RAMONES and Environmental Intelligence: Progress Update

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RAMONES is an EU H2020 FET Proactive Project which aims to offer a new fleet of instruments to perform continuous and *in situ* measurements of natural and artificial radioactivity in the marine environment as part of its main objectives. Those instruments will be developed, optimized, validated and deployed in the field, based on implementing specific functional characteristics, optimizing integrated solutions, and fine-tuning their overall architecture. The main effort in RAMONES is to define the new state-of-the-art in radioactivity monitoring in ocean ecosystems investing on innovative stationary and mobile platforms. RAMONES will develop light-weight, high-resolution, power-efficient radiation spectrometers integrated aboard autonomous underwater vehicles. A benthic laboratory will additionally be developed as a multi-instrument platform to offer high-resolution spectroscopy and imaging capabilities equipped with additional sensors. Radioactivity monitoring will offer several opportunities to understand the dose impact on ocean ecosystems in various extreme locations, such as underwater volcanoes, seismic faults or deep-ocean drilling locations. Artificial intelligence and robotics will core factors in achieving the new state-of-the-art in coordinated navigation and decision making, and will provide the tools for risk forecasting and risk mitigation. In this paper, a progress update on RAMONES instruments is reported, jointly with a report on the RAMONES contributions to the Environmental Intelligence initiative.

CCS Concepts: • **Hardware → Sensors and actuators**; **Modeling and parameter extraction**; **Hardware validation**; **Hardware test**; **Emerging technologies**; • **Computer systems organization → Robotics**; • **Information systems → Data management systems**; • **Computing methodologies → Artificial intelligence**; **Modeling and simulation**; • **Applied computing → Environmental sciences**; **Forecasting**.

Additional Key Words and Phrases: Radioactivity Monitoring, Environmental Intelligence, Marine Robotics and Applications, Ocean Ecosystems

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1 INTRODUCTION

RAMONES is a European Innovation Council (EIC) FET Proactive project in the Environmental Intelligence Scope B, related to radically novel approaches to resilient, reliable and environmentally responsible in-situ monitoring, funded by European Union under Horizon 2020 FET proactive programme, via grant agreement No. 101017808 [7].

RAMONES project's main objective is to close the current marine radioactivity under-sampling gap and foster novel interdisciplinary research in ocean ecosystems. RAMONES will invest a significant effort to provide tools to enable long-term data acquisition missions, rapid deployments, low cost per information byte, and propose new AI and Robotics-driven and supported methodologies, being ambitious to eventually offer scaled-up solutions to researchers, policy makers and communities. All these will be achieved by combining state-of-the-art (SoA) methodologies and equipment from various disciplines in a well-balanced synergy, and designing new and effective methodologies targeting the marine environment, which will provide efficient response to existing natural and man-made hazards, and shape future policies for the global population. RAMONES will additionally contribute to shaping a blueprint on Environmental Intelligence in the EU and worldwide.

This paper describes the recent progress made by the RAMONES consortium, especially in relation to the general description of the project in the previous instance of the GoodIT Conference Series in 2021 [12]. In that document, the basic research objectives and innovative technology targets were identified and discussed in some detail. Building upon the progress made since [12], this paper reports on recent advancements, *focusing almost exclusively* on the novel instrumentation currently being developed for deployment in the marine environment.

In addition, a short description of the RAMONES consortium partners' effort regarding their participation in the Environmental Intelligence initiative is included in the closing section.

2 RAMONES CONCEPT

2.1 Radiation detection in the marine environment

Radioactivity exists in the marine environment as everywhere, but it is still significantly under-sampled, unmeasured, and understudied. In particular, radioactivity monitoring in the marine environment with the current state-of-the-art instrumentation is considered relatively limited on both short and long temporal scales, focusing mainly on studies near the ocean surface (thermocline) and using instrumentation and methods optimized for land and air studies, but rather incompatible with the harsh marine environment.

The massive ocean volume acts as a protective shield to the human population from radioactivity sources deep inside the water, of either natural or man-made origin. Oceans are very often connected to natural resources or intense phenomena probably correlated with natural radiation, such as earthquakes, but radioactivity in marine environments is widely ignored in terms of the induced environmental and possibly human health risks.

