6 marine-grade stainless steel only	Must	Build inspection
Welded or adhesive structural joints	None permitted; all structural connections bolted	Must	Build inspection
Bolted joint into polymer host material	Penny washers required to spread bearing load over polymer surfaces	Must	Build inspection

A.4 Flotation and Stability

Requirement	Value	Priority	Verification
Hull buoyancy concept	Free-flooded compartment with sealed buoyant core; reserve buoyancy independent of compartment integrity	Must	Section 3.2
Buoyant core material	Closed-cell foam, non-water-absorbing, marine-rated	Must	Material data
Reserve buoyancy	≥ 50 % of fully loaded platform mass when hull compartment fully flooded	Must	Section 3.6
Failure mode on hull breach	Positive buoyancy preserved by sealed foam core; no single hull breach to cause sinking	Must	Tank test, Section 6.3
Metacentric height (small-angle stability)	Positive at loaded condition with maximum ballast	Must	Section 3.7.1, tank test
Large-angle stability	Positive righting moment for heel angles up to 60°	Should	Section 3.7.2, tank test
Self-righting	Not required; behaviour characterised in tank test	Could	Section 3.7.2

A.5 Sensing Subsystem

Requirement	Value	Priority	Verification
Acoustic sensor	Hydrophone with frequency response covering 10 Hz to 50 kHz minimum	Must	Component data sheet
Hydrophone deployment depth	Adjustable between 0.5 m and 3.0 m below hull base via tether rope length	Must	Section 3.3.3
Hydrophone strain relief	Tether rope shall carry mechanical load; signal cable shall carry signal only	Must	Build inspection
Motion measurement	3-axis acceleration and 3-axis angular rate, sampled at ≥ 50 Hz	Must	Bench test, Section 6.3

Temperature measurement	Seawater temperature, ± 1 °C accuracy minimum, range 0 °C to 35 °C	Must	Bench test
Audio capture	Minimum 48 kHz, 16-bit; target 96 kHz, 24-bit	Must	Bench test
Environmental sensor sampling rate	≥ 1 Hz nominal across IMU and temperature channels	Must	Bench test

A.6 Compute, Logging and Communications

Requirement	Value	Priority	Verification
Primary compute capacity	Sufficient for continuous audio capture , parallel logging, and concurrent telemetry tasks	Must	Bench test
Secondary microcontroller	Real-time interface for IMU and analogue sensors, independent of primary compute	Must	Bench test
Local storage capacity (data)	≥ 500 GB to accommodate continuous audio over short campaign	Must	Build inspection
Local logging integrity	All raw critical data shall be stored locally; telemetry shall not be relied upon for data recovery	Must	Bench and field test
Telemetry	4G LTE coverage where available; transmission of health and status data only	Must	Field test, Section 6.4
Positioning	GNSS position update at ≥ 1 Hz with clear sky view	Must	Field test
Telemetry availability	Operational where nearshore 4G coverage exists; no satellite backhaul required	Must	Field test
Software environment	Linux-based operating system on primary compute; documented build and deploy procedure	Must	Documentation, Section 7

A.7 Power Subsystem

Requirement	Value	Priority	Verification
Onboard energy storage	≥ 100 Wh usable energy from a single rechargeable pack	Must	Component data sheet
Battery chemistry	Non-flammable chemistry suitable for marine environment (e.g. $LiFePO_4$)	Must	Material data
Voltage rails	Stable 12 V and 5 V rails; 5 V rail capable of ≥ 3 A continuous	Must	Bench test
Continuous-operation endurance	≥ 12 hours without recharge under nominal sensing and telemetry load	Must	Power budget, Section 6.5
Duty-cycled endurance	≥ 24 hours under campaign profile using duty cycling	Should	Power budget, Section 6.5
Solar augmentation	Not required for prototype; identified as future-work item	Could	Future work, Section 7
Battery overcharge and undervoltage protection	Required and integral to the battery system	Must	Component data sheet

A.8 Environmental Protection

Requirement	Value	Priority	Verification
Electronics enclosure rating	IP68, verified by 24-hour fresh-water submersion test	Must	Section 6.3
Cable gland seal	Marine-grade glands with verified watertight seal at the cable jacket	Must	Section 6.3
Hardware exposed to saltwater	Marine-grade corrosion resistance (A4 / 316 stainless, marine-painted aluminium, or polymer)	Must	Material spec

Aluminium components in saltwater service	Protected by marine paint or marine-grade anodising; pre-deployment paint integrity inspection required	Must	Section 3.4
Polymer UV exposure	Materials selected for short-term UV stability; long-term creep / yellowing flagged as future-work concern	Should	Future work, Section 7
Biofouling protection	Not required at prototype stage; mitigated by short campaign duration	Excluded	Out of scope

A.9 Deployment and Recovery

Requirement	Value	Priority	Verification
Deployment crew	2 persons minimum, working from supervised small craft	Must	Field test, Section 6.4
Deployment time	≤ 30 minutes from craft to on station	Should	Field test
Recovery time	≤ 30 minutes from on station to craft	Should	Field test
Mooring configuration	Two-buoy (surface plus sub-surface float)	Must	Section 5.2
Lifting attachment points	Located so that the buoy can be lifted by two persons without contact with sensing hardware	Must	Build inspection
Maximum design tether load (quasi-static)	Defined by combined wind plus current drag at OE.3 and OE.4	Must	Section 3.8.3
Dynamic snatch-load handling	Managed operationally (deployment from controlled vessel) and structurally (sub-surface float in mooring line)	Must	Section 5.2

A.10 Cost and Schedule

Requirement	Value	Priority	Verification
Hardware budget (total)	≤ £2,500	Must	BOM review
Development cycle	Single academic year	Must	Schedule
Inherited platform reuse	Existing hull, top plate, bracing ring, and sensor mounts to be retained where structurally adequate	Must	Section 3.2, Section 2.2
Component sourcing	Off-the-shelf where possible; custom fabrication only where no commercial option exists	Should	BOM, Section 3.4

A.11 Modularity, Maintainability and Handover

Requirement	Value	Priority	Verification
Connection strategy	All structural connections bolted; no welded or adhesive joints	Must	Build inspection
Subsystem replaceability	Any single subsystem removable using M5 or M6 hand tools without dismantling adjacent subsystems	Must	Build inspection
Workshop manufacturability	All new components fabricable using university workshop facilities (hand cutting, drilling, bending, laser cutting, FDM 3D printing)	Must	Build record
CAD handover	Full CAD model of added subsystems delivered	Must	Documentation, Section 7
Wiring documentation	Wiring diagrams and BOM delivered	Must	Documentation, Section 7
Software handover	Code repository with build and run instructions delivered	Must	Documentation, Section 7

Test record handover	Test plans and results delivered for waterproofing, tank, and field tests	Must	Documentation, Section 7

A.12 Exclusions (Items Explicitly Out of Scope)

Item	Rationale
Offshore deployment certification	Beyond prototype envelope (Section 1.1)
Formal EMC certification	Not required for prototype validation
Satellite backhaul (Iridium, Argos)	Not within budget or scope
Certified mooring hardware specification	Mooring concept selection only (Section 5.2)
Storm and extreme-weather survivability	Beyond sea state 4 envelope
Design for manufacture and series production	Single prototype only
Biofouling mitigation system	Mitigated by short campaign duration
Long-term endurance certification (≥ 14 days unattended)	Architectural validation prioritised over endurance certification (Section 1.2)

Appendix B: Inherited Buoy Feature Audit

Feature	Status	Justification
HDPE moulded shell (D = 0.70 m, H = 0.25 m, 4 mm wall)	**Retained**	Proven flotation body from prior MECH0020 project; ~50 kg reserve buoyancy already validated. Manufacture from scratch would consume significant time and budget for no functional gain.
Free flooded internal compartment	**Retained**	Free flood architecture eliminates the need for a single large pressure boundary, which is a major waterproofing risk. Local seal failures (one IP68 box) are not catastrophic.
External 5083 aluminium bracing ring (bolted ~50 mm below flange)	**Retained**	Provides hoop stiffness to the HDPE shell at the rim where padeyes and mooring fittings load it. Removing it would require redesigning the rim attachment scheme.
Polycarbonate top plate (5 mm)	**Retained**	Provides the upper mounting surface for the tripod, navigation light, and GPS puck. FEA (Section 3.7) confirmed peak von Mises stress of 0.66 MPa, well within polycarbonate yield.
Expanded polystyrene (EPS) foam fill	**Replaced**	EPS exhibited bead shedding and water absorption in earlier testing, contaminating the surrounding water and degrading buoyancy. Replaced with Plastazote LD45 closed cell polyethylene (45 kg/m³), bespoke cut to the internal geometry to eliminate voids.
ADCP mounting bracket (below shell base)	**Repurposed**	Inherited bracket originally intended for an Acoustic Doppler Current Profiler. Repurposed as the ballast cartridge support: 12 mounting slots now hold up to 6 × 2 kg scuba weights distributed at three vertical positions, lowering the centre of gravity by 0.124 m.
Light duty mooring rope	**Replaced**	Original rope was sized for short station keeping and showed UV degradation. Replaced with heavy duty marine rope rated for sustained snatch loading observed in wave tank testing.
Mooring attachment lugs	**Replaced**	Inherited lugs were single point fastenings with marginal pull out resistance in HDPE. Replaced with 4 cast marine stainless-steel D-shackles (400 kg WLL each, ~10× design load) attached through 12 marine stainless eyebolts through bolted at the shell base.
Internal mounting plate (acrylic, central)	**Removed**	Original design relied on a single internal acrylic plate as the load path for the previous topside mast. Removed in favour of bolting IP68 enclosures and tripod legs directly to the shell base and shell flange, eliminating a fragile load bearing component.

Original sensor mounts on top plate	**Removed**	Sensor suite has changed entirely (hydrophone primary, IMU, GPS, navigation light, daymark). All mounts redesigned and remanufactured.
Tripod (3 × 7075 aluminium legs, bolted to shell flange)	**Added**	Newly designed three leg tripod to carry the mast, daymark, navigation light, and GPS puck above the waterline. Bent at Here East, painted yellow for identification and corrosion protection, with reflective tape.
Cross daymark (laser cut acrylic, 300 × 300 mm)	**Added**	Newly fabricated to meet IALA Special Mark requirements (single yellow X top mark).
Mast pole (carries cross daymark)	**Added**	Newly fabricated central pole rising above the tripod apex, sized as the minimum height for the cross to clear the buoy silhouette.
Tripod top plate (laser cut at MechSpace)	**Added**	Newly fabricated apex plate that secures the three legs and carries the mast base. Designed with multiple bolt patterns for modular future hardware.
IP68 electronics enclosure (PEBA box)	**Added**	Newly purchased and integrated. Houses the custom PCB, Arduino Nano 33 BLE Sense Rev 2, and supporting circuitry. 8 cable glands sized for 4 to 8 mm cable diameter; lid torque specified at 0.5 Nm.
IP68 battery enclosure (A19-200X15)	**Added**	Newly purchased and integrated. Houses the 12 V $LiFePO_4$ battery pack, with bare cell construction and inline fuse on the PCB.
Aquarian H2dM hydrophone	**Added**	Supplied by supervisor. Routed through a sealed hole in the shell base with strain relief loops and a supportive rope taking the mechanical load.
GPS/4G puck (combined antenna, IP66)	**Added**	Newly purchased. Mounted on the top plate above the waterline. Supplemented by a redundant internal GPS in the IP68 box and an independent waterproof external GPS as failsafe.
Navigation light (12 V, battery powered)	**Added**	Newly purchased. Mounted on the top plate to indicate buoy status. Switched via MOSFET module under PCB control.
Ballast weights (6 × 2 kg vinyl coated lead scuba weights)	**Retained**	Newly purchased. Held to the ADCP bracket by two zip ties per weight (each rated ≥10 kg, giving ≥5× over specification per weight).

Appendix C: Material Selection Table

Component	**Material**	**Reason for selection**
ADCP bracket	Aluminium 5083	Marine-grade alloy with excellent saltwater corrosion resistance and good weldability/formability; standard choice for boat hulls and submerged aluminium structures.
Tripod legs	Aluminium 7075	High strength-to-weight ratio and workshop availability; selected for structural performance over corrosion resistance (see protection strategy below).
Bracing ring (top plate)	Aluminium 5083	Marine-grade alloy with excellent saltwater corrosion resistance; provides the structural ring through which tripod and padeye loads are reacted.
Top plate of buoy	Polycarbonate	Impact-resistant, UV-stable, transparent for visual inspection of internal hardware; tougher than acrylic.
Tripod top plate	Acrylic (laser-cut)	Lower load environment than the buoy top plate; laser-cuttable on-site at MechSpace, enabling rapid iteration on the cross-mounting geometry.
Buoy shell	HDPE	Inherited; impact-, UV-, and chemical-resistant; near-neutral density in seawater.

Foam core	Plastazote (45 kg/m³)	Closed-cell, hydrophobic, retains buoyancy if the shell is breached; replaces the previous EPS core, which absorbed water over time.
Fasteners	316 stainless steel (M5/M6)	Excellent saltwater corrosion resistance; standard marine fastener grade.
Ballast	Vinyl-coated lead (scuba weights)	Off-the-shelf; vinyl coating prevents direct lead-seawater contact and avoids galvanic coupling.
Hydrophone casing	3D-printed polymer	Custom-designed casing, printed in-house; geometry detailed in Appendix.

Appendix D: Full Mass Budget and Centre of Gravity Calculation

Component	Qty	Mass (kg)	z (m)	Moment m_z (kg·m)
Tripod legs	3	1.50	0.500	0.750
Navigation light	1	0.27	0.475	0.128
Top plate of buoy	1	2.70	0.250	0.675
Cross (regulatory)	1	0.16	1.050	0.168
Pole for cross	1	0.06	0.900	0.054
Top plate (tripod top)	1	0.32	0.750	0.240
GPS puck (estimated)	1	0.10	0.250	0.025
Foam (Plastazote LD45)	—	3.50	0.125	0.438
D-shackles	4	0.36	0.000	0.000
Rope around buoy	1	0.50	0.200	0.100
Rope at base	1	0.25	0.000	0.000
Eyebolts	10	1.10	0.000	0.000
IP68 box (electronics)	1	0.67	0.070	0.047
IP68 box (battery)	1	0.52	0.070	0.036
Battery	1	1.20	0.070	0.084
Electronics inside IP68 (est.)	1	0.60	0.070	0.042
Buoy shell (HDPE)	1	5.72	0.125	0.715
Ring segments	4	2.60	0.200	0.520
ADCP bracket	1	0.64	−0.200	−0.128
Hydrophone / sensor mounts	6	0.36	−0.200	−0.072
Subtotal (no ballast)	—	**23.13**	—	**3.821**
Ballast weights (max config)	6	12.00	−0.200	−2.400
Total (max ballast)	—	**35.13**	—	**1.421**

Appendix E: Buoyancy, Draft and Freeboard Calculation

Shell internal volume (cylinder, accounting for 4 mm wall thickness):

$$V_{shell_{int}} = \pi \times (0.346)^2 \times 0.246 = 0.0925\, m^3$$

IP68 boxes (two enclosures, each ~0.20 × 0.15 × 0.10 m):

$$V_{boxes} = 2 \times 0.003 = 0.006\, m^3$$

Foam volume from measured mass and known density (45 kg/m³):

$$V_{foam} = 3.50 / 45 = 0.0795\, m^3$$

This is consistent with foam filling approximately 92% of the shell interior, with remaining volume occupied by the IP68 boxes and small voids.

$$F_b, max = \rho_w \cdot V_{buoyant} \cdot g = 1025 \times 0.0855 \times 9.81 = 859.6\, N \ (\approx 87.6\, kg)$$

$$h_{sub} = V_{disp}/A_{wp}, \ A_{wp} = \pi \times (0.35)^2 = 0.385\, m^2$$

Assumptions: Shell HDPE treated as neutrally buoyant in seawater. Submerged steel components displace only their material volume (conservative). Waterplane treated as a perfect circle at shell external radius.

