SU-DRS04-2019-2020

Research and Innovation Action

eu - radion

European System for Improved Radiological Hazard Detection and Identification

Final Project Report

Authors: Łukasz Szklarski (Project Coordinator, ITTI), Patryk Maik (ITTI), Anna Wieczorek (ITTI)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883204

CONSORTIUM

Deliverable nature:	Report (R)
Dissemination level: (Confidentiality)	Public (PU)
Version:	2.0
Date:	28.02.2024
Keywords:	Project Report, progress, project summary, EU-RADION, CBRN, results

Executive summary

The following is the final project report of the EU-RADION project. This report summarizes the work performed within the span of the project. This is the third and last of the reports (first two being the Annual Reports) which were set to be delivered during the duration of the project.

The EU-RADION project emerged in response to the escalating threat of terrorist activities within the European Union (EU), notably the alarming increase in Chemical, Biological, Radiological, Nuclear, and explosives (CBRNe) threats. With a focus on enhancing the EU's preparedness and response capabilities, the project aimed to address critical capability gaps in rapid detection and identification of radiological and nuclear materials, as highlighted by significant initiatives and studies such as ENCIRCLE and IFAFRI.

The EU-RADION project was strategically designed to fulfill four High-Level Objectives (HLOs), aiming to enhance the capabilities of first responders, augment situational awareness, stimulate the European CBRNe market's innovativeness, and demonstrate the operational efficacy of the solution under relevant conditions.

Key technological advancements included the development of a comprehensive system for real-time detection and identification of RN materials, integrating advanced sensor technologies and sophisticated data processing capabilities. This system, supported by wireless RN sensors and data fusion algorithms, aimed to provide a networked solution enhancing situational awareness through interoperable components.

The project successfully achieved its predetermined milestones, marking significant progress across all Work Packages. These milestones ranged from system requirements specification, technical architecture development, prototype creation, to final system integration and validation, culminating in a demonstration under relevant conditions.

A consortium of partners, including academic institutions, research organizations, and industry leaders, brought diverse expertise to the project, facilitating its progress from conceptual design to a market-ready solution. This collaborative effort resulted in notable intellectual outputs, including peer-reviewed publications and conference presentations, underscoring the project's impact on the field of CBRNe security.

The project's culmination was marked by a comprehensive demonstration, validating the EU-RADION solution's effectiveness in enhancing the EU's CBRNe preparedness and response capabilities. This demonstration illustrated the project's trajectory from inception to conclusion, showcasing the developed technologies and methodologies' practical applicability and effectiveness.

The EU-RADION project stands as a testament to the EU's commitment to advancing its CBRNe security framework through innovative research and development, strategic partnerships, and a focused approach to addressing critical capability gaps. Its success promises to significantly contribute to the safety and security of the EU and its member states, aligning with the broader objective of enhancing situational awareness and response capabilities in the face of RN challenges.

Document Information

Project Number	H2020 - 883204	Acronym	EU-RADION
Full Title	European System for Improved Radiological Hazard Detection and Identification		
Project URL	www.eu-radion.eu		
EU Project Officer	Marc Carton		

Date of Delivery	Contractual	M42	Actual	M42

Authors (names and affiliations)	Łukasz Szklarski (ITTI), Patryk Maik (ITTI), Anna Wieczorek (ITTI)

Reviewers (names and affiliations)	Łukasz Szklarski (ITTI), Anna Wieczorek (ITTI), Aleksander Zbroszczyk (ITT), Patryk Maik (ITTI)

PROJECT

European Commission

Grant Agreement Number: 883204
Name: European System for Improved Radiological Hazard Detection and Identification
Acronym: EU-RADION
Duration: 36 months, starting on 01.09.2020
Budget: 3 490 626,25 EUR
Consortium: 8 partners (4 countries)
Response to call topic SU-DRS04-2019-2020

eu - radion

CONSORTIUM

ITTI, FOI, University of Warsaw, AIRSENSE, FFI Forsvarets forskningsinstitutt Norwegian Defence Research Establishment, tms

COORDINATOR

iTTi

ITTI Sp. z o.o.
Rubież 46, 61-612 Poznań, Poland
www.itti.com.pl
sekretariat@itti.com.pl

Łukasz Szklarski, PhD
Project Coordinator
Head of CBRN Department
lukasz.szklarski@itti.com.pl

Final demonstration video available under:

https://www.youtube.com/watch?v=o6N21eTfoVI

Table of Contents

List of figures

Abbreviations

AP	Access Point
API	Application Programming Interface
AS	AIRSENSE
CBRNe	Chemical, Biological, Radiological, Nuclear and explosives (hazards)
CLOR	Central Laboratory for Radiological Protection
Cs-137	Caesium-137
CsI(Tl)	Cesium Iodide
CZT	Cadium Zinc Telluride
D	Deliverable
DE	Dispersion Engine
EC	European Commission
EU	European Union
FFI	Forsvarets Forskninginstitutt
FOI	Totalförsvarets Forskningsinstitut
FWHM	Full Width Half Maximum
GM	Geiger-Müller
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GUI	Graphical User Interface
HLO	High-Level Objective
IFAFRI	International Forum to Advance First Responder Innovation
INS	Inertial Navigation System
KPI	Key Performance Indicator
KPP	Key Performance Parameters
M	Month
MPPC	Multi-Pixel Photon Counter
MR	Management risks
MS	Milestone
MQTT	MQ Telemetry Transport
NaI	Sodium iodide
NC	Network Controller
PCB	Printed Circuit Board
RDD	Radiological Dispersal Device
RN	Radiological and Nuclear
SA	Situational Awareness Engine
SIU	Sensor Integration Unit
SM	Social Media
SME	small and medium enterprises
SoS	System of Systems
SSFK	Sensor System Filter Kernel
S&T	Science and Technology
TCT	Tactical Command Tool
TCP/IP	Transmission Control Protocol/Internet Protocol
TE-SAT	EU Terrorism Situation and Trend Report
TMS	Technisch-mathematische Studiengesellschaft mit Beschrankter Haftung
TRL	Technology Readiness Level
UAV	Unmaned Air Vehicle
UGV	Unmanned Ground Vehicle
UI	User Interface
URS	User Requirements Specification
UW	University of Warsaw
WLAN	Wireless Local Area Network
WP	Work Package

1 Introduction

In the past few years, the European Union (EU) has faced a tangible escalation in the threat of terrorist activities, with a particularly alarming increase in the use of Chemical, Biological, Radiological, Nuclear, and explosives (CBRNe) by terrorist groups. The Europol's annual EU Terrorism Situation and Trend Report (TE-SAT) of 2018 [1] reflected a 45% surge in terrorist incidents, marking a significant deviation from previous downward trends. The potential for CBRNe threats, underscored by incidents such as the looting of 40 kg of low enriched uranium from Mosul University by ISIS, has propelled the EU to prioritize the enhancement of its preparedness and response capabilities.

Acknowledging the evolving threat landscape, the EU formulated the 2017 Action Plan [2] complementing the 2012 CBRNe Agenda. This strategy underlines the necessity for rapid and effective detection systems for CBRNe agents, as quick detection is a critical determinant of timely response and mitigation of hazard exposure. Despite these efforts, existing detection technologies exhibit notable deficiencies, particularly in terms of their standalone functionality and lack of network integration, emphasizing the need for multipurpose, networked sensor solutions equipped with advanced data processing capabilities.

The EU-RADION project arose from this critical need, informed by the technological gaps identified in the ENCIRCLE project [3] and the IFAFRI study [4], as well as directives from the EU CBRN Agenda. The project aims to bolster the capabilities of first responders in the face of RN challenges, enhancing situational awareness through a network system of interoperable components. The system will integrate wireless RN sensors across various platforms, supported by sophisticated computational and data fusion algorithms.