Natural radioactivity in the marine environment has been present since the Earth's formation, while artificially produced radionuclides have been introduced into the oceans since 1944. While the input of radionuclides into the atmosphere -and ultimately into oceans- was considerably reduced with the 1963 test-ban agreement between USA, USSR and UK, other direct sources exist, such as low-level liquid discharges from reprocessing plants, large-scale releases due to natural disasters (e.g., Fukushima Dai-Chi reactors in 2011 and smaller-scale radiological events (e.g., nuclear vessel wrecks or marine disposal of nuclear material). Radioactivity detection in the marine environment presents inherent difficulties originating from the very slow advances in sensor technology focusing on the marine environment, as well as the harsh conditions of the oceans, which pose severe limitations to long-term, continuous and agile radiation monitoring. Radiation length is significantly smaller in water than air, adding more limitations to efficient measurements performed inside aqueous environments, including lagoon, rivers, basins etc.

Solutions to open questions of radiation detection in marine environments can be provided by investing in a high-risk yet promising effort to develop methodologies based on existing state-of-the-art (SoA) interdisciplinary approaches and benefit from the latest advances in marine technology. RAMONES intends to fully confront such needs and invest on innovative solutions to tackle these open questions and problems.

2.2 Radiation Mapping and Imaging

Besides detection in the water column, various underwater sources of radioactivity exist, offering unique opportunities for research and applications. It is rather well known that active seismic faults are related to radioactive radon emanation through cracks and fractures of the crust, which typically becomes earlier than earthquake events. This correlation has been established in continental faults (see e.g. [11] and is expected to hold for underwater faults, as well. Hydrothermal vent field activity is also related to radon and other natural uranium decay daughters releases. Similarly, oil drilling sites can drive spreading of trapped naturally occurring radioactive materiasl (NORM) in the ocean crust creating potential radiation hotspots in deep-water locations [17].

It is clear from the above examples that having the means to efficiently map and image radiation fields can provide valuable information on phenomena, processes and events that may pose serious risks to human populations and marine ecosystems. Correlation of radiation with other environmental parameters will provide completely new tools and methods for understanding the hidden dynamics of the oceans. RAMONES will invest effort on providing efficient, *in situ* solutions of mapping and imaging radiation in the marine environment, being ambitious to define the new state of the art in such environments.

2.3 Instrument marinization

Developing or upgrading the instruments to perform in the marine environment poses grand challenges. Operation in deep waters demands resistance to high pressures, corrosive and abusive seawater forces, to offer accurate measurements. Standard techniques include optimization of housing material and thickness for withstanding the desired depth pressure. However, the instruments that will be developed in RAMONES have requirements that significantly increase the design challenges. The material density has a direct effect on the radioactivity detector's efficiency and resolution, and as such, detailed simulations are required to provide specifications for housing pressure tolerance, in combination with the measurement attenuation with different material and thicknesses.

Other housing challenges include: the αSpect sensor which will need to extract the particles from the water and bring them in contact with the sensor under vacuum, the optical-based detectors that are required to detect single photons, as well as window material and filters that need to be very carefully modeled and chosen.

In addition to housing materials, energy consumption is an important instrument marinization critical factor for battery operated autonomous systems. Low-power electronics and smart power management techniques will be developed for maximizing the operation endurance of the systems. As an example, the high-resolution GASPAR instrument will be developed and built around an HPGe crystal that in a laboratory environment needs to be cryocooled either with liquid nitrogen or an electromechanical heat abduction system. An innovation approach will be to explore seawater's high thermal absorsion together with electromechanical parts to assist cooling the sensor and reducing power requirements.

2.4 Mobility of instruments

One more RAMONES innovation is to spatially extend radioactivity measurements horizontally, but also in the water column. This is expected to be accomplished with the use of two autonomous underwater glider-type robotic platforms (AUGs). These vehicles, propelled mostly by exploiting variations in buoyancy, can operate for extended periods of time in the ocean, in striking contrast to classical, small-to-medium sized propelled robotic vehicles with reduced autonomy due to their energy hungry actuators and subsystems. Moreover, AUGs are peculiar in that their natural motions of sawtooth vertical profiles (glider "flying" at a given flight path angle), which allow them to sample to a great extent the water column while performing their path pattern. The AUGs will be equipped with small-size γ-detectors, processing intelligence and communication modems, which will allow capturing the evolution of radioactive phenomena along an extended survey area, including the water column.

