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Ministry of Higher Education and Scientific Research

وزارة التعليم العالي و البحث العلمي

National Higher School of Marine Science and Coastal Development (ENSSMAL)

المدرسة الوطنية العليا لعلوم البحر وتهيئة الساحل

Final year thesis

In order to obtain the State Engineer diploma in Coastal Engineering and Planning, at Master's level

Design and Development of an Autonomous Ocean Data Collection System

Presented by:

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Option:

Coastal Engineering and Planning

Defended on 29/06/2026, before the examination committee:

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Information Sheet

1. Supervision Team:

Supervision Team	Faculty	Specialty
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2. Project Team:

Project Team	Faculty	Specialty
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Laib Soheyb	ENSSMAL	Coastal Engineering and management
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DEDICATION

To our parents,

For everything they have given, and everything they have endured, for their support, their sacrifices, and the quiet confidence they have always shown in us, this work is, in many ways, the result of the foundation they built for us, we hope it stands as a worthy reflection of their efforts.

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To all those who believed in us,

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To our school,

To this institution that welcomed us, shaped us, and gave us the tools to grow, within these walls, we did not only learn a discipline, we learned a way of thinking, a sense of rigor, and a taste for the work well done, we leave with more than a degree, we leave with a foundation we will carry for the rest of our lives, we are proud to have been part of this school, and we hope to honor its name through whatever comes next.

To those who will come after us,

To the students who will one day hold this work in their hands, perhaps at the beginning of their own journey, do not be intimidated by the scale of what lies ahead, Every project that exists was once just a blank page, Every result was once just an idea, start, ask questions, push through the hard days, the path is long, but it is absolutely worth walking.

"They can conquer who believe they can.". Virgil

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List of Abbreviations

ADC: Analog-to-Digital Converter

AI: Artificial Intelligence

AOI: Automated Optical Inspection

ARPT: *Autorité de Régulation de la Poste et des Télécommunications* (Algerian Post and Telecommunications Regulatory Authority)

ASA/ABS: Acrylonitrile Styrene Acrylate / Acrylonitrile Butadiene Styrene

ASF: Algerian Startup Fund

BM: Metacentric Radius (distance from Center of Buoyancy to Metacenter)

CAD: Computer-Aided Design

CE: *Conformité Européenne* (European Conformity marking)

CEP: Circular Error Probable

CIAMEL: *la Conférence (Interactions Anthropiques avec la Mer et le Littoral)/ Conference on Human Interactions with the Sea and the Coast*

CNC: Computer Numerical Control

CSV: Comma-Separated Values

CTD: Conductivity, Temperature, and Depth (sensor)

DGD: Directorate General of Customs (Direction Générale des Douanes)

DGMM: General Directorate of the Merchant Marine (Direction Générale de la Marine Marchande)

DGRSDT: Direction Générale de la Recherche Scientifique et du Développement Technologique (General Directorate of Scientific Research and Technological Development)

DO: Dissolved Oxygen

EBITDA: Earnings Before Interest, Taxes, Depreciation, and Amortization

EMS: Electronics Manufacturing Services

ENSEREDD: Higher National School of Renewable Energy, Environment and Sustainable Development

EPDM: Ethylene Propylene Diene Monomer (rubber, used for O-rings/gaskets)

ESP32-S3: Espressif ESP32-S3 microcontroller (Wi-Fi/Bluetooth SoC)

FDM: Fused Deposition Modeling

FR4: Flame Retardant 4 (glass-reinforced epoxy laminate for PCBs)

GF30: Glass-Fiber-reinforced (30%) plastic compound

GM: Metacentric Height

GNSS: Global Navigation Satellite System

GOOS: Global Ocean Observing System

GPS: Global Positioning System

GZ: Righting Arm (in stability curves)

HDPE: High-Density Polyethylene

HNS-RE2SD: Higher National School of Renewable Energy, Environment and Sustainable Development

IALA: International Association of Marine Aids to Navigation and Lighthouse Authorities

IANOR: Institut Algérien de Normalisation (Algerian Institute of Standardization)

IEC: International Electrotechnical Commission

IMU: Inertial Measurement Unit

INAPI: Institut National Algérien de la Propriété Industrielle (National Algerian Institute of Industrial Property)

IOC-UNESCO: Intergovernmental Oceanographic Commission of UNESCO

IP68: Ingress Protection rating 68 (dust-tight, protected against continuous immersion)

ISO: International Organization for Standardization

ITU: International Telecommunication Union

JCOMM: Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology

KB: Height of the Center of Buoyancy above Keel

LCJ: LCJ Capteurs (sensor manufacturer)

LED: Light-Emitting Diode

LLDPE: Linear Low-Density Polyethylene

LSB: Least Significant Bit

MCB: Maître de Conférences B (Algerian academic rank, Assistant Professor Class B)

MED: Marine Equipment Directive

MESRS: Ministère de l'Enseignement Supérieur et de la Recherche Scientifique (Ministry of Higher Education and Scientific Research)

MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor

MPPT: Maximum Power Point Tracking

NEO-7M: u-blox NEO-7M GNSS/GPS receiver module

NESDA: National Entrepreneurship Support and Development Agency

NOAA: National Oceanic and Atmospheric Administration

PA66: Polyamide 66 (Nylon 6,6)

PCB: Printed Circuit Board

PLA: Polylactic Acid

QC: Quality Control

RED: Radio Equipment Directive

RS-485: Recommended Standard 485 (serial communication standard)

SD: Secure Digital (memory card)

SMT: Surface-Mount Technology

SPI: Serial Peripheral Interface

STL: Stereolithography (3D file format)

STM32: STMicroelectronics STM32 microcontroller family

TCA9548A: TCA9548A I^2C multiplexer (Texas Instruments)

UART: Universal Asynchronous Receiver-Transmitter

USB: Universal Serial Bus

UTC: Coordinated Universal Time

UV: Ultraviolet

WMO: World Meteorological Organization

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First axis: Project presentation

1. The project idea:

The project is positioned within the industrial marine and coastal engineering sector, with applications in environmental services, oceanographic monitoring, and maritime infrastructure support systems.

The idea emerged from the observation that Algeria lacks locally manufactured oceanographic buoys, while systems that have been deployed in Algeria are very limited, predominantly foreign made, expensive, inaccessible to most local research institutions, and mainly imported for short term missions, limiting continuous coastal data collection, this need was identified through academic and practical exposure to coastal engineering challenges, and validated through one on one interviews with field specialists, who confirmed the importance of continuous wave and environmental data for optimizing coastal infrastructure design, particularly in terms of material use, structural sizing, and cost reduction.

Figures 1 to 4 present global maps of deployed oceanographic buoy networks operated by various international organizations, highlighting the near absence of such monitoring systems along the Algerian coastline.

The objective is to design a scalable autonomous oceanographic monitoring system capable of continuously measuring key marine parameters, including wave conditions and surrounding environmental data, using embedded sensors.

The system operates by collecting environmental data through onboard sensors, processing it, and transmitting it via a communication module to a remote platform for storage, visualization, and analysis, enabling continuous monitoring and decision support.

The project is carried out by a student engineering team composed of Khemis Fares, Soheyb Laib, and Geuttouche Nadji, under academic supervision, combining skills in mechanical design, embedded systems, and data integration.

Development and testing are conducted within an academic laboratory environment, while future deployment targets selected coastal sites along the Algerian shoreline for real condition validation and application.

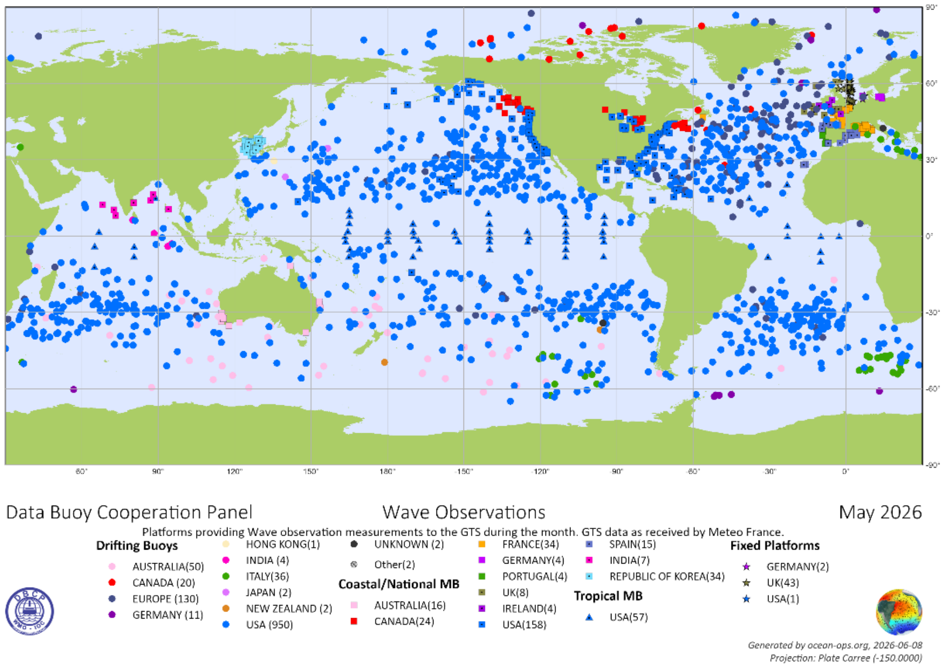


Figure 1 : Map of all the deployed Data Buoy Cooperation platforms

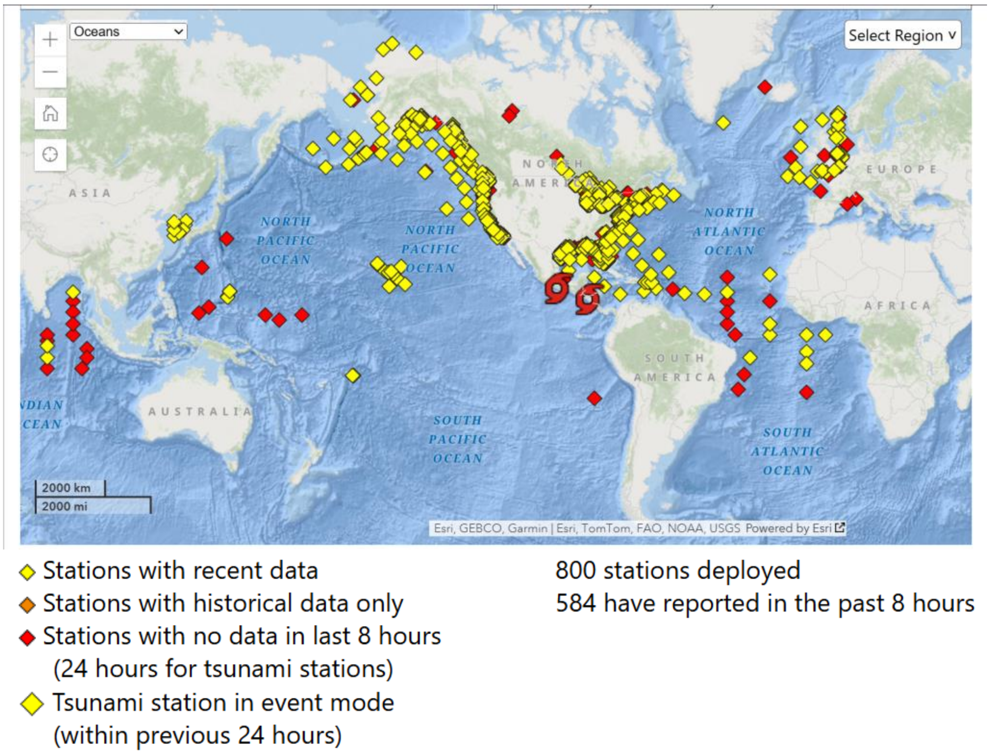


Figure 2 : Spatial Distribution of Oceanographic Buoys Deployed by NOAA

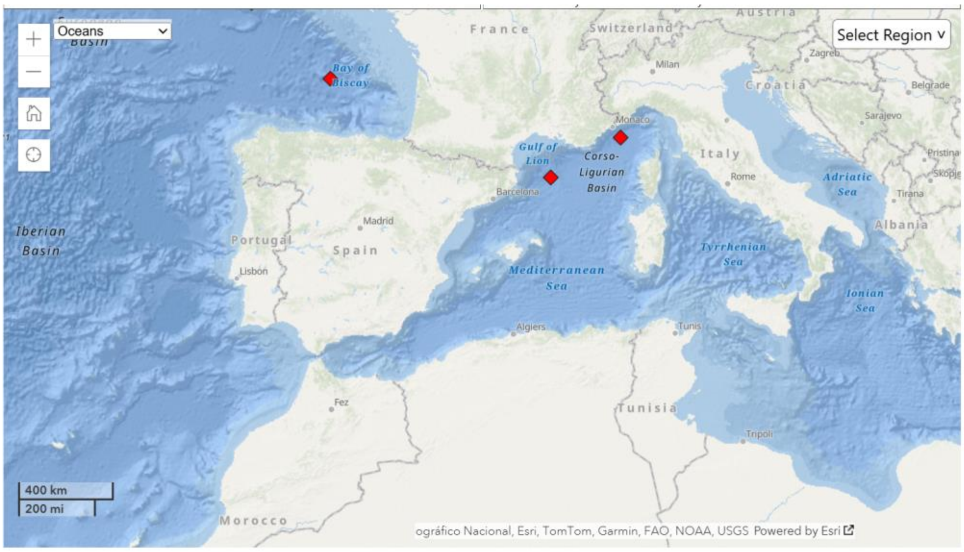


Figure 3: Spatial Distribution of Oceanographic Buoys Deployed by NOAA (Zoomed in on the Mediterranean Sea)

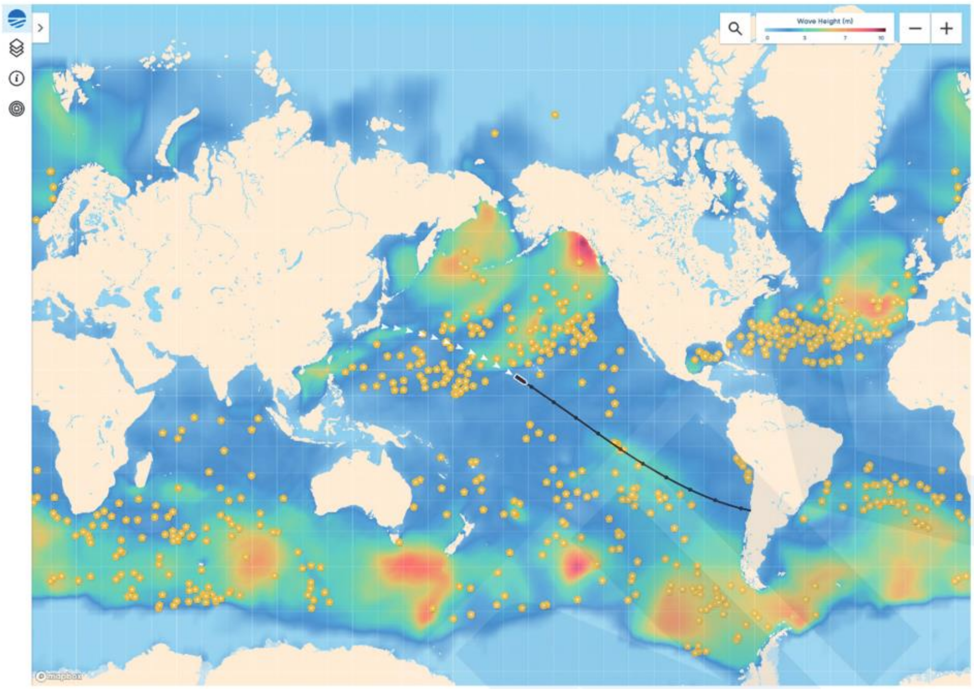


Figure 4: Map of buoys deployed by Sofar Ocean as a July 2022 45) (yellow dots: buoys, contour lines: wave height)

2. Proposed Values:

Building on the context established above, this system delivers value across the following dimensions:

- **Reducing uncertainty and costs in coastal and maritime infrastructure**: In the absence of local monitoring data, infrastructure projects rely on conservative safety margins, imported datasets, or costly measurement campaigns, the economic consequence is amplified by the nature of coastal engineering calculations, wave height appears raised to the third power in structural design formulas (as presented below by Hudson's formula)[1], meaning even modest measurement errors translate into cubic overestimations of design loads and therefore massively oversized, over budgeted structures, At the scale of portuary and coastal infrastructure projects, this compounding effect represents enormous unnecessary expenditure, Accurate, site specific wave data directly cuts this at the source.[1]

- **Local affordability**: Domestic design and manufacturing substantially reduces the cost barrier compared to imported equivalents, while keeping maintenance capacity and intellectual ownership within Algerian institutions.
- **Technical relevance**: Real time acquisition of physical, chemical, and wave parameters serves the needs of coastal engineers, environmental researchers, and maritime planners who currently lack access to such data at this resolution and cost.
- **Scalability and modularity**: Sensors, communication modules, and measured parameters can evolve with user requirements and real deployment conditions over time, without redesigning the core system.
- **Operational simplicity**: The system is designed to be easy to deploy, maintain, and interpret, lowering the technical barrier for institutions without dedicated oceanographic engineering staff.

$$W_{50} = \frac{\rho_r \, g \, H^3}{K_D \Delta^3 \cot\alpha}$$

Equation 1 : Hudson's equation for armor block weight[1]

Where:

- W_{50}: Median weight of armor block
- ρ_r: $Unit\ weight\ of\ armor\ block$
- H: $Project\ wave\ height\ (significant\ wave\ height)$
- K_d: $Stability\ Coefficient$
- Δ: $Relative\ density$
- $\cot\alpha$: $Slope\ of\ the\ structure$

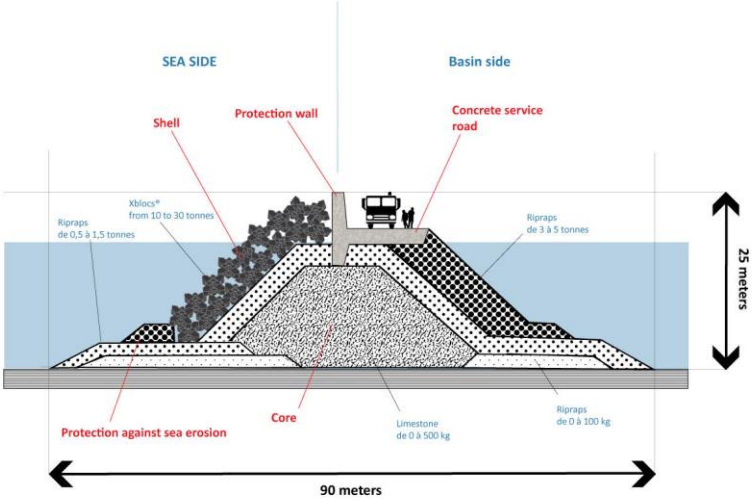


Figure 5: Typical cross-section of a Rubble-mound breakwater

Figure 6: Rubble-mound breakwater during armor layer construction

3. Project team:

The project team is composed of the following members:

Table 1: the project's team, their qualifications and tasks.

Member	Skills / Qualifications	Tasks
Supervisor: Mr. Mezouar Khoudir	Academic supervisor, Phd in coastal engineering	Overall supervision of the project, scientific validation, and guidance throughout all development phases
Co-Supervisor: Mr. Ghoggali Salim	Co-supervisor, Phd in Electronics and Electrical Engineering	Technical supervision, methodological support, and review of design and implementation choices
Student 01: Mr. Khemis Fares	Coastal engineering student, with skills in System design, CAD modelling and 3D printing.	- Overall system design. - 3D modelling of the buoy structure. - Structural stability and buoyancy analysis of the buoy system. - fabrication using 3D printing, - structural assembly and waterproofing. - development of the system algorithm and embedded code.
Student 02: Mr. Laib Soheyb	Coastal engineering student with skills in business management.	- Manufacturing Strategy and Operational Resource Management. - Financial Feasibility Assessment and Investment Analysis. - Production Cost Modeling. - Market Research.
Student 03: Mr. Guettouche Nadji	Coastal engineering student with skills in electronics and PCB design.	- Design and development of the electronic architecture. - PCB design and fabrication. - Assembly of the embedded electronic system. - development of the system algorithm and embedded code.

4. Project Objectives:

4.1 Short and Medium Term Objectives:

- Develop and validate a fully functional prototype of the intelligent oceanographic buoy within 12 months, demonstrated operational in at least one controlled and one real marine environment, with sensor accuracy and transmission reliability verified against defined technical benchmarks.

- Achieve recognition as a locally developed, cost competitive alternative to imported systems within 18 months, with a documented cost comparison showing a minimum 30% reduction in acquisition cost relative to equivalent foreign solutions.

- Establish formal partnerships with a minimum of 3 universities, research laboratories, or coastal engineering institutions within 12 months, resulting in at least one signed collaboration or field testing agreement.

- Present the prototype at a minimum of 3 national academic conferences or innovation events within 18 months, generating documented institutional interest and at least one letter of intent from a prospective client or partner.

4.2 Long-Term Objectives:

- Achieve deployment of at least 20 operational buoys along the Algerian coastline within 5 years, providing continuous marine data coverage across a minimum of 5 distinct coastal zones.
- Enter at least 2 regional or African coastal markets within 5 years, with a minimum of one signed commercial contract or institutional partnership outside Algeria.
- Generate recurring revenue through a mixed commercial model sales, leasing, and data as a service, reaching financial self-sustainability within 4 years of initial commercialization, with leasing and service contracts representing at least 30% of total revenue.
- Secure at least 3 active contracts with strategic sector clients, port authorities, environmental agencies, or coastal infrastructure developers, within 4 years, directly supporting applications in coastal risk management, maritime safety, or climate monitoring.
- Reduce institutional dependence on imported oceanographic systems by supplying locally manufactured equipment to a minimum of 5 Algerian public institutions within 5 years, contributing measurably to national technological independence in marine monitoring.

5. Project implementation schedule:

The calendar of this project can be divided into two main phases, the first phase represents the development timeline followed by the team throughout the realization of the project and the construction of its prototype, starting in January 2025 and concluding with the validation of the prototype and the completion of the Business Model Canvas, The second phase concerns the projected roadmap for the creation and launch of the project's startup, beginning in June 2026.

The following Gantt diagrams, created using GanttProject software, present the project schedule in terms of task durations expressed in days, in addition to illustrating the chronological sequence of activities, they highlight major project milestones, the critical path, and the dependency relationships linking individual tasks.

