TÉCNICO LISBOA

Innovative Solution for Robust and Cost Effective Wind Measurements

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Electrical and Computer Science Engineering

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Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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And at last but not least, to my girlfriend for the inexhaustible patience and support.

Abstract

Nautical instrumentation, for competitive and recreational sailing, is a multimillionaire industry that most contributes for today's effectiveness and safety that characterize them. Great investments are made to develop technologies that allow an accurate representation of the environmental features, which lead to an ever-increasing automated approach of many navigation and weather forecast aspects. Even though, robust and affordable instruments are still lacking in the market, which leave an important part of the nautical community without dedicated solutions. One area where this issue is evident is wind measurement, whose theoretical principles are the basis of this project. The ultrasonic technology is the center piece of the anemometry study, whose superior performance is widely accepted by the nautical community. Although, the existing systems are prohibitively expensive for the common user and tend to have architectures that require expert handling and maintenance.

The main goal of this project is the development of a compact, robust and cost-effective wind measurement solution that will rely on consumer electronics like smartphones, tablets and PC for control and data visualization. This approach intends to be an alternative to the actual instrumentation networks, by offering an equivalent solution for a small fraction of their price. The result comprises a functional prototype, which will be taken to a higher level, in the form of a complete weather station with navigation capabilities. Although this solution is primarily dedicated to sailing, powerboats or even maritime and terrestrial weather stations can be considered as possible fields of application.

Keywords: cost-effective nautical instrumentation, ultrasonic anemometry, NMEA 0183 devices.

Resumo

A instrumentação náutica, direccionada para a vela de competição e recreativa, é uma indústria multimilionária que contribui activamente para a actual eficiência e segurança que as evidenciam. Grandes investimentos são feitos no desenvolvimento de tecnologias que permitem uma representação fiel das características ambientais, o que tem levado a uma crescente automatização de variados aspectos da navegação e previsão meteorológica. Ainda assim, o mercado carece de instrumentação robusta e acessível, deixando uma parte importante da comunidade náutica sem soluções dedicadas. Uma área onde esta questão está patente é a monitorização do vento, cujos princípios teóricos são as bases deste projecto. A tecnologia ultrassónica é o ponto principal do estudo da anemometria, cujo desempenho superior é amplamente aceite pela comunidade náutica. Contudo, os sistemas existentes são proibitivamente dispendiosos para o utilizador comum e tendem a possuir arquitecturas que requerem utilização e manutenção especializadas.

O objectivo principal deste projecto é o desenvolvimento de uma solução de monitorização do vento, robusta e acessível, que dependerá de dispositivos electrónicos de consumo, como *smartphones*, *tablets* e *PC*, para controlo e visualização de dados. Esta abordagem pretende ser uma alternativa às redes de instrumentação actuais, oferecendo uma opção equivalente por uma pequena fracção do seu custo. O resultado compreende um protótipo funcional, que será elevado a um nível superior, na forma de uma estação meteorológica com capacidades de navegação. Embora este sistema seja primariamente dedicado à vela, embarcações motorizadas, ou mesmo estações meteorológicas marítimas e terrestres poderão ser consideradas como possíveis campos de aplicação.

Palavras-chave: instrumentação náutica acessível, anemómetria ultrassónico, dispositivos NMEA 0183.

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List of Acronyms

3GPP	3rd Generation Partnership Project
AES	Advanced Encryption Standard
AT	ATtention
CR	Carriage Return
CRC	Cyclic Redundancy Check
CPU	Central Processing Unit
DC	Direct Current
DPCU	Data Processing and Communication Unit
EDGE	Enhanced Data rate GSM Evolution
ETSI	European Telecommunications Standards Institute
EGNOS	European Geostationary Navigation Overlay Service
EEPROM	Electrically-Erasable Programmable Read-Only Memory
FDMA	Frequency Division Multiple Access
FTDI-Interface	Future Technology Devices International Interface
GBP	Great Britain Pounds
GEO	Geosynchronous Earth Orbit
GES	Gateway Earth Station
GPIO	General Purpose Input/output
GPRS	General Radio Packet Service
GPS	Global Positioning System
GSM	Global System for Mobile communications
HCTML	Hyper Compressed Text Mark-up Language
HMI	Human Machine Interface
HTTP	Hypertext Transfer Protocol
I2C	Inter-Integrated Circuit
IoT	Internet of Things
IEC	International Electrotechnical Commission
IMEI	International Mobile Equipment Identity
IP	Internet Protocol
IP Code	International Protection Marking
LDA	Laser Doppler Anemometer
LED	Light Emitting Diode
LEO	Low Earth Orbit
LF	Line Feed
Li-ion	Lithium-ion
LPGL	Lesser General Public License
LTE	Long Term Evolution
MicroSD	micro Secure Digital

NMEA	National Marine Electronics Association
NMT	Navy Multiband Terminal
NOC	Network Operations Center
OS	Operating System
PC	Personal Computer
PCB	Printed Circuit Board
PTFE	Polytetrafluoroethylene
RAM	Random Access Memory
RPM	Revolutions per Minute
RS	Recommended Standard
SBD	Short Burst Data
SONAR	Sound Navigation and Ranging
SSID	Service Set Identifier
SDRAM	Synchronous dynamic random access memory
SIM	Subscriber Identity Module
SMS	Short Message Service
SONAR	Sound Navigation and Ranging
TCP	Transmission Control Protocol
UART	Universal asynchronous receiver-transmitter
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
VAT	Value Added Tax
VDC	Volts Direct Current
VSAT	Very Small Aperture Terminal
WAAS	Wide Area Augmentation System
WEP	Wired Equivalent Privacy
WLAN	Wireless Local Area Network
WPA	Wired Protected Access
Wi-Fi	Wireless Fidelity

List of Symbols

c	Speed of sound in m/s (meters per second)
C	Battery capacity in mAh (miliampere hour)
i	Electrical current in A (ampere)
L	Distance in m (meters)
ρ	Fluid density in kg/m^3 (kilogram per cubic meter)
P_d	Dynamic pressure in Pa (pascal)
P_s	Static pressure in Pa (pascal)
P_t	Total pressure in Pa (pascal)
SF	Safety factor in %
t	Time in h (hours)
T_1	Time in s (seconds)
T_2	Time in s (seconds)
v	Wind speed in m/s (meters per second)

1 – Introduction

Maritime navigation is a complex way of transportation that requires not only the vehicle domain but also a correct interpretation of a volatile environment. Unstable weather conditions, a fluid as mean of locomotion and the lack of reference points would be strong reasons to forsake this kind of traveling [2] [19]. Although, this is currently one of the safest ways of transportation [16]. Not being fast as an aircraft, vessels can accomplish the longest journeys, with the heaviest cargo and have established routes all over the world [2] [13] [18] [19]. With an embracing market, nautical industry have strong strands in competition, cargo and people transportation, research, military and recreational applications.

Excluding new methods and technologies to design vessels, like new materials, structural calculus algorithms, propulsion systems, etc. nautical instrumentation is the area that most contributed to the actual effectiveness and safety of navigation [2] [13] [19]. The state of art includes valuable tools for weather forecasting, mapping, long range communications and autonomous navigation.

Although, these advanced technologies come with a price and many of the available systems in the market are prohibitively expensive, or too complex, for most of the small sailors. This issue applies to competition, commercial and recreational purposes [2] [18] [19]. These potential costumers represent an important gap in the market that lacks of robust and cost-effective navigation and weather instrumentation. One area where this issue is most evident is wind measurement. Over many years of development, most of nautical necessities were identified and specific technologies were created to suppress each one of them. Even though, regarding wind measurement, there are still available several technologies within a wide cost and performance ranges [2] [19]. The device used to measure the wind is an anemometer and the ultrasonic principle has proven to have important advantages over the existing alternatives [4] [19]. For this reason, the ultrasonic technology is the center piece of the anemometry study, whose superior performance is widely accepted by the nautical community.

Due to the crescent number of different devices that can be used in a vessel, nautical instrumentation evolved into a network structure, as shown in Figure 1.1 [2] [19] [23]. This approach allows an efficient implementation, while it is possible to include only the required modules and further modifications are allowed in a plug-and-play approach. Usually, these networks have a star topology, being the center node the central unit. This unit manages data from all sources, which could be weather stations, GPS, radars, SONAR's, consoles, plotters, etc. Another advantage is that nautical instrumentation is regulated by National Marine Electronics Association, which developed the NMEA 0183 and NMEA 2000 electrical and communication standards [77]. These assure compatibility from a wide variety of data sources when operating within the same network [1] [77].

A medium range central unit and a console or plotter, with all the ancillaries, reach easily to € 20,000 [35] [36] [37] [38] [39] [40] [41]. These are the basic components, consisting on the network center node plus a visualization device, which are useless without any other sensor to provide data. To give access to this technology to a wider market, one of the goals of this project is to provide a low-cost alternative for the basic components. This allows the application of a larger share of a certain budget, which is assumed to be little, in sensor acquisition.

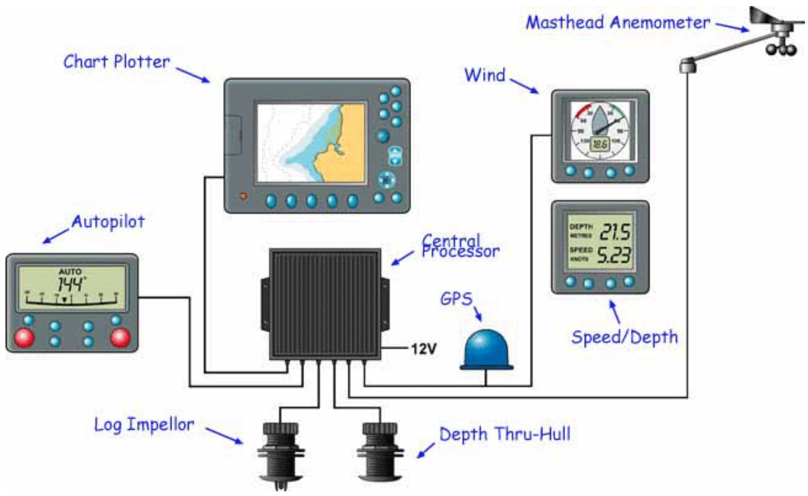


Figure 1.1 – Modern vessel network [23].

1.1 – Objectives

The course of this work is divided into two main objectives: the study of anemometry technologies used in nautical applications, emphasizing the ultrasonic one; the development of a functional prototype that can substitute the expensive nautical instrumentation networks for low-cost alternative. At an early stage, the theoretical understanding of the wind genesis serves as a basis to the comparison between the most used anemometry technologies in nautical applications. After this theoretical research, the development of the prototype takes place. The requirements comprise a small open-source, lightweight, portable and low-cost central unit that can communicate with licensed navigation and weather station devices, through the NMEA 0183 protocol. Plus, in order to reduce the system cost of basic components, the unit must wirelessly rely on smartphones, tablets and PC for control and data visualization. This suppresses the need of the expensive and dedicated consoles presented in Figure 1.1. As an option, long range communications to assure control from remote places, is a valuable resource to integrate the prototype. The intended fields of application of this system are listed below:

- **Competitive and recreational vessels:** Although the main goal is the application in sailing, powerboats can be considered too. The budget for instrumentation applied mostly to quality and varied sensors, by diminishing the economical effort of acquiring the basic processing and visualization devices, is where the prototype contributes to improve small vessel networks. Figure 1.2 shows an example of a vessel that could benefit with this system.

Figure 1.2 – Racing Hydrofoil [15].

- **Maritime monitoring buoys and land weather stations:** As secondary fields of application are maritime monitoring buoys, shown in Figure 1.3, and land weather stations, shown in Figure 1.4. Although these are usually systems with special characteristics for specific purposes, the same kind of instrumentation networks can be applied. NMEA devices include maritime and land applications. Due to the nature of these systems, installed many times in remote places, long range communications are an important feature to integrate the prototype.

Figure 1.3 – Monitoring Buoy from WaveEC association.

Figure 1.4 – Land weather station [27].

1.2 – Structure of the dissertation

- **Chapter 1:** Regarding motivation and background, this section presents the characteristics of nautical travelling, modern instrumentation networks and the identification of the market gap in robust and cost effective weather and navigation solutions. Along with the need of exploiting the actual anemometry technologies, due to their wide cost and performance ranges, these form the basis for the development of a functional prototype.

- **Chapter 2:** Theoretical study on wind genesis and interpretation, as well on three most used anemometry technologies, in nautical applications: Cup and Vane, Pitot tube and Ultrasonic.

- **Chapter 3:** Market analysis regarding the prototype requirements, as well the gathering of empirical knowledge on how the alternative solution, proposed by this project, is seen by the target audience.

- **Chapter 4:** Prototype development, including all the steps concerning the hardware, software, power supply and enclosure.

- **Chapter 5:** Tests and results with the objective of validating and classifying the prototype in terms of operation and robustness in controlled environments and outdoors.

- **Chapter 6:** Conclusions of the dissertation: discussion on the application of the ultrasonic anemometer as standard solution; performance and implications of the prototype, as an alternative for the actual instrumentation networks.

2 – Wind Measurement

Weather is mainly the result of the Earth exposure by the Sun [2] [19]. The incident radiation is responsible for a great energy transfer that heats large masses of air. The hot air rises and is substituted by cold air, which is heavier and denser. This phenomena creates atmospheric pressure differences, leading to a continuously unbalanced system [2] [19]. The wind is the natural attempt of pressure leveling, and consists on air mass flows from high pressure areas to low pressure ones [2] [19].

The ocean currents are responsible as well for displacing air masses around the globe [2] [19]. High temperature differences between the poles and the equator, together with the Earth's rotation, creates low pressure bands in the equator and middle latitudes and high pressure bands in the poles and subtropics [2] [19]. These pressure bands, presented in Figure 2.1, generate a global and stable wind system, which is disturbed by temperature changes in land [2] [19]. The Earth's rotation makes clock-wise winds in the Northern hemisphere and counter clock-wise ones in the Southern hemisphere [2] [19].

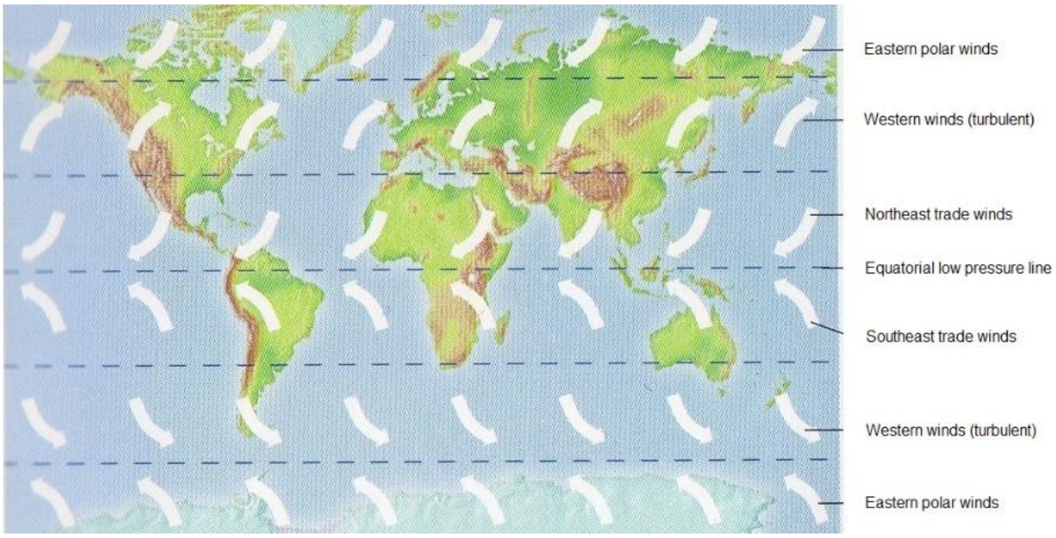


Figure 2.1 – Global wind system, adapted from [19].

2.1 – Wind Interpretation

The wind felt by an object can be decomposed in True, Heading and Apparent components [2] [19] [25]. The predictability, magnitude and relation between them are critical factors when choosing an appropriate anemometer. Figure 2.2 shows the decomposition of the wind for a flat ground and flat water conditions, assuming no external influences:

- **True Wind:** The wind an object feels when it is not moving (i.e. stationary relative to Earth). This component depends on the atmospheric conditions and is usually the only way the wind is defined in land, as the measurements are made from fixed locations [2] [19] [25].

- **Heading Wind:** The wind created by an object's motion, which directly relates with drag force. Has the same speed of the object, but with opposite direction [2] [19] [25].

- **Apparent Wind:** The sum of both previous wind components results the Apparent Wind. This component is the wind which is actuality felt by an object.

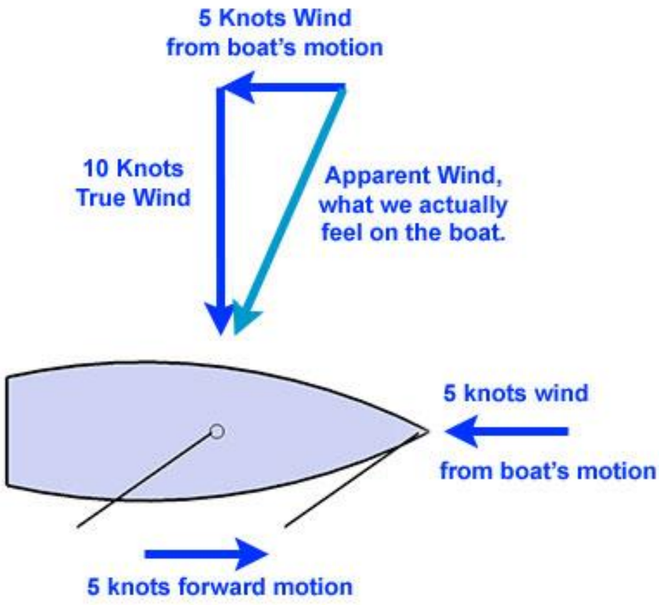


Figure 2.2 – Wind components, adapted from [25].

A critical feature regarding anemometry is that it is only possible to measure the Apparent Wind, as the Earth's and anemometer references frames are independent. If the anemometer is in a fixed location, Apparent Wind equals to True Wind. Land weather stations are an example of this situation. But if the anemometer is moving, relative to Earth, special mechanisms to decompose the wind are needed. To know the velocity of a vessel it is essential to know the wind it produces [2] [19] [25].

2.2 – Terrain and Wave Influence

Any type of outcrop, like a rock formation, influence the Apparent Wind by introducing noise to the measurements. The air tends to flow without turbulence across smooth surfaces, according to Bernoulli's law, which states the balance between pressure and velocity of a certain flow [20]. Turbulence is local and can be experienced near any abrupt wind flow interruption [19] [20]. Weather stations in land can be positioned where the wind flow is more stable, by choosing safe distances from objects in order to avoid turbulence [19] [20]. At sea, the environment is more complex due to the fact that noise sources are inconstant in number and in magnitude [19]. Coast lines or other outcrops surrounded by wind currents could generate unexpected gusts and transition from exposed to protected zones are susceptible to turbulence, as shown in Figure 2.3 [2] [19] [20]. The combination of these several noise components could result in meaningless readings by the anemometer. This is the main reason why the anemometer is set near the tip of the mast, far from sails and wave influence [19] [20]. Anemometers with higher inertias filter better turbulent regimes, but at the same time are less responsive to changes in the environment, or to the course of the vessel.