The EU-RADION project is committed to four High-Level Objectives (HLO):

1. *To address capability gaps for European first responders as indicated by the ENCIRCLE catalogue and IFAFRI study.*
2. *To augment situational awareness during both preparedness and response phases.*
3. *To stimulate innovativeness in the European CBRNe market and reinforce its competitiveness.*
4. *To demonstrate the operational efficacy of the EU-RADION solution to stakeholders under relevant conditions.*

To complement this comprehensive report and provide a deeper understanding of the project's outcomes, we warmly invite readers to view a short video showcasing the EU-RADION project's demonstration, available at the project's website: https://eu-radion.eu/final-demonstration/ The footage is also available publicly at the link: EU-RADION Final Demonstration movie.

We strongly suggest viewing the film prior to reading the report. It serves as an introductory overview, providing a dynamic understanding of our project's breadth and achievements, setting the stage for the in-depth details and analysis contained within the following pages. This invitation aims to enrich the reader's experience and comprehension of the EU-RADION project's significant contributions to enhancing the EU's CBRNe preparedness and response capabilities. This video highlights the project's most significant achievements in a visually engaging format, offering insights into the practical applications and impact of our work. Prior to delving into the report, viewing this video will furnish you with a vivid illustration of the innovative solutions and technologies developed within the EU-RADION project, thereby enriching your grasp of the material presented herein. This invitation aims to enhance your appreciation of the project's contributions to CBRNe security and preparedness, as demonstrated through our collaborative efforts and strategic partnerships.

The EU-RADION project is strategically divided into nine work packages (WPs), each tailored to fulfill the overarching objectives through systematic development, integration, and validation phases. The WPs cover a broad spectrum of tasks, from project management, user requirement gathering, and system architecture design, to the development of sensor integration units, sensor platforms, situational awareness tools, and extensive field testing. The final stages focus on system integration, verification, validation, and comprehensive dissemination, exploitation, and demonstration activities to ensure the project's results are effectively communicated and utilized.

The project involves a consortium of partners with diverse expertise, including academic institutions, research organizations, and industry leaders. These partnerships are instrumental in the work conducted across all WPs, contributing to the progression from conceptual design to the realization of a market-ready EU-RADION solution.

As a result of the collective efforts within the EU-RADION project, a range of contributions has emerged, including peer-reviewed publications, conference presentations, and active engagements in workshops and forums. These intellectual outputs, alongside the development of innovative technologies and methodologies, underscore the project's substantive impact on the field of CBRNe security and its alignment with the EU's strategic security framework.

This deliverable serves as a comprehensive report detailing the final outcomes of the EU-RADION project. It encapsulates the cumulative efforts and achievements of the consortium, illustrating the project's trajectory from inception through to its conclusion at the end of the second cycle. For the convenience of reviewers and stakeholders, this report provides a high-level summary of the development of the service and the accomplishments of this cycle, with references to preceding deliverables for additional details.

In summary, the EU-RADION project stands as a testament to the EU's commitment to elevating its CBRNe preparedness and response capabilities. Through innovative research and development, strategic partnerships, and a steadfast focus on the objectives outlined, the project promises to make a significant contribution to the safety and security of the EU and its member states.

1.1 Document scope

The deliverable is composed of the following sections:

Section 2: **Research Methodology Overview** - This section outlines the research methodology utilized in the project.
Section 3: **Project Overview** - This section provides a summary of the activities and achievements across each Work Package throughout the duration of the project.
Section 4: **Project Risks Summary** - The EU-RADION project meticulously managed risks by distinguishing between those anticipated at the proposal stage and unforeseen risks that surfaced during execution. This section outlines the identified risks and the mitigation strategies employed to navigate these challenges effectively.
Section 5: **Lessons Learned and Recommendations** - This section highlights key insights gained from the project and outlines considerations for future research on similar topics.
Section 6: **Project Conclusions** - This section details the primary outcomes and findings of the project.

2 Project methodology

The EU-RADION project concept is centred on developing a comprehensive system for the real-time detection and identification of radiological and nuclear materials, utilizing a blend of advanced software and hardware. This system integrates sensor integration units equipped with Geiger counters, Cadmium Zinc Telluride detectors, and gas sensors, deployed as both stationary and mobile units. These units are designed for swift identification of radioactive substances by matching detected spectra with a predefined nuclide library. The methodology emphasizes mobility, facilitated by wireless communication and non-proprietary, easily replaceable power sources, ensuring operational flexibility. A key feature is the system's ability to generate real-time threat maps and hazard source estimations through a dispersion engine, enhancing situational awareness for emergency response teams.

The EU-RADION project adopts a user-centric and scenario-driven methodology, recognizing the complexities of developing a novel RN detection and identification system. It emphasizes involving stakeholders and end-users from the outset to align the system's development with their needs and expectations. Through workshops, continuous feedback, and rigorous testing in both lab and field settings, the project ensures that the final system prototype is both reliable and user-friendly, tailored to real-world scenarios and user requirements. This approach underlines the project's commitment to practical applicability and effectiveness in RN hazard management.

The methodology used to fulfil the realization of the project, encompassed the following aspects:

1. User-Centric and Scenario-Driven Approach: The methodology begins with acknowledging the complexity of developing an RN detection and identification system tailored to end-user needs. Initial stages involve workshops with stakeholders to gather requirements, expectations, and feedback, particularly focusing on the system's practical deployment scenarios.

2. Iterative Design and Development Process: The project employs an iterative approach to system design and development, incorporating feedback from end-users and stakeholders at each stage. This process ensures that the system architecture, developed under the leadership of ITTI, adheres to the requirements translated from end-user needs.
3. Sensor Integration and Platform Adaptation: The project details the development of Sensor Integration Units (SIUs) equipped with diverse sensors for RN material detection. These units are designed for adaptability across different platforms, including stationary, handheld, and unmanned platforms, each undergoing iterative development to meet operational requirements.
4. Software Development and Situational Awareness Tools: The development of EU-RADION's software components, including the Tactical Command tool, is emphasized. These tools are designed to enhance situational awareness by integrating and analyzing data from the SIUs, with significant input from end-users to ensure usability.
5. Integration, Verification, and Validation: The chapter would detail the integration of hardware and software components into a cohesive system, followed by thorough testing and validation in laboratory settings and real-life conditions, culminating in a final demonstration in a challenging environment such as the Runehamar tunnel in Norway.
6. Stakeholder Engagement and Feedback Incorporation: Throughout the methodology, continuous engagement with stakeholders and incorporation of their feedback is highlighted as a critical element, ensuring the system's relevance and effectiveness in real-world RN detection and response scenarios.

This structured approach not only outlines the technical aspects of the project but also emphasizes the importance of stakeholder involvement, iterative development, and real-world applicability, ensuring the final system meets the operational needs and expectations of end-users in the RN domain.

3 Project Summary

3.1 Milestones

During the initial phase of the project, the consortium outlined a series of benchmarks to monitor advancements. The following table summarizes these predetermined milestones established by the project partners.

Milestone number	Milestone name	Related work package(s)	Estimated date	Means of verification
MS1	Requirements for the system	WP2	M8	Use-cases adapted, user requirements collected and key performance parameters defined.
MS2	Technical Requirements and the first version of the architecture	WP3	M12	Technical requirements for the components are specified and first version of the architecture is released.
MS3	Interfaces and data model	WP3	M18	A second version of the architecture is delivered. Interfaces and data model are defined and final.

MS4	A prototype of the EU-RADION system	WP3-8	M21	The first, prototype version of the system is provided. Measurements can be acquired from sensors by the system.
MS5	Core functionalities implemented	WP3-8	M27	The core functionalities of the system are implemented (semi-final versions) and successfully integrated.
MS6	Final version of the system	WP3-8	M33	The system is successfully integrated, validated and is ready for the demonstration.
MS7	Final Demonstration	WP9	M34	The system is successfully demonstrated.

Table 1 Milestones of the EU-RADION project

Throughout the project's duration, every milestone outlined at the outset has been successfully achieved, serving as crucial indicators for tracking the progress and effectiveness of the research and development activities undertaken by the EU-RADION consortium. The subsequent sections will provide a concise summary of the advancements made in each work package of the EU-RADION project.

