Radioactivity Monitoring in Ocean Ecosystems (RAMONES)

T.J. Mertzimekis
P. Nomikou
E. Petra
tmertzi@phys.uoa.gr
evinom@geol.uoa.gr
elenipetra4@gmail.com
National and Kapodistrian University of Athens
Athens, Greece

P. Batista
D. Cabecinhas
A. Pascoal
L. Sebastião
pbatista@isr.tecnico.ulisboa.pt
dcabecinhas@isr.tecnico.ulisboa.pt
antonio@@isr.tecnico.ulisboa.pt
l.sebastiao@@isr.tecnico.ulisboa.pt
Instituto Superior Técnico (IST-ID)
Lisbon, Portugal

J. Escartín
escartin@geologie.ens.fr
Ecole Normale Supérieure de Paris, PSL University
Paris, France

K. Kebkal
kebkal@evologics.de
EvolLogics GmbH
Berlin, Germany

K. Karantzalos
karank@central.ntua.gr
National Technical University of Athens
Athens, Greece

A. Mallios
amallios@ploatech.com
Ploa Technology Consultants S.L.
Girona, Spain

K. Nikolopoulos
kostas.nikolopoulos@durham.ac.uk
University of Durham
Durham, UK

L. Maigne
lydia.maigne@clermont.in2p3.fr
Université Clermont Auvergne
Clermont Ferrand, France

ABSTRACT

Natural radioactivity in the marine environment has been present since the Earth's formation, while artificial radionuclides were introduced into the oceans in 1944. More recent direct sources exist that feed the oceans, such as low–level liquid discharges from reprocessing plants, large–scale releases due to disasters (e.g. Fukushima hit by the tsunami in 2011), and smaller–scale radiological events. Exploration of submarine environments should consider the existence of radioactivity in terms of its short– and long–term impact on marine and coastal ecosystems, also in correlation to natural hazards, such as seismic activity over submarine faults or activity of hydrothermal vent fields near the seabed. Significantly undersampled in oceans, radioactivity poses real risks to marine ecosystems and human population, urging for detailed, data-driven modeling.

RAMONES is a new H2020-EU FET Proactive Project [2] aiming to offer new and efficient solutions for in *in situ*, continuous, long–term monitoring of radioactivity in harsh subsea environments. A new generation of submarine radiation sensing instruments, assisted by state–of–the–art (SoA) robotics and artificial intelligence (AI) will be developed towards understanding radiation related risks near and far from coastal areas, while providing data towards shaping new policies and guidelines for environmental sustainability, economic growth and human health, offering a framework for defining future environmental intelligence guidelines and practices.

The main ambition is to lay a radical new path to close the existing marine radioactivity under-sampling gap and foster new interdisciplinary research in threatened natural deep-sea ecosystems. RAMONES will invest a significant effort to provide tools for long-term, rapid deployments, propose new robotics and AI–driven supported methodologies, and offer scaled-up solutions to researchers, policy makers and communities. RAMONES will combine SoA equipment from various disciplines and advanced modeling in fine synergy, and design new and effective approaches for the marine environment to provide efficient response to natural and man-made hazards, shaping future policies for the global population.

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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**.

KEYWORDS

Radioactivity Monitoring, Environmental Intelligence, Ocean Environment

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1 INTRODUCTION

RAMONES is a new H2020–EU FET Proactive Project [2] aiming to offer new and efficient solutions for *in situ*, continuous, long–term monitoring of radioactivity in harsh subsea environments.

Even though radioactivity and radionuclides exist in the marine environment (as also on land and in the atmosphere), they are still significantly under–sampled, largely measured, and generally understudied. In particular, radioactivity monitoring in the marine environment with current instrumentation is relatively limited on both short and long–term periods, focusing on studies in the thermocline and using instrumentation and methods developed mainly for land and air studies [3]. The International Atomic Energy Agency (IAEA) has developed the Marine Radioactivity Information System (MARIS) [5] to be used globally by scientists and policy makers, yet the gap, comparing with land/air radioactivity measurements, remains enormous.