Appendix F: Small Angle Stability Calculation

$$KB = h_{sub} / 2$$

$$I = \pi \times R^4 / 4 = \pi \times (0.35)^4 / 4 = 0.01178\, m^4$$

$$BM = I/V_{disp}$$

Term	Change (adding 12 kg ballast)	Effect on GM	Physical explanation
KG	−0.125 m (lowers)	+0.125 m (improves)	Ballast pulls CoG down
KB	+0.015 m (rises)	+0.015 m (improves)	More volume submerged
BM	−0.178 m (decreases)	−0.178 m (worsens)	More V_disp → smaller I/V ratio
Net ΔGM	—	**−0.038 m**	BM reduction dominates; stability is geometry-driven

Appendix G: Large Angle Stability and GZ Methodology

Numerical Model

The buoy was modelled as two buoyant volumes: the foam filled shell (cylinder D = 0.70 m, H = 0.25 m, effective buoyant volume scaled to $V_{buoyant} = 0.0855\, m^3$) and the tripod and topside hardware (0.003 m^3 centred at z = 0.65 m). Mass distribution was modelled as point masses at the positions in Appendix C. The shell was discretised into 16,000 voxels (20 radial × 40 azimuthal × 20 vertical); the tripod buoyancy as 50 voxels with small random offsets. Each voxel carries a position and a sub volume; total voxel volume sums exactly to $V_{buoyant}$ by construction.

GZ derivation at one heel angle

At heel angle θ, the voxel cloud and the centre of gravity G are rotated about the body y axis by θ. After rotation, world frame z aligns with gravity and world XY is the still water surface. Submerged voxels are identified by sorting on world frame z and selecting the lowest subset whose cumulative volume equals the equilibrium displacement:

$$V_{req} = m_{total}/\rho_{seawater} \quad (\rho_{seawater} = 1025\, kgm^{-3})$$

The centre of buoyancy is the volume weighted centroid of the submerged voxel subset:

$B(\theta) = \Sigma(v_i \cdot r_i)/\Sigma\, v_i$ *summed over submerged voxels only*

GZ is the perpendicular horizontal distance between G and the vertical line through B, taken in the world frame:

$$GZ(\theta) = B_x - G_x$$

Sign convention: positive GZ corresponds to a restoring moment toward upright (B displaced toward the heeled side, producing a couple that rotates the buoy back); negative GZ corresponds to a capsizing moment toward inversion. The angle of vanishing stability (AVS) is the first zero crossing of GZ after the peak, beyond which GZ is negative, and the buoy will continue to overturn if disturbed.

Assumptions

Rigid body in still water; free surface and dynamic wave effects neglected. Foam treated as part of the buoyant envelope, justified by closed cell composition and bespoke fit. Initial GM recovered from the small angle slope (GZ → GM·sinθ as θ → 0) agreed with the Section 3.7.1 metacentric value within 14%. The discrepancy is attributable to the metacentric formula assuming a prismatic vertical walled body whereas the voxel model tracks the true wetted geometry as the buoy heels.

Results

Tabulated GZ values at 15° intervals for the three configurations analysed in Section 3.7.2:

θ (°)	GZ no ballast (mm)	GZ max ballast (mm)	GZ extended bracket (mm)
0	2	0	0
15	84	84	102
30	108	149	183
45	95	161	209
60	57	149	208
75	10	122	188
90	−40	89	157
105	−54	84	150
120	−58	40	99
135	−91	−6	43
150	−102	−38	−4
165	−84	−29	−12
180	−12	−8	−8

Table F.1: Computed GZ(θ) at 15° intervals across the full heel range for three ballast configurations.

Appendix H: Wind Heeling Calculation Detail

Drag coefficient $C_d = 1.2$, taken as a conservative value for the mixed mast, plate, and cylinder geometry presented to the wind. Air density $\rho_{air} = 1.225\ \mathrm{kg/m^3}$ at standard atmospheric conditions. All component areas are projected perpendicular to the incident wind.

Component projected areas

The bar chart in Figure 3.5 is built from the following geometry:

Component	Source	Area no ballast (cm²)	Area max ballast (cm²)
Shell freeboard	0.70 m × freeboard height	1337	1127
Tripod legs	3 legs, exposed length above shell top, projection cos(30°)	181	181
Mast	Cylindrical pole, length above tripod apex	262	262
Cross / daymark	0.30 × 0.30 = 0.09 m² (laser cut acrylic, Appendix B.4.2)	900	900
Nav light	Manufacturer datasheet projection	96	96
GPS puck	Manufacturer datasheet projection	79	79
Total A	—	2855	2645

Effective windage centroid height h_c

Computed as the area weighted average of each component centroid height above the still water surface, $h_c = \Sigma(A_i \times z_i, wl)/\Sigma A_i$, this gives $h_c = 0.475\ m$ (no ballast) and $h_c = 0.482\ m$ (max ballast). The cross/daymark contributes 65% of the total moment despite being 31% of the total area, due to its mounting height of approximately 0.99 m above the waterline.

Limiting wind speed

At the stability limit the wind heeling moment equals the peak righting moment from the GZ curve (Appendix F):

$$F\_wind \cdot h_c = m \cdot g \cdot GZ_{max}$$

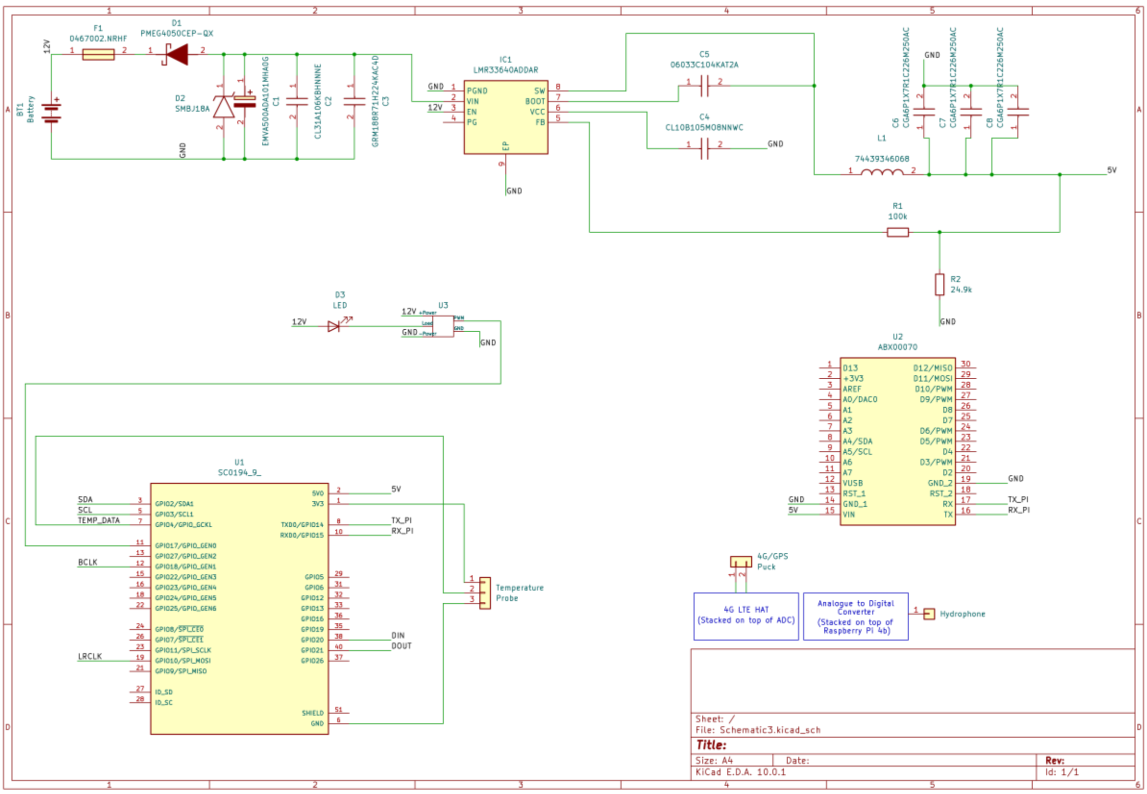
Solving for v from $F_{wind} = ½ \cdot C_d \cdot \rho_{air} \cdot A \cdot v^2$ gives:

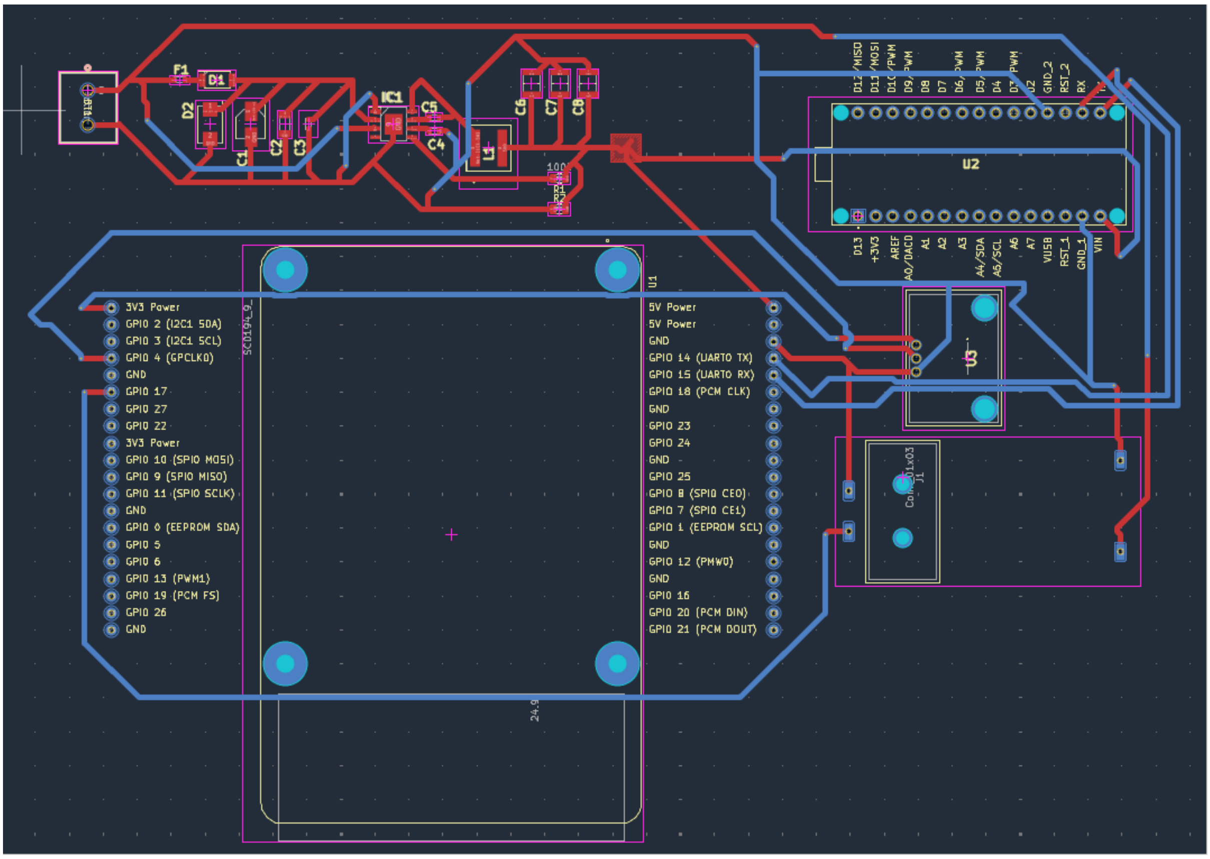
$$v\_limit = \sqrt{2 \cdot m \cdot g \cdot GZ_{max}/(h_c \cdot C_d \cdot \rho_{air} \cdot A)}$$

Substituting the values for each configuration:

Quantity	**No ballast**	**Max ballast**
Mass m (kg)	23.13	35.13
Peak GZ (mm) at angle	108 at 30°	161 at 45°
Peak righting moment m·g·GZ (N·m)	24.5	55.5
Windage centroid h_c (m)	0.475	0.482
Total projected area A (m²)	0.2855	0.2645
Limiting wind speed v_limit (m/s)	15.9	24.7

Appendix I: Circuit Schematic and PCB Layout





Appendix J: Future Work Register

Item	Addresses	Proposed work	Priority
Operational reliability, closes known prototype weaknesses			
LTE recovery automation	Manual pwrkey press required to re register the modem after brownout or restart.	Add an automatic LTE recovery circuit so the modem re registers after power interruption without manual intervention. Bench validate over multiple forced brownout cycles.	**High**
GNSS antenna relocation	GPS reliability issues observed during testing, attributable to limited sky view from the current internal antenna position.	Relocate the antenna externally above the top plate. Repeat static land tests, moving land tests, and coastal tests before relying on live position data.	**High**
Hydrophone gain configuration	Analogue gain currently insufficient for lower level ambient noise; signal sits close to the digitiser noise floor.	Reconfigure the ADC gain stage, repeat the tank reference recording, and confirm the signal sits clearly above the noise floor. Likely a configuration fix rather than a redesign.	**Medium**
Extended deployment readiness, required before any deployment longer than the Brighton trial			
Power autonomy upgrade	Current battery configuration is sized for short attended deployments and does not meet the original long duration ambition (Section 3.6 power budget).	Validate a longer endurance configuration using either additional $LiFePO_4$ capacity within the existing enclosure or a duty cycled operating mode for the Raspberry Pi, hydrophone, and telemetry. Confirm via continuous bench runtime test before any field deployment.	**High**
Longer field deployment	Brighton trial demonstrated operational behaviour over a few hours, not long term reliability.	Conduct a 24 to 72 hour field deployment to validate endurance, waterproofing, telemetry reliability, thermal behaviour, and data integrity under realistic conditions.	**High**
IMU calibration against wave reference	IMU outputs are currently indicative; wave period and amplitude estimates	Calibrate the IMU pipeline against a wave gauge, calibrated video, or known tank	**Medium**

	are not verified against an independent reference.	input so that wave statistics can be treated as verified measurements.	
Tripod material upgrade	7075 aluminium is acceptable for the prototype but corrodes preferentially in seawater compared with marine grades (Section 3.7 material discussion).	Remake tripod legs in 5083 marine grade aluminium for longer unattended deployments. Inspect alongside the lower bolt hole region identified by FEA as the critical stress location.	**Medium**
Design refinements, improve the design but do not block deployment			
Domed top plate for full self righting	Flat top plate creates a stable inverted equilibrium; angle of vanishing stability is 133° rather than 180° (Section 3.7, Appendix F).	Replace the flat top plate with a domed or curved upper surface to eliminate the stable inverted condition. Verify through updated GZ analysis and repeated inversion testing.	**Medium**
Adjustable hydrophone depth	Hydrophone depth is currently fixed by cable length; changing depth requires modifying cable routing.	Add a simple manual depth adjustment using a marked line, cleat, or indexed attachment points. A motorised solution is not justified at this stage.	**Low**

Appendix K: IMU Dynamic Response

The BMI270 was logged at about 10 Hz over runs of 60 to 120 s. Each record was trimmed to its steady section to remove wavemaker start-up and shutdown transients, and the acceleration was projected onto the mean-gravity direction. A Welch PSD with roughly 25 s segments (frequency bins about 0.04 Hz wide) identified the detected peak frequency and its signal-to-noise ratio. Heave amplitude was estimated from the fitted acceleration amplitude via $x = \frac{a}{(2\pi f)^2}$.