3.2 WP1 Project Management

Led by ITTI, Work Package 1 (WP1) - Project Management was dedicated to ensuring the efficient management and coordination of the EU-RADION project from inception to completion. This encompassed various tasks aimed at maintaining communication, managing administrative and financial aspects, mitigating risks, and ensuring compliance with ethical standards. It also included communication within the Consortium and communication between the Consortium and the European Commission. In the EU-RADION project, a comprehensive management structure has been established to ensure the effective execution and oversight of the project's objectives, in line with the stipulations set forth in the Grant Agreement (GA). Dr. Łukasz Szklarski has been appointed as the project coordinator.

The WP1 covered the following Tasks:

- Task 1.1: Project Coordination and Administrative Management involved ITTI overseeing project management, including administrative and contractual relationships with partners and the European Commission. The Project Coordinator verified work against accepted schedules, collected progress reports and deliverables, managed funding distribution, and ensured compliance with EC standards. All project partners were involved in reporting and monitoring.
- Task 1.2: Technical Management supported the Project Coordinator in overseeing technical aspects, ensuring proper development, quality, and consistency of scientific and technical work packages. The Technical Manager verified technical objectives' achievement, updated the Project Coordinator on task progress, and proposed modifications if necessary.
- Task 1.3: Risk Management entailed continuous monitoring and management of potential project risks, maintaining a risk register, and proposing solutions to minimize their impact.
- Task 1.4: Ethics Management focused on ensuring project compliance with ethical requirements and addressing dual-use items produced within the project. The coordinator obtained necessary export licenses for hardware exchange between EU members and Norway.

Deliverables produced by the WP1 included:

- Project Handbook (D1.1), detailing project management and administrative procedures [5],
- Project Website (D1.2), providing up-to-date project information [6],

- Annual Reports (D1.3, D1.4) summarizing yearly work [7] [8],
- Final Project Report (D1.5), offering a comprehensive overview of the entire project.

3.2.1 Project Meetings and Progress Overview

The EU-RADION project progressed through a series of meetings and status updates, facilitating collaboration and ensuring project milestones were met.

Consortium Meetings:

- 10-11.09.2020 – Kick off EU-RADION, Warsaw, Poland: The inaugural consortium meeting aimed to introduce the project's ambition and foster collaboration. The plan for Work Package 1 (WP1) was outlined, emphasizing iterative technical work.
- 26.04.2021 – Consortium Meeting Online: Addressing the project's progress and challenges, this meeting highlighted complications due to the supply chain crisis and emphasized the need to enhance social media (SM) activity.
- 11th-14th October 2022 - The consortium convened from 11th to 14th October 2022 to address pivotal aspects of the project. Discussions centered on several critical topics, including the necessity of a project extension prompted by the ongoing pandemic. Additionally, plans were made for conducting laboratory tests in Warsaw, showcasing progress in Work Package 6 (WP6), and exploring alternative options for the demonstration due to construction work scheduled in the VEAS tunnel. These deliberations were crucial for ensuring the project's continuity and adapting to unforeseen challenges, thereby maintaining momentum towards achieving its objectives.
- The final consortium meeting held in Stockholm, Sweden, from 9th to 11th October 2023 served as a pivotal event for summarizing the overall status of the EU-RADION project. Specifically, discussions focused on assessing the progress of Work Packages 1, 8, and 9. Additionally, comprehensive planning for the final tests and demonstration was undertaken during this session, marking a crucial milestone in the project's conclusion.

Status Update Teleconferences:

- EU-RADION Status Update Telco #1 (20.11.2020): Discussion on WP2 progress, Stakeholder workshop plans, and the switch from UAVs to UGVs.
- EU-RADION Status Update Telco #2 (21.12.2020): Review of submitted deliverables including the Handbook, status updates, and potential additions to the Stakeholder Group.
- EU-RADION Status Update Telco #3 (05.02.2021): Update on deliverable status (e.g., communication plan readiness), partners' progress, and plans for the Stakeholder Workshop.
- EU-RADION Status Update Telco #4 (29.03.2021): Discussion on deliverable and financial report updates, with plans for the Consortium meeting.
- EU-RADION Status Update Telco #5 (20.07.2021): Deliberation on upcoming deliverables, progress in WP4, and emphasizing proactive social media usage.
- EU-RADION Status Update Telco #6 (02.02.2022): Focus on submitted and upcoming deliverables, closing of the first reporting period, and discussion on the demonstration tunnel.
- EU-RADION Status Update Telco #7 (11.04.2022): Key updates on initial outdoor UGV tests, SIU testing, and integration.
- EU-RADION Status Update Telco #8 (12.07.2022): Discussion on swarm controller integration, algorithm and sensor improvements, and laboratory test progress.
- EU-RADION Status Update Telco #9 (26.01.2023): Updates on SIU integration, Navigation unit development, sensor obstacles, and pending project extension decision.

- EU-RADION Status Update Telco #10 (29.06.2023): Discussion on ITTI's participation in the ENRICH event and final Demonstration plans.

Technical Meetings:

- EU-RADION Technical Meeting #1 was held online on 18-19.11.2021, focusing on summarizing discussions on various topics including the SIU, DE-TCT interface, WP6 Kick-off, and the status of architecture and sensor platforms.
- EU-RADION Technical Meeting #2, conducted online on 6-7.12.2021, involved discussions among partners on the Database, Measurements process, test tunnel, interfaces, and the UGVs.

Key Events:

1. 11-12 February 2021 – EU-RADION Stakeholder Group Workshop: Stakeholders were briefed on project ambitions, achievements, and upcoming plans.

These meetings and updates provided a platform for effective communication, ensuring alignment with project objectives and addressing challenges encountered throughout the EU-RADION project lifecycle.

3.2.2 Project Amendment

In August 2023, the Amendment Letter was sent to the European Commission. The decision to apply for a 6-month project extension was made unanimously by the EU-RADION consortium in response to challenges exacerbated by the COVID-19 pandemic. The global disruption in the electronic market, stemming from the pandemic, led to an acute shortage of electronic components, significantly impeding the production of hardware prototypes crucial for project milestones. These prototypes included the Adaptable Navigation Unit, Sensor Integration Unit, and Swarm of Unmanned Ground Vehicles. Despite early identification and discussion of this risk during the first periodic review in May 2022, the shortage persisted, posing a formidable obstacle to project progress. Mitigation measures proved insufficient, necessitating the extension to mitigate the adverse impact on project timelines. This letter serves to provide further elucidation and justification for the encountered delays and their anticipated impact on the project.

Consequently, the project duration was extended by 6 months to deliver the full scope of the project with very good quality.

3.3 WP2 Operational Needs and Requirements

WP2 User Requirements & Scenarios (WP Leader: CLOR) was led under the coordination of end users and focused on specifying user requirements for the system. Its goal was to fulfil the High-Level Objective 1 (HLO 1):

To cover selected capability gaps of European first responders and CBRNe practitioners indicated in ENCIRCLE catalogue and IFAFRI study by development of relevant technologies.

The resulting effect of work within WP2 constitutes a set of user requirements, adapted scenarios and key performance parameters (defined by Science and Technology Objective 1 and resulting in fulfilling KPI 13, being of qualitative nature: “The system reflects multinational interdisciplinary needs of stakeholders and end users”).

During the initial phase, a set of adapted scenarios was produced with end-user and stakeholder engagement, with reference to other projects. Subsequently, user requirements were established based on the scenarios and stakeholder workshop. The task also formulated key performance parameters, which were used during the system design, assessment, and validation. The outcome of this work package served as a direct input to WP3.

There were three Tasks associated with the WP2:

2. Task 2.1 involved adapting existing scenarios for the EU-RADION project, focusing on current challenges and end-user needs. The consortium initially defined scenarios for potential RN incidents and refined them during a Stakeholder Workshop with end-users and stakeholders.
3. In Task 2.2, the team gathered detailed end-user requirements for the EU-RADION system and its components. This task was facilitated through a Stakeholder Workshop, where end-users reviewed the technical concept and provided feedback on the proposed functionalities.
4. For Task 2.3, based on the scenarios and user requirements collected earlier, key performance parameters (KPPs) were established. These KPPs, initially formulated by the consortium, were refined through tests and stakeholder engagement to ensure they met the user requirements and performance goals of the EU-RADION system.