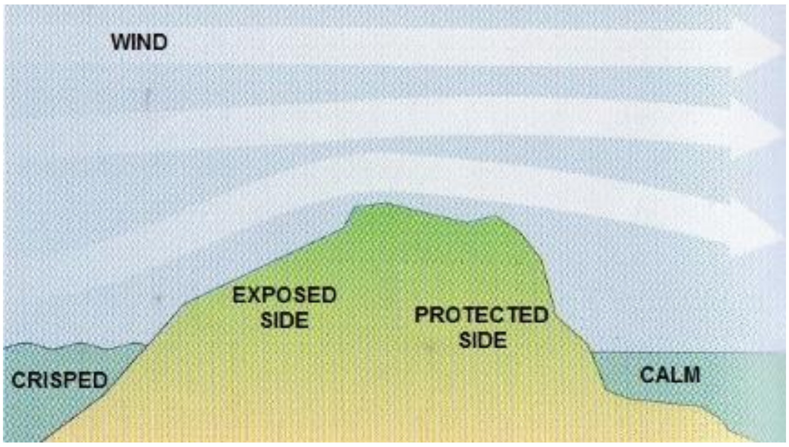


Figure 2.3 – Outcrop influence in the sea, adapted from [19].

2.3 – Anemometers

Wind measurements are performed by anemometers, which are classified into two types: wind pressure and wind speed anemometers [4]. The first ones have joints made of a soft material that warps against the wind force [4]. This applied force leads to a material deformation, which is measured and is proportional to wind speed [4]. The second ones have mechanisms to measure the speed of air particles in an air stream [4]. Initially used for weather applications only, the anemometer proved to be a useful tool in many industrial and scientific applications [4] [14]. Speed anemometers, like the LDA, are used in non-intrusive applications regarding measurements of air and liquid particles. Chemically reacting or high-temperature media and rotating machinery are some examples [14]. The hot-wire anemometer is another wind speed example of a widespread device, used in industrial applications related with laminar, transitional and turbulent boundary layer flows [12]. In spite of the high precision of these devices, they are used in controlled atmospheres, as they are too complex or too fragile for outdoors [4] [11] [12] [14]. In weather applications, especially in maritime environments, are required robust devices capable of delivering trustworthy data while experience long lasting periods without maintenance, calibration or extreme weather conditions [2] [4] [15] [19].

In order to study a suitable anemometer for the prototype, regardless the above characteristics, it must be taken into account that will be primarily installed in a moving vessel. This leads to the necessity of auxiliary mechanisms to decompose the wind. As the anemometer can only read the Apparent Wind, we need to obtain another component (see section 2.1). Measuring the Heading Wind is the easiest way but, as the water do not allow static reference points, GPS systems are used to calculate the velocity of the vessel. [2] [4] [15] [19].

2.3.1 – Cup and Vane Anemometers

These devices are one of the most common wind speed anemometers, invented in 1845 by Dr. John Thomas Romney Robinson, in Ireland [4]. The simple cup anemometer, shown in Figure 2.4 (a), evolved into the vane architecture of the Figure 2.4 (b), but both are used today and share the same operating principle [10] [17]. The first one have the blades in the form of hollow hemispheres, with their concavity facing away from the air flow and the rotation axle is perpendicular to the wind [10] [17]. This architecture only can measure wind speed. For the wind direction, a vane[1] must be installed, as shown in Figure 2.4 (a). The second one can have the same architecture, or plane blades with an attack angle around 45º, instead. The main difference is the plane of rotation, which is parallel to the direction of wind flow in the first case and perpendicular in the second [4] [17]. Both architectures are used in vessels, weather stations and weather buoys [2] [19].

(a) (b)

Figure 2.4 – Cup Anemometer plus external vane (a); Vane anemometer (b). Adapted from [29] [50].

The operating principle of this anemometer consists on relating the rotation of the shaft, where the blades are attached to, with the wind speed [4]. To achieve this, two transduction methods are available and are described below:

- **Rotational Speed:** The shaft is connected to an encoder, which could be of one step only, producing a lap counter mechanism. This allows relating the angular speed of the shaft with the wind speed, as shown in Figure 2.5 (a).

- **Inducted Current:** The shaft is part of the rotor of a DC motor, which works like a generator. An electrical current is inducted, whose intensity is proportional to the shaft rotation. Again, this rotation can be related to wind speed, as shown in Figure 2.5 (b).

[1] "Vane" and "Vane Anemometer" are different devices. A "Vane" is used only to measure wind direction, while a "Vane Anemometer" refers to the device present in Figure 2.4 (b).

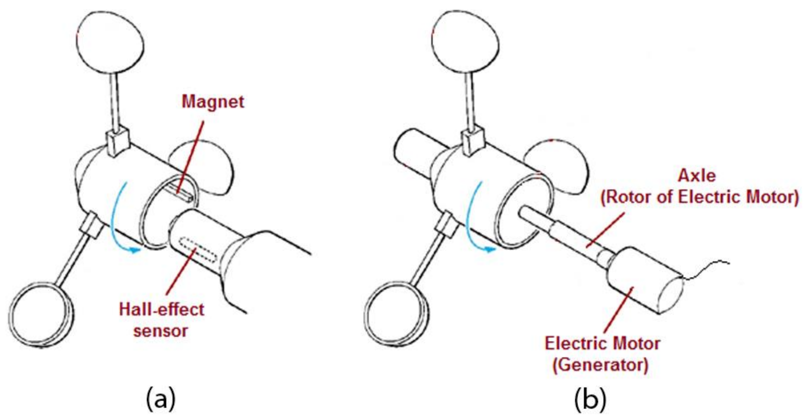


Figure 2.5 – Rotation speed measurement (a); Inducted current measurement (b). Adapted from [17].

Regarding the vane operating principle only, is usually a variation of the first transduction method [4]. As the vane indicates from where the wind blows, using a high resolution encoder, it is possible to match the vane position with the wind direction. Higher the resolution, more accurate is the vane, but more prone to turbulence too.

These anemometers are a robust and cost-effective solution with very reasonable performance. Have a wide operation range with very low power consumption [4]. In fact, they do not need power supply because the input is an inducted electrical signal. The drawback of this architecture is the exposed encoder and bearings, which are especially sensitive to low temperatures and corrosion [4] [19]. In icy or salty conditions, the accumulated waste changes the weight distribution, blocking the shaft rotation [4] [19]. Extreme low or high temperatures change the bearings lubrication, with negative consequences for the shaft rotation too.

In spite of the low inner drag of these anemometers, the inherent inertia could be an obstacle in applications where fast wind variations are experienced. It is a good choice for static weather stations, but it could bring some issues in vessels, while it cannot react as fast as other architectures [4] [30] [32]. Due to the lower cost, when compared with other technologies, regular but easy maintenance and a reasonable performance in most applications, cup and vane anemometers are a popular choice for wind measurements in many nautical and weather applications [2] [4] [19].

2.3.2 – Pitot Tube Anemometer

Tube anemometers are of pressure type and have seen its design being evolved since they were invented in 1775 by James Lind [4] [30]. In early 18th century Henri Pitot redesigned the concept that led to the modern pitot tubes by Henry Darcy in the mid-19th century, shown in Figure 2.6 [4] [30]. It is widely used to determine the airspeed of an aircraft, water speed of a boat and wind velocity in vessel and weather applications [30].

Figure 2.6 – Pitot tube, adapted from [32].

The system uses a pitot-static tube, which is a pitot tube with two ports, as presented in Figure 2.7: pitot and static [30] [32]. The pitot port measures the dynamic pressure of the "open mouth" of a tube pointed directly to the wind and the static port measures the static pressure from small holes alongside on that tube, through an inner fluid [20] [30] [32]. This moving fluid is brought to rest (i.e. stagnates) as there is no outlet to allow flow to continue [20] [30] [32]. This pressure is the stagnation pressure of the inner fluid, also known as the total pressure, stated by Bernoulli's Law (1) [20] [30] [32]. The output are two solid lines down to the control system, in order to measure the pressure differential between them, being this differential proportional to wind speed (2) [30] [32].

$$P_t = P_d + P_s \tag{1}$$

Where P_t: Total Pressure (Pa); P_d: Dynamic Pressure (Pa); P_s: Static Pressure (Pa)

$$P_t = \frac{\rho \cdot V^2}{2} + P_s \leftrightarrow v = \sqrt{\frac{2(P_t - P_s)}{\rho}} \tag{2}$$

Where ρ: Fluid density (kg/m^3); V: Wind speed (m/s)

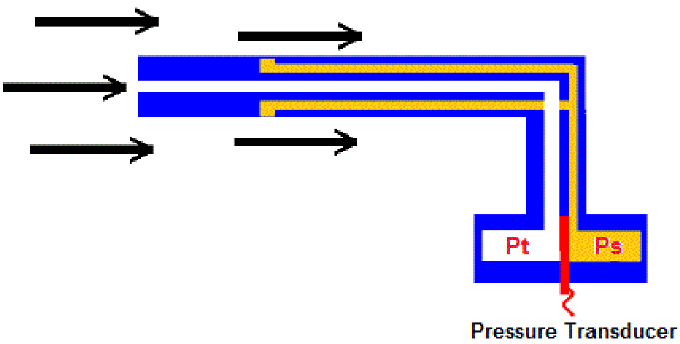


Figure 2.7 – Pitot tube fluid schematic: Total Pressure (P_t); Static Pressure (P_s), adapted from [32].

Although this anemometer can be installed in a vane architecture, is usually fixed pointing to the primary moving direction. They are heavy sensors with implicit high inertia and could decrease performance if required to change direction too fast [32]. This is not a problem in an aircraft, where they are fixed and pointing forward to the flight direction, where forward velocity is much higher than transversal ones. In maritime applications this anemometer could be a slow response solution.

As the tube head must be very small to reduce turbulence (less than 5mm), very low temperatures, ice or rime are critical factors. Reason why these devices are usually installed together with a heating system [32]. Although this system could be power demanding due to this, the sensor itself do not need supply. Like the cup and vane architecture, the measurement is an induced process.

In spite of its complexity and potentially slow responsiveness, this is one of the most accurate anemometers and is approved to be used in nautical applications [32]. It can measure wind speed near 0 to near Mach 1 but usually they are built with smaller operating ranges to maintain a linear characteristic [30] [32] [34].

Like cup and vane anemometers, this device cannot measure wind direction itself. A structure similar to vane anemometer is required, in order to face the tube mouth to the wind [30].

2.3.3 – Ultrasonic Anemometer

Ultrasonic anemometers, first developed in the 1950s, are another type of wind speed sensors, which main fields of application are in vessels and weather stations [2] [19]. They use ultrasonic pulses to measure wind velocity, based on the Time Of Flight Theory, as presented in Figure 2.10 [4] [7] [20]. Several pairs of independently activated transducers can be combined to yield a measurement of velocity in 1-, 2-, or 3-dimension [4] [20]. The spatial resolution is given by the distance between transducers, which is typically 5 to 20 cm [4] [7]. Longer distances implies lower sampling rate, while the system have to wait more time between the emission and reception of a certain pulse and lower distances need faster processing, which have an important impact on the equipment cost.

2-dimensional ultrasonic anemometer architecture, as shown in Figure 2.9 (a), is the most usual configuration in vessels and weather stations, but a 3-dimensional approach, presented in Figure 2.9 (b), is also a relevant architecture [4] [24]. Both operating principles are described below:

- **2-dimensional architecture**: This structure have four arms, each one having an ultrasound emitter and a receiver, forming two ultrasound paths. Each pair emits pulses both ways for redundancy purposes, with the order presented in Figure 2.9 (a), helping filtering turbulent regimes. The average speed of the two pulses of the same arm is the speed of sound at some temperature. With this configuration it is possible to calculate a velocity vector, as shown in Figure 2.8, together with **Time Of Flight** equation system (3).

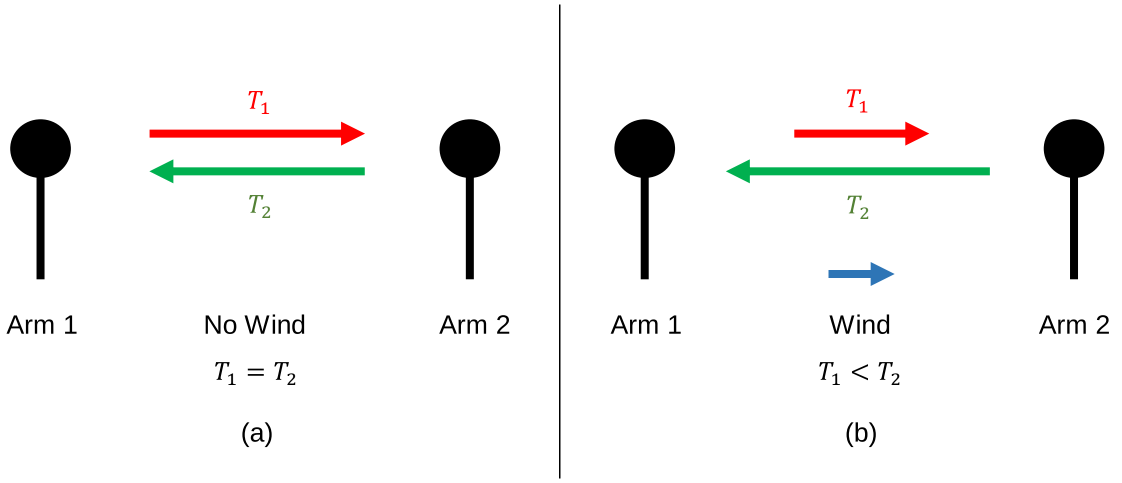


Figure 2.8 – Wind velocity vector calculation in a two arm example.

- **3-dimensional architecture**: These sensors have 6 arms and the same operating principle than the 2-dimensional case. The extra pair gives one redundancy path between the pulses of the angled arms, improving the sensor accuracy by minimizing the aerodynamic turbulence of its own physical structure [4] [7]. The pulse order is presented in Figure 2.9 (b).

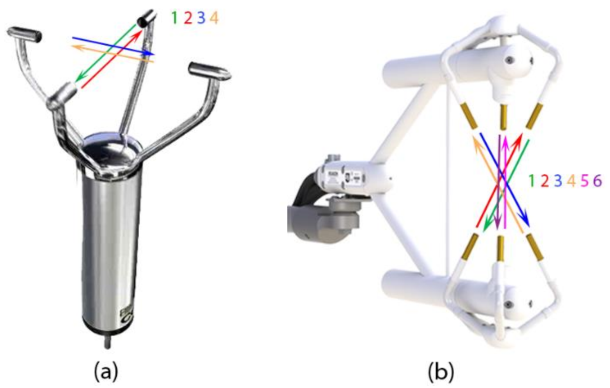


Figure 2.9 – 2-dimensional two path ultrasonic anemometer (a); 3-dimensional three path ultrasonic anemometer (b). Number sequences are the order of ultrasonic pulses. Adapted from [7] [29].

The ultrasonic measurement method is based on the **Time of Flight Theory**, presented in Figure 2.10 [20]. Taking the four arm configuration as an example, the system measures the time interval a pulse needs to travel from the North transducer to the South transducer and compares it with a pulse in reverse direction. This second pulse is emitted immediately after the receiving of the first. Likewise, times are compared the same way between West and East transducers [6] [7] [20]. If there is no wind, pulse travel times are equal. If the wind blows in the same direction of the pulse, this will arrive sooner to the other transducer, otherwise will take longer (3). In a reference frame centered equidistant from the poles it is possible to know the balance of the system [6] [7] [20].

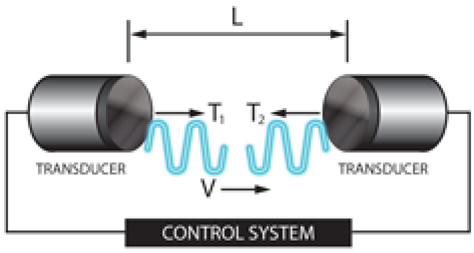


Figure 2.10 – Transducer behavior according to Time of Flight Theory [17]: Distance between transducers (L); Travel time for the first e second pulses (T_1 and T_2); Wind speed (V).

$$\begin{cases} T_1 = \dfrac{L}{c - v} \\ T_2 = \dfrac{L}{c + v} \end{cases} \rightarrow \begin{cases} v = \dfrac{L}{2}\left(\dfrac{1}{T_1} - \dfrac{1}{T_2}\right) \\ c = \dfrac{L}{2}\left(\dfrac{1}{T_1} + \dfrac{1}{T_2}\right) \end{cases} \qquad (3)$$

Where L: Distance between transducers (m); T_1 and T_2: Time of flight of the pulses (s); v: Wind speed (m/s); c: Speed of Sound (m/s).

Ultrasonic anemometers can take measurements very quickly, 20 Hz or higher, which makes them well suited for measurements in turbulent regimes. As they have dedicated processing it is possible to filter outlier samples, in order to obtain a smooth measurement curve in real-time [4] [7]. The lack of moving parts means they do not have inertia related issues and together with the high sampling rate they are perfect solutions for dynamic applications [4] [7]. Another advantage of this technology is the long-term operation without maintenance, while the lack of moving parts allows a more hermetic and compact enclosure [4].

Since the speed of sound is directly related with air temperature and is virtually stable with pressure changes, ultrasonic anemometers depend on an internal thermometer for measurement compensations [4] [20].

2.3.4 – Technical comparison between anemometry technologies

Vane and Pitot tube anemometers have many similar characteristics and consequently share a few issues. They are accurate devices but, at least the vane capability is assured by the use of bearings for rotation and encoders for measurement. This have an immediate impact on corrosion resistance, life cycle without assistance and maintenance, as described in section 2.3.1:

- Need periodic calibration.
- Even tough with a long life span, have consumable parts.

- Need periodic inspection to evaluate if nothing is blocking their functionalities. Rotational parts and the small holes of the Pitot tube are prone to accumulate waste, which changes the weight distribution or prevents the operation.

By not having moving parts, ultrasonic anemometers overcome the above issues and are the best solution for applications in hard to reach or remote areas. Although, with less impact, need periodic inspection for transducer cleaning.

During operation, due to the higher inertias of the Vane and Pitot architectures, those are less responsive than the ultrasonic. The good turbulent regime filtering of the Pitot do not compensate its slower response, when compared with the ultrasonic, as this anemometer have good performance in both tasks. The cost could be an issue, while the ultrasonic is far more expensive than the cup and vane anemometers. Performance is achieved with complex electronics. The cost of the Pitot tube, with similar performance characteristics than a cheaper architecture, could explain why it is less used in general.

Not directly dependent on the anemometry technology used, after a market research is possible to observe that ultrasonic anemometers are the ones sold with integrated GPS capabilities, usually in the form of a compact weather station [35] [36] [37] [38] [39] [40] [41]. In order to measure the Heading Wind, and implicitly True Wind, the other two architectures need an independent device to perform this task. Plus, ultrasonic devices with the above characteristics could be expensive but integrate several navigation and weather capabilities in a single module. Table 2.1 resumes the most relevant analyzed areas.

Feature	Cup and Vane Anemometers	Pitot tube Anemometer	Ultrasonic Anemometer
Accuracy	High	High	High
Corrosion resistance	Fair	Fair	High
Cost	< € 1000	< € 3000	< € 3000
Inertia	Fair	High	Null
Life cycle without assistance	Mid-term	Short-term	Mid-term
Maintenance	Mid-term	Long-term	Long-term
Moving parts	yes	yes	no
Operating Temperature	-50 to 50 ºC	-60 to 100 ºC	-30 to 60 ºC
Power Consumption	Null	Null	Low
Range	0 to 120 knots	0 to ~661 knots	0 to 200 knots
Structure	Modular	Modular	Compact
Turbulent regime filtering	Low	High	High

Table 2.1 – Technical Comparison between outdoor anemometry technologies [2] [7] [10] [17] [19] [24] [29] [32] [34] [35] [36] [37] [38] [39] [40] [41].