Predicted heave natural frequency. In heave the buoy behaves as a single-degree-of-freedom mass-spring system with hydrostatic restoring stiffness set by the waterplane area:

Where ρ is the water density, A_w the waterplane area, and m_{eff} the buoy mass plus the added mass of water.

With $\rho = 1000\text{kg} / \text{m}^3$, $A_w = 0.385\text{m}^2$ and a buoy mass of 35 kg, the stiffness is about 3.8 kN/m. Ignoring added mass gives an upper bound of 1.65 Hz; including added mass of 50 to 100% of the buoy mass lowers this to 1.35 to 1.17 Hz. The expected heave resonance therefore lies between roughly 1.2 and 1.7 Hz, just above the observed response peak near 1 Hz, as expected once damping is included. A fixed heave amplitude produces an acceleration that scales with f^2. A 0.04 m heave generates only about 0.05 g at 0.55 Hz but about 0.47 g at 1.70 Hz. At the lowest frequencies the acceleration signal is small, which weakens the amplitude estimate even where the frequency peak is sharp.

Wave conditions for Test 1 to 9:

Test	Commanded f (Hz)	Detected f (Hz)
1	still water	—
2	0.55	0.53
3	0.70	0.70
4	1.00	1.00
5	1.15	1.07
6	1.30	1.17
7	1.45	1.30
8	1.70	1.60
9	1.00 (0.08 m amp)	1.00

Appendix L: Generic Risk Assessment for UCL Towing Tank

Reference: RA108558/1
Status: Authorised

Reference	RA108558/1
Status	Authorised

Summary

Date Created	13/03/2025	**Confidential?**	No
Start Date	14/03/2025	**End Date**	14/03/2026

Assessment Title:

Generic Risk Assessment for UCL Towing Tank

Assessment Outline:

The UCL Towing Tank is used for teaching and research purposes. This risk assessment will consider the typical activities, hazards and controls adopted to ensure they are run safely.

Area Responsible (for management of risks)		**Location of Risks**	
Division, School, Faculty, Institute:	Faculty of Engineering Sciences	**On/Off Site:**	On-Site
Department:	Dept of Mechanical Engineering	**Building:**	Roberts Building
Group/Unit:	All Groups/Units	**Area:**	Basement
		Sub Area:	Laboratory

Further Location Information:

Towing Tank in the Fluids Lab Sub Basement Roberts Building LB08

Filename	Category	File size	Date uploaded
RA_chlorine.pdf	Maps, Diagrams & Photographs	109285	13/03/2025

Description of attachments	For the cleaning operations and maintenance of the Ocean tank, Risk Assessment RA098432/1 is attached. This latter document is only relevant to members of the technical teams, and not to researchers / users.
Location-non-electronic-documents	Ocean Water tank, main cabinet.

Assessor(s)	**Approver(s)**
Grande, Davide	GILES THOMAS
GRECH LA ROSA, ANDREA	

Authorised By	**Date**
GILES THOMAS	14/03/2025 13:58

none

Assessor Safety Competence			
Team Leader			
Reason For Review Type		**Reason For Review**	

Appendix M: Wave Tank Test Plan

Test Plan

Wave Tank Characterisation of Autonomous Coastal Buoy Prototype

UCL Mechanical Engineering Fluids Laboratory, Ocean Towing Tank

Field	Value
Document ID	MECH0073-TP-WT-001
Revision	v1.0
Date of test	24/04/2026
Test facility	UCL Fluids Lab, Ocean Towing Tank
Test article	Integrated buoy prototype (RPi 4 stack + Arduino Nano 33 BLE + Aquarian H2DM)
Related requirements	R-01, R-04, R-05, R-08, R-10
Predecessor evidence	MECH0020 tank tests (2024 to 2025): natural frequencies identified at 1.13, 1.45, 1.68 Hz

1. Purpose and Scope

This test plan governs a single controlled-wave session of the integrated buoy prototype in the UCL Fluids Lab Ocean Towing Tank. The session is part of the staged verification and validation work. It provides primary evidence against requirements R-01 (flotation and stability), R-04 (integrated IMU / hydrophone / temperature logging), R-05 (hydrophone self-noise), R-08 (power subsystem behaviour under prototype operating mode), and R-10 (staged validation evidence).

The scope of this plan is limited to characterising how the as-built buoy responds to known wave excitation and how the onboard sensing and logging chain performs simultaneously. It does not cover field deployment, long-endurance autonomy, mooring validation, or ecological acoustic interpretation. Those items remain in the downstream validation work.

2. Objectives

The session pursues six objectives. Each is independently measurable and each maps to a distinct analysis output in Section 8.

O1. Frequency response characterisation

Identify the buoy's natural frequencies in heave, pitch, and roll from regular-wave runs at multiple excitation frequencies, and compare against the predecessor prototype's values of 1.13, 1.45, and 1.68 Hz. A shift in any mode indicates that the modified mass distribution, ballast placement, or suspended-sensor load has measurably changed the hydrodynamic behaviour of the platform.

O2. Sea-state retrievability from IMU

Confirm whether the onboard IMU and downstream processing pipeline can recover wave peak period Tp and significant wave height Hs from accelerometer time series under irregular (JONSWAP) excitation. This directly tests the short-term sea-state estimation claim scoped for the final report and bounds the tolerance within which the IMU alone can be trusted as a wave sensor.

O3. Motion-acoustic correlation

Quantify how hydrophone noise level and spectrum vary with wave amplitude and frequency. The specific hypothesis to be tested is that wave-induced acoustic noise scales with heave acceleration RMS. The outcome supports interpretation of future field hydrophone data, where wave-driven noise is expected to be a major confounding term.

O4. Resonance assessment against realistic sea-state bands

Test whether the buoy's dominant natural frequencies fall inside the energy bands of realistic deployment seas. Typical North Sea wind-sea peak periods correspond to frequencies of approximately 0.1 to 0.3 Hz; a natural heave frequency well above this band is acceptable, one close to or below it is a design concern. This objective reuses the data produced by O1 and is treated as an interpretation step rather than a separate trial.

O5. IMU-derived wave-period tolerance

Establish an error bound between IMU-derived wave period and the paddle's commanded period across the regular-wave sweep. This is the engineering quantity that determines whether the IMU can be deployed as a standalone short-term wave sensor or only as a supporting channel for acoustic interpretation. This objective reuses the regular-wave data produced by O1 and is treated as a separate analysis step.

O6. Paddle and pump machinery noise characterisation
Document the tank's own acoustic signature so that wave-induced hydrophone results can be cleanly caveated. Paddle and pump machinery are expected to dominate the hydrophone spectrum at tank scale. The objective here is to identify which spectral features originate from the facility rather than from the buoy's hydrodynamic interaction with the wave field.

3. Test Article and Instrumentation

3.1 Buoy platform

The test article is the integrated coastal buoy prototype in its deployment configuration: ballast installed per specification, waterproof enclosure sealed, antennas mounted, suspended hydrophone and temperature probe fitted beneath the hull on the underside rope. The only deviation from field configuration is the use of bench power or a fully charged 12 V 10 Ah battery (see Section 4).

3.2 Onboard instrumentation and data rates

Channel	Sensor	Host	Rate / format	Storage path
Linear acceleration (3-axis)	BMI270 accel	Arduino Nano 33 BLE Sense Rev 2	104 Hz, ±4 g	Pi SSD via serial log
Angular rate (3-axis)	BMI270 gyro	Arduino Nano 33 BLE Sense Rev 2	104 Hz, ±2000 dps	Pi SSD via serial log
Magnetic field (3-axis)	BMM150	Arduino Nano 33 BLE Sense Rev 2	20 Hz, ±400 µT	Pi SSD via serial log
Enclosure temp / humidity	HS3003	Arduino Nano 33 BLE Sense Rev 2	1 Hz	Pi SSD via serial log
Hydrophone audio	Aquarian H2DM → HiFiBerry DAC+ADC	Raspberry Pi 4B	96 kHz, 32-bit, WAV	Pi SSD /mnt/harddrive/audio/
Water temperature	DS18B20 (1-Wire on GPIO 4)	Raspberry Pi 4B	1 Hz	Pi SSD /mnt/harddrive/env/
System power	FNB58 USB tester inline at Pi input	Laptop via FNB58 software	1 Hz, V / I / P	Laptop (export to CSV post-test)

3.3 Facility-side instrumentation

- Wave paddle controller: commanded frequency, amplitude, and wave type recorded per trial.
- Wave probe(s): surface elevation time series, if available. This is the authoritative input reference for post-test analysis.
- Qualisys motion capture: optional, used only if reflective markers can be fitted without compromising buoy mass distribution or waterproofing.
- External video reference: smartphone on tripod, side-on to the tank, continuous recording throughout the session. Free visual ground truth for heave and pitch.

4. Test Setup

4.1 Physical configuration

The buoy is placed in the Ocean Towing Tank with its principal axis of symmetry vertical in still water. Two slack restraint lines are attached between the buoy and the tank rails on opposite sides to prevent drift into the tank walls; these lines must remain slack throughout each trial to avoid contaminating the motion signal. The wave propagation direction and the IMU axis convention are fixed at the start of the session and photographed; this photograph is a required output (see Section 10).

4.2 Axis convention

The following right-handed convention is used throughout the session. It must be recorded by photograph before the first trial.

Axis	Direction on buoy	Primary motion captured
X (surge)	Horizontal, aligned with wave propagation direction	Surge (forward/aft motion along wave travel)
Y (sway)	Horizontal, perpendicular to wave propagation	Sway (lateral motion)
Z (heave)	Vertical, positive upward	Heave (vertical motion)

Rotational conventions follow the same axis set: roll about X, pitch about Y, yaw about Z.

4.3 Power

The session is conducted on bench power via the FNB58 USB tester, not on battery, for two reasons. First, it removes any ambiguity from battery state-of-charge during the session. Second, the FNB58 inline measurement is the intended method for refining the 10-day battery budget; operating on bench power with continuous logging yields a directly usable wet-operation watts figure. A fully charged 12 V 10 Ah battery is on standby as a backup power source and for any end-of-session battery-powered verification run if time permits.

4.4 Time synchronisation

The Raspberry Pi system clock and the Arduino log start are not inherently synchronised, and cross-sensor analysis depends on a reliable time alignment. At the start of each trial the operator performs an audible sync event by tapping the top of the enclosure once, firmly. This event is visible in both the accelerometer trace (transient on the Z-axis) and the hydrophone trace (sharp broadband click) and is used during post-processing to align the two time bases. A second sync tap is performed at the end of each trial to bound the alignment.

5. Test Matrix

The matrix is executed in the order listed. Earlier baselines are essential: the still-water ambient trial defines the acoustic and motion noise floor against which all wave trials are interpreted.

Trial ID	Type	f_0 / fp [Hz]	Amp / Hs [m]	Record duration	Notes
0.1	Dry bench check	—	—	60 s	Lab, before transport. Confirm all channels log.
1.1	Ambient, still water	—	—	120 s	Buoy in tank, paddle off, pumps off. Acoustic and motion noise floor.
1.2	Paddle motor idle	—	—	60 s	If facility can hold paddle stationary with motor energised. Isolates motor tonal signature.
2.1	Regular sine	0.40	0.04	90 s	Below expected resonance band.
2.2	Regular sine	0.55	0.04	90 s	Matches MECH0020 low-frequency trial.
2.3	Regular sine	0.70	0.04	90 s	Matches MECH0020 mid-frequency trial.
2.4	Regular sine	0.85	0.04	90 s	
2.5	Regular sine	1.00	0.04	90 s	
2.6	Regular sine	1.15	0.04	90 s	Near predecessor ω_1 = 1.13 Hz.
2.7	Regular sine	1.30	0.04	90 s	
2.8	Regular sine	1.45	0.04	90 s	Near predecessor ω_2 = 1.45 Hz.
2.9	Regular sine	1.60	0.04	90 s	
2.10	Regular sine	1.70	0.04	90 s	Near predecessor ω_3 = 1.68 Hz.
2.11	Regular sine	1.90	0.04	90 s	Above expected resonance band.
3.1	JONSWAP irregular	0.70 (fp)	Hs = 0.04	300 s	Matches MECH0020 low-peak spectrum.
3.2	JONSWAP irregular	1.30 (fp)	Hs = 0.04	300 s	Matches MECH0020 high-peak spectrum.
4.1	Linearity check (optional, time-permitting)	1.15	0.02	90 s	Half-amplitude repeat near resonance.

Trial ID	Type	f_0 / fp [Hz]	Amp / Hs [m]	Record duration	Notes
4.2	Linearity check (optional, time-permitting)	1.15	0.06	90 s	1.5× amplitude repeat near resonance.
5.1	Post-test ambient	—	—	60 s	Repeat of 1.1. Checks for drift in hydrophone self-noise over the session.