Work Package 2 delivered the following reports:

- Suite of Adapted Scenarios (D2.1) presented a report summarizing the outcomes of Task 2.1, detailing the adapted scenarios for the EU-RADION project [9].
- User Requirements Report (D2.2) included a compilation of the user requirements gathered during the Stakeholder Workshop, ensuring they were prioritized, consistent, traceable, and unbiased. It also reviewed current RN detection technologies [10].
- Key Performance Parameters List (D2.3) comprised the established key performance parameters, which were set to guide the verification and validation processes throughout the project [11].

3.3.1 Background and Context

The EU faces growing terrorism threats, with a significant increase in terrorist activities as reported by Europol. The concern extends to CBRNe terrorism, evidenced by terrorist groups acquiring chemical and radiological materials. In response, the EU's 2017 Action Plan [2] aims to enhance CBRNe preparedness, highlighting the need for advanced detection systems. Current RN detection technologies show limitations, underscoring the need for integrated sensor networks and software solutions. The International Forum to Advance First Responder Innovation (IFAFRI) [4] identifies critical gaps in first responder capabilities, further emphasizing the necessity for improved technological solutions like those proposed in the EU-RADION project.

3.3.2 Concept and Approach

The EU-RADION project aims to develop a comprehensive system for detecting and identifying radiological and nuclear materials, utilizing a blend of innovative software and hardware. This includes a network of sensor units, both stationary and mobile, equipped with multiple sensors for accurate hazard assessment. These units, powered by easily replaceable sources, enable real-time monitoring and threat mapping, enhancing response actions in the RN domain. The system emphasizes mobility, real-time data processing, and the creation of a joint operational picture for effective command center coordination (Figure 1).

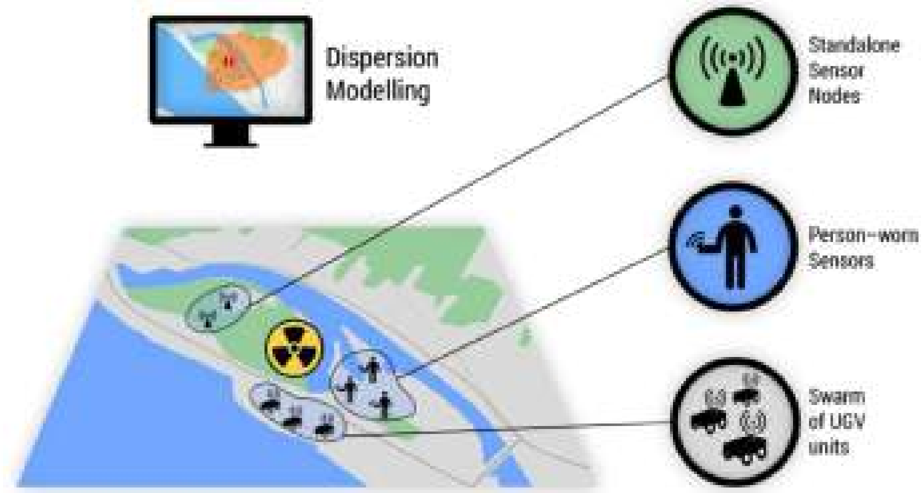

Figure 1 The operational concept behind the EU-RADION project

3.3.3 Collection of User Requirements

In the EU-RADION project, user requirements and scenario adaptation were central to the design and development process, ensuring the system's relevance and effectiveness. Work Package 2, led by CLOR, engaged stakeholders in workshops to gather feedback, which was crucial for refining scenarios and aligning the system with real-world needs. Technical partners validated these requirements to confirm feasibility, culminating in reports that outlined adapted scenarios and user requirements. This foundational work informed the iterative design process in Work Package 3, focusing on creating an adaptable and interoperable RN detection system, guided by a system-of-systems approach.

3.3.4 Suite of scenarios

During the online meeting held on November 20, 2020, the EU-RADION participants reviewed various scenarios aimed at demonstrating the capabilities of the system. It was collectively decided to focus on two main types of scenarios: outdoor and indoor. This division allowed for a comprehensive exhibition of the system's functionalities. Specifically, scenarios 3 (outdoor) and 4 (indoor), proposed by CLOR, were chosen for this purpose.

- **Scenario No. 3: Explosion and Fire at an Illegal Depot**

This outdoor scenario aimed to showcase the system's ability to calculate the dispersion of radiological/nuclear (RN) material and identify potential sources, along with the detection of multiple radionuclides present at the scene. The scenario simulated illicit or terrorist activities involving the illegal possession of nuclear or radioactive materials, combined with explosives. An explosion occurs during the construction of a Radiological Dispersal Device (RDD), causing a fire and partial collapse of the depot. The scenario included tasks such as delineating safety perimeters, searching for radioactive sources, performing radiological mapping, and preparing prognoses on the radiological impact.

- **Scenario No. 4: Traffic Accident Inside a Tunnel**

This indoor scenario aimed to demonstrate the system's telemetry features (in the absence of GPS signal) and its capabilities in source search and radiological mapping. It simulated a traffic accident inside a tunnel involving a truck carrying a strong Cs-137 radioactive source and a cistern with kerosene, leading to a subsequent fire, explosion, and release of radioactive material. Tasks included determining safety perimeters, performing radiological mapping, searching for radioactive sources/debris, and preparing prognoses on the radiological impact, considering the specific conditions of the tunnel environment.

Both scenarios could be adjusted to demonstrate the system's capabilities both indoors and outdoors, showcasing its versatility and adaptability in different operational environments. For the Final Demonstration of the project, Scenario No. 4 was chosen and carried out in the Runehamar Test Tunnel in Norway.

3.3.5 Prioritization and Categorization of the User Requirements

The User Requirements Specification (URS) outlines the essential operations and activities that the EU-RADION system must perform to meet the needs of stakeholders effectively.

- **System Description:**

The EU-RADION system aims to provide comprehensive detection and identification of radiological and nuclear (RN) materials, facilitating emergency and post-emergency response activities. It is designed to be utilized by first responder teams in various scenarios, including simple and complex emergencies involving nuclear and radiological threats. The system offers flexible deployment options, allowing sensors to be mounted on unmanned ground vehicles (UGVs), worn by emergency personnel, or stationed at fixed posts. To manage deployed sensor groups effectively, positioning equipment is integrated with the RN detectors. Additionally, certain sensor integration units are equipped with optical systems (cameras) for imaging and recording purposes to assess the situation visually.

- **Functionality:**

The primary function of the EU-RADION system is to collect data from mobile and stationary sensor groups and transmit it to the Center of Operations. This data is aggregated and presented through a Tactical Command Tool, which generates a Joint Operational Picture (Situation Display). This display provides a clear overview of the situation, allowing for efficient management and redeployment of hardware and personnel, protection against dangerous exposure, and support for decision-making. Moreover, the Tactical Command Tool includes a module for running radiological dispersion prognoses, aiding in scenarios involving the release of radioactive substances into the atmosphere.

- **User Requirements Attributes:**

The user requirements for the EU-RADION system adhere to key attributes outlined by ISO IEC 29148:2018 [12]. These requirements are necessary, implementation-free, unambiguous, consistent, complete, singular, feasible, traceable, and verifiable. Each requirement defines an essential capability, avoids unnecessary constraints on architectural design, is stated clearly, and is free of conflicts with other requirements. Additionally, all requirements are technically achievable, traceable to specific stakeholder statements, and verifiable to ensure system satisfaction.

The user requirements for the EU-RADION system serve as a fundamental guide for system development, ensuring that it meets the needs of stakeholders effectively and efficiently. By adhering to the specified attributes, the system will be capable, adaptable, and reliable, fulfilling its intended purpose in emergency response scenarios involving radiological and nuclear threats.