3 – Market analysis: the prototype requirements

In spite of the preliminary research that led to the reason of existence of this work, it is important to exploit the knowledge of potential customers, in order to adjust the prototype requirements. Systems to be available to the general public have to do more than fulfilling a market gap, to achieve success. Must be user-friendly, easy configurable and have some details that, although not included in the primary scope, have to be considered in order to obtain a sellable product. The objective of creating a system that offers a low-cost alternative to the ones available in the market is legitimate, but for itself, can cause distrust among possible costumers.

This chapter intends to present the feedback given by a group of experienced sailors, regarding this work scope, through the realization of a survey. Together with the opportunity to have some useful and informal conversations with some of the interviewees, was possible to gather valuable information to validate the initial scope. The sample was composed by 18 recreational and professional sailors from sports, fishing and merchant marine fields of activity. The interviewees had between 22 and 50 years old, with experiences between 5 and 32 years. Although it is a small sample, the background of the interviewees was considered enough to give a high level of confidence to the study. The most relevant features to characterize the sample are presented in Figure 3.1: age, time of experience, field of activity, type of vessel, instrumentation budget and technical knowledge distributions. The inquiry *specimen* is presented in Annex H.

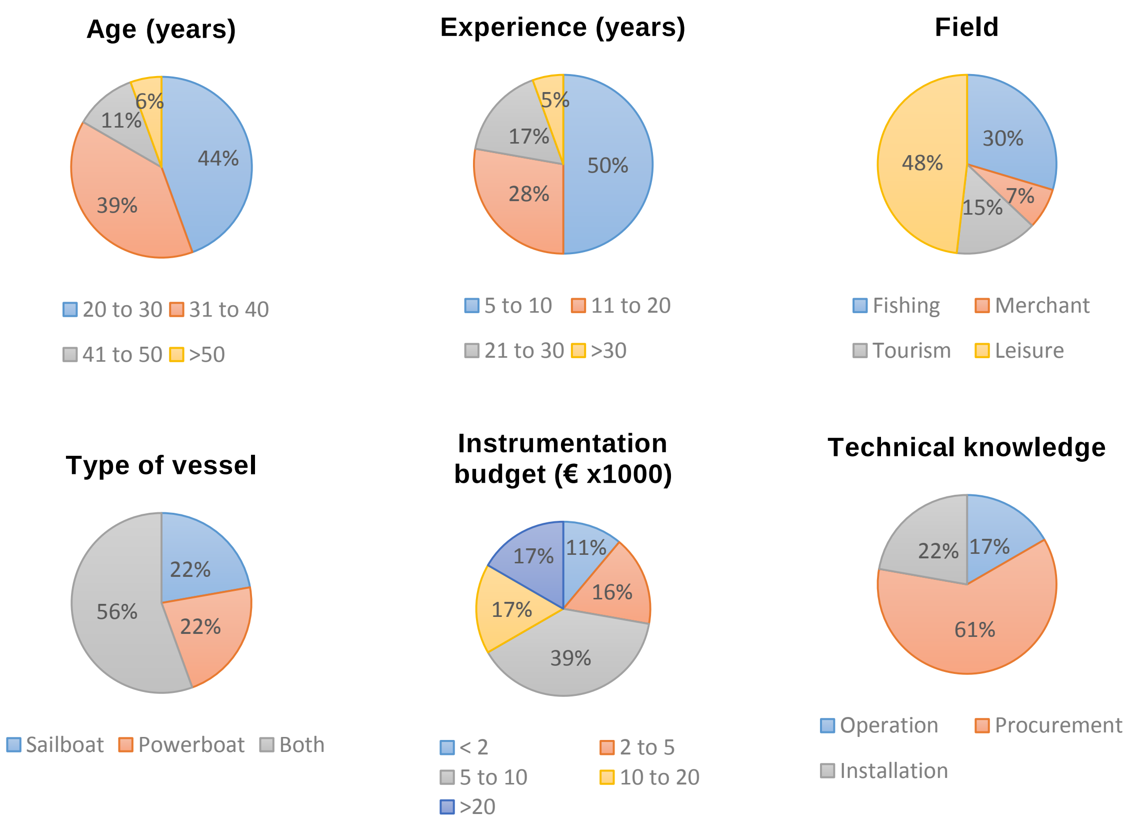


Figure 3.1 – Market analysis sample distributions: 6 graphs.

The survey allowed to draw some important conclusions about the target audience, which could be interpreted as a specification list:

- Instrumentation budgets below € 5000 do not integrate all the recommended components.
- An important part of the budget is spent on installation services, cabling, control units and plotters or consoles, especially in larger vessels.
- Sailboats tend to have more expensive instrumentation than powerboats.
- The great majority of the trips[2] lasts less than 12 h[3] and are performed during day[3].
- Younger sailors are more prone to experiment alternative and adapted solutions than older ones.
- Younger sailors are more prone to do the procurement and installation of their own networks than experienced ones, who prefer to do the procurement but let the installation be done by another entity.
- Nautical instrumentation lacks of portability and the attempts to change this situation begin to appear in the market, but are too expensive and dependent from the existing architectures.
- Small sports and leisure sailboats applications are the ones who claim more for portable and compact instrumentation systems.
- The modular network approach is too embracing and expensive, and the market lacks of compact solutions with several integrated functions, including internal supply.
- Compatibility with consumer electronics like smartphones, tablets and PC for control and visualization are valuable features, especially for smaller boats.
- Ultrasonic anemometry is assumed as the best technology but the price is discouraging. Is the most accurate, compact and less prone to suffer with corrosion or debris.
- Long range data communications through satellite are useful for remote tracking of a vessel course or for weather monitoring in remote places.
- Long range data communications through satellite is an important feature to integrate the prototype but the interviewees do not want to pay for this if they do not need. Should be an optional feature.
- A central unit with the present project scope for less than € 500 is very appealing.
- The central unit should be available with several quantities of allowed devices to save cost.

[2] The term trip here is assumed as the travel between A and B locations and not the time spent on each one.

[3] Merchant marine excluded.

4 – Prototype system development

The prototype system, which is represented in Figure 4.1 comprises two distinct stages:

- Integration with licensed nautical instrumentation, more specifically weather stations with ultrasonic anemometry technology and compatible with NMEA 0183 protocol. This protocol is explained in Annex F.

- Development of a low cost Data Processing and Communication Unit, or DPCU, as an alternative to the central processors presented in chapter 1.

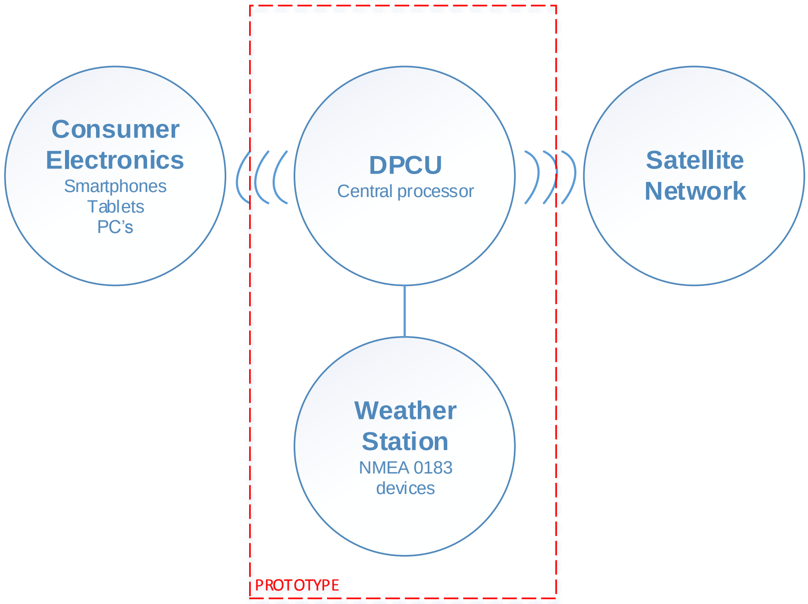


Figure 4.1 – Prototype structure.

In order to achieve a functional prototype, the first step is the definition of a suitable weather station and then, the DPCU development will take place. This unit will work as an interface between the weather station and a wireless terminal point for visualization and remote control. The output of the weather station is decoded and transmitted through two types of wireless communications: standard close range communication for smartphones, tablets and PC and an optional long range communication for global connection applications. To reinforce portability, the DPCU will integrate an internal battery.

As a secondary feature, a logger functionality through an internal MicroSD Card, in order to save the sensor activity in the form of NMEA 0183 messages, will be available.

4.1 – Ultrasonic Weather Station

Fulfilling the requirements of the prototype regarding weather data, more specifically wind measurements, the conclusions of section 2.3.4 shows that the ultrasonic technology is the most accurate, robust and compact solution to integrate the prototype. Navigation capabilities are also included thanks to opportunity of using two quality and embracing weather stations available on the market.

The AIRMAR PB200 and LB150 models, both presented on Figure 4.2, are two renowned compact and licensed weather stations with navigation capabilities. They are equivalent in many aspects but have different fields of application. The PB200 is more suitable for navigation while the LB150 is appropriate for weather applications, like land weather stations or monitoring buoys [24] [57]. The first one has available the yaw angle and rate of turn of the vessel and the second one, has an internal hygrometer instead, which allows the access to relative humidity, heat index and dew point temperature [24] [57].

(a) (b)

Figure 4.2 – AIRMAR PB200 (a) and LB150 (b) ultrasonic weather stations [24] [57].

Apparent Wind is measured using four ultrasonic transducers and the internal three axis compass, together with the WAAS/EGNOS GPS engine, provides the other wind components. The internal temperature, hygrometer and barometric pressure sensors help to measure and predict changing weather patterns, which combined with the internal heading sensor, most of navigation needs are fulfilled [24] [28] [57] [85]. Regarding navigation data, these systems also provide magnetic variation and are suitable as a primary GPS source [24] [28] [57] [85].

These compact solutions open a wide range of possibilities that will increase the value of the prototype and also permits to evolve in the future. By preparing the DPCU for weather and navigation capabilities, especially in terms of software, updating these weather stations by newer models will be easy, as they communicate through the NMEA 0183 protocol.

KEY FEATURES:

- True, Apparent and Heading speed and direction.
- Barometric pressure.
- Air temperature and wind chill temperature.
- Internal WAAS/EGNOS GPS.
- Three-axis solid-state compass.
- Three-axis accelerometer provides stabilized pitch, roll and yaw angles in dynamic conditions.
- Outputs both NMEA 0183 and NMEA 2000 data.
- Plastic Enclosure is less prone to lightning strikes.
- 360° calibration results in precise wind direction accuracy.
- Maintenance-free operation – no moving parts.
- Wind Chill temperature, Relative Humidity[4], Dew Point[4], Heat Index[4].
- 9 to 16 VDC power supply.

4.2 – Close Range Communications

Close range communications are used for remotely control the DPCU and providing a wireless graphical interface based on smartphones, tablets and PC. These devices have mainly available two technologies regarding wireless networks: Bluetooth and Wi-Fi. Wi-Fi offers better performance and security protocols in both local and internet applications, while Bluetooth can be considered a wireless substitution of the cable used with RS232 devices and COM ports, like printers or music hubs [2] [19] [43] [44]. Nevertheless, three characteristics are critical to decide in favor of Wi-Fi:

- Less prone to suffer interferences in maritime conditions [45] [46] [48] [52].
- Have better security protocols [43] [44] [63] [64]. Wi-Fi uses WPA2 AES 256-bit encryption while Bluetooth uses only AES 128-bit encryption. As the DPCU could be connected to the internet through this type of communication, using a wireless router or access point, the appropriate encryption methods are offered by Wi-Fi technology.
- Have longer range [43] [44] [47] [48] [52]. In ideal conditions, the Wi-Fi can have 100 m range while the Bluetooth does not go beyond 10 m. This last feature is the most important limitation, as Bluetooth only allow the application in very small vessels [2] [19] [43] [44].

As NMEA 0183 messages transmission involves packages of several bytes only, bandwidth and latency times are not issues to consider.

[4] Airmar LB150 model.

4.2.1 – µPanel SCF-01 Wi-Fi Module

Close range communications are provided by the µPanel system, specially designed for IoT applications by SCF Electronics.

This system consists on a programmable Wi-Fi radio, a free mobile App and an optional and also free, Cloud server [65]. These three elements allow the user to control the DPCU, either locally or through Internet [65].

The µPanel APP shows the graphical interface configured by the microcontroller of the DPCU, as explained in section 4.6.3, allowing the user to interact with it. Thanks to the new graphical language HCTML, the APP is completely defined by the microcontroller, without having this to process graphical objects [65]. The main advantage is that the microcontroller is only responsible for the scripts and object control. The graphical capabilities, or object processing, depends on the wireless connected device, which could be a smartphone, tablet or PC. This makes µPanel system a suitable solution for small microcontrollers with limited amount of memory [65] [66] [68]. This is a flexible solution for IoT systems, thanks to powerful functions that can access TCP/UDP sockets and an integrated File System and File Transfer [65].

As the APP is compatible with iOS and Android systems, the need of creating a dedicated interface for each system is suppressed, being this a major breakthrough for the prototype. By developing an application through µPanel system and using an Android emulator for Microsoft Windows and Mac OS, as explained in section 4.6.3, a major part of this type of consumer electronics is covered.

The Wi-Fi module is the µPanel SCF-01, shown in Figure 4.3, which is formed by two parts: the ESP01 Wi-Fi module, with the Espressif ESP8266 chip, and the ADP-01 adapter, specially designed to work with the ESP01 module. This adapter assures a compact installation with 5 VDC supply compatibility[5], instead of the 3,3 VDC of the ESP01 module [68].

The system allows Wi-Fi Direct, WLAN, Internet and cloud connections, which are represented in the Figures 4.4 to 4.7, respectively, being the first one the preferred method.

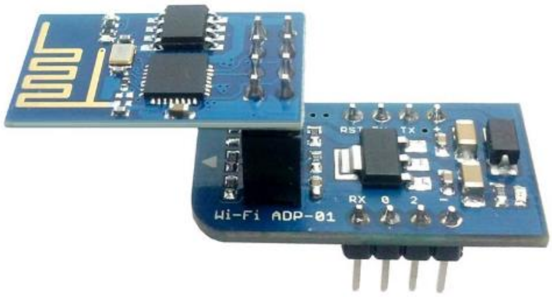


Figure 4.3 – µPanel SCF-01 Wi-Fi module: ESP01 Wi-Fi module plus ADP-01 adapter [68].

[5] 5 VDC is the preferable control voltage of the system, as sensor UARTs communicate in this voltage range (see section 4.5 and 4.5.1).

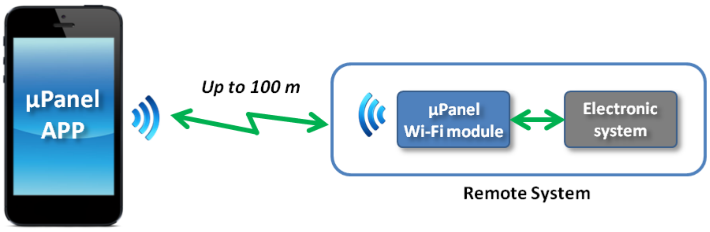


Figure 4.4 – Direct connection [65].

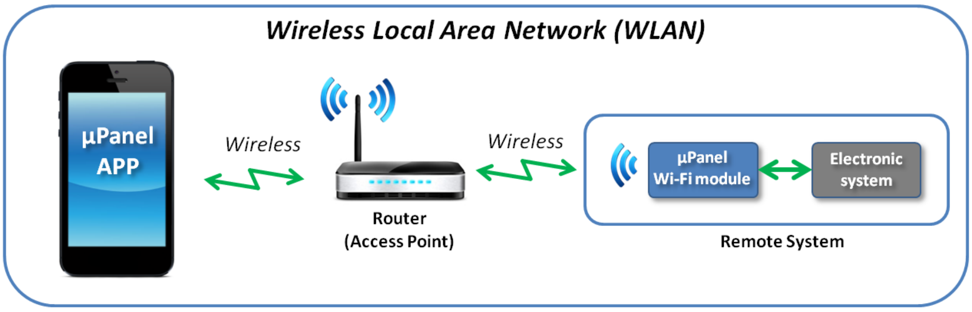


Figure 4.5 – WLAN connection [65].

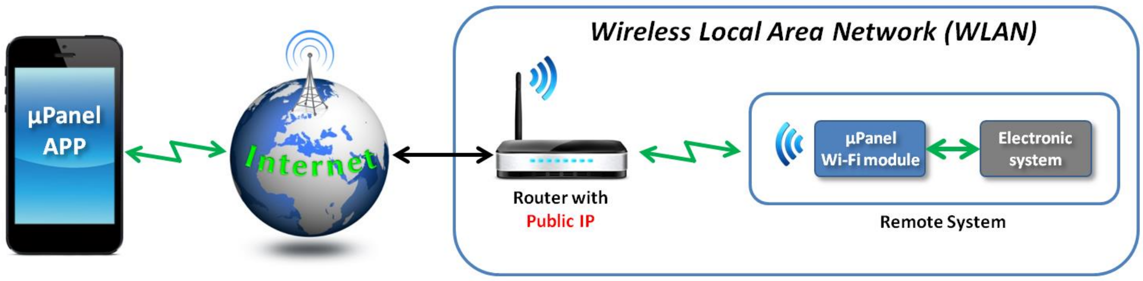


Figure 4.6 – Internet connection [65].

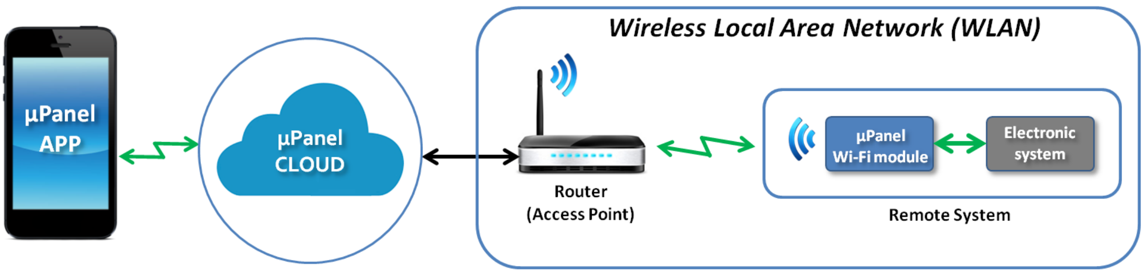


Figure 4.7 – Cloud connection [65].

4.3 – Long Range Communications

Long range communications are an innovative feature to integrate the prototype, while the systems which is supposed to compete with have separate modules to perform this task [36] [37] [38] [39] [40] [41]. This type of communication intends to offer a logger functionality that can be accessed remotely. Application examples are the course tracking of a vessel or weather monitoring from remote places.

In order to provide this functionality, the prototype must comply with the systems available to general public for this type of communications, which are cellular and satellite networks [69] [73]. Although, cellular networks have a critical limitation, which is the coverage in remote areas [33] [53] [54] [59]. In this system, an area to be supplied is divided into regular shaped cells, each one covered by an antenna [54] [56] [58]. In open ground, the range of each antenna varies from 12 to 27 km, depending on the frequency used, being needed adjacent cells to increase the covered area [54] [56] [58]. Service providers only have good coverage in urban areas, where the great volume of potential clients is concentrated [56] [58]. For this reason, remote areas in land and especially in high seas are dead zones with no interest on expanding a cellular network. This limitation leads us to the remaining hypothesis, which are the satellite communications. Satellite networks rely on constellations of cross-linked satellites, assuring a global coverage [60] [61]. The drawbacks are the high cost of the communications and the lower latency when compared with cellular networks [60] [61]. Annex G details this kind of communication regarding its network structure, specifications and meteorological issues.

