Synchronous Oceanic and Atmospheric Data Acquisition: field test release and validation of atmospheric, oceanographic, and deep-sea probes in the Azores Islands

Tiago Matos
CMEMS
Universidade do Minho
Guimarães, Portugal
matos.tiagoandre@cmems.uminho.pt

Marcos Martins
INESC TEC
FEUP
Porto, Portugal
marcos.martins@inesctec.pt

Alexandra Moutinho
IDMEC, Instituto SuperiorTécnico,
Universidade de Lisboa
Lisboa, Portugal
alexandra.moutinho@tecnico.ulisboa.pt

Carlos Diogo Henriques
IDMEC, Instituto Superior Técnico,
Universidade de Lisboa
Lisboa, Portugal
carlos.diogo@tecnico.ulisboa.pt

Dário Silva
IDMEC, Instituto Superior Técnico,
Universidade de Lisboa
Lisboa, Portugal
dario.silva@tecnico.ulisboa.pt

José Pacheco
IVAR
Universidade dos Açores
São Miguel, Açores, Portugal
Jose.MR.Pacheco@azores.gov.pt

Sérgio Oliveira
IVAR
Universidade dos Açores
São Miguel, Açores, Portugal
Sergio.NF.Oliveira@azores.gov.pt

Carlos Faria
CMEMS
Universidade do Minho
Guimarães, Portugal
carlosfaria@dem.uminho.pt

João Rocha
CMEMS
Universidade do Minho
Guimarães, Portugal
id10563@uminho.pt

Luís Gonçalves
CMEMS
Universidade do Minho
Guimarães, Portugal
lgoncalves@dei.uminho.pt

Fátima Viveiros
IVAR
Universidade dos Açores
São Miguel, Açores, Portugal
Maria.FB.Viveiros@azores.gov.pt

Paulo Fialho
IVAR
Universidade dos Açores
São Miguel, Açores, Portugal
paulo.jl.fialho@uac.pt

Diamantino Henriques
Instituto Português do Mar e da Atmosfera
Portugal
diamantino.henriques@ipma.pt

Rui Neto
IDMEC, Instituto Superior Técnico,
Universidade de Lisboa
Lisboa, Portugal
costaneto@tecnico.ulisboa.pt

***Abstract*— The oceans are abundant in natural diversity, minerals and energy resources, and there is an urgent need for a better understanding of its ecosystems and dynamics. The Synchronous Oceanic and Atmospheric Data Acquisition (SONDA) Project intends to contribute to better atmospheric and oceanic modelling and monitoring by launching High-Altitude Balloons (HAB) equipped with atmospheric and deep-sea probes to be released in oceanic areas of interest. This work reports the development and validation of three different probes: 1) atmospheric monitoring with APRS communications to be launched by HAB; 2) oceanographic monitoring; and 3) deep-sea monitoring with satellite communications. All probes were preliminarily tested in a semi-controlled fluvial environment, and posteriorly in real field conditions in the Azores Islands, Portugal. During the campaign, the Atmospheric probe was launched by HAB and its communications were tested with fixed and mobile ground stations, the oceanographic probe was deployed for three days to monitor the effect of a geothermal spring in the sea and the deep-sea probe was released into the Atlantic Ocean.**

Keywords—atmospheric monitoring, deep-sea monitoring, high-altitude balloon, swarm of disposable probes, oceanography.

I. INTRODUCTION

The potential of the oceans for society has long been recognized. However, there is an urgent need for a better ocean understanding providing the tools for the preservation of marine wildlife and sustainable use of natural resources [1]. Although significant advances have been made in characterizing them, further investigation is needed to address key research challenges in terms of atmospheric science, ocean science, climate change, and space science and technology.

Even though an attractive area of research, the oceans remain a challenging field due to their vast extension of water with several kilometers in depth; the high cost of exploration, either by air or by sea; and the harsh environmental conditions to which vehicles and equipment are exposed in the ocean due to wave action, pressure and corrosion [2]. Precise, but bulky and expensive vehicles are used to sample the vast ocean, limiting the massification of monitoring systems, thus resulting in insufficient spatial/temporal resolution.