Between trials, the tank is allowed to settle for at least 2 minutes or until visual surface motion is negligible, whichever is longer. Regular-wave trials must further observe a run-up period of approximately 30 s after paddle initiation before the recorded window is considered steady-state; analysis will discard the first 30 s of each regular-wave record.

6. Data Management

6.1 File naming convention

All files use a single convention so that post-session sorting and cross-channel alignment are trivial.

Format: TK_YYYYMMDD_TRIALID_CHANNEL_params.ext

- TK indicates tank test (distinguishes from bench and field datasets).
- YYYYMMDD is the session date.
- TRIALID matches the Trial ID column in the test matrix (e.g., 2.6).
- CHANNEL is one of: HYD (hydrophone), IMU (Arduino log), TMP (DS18B20), PWR (FNB58 export), VID (phone camera).
- params encodes the wave parameters where relevant, e.g. f115Hz_A04mm for 1.15 Hz / 0.04 m amplitude.
- Example: TK_20260424_2.6_HYD_f115Hz_A04mm.wav

6.2 Run sheet

A paper run sheet is maintained alongside the digital logs. One row per trial. Minimum columns: Trial ID, start time (HH:MM:SS), commanded frequency, commanded amplitude, duration, hydrophone filename confirmed (Y/N), IMU filename confirmed (Y/N), sync tap performed (Y/N), tank condition, anomalies. The run sheet is photographed at end of session and included in the evidence pack.

6.3 Backup

Before leaving the facility, all session data is copied from the Pi SSD to a laptop. The SSD is not reformatted on site. A second copy is made to a separate external drive or cloud location within 24 hours. The evidence pack is not considered safe until it exists in at least two independent physical locations.

7. Success Criteria

The session is considered successful if all of the following are true at end of session.

- All four primary data streams (IMU, hydrophone, DS18B20, system power) logged without dropout for at least 80% of the planned wave trials (2.1 through 3.2).

- At least one pronounced resonance peak is identifiable in the heave acceleration spectrum across the regular-wave sweep.
- At least one JONSWAP trial yields an IMU-derived peak period within ±10% of the commanded peak period.
- Sync-event taps are identifiable in both accelerometer and hydrophone channels for every wave trial.
- Post-session interior enclosure inspection shows no liquid water ingress and no new corrosion on connectors.
- Run sheet is complete; file manifest reconciles with run sheet with no missing channels.

Partial success is acceptable but must be documented: a failed trial is data, not a disaster, provided the failure mode is identified and noted in the run sheet.

8. Risks and Mitigations

Risk	Likelihood	Consequence	Mitigation
Enclosure seal failure causing interior wetting	Medium, prior test failed on this item	Loss of electronics; data unrecoverable for affected trials	Torque check on all fasteners pre-session; 3:1 heat-shrink on cable exits confirmed; exterior inspection every four trials; no mid-session opening
Cable snag on paddle or tank rails	Low	Mechanical damage to hydrophone cable or connector	Slack restraint lines kept clear of paddle zone; hydrophone cable routed along underside rope and photographed before launch
Pi clock and Arduino log drift, breaking cross-sensor alignment	High if not actively managed	Analysis for O3 (motion-acoustic correlation) invalidated	Sync-event tap at start and end of every trial; post-session alignment using these events
Reflected waves contaminating regular-wave trials	High, inherent to closed-tank geometry	Natural-frequency peaks obscured by standing-wave components	Discard first 30 s of each regular-wave record; keep recorded window to 60 s of steady-state data; settle tank for at least 2 minutes between trials
Paddle motor tonal noise dominating hydrophone	High, expected	Misinterpretation of tonal features as buoy-origin	Explicit paddle-motor-idle baseline trial (1.2); objective O6 treats this as a characterisation task rather than a problem to eliminate
SSD dismounts under sustained high-rate writes	Low but observed during bench integration	Loss of hydrophone data for affected trial	Confirm mount with findmnt at start of session and after every four trials; verify free space; do not rely on post-trial file list without checking file size
Battery or bench power interruption	Low	Partial trial loss	Bench power with FNB58 inline; battery on standby; Pi left running between trials to avoid boot-time sensor re-initialisation

Risk	Likelihood	Consequence	Mitigation
Qualisys markers compromising waterproofing or mass distribution	Medium if used	Bad waterproofing is worse than no Qualisys data	Qualisys is optional; only fit markers if they can be attached without hull penetration or significant mass change

Appendix N: Plan for Field Deployment Test (Brighton)

FIELD TEST PLAN v4

Boat-deployed Validation Test of Coastal Monitoring Buoy Prototype

UCL Mechanical Engineering MEng Group Design Project

Project	UCL MEng Group Design Project, Coastal Monitoring Buoy
Document version	v4
Test date	Friday 1 May 2026
Location	Brighton Marina, BN2 5UP, boat-deployed test, 100 to 200 m offshore
Test type	Boat-deployed, tethered nearshore validation and stress test
Estimated duration	Full day (~9 hours UCL-to-UCL); 2-hour boat hire window
Team members	Priestly Adejo and four project team members (names removed from public copy)
Boat operator	Licensed skipper hired with the boat (commercial small craft operator)
Supervisor	Andrea Grech La Rosa
PGTA	Vedika
Stakeholder	Helen Czerski

1. Summary and Changes from v2

This v3 plan supersedes the v2 plan. The two key changes are: (a) the test location has moved from Southend-on-Sea to Brighton Marina, and (b) the deployment method has changed from a shore-based, wading-and-tether approach to a boat-deployed test 100 to 200 m offshore using a hired small boat with a licensed skipper. The buoy will be deployed on a primary safety tether to the boat plus a secondary working line tended by a team member.

The change in deployment method introduces additional risks (boat operations, line handling on a moving platform, recovery in open water) and additional requirements (skipper briefing, lifejackets for all on-water personnel, VHF/comms). These are addressed in sections 6, 8 and 11.

Summary of changes from v2

- Location: Southend-on-Sea → Brighton Marina
- Date: 30/04/2026 → Friday 01/05/2026
- Deployment method: shore-based wading with single tether → boat-deployed with controlled tether
- Boat operator added: licensed skipper hired with boat
- New section 7: Boat operations and on-water safety
- New section 8: Roles and responsibilities (named)
- New section 9: Risk register (likelihood × severity × mitigation × owner)
- New section 11: Emergency procedures and contacts
- Site map and photo placeholders added (per Helen's review)

2. Test Objective

This test evaluates the buoy prototype as an integrated system in a real coastal environment, deployed from a boat 100 to 200 m offshore of Brighton Marina.

The test will assess whether the buoy:

- remains stable in natural nearshore wave conditions
- can be deployed and recovered safely from a small boat using the controlled tether arrangement
- retains a functional onboard electrical system through transport, deployment, and recovery
- achieves and maintains GPS lock in open coastal conditions
- maintains reliable 4G connectivity at deployment range
- captures usable hydrophone and temperature data in the field
- communicates correctly with the dashboard monitoring system
- survives the test mechanically with no significant water ingress or component loosening

This is a controlled validation and stress test. The buoy is tethered at all times and is never released free. The test is intended to represent the closest practical version of the final coastal use case within a safe 2-hour boat window.

3. Description of Test Article

The test article is a prototype coastal monitoring buoy designed for environmental sensing and remote data communication. The configuration tested is the integrated prototype as it stands following lab validation.

Major subsystems

- Floating buoy body with internal/external ballast
- Mast / mounting structure
- Onboard electrical system with battery and isolator

- IMU-based motion sensing
- GPS module
- 4G communication module
- Hydrophone
- Temperature sensor
- Dashboard communication interface

Photographs of the test article

Figure 1: Fully assembled buoy prototype prior to deployment

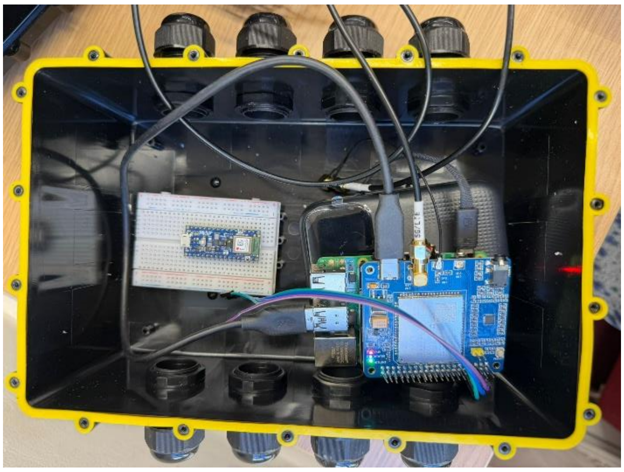


Figure 2: Internal electronics enclosure showing battery, IMU and comms modules

4. Equipment

Buoy and test equipment

- Buoy prototype (charged, sealed, pre-test inspected)
- Primary safety tether (rated, length sufficient for 200 m + boat freeboard, with thimble and shackle)
- Secondary working line (tended hand line, with cleat-attachment)
- Spare line and shackle

Documentation and monitoring

- Laptop / tablet for dashboard monitoring (charged, with mobile data backup)

- Phone with mobile data, secondary dashboard
- Camera and/or phone for photo and video documentation
- Printed copy of this test plan (waterproof sleeve)

Lifejackets / buoyancy aids are provided by the skipper / boat operator and worn by all personnel on the boat.

Safety equipment (mandatory)

- First aid kit
- Emergency contact list (this document)
- Fire extinguisher on the boat (provided with hire)
- Marine VHF radio on the boat (provided with hire)
- Mobile phones (charged, in waterproof cases)
- Thermal layers and dry kit (spare set, kept ashore)

Transport

- Car to Brighton
- Boat to testing location

5. Site Description: Brighton Marina

Brighton Marina (BN2 5UP) is the UK's largest marina, operated by Premier Marinas. It comprises an inner locked harbour and an open outer harbour with 24-hour access to open water between two breakwater arms. The dredged entrance channel is marked by red and green channel buoys. An RNLI inshore lifeboat is stationed on the west quay.

The deployment zone is 100 to 200 m south of the harbour entrance, in open water beyond the breakwaters but well within sight of the marina.

Site contact details: Brighton Marina office, 01273 819919, VHF Channel 37 or 80.

Why this site

- Sheltered approach via the marina; rapid recovery option
- RNLI inshore lifeboat co-located on west quay
- Premier Marinas operates a professional, contactable harbour office
- Open water access without crossing a lock
- Out of bathing water and main swimming areas

Local hazards to note

- In strong south-easterly winds the entrance becomes impassable, see go/no-go criteria
- Lobster pots inshore to the east of the marina, keep deployment to the south of the entrance
- Shoaling near the eastern breakwater between dredges; channel must be followed
- Marina internal speed limit is 8 knots; traffic in the entrance channel must be respected

Site map

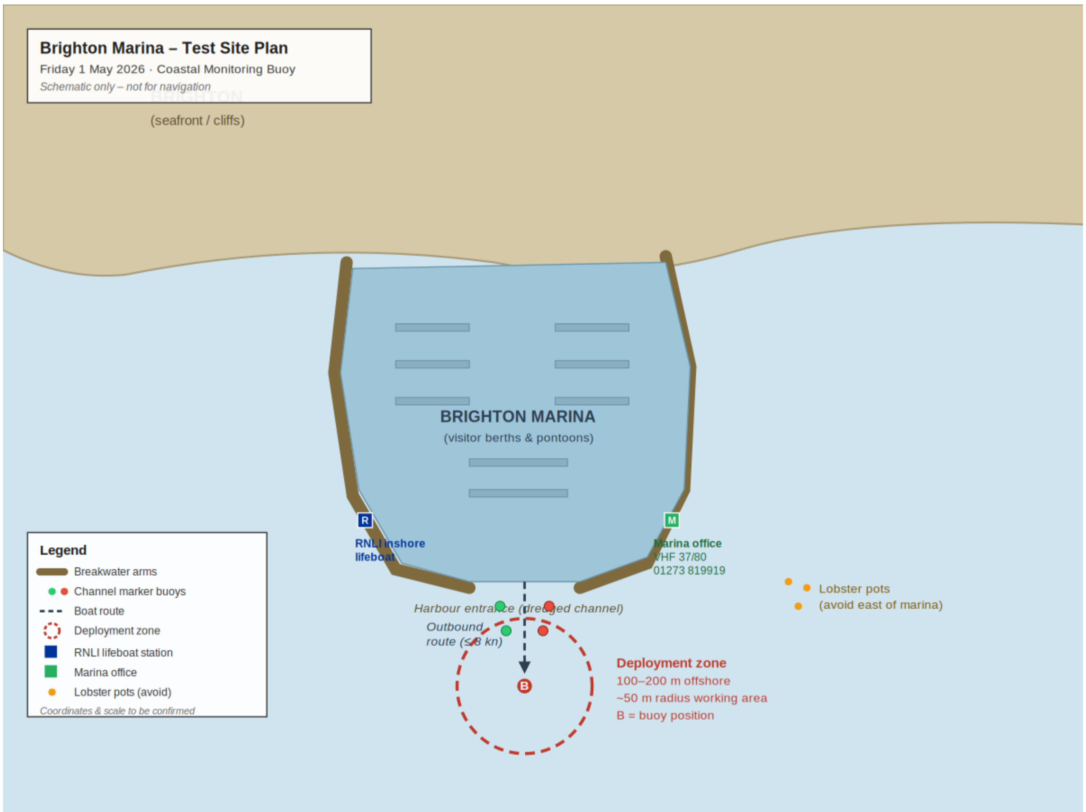


Figure 3: Schematic of Brighton Marina, planned route, and 100 to 200 m deployment zone south of the breakwater entrance. Schematic only, not for navigation.

6. Go / No-Go Criteria

Test will only proceed if all the following criteria are met. The Test Coordinator and Skipper jointly have authority to abort or postpone.

Parameter	Go criterion	No-go / abort if
Wind	≤ Force 4 (≤ 16 kn) sustained, gusts ≤ 20 kn	Sustained > Force 4, gusts > 20 kn, or southerly gale forecast (Brighton entrance is impassable in SE gales).
Sea state	Slight to moderate (≤ 1.25 m significant wave height)	Moderate-rough or above; breaking waves at marina entrance.
Visibility	≥ 1 km, daylight throughout test window	Fog warning active, marina fog horn sounding, or visibility < 1 km.
Tide	Within ±2 hours of high water for the deployment window (verify on day)	Test cancelled if deployment would fall on or near low water springs (entrance shoaling risk).
Weather warning	No active Met Office yellow/amber/red warning for the area	Any active warning issued for wind, rain, thunderstorms or coastal.