2.5 Communication and synergy of instruments

Underwater Acoustic (UWA) communications and positioning belong to key components of the RAMONES system. The project foresees the use of an autonomous surface vehicle (ASV) as the master communication and main geo-localization node, providing the possibility for distribution of different data streams to other vehicles, benthic and shore stations.

A set of additional functionalities will be included in the standard UWA modems carried by the AUGs. Cooperative navigation of the AUGs aims to estimate the state of multiple submarine vehicles involved in a given mission by exploiting inter-vehicle communication links and the use of relative range and/or bearing measuring units among vehicles.

Continuous radioactivity monitoring will include the AI-based module providing detection of abnormal radioactivity levels, which will have an impact on the behavior of the glider by affecting the planning operations of the vehicle. Particularly, the event of abnormal radioactivity will trigger communication with the master communication node, passing relevant information for further processing. Similarly, events detected at the benthic lab will be evaluated by the decision-making mechanisms onboard to adjust the instrument array, direct the sensors to an area of interest, as well as trigger communication with the master node.

In general, collaborative analysis and data exchange between robotic assets through underwater acoustics and data-driven behavior of the underwater vehicles will be based on integration of the off-shelf acoustic modems (with further developments during the project) capable for operation in different networking scenarios. As an example, "negotiations" of the AUGs, for joining the mission (that represents a data-driven event), will require operative (on-line) data exchange, that will be solved by means of the underwater acoustic network, capable of finding the shortest (fastest) route for data exchange.

3 LIST OF INSTRUMENTS AND CURRENT STATUS

3.1 GASPAR

GASPAR stands for *Gamma Spectrometer for Marine Radioactivity Studies*. GASPAR is a radiation instrument aimed at performing high-resolution, *in-situ* γ spectrometry. The instrument will be developed and built around an electromechanically cooled HPGe crystal. This type of technology has very recently entered the commercial domain and is currently becoming available for nuclear physics experimental installations.

GASPAR will be mounted on a stationary benthic laboratory, which is currently designed to potentially carry additional sensors in various configurations. The benthic laboratory is currently being designed to operate on the seabed, featuring high-resolution γ-ray sensors and peripheral instrumentation for geochemical and oceanographic studies. To achieve the main goals, both γ−ray detection efficiency and good resolution are important.

The main design is based on optimizations of the underwater spectrometer via detailed Monte Carlo simulations in various realistic scenarios, where even small details of the sensors, housings, and environmental conditions are taken into account. Design is optimized using the state-of-the-art codes, Geant4 [1] and MCNP [5] used widely in large infrastructure, such as at the Large Hadron Collider (LHC) at CERN.

The GASPAR detector is currently under development.

3.2 γ-Sniffers

The benthic lab will be able to operate both independently and synergistically with the mobile spectrometers on the AUGs and the ASV (γ−Sniffers), offering novel capabilities for radiation monitoring, hotspot imaging, modeling and radiation risk assessment in near-real-time for the first time in the marine environment. We envision agility in measurements and fast response to "exotic" events, wide applicability via modularity and portability, detailed and reliable synthetic modeling of information from the full range of deployed sensors, as well as ease of scalability in deployment to study the important and fragile components of the marine environment.

The type of detectors that are planning to be used for γ-Sniffers are the compact high-resolution γ-ray CdZnTe solid state detectors. Simulations were performed initially for two point−calibrated sources (^{137}Cs, ^{152}Eu) placed 10 cm away from the detector's entrance window in room conditions by employing the Geant4 code. In fig 2, the simulated γ−ray spectrum of ^{137}Cs source is illustrated. Regarding the efficiency of the detector, the full−energy peak efficiency (FEPE) was calculated as a function of energy, using the following equation [9]:

$$\epsilon = R/(S \times P\gamma) \tag{1}$$

where R denotes the full−energy peak count rate (in counts per second), S is the source strength (activity) in disintegrations per second and P_γ corresponds to the probability (intensity) of emission of the gamma−ray studied.