Although, satellites have been gathering meaningful data regarding the exploration of both oceans and atmosphere. However, this solution is limited to discrete broad-range analysis, not allowing continuous measurements or precision/detailed analysis of a specific area in the ocean/atmosphere and not suited to exploring under sea surface [3], [4].

The ongoing Argo program (http://www.argo.ucsd.edu) currently has almost 4000 floats throughout the global ocean, providing unique data on global circulation patterns and water properties. Recently, a swarm of 18 profiling drifters were deployed in a 2 km diameter patch [5]. However, despite significant advances in using drifters and gliders to sample the large-scale dynamics of the ocean, there has been no deployment of a swarm of such autonomous deep-sea vehicles.

Apart from the dimensions and observation capabilities of the oceanic probes, another difficulty in acquiring oceanic data is the deployment of the probes. Typically, they are deployed by maritime transportation, entailing massive financial resources and complex logistics. This is due to the long distances involved, with the ships having to remain in the ocean for long periods, distant from seaports and other support infrastructures, sometimes sustaining harsh environmental conditions. Resorting to the volunteer Ship Of Opportunity Programme might reduce the deployment cost, but it will limit it to pre-defined shipping routes.

This project (sondaproject.tecnico.ulisboa.pt) intends to contribute to better atmospheric and oceanic monitoring by proposing the development of a complementary system to the existing observation means. This system is two-fold and brings innovation in the respective vectors: (i) the probes and (ii) the probes' carrier. Regarding the probes, the innovation is relative to their ability to continuously monitor parameters of interest from near space to the deep sea. The probes will be customizable allowing the integration of atmospheric sensors, motion sensors and marine sensors. When the probe reaches the bottom of the deep sea, it will remain there for a predefined period monitoring all variables plus soundscape from the ground. It will then return to the surface transmitting the data to a ground control station through a satellite or other available communication link, operating as a drift until it stops functioning due to material degradation.

Regarding the carrier of the probes, a High-Altitude Balloon (HAB) will be used. This low-cost solution with high cargo capability travels passively through the atmosphere to reach targeted areas, but with low positional accuracy. In the scope of this project, we intend to develop a control solution to endow the aerostat with some positioning capability, by controlling its altitude in agreement with the available wind currents. Limiting the HAB rise will also allow to keep it aloft for longer periods, making it not only an excellent atmospheric monitor but also a communications relay between the probes launched in desired locations and a ground control station, reducing the usual satellite communication costs.

The proposed SONDA system, composed of HAB + swarm of probes, will allow the acquisition of data otherwise unreachable in a cost-effective and integrated manner, from near-space to deep-sea (Figure 1). The HAB platform will be capable of deploying disposable probes over hundreds of kilometers, at significant altitudes, something unachievable by other technologies, such as the commonly named drones. This solution also bridges the existing gap between space and surface instrumentation, adding to the available satellite information the detailed long-term analysis of targeted areas.

This work reports the results of the initial field tests of SONDA, in a campaign in São Miguel Island (Azores, Portugal), in 2021, after a first set of tests in a semi-controlled fluvial environment. The overall system of the project was divided into three different modules to be independently tested: (1) a probe with real-time Automatic Packet Reporting System (APRS) communications to be launched by HAB; (2) a low-depth oceanographic probe to be deployed in the coastline to test oceanographic sensors and data acquisition; (3) a deep-sea probe to be released into the deep-ocean to measure the oceanic vertical profile.