Parameter	Go criterion	No-go / abort if
Team	All key roles present and briefed	Any of: skipper, test coordinator, electronics lead, deployment lead absent.
Equipment	Buoy passes pre-departure functional check; both tethers intact	Failure of any safety-critical item: tether, lifejacket, communications.
Marina advisory	Marina office confirms entrance is open and no advisories	Marina advises against departure for any reason.

Forecast and tide check times: (a) evening before the test (final-go review), (b) morning of the test before departure from UCL, (c) on arrival at Brighton Marina before boarding the boat. Tide times to be confirmed via the Premier Marinas Brighton Marina tide page on the day.

7. Boat Operations and On-Water Safety

This section describes how the test team operates as a unit on the hired boat, alongside the licensed skipper. The skipper has sole authority over boat handling and safety on the water; the team follows the skipper's instructions at all times.

7.1 Boat hire

- Vessel: small leisure boat (~5 to 7 m, suitable for 8 persons excluding skipper), hired locally at Brighton Marina
- Operator: licensed skipper supplied with the hire
- Hire window: 2 hours, scheduled to start at approximately 11:00
- Insurance and competence: covered under the hire company's commercial operating arrangements

7.2 Personal safety on the boat

- Follow Skippers direct instructions
- Phones in waterproof cases or pockets that close

7.4 Deployment procedure (boat-side)

The buoy is deployed only when the boat is on station, engine in neutral or off, and a 360° visual scan has confirmed no other vessel or water user is within 50 m.

- **Step 1:** Skipper brings boat to deployment position. Engine to neutral.
- **Step 2:** Electronics Lead confirms buoy is powered, dashboard receiving data, GPS lock acquired.
- **Step 3:** Deployment Lead confirms primary tether is cleated to the boat and the working line is belayed (not held bare-handed) through gloves.
- **Step 4:** Skipper confirms engine off / neutral and area clear.
- **Step 5:** Buoy is lowered (not thrown) over the side opposite the outboard. Two team members for the lift.
- **Step 6:** Lines are paid out gradually. Working line tender keeps slight tension; primary line slack (it is the safety line, not the working line).
- **Step 7:** Skipper resumes minimal way to hold position downwind of the buoy. Observation period begins.

7.5 Recovery procedure (boat-side)

- **Step 1:** Skipper brings boat onto a slow approach upwind of the buoy.
- **Step 2:** Engine to neutral when within ~10 m of the buoy.
- **Step 3:** Working line is recovered first (hand-over-hand, gloved); buoy is brought alongside on the deployment side.
- **Step 4:** Two team members lift the buoy aboard. Primary tether is cast off only after the buoy is on board.
- **Step 5:** Engine remains off until all lines and the buoy are clear of the water and the side of the boat.

7.6 Abort and emergency-stop procedure

- Anyone (team member, skipper, or shore) may call "ABORT" at any time
- On abort: stop the operation in progress, stabilise the buoy and lines, await skipper instruction
- If person enters water: skipper takes over completely; team follows MOB procedure as briefed by skipper
- If line snags propeller: engine immediately off; skipper uses line cutter; do not put hands near prop while line is under tension
- If buoy malfunctions (smoke, fire) on boat: power isolator off; move buoy to side; ready fire extinguisher; if uncontrollable, jettison overboard while still tethered (it is recoverable later) and run for marina

8. Roles and Responsibilities

Roles are assigned in advance. A team member may not switch roles during the test without explicit handover.

Role	Assigned to	Responsibilities on the day
Test Coordinator	Project team member	Overall coordinator. Owns the go/no-go decision with the skipper. Holds the test plan and ensures the team follows the planned validation and stress-test sequence.
Skipper	[hired with boat]	Sole authority on boat operations. Final say on weather, sea state, and any decision to return to harbour. Briefed on test plan beforehand.
Deployment Lead (on boat)	Project team member	Executes the deployment and recovery procedure. Tends the working line. Communicates with skipper.
Electronics / Software Lead (on boat)	Project team member	Powers up the buoy. Confirms IMU, GPS, 4G, hydrophone, temperature sensors are operating before deployment.
Dashboard / Data Operator (on boat)	Project team member	Monitors the dashboard from the boat. Logs receipt times, dropouts, and any anomalies. Confirms whether data are live-streamed or only stored onboard.

Role	Assigned to	Responsibilities on the day
Documentation / Photo Lead	Priestly Adejo	Records timed observations, takes photos and video, completes the data sheet. Records any deviations from the plan.

9. Risk Register

Likelihood (L) and Severity (S) are scored as L = Low, M = Medium, H = High, based on residual risk after mitigation. Items rated High likelihood × High severity after mitigation would prevent the test from going ahead, none of the items below are scored at that level after mitigation.

Risk	L	S	Mitigation	Owner
Team member injured during transport / loading of buoy	L	M	Use correct manual handling technique; minimum 2 people for any lift; secure load with straps in van; inspect for sharp edges before handling.	All team members
Person enters water unintentionally (slip, trip, fall on boat or pontoon)	M	H	All personnel on boat or near water edge wear skipper-provided lifejackets / buoyancy aids at all times; non-slip footwear; one-handed-for-self rule when moving on boat.	Skipper / Test Coordinator
Buoy lost at sea (drifts away, becomes hazard to navigation)	L	H	Buoy remains tethered throughout deployment. A laser-engraved placard inside the buoy includes Helen Czerski's UCL contact details so that, if recovered by a third party, UCL can be contacted.	Deployment Lead
Tether line snags propeller during deployment or recovery	L	L	Low residual risk because the test boat will be operating slowly or stationary. Engine to neutral/off during deployment and recovery; lines kept on the side opposite the propeller and kept short enough to avoid drifting under the hull.	Skipper
Line under load injures team member (rope burn, jerk injury)	L	L	Low residual risk because the buoy is small, wave loads are limited, and the line is not expected to build large tension. Gloves used when tending line; avoid standing in bights; do not wrap line around hands.	Deployment Lead

Risk	L	S	Mitigation	Owner
Adverse weather / sea state develops during test	L	H	Strict go / no-go criteria checked morning of test (see section 6). Skipper has authority to abort. Test window kept short (~2 hours). Forecast checked again on departure from marina.	Skipper / Test Coordinator
Collision with other vessel during test	L	H	Deployment zone selected outside main navigation channel; skipper monitors VHF Ch 16/12; visible position; test conducted at off-peak time where possible; no test during regatta or scheduled marina events.	Skipper
Electrical fault on buoy (battery short, smoke, fire) while on boat	L	M	Buoy battery isolator switched OFF until just before deployment; charged battery secured in approved case during transport; fire extinguisher present on boat; power-down procedure briefed.	Electronics Lead
Hypothermia from immersion or cold exposure	L	M	Dry kit and thermal layers carried; lifejackets worn; sea temperature noted; immersion = immediate recovery to boat or shore; warm fluids available.	Test Coordinator
Public swimmer / paddleboarder enters deployment zone	L	M	Visual scan before each deployment; deployment zone is offshore in non-bathing waters; immediate retrieval of buoy if any water user comes within 50 m; verbal warning given if needed.	All on boat
Damage to buoy enclosure causing water ingress / sinking	L	M	Pre-test waterproofing check; secondary tether means buoy is recoverable even if it loses buoyancy; post-deployment inspection.	Mechanical Lead
Loss of dashboard / 4G connectivity during test	M	L	Test continues with on-buoy logging; data retrieved post-test from onboard storage; not a safety issue, only a data issue.	Software Lead

10. Test Procedure (Step-by-Step)

10.1 Pre-departure (UCL, day before)

- Charge buoy battery to 100%; verify with a load test
- End-to-end test: buoy → 4G → dashboard. Confirm hydrophone and temperature data flow
- Inspect tethers, shackles and attachment hardware for wear
- Check forecast (wind, sea state, visibility) and Met Office warnings
- Confirm boat hire, marina office contact, and skipper booking
- Pack and label all equipment using the equipment list (section 4)

10.2 Pre-departure (UCL, morning of)

- Final forecast and tide check
- Brief team on the day's plan and any changes
- Load car; secure buoy and equipment
- Confirm with skipper that the boat is available

10.3 On arrival at Brighton Marina

- Check in at marina office; collect any advisories
- Set up dashboard station within sight of the deployment zone
- Power on buoy; confirm dashboard handshake, GPS lock, 4G connectivity
- Brief skipper using the briefing items in section 7.2
- All on-water personnel don lifejackets before stepping onto the boat

10.4 On the water

- Transit to deployment zone at marina speed limit (8 kn) until clear of breakwater
- Execute deployment per section 7.4
- Observation period: 60 to 90 minutes, see section 12 (Data)
- Execute recovery per section 7.5
- Transit back inside 2-hour boat hire window

10.5 Post-test on shore

- Visual inspection: water ingress, mast, ballast, mounting
- Power-on test: confirm electronics still functional after recovery
- Download any onboard-logged data
- Pack and load car

11. Emergency Procedures and Contacts

11.1 Person in water

- Skipper takes over completely; team follows skipper's MOB procedure
- Throw flotation; keep visual contact; alert marina via VHF Ch 16 or call 999 / Coastguard
- Recover to boat or to nearest safe shore (RNLI station is on the west quay)

11.2 Medical emergency

- Call 999, request ambulance and Coastguard if on water
- If non-life-threatening: Royal Sussex County Hospital A&E (~10 min from marina)
- First aid kit is on the boat and ashore

11.3 Lost or runaway buoy

- If primary tether parts: use working line

- If both lines part: skipper makes recovery attempt; mark last known GPS position; notify marina office and Coastguard so it does not become a hazard to navigation

11.4 Boat incident (engine failure, collision, fire)

- Skipper handles the situation; team follows skipper's instructions
- VHF Ch 16 distress call if required (skipper)

11.5 Contacts

Contact	Number	When to call
Emergency services (Coastguard / ambulance / fire / police)	999, ask for Coastguard for water emergencies	Any life-threatening incident. Person in water and not recovered. Lost vessel. Fire on boat.
HM Coastguard (non-emergency, marine)	VHF Channel 16 / 999	Marine incident reporting. The skipper handles this.
Brighton Marina office	01273 819919, VHF Ch 37 or 80	Marina advisories, entrance status, berthing, lost equipment.
RNLI Brighton (inshore lifeboat)	Co-located on west quay, call via 999 / Coastguard	Person in water; vessel in distress; called via Coastguard.
Royal Sussex County Hospital A&E	01273 696955, Eastern Road, Brighton BN2 5BE	Non-emergency injury requiring hospital attention (~10 min from marina).
NHS 111	111	Non-emergency medical advice.

12. Data to be Collected

Mechanical performance

- Qualitative observations of buoy motion, freeboard, stability
- IMU data (logged onboard and streamed)
- Photos and video of the buoy under wave action
- Launch and recovery behaviour, what worked, what did not

Electrical and system performance

- Successful startup; uptime through deployment; any resets / faults
- Battery voltage profile (start, mid-test, end)

Communications

- Time to first GPS lock
- Time to first 4G dashboard handshake
- 4G dropouts (count, duration)
- Latency observations (rough order)

Sensor performance

- Hydrophone signal quality and any boat / engine noise contamination
- Temperature data (continuity, plausible range)
- Whether all sensor channels are simultaneously available

Operational metrics

- Time from boat departure to deployment

- Time from deployment to first usable data
- Time from recovery decision to buoy on boat
- Number of operators required for each phase

13. Scenario-Based Testing

The boat hire window is limited to 2 hours, so the test is split into short, evidence-led scenarios. The aim is not just to prove that the buoy floats, but to validate the final coastal use case and deliberately stress the prototype in controlled ways.

Each scenario should be timed, filmed, and linked to the corresponding IMU, GPS, 4G, hydrophone and temperature data where available.

Window	Scenario	Procedure	Evidence / pass criteria
0-10 min	Pre-deployment system check	Power buoy on while still aboard. Confirm GPS lock, 4G/dashboard connection, sensor logging and battery voltage.	System reaches operational state before entering water; time to GPS and dashboard handshake recorded.
10-25 min	Controlled launch validation	Lower buoy into water on the deployment side. Keep engine neutral/off. Observe initial float, trim and freeboard.	Buoy floats upright, no immediate water ingress, tether arrangement manageable by team.
25-45 min	Baseline coastal drift/wave response	Let buoy sit in natural wave conditions with minimal boat influence. Record video side-on where possible.	Stable freeboard, no repeated deck submergence, IMU data continuous.
45-65 min	Live-data validation under normal use	Monitor GPS, 4G, hydrophone, temperature and IMU while buoy is in realistic coastal motion.	All required channels either stream live or log locally; dropouts and latency recorded.
65-85 min	Stress scenario 1: wake / higher wave disturbance	With skipper approval only, expose buoy to passing wake or gentle boat-induced disturbance while maintaining safe separation and tether control.	Buoy recovers without capsize, excessive roll, tether instability, reset, or water ingress.
85-100 min	Stress scenario 2: line-handling and recovery approach	Bring buoy alongside, pause, then let it move away again under controlled line handling. Do not fully recover yet.	Line remains controllable; no dangerous bights; buoy does not strike hull heavily.
100-115 min	Recovery validation	Recover buoy aboard using planned two-person lift and controlled line handling.	Recovery completed safely; time from recovery decision to buoy aboard recorded.

115-120 min	Immediate post-test inspection	Open/inspect external seals and visible enclosure areas; check loose fixings, water ingress signs and electronics state.	No significant water ingress or structural loosening; system still powers and data remain accessible.

Specific wave / disturbance situations to target

- Calm or sheltered water inside/near the marina approach: establishes baseline float, trim, launch and sensor operation.
- Natural slight coastal chop offshore: closest representation of intended nearshore monitoring use.
- Passing wake or skipper-approved induced disturbance: controlled stress case to test roll/pitch recovery and tether behaviour.
- Beam-on waves where practical: checks worst-case roll response when waves approach the side of the buoy.
- Head-on / following waves where practical: checks pitch response and mast/electronics exposure.
- Recovery alongside the boat in disturbed water: validates the highest-risk handling phase of the real use case.