As referred in chapter 1 and 3, long range communication is an important feature that increases the value of the prototype, but should be optional, as only a niche of the target audience will show interest in having this functionality. Nevertheless, the DPCU was developed taking into account a plug-and-play of a satellite hub anytime. This approach optimizes the software and the electronic circuit, by having the same configuration and not adding any cost.

4.3.1 – Rock Seven RockBLOCK Mk2 Iridium SatComm hub.

Satellite communications are assured by the Rock Seven RockBLOCK Mk2 hub, present in Figure 4.8. This especially designed module for prototyping applications allows send and receive short messages from anywhere on Earth, through the Iridium satellite network, offering a quality solution as other dedicated devices, at a lower cost [69] [71] [72] [74] [75] [76]. This satellite service is provided through a constellation of 66 cross-linked LEO satellites, at 780 km from the Earth, assuring a global coverage, even in the poles [73].

At the heart of RockBLOCK module is an Iridium 9602 satellite modem, providing an integrated antenna and a 0.1" header for power and UART data connections [69]. The header includes an FTDI-compatible serial interface that can be connected directly to a microcontroller serial port [69] [76].

The message system is a bandwidth-limited SBD, capable of transmitting and receiving packets of 340 and 270 bytes, respectively, which suits NMEA 0183 messages [80] [84]. With clear skies, it is possible to send or receive messages approximately once every 40 seconds, not being suitable if very low latency is required (i.e. less than 1 minute), or if data to be transmitted is larger than a few thousand bytes [80] [84]. The subscription plan, provided by Rock Seven, states that 1 credit is used per 50 bytes in a message [79], so a NMEA 0183 message takes a maximum of 2 credits to be transmitted, as detailed in Annex C.

Due to the cost of the hub, as stated in Annex B, it was an unsustainable acquisition to the project at this phase. Luckily, with the available tools and information, it is possible to accurately describe the integration process without a real implementation, in order to be considered a valid solution, as described in sections 4.6.2, 4.6.3 and 4.6.4.

Figure 4.8 – Rock Seven RockBLOCK Mk2 Iridium SatComm Module [69].

4.4 – Microcontroller platform

In order to reduce the DPCU cost, an open source development board was considered for an embedded CPU and I/O system [87] [88] [89]. This also improves prototyping flexibility and eliminates software licensing. Three renowned microcontroller platforms were selected and their specifications are presented in Table 4.1 [86] [87] [88] [89].

As the prototype need to have at least three serial ports, for connections with the weather station, Wi-Fi module and the satellite hub, the number of UART's was considered the bottleneck criteria to choose a suitable prototype board. This condition is sufficient to analyze which scenarios are possible:

- **Arduino Nano:** With one UART available, this configuration needs a network of three boards connected through I2C protocol, having one serial device per board. The tasks must be divided among the boards. The drawback is the increase of complexity by adding I2C communication to have the same UART ports available than an Arduino MEGA 2560, with 37.5 % of the memory and 300 % the processing capacity, which is not needed, for a price 45 % higher.

- **Arduino MEGA 2560 Rev 3:** This balanced option have four UART ports available and more than enough memory and clock speed for the requirements, associated to a low power demanding.

- **Raspberry Pi 3:** The overkill characteristics for a similar price when compared with Arduino MEGA 2560 Rev3 makes this option very underappreciated for the system requirements, since the graphical processing was removed from the microcontroller. However, as the power consumption is much higher than the Arduino boards and have only two accessible UART's, while the third serial port must be done through USB, this board is not an efficient choice.

Board	Arduino NANO	Arduino MEGA 2560	Raspberry Pi 3
Cost	€ 23,37[6]	€ 48,34[6]	€ 44,16
CPU Frequency	16 MHz (Single-core)	16 MHz (Single-core)	1,2 GHz (Quad-core)
CPU Model	Atmel ATmega328P	Atmel ATmega328P	ARM Cortex-A53
Dimensions (LxWxH)	45 x 18 x 6 mm	102 x 53 x 15 mm	85 x 56 x 18 mm
Memory	1 kB EEPROM 1 kB RAM 32 kB Flash	4 kB EEPROM 8 kB RAM 256 kB Flash	N/A EEPROM 1 GB RAM MicroSD Card
Operating Humidity	N/A	N/A	N/A
Operating Temperature[7]	-45 to 85 ºC	-45 to 85 ºC	N/A
Operating Voltage	5 VDC	5 VDC	5 VDC (3,3 VDC GPIO)
Power Consumption	18 mA (idle) 233 mA (max)	35 mA (idle) 233 mA (max)	310 mA (idle) 800 mA (max)
Supply Voltage	7 – 9 VDC	7 – 12 VDC	5 VDC
UART	1	4	2 (1 GPIO and 1 USB)

Table 4.1 – Microcontroller platform critical features.

The Arduino MEGA 2560 Rev3 board meets the right specifications to proceed the integration in the DPCU. Operating temperature, humidity and vibration/impact resistance are important features that were not possible to confirm from datasheets associated to the boards [87]. Although, these are sensitive topics to be empirically analyzed during physical assembly and testing.

[6] These are brand original prices but are available similar boards from other brands at much lower prices.

[7] Chip based. Complete board information not available.

4.5 – Electronic Circuit

All the functionalities and hardware discussed until this point culminated in the electronic circuit of the DPCU, presented in Annex A, together with the description of other integrated components and solutions. Figure 4.9 shows a block diagram of the circuit, with the main electrical paths and Figure 4.10 the assembled version.

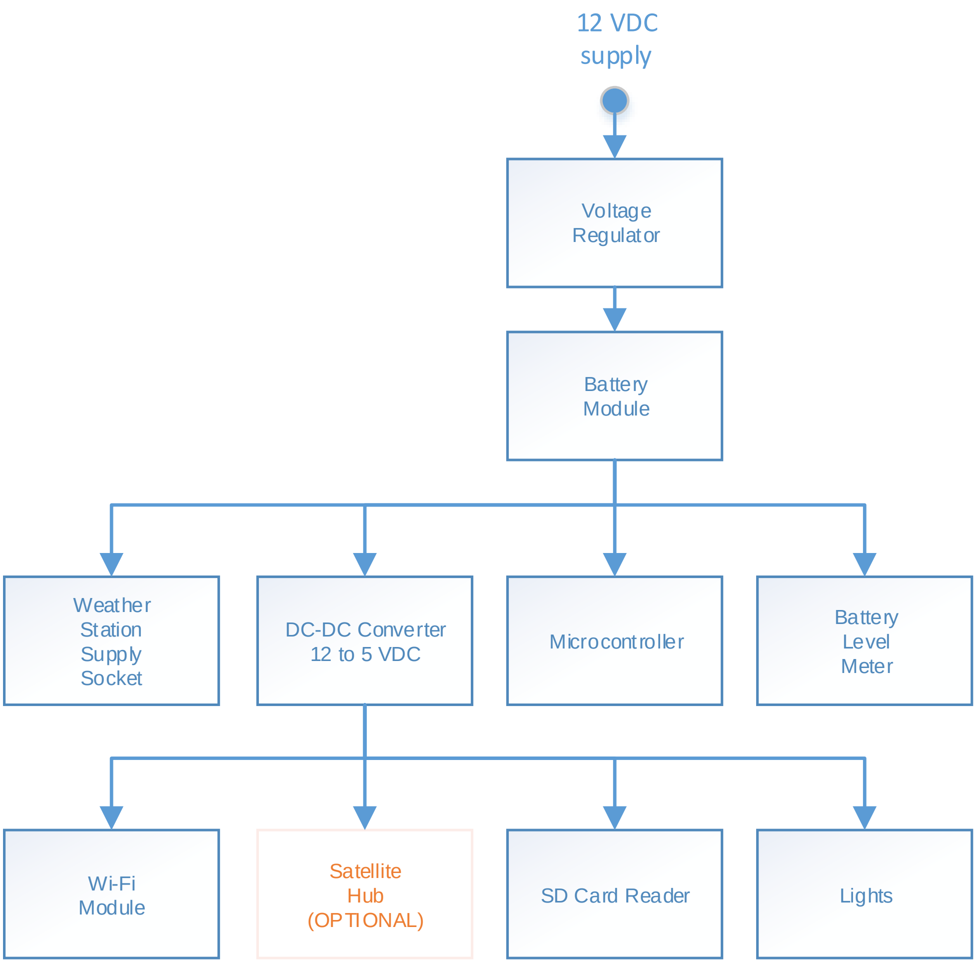


Figure 4.9 – DPCU Electrical path diagram.

Main supply voltage was defined by the components with the highest voltage, which are the microcontroller and the weather station. These have input ranges of 7 to 12 VDC and 9 to 16 VDC respectively. 12 VDC was considered to supply the DPCU, as it is within the desired range and is one of the supply standards for electronic devices available in the market.

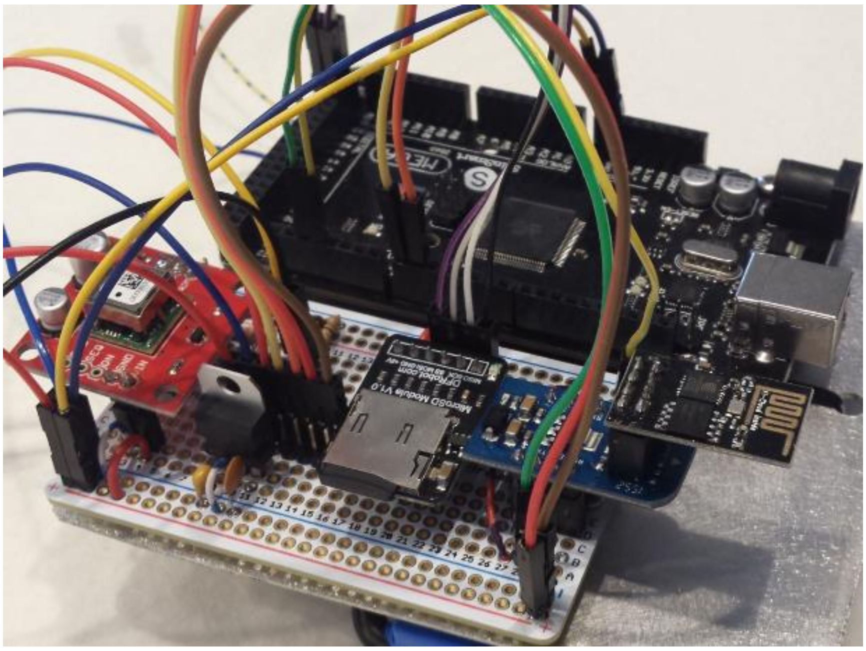


Figure 4.10 – Assembled DPCU electronic circuit.

4.6– Software

The prototype system software is divided into two programs:

- The DPCU software which is responsible for all the communications, configurations, NMEA 0183 protocol decoding and loggers, is the central piece of the system.

- The µPanel APP, which processes the graphical interface in the wireless terminal points and is remotely controlled by the DPCU.

The satellite hub, although controlled by the DPCU, can be remotely accessed via satellite. The respective process is be described in section 4.6.4 .

4.6.1 – System Network

The DPCU is the central node of the network, which is represented in Figure 4.11. The weather station is cable connected, forming a dedicated supply and communication channel, while smartphones, tablets and PC are wirelessly connected for control and visualization purposes.

The satellite hub, even integrated in the DPCU circuit, could be considered as a node of the network. Although controlled by the DPCU microcontroller, has its own processing and the functionality of communicating outside the local network. Plus, it can be controlled remotely, as described in section 4.6.4.

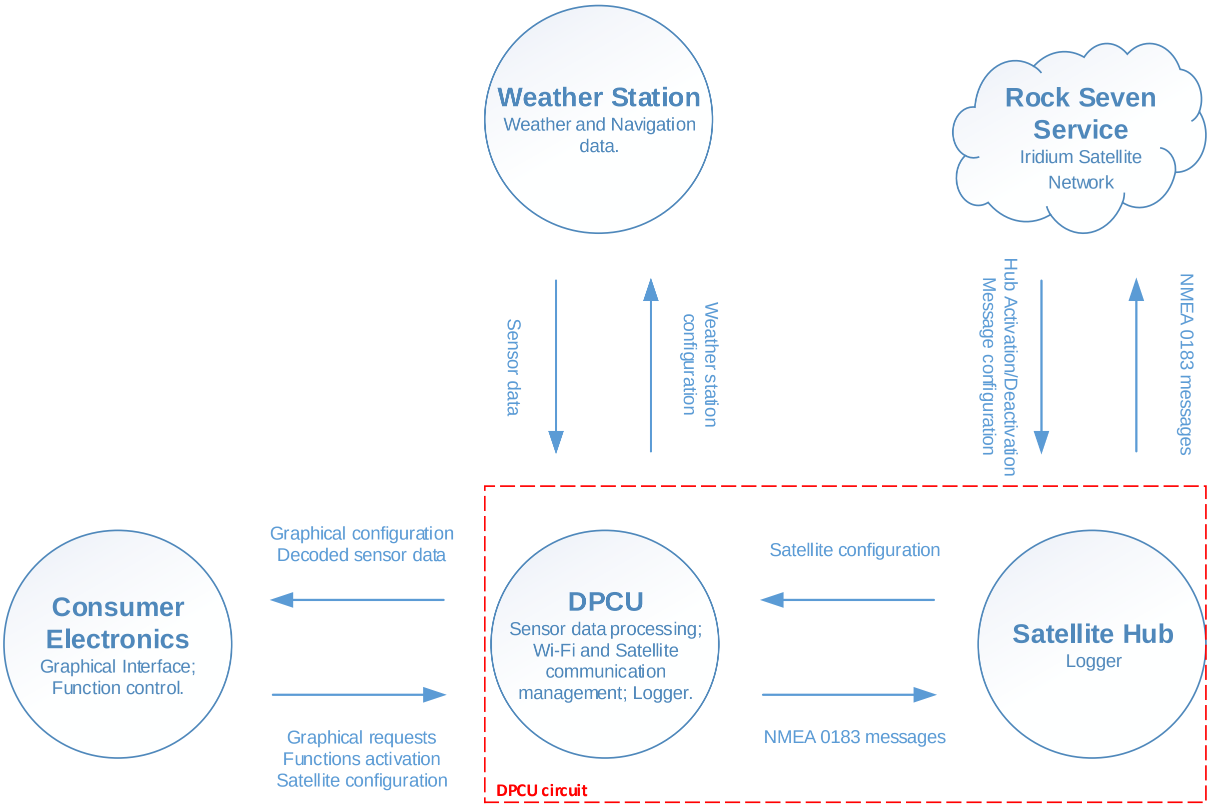


Figure 4.11 – System network.

4.6.2 – DPCU software

The DPCU has four main tasks: Connection management and decoding weather station data; connection management and interface with Wi-Fi consumer electronics; connection management of the satellite hub; internal log through a MicroSD Card. Each of these tasks has an associated physical serial port, except for the MicroSD Card module, which is software emulated. The software flow chart is shown in Figure 4.12.

- **Weather station connection:** This communication channel is the only that stays active independently from the others. To avoid losing information, the sensor is read continuously by turning raw data into NMEA 0183 messages. After the decoding process, the system tests if a possible message destination is active: Wi-Fi, satellite or MicroSD Card. If no one is, the current message is discarded. From the moment the sensor is energized, the startup is automatic, but waits for correct configuration. Baud rate at 4800 bps [8], standard for NMEA 0183 communications and the enabling of all possible messages [28] is the configuration sent before start receiving data for decoding.

[8] Baud rate at 38400 bps it is also possible.

- **Wi-Fi connection:** When a device connects via Wi-Fi, a signal is sent to activate this communication channel in the DPCU and a bidirectional communication starts at 115200 bps. The DPCU configures and controls the µPanel APP, sends the requested NMEA 0183 message content and waits for requests about the internal MicroSD Card logger and satellite communication hub.

- **Satellite connection:** This functionality is enabled and configured locally through µPanel APP or remotely by the Rock Seven service. Traffic management and the operating modes of the hub are controlled by the DPCU. The NMEA 0183 messages to be transmitted are selected, and then sent with 1 min interval. Rock Seven developed a convenient library that allows an efficient comprehension of the extensive AT command list [82] [84]. This library, "IridiumSBD", distributed under the terms of the GNU LGPL license, uses the RockBLOCK/Iridium's SBD protocol to send and receive short messages [84]. As the satellite hub was not physically acquired to be a permanent component of the circuit, as referred in section 4.3.1, instead of a schematic explanation of the functionality, a code script is presented in Annex E.

- **Internal MicroSD Card logger:** This functionality is enabled by through µPanel but is fully controlled by the DPCU. The decoded messages from the sensor are saved in the MicroSD Card before any other instruction. This module was programmed using the open source Arduino library "SD.h".

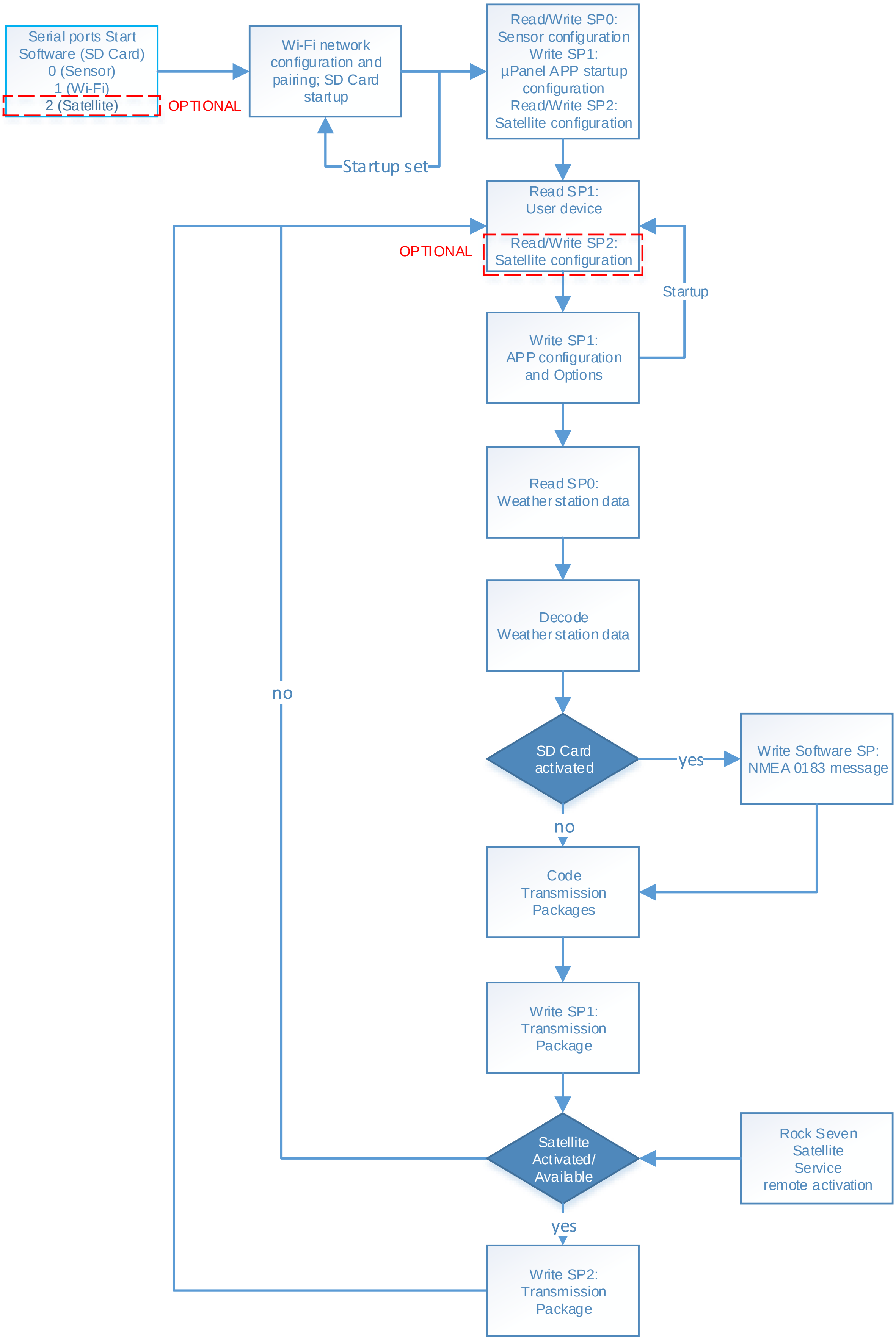


Figure 4.12 – DPCU software flow chart.