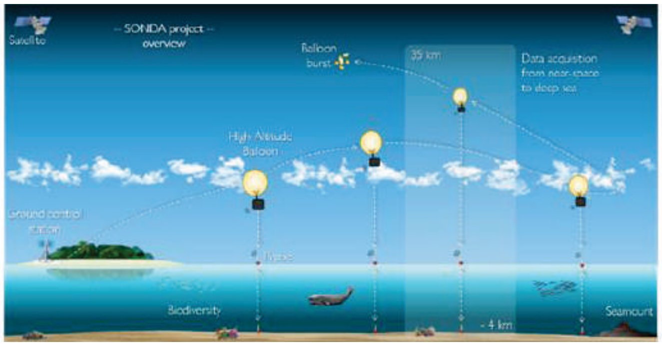

Fig. 1. SONDA concept overview. https://sondaproject.tecnico.ulisboa.pt/

II. PROBES DESIGN

A. Atmospheric Probe

The atmospheric probe was developed with APRS communications to transmit the GPS coordinates and atmospheric data between the HAB and a ground control station during the atmospheric monitoring phase. From the HAB launch to its bursting up to 35 km high, the atmospheric probe is intended to take vertical profile measurements. After the burst of the balloon, the probe falls with a parachute into the ocean and is not recovered. To collect these data, real-time communications between a ground station and the balloon are crucial. The use of APRS communications for HAB flights was validated in previous launches and it is worldwide used [6].

The probe uses a WiMo PicoAPRS-Lite APRS Transceiver Module that provides wireless long-range communications, pressure and air temperature measurements and Global Position System (GPS). A 250mW solar panel and super-capacitor were used to supply the module.

The probe was built in a spherical form, with a 200mm diameter, in polyurethane material (HB R 16/25—HBQUIMICA) and weights 1.8kg. The solar panel was coated with epoxy resin (HB EPOSURF2—HBQUIMICA) to protect it from the environment while keeping transparency (Fig. 2).

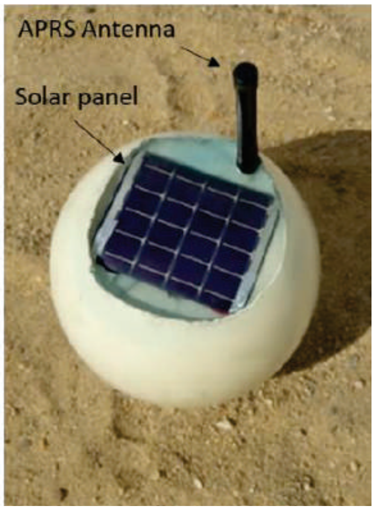

Fig. 2. Atmospheric probe.

B. *Oceanographic Probe*

The oceanographic probe was developed to test generic sensors for water monitoring. For this probe, the concerns about depth and high-pressure needs were not considered. The main purpose was to test sensors in underwater conditions, validating their acquisition and the watertight of the probe.

The electronics of the probe were designed with a power module, customized data logger and sensors to measure water parameters. The power module uses a 3.7V 2500mA LiPo battery and a LiPo Rider V1.3 power manager to supply the electronic system. The data logger uses a stm32L496ZG processor, an integrated real-time clock (RTC) to keep date and time, and a microSD card to store the monitoring data. The probe measures water temperature and absolute pressure (to calculate water depth) using the integrated circuit sensor MS5837-30BA, luminosity, and turbidity using infrared direct light transmission detection. Test and validation of these customized sensors were presented before [7], [8].

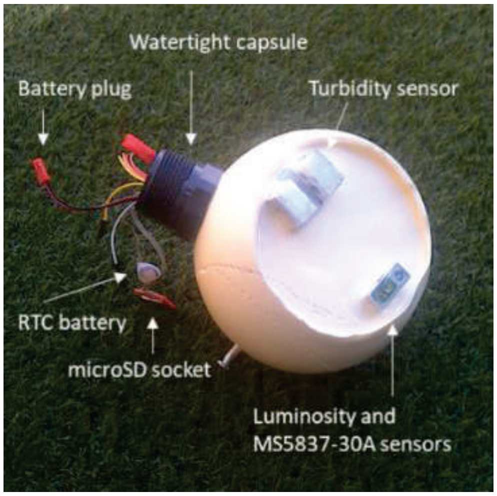

Fig. 3. Oceanographic probe.

The measured parameters are saved with the date and time on the microSD card. With a sample period of 2 seconds, the probe has autonomy for three months of continuous monitoring.

The probe was built in polyurethane material with a watertight capsule that can be opened to access the microSD card (to download the data) and to plug and charge the battery (see Fig. 3).