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. To this end, RAMONES offers a radical vision of science-enabled cutting-edge solutions in both instrumentation and robotic sensing platforms towards a step change in Radioactivity Monitoring in Ocean Ecosystems.

In particular, RAMONES is an extremely ambitious, high-risk project with the aim to prove that innovative combination and advancement of recent developments in sensory materials, low-power autonomous robotic systems, and process modeling theories, have the potential to overcome current limitations and open the window to high temporal and spatial resolution underwater radioactivity measurements, *in situ* and in near real time, forming a game changer in deep-water environmental monitoring.

There is a clear distinction between naturally occurring radioactive materials (NORM) and anthropogenic radioactivity. NORM refers mainly to isotopic chains originating from long–lived uranium and thorium isotopes posing a low, but long–term risk in ecosystems. Artificial radioactivity is related mainly to unstable isotopes produced by human activity, such as medical radioisotopes, or waste treatment from Nuclear Power Plants (NPP). Technological activities (e.g. mining) can further increase the concentration of NORM in the environment. Even though these Technologically Enhanced NORM (TENORM) pose significant public health risks, they are poorly monitored worldwide. Existing directives by international bodies, such as the EU Radiation Safety Commission and IAEA stress the importance and need for continuous monitoring to understand their environmental impact [1, 4].

Solutions to open questions can be provided by investing in the development of radically new methodologies based on existing state–of–the–art (SoA) interdisciplinary approaches and benefit from the latest advances in marine technology. RAMONES will design, develop and validate a new generation of radiation–sensing instruments, providing both high efficiency and fine resolution to perform spectroscopic studies in the marine environment. SoA sensors and methods will be developed and cross–combined to create a novel, currently non–existing, generation of low–power and fast integration–time underwater instruments for radiation measurements in extreme oceanic locations.

Deployed on SoA low–power, long–endurance glider–type autonomous underwater and surface vehicles, RAMONES will enable rapid deployment, with dense spatial and temporal surveys over large areas for extended periods of time. With near real–time and *in situ* measurements, RAMONES will provide real–time assessment of environmental risks, facilitating prompt response for risk mitigating (humans, environment). We envision to significantly progress beyond the state–of–the–art (BSoA) in measuring and imaging radioactivity in the deep ocean.

2 RAMONES OBJECTIVES

Exploration of submarine environments should comprehensively consider the existence of natural and artificial radioactivity in terms of its short– and long–term impact on marine and coastal ecosystems. Significantly under–sampled and understudied, radioactivity poses real risks to marine ecosystems and human population. In RAMONES, the goal is to offer new and efficient solutions for *in situ*, continuous, long–term monitoring of radioactivity in harsh underwater environments. We propose a new generation of submarine radiation–sensing instruments, assisted by SoA robotic and artificial intelligence (AI) solutions towards understanding radiation related risks near and far from coastal areas, while providing data for the international community towards shaping new policies and governance guidelines for environmental sustainability, economic growth and human health.

The main objective in RAMONES is *to close the current marine radioactivity under–sampling gap and foster new interdisciplinary research in ocean ecosystems.*

RAMONES will invest a significant effort to provide tools for long–term, rapid deployments, low cost per information byte, and propose new robotic, AI–driven and supported methodologies, being ambitious to eventually offer scaled–up solutions to researchers, policy makers and communities. All these can be achieved by combining SoA 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. Namely, we propose to:

- Design, develop and validate for the first time, a broad set of novel instruments for measuring radioactivity in seabed and water column. RAMONES will develop novel radiometry instruments specially designed as payload to a group of new submarine platforms and vehicles, closely collaborating and cross-assisting each other to achieve the proposal's main goals. The focus is on employing and integrating the new generation of detectors and sensors, offering radiation imaging capabilities near the ocean seabed. RAMONES will invest in developing and deploying high–resolution γ–ray spectrometers and offer for the first time 2D imaging of radioactivity distribution near the seabed.