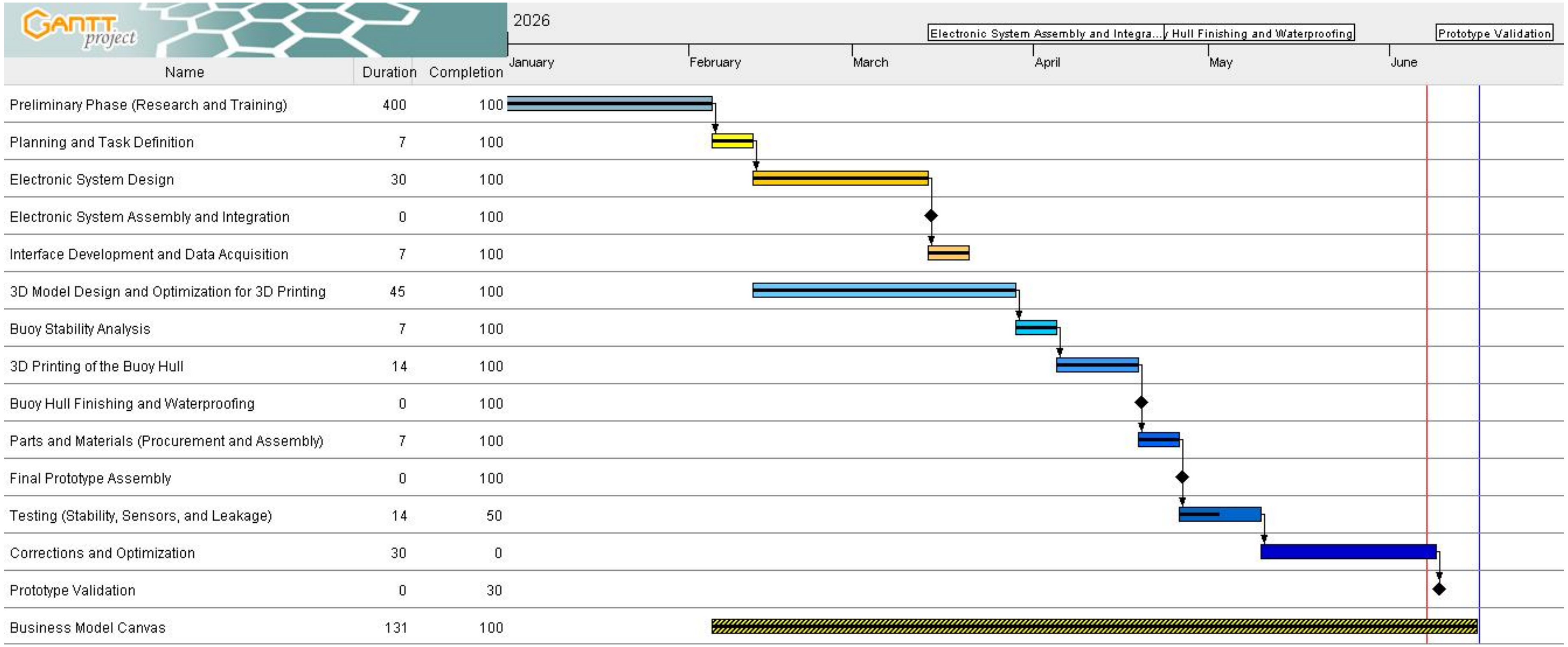


Figure 7: Project planning, (phase 1)

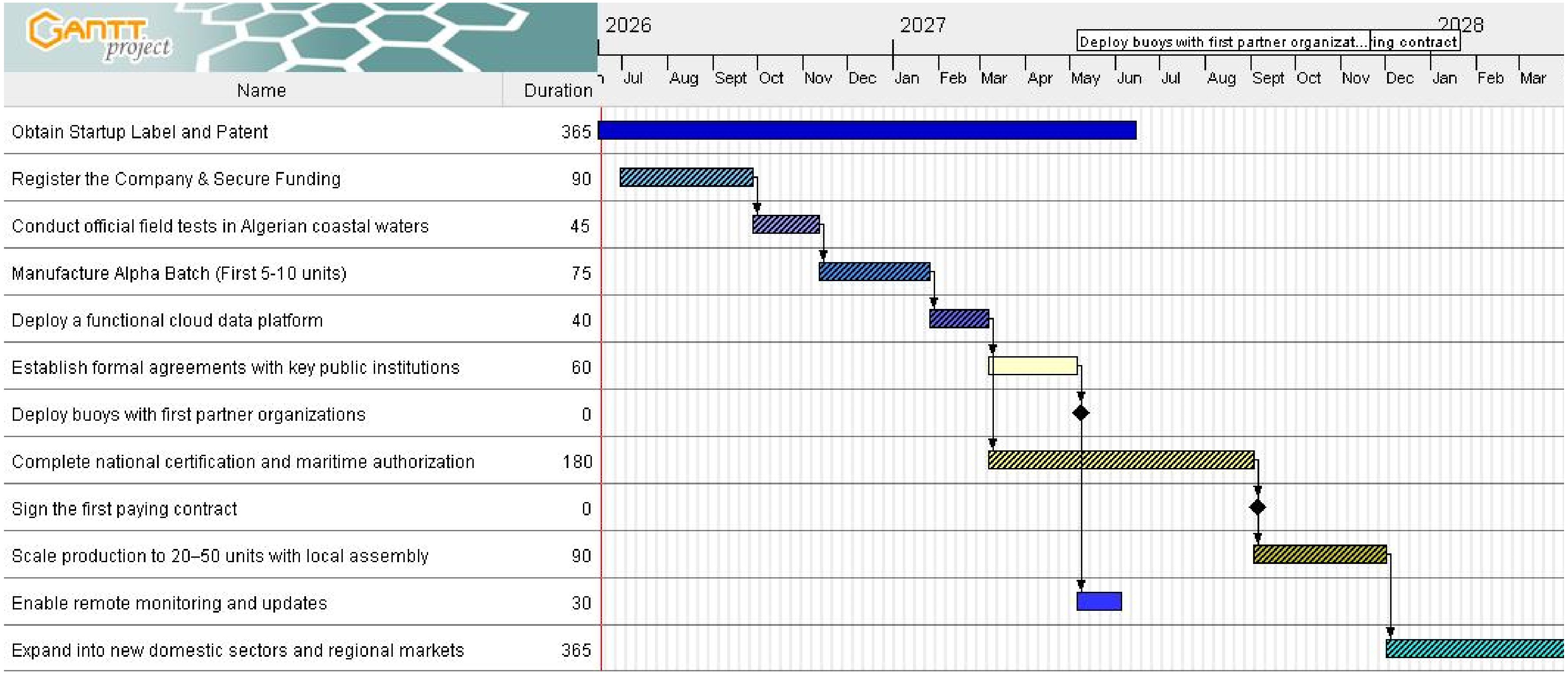


Figure 8:Startup planning (phase 2)

Second Axis: Innovative Aspects

1. Nature of Innovations:

The project's innovation operates at both the technological and market levels.

At the market level, the few oceanographic monitoring systems present in Algeria are exclusively imported, prohibitively expensive (at around **15000000 DA** per unit)[2], and typically deployed only for short missions, their high logistical demands, specialized maintenance requirements, and dependence on foreign servicing making continuous long term deployment practically unviable, the project directly addresses this gap by introducing a locally designed, autonomously operating buoy that can be permanently deployed, maintained domestically, and scaled across multiple coastal sites without the logistical overhead of imported systems, making long term coastal monitoring operationally and economically viable for local institutions.

At the technological level, the innovation lies in three deliberate design choices, a scalable hull architecture spanning 30 cm to 1 m that adapts to deployment conditions without any architectural redesign, an array of multiple IMU units processed through a Madgwick sensor fusion filter for high accuracy wave characterization, an approach that also opens the door to future AI based wave modeling and prediction, and a fully integrated multi-parameter sensor suite covering physical, chemical, and biological ocean parameters within a single compact, locally manufacturable platform.

Together, these characteristics position the project as a locally owned, technically credible, and economically relevant response to a documented and currently unmet need.

2. Innovation Areas:

Overall, the project's innovation spans the following dimensions:

- A scalable, locally manufactured oceanographic buoy platform, the first of its kind in Algeria, eliminating dependence on imported systems and their associated logistical constraints.

- A multi-IMU wave sensing architecture processed through a Madgwick fusion filter, delivering high-accuracy wave characterization and providing a foundation for the integration of AI-based wave analysis, pattern recognition, and predictive modeling directly on or alongside the platform.

- A fully integrated multi parameter sensing capability covering physical, chemical, and biological ocean parameters within a single compact, field deployable system, producing the rich, continuous datasets that AI and machine learning models require to be meaningful.

- A contribution to Algerian technological sovereignty in marine science, replacing a critical dependency on foreign instrumentation with a domestically owned, maintainable, and continuously improvable solution, one designed from the outset to evolve with advances in embedded AI and edge computing.

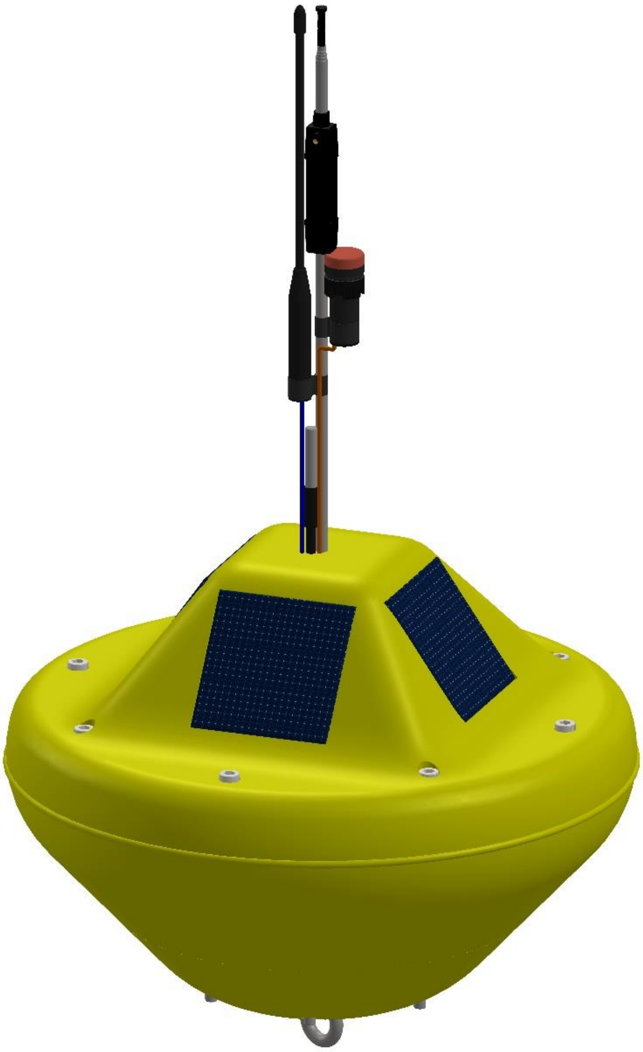


Figure 9: buoy's 3D model

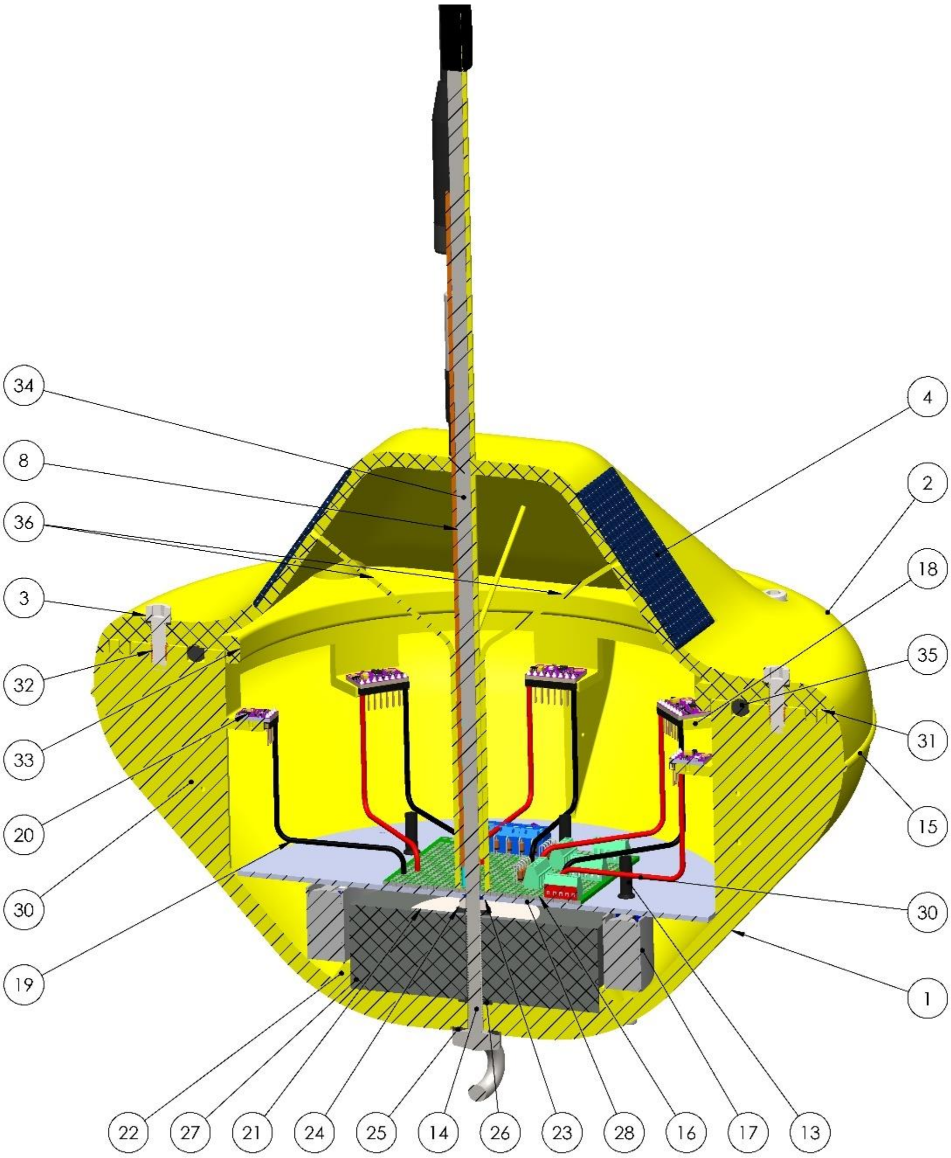


Figure 10:Isometric view of the Buoy's cross section showcasing its internal architecture

Third Axis: Strategic Market Analysis

1. Market Segment:

1.1 Potential Market:

The potential market primarily includes institutions and companies involved in marine infrastructure, maritime operations, and navigation safety in Algeria and African coastal regions, these stakeholders require reliable and continuous oceanographic data for port operations, offshore infrastructure management, coastal engineering projects, maritime navigation, and operational risk assessment.

The increasing development of ports, coastal infrastructure, and offshore activities creates a growing demand for real time marine monitoring solutions capable of improving safety, operational efficiency, and decision making processes.

The project also targets institutions involved in environmental monitoring, coastal management, and scientific research, including universities, research laboratories, and environmental agencies, these organizations require accurate oceanographic data for climate studies, marine ecosystem monitoring, coastal dynamics analysis, and environmental assessment.

As part of the study, an interview was conducted with the Director of the National Office of Maritime Signaling (ONSM), who provided insights into operational needs for oceanographic data, He also highlighted the high cost of foreign oceanographic buoys and noted that their use is often limited to short term deployments due to their expense relative to mission duration, He further confirmed the clear need for such a system in Algeria and expressed interest in the proposed solution as a potential future client for the project.

1.2 Target Market:

The primary target market comprises public and private engineering consultancies, contractors, and organizations involved in the design, construction, operation, and monitoring of marine and coastal infrastructure, including:

- Maritime Studies Laboratory **(LEM)**
- Hydro-Marine Engineering **(HMI)**
- National Agency for the Realization of Port Infrastructure **(ANRIP)**
- **GITRAMA Group, through its subsidiaries:**
    - Mediterranean Marine Works Company **(MEDITRAM)**
    - Algerian Company for Dredging and Hydraulic Port Infrastructure **(ALDIPH)**
    - Eastern Maritime Works Company **(SOTRAMEST)**
    - Western Maritime Works Company **(SOTRAMO)**

Figure 11 : LEM Logo

Figure 12: HMI Logo

Figure 13:ANRIP Logo

Figure 14:GITRAMA Group Logo

Figure 15: MEDITRAM Logo

Figure 16: ALDIPH Logo

Figure 17: Logo SOTRAMO

Figure 18:SOTRAMEST Logo

- **National Maritime Institutions and Authorities**

  The proposed system is also intended to serve national maritime institutions and authorities involved in maritime safety, navigation, coastal management, marine operations, and the monitoring of Algeria's maritime domain, including:

- Algerian Navy **(Forces Navales Algériennes)**
- Hydrographic Service of the Naval Forces **(SHFN)**
- National Office of Maritime Signaling **(ONSM)**
- Ministry of Transport
- Port Authorities

- Algerian Coast Guard

Figure 19: Algerian navy logo

Figure 20: SHFN logo

Figure 21: ONSM logo

Figure 22:Ministry of Transport Logo

Figure 23: Port of Algiers enterprise Logo

Figure 24: Algerian Coast Guard Logo

National institutions and authorities responsible for coastal and environmental management:

This category includes national institutions and governmental bodies responsible for coastal zone management, environmental protection, marine ecosystem monitoring, and the sustainable regulation of natural resources along the Algerian coastline, These organizations play a key role in coastal resilience, pollution control, and environmental governance, the main institutions include:

- National Coastal Commission **(CNL)**
- Ministry of Environment and Quality of Life
- Ministry of Agriculture, Rural Development and Fisheries
- National Agency of climate changes **(ANCC)**
- National Observatory of Environment and Sustainable Development **(ONEDD)**
- National Meteorological Office **(ONM)**

Figure 25: CNL Logo

Figure 26:Ministry of Environment and Quality of Life Logo

Figure 27:Ministry of Agriculture, Rural Development and Fisheries Logo

Figure 28: ANCC Logo

Figure 29: ONEDD Logo

Figure 30: ONM Logo

Universities, research centers, and higher education institutions involved in marine, coastal, and environmental studies.

- Ministry of higher education and scientific research
- Universities and Higher Education Institutions specialized in marine sciences, oceanography and environmental sciences.
- National Centre for Research and Development of Fisheries and Aquaculture **(CNRDPA)**

Figure 31:Ministry of higher education and scientific research Logo

Figure 32: CNRDPA Logo

The choice of this target market is based on a preliminary analysis of the needs of Algerian institutions involved in marine monitoring, coastal management, and environmental research, these actors show a strong interest in innovative solutions that provide reliable, real time oceanographic data.

These institutions require accurate marine data to support scientific research, engineering studies, and coastal infrastructure projects such as ports and coastal protection works, which depend on long term wave and environmental datasets that are often unavailable locally.

The lack of continuous and accessible marine data in Algeria is a major limitation for engineers and researchers, the proposed oceanographic buoy addresses this gap by enabling real time data acquisition and supporting the development of long term datasets for analysis and decision-making.

Meteorological and environmental monitoring systems in Algeria also remain limited in marine environments, this solution improves local data availability and supports national efforts in coastal management and environmental observation.

These organizations are directly involved in marine and coastal projects, making them the primary users of such technologies due to their need for continuous data collection and analysis.

In the Algerian context, no local manufacturer currently produces oceanographic buoy systems, the market remains dependent on imported solutions from international companies, making this project a pioneering local initiative in this field.

- **The main direct competitors are international companies:** such as *Sofar Ocean*, *DataWell, Aanderaa Data Instruments*, *Sea-Bird Scientific*, *Nortek* and *Ocean Scientific International Ltd.* These companies provide advanced oceanographic monitoring systems that could be imported and used by research institutions and specialized organizations in Algeria, however, their presence in the local market remains indirect due to high cost and limited accessibility.

Figure 33:Logos of international companies in the field of oceanographic data

- **Indirect competition includes** traditional marine data collection methods used in some research studies, standalone sensors without integrated systems, and partial use of satellite based data for marine observation.
- **Strengths of competitors:** these international companies have strong technological expertise, high precision instruments, and a solid international reputation in marine and oceanographic monitoring, their systems are widely used in advanced scientific and industrial applications.
- **Weaknesses of competitors:** their solutions are very expensive, which limits their accessibility for Algerian institutions, they also depend on importation, which leads to delays in delivery and technical support, in addition, their systems are not always adapted to local coastal conditions and do not offer low cost solutions suitable for academic or small scale projects.

2. Marketing Strategy of the Project:

Our strategy to promote and develop this oceanographic buoy is mainly based on a direct professional and institutional approach, since the project targets companies, research centers, and governmental organizations rather than the general public.

The communication will be carried out mainly through professional channels, especially official emails, technical presentations, and detailed project dossiers sent directly to potential partners and clients.

Instead of traditional media such as television or radio, the focus will be on scientific and industrial visibility, through participation in local and international conferences, marine technology exhibitions, and direct networking with companies working in the field.

The objective is to attract financial and technical partnerships from companies and institutions, including technology firms, environmental agencies, and maritime organizations, which may support the deployment of buoy systems through funding, equipment supply, or collaboration agreements.

Regarding the business model and pricing strategy, the buoy will be positioned as a Skimming pricing strategy, High performance alternative to expensive foreign marine monitoring systems, the goal is to make this technology accessible to developing countries and research institutions while maintaining high reliability and data quality.

Finally, collaboration will be reinforced through formal agreements, contracts, and research partnerships, ensuring long term cooperation with international actors interested in ocean monitoring, climate research, and marine data collection.

Figure 34: A picture of the project team during our participation in CIAMEL 2026, as part of our visibility and marketing strategy.

Fourth Axis: Production and Organizational Plan

1. Overview of the Production Process

The oceanographic buoy is a precision instrument used to collect environmental data (temperature, salinity, wave height, GPS position, etc.) in marine environments, its production combines mechanical engineering, electronics integration, surface treatment, and rigorous quality control.

The manufacturing process is structured around six major phases:

Table 2: manufacturing process

Phase	Name	Key Activity
1	Raw Material Procurement	Sourcing LLDPE/HDPE resin, electronic components, seals, sensors
2	Rotational Molding (Rotomolding)	Mold preparation, heating/rotation cycle, single piece hull production
3	Surface Treatment	UV stabilization, anti-corrosion coating for marine environment
4	Electronics and Sensor Integration	PCB assembly, GPS, sensors, data logger, antennas
5	Assembly and Sealing	Mechanical assembly, O-ring sealing, watertightness tests
6	Conditioning and Packaging	Quality Control tests, certification, packaging, and shipping

2. Raw Material Procurement

2.1 Primary Structural Material, LLDPE Resin for Roto-molding

The primary structural material for the buoy hull is Linear Low Density Polyethylene (LLDPE) resin, specifically selected for rotational molding, the recommended grades for an oceanographic buoy are:

Table 3 : recommended grades for an oceanographic buoy are:

Material	Grade	Characteristics	Application
LLDPE (Hexene copolymer)	Sealite/ Rotoline grade	High ESCR, toughness, flexibility, low environmental impact	Main buoy hull (rotomolding)

LLDPE (Butene copolymer)	General rotomolding grade	Good processability, cost-effective, UV-stabilised	Flotation collar, secondary shells
HDPE foam	Closed-cell, 25–35 kg/m³	Waterproof, lightweight, non-compressible flotation	Internal buoyancy core
HDPE (rigid)	Standard injection grade	Corrosion-resistant, machinable	Hatch covers, mounting frames

2.2 Other Raw Materials

- Stainless steel 316L (bolts, fasteners, marine grade cables)
- EPDM / Viton O-rings and gaskets for IP68 watertight sealing
- UV resistant polycarbonate or tempered glass for sensor windows and solar panel covers
- Copper clad laminate (FR4) for PCBs
- Marine epoxy resin for potting and encapsulation of electronics
- Closed cell HDPE foam (25–35 kg/m³) for internal flotation core

3. Fabrication (Rotational Molding)

3.1 Process Description

The main structural component of the buoy (outer hull, top and bottom domes, collar) is manufactured by Rotational Molding (Rotomolding), this is the dominant and most efficient method for producing large, seamless, hollow plastic parts ideal for marine buoy hulls, our dedicated automatic biaxial rotomolding machine enables consistent, repeatable production cycles with precise temperature and rotation speed control.