C. *Deep-Sea Probe*

The deep-sea probe is expected to measure the vertical profile of the ocean, from the surface to the seafloor, in areas up to 4000m in depth. One of the challenges for the dive of the probe is to make it sink when released into the water and be able to return to the surface after a predefined period (without the use of a propeller).

To accomplish it, the probe itself was designed with positive buoyancy that becomes negative when added a salt ballast. With this configuration, when the probe is submerged it will sink while the salt is dissolved in the seawater. Once the buoyancy turns positive again, the probe will return to the surface. At this stage, the probe becomes a drifter sending the acquired data during the dive using satellite communications, as Fig. 4 shows.

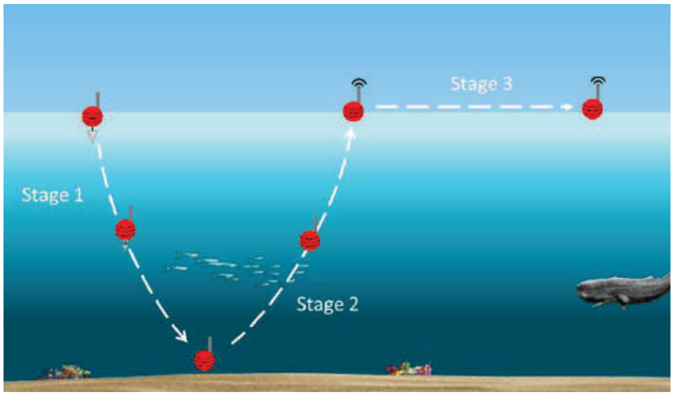

Fig. 4. Dive of the deep-sea probe. Stage 1: when the probe is released in open waters, the salt ballast will make it sink to the ocean floor.; Stage 2: Once the salt dissolves in the water, the probe will return to the surface due to its positive buoyancy; Stage 3: At the surface, the probe will act as a drifter and transmit by satellite communications the GPS position and the measurements recorded during Stages 1 and 2.

The electronics were designed with a 3.7V 6000mA LiPo battery and solar panel (to keep power for an indeterminate time during the drifter phase), an stm32L412K8T processor, depth, temperature and luminosity sensors, an L76X GPS module, and RockBlock 9603 IRIDIUM communications. A 400bar Sensata Technologies PTE7100 sensor was used to estimate depth, a TMP235AEDCKRQ1 integrated circuit enclosed in epoxy resin to measure water temperature, and a Vishay TEPT5700 photodiode to measure luminosity. In this prototype, and for testing purposes, a SEACON underwater connector was used to plug the power and program the firmware of the probe.

The probe (Fig. 5) was built with a mixture of polyurethane and borosilicate glass microspheres (<10µm diameter) in a proportion of 3:1. The borosilicate spheres were used to reduce the density of the probe so it was able to float. Its final form weighs 1.6kg and has 27% positive buoyancy.

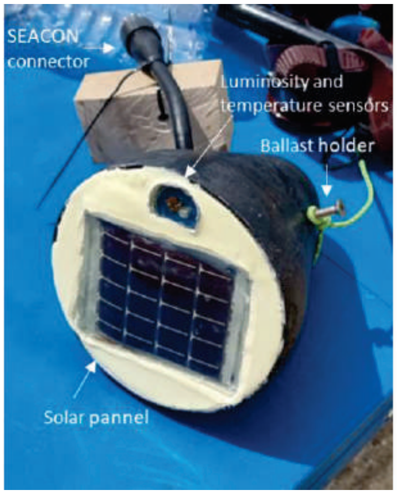

Fig. 5. Deep-sea probe.

III. PRELIMINARY TESTS IN A SEMI-CONTROLLED ENVIRONMENT

On the 6th of September 2021, preliminary tests were conducted for the three probes in Douro River, Portugal (41°03'59.2"N 8°24'20.8"W). The experiments were made to test the watertight of the three probes and their operations.

A. *Atmospheric probe*

The short-range communications of the Atmospheric probe were tested using a KENWOOD TH-D74 as the receiver APRS station. The probe was not launched by balloon. At this phase, the tests were only conducted on the ground.