- Design, develop and validate novel adaptation, self–deployment and self–awareness collaborative marine robotics capabilities for the efficient operation and sensing with the new marine radiometry instrumentation. RAMONES will study, implement and offer optimal operation scenarios for the developed sensors, enabling collaborative multi–agent robotic radioactivity monitoring and surveys of extended areas and volumes of the ocean waters. Through adaptive planning, AUG will sense the subsea environment, while an Autonomous Surface Vehicles (ASV) will be the master communication and main geolocalization node, performing also long–term radioactivity measurements at the air–sea interface. These SoA AUG and ASV will offer versatile and autonomous operation, showcasing self–awareness abilities to be developed and optimized for the specific operations and sites. Ultimately, they will be able to adapt their sampling behavior for flexible monitoring and fast response to online detected episodic events (e.g., elevated radioactivity levels in the water column).
- Design, develop and validate novel statistical, artificial intelligence and environmental modeling methodologies for processing and modeling marine radioactivity multi–modal data. Based on the collected data, RAMONES will: (i) develop cutting–edge recurrent neural networks coupled with online learning frameworks for efficient time series analysis and abnormal radioactivity level detection–monitoring together with deep learning frameworks for detecting radioactivity hotspots from multi-dimensional imaging datasets, as well as (ii) develop novel modeling solutions for critical tasks including radiation dose and health risks assessment, geohazards and radiation modeling, industrial waste and radiation modeling.
- Introduce novel monitoring and response channels to inform key socio–political stakeholders at regular intervals at medium (daily, weekly) to low (monthly to inter–annually) frequencies. Based on short–, medium– and long–term monitoring tools, RAMONES will forecast the chances of radon emanation over standard thresholds, while after consultation with IAEA and EU it will propose new risk indices and create policy recommendations, a disaster Response model, and a framework to support Policy Implementation Strategies.
- Increase local and citizen awareness and involvement based on diverse dissemination, communication and outreach activities, through scientific evidence and FAIR data principles. RAMONES is adopting several intense dissemination and communication strategies towards raising public awareness and attract citizen involvement through multiple identified channels and target groups.

3 CONCEPT AND METHODOLOGY

Radiation mapping in deep oceans is virtually non–existent. Existing 2D radiation maps in the marine environment focus on localized areas, such as offshore locations near Fukushima or surface monitoring of radiation circulation in ocean waters. The vast majority of these maps are reconstructed from activity measurements in sediment and water samples, at non–continuously monitored deep–water locations. Mapping over large seabed or coastal areas will have a significant impact on

(i) modeling seasonal variations of natural radioactivity;
(ii) understanding the physical and geochemical mechanisms driving release and diffusion of radon through the crust–water interface;
(iii) studying and modeling the non-linear dynamics existing in hydrothermal vent fields based on combination of NORM concentrations;
(iv) modeling and correlating natural gases released based on radiotracers mobility.

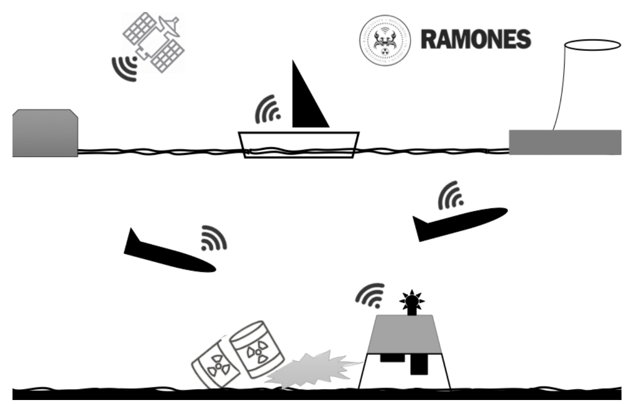

Figure 1: A simplified sketch of the RAMONES concept

RAMONES offers a comprehensive radioactivity monitoring solution for both deep–water and coastal zones covering the full spectrum of underwater environments. The set of instruments developed within the context of the project will be deployed by using a combination of suitable underwater vessels (see Fig 1). In brief, our goal is to provide a new scalable technology that can be widely adopted and deployed, to contribute to global marine environmental monitoring and initiating new efficient EU and International Policies.