4.6.3 – Graphical interface software and µPanel APP

Allowing a real-time data visualization and control, this software provides a low-cost and effective alternative to licensed consoles, substituting them by a smartphone, tablet or PC. The application provided by µPanel, presented in section 4.2.1, is a major breakthrough, while it is compatible with Android and iOS, the most popular operating systems used in smartphones and tablets. This µPanel APP acts like an interface between the Wi-Fi connected device and the DPCU and has two main advantages: integrates security Wi-Fi protocols for an automatic and secure network connection; stores a library of graphical objects, thanks to the integrated HCTML programming language, which eliminates graphical processing from the microcontroller.

The compatibility with Microsoft Windows and Mac OS is assured through an Android emulator. BlueStacks Android Emulator was the chosen platform, which is a free, stable and straightforward emulator, whose operation is the same than operating a native Android device. µPanel APP is installed inside BlueStacks and then a shortcut can be created as a direct launcher [101].

The µPanel APP is totally controlled by the DPCU microcontroller and, from its point of view, all graphical objects are parameterizable messages. The configuration is then sent to the Wi-Fi connected device, where it is processed and kept in memory. Below is shown how the Heading Wind direction gauge graphical object, used in Navigation Panel shown in Figure 4.14, is defined and controlled. This illustrates, as a simple example, how HCTML language works on µPanel APP:

Graphical object definition message[9]: A0G:5.26:5.21:0::142:1

- "A": Analog bar object type.
- "0": Object index.
- "G": Analog gauge object sub-type.
- "5.26": Background image.
- "5.21": Needle image.
- "0": Startup rotation from origin, in degrees (i.e. needle startup position).
- "142": Offset rotation from the object origin, in degrees (i.e. align the desired object origin with the background image).
- "1": Input moving scale, in degrees.

Graphical object control message: #A1:150

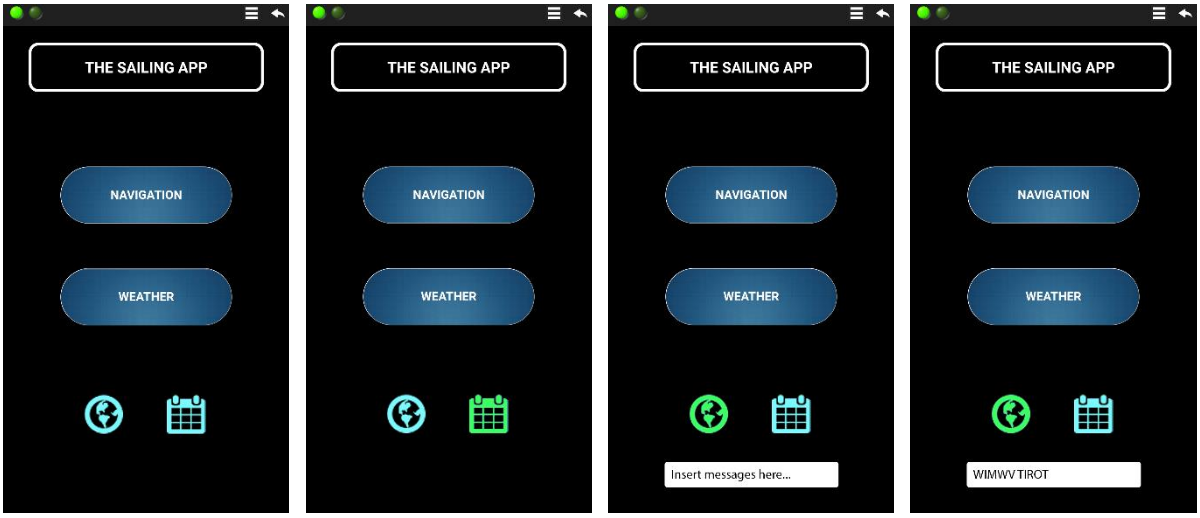
- "#": Control object character.
- "A": Object type.
- "1": Object index.
- "150": degree angle to be updated, according to the scale defined above, where the value in degrees is the control message value times the input scale.

[9] This object have many other available parameters, defined within same principle.

Each complete panel is totally defined into one string message to be sent to the µPanel APP over Wi-Fi. All object definition messages are concatenated into one string before being sent. Control object messages are independently sent, with the same principle. Every time a panel is changed somehow, have to be totally defined again, but if an object change its state, the control is independent. This software is formed by three distinct panels, whose interface is explained below:

- **Startup panel:** When the APP establishes connection with the DPCU, the default panel is shown in Figure 4.13 (a). In this step, the DPCU is not transmitting and all the systems are standby.

    - **Navigation button:** Redirects to Navigation panel.
    - **Weather button:** Redirects to Weather panel.
    - **Satellite button (i.e. "world" icon):** Enable (green icon) or disable (blue icon) satellite message transmission logger. When enabled, a text box appears below, as shown in Figure 4.13 (c), where the desired messages must be introduced, separated by blank spaces, as shown in Figure 4.13 (d). These messages will be transmitted once a minute in the introduced order.
    - **Logger button (i.e. "table" icon):** Enable (green icon) or disable (blue icon) internal MicroSD Card logger, as shown in Figure 4.13 (b). All the messages will be saved in the internal MicroSD Card.



(a) (b) (c) (d)

Figure 4.13 – Startup panel.

* **Navigation panel:** Real-time navigation data, presented in Figure 4.14. “Return” icon redirects to Startup panel.

Figure 4.14 – Navigation Panel.

* **Startup panel:** Real-time weather data, presented in Figure 4.15. “Return” icon redirects to Startup panel.

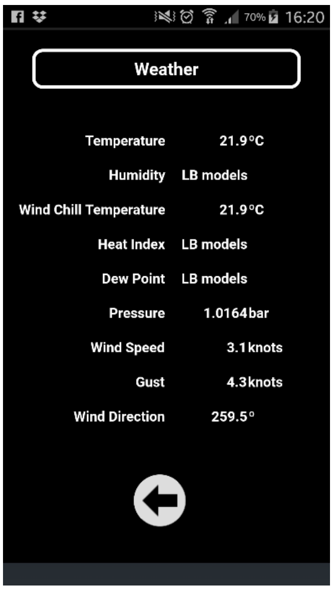


Figure 4.15 – Weather panel.

The µPanel APP flow chart is shown in Figure 4.16.

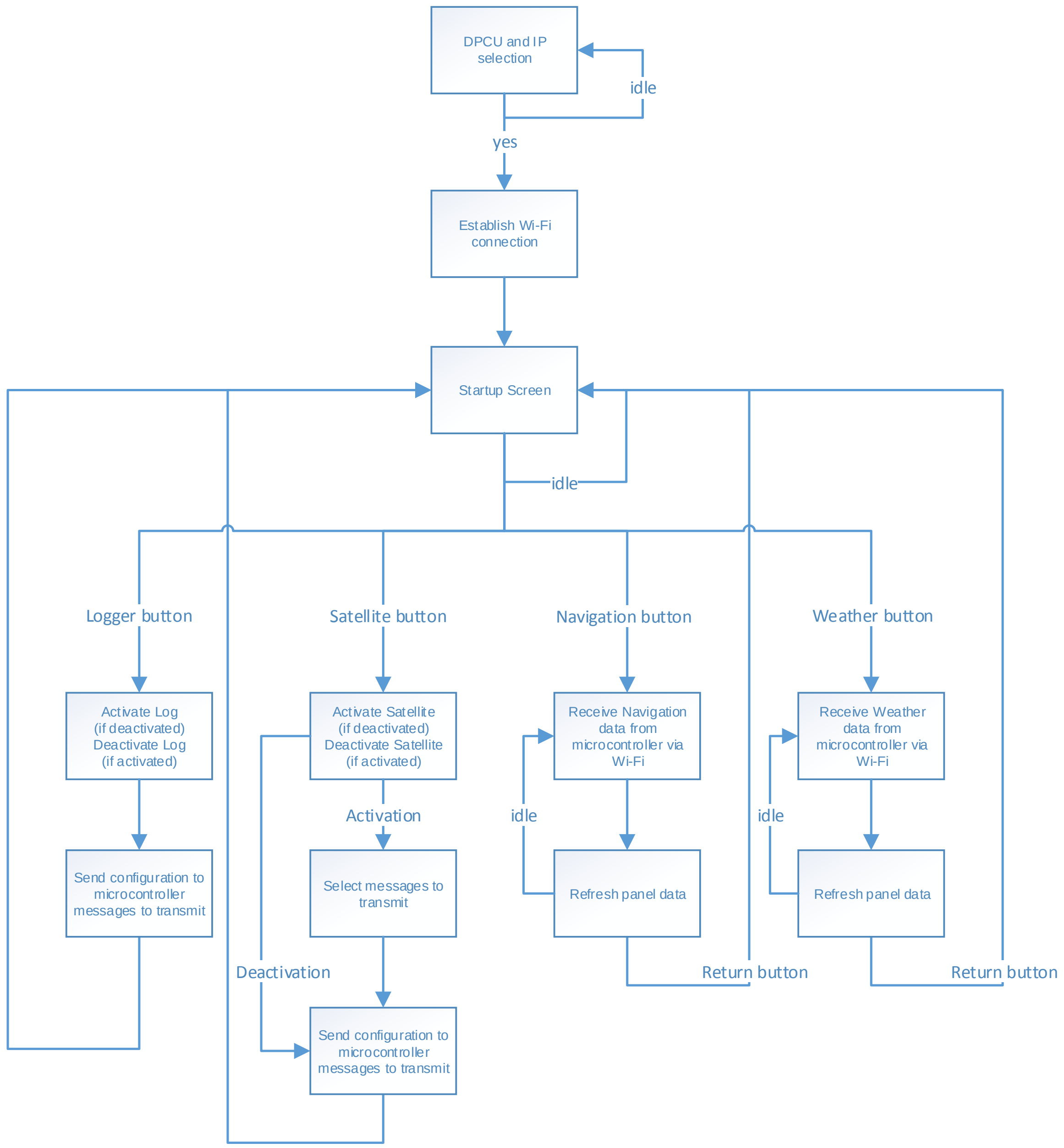


Figure 4.16 – µPanel APP flow chart.

4.6.4 – Satellite hub remote control

The RockBLOCK satellite hub is responsible for the long range logger capability. It can be controlled remotely and is primarily dedicated to send complete NMEA 0183 messages from virtually all over the globe. The module appears as a serial interface and can be control it using sets of AT commands [79] [80] [81] [82]. Messages sent can either be delivered to an email address or sent to the personal Rock Seven web service as a HTTP POST [79] [80] [81]. Receiving messages are processed in the inverse way by sending a HTTP POST from the referred web service or a request to an URL [79] [80] [81]. The message is than queued on the satellite network, being ready for download [79] [81]. To activate the service, an account have to be freely created to associate the module IMEI, with a username and password. For this system, which is presented in Figure 4.17, to work smoothly, messages should not be theoretically exchanged in intervals less than 40 s [79]. As previously referred, the DPCU is configured to send messages through this channel with a minimal of 1 min interval.

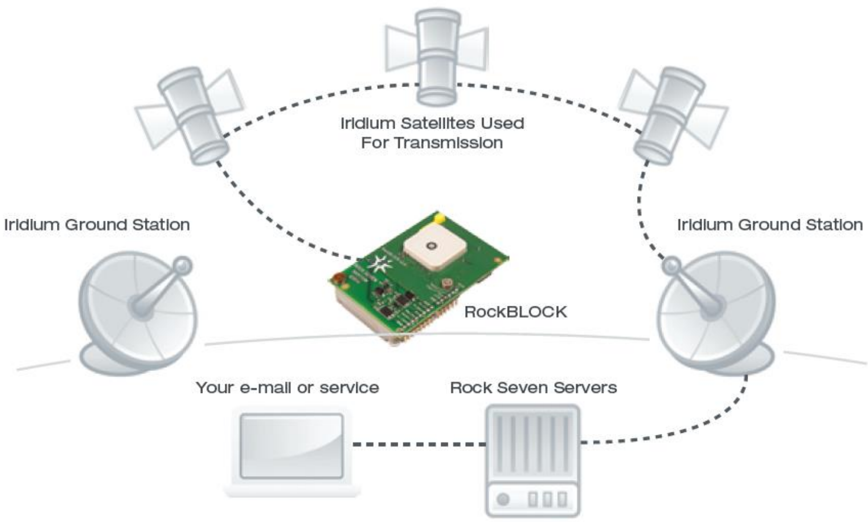


Figure 4.17 – Rock Seven communication system.

In order to control the DPCU satellite hub remotely the procedure is similar to the one used in µPanel APP. To activate the communication channel in the DPCU, a message with the NMEA 0183 tags spaced by blanks have to be sent to the hub. To deactivate the channel, a message with the text “OFF” have to be sent instead. This procedure can be followed in two ways, described below:

- HTTP POST requested to the URL https://core.rock7.com/rockblock/**’MT’** where **MT** is the IMEI, username, password and message with no spaces between [81]. If the message was successfully transmitted, the resulting feedback message will be “OK,’messageID’ ” [81]. If not, will be “FAILED,’error code’,’Textual description of failure’ “ [81].

- Using Rock Seven Core, shown in Figure 4.18, to directly send a message.

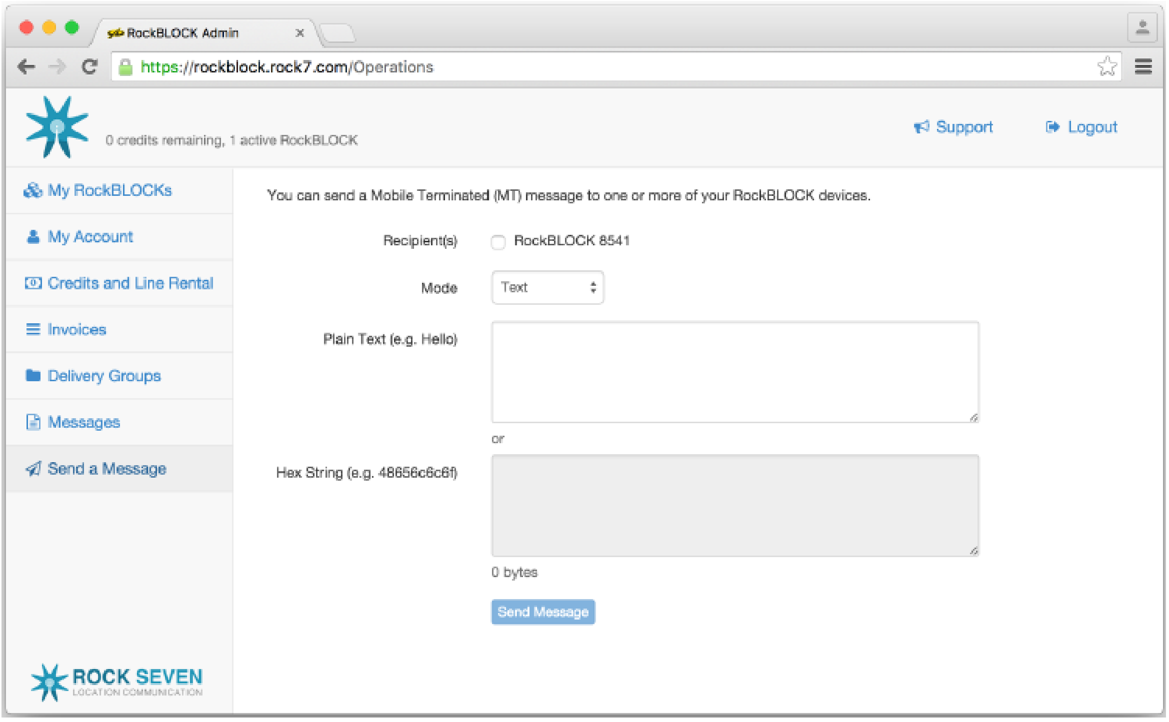


Figure 4.18 – Rock Seven Core.

4.7 – Power Requirements and Battery Capacity

Operating the DPCU without an external power supply is one of the system goals. By eliminating a permanent external supply, the system portability is improved and the DPCU cost is reduced, as it is possible to discard expensive waterproof sockets that maintain water tightness during use[10].

In order to determine the power requirements of the system, peak and nominal consumptions must be considered. The first one is referred to the maximal power requested from the power supply and the second is referred to the power consumption during regular operation:

- **Peak power:** this value is usually hard to measure, as is referred to the system with all the components at maximal power, but it can be easily estimated. The maximal power is achieved during startup or during transmission phase of the Wi-Fi and satellite modules. Manufacturer datasheets [24] [57] [69] [87] [91] provide the power requirements for their components, and based on Table 4.2, the system will be under 5.2 W[11]. Supplied at 12 VDC corresponds to 433 mA. The little dissipation from other elements, like voltage regulators, capacitors or resistors, is negligible for this topic but are considered in a general safety factor (4).

[10] The one used in the DPCU is waterproof while not charging the system, as described in section 4.6.

[11] Connected to the Airmar PB200 weather station, which is the most power demanding.

Element	Voltage [V]	Current [mA] (max)	Power [W] (max)
DC-DC Converter	12	60	0.720
Lighting	5	40	0.200
Microcontroller	5	217[12]	1.085
Satellite Module	3.3	470	1.551
PB 200 Weather Station	5	220	1.100
Wi-Fi Module	3.3	140	0.462

Table 4.2 – Component theoretical maximal power requirements.

- **Nominal power:** In order to measure this component, the circuit of Figure 4.18 was used. The final version of the DPCU software was uploaded to assure a reliable reading. The only excluded component is the satellite module, as explained in section 4.3.1, whose theoretical 100 mA idle current can be added posteriorly for an approximate total load.

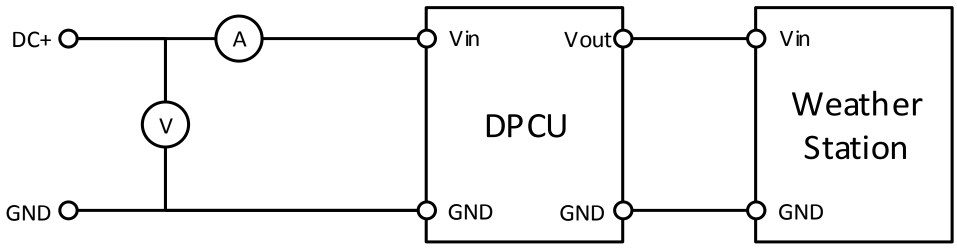


Figure 4.19 – Power consumption testing circuit: “A” refers to ammeter and “V” to voltmeter.

The results of the three possible combinations are shown in Table 4.3.

Element	Current [mA]	Power [W]
DPCU	153	1.836
DPCU + Airmar LB150	199	2.388
DPCU + Airmar PB200	215	2.580

Table 4.3 – Nominal currents and power drained by the DPCU.