The communication tests were performed during cloudy weather, which did not represent a problem for the operation of the probe (this is an important factor since the probe does not have a battery and works on solar power).

The APRS probe was tested successfully, with communications received by the mobile station.

B. *Oceanographic Probe*

The oceanographic probe was set with a sampling period of 1 minute and deployed on the river at 2m and 5m depth. Fig. 6 shows the measurements recorded.

The battery was plugged in at 11h30 with the probe outside the water for five minutes. At 11h35 the probe was submerged up to 2m depth and remained submerged for ten minutes. At 11h46, the probe was taken to 5m depth for three minutes and then returned to the surface.

The temperature recorded in the initial minutes of the experiment was 28.2ºC (at this stage, the sensor was measuring the temperature of the air, not water), gradually decreasing to 22.3ºC at 2m depth and 22.1ºC at 5m depth. When the probe returned to the surface, the temperature increased again to values close to 28ºC (there is a delay to reach the initial air temperature values because of the thermal capacity of the probe).

The digital values of luminosity recorded by the probe were converted to a scale of 0-100%, being 100% the maximum luminosity measured during the experiment when the probe was outside the water and 0% the luminosity with the probe on the dark. The values measured at the beginning and end of the experiment, when the probe was outside the water, were 100%. The luminosity values decreased to 76% at 2m depth and 47% at 5m depth.

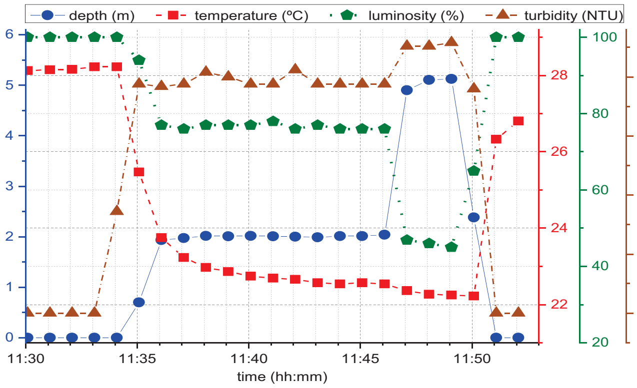

Fig. 6. Oceanographic probe measurements during the river deployment. Depth in blue circles and blue line (principal blue Y-axis), water temperature in red squares and red line (secondary red Y-axis), relative luminosity in green pentagons and green line (secondary green Y-axis) and turbidity in brown triangles and brown line (secondary brown Y-axis).

The turbidity measured with the probe outside the water was 0 NTU, as expected, decreased to 190 NTU at 2m depth and 250NTU at 5m depth. When the probe was deployed at 5m depth, it was already on the stream bed, so this turbidity difference from 2m to 5m can be explained due to streambed turbulence and re-suspension of streambed solids that increase turbidity.

The oceanographic probe was successfully validated in this experiment: the systems acquisition and electronics worked as designed; the results for depth, temperature, luminosity and turbidity are compliant with the theoretical expected; and the watertight capabilities were verified.

C. *Deep-Sea Probe*

The deep-sea probe was also tested in the river and set to take measurements with a sample period of 30 seconds. The battery was plugged with the probe outside the water and then it was left floating for five minutes at the surface of the river. During this phase, the probe was intended to be recording measurements and the satellite communication was disabled. Then, the probe was submerged at 8m depth for three minutes and returned to the surface. The software of the probe for this experiment was set to detect its return to the surface, take another three minutes of measurements, and enable the GPS and satellite communications to send the recorded data (drifter mode, stage 3 of Fig. 4).

Fig. 7 shows the measurements recorded by the deep-sea probe, received by the IRIDIUM communications. The results are similar to the experiment using the oceanographic probe: when the probe sinks into the river stream, there is a decrease in the water temperature and luminosity. The GPS also measured an accurate position of 41°04'00.1"N 8°24'24.57"W.