3.1 RAMONES instruments

Two instrument classes will be developed, tested, optimized, validated and deployed:

(i) a static benthic laboratory equipped with a novel suite of high-resolution instruments
(ii) mobile and lightweight γ–spectrometers (γ–sniffers) specially designed as payload for autonomous vehicles.

3.1.1 Benthic gamma laboratory. A stationary benthic gamma laboratory will be combined with radiation instruments onboard AUG and an ASV to monitor large water volumes and offer fast–response capabilities based on AI–assisted decision making in various scenarios. Novel sensors will be incorporated into an efficient design that will be able to reach significant depths and record the radiation field due to radon or other natural and artificial radioisotopes, *in situ* and autonomously.

The benthic laboratory will be designed to operate on the seabed, featuring cutting-edge radioactivity sensors and peripheral instrumentation for geochemical and oceanographic studies. To achieve the main goals, both γ–ray detection efficiency and good resolution are important. We plan to develop a novel γ-radiation spectrometer built around a SoA electromechanically cooled High-Purity Germanium (HPGe) crystal to achieve this objective, defining the future path for high–resolution γ-spectroscopy in underwater studies. The new technology of cooling HPGe crystals has been recently introduced and is becoming the standard detection equipment in large detection arrays for fundamental nuclear physics studies [7] providing flexibility in detection geometry and ease of operation due to the more compact designs with lower maintenance cost and environmental footprint. This SoA technology overcomes the prohibiting need for liquid nitrogen supply to ensure HPGe detectors function and we plan to use the water's high thermal capacity to reduce further the needed cooling power. Automated cross-checked calibration, detection efficiency, and overall quality assurance of sensor operation will be implemented in the spectrometer, minimizing human supervision.

3.1.2 γ-Sniffers. The benthic lab will be able to operate both independently and synergistically with the mobile spectrometers on AUG and 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.

3.1.3 SUGI. The benthic gamma laboratory will additionally host a novel γ-imaging camera to scan for radioactivity hotspots in the water body and/or near the seabed, aiming to define the BSoA and open the pathway for underwater radiation imaging in the years to come. Data collected by the instruments will be combined, expanding the overall efficiency and range of applications. Such γ-cameras have been proven invaluable for Nuclear Power Plants decommissioning projects, radioactive waste management, and fast-and-easy detection of localized radiation hotspots. We envision a wide range of applications in the marine environments, e.g. locating weak hydrothermal vent activity by detecting emanating radon, imaging the illegal or accidental spread of radioactive substances in the oceans, estimate the diffusion of radiotracers from mining or oil–drilling activities, and many more. Such imaging capabilities are currently not available in marine applications.

3.1.4 αSPECT. RAMONES envisions to 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.

3.1.5 CHERI. Additionally, ionizing radiation emitted by radon or other radioactive isotopes from hydrothermal vents may be the source for the uncounted light [12] due to Cherenkov radiation effect in water. To test this hypothesis, RAMONES will develop a low–light imaging instrument, capable of single–photon counting, optimally tuned to the blue–green spectrum. If this effort becomes successful, it has the potential to revolutionize relative research, such as hydrothermal vents biology and tectonic activity prediction.

3.2 Novelty in Marine Robotics, Engineering and Applications

3.2.1 Novel self–deployment, self–awareness, adaptive robotic solutions. RAMONES sets forth the innovative concept of autonomous, adaptive radioactivity monitoring using data acquired by a static benthic gamma laboratory and radiation instruments on board three off-the-shelf glider-type autonomous vehicles. The objective is to monitor large water volumes and offer fast response capabilities based on online, event–driven decision–making processes in various scenarios. These vehicles, propelled mostly by environmental energy (buoyancy variance for AUG and wave or wind energy for ASV), can operate for extended periods of time in the ocean, in striking contrast to classical, medium–sized propelled robotic vehicles with reduced autonomy due to their energy hungry actuators and subsystems. Gliders are therefore key enabling tools given the requirements to acquire radiation-related measurements unattended for periods of days.