Compared to other processes, rotomolding offers:

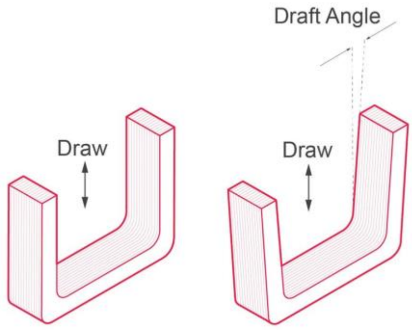
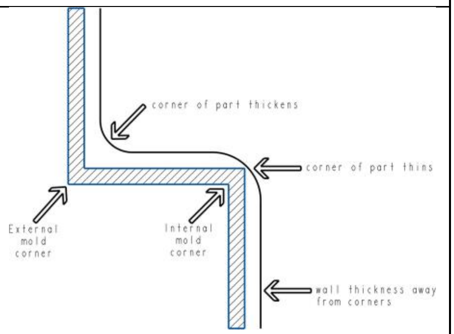
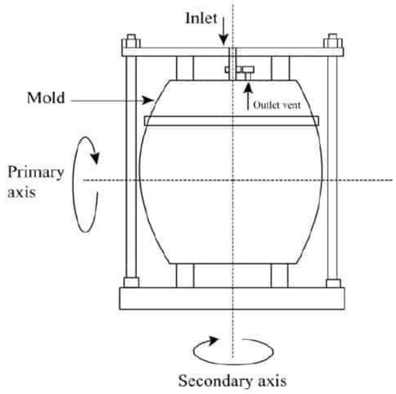
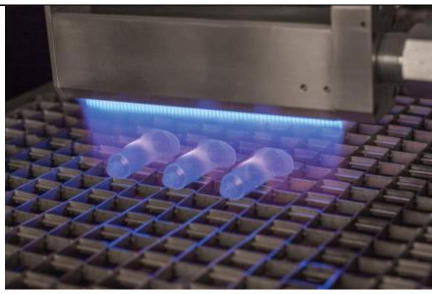
- Lower tooling costs than injection or blow molding (molds in aluminum or steel, no high pressure tooling required).
- Zero material waste, the process uses exactly the powder quantity loaded into the mold.
- Longer mold service life due to the very low pressures involved in the process.
- Single piece seamless hull, no weld lines or joints, eliminating weak points and guaranteeing full watertightness even under impact or immersion.
- Uniform wall thickness achievable across complex 3D geometries by controlling rotation ratio and heating profile.

3.2 Mold Design

The rotomolding mold is manufactured from fabricated steel or cast aluminium (A356). The table below presents the key mold design considerations for the oceanographic buoy hull:

Table 4 : Key mold design considerations

Parameter	**Specification / Value**	
Mold material	Fabricated steel or cast aluminum (A356), polished inner surface	 *Figure 35: rotomolding mold*
Mold type	Two part clamshell mold with removable inserts for ports and through-holes	 *Figure 36:two part mold*
Number of cavities	One cavity per mold (single hull per cycle)	 *Figure 37:mold cavity*

Draft angles	2°–5° on all walls to facilitate part release	 *Figure 38: mold draft angles*
Wall thickness (target)	6–12 mm uniform wall, controlled by powder charge weight	 *Figure 39: mold wall thickness*
Rotation ratio (biaxial)	Main axis, secondary axis ≈ 4:1 (typical), optimized per geometry	 *Figure 40:rotation axis of the mold*
Oven temperature	260–370°C (depending on LLDPE grade and wall target)	 *Figure 41: rotomolding oven*

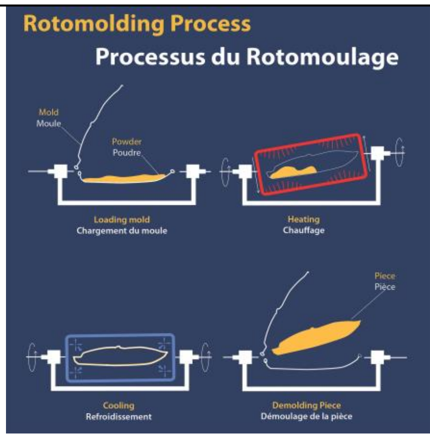
<table>
<tr><td>Cycle time</td><td>20 - 45 min total (heat: 12–20 min, cool: 8–25 min)</td><td>

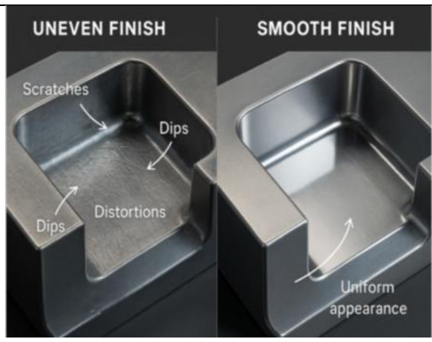
Figure 42:rotomolding cycles</td></tr>
<tr><td>Surface finish (inner)</td><td>Ra 3.2 - 6.3 µm (natural texture from mold surface)</td><td>

Figure 43: surface finishing of the mold</td></tr>
<tr><td>Sealing face finish</td><td>Machined post-process to Ra 0.8–1.6 µm</td><td>
Figure 44: Sealing face finish</td></tr>
</table>

3.3 Rotomolding Process

The following sequence is executed on the automatic biaxial rotomolding machine:

1- **Mold preparation:** Clean mold interior, apply release agent (ex: silicone based or PTFE spray) to all inner surfaces.

2- **Powder loading:** Weigh and load the precise quantity of LLDPE powder (ex: hexene-copolymer grade) into the open mold, close and clamp the mold.

3- **Oven phase (heating):** Transfer mold to the oven arm, rotate biaxially at controlled speed ratio (ex: 4:1), Heat at 280-340°C for 12-20 minutes until the resin fully melts and coats the inner wall uniformly.

4- **Cooling phase:** Transfer mold to the cooling station, continue biaxial rotation while cooling with forced air and/or water mist until part solidifies (8–25 minutes), controlled cooling rate prevents warpage and sink marks.
5- **Demolding:** Open the mold and extract the finished hull, the seamless single piece hull requires no trimming of parting lines.
6- **Flash trimming:** Remove any minor flash at vent holes using hand trimmer or CNC router.
7- **Inspection:** Inspect wall thickness by ultrasonic gauge, check for voids, pinholes, or incomplete fusion, verify weight against specification.

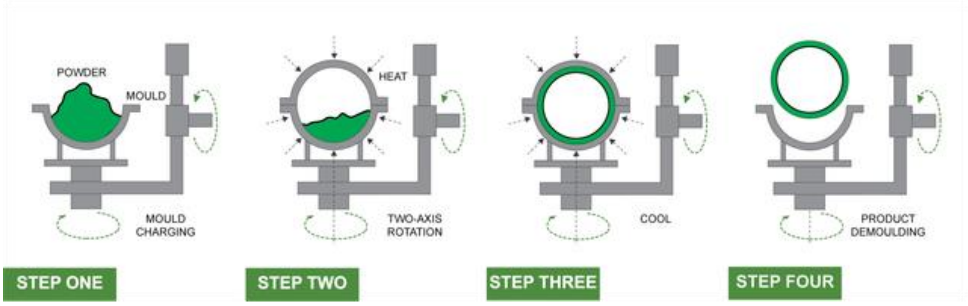


Figure 45: The main rotomolding process steps

3.4 Post-Molding Machining

After rotomolding, the following CNC machining operations are performed on the hull:

- Face milling of sealing flanges to achieve flatness tolerance ±0.10 mm
- Drilling of sensor port openings to precise diameters
- Reaming of O-ring grooves (width and depth to ISO 3601 standard)
- Tapping of bolt holes
- Thread milling for cable penetrators and pressure fittings

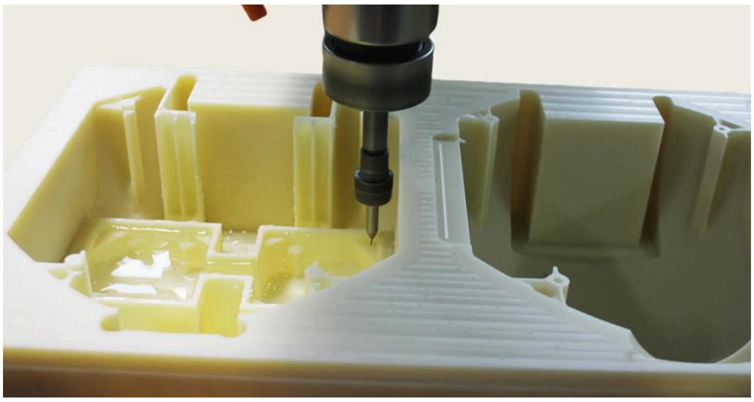


Figure 46 : CNC machining operations

4. Surface Treatment and Anti-Corrosion

Marine environments (saltwater, UV radiation, biofouling) are extremely aggressive, the LLDPE hull requires a specific surface protection system adapted to polyethylene (non-metallic surface):

Table 5: Surface Treatment & Anti-Corrosion specifications

Treatment	Process	Purpose	Thickness
UV Stabilizer (in-resin)	Carbon black or HALS additives compounded in LLDPE	UV degradation resistance over 10+ year service life	Integral (bulk)
Surface flame treatment	Gas flame or corona discharge pass on outer surface	Improve adhesion of paints and coatings	//////////////
Epoxy primer	Spray application, 2 component marine epoxy	Adhesion bond coat over polyethylene	50–75 µm
Polyurethane topcoat	Spray, marine grade (ex: Hempel, Jotun)	UV resistance, color coding, final protection	50–80 µm
Anti-fouling coating	Ablative anti-fouling paint on submerged surfaces	Prevents barnacle and algae growth	100–150 µm

5. Electronics and Sensor Integration

5.1 Electronic Components

The electronic sub-assembly represents the core intelligence of the oceanographic buoy, all components are integrated on a custom designed PCB manufactured by a certified EMS provider to ensure reliability in marine environments.

The system integrates multiple environmental sensors, including:

- Water temperature sensor
- Air temperature sensor
- Wind speed sensor
- Wind direction sensor
- pH sensor
- Dissolved oxygen sensor
- Turbidity sensor
- Salinity sensor
- Chlorophyll concentration sensor

A GNSS/GPS module is used for:

- Real-time positioning of the buoy
- Drift tracking
- Recovery operations

A LoRa communication system is used for:

- Low power data transmission
- Long range communication with coastal stations
- Cloud data transfer (via gateway)

Wave characterization is performed using:

- An array of 8 IMU motion sensors (accelerometers + gyroscopes + magnetometers)
- Data fusion using the Madgwick filter algorithm
- Estimation of wave height, wave direction, and buoy motion dynamics

The power system includes:

- Four marine grade solar panels
- Lithium-ion battery pack
- MPPT (Maximum Power Point Tracking) charge controller
- Continuous 24/7 autonomous energy management

Additional system features include:

- LED status indicators
- Alarm outputs for system faults or low power
- IALA standards compliant signaling light for maritime visibility and navigation safety

Optional equipment:

- Underwater acoustic transponder for deep water positioning and recovery missions

5.2 PCB Assembly Process

1. **Paste:** Solder paste printing on bare PCB (stencil printer).
2. **Pick and Place:** SMD component placement by pick and place robot (0402 to QFP/BGA packages).
3. **Reflow:** Reflow soldering in nitrogen atmosphere oven (peak 250°C, SAC305 lead free solder).
4. **Wave Solder:** Wave soldering for through hole components.
5. **Inspection:** Automated Optical Inspection (AOI) and X-ray inspection for BGA.
6. **Testing:** In-circuit testing (ICT) and functional test.
7. **Coating:** Conformal coating (acrylic or polyurethane) to protect against moisture and salt spray.
8. **Potting:** Potting critical modules with marine epoxy resin (IP68 rating).

6. Mechanical Assembly and Sealing

6.1 Assembly Sequence

1. **Flotation core:** install flotation foam (HDPE closed cell) inside bottom hull section.
2. **Electronics installation:** Mount battery pack, electronics chassis, and cable harnesses inside the hull.

3. **Cable management:** Route and seal all cable penetrators with marine grade cable glands (IP68).
4. **Sensor installation:** Mount sensors in their precision machined ports.
5. **O-ring sealing:** Apply lubricant (Molykote 111 or similar) to all O-ring grooves, install double O-ring seals on all mating flanges.
6. **Final assembly:** Torque all fasteners to specified values (stainless steel bolts) using calibrated torque wrench.
7. **Solar panel:** install solar panels on top dome with UV-resistant silicone sealant.
8. **Mooring attachment:** Attach mooring hardware (shackle, swivel, chain section) to bottom keel.

6.2 Watertightness Tests

The following table summarizes the provisional required watertightness tests and their specifications:

Table 6: watertightness tests and their specifications

Test	Method	Standard	Pass Criteria
Vacuum test	Apply -0.5 bar vacuum for 10 minutes	IP68 / IEC 60529	No pressure loss > 5%
Pressure test	Pressurize to 3 bar air for 15 minutes	Internal QC procedure	No bubbles in water bath
Immersion test	Submerge in freshwater tank at 1 m for 30 min	IP68	No water ingress
Depth pressure test	Pressure vessel to simulate rated depth (ex: 200 m = 21 bar)	ISO 20653	No structural deformation or leakage

7. Quality Control and Testing

7.1 Dimensional and Visual Inspection

- 100% dimensional inspection of machined sealing surfaces with CMM (Coordinate Measuring Machine)
- Wall thickness verification by ultrasonic testing (UT), minimum 3 points per hull
- Visual inspection for molding defects (voids, pinholes, incomplete fusion, warpage)
- Weight check against specification ±2% tolerance

7.2 Functional Tests

The following table presents all the provisional required functional tests and their specifications

Table 7: Functional tests and their specifications

Test	Description	Acceptance
Battery autonomy test	Full charge/discharge cycle, verify 6 months minimum battery life at 1 transmission/hour	Capacity ≥ specification
GPS accuracy test	Open air test, 60 minute fix, compare to reference coordinates	CEP50 ≤ 2.5 m
Sensor calibration	Calibration of temperature, salinity, pH, dissolved oxygen and turbidity sensors using certified reference solutions	Accuracy: ±0.01°C (temp), ±0.01 psu (salinity), sensor specific limits
Communication test	LoRa link test, data packet transmission and receipt confirmation	100% packet delivery in 3 tests
Salt spray test	72 hour salt spray chamber (5% NaCl, 35°C) per ISO 9227	No corrosion or coating delamination
Drop test	Drop from 1 m height on concrete slab (simulates handling)	No cracking, no loss of function

8. Conditioning and Packaging

8.1 Pre-Shipment Preparation

- Clean all external surfaces with fresh water and anti-salt rinse.
- Apply protective film on solar panels and optical sensor windows.
- Power-off the unit in shipping mode (low-power standby)
- Install handling/shipping plugs on all sensor ports.
- Attach serialized QC label, certification label (CE, FCC, ICES), and asset tracking QR code.

8.2 Packaging

- Individual custom foam lined wooden crate or heavy-duty plastic transit case
- Silica gel desiccant packs placed inside to prevent condensation.
- Shock indicators (ex: Shock Watch) attached to outer crate.
- Complete documentation pack: calibration certificates, test reports, user manual, mooring guide
- Mooring accessories (shackles, rope, chain section) packed in labelled bag separate inside crate.

8.3 Shipping Requirements

- Classify as non-hazardous equipment (battery must comply with IATA PI 965/966 if air freight)
- Export documentation: Certificate of Origin, Commercial Invoice, Packing List

- Storage conditions: 5–35°C, relative humidity < 70%, no direct sunlight

9. Production Timeline Summary

Table 8: production timeline

Phase	Activity	Duration (per unit)	Key Equipment
1	Raw material procurement and reception control	1–2 days	Spectrometer (resin verification), incoming QC scale
2	Rotomolding (mold prep and cycle)	0.5–1 day	Automatic rotomolding machine (biaxial carousel), oven
2b	Post-mold machining of sealing faces and ports	0.5–1 day	CNC milling center, CMM
3	Surface treatment (flame treat + coating)	2–3 days	Flame treatment unit, spray booth, UV cure station
4	PCB assembly and electronics prep	1 day (outsourced)	SMT line, AOI, reflow oven
4b	Sensor calibration	0.5–1 day	Calibration bath, reference instruments
5	Mechanical assembly	0.5 day	Torque tools, O-ring grease station
5b	Watertightness & pressure tests	3–4 days	Pressure test bench, water immersion tank
6	Functional tests and QC	0.5–1 day	GPS test receiver, comms tester, salt spray chamber
7	Packaging and documentation	0.5 day	Custom crate, label printer, DMS

10. Procurement

10.1 Purchasing Policy:

Our purchasing policy covers three categories as defined in the oceanographic buoy production process:

Raw Materials:

The primary structural material of the hull is marine grade, UV stabilized High Density Polyethylene (HDPE), used for the main hull manufactured by injection molding, LLDPE powder resin is used for the rotomoulding process (automatic biaxial machine integrated in our investment plan at 1078382 DZD), other raw materials include glass filled nylon PA66-GF30 for structural brackets, UV resistant ASA/ABS blend for the top dome, closed cell HDPE foam for the internal buoyancy core, and marine epoxy resin for electronics encapsulation.

Materials and Supplies:

Stainless steel 316L (marine grade bolts, fasteners, mooring fittings), EPDM/Viton O-rings (IP68 watertight sealing), FR4 copper clad laminate (PCBs), marine anti-corrosion coatings (epoxy primer + polyurethane topcoat, Hempel or Jotun), anti-fouling paint for submerged surfaces, UV-resistant silicone sealant.

Equipment:

The automatic biaxial rotomoulding machine is the central investment (1078382 DZD according to our financial plan), it is complemented by a CNC machining center for post-molding operations (flange face milling, sensor port drilling), a pressure and watertightness test bench, a surface treatment spray booth, and a salt spray chamber (ISO 9227).

Most Important Suppliers:

Table 9: main suppliers

Category	**Supplier Type**	**Material / Component**
Petrochemical supplier	Polymer resin distributor	Marine grade HDPE, LLDPE rotomoulding powder, ASA/ABS, PA66-GF30
Electronics distributor	EMS provider / IoT modules	IMU sensors (GY-9250 ×8), GPS/GNSS, LoRa module, ESP32/STM32 microcontroller, Li-Ion batteries
EMS subcontractor (PCB)	External PCB assembly	SMT line, AOI, reflow IP68-compliant PCB
Sealing and gasket supplier	Industrial seal manufacturer	EPDM/Viton IP68 O-rings, Dowty washers, brass threaded heat-set inserts
Marine coatings supplier	Industrial paint distributor	Epoxy primer, polyurethane topcoat, anti-fouling paint
Foam and composites supplier	Buoyancy materials distributor	Closed-cell HDPE foam, PLA filament for prototyping

10.2 Labor (Main d'Œuvre):

Our team does not require large scale industrial staffing, The founding team covers all critical functions, and recruitment will scale progressively based on revenue milestones, keeping our operational structure lean and cost efficient.

Table 10: Working staff and positions.

Position / Profile	Number	Specialization
Electrical engineer	1	Electronic design, PCB development, sensor integration, embedded systems, power management
Mechanical/3D modelling engineer	1	CAD modelling, mechanical design, structural analysis, 3D printing, design for manufacturing (DFM)
Software developer / web designer	1	Firmware development, IoT communication, Python data processing, web platform development, database integration
Rotomolding/production technician	2	Rotomolding machine operation, mold setup, demolding, production process monitoring, buoy assembly, quality control
Project manager	1	Project planning, budget and schedule management, team coordination, risk management, stakeholder communication
Accountant/business and legal consultant	1	Financial management, accounting, business planning, contracts, intellectual property, regulatory compliance
Field deployment/testing technician	2	Prototype assembly, O-ring sealing, waterproofing tests, IP68 pressure testing, CTD calibration, field deployment, maintenance, data collection

11.Key Partners

As a startup project, our partnerships are lean but strategic, each partner has been selected for its direct impact on cost reduction, technical access, market entry, or regulatory compliance without adding structural weight to the project.

Suppliers:

Direct procurement of electronic components (sensors, GPS, IMU, IoT/Iridium modules), HDPE/LLDPE resins, and structural materials, without intermediaries, this is our primary competitive advantage in terms of cost and lead time.

University incubators:

We already benefit from the support of the Blue Incubator (ENSSMAL), which provided us with an innovation environment, access to equipment, and quality accompaniment throughout our development, we further recommend applying to more startup incubation organisms whose incubation spaces can significantly reduce our rent expenses, as identified in our optimized financial plan.

Academic Supervision:

ENSSMAL and HNS-RE2SD provide technical supervision and access to laboratory equipment that proved indispensable to the realization of the prototype at no cost to the project.

Financing Structures:

Our total financing requirement has been reduced by -34.6% through optimization, targeted sources include: ASF and NESDA (zero interest startup loans), MESRS/DGRSDT (research and innovation grant for scientific equipment), Algeria Venture / Guarantee Fund (bank loan guarantee), and the Horizon Europe Program (Euro-Mediterranean maritime and climate tech call for projects).

Confirmed Institutional Clients:

Following our market study, the director of the ONSM confirmed the genuine need for such a system in Algeria and expressed direct interest as a potential future client, additional target partners identified and documented are presented in more detail in the third axis.

Certification and Regulatory Bodies:

For an oceanographic buoy deployed in Algerian and international maritime waters, the following regulatory and certification organizations are identified as key institutional partners whose frameworks, standards, and approvals govern our product's legality, safety, and market acceptance:

- **Intellectual Property Protection (INAPI):** INAPI is responsible for the protection of intellectual property rights, including patents, industrial designs, trademarks, and software related innovations, The buoy system, covering mechanical design, sensor integration architecture, embedded firmware, and communication protocols can be protected through patent filing and industrial design registration, this ensures exclusivity over the technology and strengthens its commercial positioning for future scaling or international licensing.
- **Algerian National Bodies: IANOR** (*Institut Algérien de Normalisation*), the Algerian national standards body, responsible for issuing and enforcing technical standards applicable to locally manufactured electronic and marine equipment, compliance with IANOR standards is required for any product seeking official homologation in Algeria.
- **Directorate General of Customs (DGD):** for import clearance of electronic components, sensors, and specialized equipment procured internationally, ensuring compliance with Algerian customs regulations and avoiding supply chain delays.
- **Ministry of Transport / General Directorate of the Merchant Marine (DGMM)**: governs the deployment of any object or structure in Algerian maritime waters, including moored buoys, authorization from DGMM is required before any coastal or offshore deployment.