Besides the operation of the sensors, this experiment was intended to test the algorithm of the firmware of the probe (detect when the probe is on the surface, the dive, and the returning to the surface to enable the communications) and the efficiency of the IRIDIUM. The firmware was successfully validated but the IRIDIUM presented communication problems.

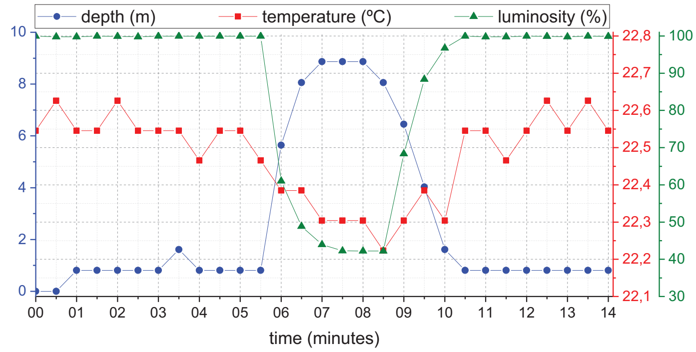

Fig. 7. Deep-sea probe measurements during the river deployment. Depth in blue circles and blue line (principal blue Y-axis), water temperature in red squares and red line (secondary red Y-axis) and relative luminosity in green triangles and green line (secondary green Y-axis).

When the probe returned to the surface and started to communicate, only 5 messages out of 20 were successfully transmitted. The test was conducted during a cloudy day, which is a concern for satellite communications that needs a clear view of the sky for a good performance. However, it was noticed that the transmission rate success with the probe outside the water increased to 16/20. This means that the mass of water around the probe had a negative impact on the data transmission. In open seawaters, the transmission rate success is expected to be lower [9].

IV. TEST AND VALIDATION IN AZORES

The field tests campaign in São Miguel island, Azores, from the 11th to the 20th of September 2021, allowed testing of the three probes in realistic scenarios: launch of the atmospheric probe by HAB, deployment of the oceanographic probe on the island coast and release of the deep-sea probe in the Atlantic Ocean (Fig. 8).

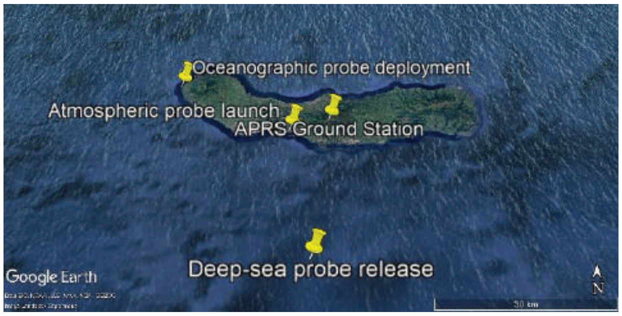

Fig. 8. Locations of the deployments of the oceanographic and deep-sea probes, the launch of the Atmospheric probe by HAB and APRS ground station.

A. *Atmospheric Probe*

On the 16th of September, the Atmospheric probe was launched by HAB in Lagoa, São Miguel (37°44'27.9"N 25°34'56.6"W, Atmospheric probe launch – Fig. 8).

The APRS communications were tested both to a mobile and a fixed ground control station. The mobile station was the KENWOOD TH-D74 receiver used during the fluvial tests. The fixed ground station was installed in Pico da Barrosa, the second highest point of the island with 947m height (37°45'37.1"N 25°29'29.3"W, APRS Ground Station – Fig. 8), and used an FM VHF/UHF and APRS transceiver and the LoRa Gateway LtAP LR8 LTE kit from Mikrotik.

Fig. 9. On the left image is presented the flight simulation of the HAB. On the right image is presented a photograph of the atmospheric probe sprayed orange with a parachute before the launch.

Fig. 9 shows the flight simulation of the HAB. The Atmospheric probe transmitted successfully to the portable station but lost communications when the HAB was at a 10km horizontal distance.

The communications were not expected to fail during the flight. The APRS transceiver was set to an automatic frequency. When the HAB was launched, the probe was communicating with the portable station using a Portuguese frequency. A possibility raised for the communication failure was the change to an International frequency when the HAB moved away from the island radius.