The γ-Sniffers are currently under development and testing in the laboratory.

3.3 SUGI

The Submarine Gamma Imager (SUGI) will be a novel real-time underwater γ-radiation imager. The goal of SUGI is to detect, localize and measure radioactivity hotspots near the seabed. The SUGI will be mounted on the benthic laboratory offering complimentary measurements to GASPAR recording the distribution of submarine radioactive hotspots. SUGI design and realization will build of similar technology currently employed in nuclear reactor decommissioning and waste management handling in land or underground facilities. Currently, there is no similar solution for underwater γ

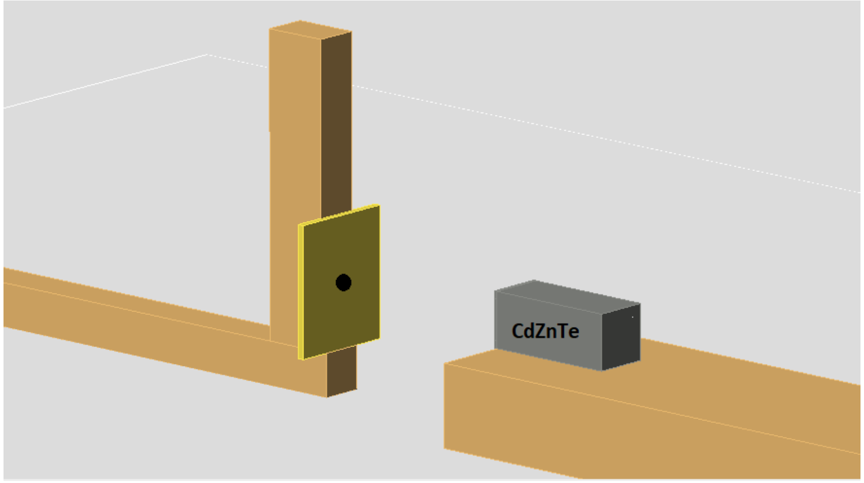

Fig. 1. Visualization of the geometry used as input in the simulations. A point–calibrated ^{137}Cs source (black dot in the center of the yellow square) was placed on a wooden support 10 cm away from the detector's front window (CdZnTe)

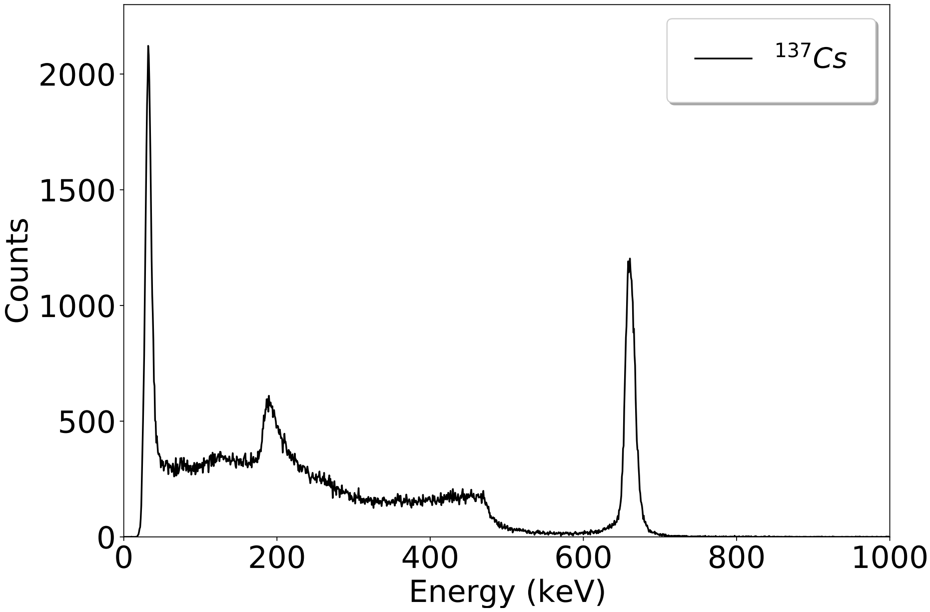

Fig. 2. A simulated spectrum of ^{137}Cs in the CdZnTe detector for the geometry in Fig. 1. The prominent photopeak on the right corresponds to the ^{137}Cs single γ–ray energy, 662 keV.