[12] Maximal demand of the chip plus the I/O used.

Table 4.4 shows the previous values corrected by the integration of the satellite module.

Element	Current [mA]	Power [W]
DPCU	181	2.172
DPCU + Airmar LB150	227	2.724
DPCU + Airmar PB200	243	2.916

Table 4.4 – Nominal currents and power drained by the DPCU, corrected by the introduction the satellite hub power consumption.

The autonomy of the system is a subjective topic, which depends on many factors, like application requirements, environmental conditions, etc. For proof of concept, the considered time interval between charges comes directly from market analysis in chapter 3, where based on the inquiry, most of the vessel trips last less than 12 hours. This value could be valid too for monitoring buoys and land weather stations, probably powered by a solar panel. With a 12 h runtime on battery it is possible discharge during the night and charge during day, assuring a continuous operation. For the referred autonomy applied to the most power demanding configuration and based on (4), the required theoretical battery capacity, corrected by a 30 % safety factor, is 3791 mAh [20] [92] [98] [99]. The safety factor intends to cover four practical situations: possible manufacturing defects that lead to a capacity different than the advertised [92] [98] [99]; capacity decreasing due to operation at extreme temperatures [20] [92] [98] [99]; capacity decreasing due to a fast discharge (i.e. Peukert effect) [20] [92] [98] [99]; residual dissipation from other circuit elements.

$$C = t \cdot i \cdot (1 + SF) \tag{4}$$

Where C: Battery capacity (Ah); t: Drain time (h); i: Current (A); SF: Safety Factor (%)

Battery capacity is not a static specification and mainly depends on the discharge rate (i.e. C-rate) and operating temperature [92] [98] [99]. For the same cell, lower discharge rates lead to higher capacities and vice-versa, reason why batteries are usually advertised for certain applications or have explicitly the maximum discharge current [20] [92] [99]. The closest battery capacity from the theoretical value, available on the market, is 4000 mAh, which recalculated runtimes are given by (4) and are present in Table 4.5. Using this battery, the system results in a C-rate between 0.04 and 0.05, without the satellite module, based on Table 4.3, and between 0.05 and 0.06 with it, based on Table 4.4, maximizing capacity.

Element	Runtime [h]
DPCU	17.0
DPCU + Airmar LB150	13.6
DPCU + Airmar PB200	12.7

Table 4.5 – Theoretical runtimes for a 4000 mAh battery module.

The battery is made of Li-ion cells, which is a popular chemistry for continuous power delivery systems [98] [99]:

- More than 500 charge/discharge cycles maintaining capacity.
- Efficient operation between - 20 and 60 ºC, which fits most of the operating conditions.
- Highest energy density meaning more energy for less weight.

4.8 – Enclosure

Accurate instrumentation is only part of the equation, as the majority of electronic devices and electrical connections have very low resistance to the environment, and so, an appropriate enclosure must be used. Enclosure classification regarding environmental protection is regulated by the International Protection Marking, or IP Code (IEC standard 60529 – EN 60529 for Europe), which states the degree of protection against intrusion (i.e. body parts such as hands and fingers), dust, accidental contact, and water by mechanical casings and electrical enclosures [93]. The code is a two digit tag (i.e. IP XY) where “X” refers to particle protection and “Y” to liquid protection [93] [94]. This standard do not comply with abrasive materials, corrosiveness and temperature, in case of liquids, and voltage above 72.5 kV [93]. All of these are special conditions that can be included or not in the tests, as separate certifications.

Although there are specialized companies in these kind of certifications, which are responsible for product licensing, these are very objective procedures that can be reproduced with a high level of confidence for academic purposes, as performed in section 5.1.

In order to build a robust enclosure for the DPCU circuit, an IP56 marking is requested. This means dust protection and resistance to powerful water jets, as described in Annex D [93]. The next degree of liquid protection is for immersion implementations, which are out of the field of application. The referred marking is in line with most nautical instrumentation for outdoor use [34] [35] [36] [37] [38] [39] [40] [41].

The DPCU electrical circuit, shown in Figure 4.21, is installed inside the enclosure of the Figure 4.20, as shown in Figure 4.22. The enclosure integrates the following independently licensed elements:

- Enclosure (IP56).
- Master Switch (S1) (IP56).
- Cable gland (IP66).
- DC socket (XSA) (IP66 when closed).
- LED sealing (IP65).

The holes made in the enclosure, as well the threads of the referred components, were protected with a silicon sealant, specifically designed for maritime applications [97] and PTFE tape, a known pipe thread sealant, respectively.

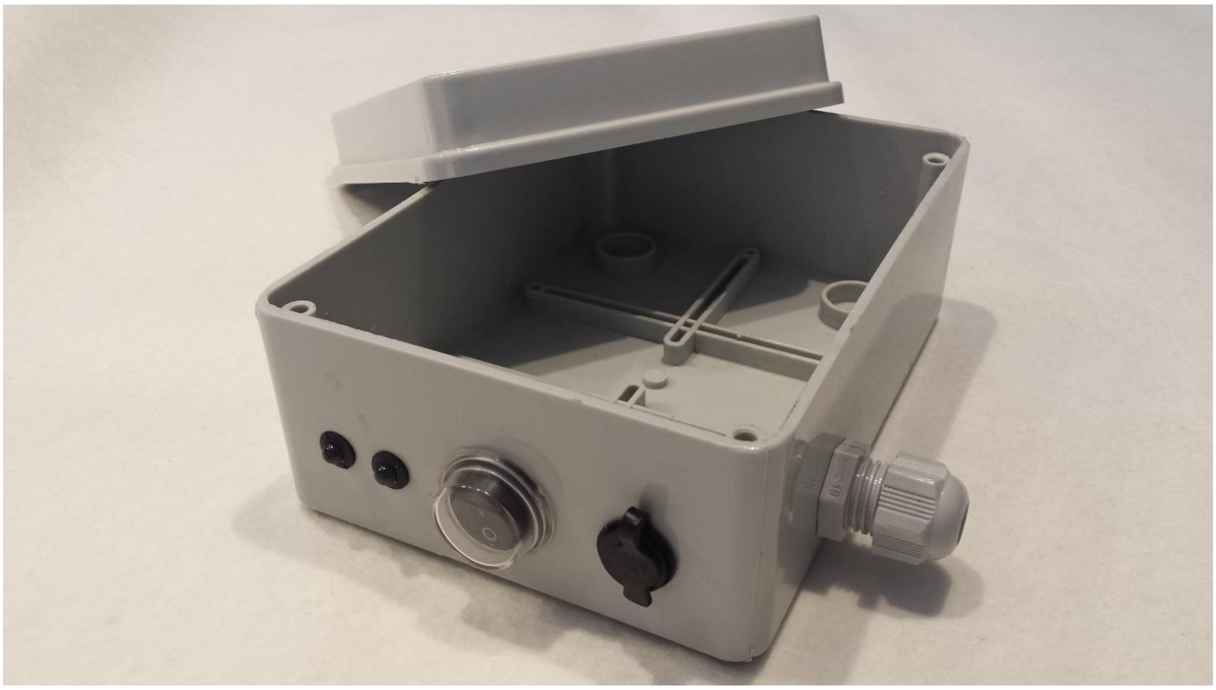


Figure 4.20 – DPCU enclosure.

In order to fit the electrical circuit inside the enclosure, a double deck configuration was used. The decks are separated by an aluminum plate, seizing its drilling holes, as shown in Figure 4.21. The assembled DPCU is shown in Figure 4.23.

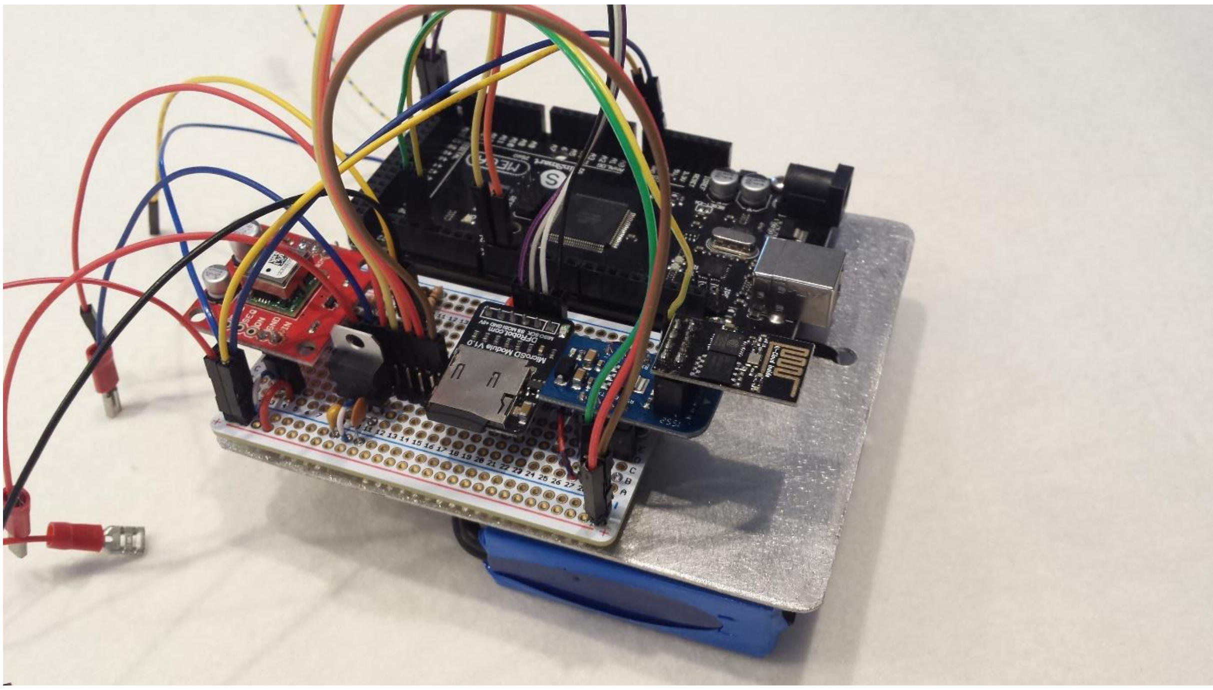


Figure 4.21 – Electronic circuit mounting plate.

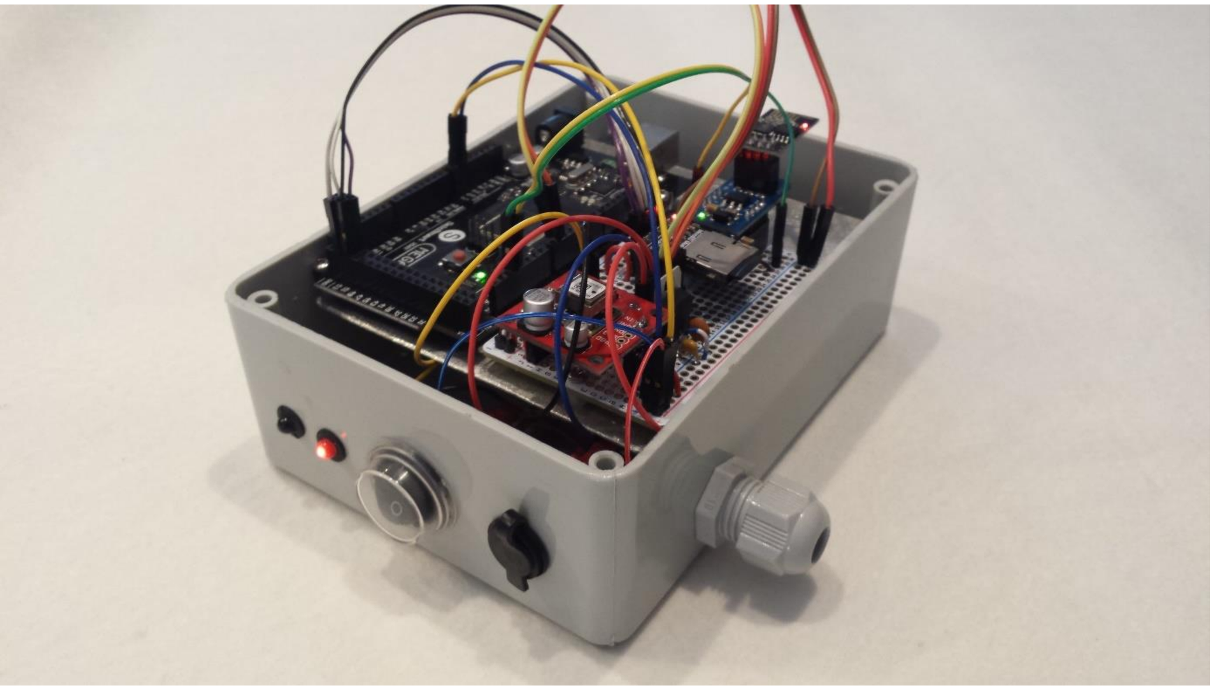


Figure 4.22 – Complete DPCU with open enclosure.

Figure 4.23 – Full assembled DPCU.

5 – Tests and Results

Although the hardware and software were developed to accomplish specific requirements, electronic circuits and batteries are easily affected when exposed to the elements. The expected operating conditions mainly include large thermal amplitudes, contact with water under pressure or in the form of condensation and corrosion due to long term exposure to the elements [2] [19]. As the weather stations used are licensed nautical instruments, extensive tests were performed before they become available to the market. The prototype DPCU needs too validation to work in maritime environment. In order to prove the robustness of the system, sections 5.1 and 5.2 regard environmentally controlled conditions to attribute standard classifications about the system limitations and section 5.3 simulates a real situation in motion. In this last one all the steps of configuration and operation were considered. Section 5.1, about IP marking, intends to simulate a real certification regarding watertight and solid intrusion protection, at the same time the exposed components structural resistance is tested against pressurized water. Section 5.2 have two main objectives, which are the test of the battery capacity when operating in a large thermal variation and the circuit resistance against condensation.

Corrosion is a complex subject that lacked of knowledge or means to be strictly performed. Nevertheless, was roughly analyzed through a careful visual inspection, after the testing stage that lasted almost two months. Between tests, the DPCU was always outdoor, luckily near the ocean, helping to speed up the corrosion process, in order to allow having some basic results regarding this issue. The circuit, plastics and sealants do not had any corrosion signs, like rust spots or dull areas, unlike the enclosure lid screws, which presented some sparse and superficial rust points on their heads only.

5.1 – IP Protection Marking

IP marking intends to validate the watertight and solid intrusion protection of the DPCU enclosure. For the required operation conditions and based on other similar equipment available on the market [2] [7] [10] [17] [19] [24] [29] [32] [34] [35] [36] [37] [38] [39] [40] [41] the test aimed an IP56 protection index, proposed in section 4.8. Some golden rules were applied in order to optimize the testing procedure and respective equipment, by relating solid intrusion with watertight [93] [96]:

- If a paper clip wire can enter the enclosure, then so can water.
- If water can enter the enclosure so can dust.
- If water gets in, let it out (IP dependent).
- If water is allowed to enter, create a path to the exit, avoiding critical areas.

The test not meant to substitute an official certification, in order to obtain a complete marking description. In this case all the stages are tested until reach the one desired, or the one that fails. For academic purposes and acknowledged by the EN 60529 standard, the procedure was unique and aimed the desired marking level, based on the first and second golden rules [93] [96]. The required test regards the IPx6 protection index, which is a common IP marking for maritime instrumentation. Figure 5.3 shows the water supply circuit and below are listed the test specifications:

- **Flow regulator device:** EN 60529 homologated 12.5 mm nozzle with internal flow regulator, shown in Figure 5.1.

Figure 5.1 – EN 60629 12.5 mm regulated nozzle.

- **Water flow:** 100 L/min ± 5% – 0.1 MPa.
- **Method:** water jet projected from a 3 m distance for 1 min in 3 different surfaces:
    - Lid top to test the screws thread watertight.
    - Lid rubber sealant to test its watertight.
    - Enclosure walls where the supply socket, master switch, LED and cable gland were installed, to test their watertight and resistance to pressurized water jets.
- **Duration:** 3 min.
- **Leakage detection:** purple blotting paper to test, by contact, all the sealants and joints of the referred areas in “Method”. This paper turns from light to dark purple with the slightest presence of liquids, as described in Figure 5.2, allowing an easy visual inspection when cleaning all the possible leakage spots.

Figure 5.2 – Blotting paper reaction in the presence of water.

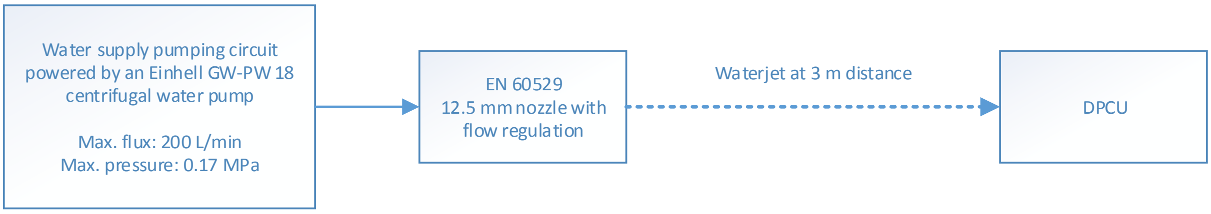


Figure 5.3 – Water circuit used in IP marking test.

After this procedure, the DPCU enclosure was opened and all the possible leakage spots were cleaned with blotting paper, as well the electrical circuit and the internal walls of the enclosure. The result was an unaltered color blotting paper, indicating that the test was a success. The enclosure rubber sealant was only wet in the vertical exterior surfaces, which means that the screws pressure on the lid was enough to compress it conveniently.

With these results, two possible IP markings can be considered: IP56 and IP66. The safe consideration is the initially aimed IP56, which is equal to the lowest component certification installed in the enclosure. The tests were performed with still water at 15 ºC ± 1ºC.

5.2 – Battery life and temperature influence

Capacity calculated in section 4.7 did not considered C-rate or temperature influence, using a safety factor instead. The chosen battery module validation depends on the real influence of these two factors during runtime. As the C-rate defined by the DPCU is low and almost constant, the temperature influence on capacity will be the main test subject. C-rate influence should be tested too if it be much higher (i.e. C-rate above 1C) or having high peaks during operation, which is not the case. The tests were performed in four different temperatures: -18 ºC; 0 ºC[13]; 20 ºC; 40 ºC. This temperature range includes almost all the possible operating temperatures that would be expected to be experienced by the system in real conditions. The above temperatures are within the operating temperature range of the battery and the weather stations. The procedure consisted on leaving the DPCU with the most power demanding weather station[14] for 1 h in the referred conditions and then turned the system ON with a Wi-Fi connection established. The time the battery has taken from fully charged, at approximately 12 VDC, to fully discharged, at 10.8 VDC, was then monitored and the results are shown in the Figure 5.4. This circuit experimentally drained approximately 215 mA, as measured in section 4.7 without the satellite hub and should ideally run for 18.6 h.

[13] Freezing threshold.

[14] Airmar PB200 weather station.