- **ONEDD (National Office for Environment and Sustainable Development**) : regulatory body for environmental monitoring activities, as our buoy collects environmental and oceanographic data in Algerian coastal zones, alignment with ONEDD frameworks and potential data sharing agreements are both a regulatory requirement and a market opportunity.
- **International Standards and Certification Frameworks:**

- **IEC (International Electrotechnical Commission)**: our electronics and embedded systems are designed in compliance with IEC standards, particularly IEC 60529 (IP68 ingress protection rating for waterproofing), which is a core technical specification of the buoy.
- **ISO (International Organization for Standardization)**: relevant standards include ISO 9001 (quality management), and oceanographic instrument standards under the ISO/TC 8 (Ships and Marine Technology) and ISO/TC 147 (Water Quality) committees, which frame the measurement reliability and data quality requirements of our sensors.
- **WMO (World Meteorological Organization):** defines data quality and formatting standards for oceanographic and meteorological observations. Compliance with WMO standards, particularly the JCOMM (Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology) data formats, ensures that data produced by our buoy is interoperable with international oceanographic databases and accepted by institutional clients such as ONM.
- **IOC-UNESCO (Intergovernmental Oceanographic Commission):** the international body coordinating ocean observation systems globally, including the GOOS (Global Ocean Observing System) and the Argo program, aligning our data outputs with IOC-UNESCO standards positions our system as compatible with international research networks and opens doors to Euro-Mediterranean collaborative projects.
- **ITU (International Telecommunication Union)**: governs satellite and radio frequency allocations internationally. Our Iridium SBD communication module operates under ITU-regulated frequency bands, and compliance is mandatory for legal satellite data transmission.
- **IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities):** sets standards for maritime signaling and buoy marking, including visual identification, light characteristics, and radar reflectivity requirements. Relevant for our buoy's physical design and maritime safety compliance, particularly given our partnership with ONSM.
- **CE Marking (European Conformity)**: while not mandatory for the Algerian domestic market, CE marking under the EU's Radio Equipment Directive (RED 2014/53/EU) and the Marine Equipment Directive (MED 2014/90/EU) will be pursued to enable future export to European and Mediterranean markets, consistent with our Horizon Europe program ambitions.

Fifth Axis: Financial Plan

1. Initial Investments:

Each investment item was carefully reassessed to identify cost-saving opportunities. Redundant expenditures were consolidated, proprietary software licenses were replaced with open-source alternatives, and office and marketing budgets were adjusted to support a digital first strategy.

Table 11: Initial investment Plan

A. EQUIPMENT FOR PRODUCTION				
Item / Description	**Amount (DA)**	**Amort. (yrs)**	**Amort./yr (DA)**	**Supplier / Link**
Biaxial Automatic Rotomolding Machine	1 102 500	5	220 500 DA	https://www.rotomolding-machine.com/sale-48866294-adjustable-rotating-speed-rotary-moulding-machine-rotomolding-equipment-fast-paced-production.html
Aluminum mold A356 for buoy hull 1 m (€3 000 × 147 DA/€)	441 000	5	88 200 DA	Local mechanical mold maker / import
CNC machining center (sealing flange milling, sensor port drilling)	350 000	5	70 000 DA	Local Algerian machinery market (Rouiba / Annaba)
Pressure and IP68 seal test bench (tank + pump + gauge)	120 000	5	24 000 DA	Local hydraulic equipment / AliExpress industrial
Surface treatment booth (epoxy + anti-fouling polyurethane spray)	180 000	5	36 000 DA	Local industrial painting equipment
Salt spray chamber ISO 9227 (NaCl 5% / 72 h corrosion test)	95 000	5	19 000 DA	Lab test equipment, import China
FDM 3D Printer Anycubic Kobra 2 Max (420×420×500 mm), prototyping	65 000	3	21 667 DA	Algiers IT market / AliExpress
Mechanical tooling (torque wrench, drill press, O-ring tool, grease station)	55 000	3	18 333 DA	Local industrial hardware

Computing equipment (×2 workstations, ESP32/STM32 dev boards, cabling)	250 000	3	83 333 DA	Algiers IT market / local suppliers
Sensor's calibration bath	79 000	5	15 800 DA	Import metrology equipment, Didactic Africa / EQUILAB
Marine deployment equipment (dive suit, test anchor, chain, shackles)	80 000	3	26 667 DA	Maritime equipment - local port suppliers
SUB-TOTAL EQUIPMENT	**2 817 500 DA**	—	**623 500 DA**	—
B. R&D, SOFTWARE, IDENTITY AND CERTIFICATION				
Item / Description	**Amount (DA)**	**Amort. (yrs)**	**Amort./yr (DA)**	**Supplier / Link**
Embedded systems R&D, Madgwick algorithm, ESP32-S3 firmware development	0	—	—	zero cost (predeveloped prototype)
CAD Software (SolidWorks)	610 344	—	—	https://www.solidworks.com
Monitoring data application, Grafana OSS + InfluxDB + lightweight React UI	350 000	—	—	Local Algerian freelance developer
Visual identity, logo, presentation materials (digital first approach)	80 000	—	—	Algerian design studio / local freelance
Professional website + 3 year hosting (low cost hosting + templates)	65 000	—	—	Local digital agency / Algerian hosting provider
Technical file IANOR + ARPT (LoRa / IoT radio module homologation Algeria)	50 000	—	—	IANOR Algiers + ARPT (regulatory dossier fees)
Intellectual property filing (INAPI)	0 (paid by ENSSMAL)	—	—	INAPI (National Algerian Institute of Industrial Property)

SUBTOTAL, R&D, SOFTWARE AND CERTIFICATION	**1 200 344 DA**			
TOTAL INVESTMENT (OPTIMIZED −26.7%)				**401 7 844 DA**
TOTAL ANNUAL DEPRECIATION ALLOWANCE				**623 500 DA / yr**

2. Production Costs

This table presents all variable costs associated with the production, testing, deployment and annual operation of a single oceanographic buoy unit, fixed costs (payroll, equipment depreciation, premises) are excluded and detailed separately in the Financial Plan.

Table 12:Annual Variable Production Cost Estimation

1. RAW MATERIALS AND STRUCTURAL COMPONENTS			
Item / Description	**Qty**	**Unit Price (DZD)**	**Total (DZD)**
HDPE granules + UV orange colorant (rotomolding resin)	1 lot	45 000 DZD	**45 000 DZD**
316L stainless steel structure + marine aluminum rings *(Brackets, sealing flange, supports)*	1 lot	38 000 DZD	**38 000 DZD**
Expanded polyurethane foam + marine epoxy resin *(Internal buoyancy fill, closed cell grade)*	1 lot	22 000 DZD	**22 000 DZD**
IP68 solar LED lantern + 40 W solar panel ×4 *(IALA compliant signaling, UV-stabilized housing)*	1 lot	148 000 DZD	**148 000 DZD**
LiFePO4 20 Ah battery pack + MPPT controller + UV cabling *(Energy autonomy; explosion proof grade)*	1 lot	62 000 DZD	**62 000 DZD**
AIS passive transponder + MC4 waterproof connectors *(Maritime safety and position tracking)*	1 lot	70 000 DZD	**70 000 DZD**
Ø18 mm galvanized mooring chain (30 m) + Ø5 mm chain + ×8 shackles *(Galvanic mooring system, depth rated)*	1 lot	72 000 DZD	**72 000 DZD**
Concrete steel anchor body (500 kg) + stainless inox eyebolts *(Armed concrete + ×4 stainless eyebolts)*	1 lot	98 000 DZD	**98 000 DZD**

Fluorescent marine paint + anti-fouling sub-marine coating *(Hempel/Jotun antifouling + epoxy primer)*	1 lot	38 000 DZD	**38 000 DZD**
A4 stainless bolts, Viton O-rings, engraved signage plate *(Bulk fasteners + joints + regulatory ID plate)*	1 lot	15 000 DZD	**15 000 DZD**
SUBTOTAL, Raw Materials and Structural Components			**608 000 DZD**
2. ELECTRONICS, SENSORS AND PCB			
Item / Description	**Qty**	**Unit Price (DZD)**	**Total (DZD)**
ESP32-S3 MCU + STM32 co-processor *(Embedded core; dual-bank firmware OTA)*	1 lot	18 000 DZD	**18 000 DZD**
IMU MPU-9250 ×8 (Madgwick wave fusion array) *(Wave characterization, non-compressible)*	1 lot	28 000 DZD	**28 000 DZD**
CTD sensor suite (Atlas EZO-EC + EZO-DO + DS18B20), (*Conductivity, temperature, depth calibrated)*	1 lot	45 000 DZD	**45 000 DZD**
GPS module u-blox NEO-7M *(Position and time synchronization)*	1 lot	8 000 DZD	**8 000 DZD**
LoRa SX1276 module + marine-grade antenna *(Long range telemetry, ARPT-certified)*	1 lot	12 000 DZD	**12 000 DZD**
pH, DO, turbidity, salinity, chlorophyll sensors *(Atlas Scientific EZO suite + DFRobot SEN0189)*	1 lot	55 000 DZD	**55 000 DZD**
Custom 2 layer PCB manufacturing (*Per-unit batch, includes SMT component placement)*	1 lot	22 000 DZD	**22 000 DZD**
Electronic consumables: solder, cables, connectors, heat-shrink, conformal coating *(Per-unit variable portion)*	1 lot	9 000 DZD	**9 000 DZD**
Potting compound (silicone/epoxy), electronics waterproofing *(Per PCB unit, non-compressible quality item)*	1 lot	9 600 DZD	**9 600 DZD**
SUBTOTAL, Electronics, Sensors and PCB			**206 600 DZD**
3. QUALITY CONTROL AND TESTING			
Item / Description	**Qty**	**Unit Price (DZD)**	**Total (DZD)**

IP68 watertightness pressure test tank + pump + gauge	1 lot	8 000 DZD	**8 000 DZD**
Sensor calibration (CTD, pH, DO, turbidity, GPS)	1 lot	15 000 DZD	**15 000 DZD**
floating and stability test (dock / tank)	1 lot	10 000 DZD	**10 000 DZD**
Electronic functional test, LoRa link, GPS fix, full sensor stream	1 lot	6 000 DZD	**6 000 DZD**
Test consumables (reference solutions, O-rings, test fittings)	1 lot	3 000 DZD	**3 000 DZD**
SUBTOTAL, Quality Control & Testing			**42 000 DZD**
4. FIELD DEPLOYMENT AND LOGISTICS			
Item / Description	**Qty**	**Unit Price (DZD)**	**Total (DZD)**
Vessel / boat rental for deployment + recovery	1 lot	35 000 DZD	**35 000 DZD**
Fuel for field mission (vehicle + vessel)	1 lot	18 000 DZD	**18 000 DZD**
Outbound freight / transport packaging	1 lot	12 000 DZD	**12 000 DZD**
Import duties and customs (electronic components)	1 lot	20 000 DZD	**20 000 DZD**
Field consumables, ropes, shackle spares, cable ties, silicone grease	1 lot	8 000 DZD	**8 000 DZD**
Maritime permit and coastal zone authorization fees	1 lot	6 500 DZD	**6 500 DZD**
SUBTOTAL, Field Deployment and Logistics			**99 500 DZD**
5. VARIABLE OVERHEADS (PER UNIT SHARE)			
Item / Description	**Qty**	**Unit Price (DZD)**	**Total (DZD)**
Electricity, rotomolding oven + CNC machining + reflow oven	1 lot	18 000 DZD	**18 000 DZD**
Compressed air, cooling water, mold release agents	1 lot	5 000 DZD	**5 000 DZD**
CNC cutting tools, drill bits, inserts	1 lot	7 000 DZD	**7 000 DZD**
Cloud hosting per deployed buoy	1 lot	12 000 DZD	**12 000 DZD**
IoT data plan, LoRa + cellular backup	1 lot	10 000 DZD	**10 000 DZD**
Packaging	1 lot	6 000 DZD	**6 000 DZD**
Waste disposal, HDPE offcuts, solvents, epoxy residues	1 lot	3 000 DZD	**3 000 DZD**

Annual maintenance kit for leased buoy	1 lot	19 000 DZD	**19 000 DZD**
SUBTOTAL, Variable Overheads			**80 000 DZD**
TOTAL VARIABLE PRODUCTION COST (1 BUOY)			**1 036 100 DZD**

Table 13: Annual Fixed Production Cost Estimation

6. PERSONNEL (PAYROLL AND EMPLOYER CHARGES)			
Item / Description	**Qty**	**Monthly Salary per position (DA)**	**Total (DA)**
Electrical engineer	1	140 000	**140 000**
Mechanical/3D modelling engineer	1	140 000	**140 000**
Software developer / web designer	1	120 000	**120 000**
Rotomolding/production technician	2	80 000	**160 000**
Project manager	1	135 000	**135 000**
Accountant/business and legal consultant	1	135 000	**135 000**
Field deployment/testing technician	2	65,000	**130 000**
TOTAL annual Salaries and employer charges	1 lot	**11 520 000 DA**	
SUBTOTAL, Personnel (Payroll and Employer Charges)			**11 520 000 DA**
7. PREMISES AND OPERATING UTILITIES			
Item / Description	**Qty**	**Unit Price (DA)**	**Total (DA)**
Rent, production facility / office	1 lot	200 000 DA	**2 400 000 DA**
Operating utilities, electricity, internet (*Charges d'exploitation*)	1 lot	31 667 DA	**380 004 DA**
SUB-TOTAL, Premises and Operating Utilities			**2 780 004 DA**
8. PROFESSIONAL AND COMMERCIAL SERVICES			
Item / Description	**Qty**	**Unit Price (DA)**	**Total (DA)**
Accounting and legal counsel (*Expert comptable et conseil juridique*)	1 lot	1 220 000 DA	**1 220 000 DA**

Commercial agent (*Agent commercial*)	1 lot	80 000 DA	**960 000 DA**
SUBTOTAL, Professional and Commercial Services			**2 180 000 DA**
9. EQUIPMENT DEPRECIATION			
Item / Description	**Qty**	**Unit Price (DA)**	**Total (DA)**
Annual depreciation allowance (per Table 11, Initial Investment Plan)	1 lot	623 500 DA	**623 500 DA**
SUBTOTAL, Equipment Depreciation			**623 500 DA**
TOTAL ANNUAL FIXED PRODUCTION COST			**17 103 504 DA**

Table 14: Total Annual Production Cost, Summary (Year 1)

TOTAL ANNUAL PRODUCTION COST, SUMMARY (YEAR 1)	
Item / Description	**Amount**
Total Annual Fixed Production Cost (Table 13)	**17 103 504 DA**
Variable Production Cost per Buoy (Table 12)	**1 036 100 DZD**
Assumed Year 1 production volume	**9 buoys**
Total Annual Variable Production Cost, Year 1 (9 × 1 036 100 DZD)	**9 324 900 DZD**
TOTAL ANNUAL PRODUCTION COST, YEAR 1	**26 428 404 DZD**

3. Projected Income Statement:

Table 15: 3 Year Sales and Fleet Deployment Plan

INDICATOR	**YEAR 1**	**YEAR 2**	**YEAR 3 (+ AFRICA)**
A. Units Produced and Sold			
Total buoys produced	9	14	28
Direct sales, Algeria	2	3	4
Export sales, Africa	0	0	8
New leasing units	4	6	9
New DaaS (Data as a Service) units	3	5	7
B. Active Fleet (Cumulative)			

Buoys under leasing contract (cumul.)	4	10	19
Buoys active under DaaS (cumul.)	3	8	15
TOTAL active buoys deployed	7	18	34

Table 16: Projected Income Statement

LINE ITEM	Year 1	Year 2	Year 3
10. REVENUE (Turnover)			
Direct sales, buoys (Algeria)	10 000 000 DZD	15 000 000 DZD	20 000 000 DZD
Export sales, buoys (Africa)	—	—	40 000 000 DZD
Leasing revenue (300 000 DZD/mo) + Leasing maintenance (200 000/yr)	18 800 000 DZD	38 000 000 DZD	72 600 000 DZD
DaaS revenue (1 000 000 DZD/yr per buoy)	3 000 000 DZD	8 000 000 DZD	15 000 000 DZD
TOTAL REVENUE (Turnover)	**31 800 000 DZD**	**61 000 000 DZD**	**147 600 000 DZD**
1. VARIABLE COSTS (COST OF GOODS SOLD)			
New buoys produced	9 units	14 units	28 units
Variable unit cost (per buoy)	1 036 100 DZD	1 036 100 DZD	1 036 100 DZD
Total variable production cost	9 324 900 DZD	14 505 400 DZD	29 010 800 DZD
TOTAL VARIABLE COSTS	**9 324 900 DZD**	**14 505 400 DZD**	**29 010 800 DZD**

GROSS PROFIT	**22 475 100 DZD**		**46 494 600 DZD**	**118 589 200 DZD**
Gross margin rate	55.9%	68.3%		80.3%
2. FIXED OPERATING EXPENSES				

Payroll, 9 employees (salaries + employer contributions)	11 520 000 DZD	11 520 000 DZD	11 520 000 DZD
Premises and utilities (rent + electricity, internet…)	2 780 004 DZD	2 780 004 DZD	2 780 004 DZD
Professional services (accountant + commercial agent)	2 180 000 DZD	2 180 000 DZD	2 180 000 DZD
Development and expansion (multi-wilaya / Africa export)	600 000 DZD	1 500 000 DZD	3 500 000 DZD
TOTAL FIXED EXPENSES	**17 103 004 DZD**	**17 980 004 DZD**	**19 980 004 DZD**

EBITDA (Earnings before depreciation and tax)	**5 372 096 DZD**	**28 514 596 DZD**	**98 609 196 DZD**
EBITDA margin	19.8%	50.7%	65.3%
3. FROM EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization) TO NET INCOME			
Depreciation and amortization	623 500 DZD	623 500 DZD	623 500 DZD
OPERATING INCOME (EBIT)	**4 739 596 DZD**	**27 891 096 DZD**	**97 985 696 DZD**
PRE-TAX INCOME (EBT)	**4 739 596 DZD**	**27 891 096 DZD**	**97 985 696 DZD**

NET INCOME	**4 739 596 DZD**	**27 891 096 DZD**	**97 985 696 DZD**
Net margin	8.2%	50.1%	72.7%

4. Cash Flow Plan:

To monitor and forecast monthly cash inflows and outflows (cash receipts and payments), a cash flow plan has been developed for the Smart Oceanographic Buoy Project Table 17, this financial planning tool enables efficient management of the project's liquidity by tracking revenues generated from buoy sales, leasing agreements, and environmental monitoring services, as well as expenses related to manufacturing, deployment, maintenance, logistics, and operational activities, it provides a clear overview of the project's financial position, helps anticipate funding requirements, ensures adequate working capital, and reduces the risk of cash shortages during both the startup and operational phases.

Table 17: Projected Monthly Cash-Flow Plan

	MONTHLY CASH FLOW BUDGET — YEAR 1												
POSTE	Jan	Fév	Mar	Avr	Mai	Jun	Jul	Aoû	Sep	Oct	Nov	Déc	TOTAL
ENCAISSEMENTS													
Leasing Buoys (300,000 DZD/buoy/month)	0 DA	0 DA	0 DA	1 200 000 DA	1 200 000 DA	1 200 000 DA	1 200 000 DA	1 200 000 DA	1 200 000 DA	1 200 000 DA	1 200 000 DA	1 200 000 DA	**10 800 000 DA**
Direct Buoy Sales (5,000,000 DZD/unit)	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	5 000 000 DA	0 DA	0 DA	0 DA	5 000 000 DA	0 DA	**10 000 000 DA**
DaaS — Oceanographic Data Services (1,00	0 DA	0 DA	0 DA	0 DA	1 000 000 DA	0 DA	0 DA	1 000 000 DA	0 DA	0 DA	1 000 000 DA	0 DA	**3 000 000 DA**
Leasing maintenance (200 000/yr)				800 000 DA	800 000 DA	800 000 DA	800 000 DA	800 000 DA	800 000 DA	800 000 DA	800 000 DA	800 000 DA	**7 200 000 DA**
TOTAL ENCAISSEMENTS	**0 DA**	**0 DA**	**0 DA**	**2 000 000 DA**	**3 000 000 DA**	**2 000 000 DA**	**7 000 000 DA**	**3 000 000 DA**	**2 000 000 DA**	**2 000 000 DA**	**8 000 000 DA**	**2 000 000 DA**	**31 000 000 DA**
DÉCAISSEMENTS													
Rent	200 000 DA	200 000 DA	200 000 DA	200 000 DA	200 000 DA	200 000 DA	200 000 DA	200 000 DA	200 000 DA	200 000 DA	200 000 DA	200 000 DA	**2 400 000 DA**
Salaries & Employer Contributions (9 emplo	960 000 DA	960 000 DA	960 000 DA	960 000 DA	960 000 DA	960 000 DA	960 000 DA	960 000 DA	960 000 DA	960 000 DA	960 000 DA	960 000 DA	**11 520 000 DA**
Operating Expenses (electricity, internet, etc.	31 667 DA	31 667 DA	31 667 DA	31 667 DA	31 667 DA	31 667 DA	31 667 DA	31 667 DA	31 667 DA	31 667 DA	31 667 DA	31 667 DA	**380 004 DA**
Accountant & Business Consultant	120 000 DA	100 000 DA	100 000 DA	100 000 DA	100 000 DA	100 000 DA	100 000 DA	100 000 DA	100 000 DA	100 000 DA	100 000 DA	100 000 DA	**1 220 000 DA**
Components & Materials (production cost)	750 000 DA	750 000 DA	750 000 DA	750 000 DA	750 000 DA	750 000 DA	750 000 DA	750 000 DA	750 000 DA	750 000 DA	750 000 DA	750 000 DA	**9 000 000 DA**
Logistics & Field Deployment	20 000 DA	20 000 DA	20 000 DA	30 000 DA	30 000 DA	50 000 DA	50 000 DA	50 000 DA	60 000 DA	60 000 DA	60 000 DA	80 000 DA	**530 000 DA**
IT & Website Equipment (initial investment)	350 000 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	**350 000 DA**
Marine Testing Equipment	0 DA	200 000 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	0 DA	**200 000 DA**
Commercial Agent	80 000 DA	80 000 DA	80 000 DA	80 000 DA	80 000 DA	80 000 DA	80 000 DA	80 000 DA	80 000 DA	80 000 DA	80 000 DA	80 000 DA	**960 000 DA**
TOTAL CASH OUTFLOWS	**2 511 667 DA**	**2 341 667 DA**	**2 141 667 DA**	**2 151 667 DA**	**2 151 667 DA**	**2 171 667 DA**	**2 171 667 DA**	**2 171 667 DA**	**2 181 667 DA**	**2 181 667 DA**	**2 181 667 DA**	**2 201 667 DA**	**26 560 004 DA**
CASH BALANCE													
Initial Funding (required financing total	17 103 004 DZD												
Monthly Net Cash Flow (Inflows – Outflows)	**-2 511 667 DA**	**-2 341 667 DA**	**-2 141 667 DA**	**-151 667 DA**	**848 333 DA**	**-171 667 DA**	**4 828 333 DA**	**828 333 DA**	**-181 667 DA**	**-181 667 DA**	**5 818 333 DA**	**-201 667 DA**	**4 439 996 DA**

Sixth Axis: Experimental prototype

1. Introduction

The prototype developed in this project is a low cost, compact, and autonomous oceanographic buoy designed for real time marine data collection and transmission, the complete system integrates environmental sensors measuring water and air temperature, wind speed and direction, pH, dissolved oxygen, turbidity, salinity, and chlorophyll concentration, together with a GPS module and LoRa communication system, all housed within a custom lenticular hull, powered by four solar panels and a lithium battery pack, the buoy is capable of continuous autonomous operation, wave characterization is performed using an array of eight motion sensors processed through a Madgwick filter algorithm, while a signaling light compliant with IALA standards ensures maritime visibility[3], [4].

A key feature of this design is its scalable hull architecture, the lenticular hull and internal platform were designed to be diameter scalable, allowing the same concept to be produced in sizes ranging from 30 cm to 1 m depending on deployment requirements, smaller variants are suited to sheltered coastal or estuarine environments, while larger versions offer greater internal volume, battery capacity, solar panel area, and hydrodynamic stability for longer duration offshore deployments, although these elements scale with hull size, the core electronics architecture, software, and waterproofing strategy remain identical across all variants.