imaging, hence special attention will be given in detecting and measuring γ emission (particularly from Rn, Cs, K and others) at low-dosages. To this end, state-of-the-art solutions employing pixelated CZT crystals coupled with pixelated

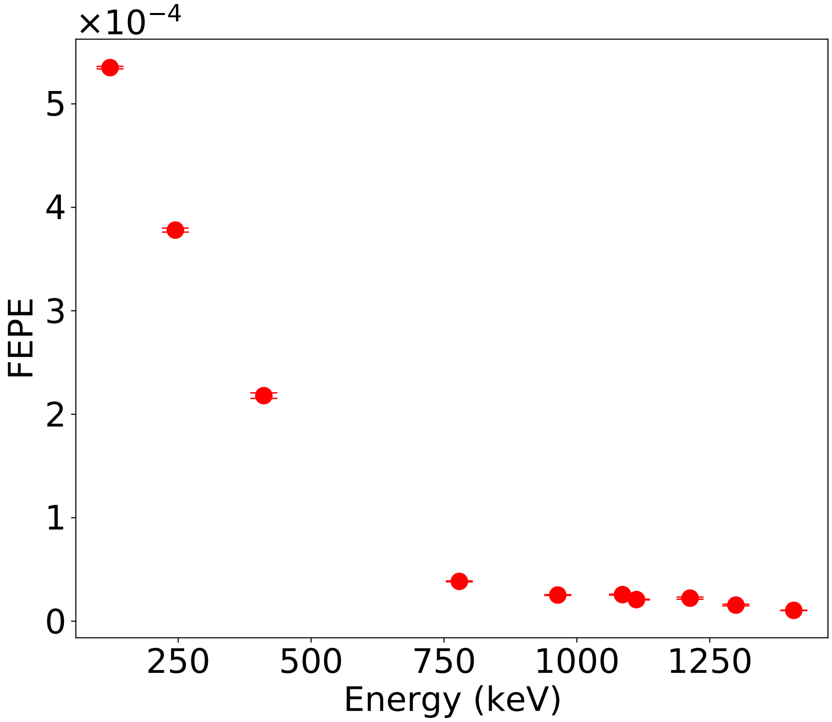

Fig. 3. FEPE results (Eqn. 1) deduced from the simulations of a point–like source ^{152}Eu placed at 10 cm distance from the detector's entrance window.

Silicon Photomultipliers (SiPM) or Single Photon Avalanche Diode (SPAD) arrays of sufficiently high spatial resolution (e.g. 11x11 or better), will be considered.

Directionality provisioning is foreseen to offer coverage of as much of the scene as possible. This will be achieved either via suitable mechanized (pan-tilt) mounting solutions or multi-module arrangements taking into account also different collimator options, such as pin-hole and Compton scatter collimation. The solution employed will be based on specific use-cases considered, taking into account aspects pertaining to overall cost of the instrument sub-system, as well as effective resolution, field-of-view provided by collimator options and scene coverage. Based on these considerations, suitable housing will also be designed and built, considering the trade-off between instrument marinization and operation conditions, with the help of simulation.

Regarding processing, SUGI will provide real-time data at short integration times for fast response. Depending on the directionality solution that is adopted, specialized processing to be performed on the benthic lab may be required to help optimize the orientation of SUGI. Simulations and extensive experimentation will be carried out to study the computational and bandwidth requirements of the instrument, to offer suitable scheduling of the measurement pipeline.

SUGI is currently under development and testing.

3.4 αSPECT

RAMONES will open a new path for *in situ* α-spectroscopy for marine applications. *In situ* environmental applications of α spectroscopy are inherently difficult due to the extremely short ranges of emitted α-rays in matter. There exist several solutions for air and land, however, to the best of our knowledge there is none for the marine environments. RAMONES will design, optimize, install and operate a new instrument (αSPECT) aboard the benthic lab. As no such other instruments exists, αSPECT aims at defining the SoA for the first time.