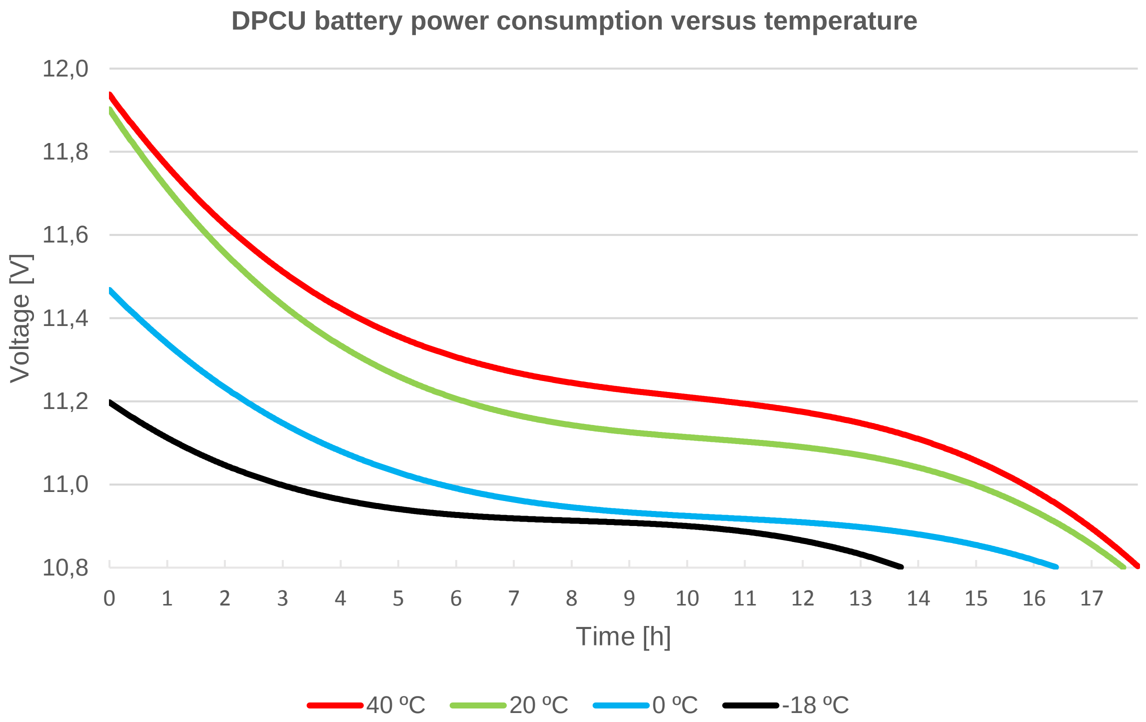


Figure 5.4 – DPCU battery power consumption versus temperature. Sampling once a minute.

Based on these results, the battery performance decreases when the temperature decreases, which is an expected behavior. Although all the curves represent runtimes that fulfill the required 12 h minimum, the performance rapidly decreases below freezing temperatures and probability will last less the 12 h between -20 and -30 ºC. At the lower extreme, Lithium-ion batteries suffer from Lithium plating of the anode causing a permanent reduction in capacity [98]. At higher temperatures, it is possible to observe a performance increasing. Although this is expected for Lithium-ion batteries, they should not be used in these conditions, otherwise life span will be reduced. At the upper extreme, together with the normal internal heat generated during discharge, the active chemicals may break down and the battery will be permanently damaged [99].

If the satellite hub was added to the circuit, we would have approximately 13 % increasing in the demanding current, producing a small variation in C-rate, from 0.05 to 0.06. This increase would not create a noticeable variation in capacity and the curves shape will remain the same, but of course, shortened by the corresponding increasing of the circuit consumption.

The recommended 30 % safety factor used in calculations of the battery capacity for Lithium-ion chemistry revealed to be a prudent option. The best result was at 40 ºC where the difference between the theoretical runtime and the experimental one was 42 min. Table 5.1 shows the capacity error related to the operating temperature. By operating within the admissible temperature range and with such a lower C-rate, the battery capacity is lower than the advertised by the manufacturer.

Temperature [ºC]	Runtime [h]	Error [%]
40	17.9	3.8
20	17.6	5.4
0	16.4	11.8
-18	13.8	25.8

Table 5.1 – Temperature influence on system runtimes.

About condensation, the secondary test subject, was only observed at 0 and -18 ºC temperatures. The little condensation present in the DPCU circuit when the 0 ºC test was performed, in liquid state throughout the process, did not produced any harm in the operation. At -18 ºC this condensation frosted during the test. It was verified that 18 messages were lost from the MicroSD Card, when compared with the internal counter programmed in the microcontroller. Is almost null considering the number of transmitted messages during the 13.8 h of the test, but represented the first operating failure. The operating range of the used MicroSD Card was -5 to 40 ºC, which could explain the writing errors. The test at -18 ºC was repeated with a different MicroSD Card, whose operating temperature was -25 to 85 ºC and no errors were detected during the 13.7 h runtime.

5.3 – Test trip and prototype validation

In order to test the system in real conditions, a 21 km round trip was performed in Torres Vedras County, whose course is presented in Figure 5.5. Although a vessel trip was not possible to accomplish, the system was installed in a car instead, with the configuration of the Figure 5.6, where some advantages could be highlighted:

- Higher speeds experienced, which could lead to stronger turbulent regimes.
- Faster velocity changes, allowing to observe sensor reaction times.
- High intensity vibrations and impacts that allow testing electrical circuit robustness.

As the Airmar PB200 weather station is more appropriate for motion applications, as referred in section 4.1, it was the model used to perform this try out. At this stage, the main goal is to test the operation of the complete system, excluding the quality of the output data of the sensor. In spite of this project had use renowned weather stations, the DPCU can read and configure any NMEA 0183 device and this feature is the one that must be tested assured. The quality testing of licensed equipment is out of the scope of this work.

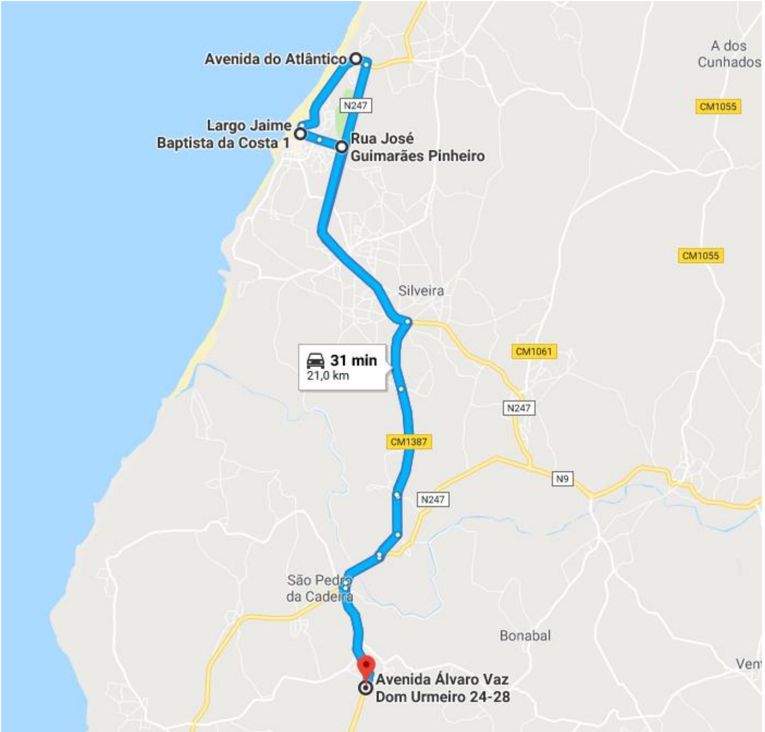


Figure 5.5 – Test trip course.

Figure 5.6 – System installation in a car: DPCU attached on the windshield and the weather station fix in a suction cup on the hood.

The steps taken to operate the system are described below, including the straightforward configuration that allows a quick startup:

- **STEP 1:** Turn ON the system by pressing the Master Switch S1 and wait for the LED H1 to lights up, as highlighted in Figure 5.7. This allows the user to know that the system booted and Wi-Fi connection is available.

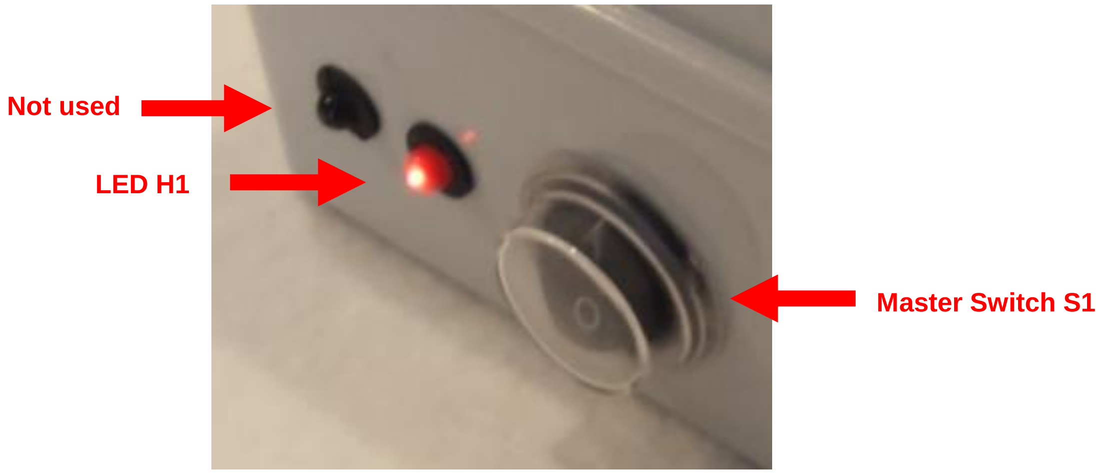
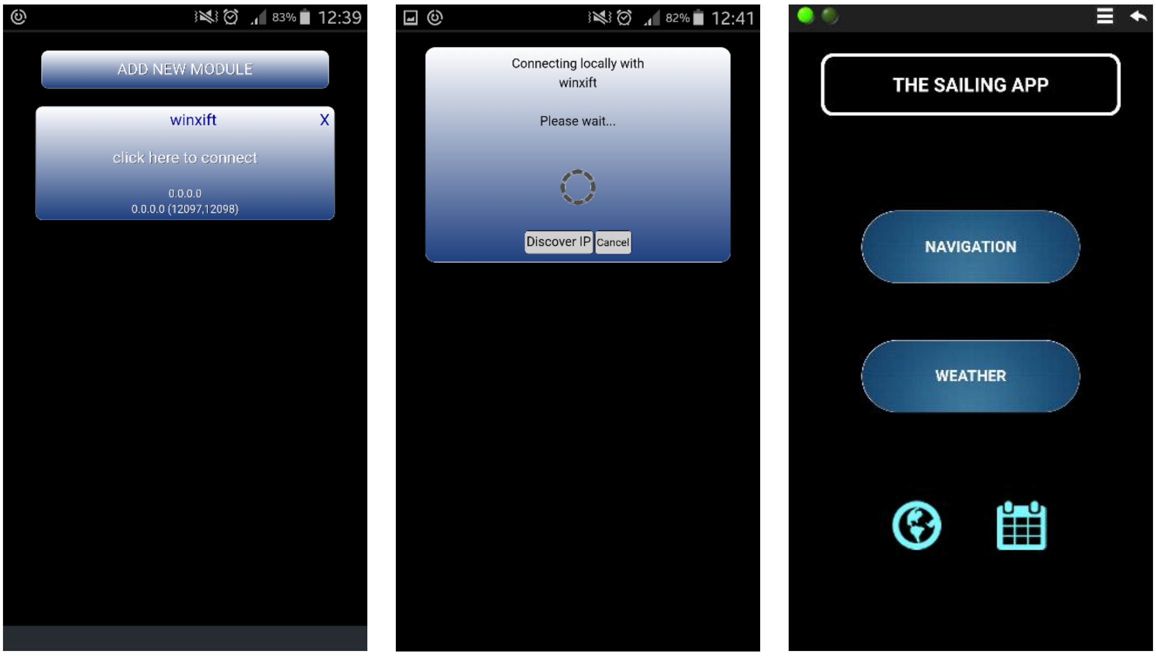


Figure 5.7 – DPCU Master Switch S1 and LED H1 location.

- **STEP 2:** Open the µPanel APP in the device to connect to the DPCU over Wi-Fi. Figure 5.8 (a) shows the startup screen, where the DPCU SSID must be chosen and Figure 5.8 (b) the connection process. After this, the APP starts to be controlled by the DPCU automatically, by showing the startup screen, present in Figure 5.8 (c).



(a) (b) (c)

Figure 5.8 – µPanel APP synchronization stage.

- **STEP 3:** The system is ready to be controlled through the µPanel APP and all the functionalities are available. In the case of the presence of the satellite hub, full control is available at this stage too. Figure 5.9 shows an example of a possible smartphone use, conveniently attached on the wrist, for viewing navigation data.

Figure 5.9 – Smartphone attached to the wrist.

- **STEP 4:** After the operation concluded, turn OFF the system by pressing the Master Switch S1.

After this successful field try out no flaws were detected on both navigation and weather data. All the sensors were correctly read and wind measurements were updated smoothly, which suggests a good noise filtering of the weather station. No missed messages were observed and below is a complete decode message cycle, extracted from the internal log functionality:

$PFEC,GPatt,,-1.5,-13.7*57
$WIMDA,30.2210,I,1.0234,B,19.0,C,,,,,,,89.8,T,93.3,M,35.7,N,18.4,M*28
$WIMWD,90.0,T,93.5,M,35.7,N,18.4,M*50
$WIMWV,153.9,R,47.2,N,A*1C
$WIMWV,204.9,T,35.6,N,A*1A
$TIROT,-281.2,A*1F
$WIVWR,154.3,R,47.1,N,24.2,M,87.2,K*6F
$YXXDR,C,,C,WCHR,C,,C,WCHT,C,,C,HINX,P,1.0169,B,STNP*44
$YXXDR,A,-3.0,D,PTCH,A,-10.4,D,ROLL*6B
$GPGLL,3905.9955,N,00921.8605,W,123008,A,D*56
$GPVTG,345.7,T,349.2,M,36.8,N,68.2,K,D*2E

$HCHDG,248.6,0.0,E,3.5,W*5E

$HCHDT,245.2,T*28

$PFEC,GPatt,,-3.3,-9.4*6B

$WIMDA,30.2180,I,1.0233,B,19.0,C,,,,,,,90.2,T,93.7,M,39.2,N,20.2,M*27

$WIMWD,90.4,T,93.9,M,39.2,N,20.2,M*5C

$WIMWV,155.5,R,46.4,N,A*11

$WIMWV,205.5,T,39.1,N,A*1C

$TIROT,-76.1,A*26

$WIVWR,155.5,R,46.5,N,23.9,M,86.1,K*63

$YXXDR,C,,C,WCHR,C,,C,WCHT,C,,C,HINX,P,1.0169,B,STNP*44

$YXXDR,A,-3.7,D,PTCH,A,-8.7,D,ROLL*56

$GPGGA,123009,3906.0051,N,00921.8645,W,2,8,1.4,53.3,M,,,,*0C

$GPGLL,3906.0051,N,00921.8645,W,123009,A,D*54

$GPVTG,342.8,T,346.3,M,36.9,N,68.3,K,D*28

$HCHDG,248.5,0.0,E,3.5,W*5D

$HCHDT,245.0,T*2A

6 – Conclusions

The ultrasonic anemometry has clear advantages over other technologies used in nautical applications, especially the widespread cup and vane anemometers. Besides the superior accuracy, the fact of ultrasonic anemometers do not have moving parts, greatly contributes for their robust architecture. Issues related with the wear of bearings and encoders, blocked parts, accuracy decreasing due changes in weight distribution, etc. are implicitly overcome. Therefore, an ultrasonic anemometer was selected for this work.

As an alternative to the central units of modern nautical instrumentation networks, the developed DPCU prototype is a broad solution that includes some functionalities usually performed by other external modules. Namely, Wi-Fi and satellite communication channels. The DPCU is a complete decoding machine of the NMEA 0183 protocol, which allows the integration of any nautical device that communicates through this protocol. The particular use of the Airmar PB200 and LB150 weather stations permitted the creation of a compact system with weather monitoring and navigation capabilities. All the controls and data visualization can be achieved through a smartphone, tablet or PC, which greatly diminishes the system cost. The use of consumer electronic devices to perform this task, by means of the µPanel APP, has two main advantages: the suppression of the need of licensed consoles, which are dedicated only to this task, eliminates an expensive and somehow redundant device from the system; as this application is totally programmed by the DPCU microcontroller and is compatible with Android and iOS systems, the software is unique. A simple Android emulator turns every PC into a device that operates the DPCU like an Android native. The satellite optional capability allows the user to operate the DPCU by controlling and gathering data from remote places. The satellite hub is totally controlled by the DPCU microcontroller and have tools to stay connected to the Iridium network. This allows a remote access through the Rock Seven interface or simply by a HTTP POST. This functionality is especially useful in land or maritime weather stations. At least, the integration of an internal logger functionality through an SD Card and a dedicated battery are two valuable resources. Although the logger is an unexceptional feature, the internal battery is a breakthrough in these kind of systems, as it is an option usually performed by an independent module.

As the system robustness is that important as the hardware and software features, the integration of all the components in a single enclosure, with IP 56 protection marking, turns the DPCU into a compact device, capable of dealing with the expected harsh maritime conditions. The only concern comprises the influence of temperature over the battery capacity. Although the chosen module performed well during the tests, the capacity decreasing at low temperatures is clearly notorious. However, different batteries could be used without changing the intrinsic structure of the system. In order to improve the DPCU robustness and presentation, a PCB could be developed to substitute the several independent components connected by jumper wires. This will eliminate the possibility of loose cables and the physical area required by the circuit will be smaller.

In terms of expansibility of the system, regarding the number of sensors, a great improvement with little investment is possible. The actual configuration of the DPCU leaves one serial port free in the microcontroller, which could be used for the integration of another sensor. For a bigger system, Arduinos offer the possibility of creating large networks using the I2C protocol to exchange data between them. For example, this prototype with two Arduino MEGA 2560 R3 boards could deal with five sensors. Of course, graphical interface have to be adapted and probably the enclosure had to be bigger or power supply stronger, but the key point is that the intrinsic prototype structure remains the same.

All the features offered by this prototype turned it into a valid alternative of the actual nautical instrumentation networks, for a small fraction of their price. This opens the possibility to fill the market with a system type that is claimed by an important part of the nautical community, which is essentially formed by small sailors from several fields of activity.