The design philosophy of this project is based on three priorities, reliability in harsh marine environments, low manufacturing cost through Rotational molding, and ease of assembly and maintenance, the objective is not only to demonstrate technical feasibility, but also to develop a robust and accurate platform suitable for future real world deployment and scalable production across multiple size variants.

The physical prototype developed in this work focuses on two key functions of the complete system, water temperature measurement and wave characterization using an array of four GY-9250 IMU units, with data transmitted via Wi-Fi for short range laboratory validation, while the remaining sensors and LoRa communication module were not physically integrated into the prototype, they are fully incorporated into the complete system design presented in the following sections.

This axis presents the complete development process, from design requirements to final validation, highlighting key decisions, rationale, and challenges, all work was carried out on the 30 cm variant, which serves as the reference implementation.

2. Design Requirements and Specifications

Before any physical or electronic design work began, a clear set of requirements and performance targets was established, all requirements are stated for the 30 cm prototype, which is the reference design documented in this chapter.

2.1. Functional Requirements

The system must continuously acquire oceanographic data and transmit it wirelessly, for the prototype, this means reading water temperature and wave motion and serving the data over Wi-Fi to a connected device in real time, with the option to export a full session log as a CSV file, the system must operate from battery power, supplemented by solar harvesting.

2.2. Environmental Constraints

The buoy must withstand saltwater exposure, UV radiation, and wave induced mechanical stresses, all electronics must be sealed against water ingress, the hull must float stably and self right after disturbance, the geometry must minimize wind induced drift.

3. Conceptual Design

3.1. Hull geometry and design

The hull geometry is a convex lenticular form, broadly ellipsoidal in cross section, widest at the waterline and tapering smoothly both upward and downward, this shape was selected after evaluating flat discoid, cylindrical, and purely spherical alternatives, the lenticular profile offers a combination of advantages that none of the simpler forms can fully replicate, its continuously curved underwater surface deflects wave energy rather than presenting a flat face to breaking crests, significantly reducing slamming loads, its maximum beam at the waterline provides a wide waterplane area for passive roll stability without requiring the full material volume of a sphere, and its tapered upper body reduces the above waterline wind exposed profile, minimizing drift forces and mooring loads, the upper portion of the hull rises to a raised central deck platform with angled facets, on which the solar panels are mounted at a tilt angle of 55° to maximize solar irradiance capture throughout the day, a central mast assembly carrying the LoRa antenna, GPS antenna, wind sensors, and the signaling lamp, is mounted at the apex of the raised deck, a mooring ring is integrated at the base of the hull for anchor line attachment, this geometry scales cleanly from 30 cm to 1 m, all curvature ratios, facet angles, and internal layout proportions are preserved at any diameter.

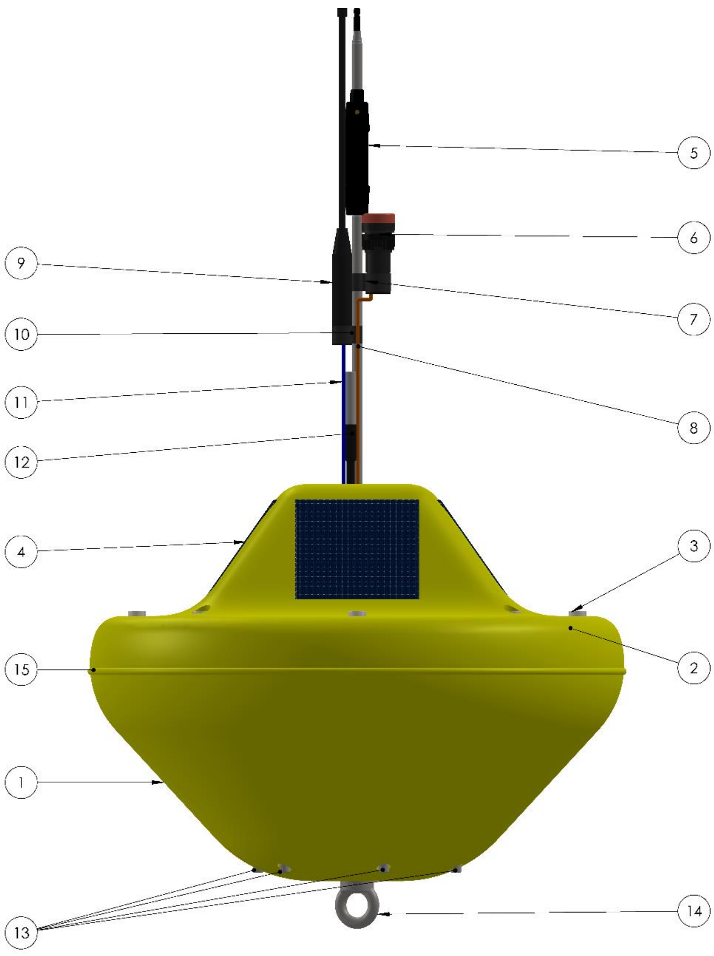


Figure 47: Front view of the buoy 3D model

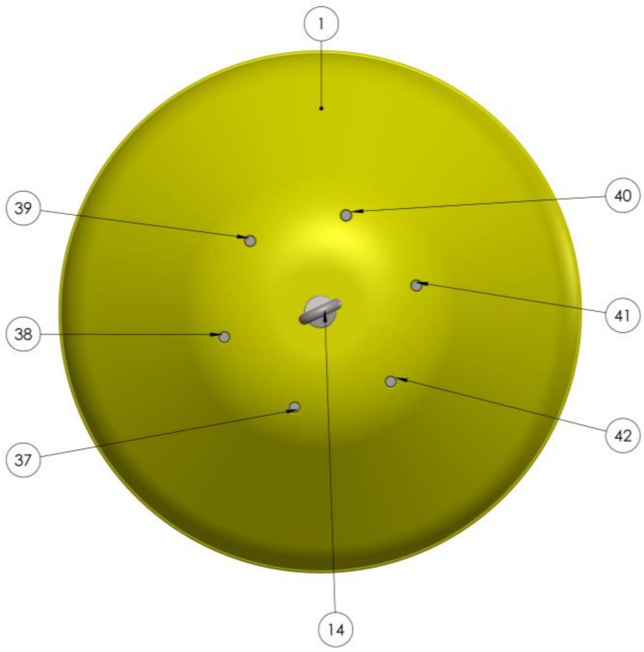


Figure 48: Bottom view of the Buoy 3D model

Table 18 provides the different buoy models we compared for our buoy's shape selection and design:

Table 18: the different buoy models we compared for our buoy's shape selection and design

Company	Model	Overall shape and design
Datawell BV	Directional Waverider DWR-G	 *Figure 49: Waverider DWR-G buoy*
Sofar Ocean	Spotter buoy	 *Figure 50: Spotter buoy*
FUGRO OCEANOR	Wavescan Buoy	 *Figure 51: Wavescan buoy*

3.2. Waterline and Split Line

The hull is split at its maximum beam, positioned slightly above the design waterline, this placement serves two purposes, it minimizes the risk of water ingress through the hull joint by keeping the sealing interface out of continuous immersion, and it ensures the entire submerged lower body presents a smooth, uninterrupted curved surface with no geometric discontinuities that would generate turbulence or parasitic drag, above the waterline, the hull tapers upward to the raised frustum deck, keeping the aerodynamic pressure center well above the hydrodynamic resistance center and contributing to directional stability.

4. Mechanical Fastening and Waterproofing

The assembly procedure was designed to achieve a watertight, structurally robust enclosure while allowing repeated access to the internal electronics bay during the testing phase, the following sub sections detail each stage.

4.1. Equatorial Sealing System

The joint at the split line is sealed through a tongue and groove interface combined with a continuous O-ring seal, the groove is formed directly into the lower flange face (depth 5.42 mm, width 7.16 mm, with a bilateral tolerance of ±0.08 mm on each wall), and the tongue on the upper flange engages to the same depth, an EPDM rubber O-ring (inner diameter 7 mm, loop outer diameter 226 mm) is seated in the groove[5], when the two flanges are brought together and clamped by the eight M6 Allen bolts, the O-ring is compressed within the groove, generating the contact stress required for a watertight hydraulic seal.

The groove dimensions were calculated to impose a controlled compression ratio on the O-ring cross section, the bilateral wall tolerance of ±0.08 mm was chosen to remain within the dimensional accuracy of the printer (rated ±0.1 mm) while preserving sufficient compression margin, a layer of epoxy resin was applied to the groove prior to assembly, providing redundancy against any micro-porosity in the printed flange walls, an inherent limitation of FDM parts that cannot be fully eliminated through parameter optimization alone.

The tongue and groove geometry also serves important mechanical functions, it constrains lateral displacement of the two hull halves during assembly and under hydrodynamic loading, ensuring that the O-ring remains correctly seated throughout the buoy's operational life [8].

In addition, the interlocking geometry increases the effective shear resistance of the joint by transferring part of the transverse loads through direct contact between the mating surfaces rather than solely through the bolts, this enhances load distribution along the flange interface and improves the overall mechanical integrity of the connection between the two hull halves.

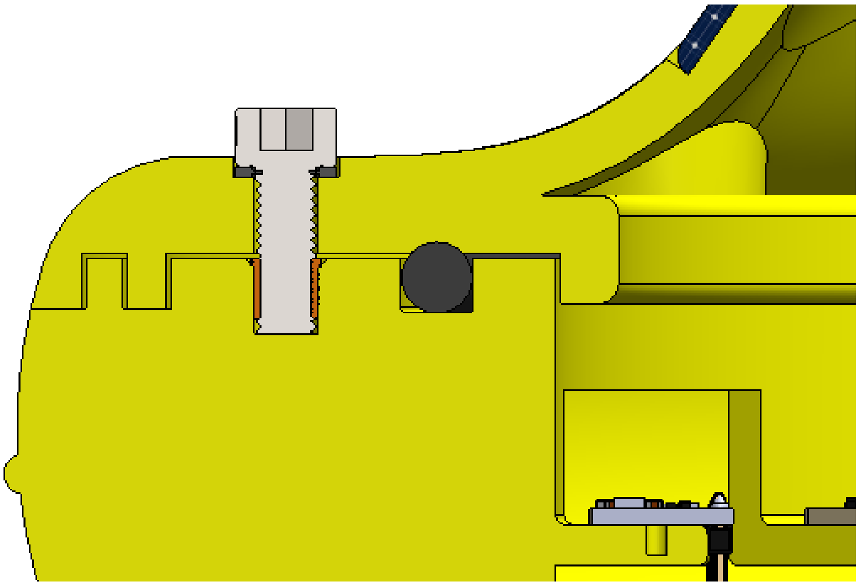


Figure 52 : Sealing mechanism of the split-line joint

Table 19: Sealing system specifications

Sealing Parameter	Specification
O-ring type	Continuous silicone O-ring (molded loop)
Internal diameter (ID)	7 mm
Outer diameter (OD) of loop	226 mm
Groove depth	5.42 mm
Groove width	7.16 mm
Dimensional tolerance (each side)	± 0.08 mm
Tongue engagement depth	5.42 mm

4.2. Sealing fasteners:

The upper and lower hull halves are mechanically clamped along the equatorial flange by eight M6 stainless steel hex socket (Allen) bolts distributed at equal 45° angular intervals around the perimeter, eight waterproof Dowty (bonded seal) washers, one per bolt, are fitted under each bolt head, each Dowty washer comprises a metallic backing ring with a vulcanized elastomer seal on the inner face, when tightened, the elastomer deforms radially to fill the clearance between the bolt shank and the countersunk through hole, preventing water ingress through the fastener passage.

To provide a durable and reliable threaded connection within the hull, brass heat set threaded inserts were embedded into the lower hull at each fastening location, the inserts were installed by controlled thermal insertion, allowing the surrounding thermoplastic material to soften and flow around the knurled outer surface of the insert before solidifying, this process creates a strong mechanical interlock between the brass insert and the printed hull structure, the M6 bolts engage directly with these metallic threads, eliminating the need for conventional nuts and significantly improving assembly robustness, compared with directly tapping threads into the polymer, the brass inserts provide superior resistance to thread wear, stripping, and repeated assembly and disassembly cycles, while ensuring consistent clamping force and long-term structural integrity of the hull joint, when the bolts are tightened, the resulting compression of the flange interface and sealing gasket, combined with the sealing action of the Dowty washers, forms a secure and watertight enclosure suitable for prolonged marine deployment.

4.3. Anchor chain attachment point:

A single M12 stainless steel eye bolt is installed at the base of the lower hull to serve as the mooring/anchor chain attachment point, the eye bolt passes through a dedicated boss at the hull base and is fastened directly to the ballast weight disk by a watertight nylon insert nut on the interior side, this through ballast fastening arrangement serves a dual purpose:

- **Structural integrity:** the mooring load path bypasses the PLA hull wall entirely, transmitting anchor chain tension directly into the dense ballast mass, his prevents stress concentration and potential hull fracture at the penetration point.
- **Alignment and stability:** the concentric attachment to the ballast disk ensures the mooring force acts through the buoy's center of gravity, reducing any tendency for the anchor chain to induce a tilting moment.

Waterproofing at the eye bolt penetration was achieved through a two stage approach, a waterproof Dowty washer was fitted on the external face between the eye bolt flange and the hull surface, additionally, two component epoxy resin was injected into the annular gap between the bolt shank and the hull boss wall, allowed to cure for 24 hours, and inspected for complete fill, this combination of mechanical seal and chemical encapsulation provides redundancy against the hydrostatic pressure at the anticipated deployment depth of the prototype.

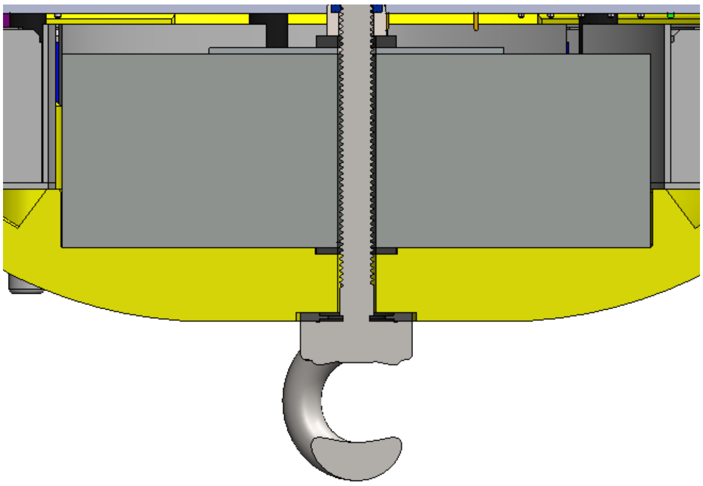


Figure 53: Anchor attachment point and ballast weight configuration

4.4. Fastening Components Summary

Table 19 provides a consolidated bill of assembly hardware used in the prototype construction.

Table 20: bill of assembly hardware used in the prototype construction.

Component	Dimensions	Quantity	illustration
Hex socket bolt	M6 × 20 mm	08	
Dowty (bonded seal) washer	M6	08	
Brass threaded heat inserts	M6	08	
EPDM rubber O-ring	ID: 7 mm OD) of loop: 226 mm	01	
Eye bolt	M12	01	
Nylon insert lock nuts	M12	01	

Dowty (bonded seal) washer	M12	01	
Rubber washer	M12	02	
Stainless steel washer	M12	02	

4.5 Internal Platform Architecture

The internal volume is organized around twelve horizontal support platforms arranged in two functional rows at different vertical levels, providing structured and accessible locations for all system components, rather than a single undivided cavity, the interior consists of dedicated mounting surfaces designed to optimize spatial organization and vertical mass distribution for stability.

The top row comprises eight support platforms dedicated to the motion sensing subsystem, these are positioned near the upper hull section to optimize exposure and isolation for the IMU and motion related sensors, ensuring reliable acquisition of motion data.

The bottom row comprises four support platforms dedicated to the core electronic architecture, including the main electronic board and processing unit, microcontroller, communication modules, and power management circuitry, all installed in a protected, low vibration environment.

The lowest structural level is positioned at keel level and incorporates a ballast weight platform designed to accept a lead disk of variable mass (2866.4 g for the 30 cm prototype), used to adjust the center of gravity to meet the stability requirements detailed in Section 5.

In addition, six housing tubes for water quality sensors are integrated into the lower hull, these are sealed with epoxy resin at the penetration points, while the sensing elements protrude externally to maintain direct contact with seawater for in-situ measurements.

Four vertical rib structures are also integrated into the internal hull geometry to enhance structural rigidity, these ribs improve load transfer between the platforms and the hull shell, reduce local deformation under hydrodynamic loading, and increase overall torsional and bending stiffness.

This two row, twelve platform architecture ensures functional separation between sensing and processing systems while maintaining optimal mass distribution, with heavier components positioned at lower elevations to improve overall stability.

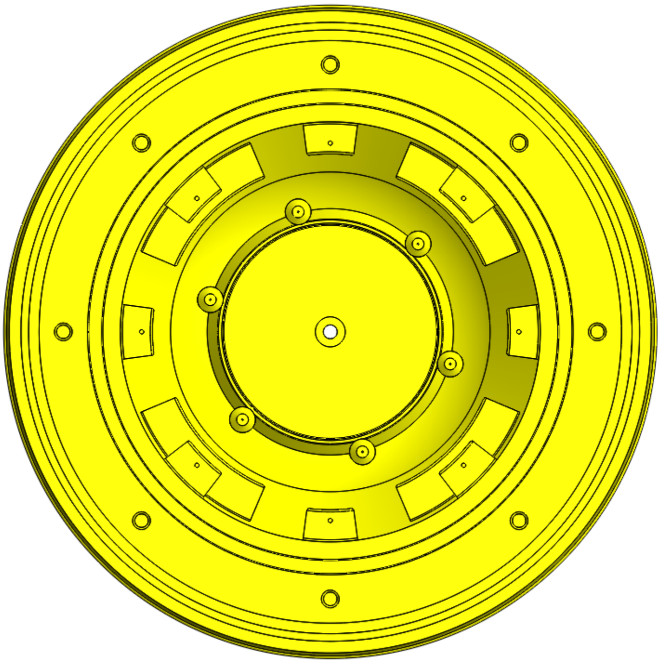


Figure 54:Top view of the lower hull of the buoy's 3D model

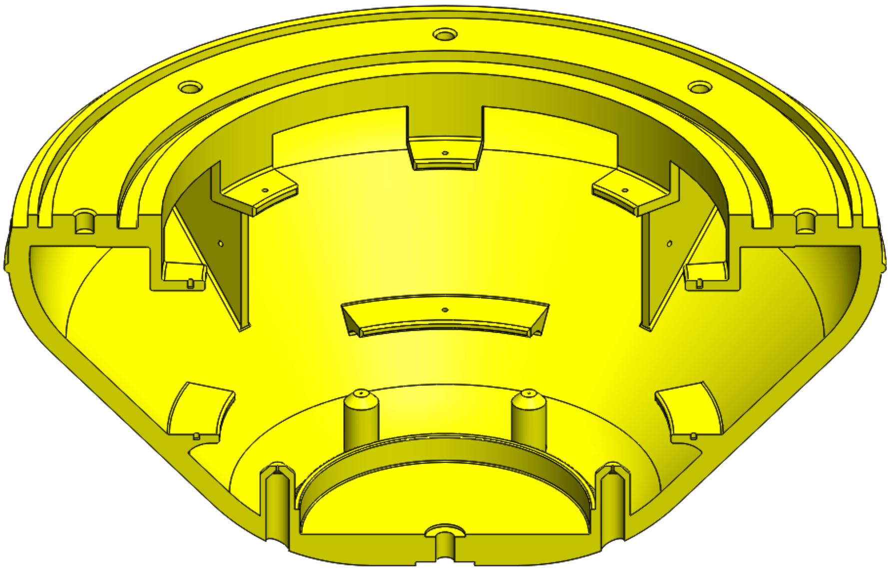


Figure 55: Isometric view of the buoy's lower half's cross section

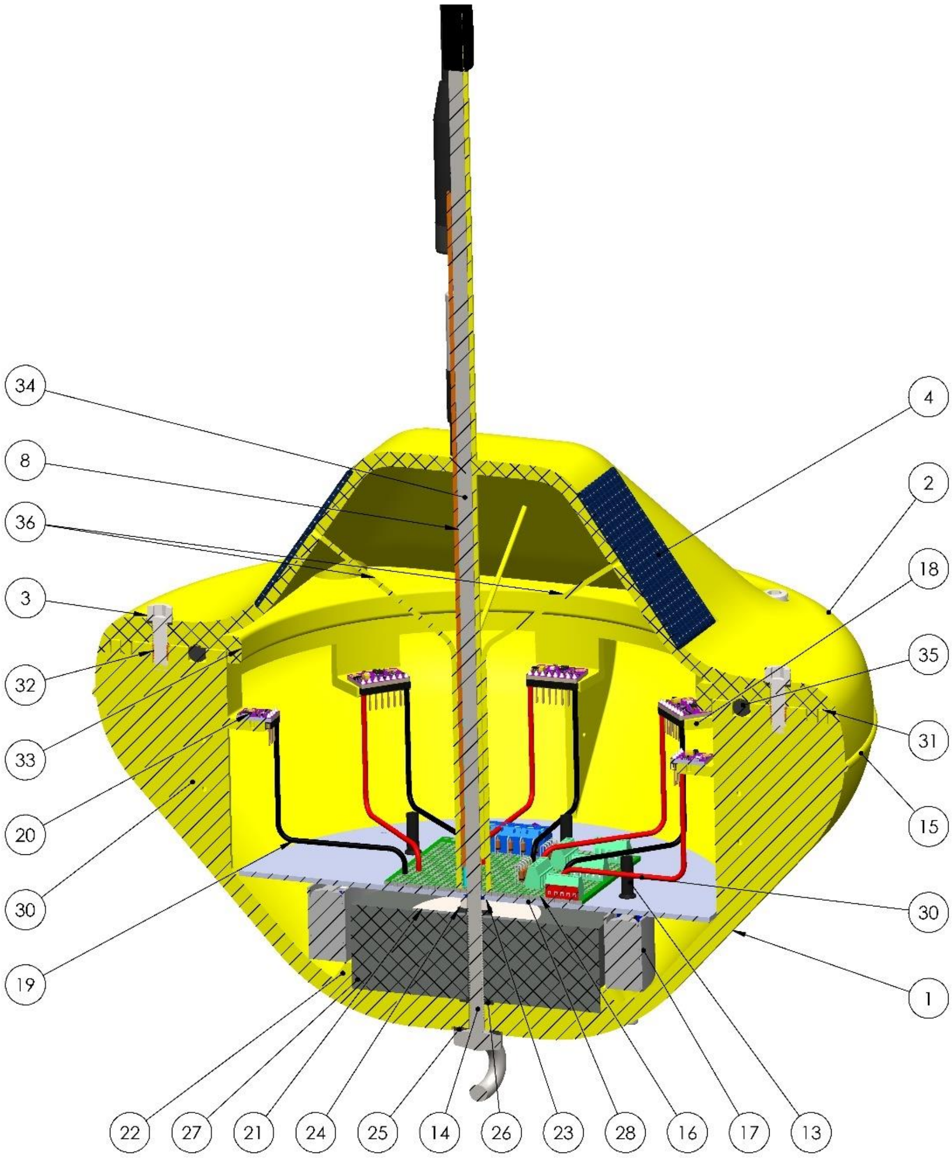


Figure 56: Isometric view of the Buoy's cross section displaying its internal architecture.