The User Requirements for the EU-RADION project encompasses several critical aspects: detecting radioactivity and hydrogen, dosimetry of ionizing radiation, radionuclide identification, system component positioning, and unmanned ground vehicle (UGV) platform specifications including power sources, data collection, and control. Additionally, it covers UGV swarm functionality, estimation of deposition and source characteristics, and the development of a situational display through a Tactical Command Tool for enhanced situational awareness, including user interface, alarming systems, technical status updates, system management, data export, external data access, and multi-user support. The said set of User Requirements was described in detail in the D2.2 – User Requirements.

3.4 WP3 System Architecture

Developing a suitable system architecture was a pivotal goal of Work Package 3 (WP3) in the EU-RADION project, aimed at achieving specific High-Level Objectives (HLOs). These objectives were:

- *HLO1, to address capability gaps for European first responders and CBRNe practitioners as identified in the ENCIRCLE catalogue and IFAFRI study through the development of relevant technologies, and*
- *HLO3, to enhance the innovativeness and competitiveness of the European CBRNe market.*

The strategic planning of the system's architecture, which follows a system-of-systems (SoS) approach led by ITTI, was crucial for fulfilling these goals, ensuring the project's overarching aims were met effectively.

The activities within Work Package 3 (WP3) of the EU-RADION project are thoroughly documented through a series of reports:

- D3.1: Technical Requirements Specification report, detailing the technical requirements set for the system [13].
- D3.2: Concept of Operation report, providing an in-depth description of the operation's concept [14].
- D3.3: The first of three iterations of the EU-RADION Architecture Report, offering an overview of the system's architecture necessary for initial development stages [15].
- D3.4: The second iteration of the architecture report, presenting detailed component and interface descriptions, informed by the prototyping phase and initial technical validations [16].
- D3.5: The final architecture report iteration, incorporating minor adjustments from further validations and measurements [17].

These reports collectively encapsulate the structured progression of WP3 towards achieving the architectural foundation of the EU-RADION system.

The EU-RADION project adopts an iterative approach to its design and development process, particularly within the framework of Work Package 3, led by ITTI, focusing on System Architecture. The initial step in system design involves translating user requirements into technical specifications, guided by the principle of a system-of-systems (SoS) approach.

The SoS approach entails the creation of task-specific, independent components, each offering distinct services or functionalities to the overall system through dedicated APIs. These components are treated as black boxes during system integration, facilitating scalability and interoperability. By adhering to this methodology, the project aims to avoid monolithic, cumbersome software components, allowing for parallel development of functionalities and easier adaptability for integration with external systems.

At a high-level overview, the system can be delineated into two major parts: the network layer and the situational awareness layer.

The network layer primarily consists of hardware components such as sensor platforms (including UGVs, stationary, and mobile units), sensors (SIU), and a singular software application known as the Network Controller, which acts as the central gateway to higher-level components.

On the other hand, the situational awareness layer of the EU-RADION system encompasses several processing components alongside the Tactical Command Tool (TCT). These processing components, namely the Dispersion Engine and Swarm Controller, contribute essential functionalities to the system, relying on data received from other components for their operation (Figure 2).

The provided diagram offers a preliminary representation of the overarching system architecture.

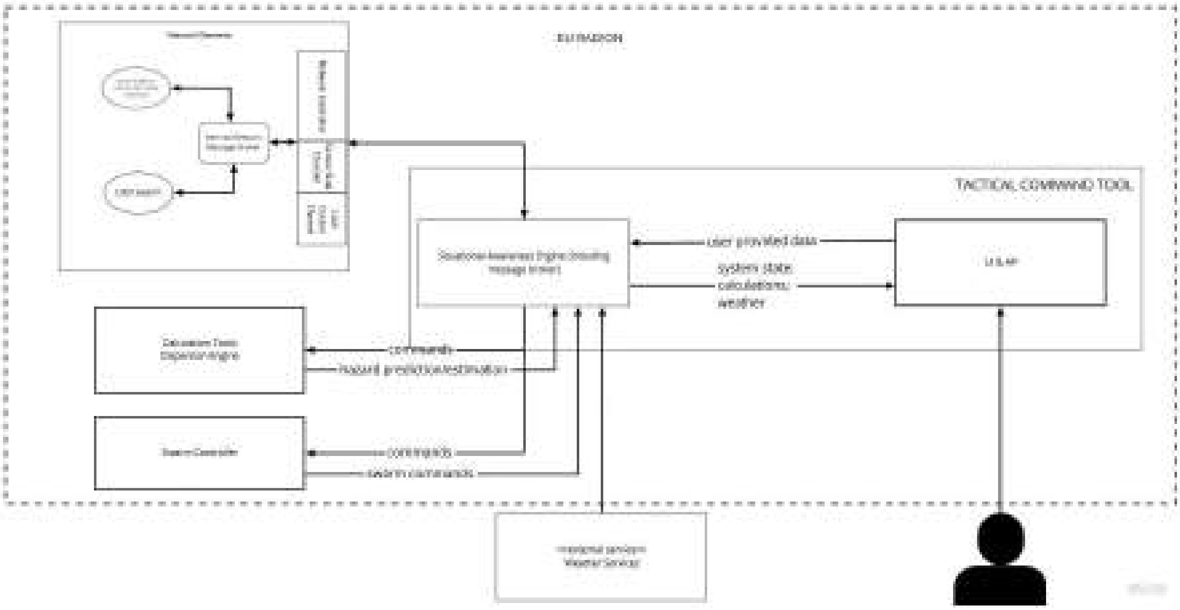

Figure 2 The overview of the EU-RADION system architecture

3.4.1 Network Layer

The Network Layer of the EU-RADION system architecture encompasses several key components aimed at facilitating seamless communication and data exchange.

At the forefront are the Sensor Platforms, including UGVs (Unmanned Ground Vehicle), Stationary, and Mobile units, designed to interface with Sensor Integration Unit (SIU) and establish data links with the Network Controller (NC). These platforms, identified as Assets within the network, are equipped with TCP/IP communication links and configuration software, ensuring efficient data transmission. The UGVs, feature SIU sensors and autonomous control capabilities, enabling navigation, obstacle avoidance, and communication with other units and the Network Controller. The Stationary Sensor Platform incorporates the SIU tailored for stationary deployment, while the Mobile Sensor Platform integrates a compact, ruggedized housing for handheld or person-worn operation. The SIU forms the backbone of the Network Layer, comprising essential components such as the RN Sensor Unit, Gas Sensor Unit, and Adaptable Navigation Unit. The SIU facilitates data collection, pre-processing, and transmission, ensuring comprehensive situational awareness. Additionally, the Network Controller acts as a middleware, facilitating communication between the network and situational awareness layers. Through MQTT channels and Kafka topics, the NC orchestrates communication among network elements and integrates a set of services, including Configuration, Status Check, and Identification Services, designed to enhance system functionality and interoperability.

3.4.2 Situational Awareness Layer

The Situational Awareness Layer of the EU-RADION system architecture comprises several crucial components designed to enhance operational understanding and decision-making capabilities. Firstly, the Swarm Controller assumes a dual role within the system. Primarily, it facilitates manual control of UGVs through an operator panel, ensuring redundant communication links for safety. Additionally, the Swarm Controller employs control algorithms to autonomously guide UGVs, generating mission plans based on input from the Dispersion Engine and Network Controller. It also features a simulator for algorithm development and verification purposes.

Secondly, the Dispersion Engine plays a pivotal role in hazard assessment and prediction. Utilizing sensor data and weather information, it calculates estimates for source location and strength, alongside deposition fields and air concentration levels. These calculations inform decision-making processes and are relayed to the Tactical Command

Tool (TCT) for user visualization and interaction. The TCT acts as the primary user interface, providing real-time status updates on network and sensor data, while facilitating limited control functionalities and interactions with the EU-RADION network.