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Annex A – Electronic Circuit

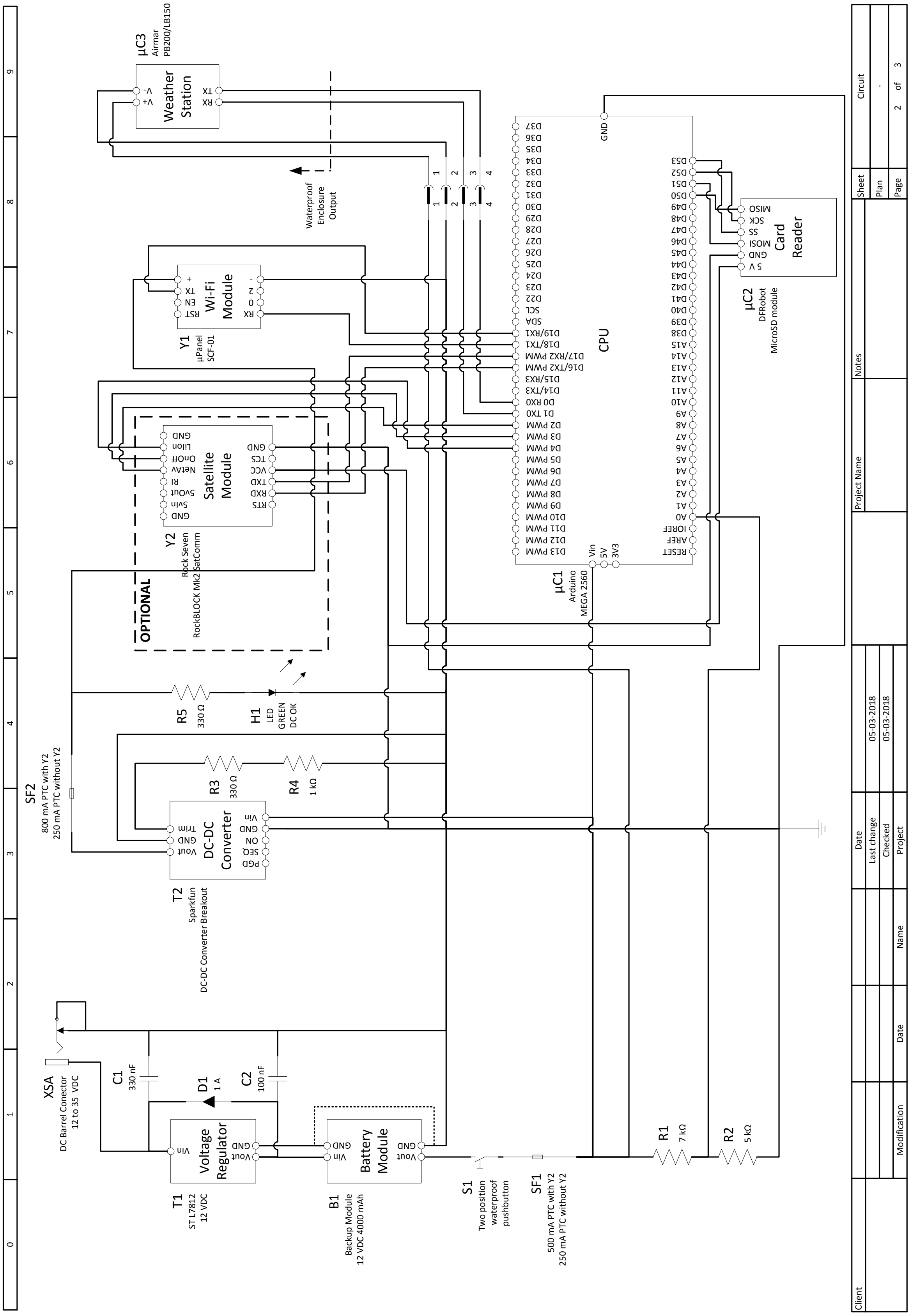

Figure A.1 – DPCU electronic circuit.

Below are described the ancillary elements of the system, identified by their tags. The microcontroller (µC1), weather station (µC3), close range communication module (Y1) and long range communication hub (Y2) were previously discussed in sections 4.4, 4.1, 4.2.1 and 4.3.1, respectively.

DC socket (XSA): DPCU 12 VDC main supply from a common 2.1 mm DC barrel socket. This socket is waterproof and is attached to the wall of the enclosure (see section 4.8).

Voltage regulator (T1), capacitors (C1 and C2) and diode (D1): In order to protect the circuit from overload or wrong polarity, this voltage regulator limits supply to safe values at the same time that allows flexibility for an input source from 12 to 35 VDC. Both capacitors stabilize the voltage regulator and the diode protects the circuit from possible capacitive overload failure from DC-DC converter (T2) [90].

Battery Module (B1): The 12 VDC module assures three functions: Internal supply for an autonomous operation; operation and charging simultaneously; series installation with the rest of the circuit for a continuous operation in case of external supply failure.

Master Switch (S1): Isolating the previous three elements from the rest of the circuit, this waterproof switch attached to the enclosure wall allows turn on and off the DPCU.

Fuses (SF1 and SF2): Short-circuit protection of the two source voltages, 5 and 12 VDC respectively. The PTC fuses assure a quick cutoff and are resettable after short-circuit removed.

Resistors (R1 and R2): Voltage divider responsible for mapping the battery voltage, in order to monitoring the respective level, obtained from an analog reading by the Arduino board.

DC-DC converter (T2) and resistor (R3 and R4): 12 VDC into 5 VDC conversion for the close range (Y1) and long range (Y2) communication modules, as well the card reader (µC2). The resistors are the TRIM load to set the voltage conversion.

LED (H1) and resistor (R5): The green LED attached to enclosure wall represents a visual signal that the DPCU is on. Lights up with the Master Switch (S1) and takes a few seconds to turn on, until the DC-DC converter (T2) starts-up.

Card Reader (µC2): Message log is saved in a microSD, inside the DPCU (see section 4.6.2).

Communication cable between the DPCU and the weather station: This link is assured by a Li2YCY low-frequency and low-capacitance screened PVC data cable. This cable type is specially designed for outdoor communications [91].

Annex B – Prototype Cost Analysis

The actual cost of the prototype components is listed in table B.1. Based on this table, the cost of the complete DPCU was € 106.73 and depending on the chosen weather station the complete system can oscillate between € 933.06 and € 1170.70. To show that the project is on track to fulfill the initial requirements with respect to the cost, when compared with the existing products, Table B.2 shows the comparison of the retail price of some modular systems with the price of the prototype, considering the most expensive weather station. The satellite hub, being and optional feature and not having similar competition regarding embedded solutions, was not included in the complete system cost. But if the value was considered, the cost percentage would remain very low.

Component	Price
Airmar PB200 Weather Station	€ 1.063.97
Airmar LB150 Weather Station	€ 827.03
DPCU complete circuit	€ 78.28
DPCU complete enclosure	€ 28.45
Rock Seven RockBLOCK Satellite Hub	€ 196.30

Table B.1 – Actual cost of the prototype.

System	Price	Prototype Cost Percentage
B&G H3000 Weather + GPS plus installation	€ 35.783,00	3.2 %
Ockam Instruments Modules Weather + GPS and display plus installation	€ 38.895,00	3.0 %
Raymarine Weather + GPS + Satellite Com. plus installation	€ 40.867,00	2.9 %

Table B.2 – Percentage of the prototype cost regarding some existing systems [35] [36] [37] [38] [39] [40] [41].

Annex C – Subscription plans

Satellite communication subscription plan provided by Rock Seven service is presented in table C.1. 1 credit is used per 50 bytes in a message. Credits do not expire unless no monthly fees have been paid for 12 months. All prices are presented in GBP and are subject to the current exchange rate at the time of purchase. Added to the presented bundles, a monthly rental of the communication line in the amount of £ 10 is required.

According to the present subscription plan and based on Annex F, as a NMEA 0183 message takes a maximum of 2 credits to be transmitted, the cost oscillate between £ 0.06 and £ 0.18 per message. Assuming an hour of transmissions once a minute, it will cost between £ 1.8 and £ 5.4.

Bundle	Price per credit	Price
500	£ 0,09	£ 45,00
1000	£ 0,08	£ 80,00
2000	£ 0,07	£ 150,00
5000	£ 0,07	£ 300,00
10000	£ 0,05	£ 500,00
20000	£ 0,04	£ 800,07
50000	£ 0,03	£ 1500,00
50000+	Further discounts available	

Table C.1 – Mobile Communications data plans

Annex D – IP Code

Tables D.1 and D.2 show how to interpret the IP Code tags present in any equipment with this type of certification (IEC standard 60529 – EN 60529 for Europe). Each tag is represented by IP XY where X and Y are digits. The first one refers to solid protection and the second to liquid protection. This standard do not comply with abrasive materials or intrusion speed in case of solids or corrosiveness and temperature in case of liquids.

Level	**Object Size**	**Effectives**
0	-	No protection against contact and ingress of objects
1	> 50.0 mm	Any large surface of the body, such as the back of the hand, buy no protection against deliberate contact with a body part
2	> 12.5 mm	Fingers or similar objects
3	> 2.5 mm	Tools, thick wires, etc.
4	> 1 mm	Most wires, screws, etc.
5	Dust Protected	Ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment; complete protection against contact.
6	Dust Tight	No ingress of dust; complete protection against contact

Table D.1 – IP Code: Solid Protection.

Level	Object Size	Effectives
0	Not Protected	No protection against liquids
1	Dripping Water	Dripping water (vertically falling drops) shall have no harmful effect.
2	Dripping water when tilted up to 15°	Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle up to 15° from its normal position.
3	Spraying water	Water falling as a spray at any angle up to 60° from the vertical shall have no harmful effect.
4	Splashing water	Water splashing against the enclosure from any direction shall have no harmful effect.
5	Water jets	Water projected by a nozzle (6.3mm) against enclosure from any direction shall have no harmful effects.
6	Powerful water jets	Water projected in powerful jets (12.5mm nozzle) against the enclosure from any direction shall have no harmful effects.
7	Immersion up to 1 m	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time (up to 1 m of submersion).
8	Immersion beyond 1m	The equipment is suitable for continuous immersion in water under conditions which shall be specified by the manufacturer. Normally, this will mean that the equipment is hermetically sealed. However, with certain types of equipment, it can mean that water can enter but only in such a manner that it produces no harmful effects.

Table D.2 – IP Code: Liquid Protection.

Annex E – Satellite hub based on IridiumSBD library

Below is present a resume of the code used to control satellite communication hub, based on the Rock Seven IridiumSBD library.

```
// Libraries
#include "IridiumSBD.h"
#include "SoftwareSerial.h"

// RockBLOCK serial port 2
SoftwareSerial ssIridium(16, 17);

// RockBLOCK object and SLEEP pin definition on 5
IridiumSBD isbd(ssIridium, 5);

// Setup configuration runs once
 void setup() {
…
isbd.setPowerProfile(1); // This is a low power application
isbd.begin(); // Wake up the 9602 and prepare it to communicate.
…
}

//Loop runs continuously
void loop(){
…
	//Callback function to allow the Arduino continuing processing information while waits
	//for a valid satellite signal, if the module is activated.
	ISBDCallback() {
…
	}
...
// Send a text message and receive one (if available)
MSG_index = sendReceiveSBDText(NMEA_MSG, NMEA_Buffer, NMEA_Buffer_size);
…
}
```

These last two functions only run if the satellite communication is activated. The nature of satellite communications is such that it often takes quite a long time to establish a link, even under ideal conditions, for the simple reason that at a given time no satellite may immediately be overhead [84]. In these cases, the library initiates a moderately elaborate behind-the-scenes series of retries, waiting for a satellite to appear [84]. With a clear sky, transmissions almost always succeed after a few of these retries, but the entire process may take up to several minutes [84]. Since most microcontroller applications cannot tolerate blocking delays of this length, IridiumSBD provides a callback mechanism to ensure that the Arduino can continue performing critical tasks, provided by the function "bool ISBDCallback()" [84]. This function will be called repeatedly while the library is waiting for long operations to complete [84].

Annex F – NMEA 0183 protocol

NMEA 0183 is a combined electrical and data specification for communication between maritime electronics such as echo sounders, SONAR's, anemometers, gyrocompass, autopilot, GPS receivers and many other types of instruments [1]. It was developed by the National Marine Electronics Association and replaces the earlier NMEA 0180 and NMEA 0182 standards [1] [77].

Recently, National Marine Electronics Association has attempted to replace NMEA 0183 with a very differently structured protocol named NMEA 2000, which is binary rather than textual, being an interpretation of the Controller Area Network (CAN) protocol, used in automotive networking [1] [21] [77] [78]. Unlike NMEA 0183, is frame-based and cannot be transmitted over serial links [1] [21]. While some newer maritime electronics can use this protocol, the great majority of devices are still being developed for NMEA 0183, or in some cases have both available [1] [77].

NMEA 0183 standard uses a simple ASCII (8 bit characters) code and a serial communications protocol that defines how data is transmitted in a sentence, or message, from one "talker" to multiple "listeners" at a time [1] [21] [55]. The electrical standard of NMEA 0183 is RS422, although most hardware outputs are also able to use single RS232 port [1] [21] [55]. The serial communication have a typical baud rate of 4800 bps with no handshake or parity [1] [21] [77]. Through the use of intermediate expanders, a "talker" can have an unidirectional conversation with a nearly unlimited number of "listeners", and using multiplexers, multiple sensors can talk to a single port [1] [21] [77]. At the application layer, the standard also defines the contents of each message type, so that all listeners can parse messages accurately [1] [55]. The maximum size of a message is 80 characters or 80 bytes [1] [21] [55].

Example of a NMEA 0183 message and field meaning (Table F.1) [1] [28] [55]:

Syntax: **$WIMWD,90.0,T,120.0,M,40.0,N,20.6,M*hh<CR><LF>**
Summary: NMEA 0183 standard Wind direction and Speed, with respect to north.
Default State: Enabled. Transmitted once per second.

Field	Description	Field	Description
$	Start message character	N	N = knots
WIMWD	Message type code	20.6	Wind speed in meters per second
90.0	Wind direction: 0.0 to 359.9 degrees True	M	M = meters per second
T	T = True	*hh	Message validating checksum CRChh where "hh" is hexadecimal and depends on the message type
120.0	Wind direction: 0.0 to 359.9 degrees Magnetic		
M	M = Magnetic	<CR><LF>	End message
40.0	Wind speed in knots	,	Data field separator

Table F.1 – NMEA 0183 message characters and field meaning [28].

Annex G – Satellite communications

Satellite communications are used to broadcast a wide variety of signals and generally relies on three primary components: a GEO or LEO satellite network, property of external enterprises; a ground station, known as gateway that relay Internet data; a VSAT dish antenna with a transceiver, or other equivalent device, as shown in Figure G.1 [60] [69] [70] [73]. Other components of a satellite Internet system include a modem at the user end, which links the network with the transceiver and a centralized NOC for monitoring the entire system [60] [70] [73]. The satellite operates a star network topology where all network communication passes through the network hub processor, which is at the center of the star. With this configuration, the number of remote VSATs that can be connected to the hub is virtually limitless [60].

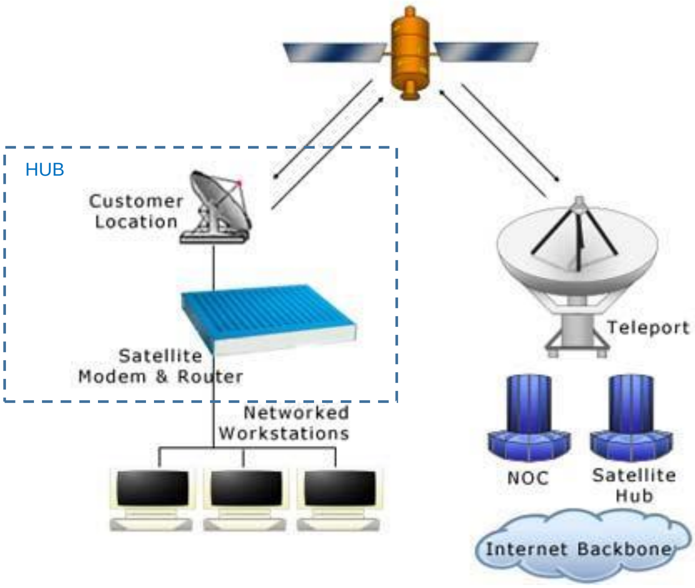

Figure G.1 – Satellite Internet diagram, adapted from [60].

In short, the gateway receives signals from the satellite on the last leg of the return or upstream payload, carrying the request originated from the end-user's site [60]. The satellite modem, at the gateway location, demodulates the incoming signal from the outdoor antenna into IP packets and sends them to the local network. Access servers and gateways manage then Internet traffic. Once the initial request has been processed by the gateway's servers, the requested information is sent back as a forward or downstream payload to the end-user via satellite, which re-directs the signal to the subscriber terminal [60].

Satellite communications are line-of-sight, so having a clear sky greatly improves speed and reliability, however, establishing contact may be difficult even under ideal conditions, for the simple reason that at a given time no satellite may immediately be overhead [60] [84]. Moisture and various forms of precipitation, such as rain or snow, in the signal path between the end user, or ground station, and the satellite being used could interfere with communications [60]. This phenomena is known as “rain fade” [60]. The effects are less pronounced on lower frequencies, L and C bands, but can become quite severe on the higher frequencies, Ku and Ka bands. Operation on the Ka band, at 19 to 29 GHz, can use special techniques such as large rain margins, adaptive uplink power control and reduced bit rates during precipitation conditions [60]. This kind of internet access is actually of very low latency with speeds up to 50 Mbps, which turns it in a smooth and fast connection like a terrestrial solution. The main disadvantages are is the price of the subscription plans and the time between independent upstream, usually over 30 seconds, which could degrade some applications [60] [61] [62] [73] [80] [84].

To perform this task, the DPCU must a have satellite hub connected to the microcontroller that communicates through a serial port, allowing messaging control and feedback. This hub usually have a modem and an integrated antenna for a compact implementation.

Annex H – Inquiry *Specimen*

Análise de mercado com o objectivo de fundamentar os requisitos para um protótipo de instrumentação meteorológica/navegação, ao abrigo da dissertação de mestrado em Engenharia Electrotécnica e de Computadores, pelo Instituto Superior Técnico – Universidade de Lisboa.

INQUÉRITO

1	Sexo	□ Masculino □ Feminino
2	Idade	_____ anos
3	Experiência em navegação	_____ anos
4	Marinheiro profissional?	□ Sim □ Não
5	Área de actuação	______________________________
6	Tipo de embarcação	______________________________
7	Distância anual percorrida	_____ milhas
8	Conhecimentos técnicos relativos à utilização e instalação de redes de instrumentação.	□ Utilizador apenas □ Responsável pela escolha de componentes □ Instalador
9	Qual a duração média de uma viagem ou período de actividade?	□ inferior a 6 h □ entre 6 h e 24 h □ entre 24 h e 48 h □ mais de 48 h
10	Utiliza uma rede dedicada para instrumentação da embarcação, seja de que natureza for?	□ Sim □ Não Porquê? ______________________ ______________________________ ______________________________
11	Tem alguma instrumentação a operar fora da dessa rede? (se respondeu “Não” em 10 ignore esta pergunta)	□ Sim □ Não Porquê? ______________________ ______________________________ ______________________________
12	A solução adoptada cumpre as espectativas?	□ Sim □ Não □ Parcialmente
13	Qual o custo da instrumentação associada à meteorologia e localização da embarcação (contemple o(s) equipamento(s) de visualização)? (se respondeu “Sim” em 10 contemple o custo da rede e da unidade de processamento)	□ inferior a € 1000 □ entre € 1001 e € 5000 □ entre € 5001 e € 10000 □ entre € 10001 e € 20000 □ mais de € 20000

14	Qual o tipo de anemómetro que usa e porquê?	______________________________ ______________________________ ______________________________
15	Acha útil/confiável uma solução open-source, de custo muito inferior às soluções licenciadas existentes actualmente, para a unidade de processamento de dados, e compatível com os sensores existentes no mercado?	◻ Sim ◻ Não Porquê? ________________________ ______________________________ ______________________________ ______________________________
16	Acha útil que a unidade de processamento de dados tenha capacidades de comunicação sem fios integradas de modo a substituir plotter, consolas, etc.?	◻ Não. ◻ Sim, com smartphones. ◻ Sim, com computadores pessoais. ◻ Sim, outra: ____________________
17	Acha útil que a unidade de processamento de dados tenha capacidades de comunicação de longa distância integradas, para controlo do sistema (não para contactos de emergência)?	◻ Não. ◻ Sim, via GSM. ◻ Sim, via Satélite. ◻ Sim, outra: ____________________
13	A integração de todos os tipos de comunicação, bateria, processamento e interfaces num só módulo é algo que suscite preocupação?	◻ Sim ◻ Não Porquê? ________________________ ______________________________ ______________________________ ______________________________
16	Quanto estaria disposto a pagar <u>apenas</u> pela unidade de processamento referida em 15?	◻ inferior a € 100 ◻ entre € 101 e € 500 ◻ entre € 501 e € 1000 ◻ entre € 1001 e € 5000 ◻ mais de € 5000

Grato pela disponibilidade.

Para qualquer esclarecimento acerca do preenchimento do inquérito, ou para envio do mesmo, utilize o seguinte endereço email: [redacted]