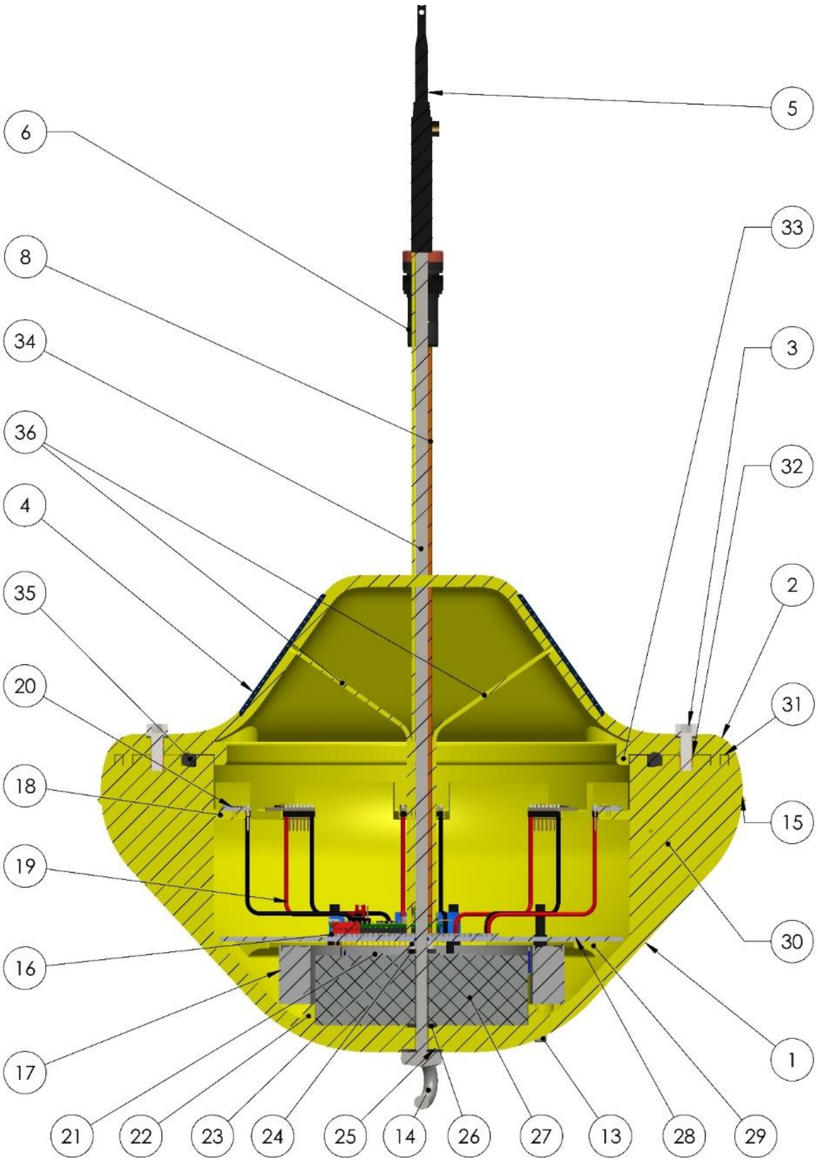


Figure 57: Front view of the Buoy's cross section showcasing its architecture

The table below provides the complete list of components, with identification numbers corresponding to all previously presented 3D models.

Table 21: Component Identification table for the 3D Model

N°	Component
1	Lower hull
2	Upper hull
3	Stainless steel socket head cap screw (Allen bolt)
4	Photovoltaic modules
5	Ultrasonic anemometer with integrated pressure and humidity sensors
6	Maritime navigation light

7	Navigation light support
8	Navigation light power cable
9	LoRa radio antenna
10	Antenna support
11	Antenna coaxial cable
12	Air temperature probe
13	Submerged multi-parameter probes
14	Forged stainless steel lifting ring (anchor point)
15	Nominal waterline
16	Main electronics board (PCB)
17	Energy storage system (battery)
18	Inertial sensor mechanical mount
19	Inertial sensor connection cable
20	Inertial measurement unit (IMU)
21	Metal washer
22	Ballast structural support
23	Nylon insert lock nuts
24	Elastomer sealing gasket
25	Sealing washer
26	Elastomer sealing washer
27	Metallic ballast (counterweight mass)
28	Electronics support platform
29	Electronics platform mechanical support
30	Reinforcement ribs
31	Tongue and groove system
32	Threaded brass inserts
33	High strength watertight structure
34	Mast
35	O-ring seal
36	Photovoltaic module power wiring
37	Water temperature probe
38	pH probe
39	Turbidity probe
40	Dissolved oxygen probe
41	Chlorophyll probe

42	Salinity probe

5. Stability and Floatability Assessment

The stability of a floating body is a fundamental design criterion in naval architecture, an oceanographic buoy deployed in open sea conditions must maintain a well defined upright equilibrium under the combined action of gravity, buoyancy, and wave induced inclinations. Poor stability leads to capsizing, loss of sensor data integrity, or a permanent tilt that degrades wave measurement accuracy, outcomes that are unacceptable for a precision instrument such as the one described in this thesis.

This section presents a complete hydrostatic stability analysis of the prototype buoy, carried out from mass properties extracted from the CAD model and buoyancy data computed from the submerged hull geometry, the analysis follows the classical approach of naval architecture, determination of the center of buoyancy B, computation of the metacentric height GM, and evaluation of the righting arm curve GZ, The results are interpreted with respect to the operational requirements of the buoy in the Algerian coastal environment.

5.1 Definitions and Theoretical Framework

The following quantities are used throughout this chapter, all vertical distances are measured upward from the keel reference plane K, which coincides with the base of the buoy hull ($Y = 0$ in the CAD coordinate system).

Centre of Mass G

The center of mass G is the point through which the resultant gravitational force $\boldsymbol{W} = \boldsymbol{mg}$ acts, for an axisymmetric structure, G lies on the vertical axis of symmetry, any lateral offset of G introduces a static heel angle proportional to that offset divided by GM.

Centre of Buoyancy B

The center of buoyancy B is the centroid of the displaced (submerged) volume, the buoyant force: $\boldsymbol{F_b} = \boldsymbol{\rho}\, \boldsymbol{g}\, \boldsymbol{V_{sub}}$, acts vertically upward through B, as the buoy inclines, B shifts toward the immersed side, generating a restoring couple with W.

Metacenter M and Metacentric Height GM

At a small angle of inclination θ, the line of action of F_b intersects the buoy's vertical axis at a point M called the metacenter, The metacentric height is:

$$GM = KM - KG = (KB + BM) - KG$$

where BM is the metacentric radius, given by:

$$BM = I_{wp} / V_{sub}$$

And I_{wp} is the second moment of area of the waterplane cross-section, a positive GM indicates stable equilibrium, any inclination generates a restoring moment returning the buoy to upright.

Righting Arm GZ

The righting arm GZ is the perpendicular distance between the lines of action of W and F_b at heel angle θ, For small angles, the linear approximation is:

$$GZ \approx GM \cdot sin(\theta)$$

The righting moment is $Mr = W \cdot GZ$.

A positive GZ across the operational range confirms self-righting behavior, a higher order correction that extends the valid range of this approximation, applicable to wall sided floating bodies, adds a second term:

$$GZ \approx sin(\theta) \cdot [GM + ½\, BM\, tan^2(\theta)]$$

This wall sided formula is used below to determine the actual angular range over which the simple linear approximation remains accurate for this hull.

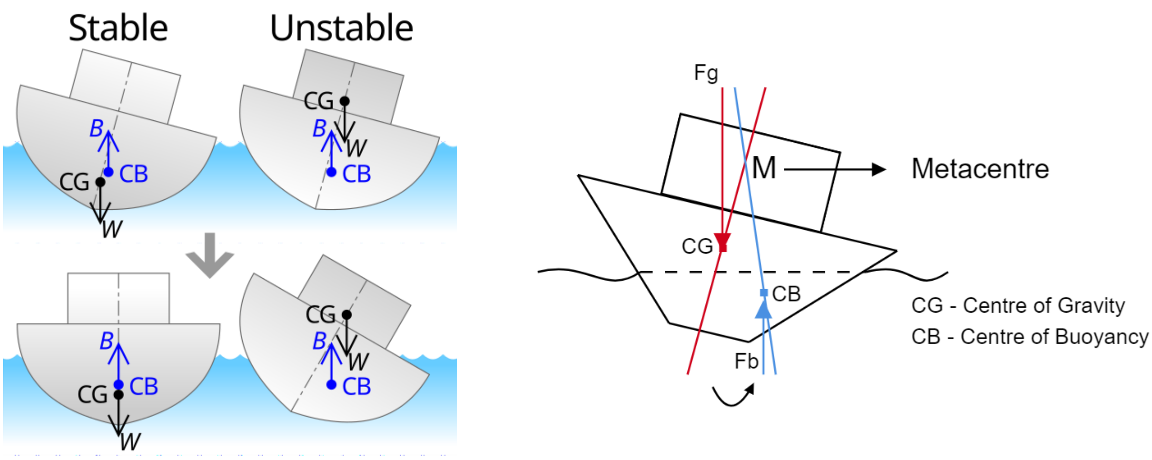


Figure 58: Ship stability illustrations explaining the stable and unstable dynamics of buoyancy (B), center of buoyancy (CB), center of gravity (CG), and weight (W)

5.2 Input Data

The following parameters were extracted from the CAD mass properties report and the hull geometry analysis.

Mass Properties of the Complete Structure

Table 21 summarizes the mass and center of mass coordinates of the fully assembled buoy, comprising hull, internal electronic platforms, sensors, four GY-9250 IMU units, ESP32 microcontroller, battery pack, and ballast disk.

Table 22: mass and center of mass coordinates of the fully assembled buoy

Parameter	Value
Total mass m	4 985 g (4.985 kg)
Gx (lateral)	0.01 mm
Gy (vertical, KG)	61.53 mm
Gz (lateral)	−0.01 mm
Outer hull diameter D	300 mm
Waterplane radius R_{wp}	150 mm

Submerged Volume and Centre of Buoyancy

The submerged volume was obtained from the CAD 3D model, The centroid of the submerged body gives the coordinates of the center of buoyancy B.

Table 23: Submerged geometry data

Parameter	Value
Submerged volume V_{sub}	4 862 251.01 mm³
BX	0.00 mm
BY (KB)	76.65mm

5.3 Hydrostatic Calculations

Weight and Buoyant Force

Using seawater density $\rho = 1\,025\ kg/m^3$ and $g = 9.81\ m/s^2$:

$$W = m \cdot g = 4.985 \times 9.81 = 48.90\ N$$

$$F_{\ b} = \rho \cdot g \cdot V_{sub} = 1025 \times 9.81 \times 4862\,251.01 \times 10^{-9} = 48.89\ N$$

The two forces differ by less than 0.02 %, confirming that the CAD submerged volume corresponds to the neutral flotation condition, the buoy floats at the design waterline with negligible reserve or deficit of buoyancy.

Waterplane Second Moment of Area

At the waterplane, the hull cross-section is circular with radius $R_{wp} = 150\ mm$, the second moment of area about the centroidal axis is:

$$I_{wp} = \pi \cdot R_{wp}{}^4 \,/\, 4 = \pi \times 150^4 \,/\, 4 = 397607820.2\ mm^4$$

Metacentric Radius BM

$$BM = I_{wp} / V_{sub} = 397\,607\,820 / 4\,862\,251.01 = 81.77\,mm$$

The large value of BM relative to the hull dimensions reflects the wide, flat waterplane of the oblate lenticular form, which is a principal advantage of this hull type for stability.

Metacentric Height GM

The vertical positions from the keel are:

$$KB = 76.65\,mm$$

$$KG = 61.53\,mm$$

$$KM = KB + BM = 76.65 + 81.77 = 158.42\,mm$$

$$GM = KM - KG = 158.42 - 61.53 = 96.89\,mm$$

Since $\boldsymbol{GM > 0}$, the metacentre M is located above G, the buoy is in stable hydrostatic equilibrium.

Summary of Results

Table 24: Complete hydrostatic stability results

Parameter	**Value**
Total mass m	4 985 g
Submerged volume V_{sub}	4 862 251.01 mm³
Weight W	48.90 N
Buoyant force F_b	48.89 N
Reserve buoyancy	−0.02 % (≈ 0)
Waterplane 2nd moment I_{wp}	397607820.2 mm⁴
Centre of Buoyancy (KB)	76.65 mm
Centre of Mass (KG)	61.53 mm
Metacentric radius BM	81.77 mm
Metacenter (KM)	158.42 mm
Metacentric height GM	96.89 mm
Lateral offset $\Delta X\ (GB)$	0.01 mm
Lateral offset $\Delta Z\ (GB)$	−0.01 mm
Static heel angle	0.006°
Static trim angle	−0.006°
GM / D ratio	0.32

5.4 Righting Arm Curve

Table 18 gives the righting arm GZ at representative heel angles, computed from the linear approximation $\boldsymbol{GZ = GM \cdot sin(\theta)}$, alongside the wall sided correction $\boldsymbol{GZ \approx sin(\theta) \cdot [GM + ½\, BM\, tan^2(\theta)]}$, for comparison at angles where the correction remains meaningful, beyond approximately 30°, neither approximate formula is reliable for this hull and exact computation requires numerical integration of the submerged volume at each angle, following the cross curve method described by Biran (Ship Hydrostatics and Stability, Ch. 5)[6].

Table 25: Righting arm GZ vs. Heel angle (linear approximation, GM = 96.89 mm)

Heel angle θ (°)	GZ linear (mm)	GZ wall-sided (mm)
0	0.00	0.00
5	8.44	8.47
10	16.82	17.05
15	25.08	25.84
20	33.14	34.99
30	48.44	55.26
45	68.51	—
60	83.91	—
90	96.89	—

The righting arm is positive and monotonically increasing from 0° to 90°, peaking at $GZ = GM = 96.89\, mm$ at 90° of heel under the linear approximation, this confirms that the buoy generates a restoring moment at all inclinations within the operational envelope, Figure 55 illustrates the full linear curve graphically.

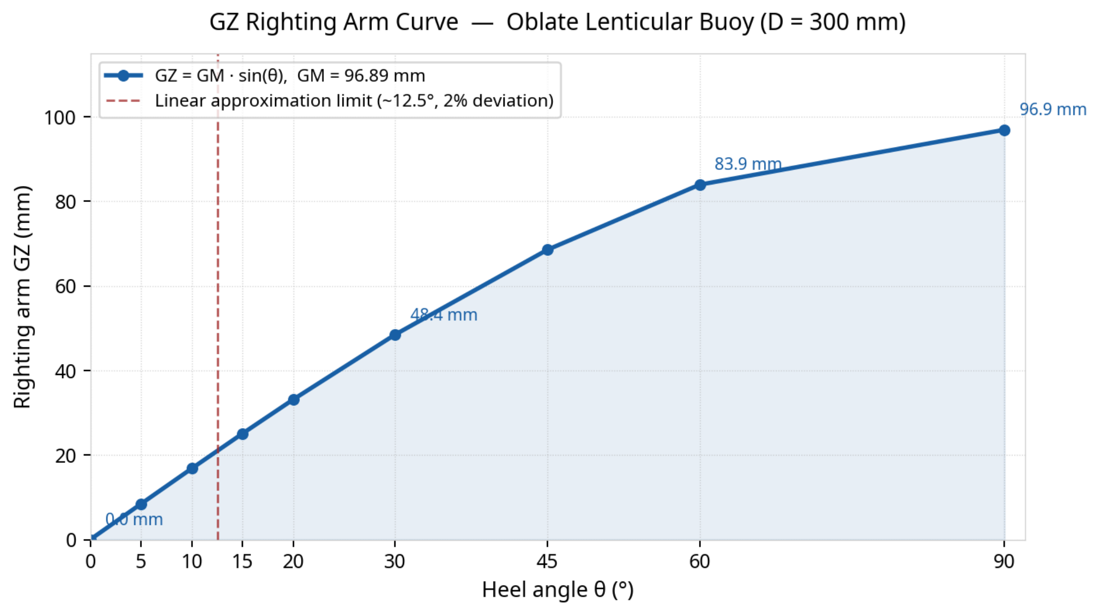


Figure 59: GZ righting arm curve for the prototype buoy (GM = 96.89 mm, D = 300 mm).

5.5 Validity of the Linear Approximation

The simple formula $\boldsymbol{GZ = GM \cdot sin(\theta)}$ is only valid while the metacentre M remains effectively stationary as the buoy heels, beyond some angle it drifts and the formula increasingly overstates the true restoring arm, Biran emphasizes that this angular limit is hull dependent rather than fixed, citing a worked example where the linear approximation departs from the true righting arm curve beyond as little as **7–8°** for a conventional ship hull, For the present buoy, applying the wall sided correction term ($\frac{1}{2}\boldsymbol{BM \cdot tan^2\theta}$) to the actual GM and BM values shows the linear approximation stays within 2% of the corrected estimate up to approximately **12.5°,** and within **5%** up to approximately **19.5°,** as shown in Figure 56, beyond roughly 20°, the deviation grows quickly and the linear formula should no longer be relied upon, a full numerical hydrostatic calculation (re-evaluating the submerged volume and its centroid at each heel angle) would be required for an exact curve at larger inclination[6]

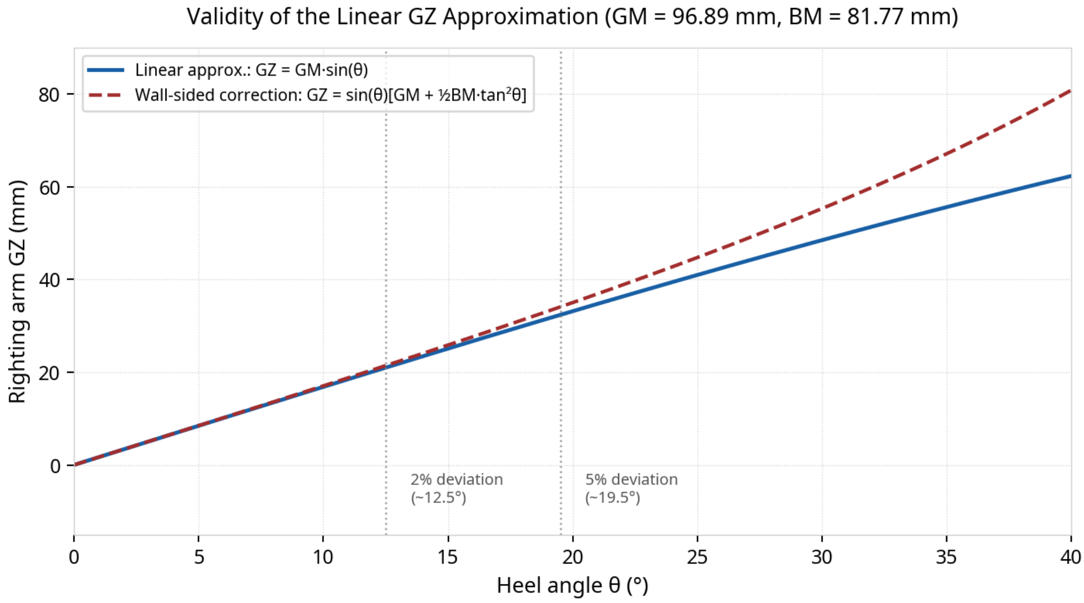


Figure 60: Deviation of the linear GZ approximation from the wall-sided correction, showing the practical validity range for this hull (GM = 96.89 mm, BM = 81.77 mm).

5.6 Discussion

Stability Performance

The metacentric height GM = 96.89 mm represents a strong stability margin for a 300 mm diameter buoy, the dimensionless ratio $\boldsymbol{GM/D = 0.323}$ is large relative to the hull's principal dimension, reflecting a wide, low buoy with a deep ballast point, This performance stems from two design decisions:

- The oblate lenticular hull form, which maximizes waterplane area and hence the metacentric radius $\boldsymbol{BM}$.
- The ballast disk positioned on the lowest internal platform, which lowers $\boldsymbol{KG}$ and increases $\boldsymbol{GM}$.

Notably, $\boldsymbol{KB = 76.65\,mm > KG = 61.53\,mm}$. This means the buoy retains positive stability even without the waterplane contribution $(\boldsymbol{BM})$, making the design particularly robust.

Alignment and Static Trim

The lateral offsets $\boldsymbol{\Delta X = 0.01\,mm}$ and $\boldsymbol{\Delta Z = -0.01\,mm}$ between **G** and **B** are far below manufacturing tolerances for both the rotomolded HDPE production hull (±1 mm) and the 3D-printed PLA prototype (±0.2 mm), the resulting static heel and trim angles of ±0.006° are negligible and will have no measurable effect on IMU orientation or wave measurement accuracy.

Reserve Buoyancy

The $-$ 0.02 % reserve buoyancy indicates that the submerged volume provided by the CAD model matches the neutral flotation condition, with a volume discrepancy of approximately

1 163 mm³ (equivalent to about 1.2 g), this is within the uncertainty of CAD surface integration and component mass tolerances, in practice, small adjustments to the ballast disk mass at the calibration stage can introduce a controlled positive reserve buoyancy if required.

5.7 Conclusion

The hydrostatic stability assessment confirms that the oceanographic buoy prototype is statically stable with a substantial safety margin. The principal results are:

- Metacentric height $\boldsymbol{GM = 96.89\,mm}$, giving $\boldsymbol{GM/D = 0.32}$.
- The metacenter **M** is located 158.42 mm above the keel, above both the center of buoyancy (76.65 mm) and the center of mass (61.53 mm).
- Static heel and trim angles are below 0.01°, confirming negligible structural asymmetry.
- The righting arm **GZ** is positive across the full 0–90° range, confirming self-righting capability, this approximation is reliable to within 5% up to approximately 19.5° of heel, beyond which exact numerical computation is needed.

These results validate the hull geometry and internal mass distribution of the buoy and confirm its suitability for deployment in the Algerian coastal marine environment.

6. Electronic System Design and Implementation

The buoy electronics are integrated on a custom two layer printed circuit board (PCB) designed using EasyEDA, which consolidates all sensor interfaces, power regulation, data storage, and communication modules. This section details the electronic architecture, sensor placement, software architecture, and user interface.

6.1 Overall Architecture:

The central controller is an ESP32-S3 module, which provides WiFi, Bluetooth Low Energy (BLE), and sufficient computational resources for real-time sensor fusion and web serving, A functional block diagram is shown in Figure 55 (textual description follows).