Contrary to the mobile station, the fixed ground station did not receive any transmission from the probe. Tests with a frequency analyzer after the HAB launch showed that other radio amateur signals in the area were producing significant noise on the station, which did not allow to receive the transmissions of the Atmospheric probe.

B. *Oceanographic Probe*

The oceanographic probe was deployed from the 17th to the 20th of September in the coastal area of Ferraria, São Miguel (37°51'29.96"N 25°51'8.23"W, Oceanographic probe deployment – Fig. 8).

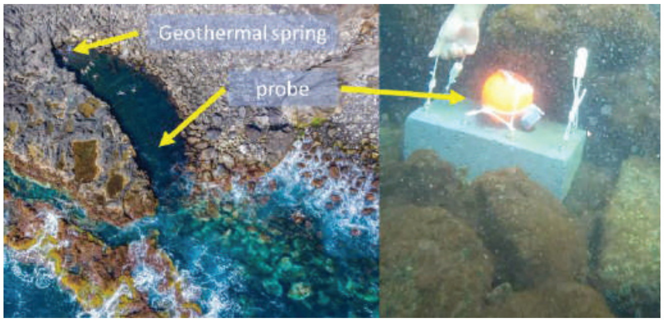

Fig. 10. Deployment of the oceanographic probe in Ferraria, Azores, close to a thermal spring. Left – aerial view of the location; right – underwater photograph of the oceanographic probe placement.

The probe was installed at 2-4m depth, close to a geothermal spring (see Fig. 10). The instrument was set to record measurements of depth, water temperature, turbidity and luminosity with a sampling period of 2 seconds.

The top graph of Fig. 11 shows the depth and water temperature data. The depth is presented in blue circles and discloses the tidal cycles with a tidal amplitude of almost 2 meters between the low and the high tide (low-frequency signal with a period of 12 hours). The data of depth also presents a signal in high frequency. This signal was caused by the small sampling period that was sufficient to measure the height of the sea wave. The water temperature is presented in red circles and correlated with the depth it shows an increase in the temperature during the low tides and a decrease during the high tides. The probe recorded a minimum water temperature of 21ºC and a maximum value of 31ºC. These high values are caused by the hot water coming from the thermal spring. The temperature amplitude between low and high tides is caused by the mixture of geothermal water and seawater. Since the sea water is colder than the geothermal spring fluid, during the high tide there is a higher volume of cold water, so the water temperature in the area decreases. The opposite happens during the low tide when the hot water coming from the spring warms the surroundings.

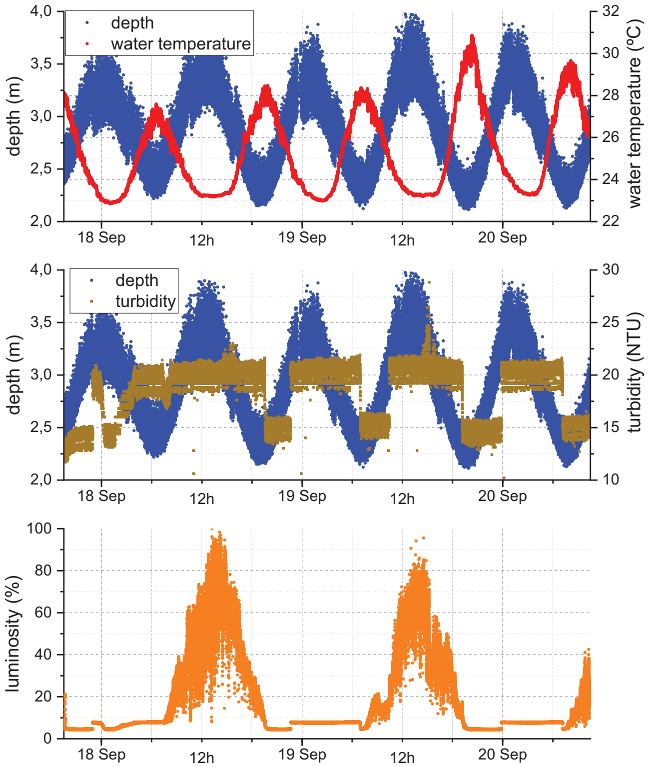

Fig. 11. Oceanographic probe measurements during the in-situ test in the Azores. The depth is displayed in blue circles and the water temperature in red circles in the top graph, depth in blue circles and turbidity in brown circles in the middle graph, and luminosity in the bottom graph.