3.2.2 Cutting-edge AI-based analytics & modeling tools. RAMONES will design, develop and validate novel statistical, artificial intelligence and environmental modeling methodologies for processing and modeling marine radioactivity multi–modal data. New time series processing frameworks based on recurrent deep neural networks will be developed for near real–time radioactivity abnormal level detection. Moreover, hotspot detection based on deep convolutional neural networks (CNNs) will be developed to tackle the task of detection and identification. SoA modeling solution will also be exploited to tackle critical tasks, including radiation dose and health risks assessment, geohazards and radiation modeling, industrial waste and radiation modeling.

3.2.3 New risk assessment indices, policy making insights and citizen awareness. RAMONES will introduce novel communication and response channels to engage key socio–political stakeholders, as required by the rise of new technologies and capabilities that need to be considered in future environmental assessments and management plans. With monitoring, a strategy of information and data access will be developed at regular intervals from medium (daily, weekly) to low (monthly to annually) frequencies, in addition to near-real-time data transfer if required.

3.2.4 Offering fast response to emergencies. The RAMONES monitoring system will be readily transportable, offer long endurance and operate autonomously, thus increasing its strategic potential in ocean exploration. It will provide a unique fleet of instruments for immediate response to any emergencies related to abnormal presence of radioactivity in the marine environment (e.g., uncontrolled release of radioactivity from NPP).

3.2.5 Novel applications to geosciences. A critical component in RAMONES will be validation and testing the developed sensors and the corresponding sensor–carrying platforms at key sites, acquiring crucial data for obtaining well–constrained geological/geochemical context and identifying radioactive sources. These test sites will facilitate the *in situ* validation of the RAMONES technological developments to carry out the first steps in understanding radiogenic transfers from the Earth's crust to the fluid envelopes and through the seafloor. *In situ* physical and chemical water column data will also be acquired with off–the–shelf sensors, deployed simultaneously and combined with the RAMONES sensor suite.

3.2.6 Understanding environmental impact. RAMONES will target monitoring of radioactivity in the coastal zones potentially affected by NPP operation. Radioactivity monitoring has been seriously considered from the early days of industrial nuclear power. To this end buoys or near–shore permanent stations host dedicated radiation monitors. Except for partial studies after Fukushima's nuclear accident, continuous *in situ* underwater radioactivity monitoring has not been pursued despite significant long–term environmental impact. In addition to NPP, land mining activities often release high concentrations of radioisotopes to coastal environments (e.g. thorium in alumina mining, potassium in phosphate fertilizers industry, uranium mining etc.), that also escape monitoring.

4 RAMONES AND ENVIRONMENTAL INTELLIGENCE

The RAMONES project has been funded by the H2020-EU FET Proactive -– Boosting emerging technologies (H2020–FETPROACT–2018-2020) Framework, which is focused on particular challenges [6]. Among other challenges, RAMONES fully aligns with:

- new synergies between the different disciplines of environmental modeling
- advanced sensor research
- Artificial Intelligence which can lead to radically new approaches for creating and using dynamic models of the environment, including predictive modelling, scenario testing and real–time tracking

Furthermore, within the Call's framework, the ultimate goal is to build a systemic understanding of the socio-environmental inter–relationships, for instance to regulate or design policies and incentives for environmental sustainability, to track their effectiveness over time and to provide intelligible options for adjusting them. An additional vision of the Call is to invest on new synergies among the various funded projects [6], bringing together multi–sided approaches across different disciplines to forge a new generation of principles, which can be used to shape the future Environmental Intelligence policies for EU and the rest of the world.

RAMONES joins I-Seed [8], ReSET [10], SMARTLAGOON [9] and WATCHPLANT [11] 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 amd 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.

5 LAST REMARKS

The present paper provides an overview of the RAMONES project concepts and highlights the principal objectives and the cutting–edge innovation we aim 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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