Supporting the TCT, the Situational Awareness Engine (SA) serves as the backend system, managing internal and user-provided data, along with information from external systems such as weather forecasts. This comprehensive data repository enables informed decision-making by supplying relevant status updates and operational insights. The SA communicates with the Network Controller to access network layer data and interfaces with components at the Situational Awareness Layer, including the UGV Swarm Controller and Dispersion Engine. Moreover, it may integrate external services to augment its data-gathering capabilities and enhance situational awareness.

3.5 WP4 Sensor Integration Unit (SIU)

In the EU-RADION project, Work Package 4 (WP4) focused on the development of the Sensor Integration Unit (SIU), marking a significant stride in sensor hardware innovation.

The objectives of Work Package 4 (WP4) in the EU-RADION project were strategically aligned to fulfil two key high-level objectives (HLOs):

1. High-Level Objective 1 (HLO1): Aimed at addressing selected capability gaps for European first responders and CBRNe practitioners as identified in the ENCIRCLE catalogue and the IFAFRI study, through the development of relevant technologies.

2. High-Level Objective 3 (HLO3): Focused on enhancing the innovativeness of the European CBRNe market and supporting its competitiveness.

These high-level objectives were pursued through the successful achievement of specific Science and Technology (S&T) Objectives within WP4:

- *S&T Objective 2: The development of a modular sensor integration unit equipped with heterogeneous detection technologies. This unit is designed for versatile deployment across stationary and mobile platforms, including person-worn and unmanned platforms, addressing the direct needs identified in HLO1.*
- *S&T Objective 4: The creation of an adaptable positioning module capable of establishing the localization of assets in environments where the Global Navigation Satellite System (GNSS) signal may not be available. This development is crucial for operational effectiveness in challenging scenarios, further contributing to the goals outlined in HLO1.*
- *S&T Objective 6: The formulation of data fusion algorithms to enable the effective utilization of all sensor data. This objective supports the broader aim of HLO3 by fostering innovation in data processing techniques within the CBRNe domain.*

Through the realization of these S&T Objectives, WP4 has directly contributed to filling the capability gaps and enhancing the technological landscape for first responders and CBRNe practitioners, while also boosting the competitiveness and innovation of the European CBRNe market.

Under the leadership of AS, an SME/Industry partner, WP4 aimed to produce a compact, versatile RN sensor unit. This unit integrates advanced sensor technologies, including Geiger counters, Cadmium Zinc Telluride detectors, and hydrogen gas sensors, alongside sophisticated data fusion algorithms. These algorithms are designed to intelligently combine sensor outputs, reducing noise and accurately classifying RN materials. The SIU also features an adaptable navigation unit, utilizing both Global Navigation Satellite System (GNSS) and Inertial Navigation System (INS) technologies, scheduled for iterative releases at M16, M22, and M26, with each version refined based on operational feedback from WP7.

This initiative directly addresses critical capability gaps identified for European first responders and CBRNe practitioners, as highlighted in the ENCIRCLE catalogue and the IFAFRI study [3] [4]. By advancing these technologies, WP4 contributes to enhancing the EU's CBRNe market's competitiveness and innovation, aligning with High-Level Objectives aimed at addressing these capability gaps.

Key achievements include the integration of a gamma spectrometer within the SIU, detection capabilities for gamma/x-ray radiation, calibration for measuring ambient dose equivalent, rigorous testing in lab and field settings, a non-proprietary and replaceable battery, compatibility across various platforms, and the development of a dedicated positioning module. This comprehensive approach ensures the SIU's efficacy in enhancing CBRNe response capabilities, addressing the project's objectives and identified capability gaps. This WP directly contributes to bridging the capability gaps highlighted for European first responders and CBRNe practitioners, as outlined in the ENCIRCLE catalogue and the IFAFRI study [3] [4].

Throughout the course of the project, WP4 achieved significant milestones, meeting Key Performance Indicators (KPIs) 2, 3, 4, 10, 15, and 16:

- KPI 2: To implement at least 2 different detection technologies in sensor integration unit.
- KPI 3: Communication and system interface are designed and developed to obtain processed sensor readouts in 1 second or less.
- KPI 4: Sensor Integration Unit is operating on non-proprietary power source.
- KPI 10: Highly accurate near real time positioning based on INS with GNSS module in indoor and outdoor environment.
- KPI 15: The application of data fusion algorithms increases the performance of the sensor integration unit compared to the single sensor readouts
- KPI 16: Data fusion at SIU level allows for identification of the RN type.

The deliverables from WP4, developed through a rigorous iterative process, include:

- SIU Technical Documentation (D4.1, D4.2, D4.3): Offering comprehensive technical specifications for the SIU, these documents ensure a secure and standardized development framework, all of these were RESTREINT UE/EU RESTRICTED Reports..
- RN Sensor Unit (D4.4, D4.5, D4.6): These deliverables focus on developing sensor units for detecting RN materials [18] [19] [20].
- Gas Sensor Unit (D4.7, D4.8, D4.9): Aimed at advancing gas sensor technologies for hazardous substance detection [21] [22] [23].
- Adaptable Navigation Unit (D4.10, D4.11, D4.12): Designed to create a flexible navigation system for integration with various platforms [24] [25] [26].
- Integrated SIU (D4.13, D4.14, D4.15): Showcasing the fully integrated SIU, these deliverables demonstrate its operational capabilities [27] [28] [29].

The EU-RADION project addresses gaps such as the lack of real-time threat assessment capabilities and the absence of cost-effective, miniature tools for CBRNE agent detection suitable for drones or robots. The SIU, central to this initiative, combines multiple detection technologies into a single unit, enhancing versatility and cost efficiency. Integrated with a swarm of unmanned ground vehicles (UGVs) and supported by the Tactical Command Tool, the SIU enables real-time threat assessment, adaptable detection tools, and improved situational awareness for field responders.

Furthermore, the project integrates a dedicated swarm of UGVs with the SIUs, thereby enhancing responders' capabilities in remote detection and identification of RN hazards. The UGV swarm, consisting of three units, will autonomously cover the designated area under the guidance of a technical expert.

Overall, the development of the SIU, integrated with UGVs and supported by the Tactical Command Tool, addresses the identified gaps by providing real-time threat assessment capabilities, cost-effective and adaptable tools for detection and identification, and enhanced situational awareness for responders in the field.

The following requirements have been met:

- The Sensor Integration Unit integrates a gamma spectrometer. The SIU design incorporates a Cadmium Zinc Telluride (CZT) detector as a gamma spectrometer, the Geiger Counter as a gamma dosimeter and a hydrogen gas sensor.
- The Sensor Integration Unit detects gamma/x-ray radiation within the range of 30 keV-2 MeV. The Sensor Integration Unit reliably indicates the radiation dose rate from gamma/x-ray radiation.
- The Sensor Integration Unit is calibrated to measure the ambient dose equivalent H*(10) for radiation fields.
- The SIU underwent rigorous testing both in laboratory settings and during field trials: the data processing algorithms demonstrated considerable capability
- The Sensor Integration Unit features a non-proprietary and replaceable battery.
- The Sensor Integration Unit is compatible with the stationary sensor platform, the person-worn sensor platform and the UGV platform.
- The swarm of UGVs consists of 2-3 units, each equipped with swarm intelligence to enable local communication between them. Additionally, every UGV is outfitted with a wireless sensor integration unit tailored for its specific functions.
- A dedicated positioning module based on Inertial Navigation System (INS) and GNSS was developed. This combination is expected to enhance overall accuracy and enable operation in GNSS-denied environments such as tunnels or underground spaces.
- The dispersion engine module computes an estimated dispersion model and identifies the source of radioactive material.

3.5.1 Sensor Technologies Utilized in EU-RADION

3.5.1.1 Radio-Nuclide Sensor Unit – Gamma dose rate meter

For the EU-RADION project, the Geiger-Müller (GM) tube 70019A from VacuTec Meßtechnik GmbH, Germany has been selected as the primary sensor technology for the Radio-Nuclide Sensor Unit (SIU, see: Figure 3). This choice was made due to the GM tube's compact design, high sensitivity, and suitability for integration into mobile and handheld versions of the detector units. The GM Tube 70019A offers an energy range from 40 keV to 2 MeV (expandable up to 10MeV) and can measure radiation levels from 1µSv/h up to 100 mSv/h, with a dose sensitivity of 1.6 imp/s / µSV/h at 662keV (Cs-137). The required supply voltage for operation is 500V.