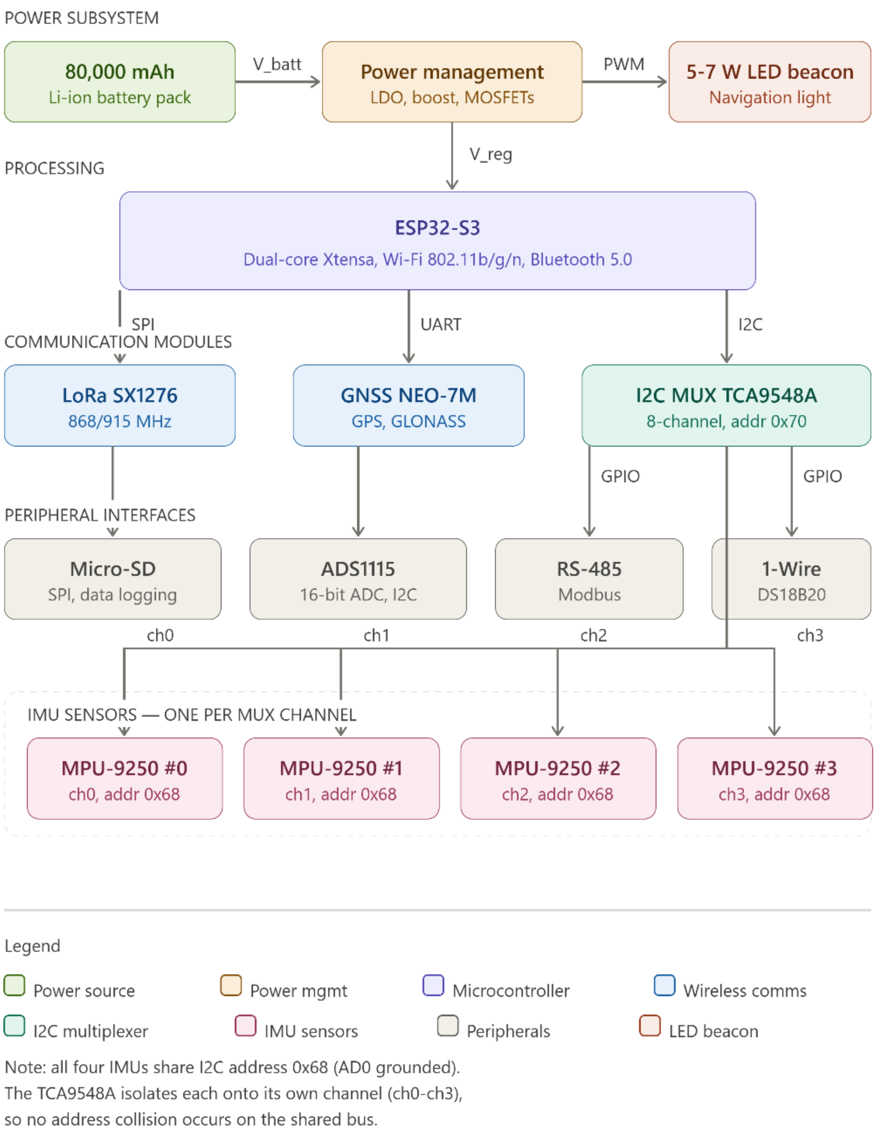


Figure 61: Electronic architecture of the Autonomous Ocean Data Collection System

All sensors are interfaced via standard digital protocols (I²C, UART, RS-485, SPI, 1-Wire) or through a 16-bit analog to digital converter (ADS1115) for analog signals, the TCA9548A I²C multiplexer resolves address conflicts between the four MPU9250 IMUs and other I²C devices.

6.2 Custom Two-Layer PCB:

All active electronics are consolidated on a single two layer printed circuit board designed in EasyEDA, the board is the physical platform that carries every sensor and module that does not need to be outside the hull, the main parts on the PCB are:

- ESP32-S3 module (WiFi and Bluetooth)
- LoRa SX1276 radio (SPI)
- u-blox NEO-7M GPS receiver (UART), its active antenna is placed on the mast, connected by a coaxial cable.
- Micro-SD card socket (SPI)

- TCA9548A I²C multiplexer
- ADS1115 16-bit ADC
- Four MPU9250 IMUs soldered directly to the PCB at the corners, they are aligned with the board axes, which are the same as the buoy's axes when the board is mounted, this rigid layout gives the correct lever arm distances for the wave measurement algorithm without any extra cables or separate mounting plates.

All connections to external sensors (mast instruments and underwater probes) use screw terminals or JST plugs, protected by TVS diodes. The board has a solid ground plane on the bottom side, wide tracks for power lines, and small capacitors next to every chip. After soldering, it is sprayed with a thin moisture-resistant coating.

The PCB is rigidly bolted to a sturdy baseplate inside the buoy's lower hull, on the waterline's level, this keeps the IMUs perfectly fixed to the hull and ensures that all motion of the buoy is directly transferred to the sensors.

Power section: The battery's 5 V output goes directly to the board, the ESP32 module creates its own 3.3 V internally, a small boost converter on the board makes 12 V for the wind sensor and the LED beacon, controlled by a MOSFET.

6.3 Sensor Placement and Mechanical Layout:

The buoy hull is a fully waterproof rotationally molded polyethylene cylinder, The interior remains dry under all operating conditions, sensors that must be in contact with seawater are mounted directly through the hull wall, with the openings sealed by a two component epoxy resin that guarantees a watertight barrier while allowing the sensor's sensitive element to be exposed to the external water.

- **Bottom section (battery):** The 80 000 mAh lithium-ion battery (5 V output, total energy 296 Wh) is mounted directly above the ballas weight, as low as possible inside the hull. Its substantial mass contributes to the overall low down weight distribution, further improving stability.
- **Middle dry compartment:** The baseplate holding the PCB is mounted horizontally at the water line's level at the top of the lower hull, all internal electronics are housed here and never come into contact with water.
- **Underwater sensors (mounted through the hull):** The conductivity probe (K1.0), pH electrode (double-junction), optical dissolved oxygen probe, turbidity sensor (DFRobot SEN0189), and water temperature sensor (DS18B20) are each inserted through individual holes drilled in the lower part of the hull, Each sensor is sealed in place with a marine grade epoxy resin that provides a permanent waterproof seal and resists saltwater corrosion, The sensors' cables run inside the hull to the PCB's screw terminals, the pressure sensor (MS5803-14BA) is mounted on the PCB itself, a small flexible tube filled with silicone oil leads from the sensor to a similar resin sealed opening in the hull, allowing accurate pressure measurement without direct exposure of the sensor to seawater.

- **Mast and atmospheric sensors:** A 0.5 m carbon fiber mast is attached to the lower eye bolt, which serves as the anchor chain attachment point, and extends vertically through the buoy to the top exterior surface, it carries:

- Ultrasonic wind sensor (LCJ *Capteurs* CV7-S) at the mast head
- Air temperature/humidity sensor (Sensirion SHT45) inside a naturally ventilated radiation shield
- Barometric pressure sensor (MS5611) on the PCB, vented to the outside through a thin tube with a Gore-Tex membrane, sealed at the hull penetration point
- Pyranometer (Davis 6450) on a short lateral arm, oriented south (in the northern hemisphere) to avoid shading
- Tipping bucket rain gauge (Davis)
- Active GNSS antenna for the u-blox NEO-7M
- Yellow LED beacon (5–7 W, 12 V) with a 360° lens

All cables from the mast run inside the pole and enter the hull through a single waterproof gland.

The completely watertight hull, combined with individually sealed sensor ports, ensures that the main electronics and the IMUs are never exposed to salt spray or condensation, significantly improving long-term reliability.

6.4 Sensor Suite Specifications:

Table 25 summarizes every sensor integrated into the buoy, the parameter it measures, the selected model, and its principal technical characteristics.

Table 26: integrated sensors and their specifications

Category	**Parameter**	**Sensor / Module**	**Accuracy, Sensitivity & Key Specifications**
Wave Motion	Heave, pitch, roll, wave height, direction, period	4× MPU9250 (on PCB)	**Gyro:** ±250 °/s, 0.0076 °/s/LSB **Accelerometer:** ±2 g, 0.061 mg/LSB **Magnetometer:** 0.15 µT/LSB; 100 Hz sampling; rigid-body fusion provides heave accuracy <1 cm after calibration.
Atmospheric Parameters	Wind speed and direction	LCJ sensors CV7-S (ultrasonic)	**Speed**: 0–60 m/s, ±0.5 m/s or 5 %. **Direction**: 0–360°, ±3°, RS-485 (NMEA 0183); IP66, maintenance-free.
	Air temperature and humidity	Sensirion SHT45 (in shield)	**Temperature:** range from -40 to 125 °C, ±0.1 °C, Humidity: 0-to 100 %, ±1.5 %, I²C, factory-calibrated.
	Barometric pressure	MS5611 (on PCB, vented outside)	10–1200 mbar, 24-bit ADC, 0.015 mbar resolution, ±1.5 mbar accuracy, I²C/SPI.

	Solar radiation (global)	Davis 6450	0–1800 W/m², cosine corrected, analog output 0-3 V, accuracy ±5 %.
	Precipitation	Davis Rain Collector (tipping bucket)	0.2 mm per tip, accuracy ±4 %, passive reed switch, no power needed.
Oceanographic Parameters	Water temperature	DS18B20 (stainless steel)	–55 to 125 °C, ±0.5 °C (-10 to 85 °C), 1-Wire interface.
	Conductivity / Salinity	Atlas Scientific EZO-EC + K1.0 probe	0.07–5000 µS/cm, salinity 0 to 42 PSU, accuracy ±2 % after calibration, UART/I²C, temperature compensated.
	Pressure (depth / tide)	MS5803-14BA (on PCB, oil-filled tube)	0-14 bar (~0–100 m), 0.2 mbar resolution, ±0.2 mbar accuracy, I²C/SPI.
	Dissolved oxygen	Atlas Scientific EZO-DO + optical probe	0-100 mg/L, ±0.05 mg/L (luminescence), no membrane, no stirring, UART/I²C.
	pH	Atlas Scientific EZO-pH + double-junction probe	0–14 pH, ±0.002 pH after calibration, UART/I²C, electrically isolated.
	Turbidity	DFRobot SEN0189 (IR backscatter)	Analog 0-4.5 V, can be calibrated to 0–1000 NTU, 880 nm light, low cost.
Currents and Drift	Surface current (speed and direction)	GPS drift from u-blox NEO-7M (on PCB)	Calculated from successive GPS fixes, position accuracy 2.5 m CEP, update up to 10 Hz.
Navigation and Positioning	Latitude, longitude, UTC time, heading	u-blox NEO-7M + 4× MPU9250 (magnetometers)	**GPS:** 2.5 m CEP, 56-channel, **Heading:** averaged **magnetometers:** ~±2° after calibration.
Communication and Logging	Local data access and long-range telemetry	ESP32 WiFi + LoRa SX1276	WiFi 802.11 b/g/n (access point mode), LoRa 868/915 MHz (range up to 15 km).
	Data storage	Micro-SD card (SPI) up to 128 GB	Stores raw IMU data at 100 Hz and summary sensor data at 1 Hz.
Power and Signalization	Power supply	80 000 mAh Li-ion battery (5 V output)	296 Wh total energy, powers the entire system.
	Solar panels	4× 5 W monocrystalline panels	Total 20 W peak, parallel via Schottky diodes, integrated charge controller.
	Visual beacon	5–7 W yellow LED (12 V) with 360° lens	Flashing at 50 % duty cycle for night visibility, controlled via MOSFET.

The sensor selection strikes a balance between research grade accuracy and cost efficiency, favoring digital interfaces (I²C, UART, RS-485) to minimize analog noise and simplify integration.

6.5 User Interface and Data Export:

The buoy creates its own WiFi access point with SSID and password when user interaction is required, any device (smartphone, tablet, laptop) that connects to this network can access the web based dashboard by navigating to http://192.168.4.1. The dashboard, built with HTML, JavaScript, and Chart.js, provides:

- A real-time summary of significant wave height (Hs), peak period (Tp), mean wave direction, wind speed and direction, and GPS coordinates.
- Rolling time series charts (10 minute window) for heave displacement, pitch/roll, air and water temperature, barometric pressure, humidity, solar radiation, conductivity, dissolved oxygen, pH, and turbidity.
- A data export section where the user selects a time range and downloads the corresponding records in CSV or JSON format, The ESP32 reads the requested data from the SD card, compresses it into a ZIP archive, and streams it to the client.

For deployments beyond WiFi range, a LoRa based shore station receives the telemetry packets and hosts a similar dashboard, allowing remote monitoring, all timestamps are synchronized to UTC via the GNSS receiver.

6.6 Power Budget and Autonomy:

The system is designed for long term unattended operation, to minimize energy consumption, most sensors are duty cycled, they are powered on only when a measurement is needed and remain off the rest of the time, table 26 lists the average power consumption of each subsystem, considering the active time and operating voltage.

Table 27: average power consumption of each subsystem

Subsystem	Voltage (V)	Active current (mA)	Duty cycle or operating mode	Average current (mA)	Average power (mW)
ESP32-S3 (CPU and peripherals)	3.3	80 (CPU active, WiFi off)	100 % awake for sampling	80	264
LoRa SX1276	3.3	120 (transmit)	1 packet / 10 min, 1 s tx	0.2	0.66
GNSS NEO-7M (power-save)	3.3	30 (tracking)	Cyclic tracking (avg)	5	16.5
4× MPU9250	3.3	14 (total)	100 %	14	46.2
Wind sensor CV7-S	12	20	On for 2 s every 10 s (20 %)	4	48
Atlas EZO (EC, DO, pH)	5	45 (3 × 15)	On for 2 min every 10 min (20 %)	9	45
Other sensors & ADC	3.3/5	-	Always on	-	30

LED beacon	12	500 (peak at 5 W)	10 % flash, 6 h/night = 2.5 % overall	12.5	150
Total					**600**

Note: The ESP32-S3 is assumed to run at 80 MHz with WiFi off, which typically draws about 80 mA, the LED beacon is operated at 10 % duty cycle (short flashes) and only during 6 hours per night, resulting in a 24 hour average of 12.5 mA at 12 V.

The total average power consumption is approximately 0.6 W, with the 80 000 mAh battery providing 296 Wh, the buoy can operate continuously for 296 Wh/0.6 W ≈ 493 hours (20.5 days) without any solar input, this confirms that a fully charged battery alone can sustain the system for about three weeks, exceeding the two week requirement with a comfortable margin.

When the four solar panels (20 W peak) are exposed to an average of 5 equivalent full sun hours per day, they generate around 100 Wh per day, this is more than twice the daily consumption (0.6 W × 24 h = 14.4 Wh), allowing the battery to be fully recharged even on partly cloudy days.

Consequently, the buoy is designed for indefinite autonomous deployment in typical Mediterranean conditions.

7. Prototype construction and assembly

This section presents the physical realization of the oceanographic buoy prototype, including the 3D printing and fabrication of the structural components, the assembly and integration of the electronic, sensing, and communication systems, and the implementation of the waterproofing measures required to ensure reliable operation in a marine environment.

7.1 Hull and Mechanical Structure:

7.1.1 Equipment and Material

All structural hull components were fabricated using Fused Deposition Modelling (FDM) on an Anycubic Kobra 2 Max printer equipped with a 0.4 mm brass nozzle, the Kobra 2 Max offers a large build volume of 420 × 420 × 500 mm, which was necessary to accommodate the lenticular hull halves at the 30 cm prototype diameter, Polylactic Acid (PLA) was selected as the printing material on account of its dimensional stability and ease of post-processing.

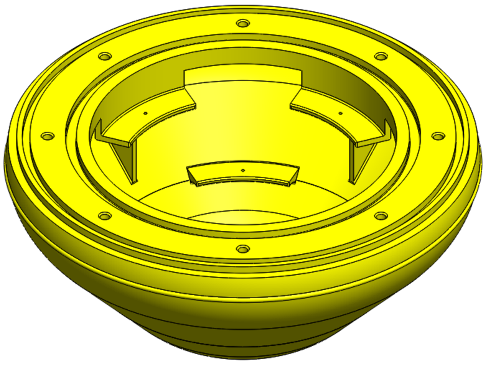


Figure 62: Isometric view of the prototype's lower hull 3D model

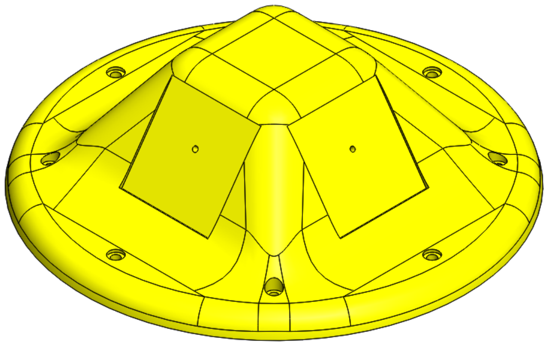


Figure 63: Isometric view of the prototype's upper hull 3D model

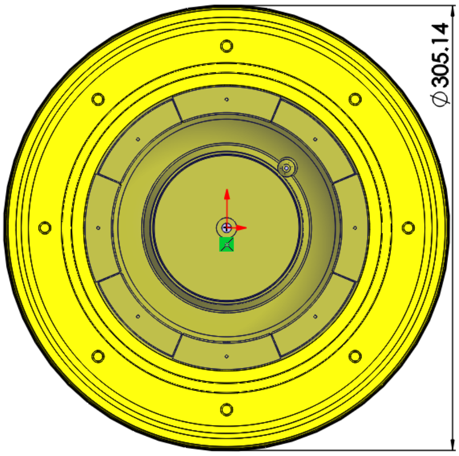


Figure 64: Top view of prototype lower hull 3D model

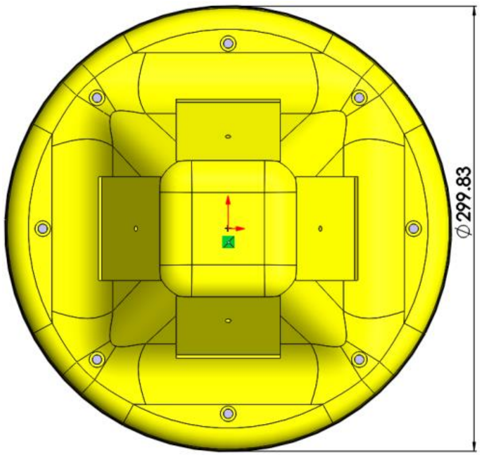


Figure 65: Top view of prototype upper hull 3D model

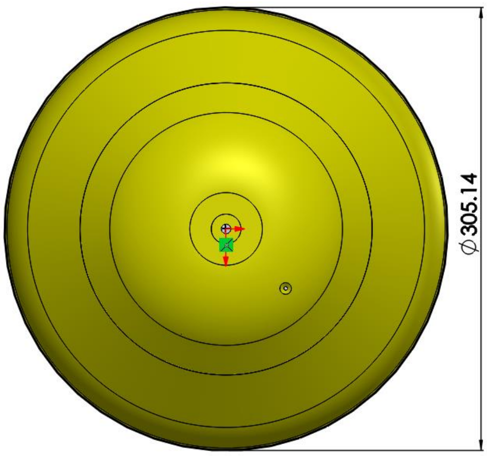


Figure 66: Bottom view of prototype lower hull 3D model

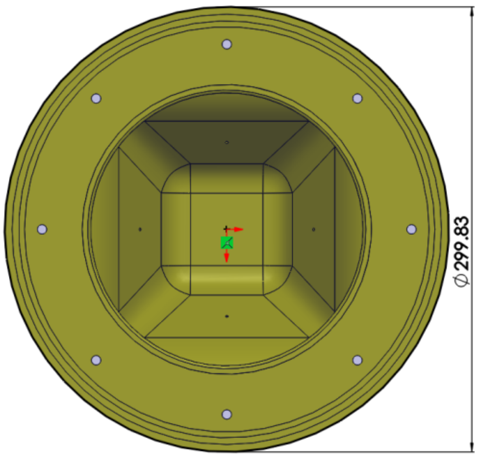


Figure 67: Bottom view of prototype upper hull 3D model

Figure 68: the 3D printers used in the project

Table 28: the principal printing parameters applied throughout the fabrication campaign.

Parameter	**Value / Setting**
Printer	Anycubic Kobra 2 Max
Nozzle diameter	0.4 mm
Filament material	PLA (1.75 mm)
Layer height	0.2 mm
Wall perimeters	4 (≈ 1.6 mm wall thickness)
Infill density	20 % gyroid pattern
Print temperature	200 °C (nozzle) / 60 °C (bed)
Print speed	60 mm s^{-1}
Support strategy	Tree supports, contact Z = 0.2 mm

7.1.2 Slicing and Print Preparation:

All STL part files were sliced using Anycubic Slicer, the proprietary slicing software provided with the Kobra 2 Max, Anycubic Slicer is built on an open source FDM slicing core and offers a profile based workflow in which machine specific constraints, build volume, extruder kinematics, and firmware limits are preloaded, reducing the risk of parameter conflicts that can arise when using third party slicers with unlocked profiles.

The slicing workflow for each component followed a consistent sequence of steps:

- **Model import and orientation:** the STL file was imported, and the part was oriented so that its largest flat face was placed on the print bed, minimizing overhanging surfaces and reducing the required support volume, for the hull halves, this meant placing the equatorial flange face down.

- **Support generation:** tree type supports were enabled with an overhang angle threshold of 45°, the tree support topology was preferred over conventional grid supports because its branching structure reduces contact area with the curved hull surface, limiting scarring and easing post print removal.
- **Parameter configuration:** layer height, wall count, infill density and pattern, print temperature, speed, and bed adhesion mode (brim) were set in the profile panel. These values were not fixed throughout the campaign, they were iteratively revised between several attempts.
- **Slicing and G-code export:** the model was sliced, and the resulting G-code previewed layer by layer to verify support placement, wall continuity at the tongue and groove features, and estimated print time before committing to a print run, files were transferred to the printer via USB.
- **Print monitoring** given the large part size and the associated risk of late stage failures, prints were monitored at regular intervals throughout their duration, any detected warping, layer shift, or adhesion failure prompted an immediate abort, parameter adjustment in the slicer, and re-slicing before the next attempt.

The slicing parameters listed in Table 16 represent the final optimized configuration reached at the end of the fabrication campaign. They should not be read as a fixed starting point, they are the outcome of a continuous refinement process driven by the failure modes described in the following section.

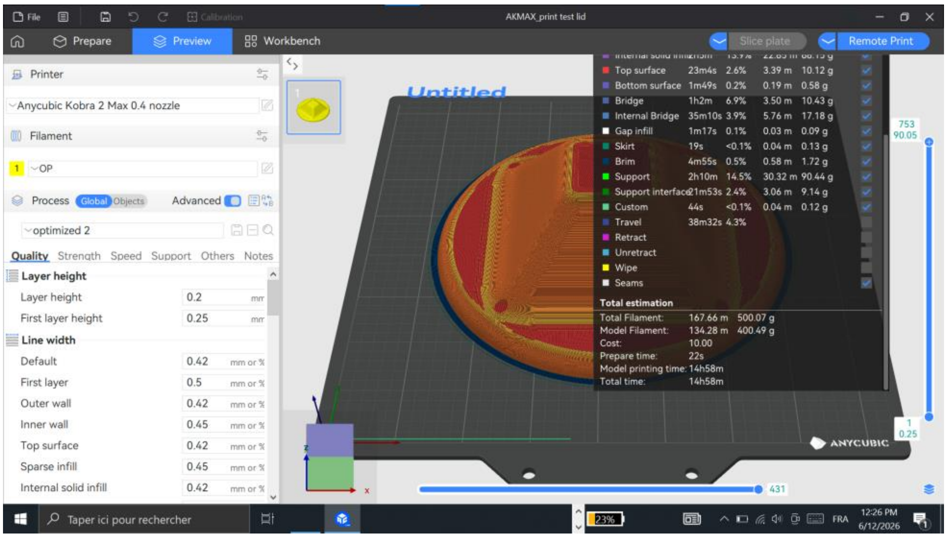


Figure 69: Sliced upper hull model

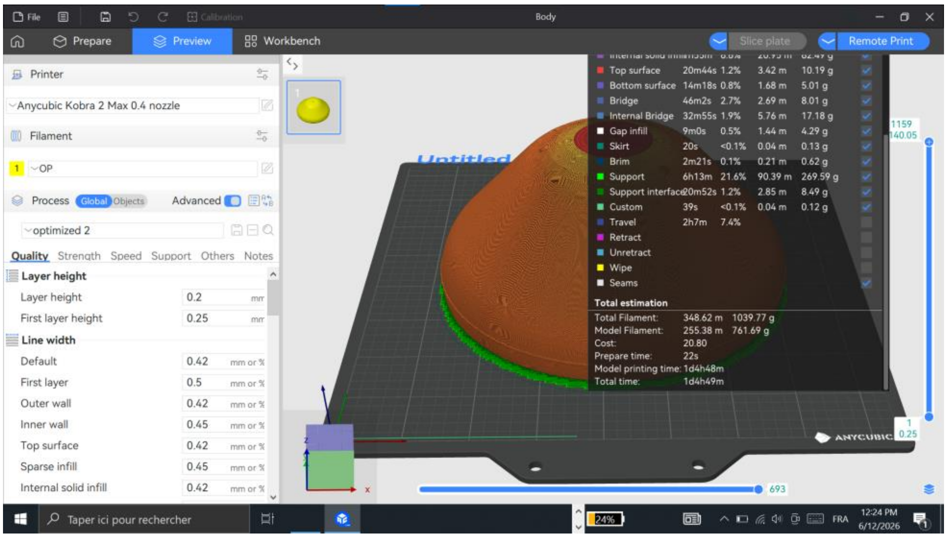


Figure 70: Sliced lower hull model

7.1.3 Printing Strategy and Observed Issues:

The hull was printed in two halves joined at the equatorial plane, The printing phase was the most challenging stage of the project, spanning roughly 20 days and requiring continuous parameter adjustment between attempts.