In principle, α-spectroscopy requires the use of ultra-high vacuum (UHV). However, αSPECT will primarily focus on radon detection, a naturally occurring [3] radioactive material and a noble gas. Using the latter property to our advantage, the α detection method which will be employed is electrostatic precipitation, a well–established method in various commercial radon detectors for daily use. Within this method, air samples are collected, and driven within a highly charged collection chamber, of either small volume or extremely high voltages [6], with a grounded detector. Following the α decay of airborne radon, the occurring charged [10] $^{218/214}$Po nuclei are electrostatically deposited onto the detector. Polonium nuclei are also α emitters, with half-lives in the order of minutes [8, 18]. The detector will detect subsequent α decays, with optimal resolution to distinguish between the polonium isotopes, and therefore, between the collected radon isotopes.

Even though this is a well-established technique, in order to achieve *in situ* α spectroscopy, the detector needs to be optimized for the extreme environment near the ocean floor. To achieve this goal, the following design is proposed: A cylindrical design, appropriate for the high pressures near the ocean floor, divided in six sub-chambers, each one with a dedicated silicon particle detector [4], as depicted in figure 4. The use of multiple silicon detectors, also seen in Ref. [2], leads to a number of advantages: Initially, it introduces the concept of modularity to the system. Variation of the number of sub-chambers allows to vary the detection volume. Therefore, the sampling volume may increase to much larger numbers, thus increasing αSPECT's lower detection limit [6]. At the same time, this increase is accompanied by smaller collection distances for the charged polonium nuclei, thus minimizing the probability of neutralization [10] and therefore detection losses of these nuclei. Consequently, the demand for the chamber voltage is lowered, thus minimizing the operational needs of the instrument.

As αSPECT is a custom prototype, it requires specialized parts. Some of them have already been procured, while others await final simulations to determine the optical specifications prior to acquiring.

3.5 CHERI

RAMONES will invest on the design, optimization, construction and deployment of a prototype underwater imager of Cherenkov radiation. The Cherenkov Imager (CHERI) is a novel imager for underwater Cherenkov radiation detection. The imager will adopt design principles and solutions proposed for SUGI. Directionality provision is also critical in this case due to the relatively low directionality of the phenomenon. The instrument will be equipped with a suitable optical filter, to maximize its sensitivity around the blue spectrum. A specially designed housing to detect Cherenkov radiation will also have to be offered, light-guiding Cherenkov radiation directly to SiPM modules. In deep ocean waters, ambient light is very low and flux from cosmic muons is reduced, offering an advantage for the envisioned operation of CHERI. Due to the unprecedented nature of CHERI, the calibration of the instrument will be challenging and novel procedures will need to be established. In addition, sensitivity limits in the present case are largely unknown, posing an additional challenge.

CHERI is currently under development.