Figure 3 The Geiger-Müller (GM) tube chosen for the EU-RADION project

To meet the demands of the GM Tube 70019A, the project developed electronic circuitry capable of providing the necessary high voltage supply and fast pulse counting (<=60µs; see: Figure 4).

Figure 4 Printed Circuit Board (PCB) featuring the GM Tube and associated electronic components

Additionally, the SIU's design allows for potential modifications, such as incorporating additional GM tubes like the 70018A for stronger gamma sources. However, it's noted that detection of such sources is outside the scope for the handheld, personal-worn version of the detector.

3.5.1.2 Radio-Nuclide Sensor Unit – Gamma spectrometer

Summary of Gamma Spectrometers for SIU:

In the pursuit of optimal gamma-ray detection capabilities for the Sensor Integration Unit (SIU), two gamma spectrometers were evaluated: the Hamamatsu C12137 and the Kromek GR1 (see: Figure 5 and Figure 6).

Figure 5 The initially selected Hamamatsu C12137, a radiation detection module incorporating a CsI(Tl) scintillator and Multi-Pixel Photon Counter (MPPC).

The Hamamatsu C12137, chosen initially, is a radiation detection module featuring a CsI(Tl) scintillator and a Multi-Pixel Photon Counter (MPPC). This module is adept at detecting gamma rays, particularly from isotopes like Caesium-137. The scintillator converts gamma rays into visible light, which is then detected by the MPPC with remarkable sensitivity even at low light levels. With integrated signal processing and Analog/Digital conversion (A/D conversion), the C12137 offers a compact solution with interfaces like USB or RS-232C. Its technical specifications include an energy range of 0.03 to 2 MeV, energy resolution of 8%, and adjustable sampling time ranging from 0.1 to 60 seconds.

Figure 6 The Kromek GR1, a high-efficiency gamma-ray spectrometer utilizing a CZT solid-state detector.

On the other hand, the Kromek GR1 presents itself as a high-performance gamma-ray spectrometer leveraging a CZT solid-state detector. It boasts an extended energy range from 0.03 to 3 MeV with an impressive energy resolution of 2.5%. Similar to the C12137, it offers adjustable sampling times and interfaces via USB. The GR1's self-contained design, coupled with its small form factor, makes it particularly suitable for compact applications like the mobile and handheld SIU.

While the GR1 surpasses the C12137 in terms of energy resolution, it comes at a higher cost, being three times more expensive. To ensure responsible allocation of project funds, it was decided to construct ten SIUs during the project, necessitating a balance between performance and cost-effectiveness. As a result, the SIU design allows for flexibility, accommodating either the C12137 or the GR1 based on user requirements. This approach enables thorough comparison and evaluation of both gamma spectrometers while meeting the diverse needs of stakeholders within the project scope.

3.5.1.3 Sensor Integration Overview

This section delineates the architecture and capabilities of the sensor nodes within the system.

The software architecture of the Sensor Integration Unit (SIU) encompasses various enhancements and adjustments aimed at optimizing signal evaluation and processing across different sensor types. Notably, for the GM tube sensor, the signal evaluation algorithm has been refined to consider both pulse count and pulse width, facilitating more accurate measurements, particularly at higher dose rates where overlapping pulses may occur. Additionally, signal smoothing has been fine-tuned to ensure stable signal representation over time, enabling safer assessment of the distance to radiation sources. While no changes were made to the software readout for the Hamamatsu C12137 and Kromek GR1 gamma spectrometers, common bugs affecting data transfer were identified and rectified. Laboratory testing revealed challenges related to energy calibration, peak shifting, and dose rate dependency, necessitating further investigation and potential software adjustments for improved spectral processing and accurate identification of radio nuclides. Field tests conducted in Oslo demonstrated the efficacy of the SIU in identifying radioactive sources, with promising results obtained through offline evaluation and data analysis. The final radionuclide library incorporated into SIU and tested during the field test is presented in Figure 7.

Project importance	Radionuclide	Half-life	Energy (keV)	Gamma intensity (%)	Category (Industrial, Medical, Nuclear, OSI)	Popularity (1-10 scale)	Comments
first 10	Am-241	432,6 y	59.54	~~77,60 (35,92)~~	Industrial	10	
first 10	Co-60	5,27 y	1332.51 1173.24 2505.75	99.99 99.85 Summing peak	Industrial	10	
first 10	Cs-137	30,05 y	661.66	94.36	Industrial	10	
first 10	K-40	1,2564E+09 y	1460.82	10.55	Industrial	10	
first 10	Ra-226	1600 y	186.21	5.96	Industrial	10	
first 10	Bi-214	19,8 min (U-Ra series: Ra-226 – 1600 y)	609.32 1764.5 1120.29 1238.12	46.42 15.39 15.14 5.9	Industrial	5	For Ra-226 identification
first 10	Pb-214	26,92 min 19,8 min (U-Ra series: Ra-226 – 1600 y)	351.93 295.22 241.99	46.96 27.29 13.72	Industrial	5	For Ra-226 identification
first 10	I-131	8,02 d	364.49 636.99 284.31	83.1 7.15 6.45	Medical	10	
first 10	Tc-99m	6,01 h	140.51	89	Medical	10	
first 10	U-235	704E+06 y	185.72 *42.01* 143.77 163.36 205.31 202.12	63.41 *24.7* 13.2 5.86 5.46 3.81	Nuclear	10	

Figure 7 Radionuclide Reference Collection Integrated into the Sensor Interface Unit (SIU)

The development of the Sensor Integration Unit (SIU) has achieved significant milestones, ensuring comprehensive functionality and integration of all specified sensors. Hardware components have been successfully developed and are operational, providing reliable support for sensor functionalities. The implementation of software and firmware for sensor readout and data processing facilitates efficient data collection and analysis. Measurement results have been obtained, indicating the system's capability to perform its intended functions effectively. Furthermore, the SIU supports sensor calibration for both energy and dose rate measurements, enhancing accuracy and reliability. Radionuclide identification, based on an initial library, has been integrated into the system, enabling precise identification of radioactive materials. Moreover, seamless communication with a superordinated data processing system ensures the timely transmission and utilization of gathered data for informed decision-making. Overall, the SIU development efforts have culminated in a robust and capable system ready for deployment in radiological and nuclear monitoring applications.

Figure 8 Handheld Sensor Integration Unit (SIU) displayed on the left; Stationary SIU showcased on the right

3.6 WP5 Sensor Platforms

In parallel with WP4, the consortium conducted work on WP5 Sensors platform, which was coordinated by AS, aiming at development of Sensor Integration Units (SIUs) adapted to three distinct platforms: stationary, handheld, and unmanned.

The objectives of Work Package 5 (WP5) within the EU-RADION project were directly aligned with fulfilling two crucial High-Level Objectives (HLOs):

1. High-Level Objective 1 (HLO1): This objective aimed to address selected capability gaps of European first responders and CBRNe practitioners, as highlighted in the ENCIRCLE catalogue and the IFAFRI study, through the development of relevant technologies.

2. High-Level Objective 3 (HLO3): The goal here was to enhance the innovativeness of the European CBRNe market and bolster its competitiveness.

These objectives were formulated in response to a significant Capability Gap identified at the heart of the EU-RADION project's motivation: *the scarcity of miniature, fieldable, and cost-effective tools and systems for the sampling, detection, and identification of CBRNe agents that could be mounted on robots or drones*.

To achieve these ends, WP5 focused on accomplishing specific Science and Technology (S&T) Objectives:

- S&T Objective 2: The aim was to develop a modular sensor integration unit equipped with diverse detection technologies. This unit was designed for deployment across various platforms, including stationary, mobile (person-worn), and unmanned platforms, addressing the need for versatile and innovative detection solutions.