As Fig. 10 shows, the location where the probe was installed is characterized by clean waters and rocky seabed. The absence of fine sediment resulted in low turbidity values recorded by the probe. The middle graph of Fig. 11 shows turbidity values of 20NTU during most time of the experiment and 15NTU during the increase of the tide (except for the first low-to-high tide on the 18th of September). One explanation for this periodical decrease in turbidity is the difference in water transparency between the water from the ocean and the hot spring. As explained for the water temperature, during the low tide the geothermal water has a higher influence in the area. However, the presented data is not sufficient to conclude.

The bottom graph of Fig. 11 presents the luminosity data, which follows the daylight behaviour. For all the days of the experiment, the luminosity level started to increase around 6h50 (sunrise), reached its peak at 14h (time of the day when the sun was in direct line to the probe) and decreased till 20h30 (sunset). At night, the luminosity was always above 0% because of the lunar light (full moon on 20th September).

C. Deep-Sea Probe

Before the release of the probe in open waters, the satellite communications were tested at the sea. As demonstrated during the tests in Douro River, the transmission rate success decreases when the probe is on the water. As expected, this rate decreased even more with the sea waves. Nevertheless, the designed experiment was carried on.

The deep-sea probe was released on the 18th of September, in the Atlantic Ocean, in a location with 1700m depth (37°28'36.00"N 25°32'1.00"W, Deep-sea probe release – Fig. 8). A ballast with 2kg of coarse salt was used and the probe was seen sinking into the deep. During the following days of the release, no satellite transmission was received and there was no feedback from the probe.

As an outcome of the test, several hypotheses were raised to explain the failure in receiving data from the probe: the probe was stuck under the surface (e.g., fishing nets or flora); malfunction of the ballast; materials did not resist to high pressures causing the collapse of the probe; change in the buoyancy level or position of the probe due to high pressure; water infiltrated into the electronics; malfunction of the software or electronics; problems with the satellite communications.

V. CONCLUSION

The SONDA Project intends to perform full monitoring of the vertical atmospheric and oceanographic profiles using the launch of probes from high-altitude balloons into the oceans. With this objective in mind, the idealized design of the project was divided into sub-task to be tested and validated: (1) APRS communications during the flight of the balloon; (2) test of oceanographic sensors and its system acquisition; (3) release of a deep-sea probe in the ocean (already close to the intended final design).

The atmospheric probe was launched in a HAB and successfully communicated to the portable station up to a horizontal distance of 10 km. Communications failed beyond 10 km, possibly because the probe was configured to an automatic frequency. To solve this problem, a fixed frequency should be used in coming launches, mainly, if the flight is performed in areas subject to frequency change as the Azores. The problem of noise detected in the fixed ground station must also be considered. A study of the local and possible interferences in the ground station must be made before the launch of the balloon.

The data acquisition of the oceanographic probe was successfully validated, proving that this instrument is a valid tool for oceanic and coastal monitoring. This technology should next be merged into the deep-sea probe aiming at an oceanographic probe capable to dive into the deep.

The system acquisition and operation of the deep-sea probe were successfully tested during the tests in Douro River. In the Azores, the probe was released in the Atlantic and was seen sinking into the deep, but there were no communications in the following days. One problem early detected during the tests with this probe was the difficulty to establish successful satellite communications when the probe was floating on the water. To improve the communication success, a new version must consider having the antenna outside the probe, the highest possible from the water surface (the antenna in this prototype was inside the probe). Another important consideration about the deep-sea probe is the sturdiness of the structural material to high pressures. Preliminary tests in pressure chambers should be conducted to evaluate if the material is suited for high depths and if the buoyancy is not affected.

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