14. Site Clean-up and Departure

- All equipment, packaging and waste removed from boat and shoreline
- No detached buoy components, cable ties, tape, or fragments left in water or on shore
- Marina office notified that the team is leaving
- Photo of the test area taken before departure to document its condition

15. Expected Outcomes

By the end of the test, the team will be able to demonstrate, with evidence, whether the buoy prototype:

- Remains stable in nearshore wave conditions (visual + IMU)
- Can be deployed and recovered from a small boat by a small team using the controlled tether arrangement (timed procedure + observations)
- Maintains operation of its onboard electrical and sensing systems through the test (uptime + post-test inspection)
- Communicates effectively with the dashboard via 4G in real coastal conditions (handshake times, dropout log)
- Provides usable hydrophone and temperature data at deployment range (sample data quality review)
- Is robust enough for further field campaigns or longer-duration deployments (post-test inspection report)

Appendix O: Bill of Materials

Item	Qty	Line Cost (£)
Raspberry Pi 4 Model B (8GB)	1	£72.00
microSD Card 32GB	1	£11.99
HiFiBerry DAC2 ADC Pro	1	£83.90
Pitalk 4G LTE HAT	1	£116.04
2-in-1 GPS + 4G Puck Antenna	1	£32.95
IPEX to SMA Female Adapter	1	£8.99
Lebara Unlimited SIM	1	£9.98
Samsung T9 Portable SSD 1TB	1	£199.00
Cable, Micro B to USB A	1	£4.00
Cable, USB A to USB C 1m	1	£9.99
Compute & Communications subtotal		**£548.84**
Arduino Nano 33 BLE Sense Rev2	1	£37.84
DS18B20 Waterproof Temperature Probe	1	£5.99
Aquarian H2DM Hydrophone	1	£167
Sensing subtotal		**£210.83**
12V 10Ah Battery	1	£37.99
D4184 MOSFET	1	£4.99
LED Navigation / Anchor Light	1	£30.48
Custom PCB	1	£165.76
Power & Electronics subtotal		**£239.22**
IP68 Waterproof Enclosure	1	£44.18
Waterproof Battery Box	1	£3.80
Acrylic Sheet	1	£15.81
PEBA Waterproof Sealing Plug	1	£7.51
M25 Cable Glands (10 pack)	1	£8.99
Threaded Cable Gland Cap	1	£12.59
Heat Shrink Tubing	1	£13.99
Floats	4	£67.96
Buoyancy Foam	1	£169.60
Net	1	£10.00
M10 Eye Bolts	12	£96.62
14mm Polypropylene Rope + 3x D-Shackles	1	£31.03
1x D-Shackle + 1x Bow-Shackle	1	£8.69
Mechanical & Structural subtotal		**£490.77**
BUILD TOTAL		**£1,489.66**

Appendix P: Dashboard Screenshots and Code Structure

This appendix captures the operating evidence for the live remote monitoring objective stated in Section 1.2 and verified in Section 6.3.4, together with the software architecture that delivers it. Section P.1 sets out the code repository structure and the four execution layers (dashboard, backend, edge Pi services, edge firmware). Section P.2 presents the dashboard screenshots recorded during the Brighton field deployment on 1 May 2026, covering all routine operating views referenced in the main text.

The complete source code, build scripts, and deployment notes are hosted at: https://github.com/PriestlyAdejo/CoastlineDataBouy. The repository is public and is intended as part of the handover package described in Section 7.1.

P.1: Code Repository Structure

The repository is organised into four execution layers and a set of shared contracts. The split reflects how the system was built and how it is operated, so that the dashboard, backend, edge Pi services, and edge firmware can each be tested in isolation before integration. Table P.1 lists the top-level directories and their purpose.

Table P.1: Repository structure and the role of each top-level directory.

Directory	Purpose
`/ (root)`	Vite/React dashboard. TypeScript source, Tailwind CSS, package.json, vite.config.ts, index.html.
`apps/api`	FastAPI backend service. REST endpoints for telemetry ingestion, file index, replay queue, and dashboard reads. Postgres for relational state, S3-compatible object storage for acoustic and binary payloads.
`edge/pi`	Raspberry Pi 4 Python services. Hydrophone capture (ALSA), Arduino serial reader (IMU), GNSS NMEA parser, 4G/LTE upload daemon, file indexer, systemd unit definitions, and smoke tests.
`edge/firmware`	Arduino Nano 33 BLE Sense Rev 2 firmware. Nine-axis IMU sampling at 100 Hz, USB-serial frame protocol to the Pi.
`schemas`	JSON Schema definitions for telemetry payloads, file manifests, and event records. Generated types for both TypeScript (dashboard) and Python (Pi and backend) are produced from these schemas to keep contracts in sync.
`docs`	Architecture notes, deployment guides, and hardware references. Includes the offline-first record-index-upload pattern used by the edge stack.
`docker`	Compose definitions for Postgres and MinIO (S3-compatible object store) for backend development and CI. Docker is optional for normal dashboard or backend development.
`scripts`	Windows .bat and PowerShell setup scripts. Create the buoy-dev Conda environment, install backend and edge Python packages in editable mode, run the dashboard and backend, and orchestrate two-terminal development.
`.github/workflows`	GitHub Actions workflows for continuous integration, lint, and schema-generation checks.
`environment.yml`	Conda environment specification. Single source of truth for all Python dependencies across backend and edge.

P.1.1: Code Repository Structure

The four execution layers are coupled by the shared JSON Schema contracts in schemas/, which prevents drift between the dashboard, backend, and edge services. Frontend types and Python types are both generated from the same schemas, so a change to a telemetry field is enforced across all consumers at build time.

The dashboard is a Vite/React application served at http://127.0.0.1:5173 in development. The backend is a FastAPI service at http://127.0.0.1:8000/v1 with OpenAPI documentation at /docs and a healthcheck at /v1/healthz. The Pi stack is offline-first: the buoy records locally to the Samsung T9 SSD, indexes new files into a local SQLite manifest, and uploads them to the backend when a cellular link is available. The Arduino firmware streams timestamped IMU frames over USB serial to the Pi as a deterministic acquisition source independent of the Linux scheduler.

P.1.2: Local Development Workflow

Development is set up by a single script that creates the Conda environment buoy-dev from `environment.yml`, installs backend and edge Python packages in editable mode, and runs `npm install` for the dashboard:

```
scripts\setup_env_windows.bat

# Then, in two terminals:
scripts\run_backend_windows.bat # FastAPI on :8000
scripts\run_frontend_windows.bat # Vite on :5173

# Or both at once:
scripts\dev_windows.bat
```

The frontend can operate against mock data for UI development, and screens are migrated to the live backend API as they are validated. This was the configuration used to record the dashboard views in Section P.2: the buoy was operating against the live backend in Replay mode, replaying the field deployment of 1 May 2026.

P.1.3: Language Mix

The repository is approximately 82% TypeScript (dashboard), 10% Python (backend and edge Pi services), 5% PowerShell and Batch (Windows development scripts), 1% C++ (Arduino firmware), and 1% CSS, as reported by the GitHub language detector at the time of submission. The TypeScript share is dominated by the dashboard's panel components, charts, and the generated schema bindings.

P.2: Dashboard Screenshots from Field Deployment

The dashboard views below were recorded on 1 May 2026 during the Brighton field deployment described in Section 6.3. The active node selector is set to "Field deployment" throughout, and the replay timeline is positioned at the deployment window. Each view is captioned with the primary information it presents and the corresponding section of the report. The view list mirrors the navigation tree of the dashboard, grouped under Monitoring (overview, telemetry, hydrophone, environment, location and map, system health, alerts) and Data and Files (historical data, files and downloads).

P.2.1: Monitoring

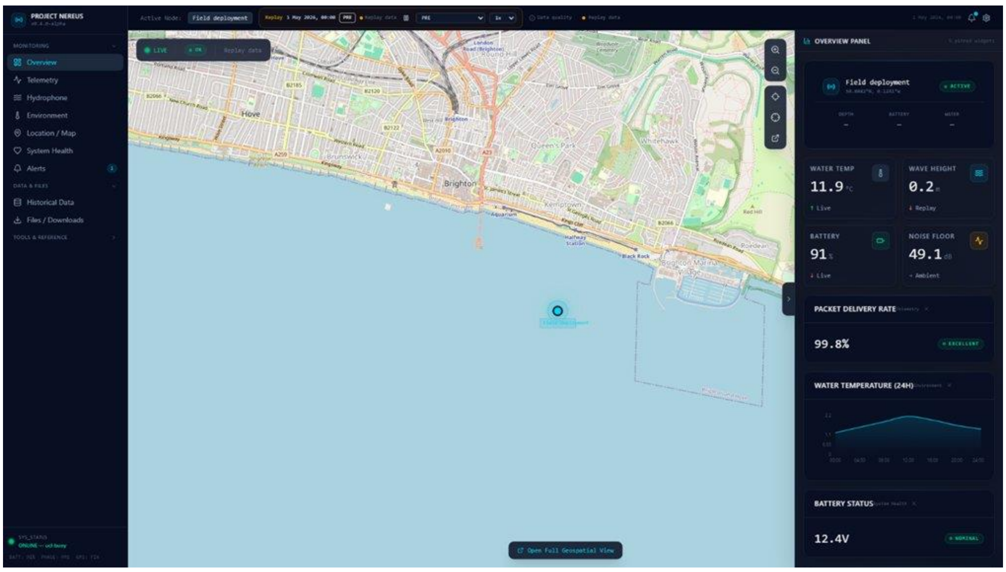


Figure P.1: Overview panel. The left pane shows the buoy's geographic position on the OpenStreetMap base layer. The right pane reports water temperature (11.9 °C, live), wave height (0.2 m, replay), battery (91%), broadband noise floor (49.1 dB rel.), packet delivery rate (99.8%, Excellent), and the 24 h water-temperature trend. The battery status panel below confirms 12.4 V at nominal. This is the principal at-a-glance health view used during the deployment.

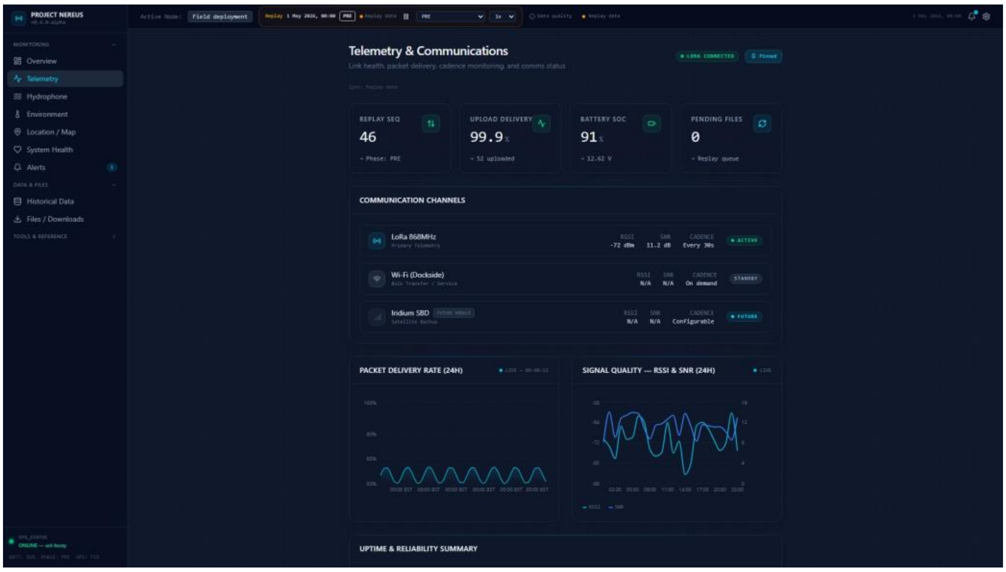


Figure P.2: Telemetry and communications panel. The replay sequence counter shows 46 batches in the PRE phase, upload delivery at 99.9% with 52 files acknowledged and 0 pending in the replay queue, and battery at 91% (12.62 V). The Communication Channels block lists three radio links: LoRa 868 MHz active as primary telemetry at RSSI −72 dBm and SNR 11.2 dB on a 30 s cadence; Wi-Fi (Dockside) in standby for bulk transfer on demand; and Iridium SBD as a future satellite-backup module. The packet delivery rate and 24 h RSSI/SNR traces are shown beneath.

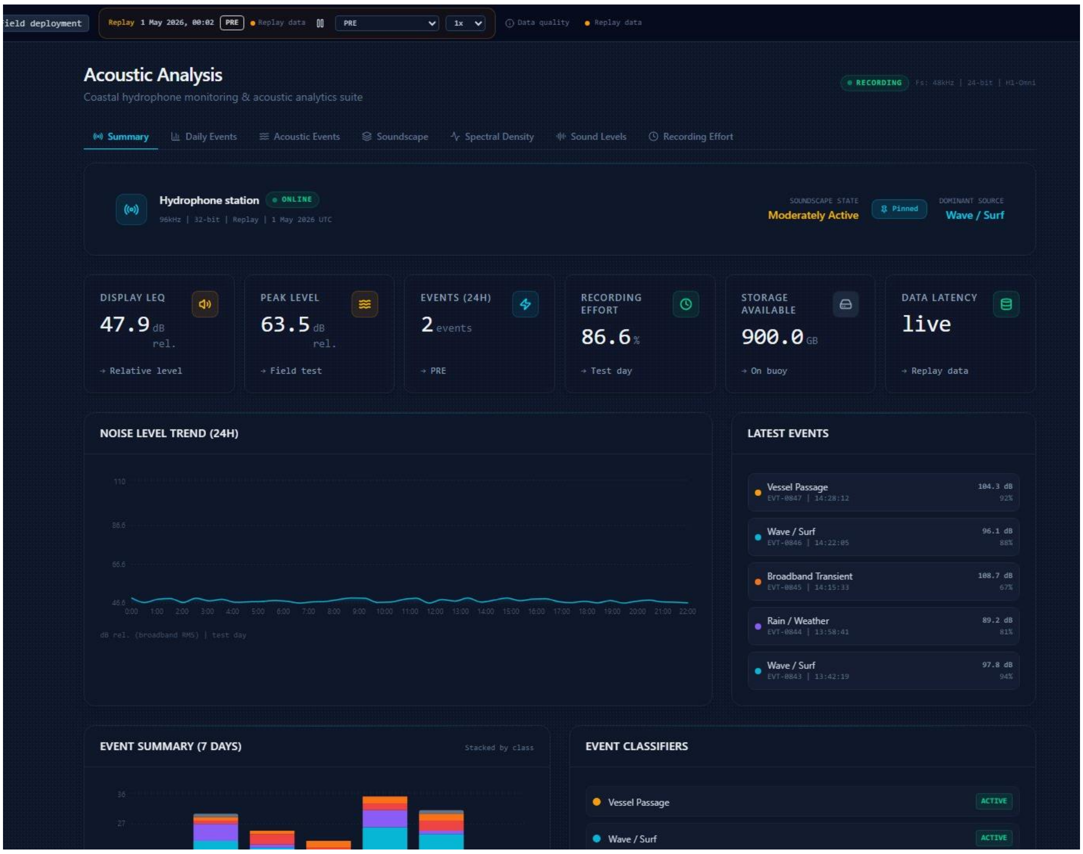


Figure P.3: Hydrophone summary view. The station is reported as Online at 96 kHz, 32-bit, with a soundscape state of Moderately Active and a dominant source of Wave / Surf. KPI tiles report Display Leq 47.9 dB rel., peak level 63.5 dB rel., 2 events in the 24 h replay, recording effort 86.6%, 900 GB of storage available on the SSD, and live data latency. The Latest Events panel lists the five most recent classifier outputs (vessel passage at 104.3 dB at 92% confidence; broadband transient at 108.7 dB; rain/weather at 89.2 dB; wave/surf events at 96.1 and 97.8 dB).