The upper half, incorporating the central frustum housing, succeeded on the first attempt. Its geometry produced a stable support structure with consistent bed adhesion throughout, and the equatorial flange met dimensional tolerances directly off the printer.

The lower half proved far more difficult. Its wide oblate footprint and large equatorial perimeter made it highly susceptible to thermal warping, as layers cooled unevenly, differential contraction caused the part edges to progressively lift from the bed, typically after several hours of printing, resulting in a failed print. Approximately ten attempts were made. Across them, parameters were systematically varied, without resolving the issue. Additional failure modes included mid-print layer shifts from support-head collisions and delamination at the tongue and groove walls from insufficient wall overlap.

The solution was to split the lower half along a vertical plane through its axis of symmetry into two equal sections, each section printed successfully within the stable adhesion range of the build plate, the two halves were then bonded using epoxy resin.

Figure 71: First printing fail

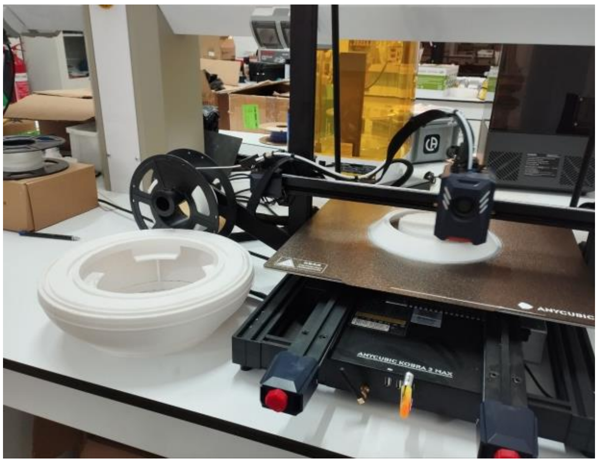


Figure 72: Lower hull printing in two segments.

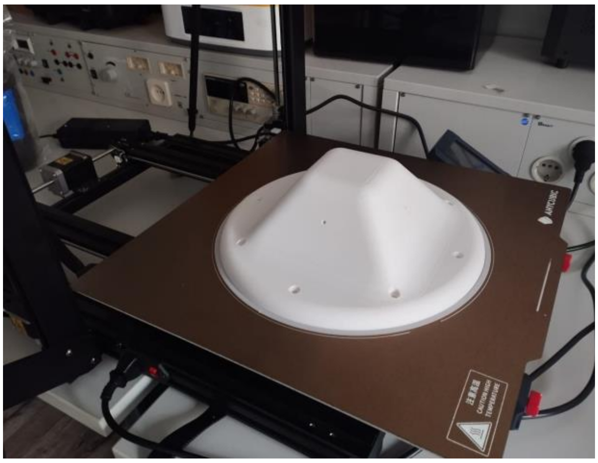


Figure 73:upper hull's successful print

7.1.4 Surface Preparation and Finishing:

Following printing, all hull surfaces were subjected to a three stage finishing sequence:

- **Mechanical sanding:** progressive grit sequence (120, 240, 400, 800) applied to the equatorial flanges, tongue and groove channel, and external hull faces to remove layer lines and improve sealing surface quality.
- **Solvent smoothing:** isopropyl alcohol wipe down to remove sanding dust and degrease bonding surfaces before adhesive application.
- **Protective coating:** the entire exterior hull surface was coated with automotive car brake caliper paint (high-temperature, moisture-resistant formulation). This finish provides UV resistance, reduces water absorption into the PLA matrix, and yields the final inspection friendly surface appearance. Two coats were applied with intermediate drying intervals of 30 minutes, full cure was achieved after 24 hours at ambient temperature.

The brake caliper paint was specifically chosen over conventional primers on account of its flexibility when cured important for a PLA substrate subject to thermal cycling and its documented resistance to water immersion, satisfying the minimal corrosion-protection requirement for a prototype deployment.

Figure 74: Finished lower hull

Figure 75: Finished assembled hull

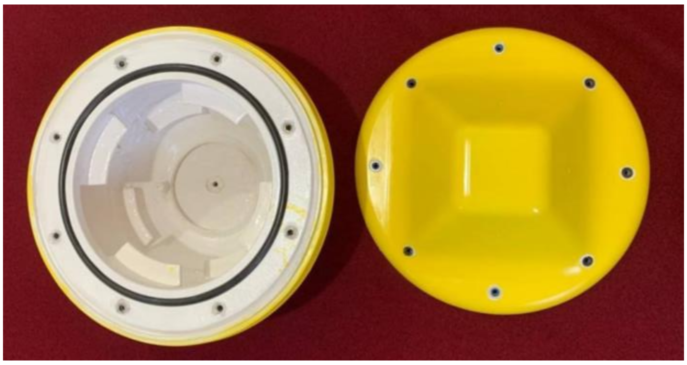


Figure 76: Finished buoy hulls

7.2 Electronic system:

7.2.1 Components and Assembly:

The prototype uses only the core sensors needed for wave monitoring, positioning, and water temperature. Table 19 lists the main hardware elements, external elements (the water temperature probe and the LED beacon) are wired to the board through screw terminals. Power is supplied by a 30 000 mAh power bank with USB Power Delivery, four small 5 V/0.5 W solar panels (one per cardinal direction) recharge the battery when daylight is available.

A dedicated USB boost converter generates the 12 V required by the yellow warning LED. The ESP32 runs firmware written in the Arduino IDE and creates a WiFi access point that serves a real-time HTML dashboard.

Table 29: bill of materials for the electronic system

Component	Qty	Description / Key Specifications	Purpose
ESP32-WROOM-32	1	Dual-core 240 MHz, WiFi 802.11 b/g/n, 520 KB SRAM	Central controller, data processing, web server
MPU9250 IMU	4	Gyro ±250 °/s, Accel ±2 g, Mag 0.15 µT/LSB	Wave motion sensing (heave, pitch, roll)

u-blox NEO-7M	1	56-channel GNSS, 2.5 m CEP, update up to 10 Hz, u.FL antenna connector	Real-time position and UTC time
DS18B20 temperature sensor	1	–55…+125 °C, ±0.5 °C, 1-Wire interface	Sea-water temperature
12 V yellow LED beacon	1	2.5 W, 360° lens, controlled via MOSFET	Visual signalling at night
USB booster (5 V → 12 V)	1	Step-up converter	Powers the LED beacon from the 5 V rail
Solar panels (5 V, 0.5 W each)	4	Monocrystalline, mounted on hull quadrants	Battery recharging
Power bank (Hoco, 30 000 mAh)	1	USB Power Delivery, 5 V output	System power supply
Custom PCB	1	135 mm × 135 mm, two-layer, designed in EasyEDA	Mechanical and electrical integration of all modules
GPS antenna (u.FL)	1	Active ceramic patch	GPS signal reception
Screw terminals	2	Two & three-position	Connection for DS18B20 and LED cables

7.2.2 PCB Fabrication and Assembly:

The prototype printed circuit board was manufactured in-house using the toner transfer method, the circuit layout, designed in EasyEDA, was printed onto glossy photo paper with a laser printer, the printed image was transferred to a blank copper-clad board by applying heat and pressure with a household iron (fer à repasser), after the paper was soaked and peeled away, the remaining toner acted as an etch resist, the board was then immersed in a ferric-chloride solution, which removed the unprotected copper and left only the desired conductive tracks.

Once cleaned and drilled, the surface was tinned to prevent oxidation, the electronic components, ESP32 module, IMUs, GNSS receiver, connectors, and passive components were manually soldered onto the board using a temperature controlled soldering station, the DS18B20 water temperature probe and the LED beacon were wired to the board via screw terminals.

After assembly, the firmware was uploaded to the ESP32 using the Arduino IDE, the code performs sensor reading, wave motion computation, and WiFi communication, the real-time dashboard, was loaded onto a smartphone or laptop connected to the buoy’s access point, confirming correct sensor operation and data visualization.

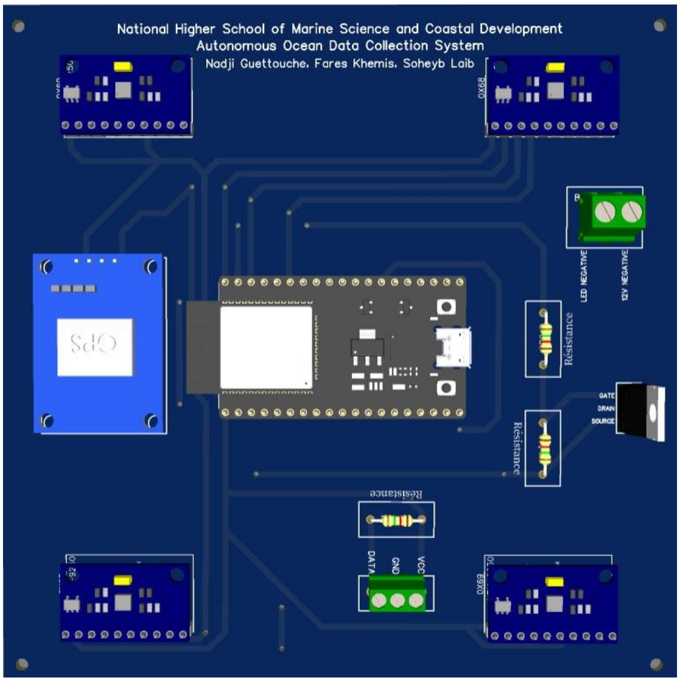


Figure 77: PCB architecture

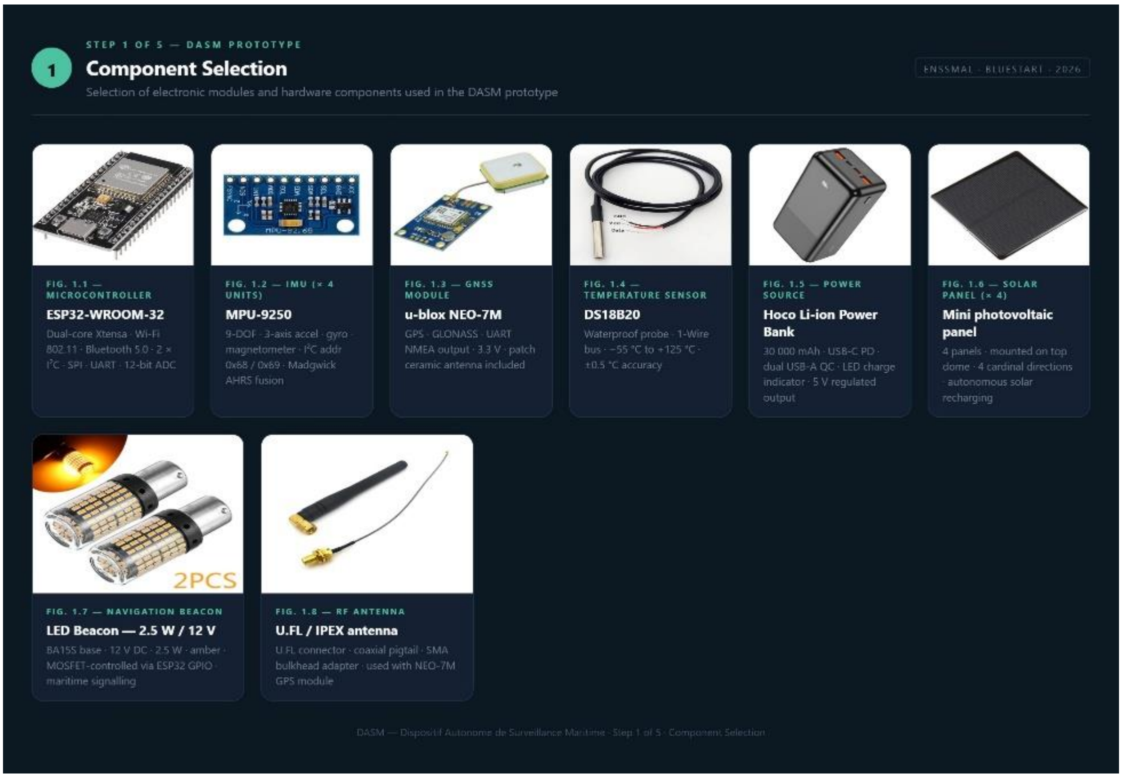


Figure 78: electronic components

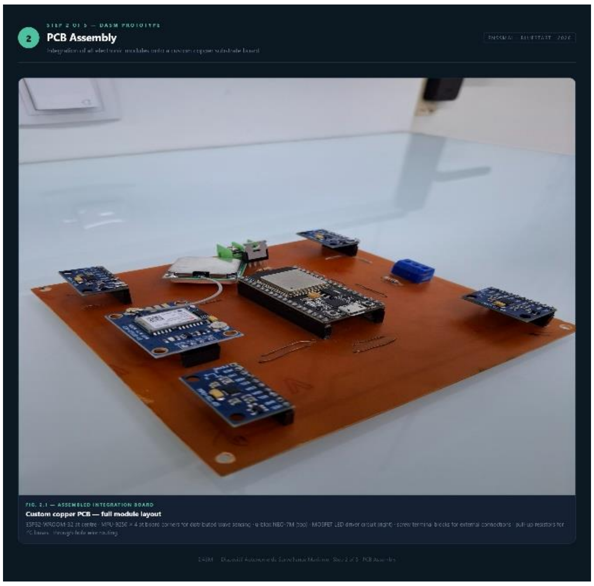


Figure 79: PCB assembly

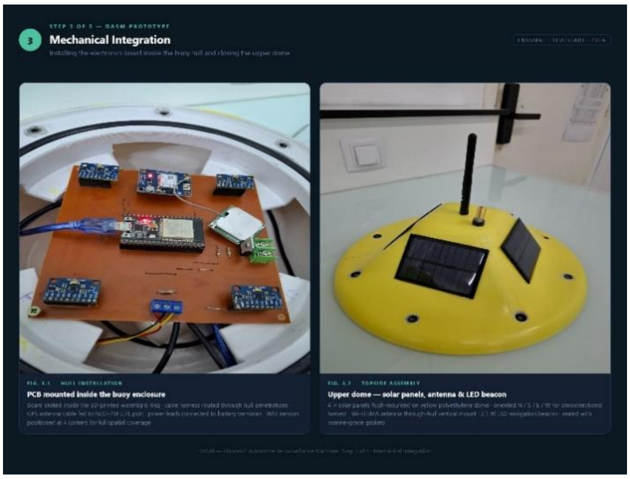


Figure 80: integration of the electronic system

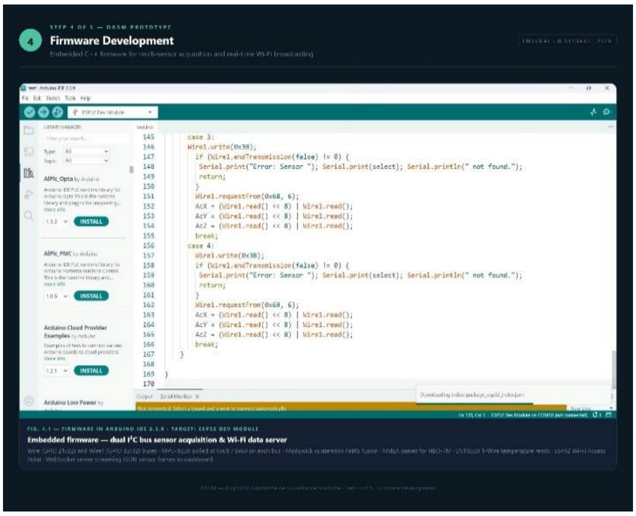


Figure 81: Firmware development

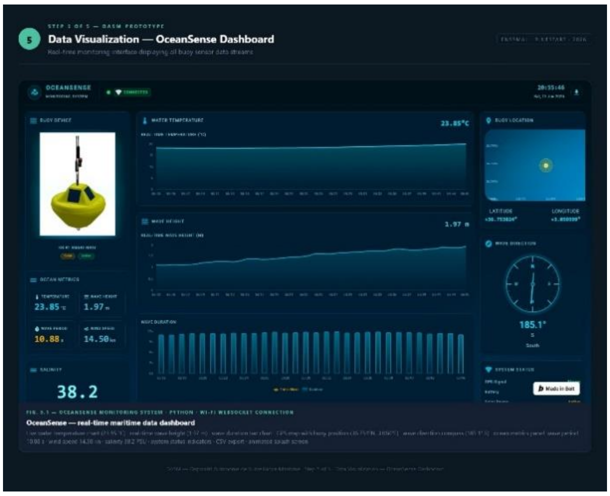


Figure 82: Data visualization

7.2.3 Autonomy:

The prototype is powered by a 30 000 mAh power bank with USB Power Delivery, which supplies a stable 5 V output, the internal battery capacity is 111 Wh (30 Ah × 3.7 V), thanks to power saving strategies, the WiFi access point is only activated when a user connects, and the LED beacon flashes with a very short duty cycle, the average power draw remains well below 0.5 W, this allows the buoy to run for up to 10 days on a full charge without any solar input.

Four 5 V/0.5 W solar panels, mounted on the hull, provide a combined peak power of 2 W, which is over four times the average consumption, even with moderate sunlight, the battery recharges during the day and the system can operate indefinitely in typical outdoor conditions.

7.2.4 Measured Parameters and User Interface:

The firmware acquires data at 100 Hz from the four IMUs, fuses them with a Madgwick filter, and computes the wave spectrum in real time, from this, the following parameters are extracted:

- Significant wave height Hs
- Peak wave period Tp
- Wave length L
- Mean wave direction (magnetic North)
- GPS position (latitude, longitude)
- Water temperature

A lightweight HTML/JavaScript dashboard, accessible over the buoy's WiFi access point, displays the current wave parameters, a rolling time series graph, and the GPS location, data can be downloaded as CSV for offline analysis, this setup allowed verification of the measurement chain in controlled conditions before final deployment.

BUSINESS MODEL CANVAS

Autonomous Ocean Data Collection System - ENSSMAL

KEY PARTNERS

- **Suppliers:** Direct procurement of sensors, HDPE/LLDPE resin, and other components (no intermediaries).
- **University incubators**: Blue Incubator (ENSSMAL)
- **Academic supervision:** ENSSMAL and HNS-RE2SD (lab access, technical guidance)
- **Financing bodies:** ASF, NESDA, MESRS/DGRSDT, Algeria Venture, Horizon Europe
- **Prospective institutional clients : ex :** ONSM (potential client)
- **Regulators/certifiers**: INAPI, IANOR, DGD, DGMM, ONEDD, IEC, ISO, WMO, IOC-UNESCO, ITU, IALA, CE

KEY ACTIVITIES

- Design and manufacturing (rotational molding) of buoy hulls
- PCB design, electronics assembly and sensor integration
- Embedded code, wave and multi-parameter fusion algorithms
- Mechanical assembly and watertightness testing
- Quality control, calibration and field deployment
- Institutional sales, leasing and data as a service operation (DaaS)

KEY RESOURCES

- Patent application and intellectual property for the overall design and engineering.
- Access to 3D printers and electronics lab equipment
- Engineering team (mechanical, electronics and programming skills)
- Scalable hull 3D model (30 cm to 1 m), reusable across variants
- Embedded algorithm and code
- Electronic system architecture
- Technical and scientific supervision
- Financial support: NESDA, ASF, Blue Incubator.

VALUE PROPOSITIONS

- **First Algerian made, autonomous oceanographic buoy**, ending dependence on costly imports.
- **More than 50% lower costs** compared to foreign systems.
- **Continuous, long term coastal data** compared to short term expensive missions
- **Cuts costly over design in coastal works** (wave height enters structural formulas cubed)
- **Locally maintainable**: Local spare parts and services
- **Scalable hull**: (30 cm–1 m) and modular sensor suite, no redesign needed
- **Multi-parameter data**: physical, chemical and biological in one unit
- **Foundation for future AI applications**

CUSTOMER RELATIONSHIPS

- **Direct, professional and institutional engagement (B2B/B2G)**
- **Technical presentations and detailed project dossiers**
- **Formal agreements, research partnerships and long-term contracts**
- **Dedicated support for leasing and Data as a Service clients**

CHANNELS

- **Official emails and direct B2B/B2G outreach**
- **Conferences, marine technology exhibitions** (ex: CIAMEL)
- **Professional networking with engineering firms**
- **Official website:** Web dashboard and cloud platform for live data access and customer support.

CUSTOMER SEGMENTS

- **Engineering consultancies and contractors involved in maritime and coastal infrastructure:** LEM, HMI, ANRIP, GITRAMA Group (MEDITRAM, ALDIPH, SOTRAMEST, SOTRAMO)
- **National maritime institutions:** Algerian Navy, SHFN, ONSM, Ministry of Transport, Port Authorities, Coast Guard
- **Coastal/environmental authorities**: CNL, Ministry of Environment, Ministry of Agriculture and Fisheries, ANCC, ONEDD, ONM
- **Academia and research institutions:** Ministry of Higher Education, universities, CNRDPA.
- **Foreign institutions:** regional/African export markets (Year 3+)

COST STRUCTURE

- **Total annual fixed costs: 17.1 M DZD**
  - payroll (11.52M DZD/yr), utilities (2.78M DZD/yr), professional services (2.18M DZD/yr), equipment depreciation (623,500 DZD/yr).
- **Variable costs per unit (1.036 M DZD/unit):**
  - Raw materials and structure (608,000 DZD/unit), electronics/sensors/PCB (206,600 DZD/unit), quality control and testing (42,000 DZD/unit), field deployment/logistics (99,500 DZD/unit), variable overheads (80,000 DZD/unit).
- **Initial investment: 4.018 M DZD (**production equipment + R&D/software/certifications).

REVENUE STREAMS

- **Direct unit sales:**
  - **Algerian market:** 10 M DZD (Year 1) increasing to 20 M DZD (Year 3).
  - **African market (excluding Algeria):** exports beginning in year 3 (40M DZD)
- **Leasing:** 300,000 DZD/buoy/month + 200,000 DZD/yr maintenance fees (from 18.8M to 72.6M DZD by year 3)
- **Data as a Service (DaaS):** 1M DZD/yr per buoy (from 3M to 15M DZD by year 3)
- **Total projected revenue:** from 31.8M DZD (year 1) to 147.6M DZD (year 3)

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