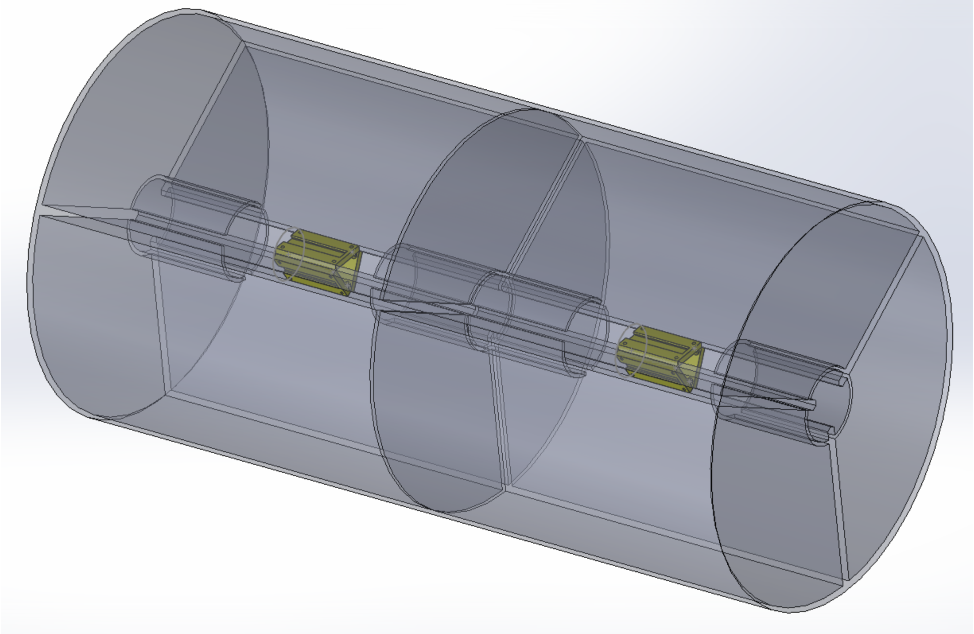

Fig. 4. Prototype design for αSPECT.

4 RAMONES IN ENVIRONMENTAL INTELLIGENCE

As part of the EU H2020 Call on Environmental Intelligence (EI) RAMONES has joined I-Seed [13], ReSET [15], SMARTLAGOON [14] and WATCHPLANT [16] in a clear-cut initiative to cross–examine potential synergies among all funded projects, to carry out common activities, and shape a set of tools and solutions to solve open problems related to critical resources and the environment. Through joint collaboration and by relying on state-of-the-art instrumentation, methods and IT resources the common initiative will provide the next generation tools in monitoring, analysis and management of important social and environmental processes towards improving quality of life and environmental sustainability, enhancing the well–being of local communities and strengthening the resilience against natural and man-made hazards.

The five projects have formed a strong core to pave the road for future endeavors along the EI goals. The projects have already produced jointly the first version of a Blueprint of EI. EI requires expertise all the way from social science through environmental science to electronic engineering, computer science, data science and networking. Bringing such a diverse range of academic and technical know-how together to develop effective, efficient and seamless EI focused on a range of different environmental contexts and issues is a challenge.

EI is not just about measurement, analysis and processing of data, but also about getting the right information to the right people at the right time in forms which support decision making and policy shaping. In this way, EI systems (EIS) are not dissimilar from decision support systems or policy support systems. The difference seems to be the greater attention to integration of a wide range of data sources and technologies in EIS, but also the use of machine learning techniques to mine such information for intelligence.

Hardware challenges include energy autonomy, environmental tolerance, processing power and ability to sense various environmental variables in harsh environmental conditions. Software challenges include the need for intelligent, adaptable processing to cope with the huge array of different data available and the constantly changing data landscape. Network challenges include both bringing together the relevant networks of decision-makers involved in complex environmental decisions, but also the challenges of computing networks for distributed sensors that are resilient and low-power. People, training and engagement challenges include managing the contentious nature of many environmental issues and issues of trust and legitimacy around data. Policy challenges include navigating the complex policy landscapes associated with environmental policy and management and bridging the toolset available in academia with those tools and processes routinely used in regulation, policy development and investment decision-making. This first iteration of the EI Blueprint explores these challenges from the perspective of the five FET projects after almost one year of work. The next three iterations in this Blueprint will take a closer look to producing the information, hardware, software, networks, people, training and engagement, as well as Policy Blueprints that are necessary for effective development and deployment of Environmental Intelligence in Europe and beyond.

5 CLOSING REMARKS

The present paper provides an overview of the progress the RAMONES project has made in its initial phase. The manuscript is focused almost exclusively on the development in sensors and related technology, while it additionally highlights some of the principal objectives and the cutting–edge innovation RAMONES aims to bring in for various cross-collaborating disciplines under a common umbrella: novel radiation instrumentation, next-generation marine robotics and engineering, new algorithms for adaptive planning and navigation of autonomous submersibles, advanced modeling for environmental sciences and geosciences, as well as new forecasting tools to shape future societal policies and increase the resilience of human communities and ecosystems.

RAMONES partners will invest significant effort to collaborate with other projects to define the new framework of Environmental Intelligence in Europe, by bringing along their extensive research experience, their advanced know–how, and their solid vision for high-quality research and development.

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