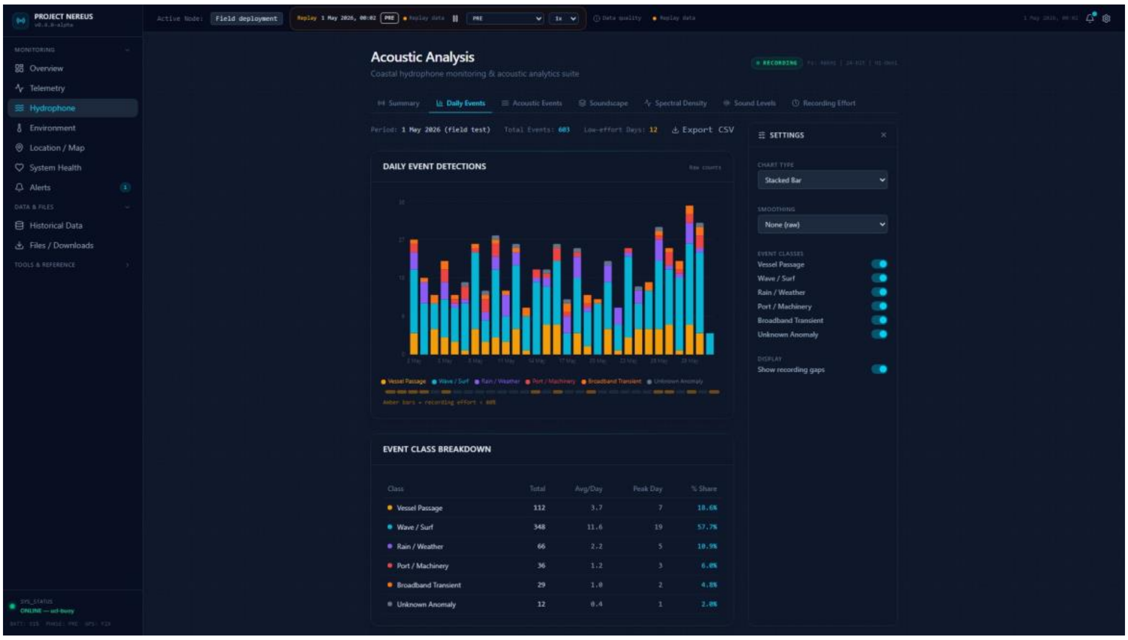


Figure P.4: Hydrophone Daily Events view. Stacked-bar chart of classified events per day across the 1 May 2026 field-test period (603 total events, 12 low-effort days flagged). The Event Class Breakdown table below the chart shows wave/surf as the dominant class at 57.7%, vessel passage at 18.6%, rain/weather at 10.9%, port/machinery at 6.0%, broadband transient at 4.8%, and unknown anomaly at 2.0%. Amber bars mark days with recording effort below 80%.

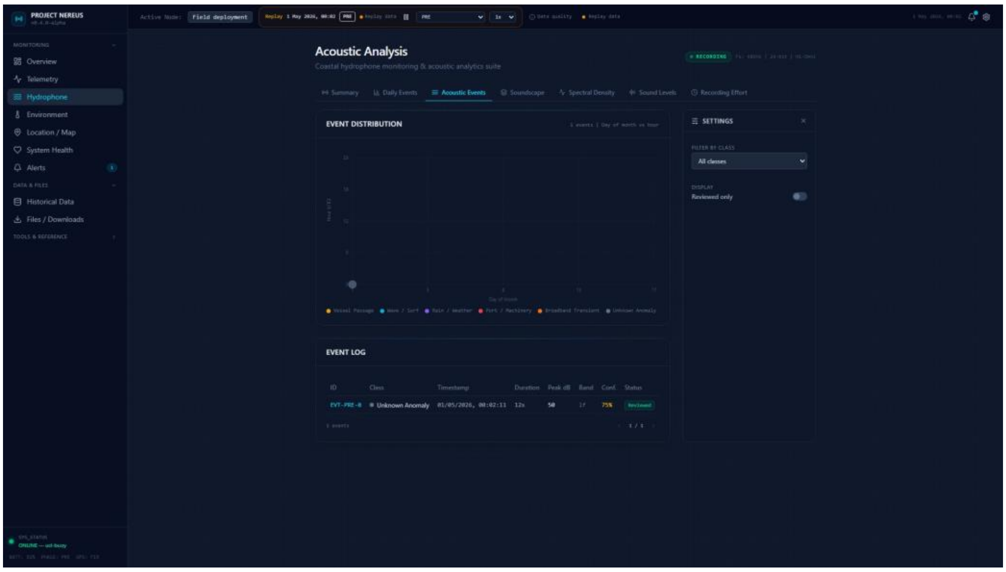


Figure P.5: Hydrophone Acoustic Events view. Event distribution scatter plot of detection hour against day of month, classified by source. The event log below the chart shows one reviewed event (EVT-PRE-0, unknown anomaly, 01/05/2026 02:11, duration 12 s, peak 50 dB, band 1F, confidence 75%). The class filter on the right allows the operator to drill into specific event types.

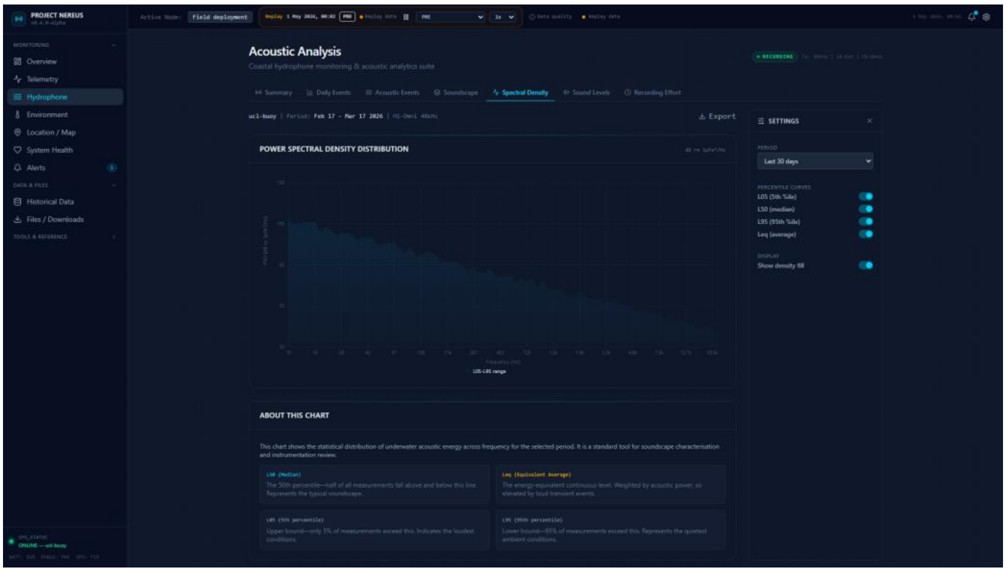


Figure P.6: Hydrophone Spectral Density view. Power Spectral Density Distribution (dB re 1 µPa²/Hz) across 10 Hz to 20.5 kHz for the period 17 Feb to 17 Mar 2026, with L05 (5th percentile), L50 (median), L95 (95th percentile), and Leq (equivalent average) curves toggled. The density-fill panel reveals the L05-L95 range used to characterise variability of the soundscape. The About This Chart panel below explains the percentile and equivalent-level interpretation conventions.

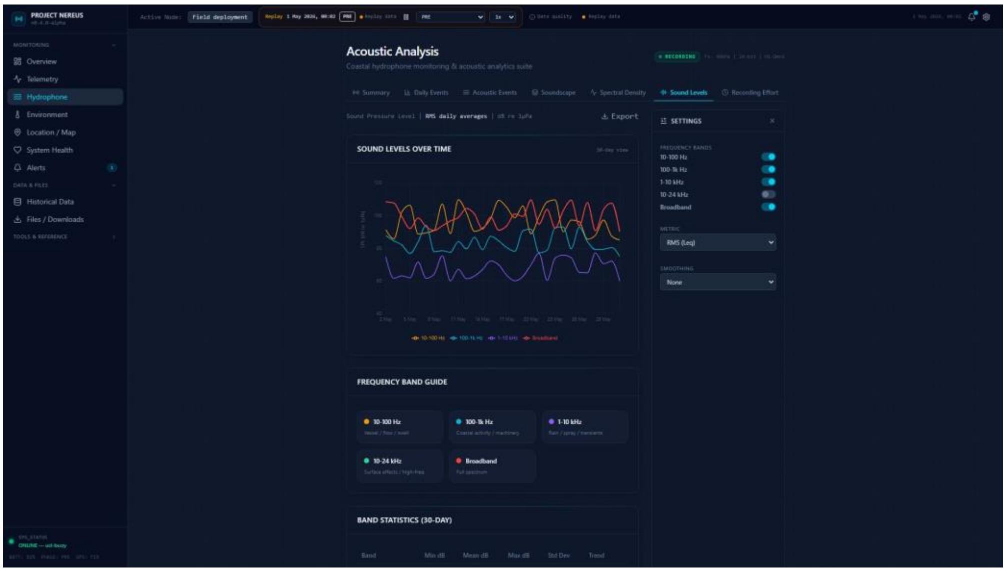


Figure P.7: Hydrophone Sound Levels view. Sound Pressure Level in dB re 1 µPa, RMS daily averages over 30 days across four frequency bands: 10–100 Hz (vessel, flow, swell), 100 Hz – 1 kHz (coastal activity and machinery), 1–10 kHz (rain, spray, transients), and broadband. The frequency-band guide and 30-day band statistics table support the interpretation in Section 6.2.5.

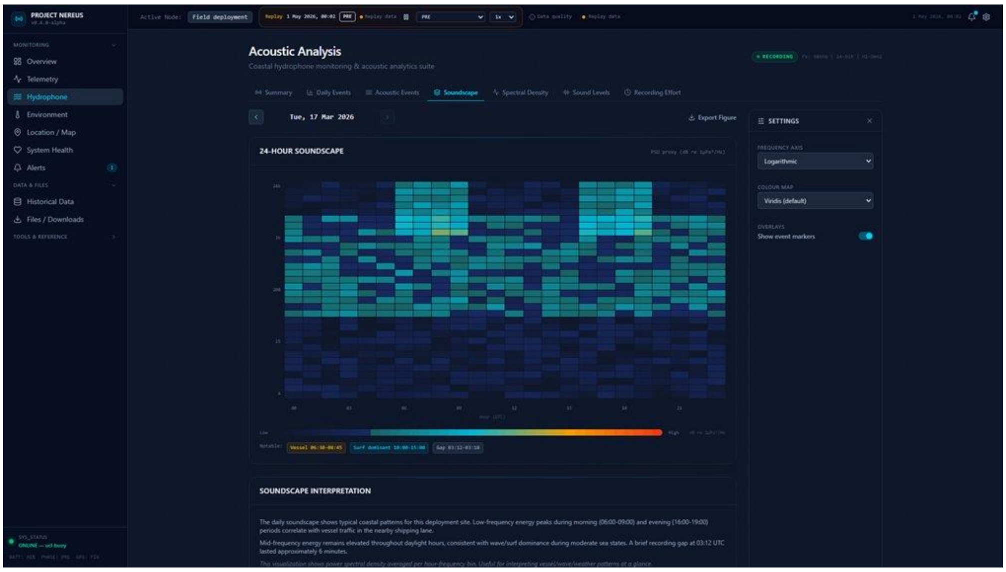


Figure P.8: Hydrophone Soundscape view. A 24-hour soundscape grid showing PSD by frequency bin (vertical axis, logarithmic, 10 Hz to upper edge) against time of day (horizontal axis, UTC). Event markers along the lower edge identify a vessel passage at 06:30-06:45, a surf-dominant period from 10:00 to 15:00, and a recording gap at 03:12-03:18. The interpretation panel beneath the grid describes the typical coastal pattern observed: low-frequency energy peaks in the morning and evening shipping windows; mid-frequency surf energy persisting through daylight hours.

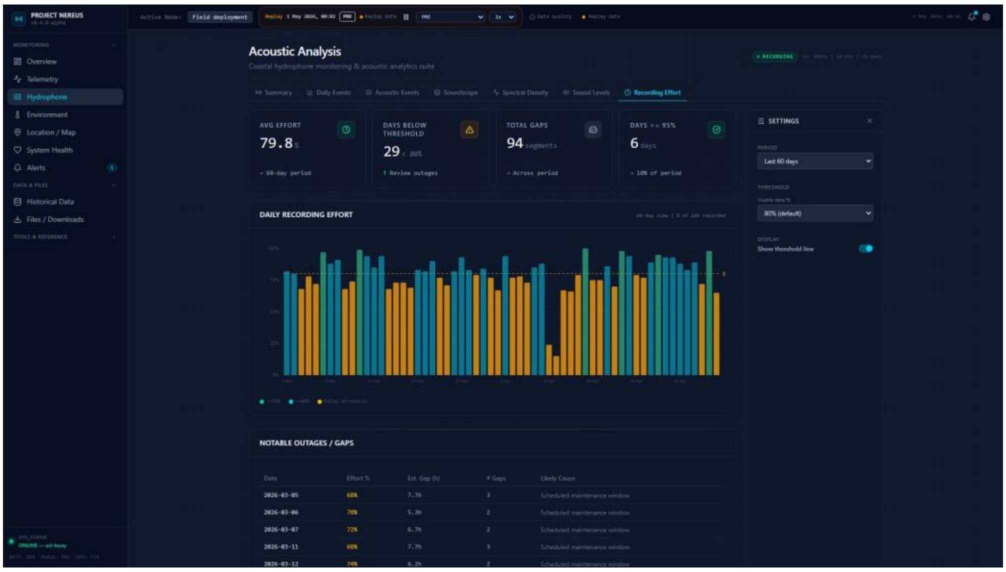


Figure P.9: Hydrophone Recording Effort view. KPI tiles report average effort of 79.8% across the 60-day period, 29 days below the 80% threshold, 94 total gap segments, and 6 days above 95% effort. The daily bar chart colour-codes each day's recording effort against the 80% threshold (orange below, blue 80–95%, green at or above 95%). The Notable Outages and Gaps table lists scheduled maintenance windows identified by the gap detector.

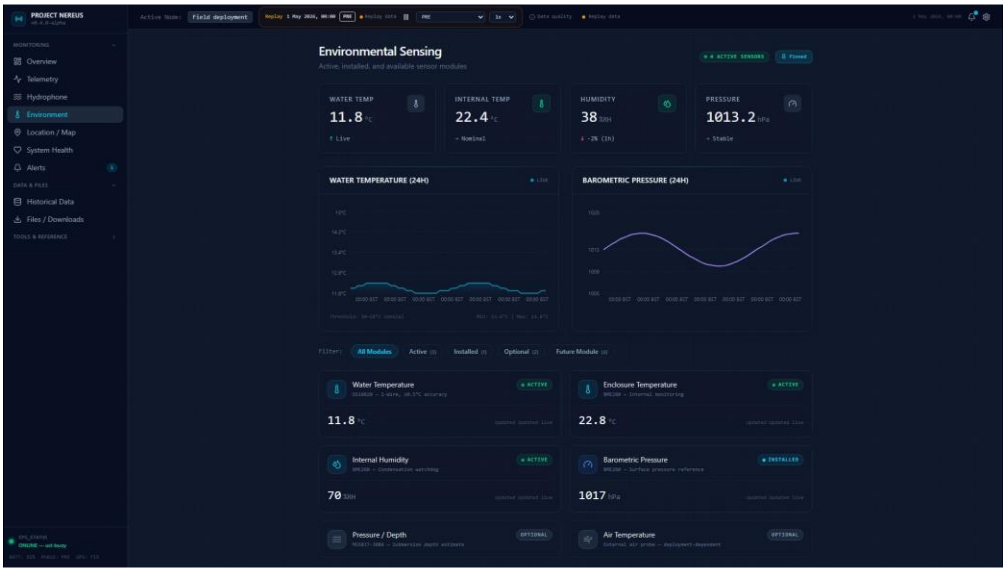


Figure P.10: Environmental sensing panel. KPI tiles report water temperature (11.8 °C, live), enclosure internal temperature (22.4 °C, nominal), internal humidity (38% RH, trending -2% over the last hour), and barometric pressure (1013.2 hPa, stable). The 24 h water-temperature trace shows a 12 to 14 °C envelope. The barometric-pressure trace shows the diurnal cycle. The active sensor module list below confirms the DS18B20 (water temperature) and BME280 (internal monitoring) as Active, with pressure/depth and external air-probe channels available as Optional or Installed but not currently used.

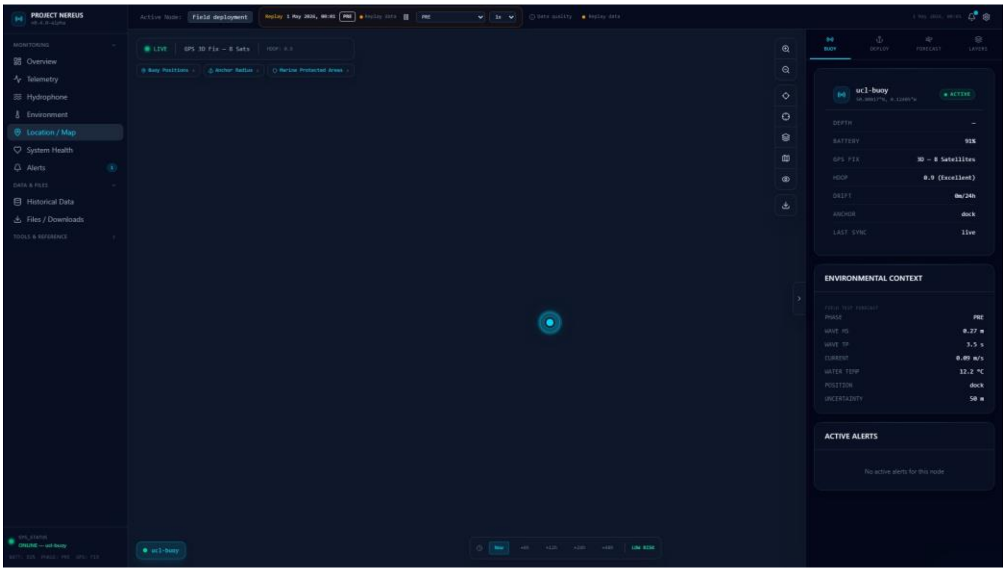


Figure P.11: Location and Map view (full geospatial mode, OpenStreetMap base). The buoy is shown at the Brighton field-test position with the marine-protected-areas overlay enabled. The right pane reports the position fix (50.80817°N, 0.12405°W), battery 91%, GPS 3D fix on 8 satellites with HDOP 0.9 (Excellent), 0 m drift over 2 h, anchor status "dock", and environmental context including the field-test forecast (Wave Hs 0.27 m, Wave Tp 3.5 s, current 0.09 m/s, water temperature 12.1 °C).

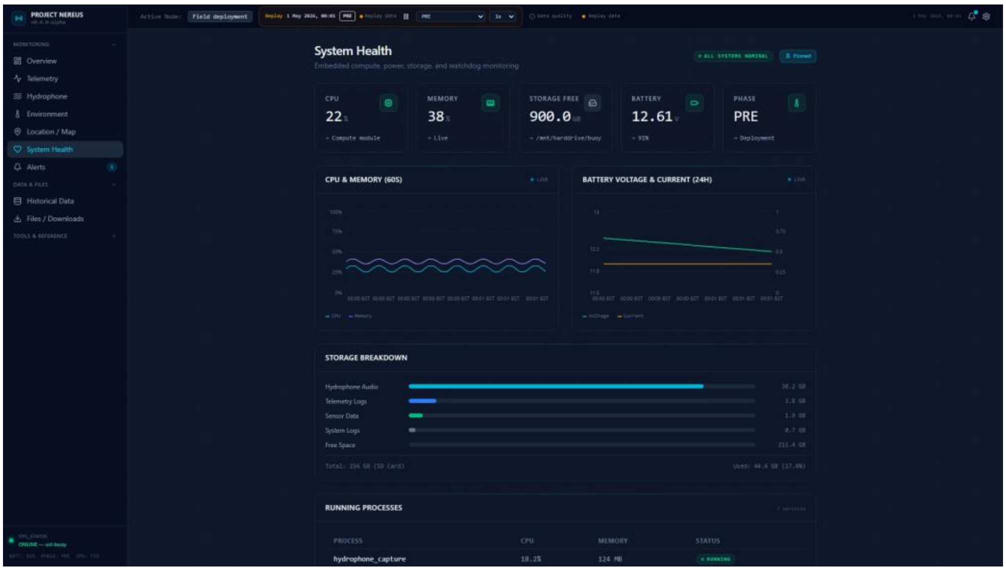


Figure P.12: System Health view. KPI tiles report CPU 22%, memory 38%, storage free 900.0 GB on /mnt/harddrive/buoy, battery 12.61 V (91%), and the current phase (PRE for deployment). The CPU and Memory trace shows the steady-state load during recording. The Battery Voltage and Current trace over 24 h shows the slow discharge profile during the replay window. The Storage Breakdown bar identifies hydrophone audio (38.2 GB), telemetry logs (3.8 GB), sensor data (1.9 GB), and system logs (0.7 GB) against 211.4 GB free of a 256 GB nominal partition.

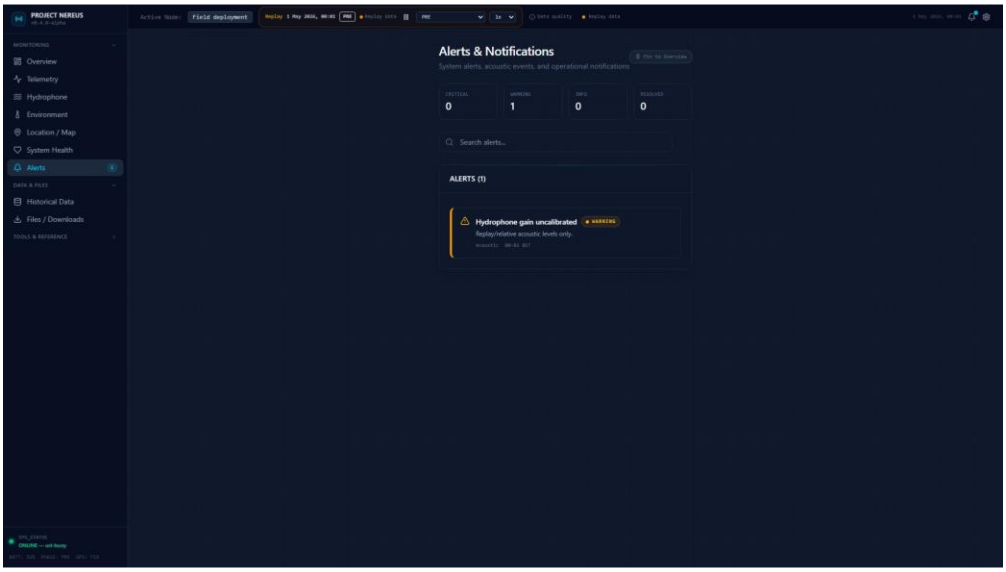


Figure P.13: Alerts and Notifications view. The counter row shows 0 Critical, 1 Warning, 0 Info, and 0 Resolved at the time of the screenshot. The single Warning event is "Hydrophone gain uncalibrated: replay/relative acoustic levels only." This alert is the operational reflection of the Partial outcome flagged in Sections 6.2.5 and 6.3.2, and is the dashboard's mechanism for surfacing the gain-closure requirement to the operator.

P.2.2: Data and Files

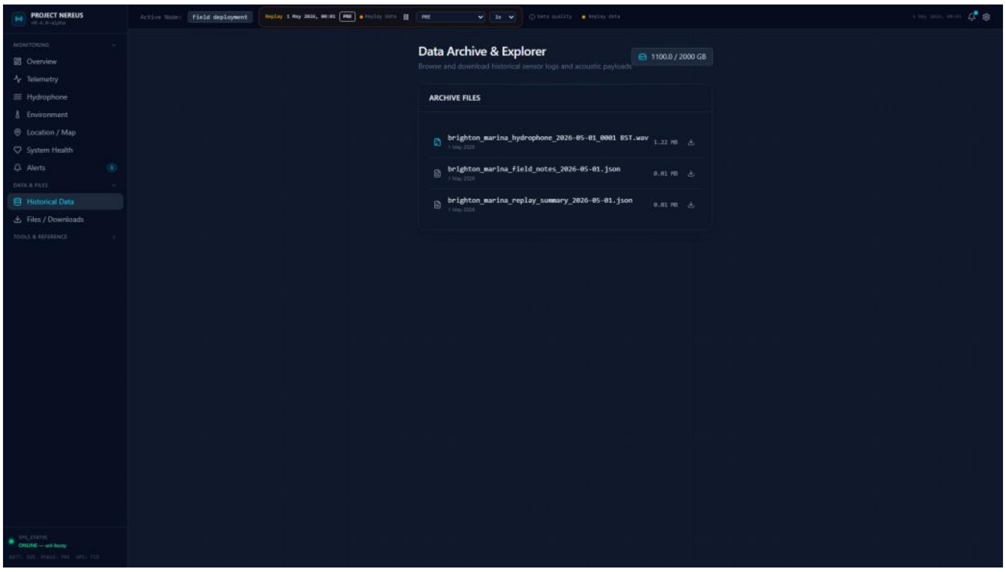


Figure P.14: Data Archive and Explorer view. The historical-data list shows the three artefacts produced by the 1 May 2026 deployment: the hydrophone WAV recording (brighton_marina_hydrophone_2026-05-01_0001_BST.wav, 1.22 MB), the field-notes JSON (brighton_marina_field_notes_2026-05-01.json, 0.01 MB), and the replay-summary JSON (brighton_marina_replay_summary_2026-05-01.json, 0.01 MB). The storage gauge in the top right confirms 1100.0 GB used of 2000 GB capacity. Each row has a per-file download action.

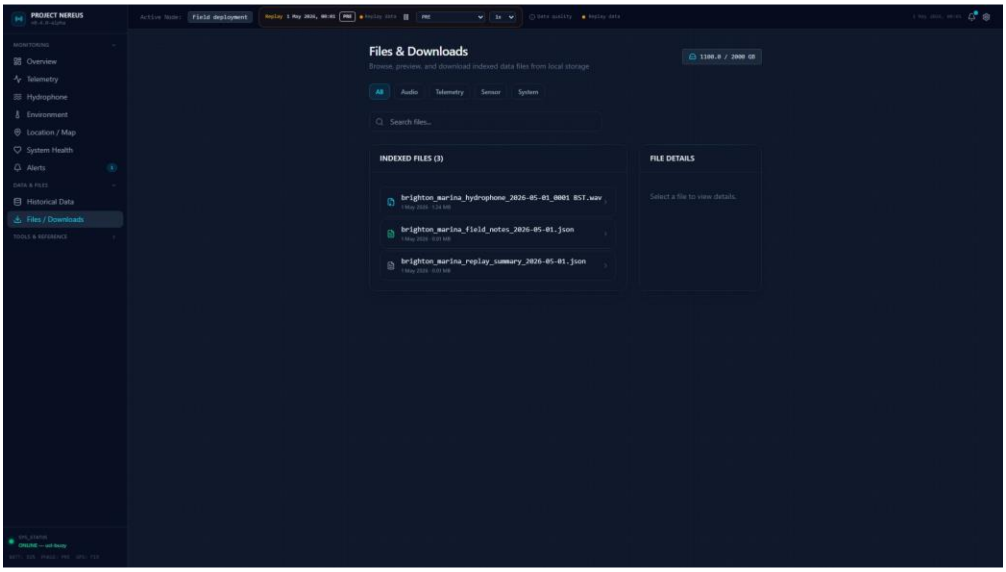


Figure P.15: Files and Downloads view. The same artefacts shown in Figure P.14 are presented under the operational file browser with category filters (All, Audio, Telemetry, Sensor, System) and a search field. The right pane is the file-detail viewer for the currently selected file. This is the route used post-recovery to retrieve the local archive from the buoy.

P.3: Cross-References

The dashboard views shown in this appendix support the following points in the main report. The overview panel (Figure P.1) and telemetry view (Figure P.2) are the operating evidence for live remote monitoring, summarised inline in Section 6.3.4. The hydrophone summary, daily events, acoustic events, spectral density, sound levels, soundscape, and recording-effort views (Figures P.3 to P.9) carry the acoustic-chain evidence referenced in Sections 4.1.3, 6.2.5, and 6.3.2. The environmental panel (Figure P.10) presents the DS18B20 and BME280 channels described in Section 4.3. The location/map panel (Figure P.11) presents the GNSS fix and position metadata cited in Section 6.3.3. The system-health and alerts panels (Figures P.12 and P.13) show the watchdog and notification surfaces used by the operator. The historical-data and files panels (Figures P.14 and P.15) close the loop between local SSD storage on the buoy and the post-recovery data-retrieval route.