- S&T Objective 3: This objective focused on developing a swarm of unmanned ground vehicles (UGVs). The envisioned swarm, consisting of 2-3 units, would incorporate swarm intelligence to enable local communication among the units. Each UGV was to be outfitted with an adapted wireless sensor integration unit, facilitating the deployment of advanced detection technologies in field operations.

Through the realization of these S&T Objectives, WP5 directly contributed to bridging the identified capability gap, showcasing the EU-RADION project's commitment to advancing the field of CBRNe detection and response. By developing these innovative technologies, the project not only aimed to enhance the capabilities of first responders but also to stimulate the European CBRNe market, driving forward its global competitiveness and innovation.

Each platform for SIU (stationary, handheld and unmanned) was designed to facilitate wireless communication with the Tactical Command Tool via the Network Controller. Tailored to specific operational requirements, each platform varied in aspects such as power supply, resistance to environmental factors like rain and dust, physical dimensions, and mounting configurations. Similar to the SIU, each platform underwent three iterations to accommodate potential modifications and enhancements. Notably, the development process for the UGV platform involved meticulous selection and testing of subcomponents, including electronics, cameras, and chassis options such as wheeled or continuous track propulsion. Under the leadership of AS, WP5 Sensor Platforms focused on the comprehensive development of sensor platforms, encompassing both handheld and stationary variants, with an additional emphasis on the creation of an unmanned mobile sensor platform.

Each offers wireless communication with the Tactical Command tool via network controller.

Work Package 5 (WP5) of the EU-RADION project directly addressed a critical capability gap identified by the International Forum to Advance First Responder Innovation (IFAFRI) study [4], which highlighted the need for miniature, fieldable, and cost-effective tools and systems for the sampling, detection, and identification of CBRNe agents. These systems are designed to be mountable on robots or drones, catering specifically to the operational demands of European first responders and CBRNe practitioners. WP5's efforts were aligned with the project's High-Level Objectives to cover selected capability gaps and to enhance the innovativeness and competitiveness of the European CBRNe market.

Key Performance Indicators (KPIs) Met by WP5:

- KPI 2: Implementation of at least two different detection technologies in the Sensor Integration Unit (SIU), enhancing the versatility and capability of detection systems.
- KPI 3: The design and development of communication and system interfaces that achieve processed sensor readouts in 1 second or less, ensuring rapid response capabilities.
- KPI 4: Operation of the SIU on a non-proprietary power source, increasing the adaptability and ease of use in various operational contexts.
- KPI 7: Adaptation of a swarm of Unmanned Ground Vehicles (UGVs) capable of operating for at least 4 hours, extending operational endurance.
- KPI 8: The formation of a UGV swarm comprising 2 to 3 units, which enhances operational flexibility and coverage.
- KPI 9: The UGV swarm exhibits required intelligence and collective behaviour, allowing for robot-to-robot communication, which significantly improves operational coordination and efficiency.

Deliverables Produced by the WP5 were produced in iterative manner, to ensure the methodology outlined in the project Proposal was implemented successfully. This approach enabled for tests and validation activities:

- Sensor Platforms Reports (D5.1 & D5.2) provided comprehensive documentation on the development and capabilities of various sensor platforms, contributing to the knowledge base and technical specifications for future advancements [30] [31].
- Handheld Sensor Platform (D5.3 & D5.4) deliverables focused on the development and refinement of portable sensor platforms, enhancing the operational flexibility and response capabilities of first responders [32] [33].
- Stationary Sensor Platform (D5.5 & D5.6) contributions included the development of fixed-position sensor platforms for continuous monitoring and detection, offering a strategic advantage in CBRNe threat assessment [34] [35].

- UGV Swarm (D5.7 & D5.8) deliverables detailed the development, implementation, and operational testing of a swarm of UGVs equipped with advanced detection technologies, showcasing a significant leap in autonomous operational capabilities [36] [37].

WP5's achievements in developing advanced detection systems and operational platforms significantly contribute to closing the identified capability gaps. Through the integration of cutting-edge technologies and the development of innovative operational methodologies, WP5 has notably advanced the state of CBRNe detection, identification, and operational response capabilities within the European context.

3.6.1 Handheld Sensor Platform

The Handheld Sensor platform utilizes a standard Airsense housing designed for mobile applications of specific detectors. This housing was modified to accommodate the Sensor Integration Unit (SIU), with a specific mounting point constructed at the front to house the Geiger-Müller tube. To actualize the hardware, multiple components were manufactured utilizing 3D printing technology (for refence, see: Figure 9).

Figure 9 On the left hand side: the CAD model of the portable Sensor Integration Unit (SIU), representing the initial phase in the development of the handheld device; the final design of the handheld SIU is presented on the right panel

This platform includes a Gamma spectrometer situated beneath the PCBs, a GM tube visible on the left side, and an adaptable navigation unit atop the PCB stack. A cover was added to the battery compartment for safety. The development of the handheld sensor platform is essentially complete, with the ability to accommodate requested changes. The Sensor Integration Unit (SIU), battery compartment, and adaptable navigation unit have all been integrated into the platform.

Figure 10 Interior view of the handheld Sensor Integration Unit (SIU)

3.6.2 Stationary Sensor Platform

The development of a stationary sensor platform was based on the RN sensor unit and the gas sensor unit. Specific adaptations were made to tailor this platform for stationary use. The power supply for this platform was derived from the common power source established in Task 4.3, which drew power from the main source. The stationary sensor platform relied on the underlying sensor integration unit outlined in D4.1 and D4.2.

For the stationary sensor platform (Figure 11), we opted for a commercially available casing. This choice also serves as the housing for the UGV-based sensor platform, streamlining resource utilization and simplifying development processes.

Figure 11 Stationary platform of Sensor Integration Unit (SIU)

Figure 12 showcases the interior view of latest iteration of the stationary sensor platform, with the version featuring the KROMEK Gamma spectrometer on the left and the Hamamatsu Gamma spectrometer on the right. The GM tubes are positioned near the front of the casing, concealed beneath the PCB. On the right side of the casing, you'll find the Hydrogen Sensor. Additionally, the new µController board, equipped with integrated WLAN connection capabilities (with the WLAN antenna positioned on the left side of the casing), is visible on the top.

Figure 12 Interior view of the stationary platform of the Sensor Integration Unit (SIU)

3.6.3 Unmanned Sensor Platform

The UGV-based platform closely resembles the stationary platform. It is easily available for integration with the Unmanned Ground Vehicle developed by ITTI. This integration is intended for situations where remote investigation is necessary due to higher risks to personnel or in hard-to-reach areas. Figure 13 depicts the UGV equipped with the boxed SIU. Both stationary and UGV-based platforms have undergone field tests at FOI facilities in Umea. The data from these tests were evaluated, and the results have been presented in a Report D7.6 - Laboratory and Field Tests Report (III) [38].

Figure 13 On the left hand side: the stationary SIU mounted on the UGV during tests in Poznań; middle panel – UGV with stationary SIU ready for deployment during the Final Demonstration; the right panel presents 3 UGVs with SIUs mounted

3.7 WP6 Situational Awareness Tools

The core motivation for the implementation of the Work Package (WP) within the EU-RADION project was addressing the Capability Gaps that were foundational to the inception of the project. These gaps include:

- *the lack of rapid identification of hazardous agents and contaminants, and*
- *the need for development of a Joint Operational Picture and tactical command toolkit.*

These critical areas underscore the project's commitment to advancing solutions that meet the urgent needs of first responders and CBRNe practitioners, aiming to significantly improve response times and operational coordination in the face of CBRNe threats.

The primary goals - to prevent the aforementioned capability gaps - have been quantified through the defined High-Level Objective 2 (HLO):

- *to enhance the situational awareness of first responders and CBRNe practitioners during preparedness and response missions.*

The development of EU-RADION's software components, a crucial aspect of the project, was undertaken within Work Package 6 (WP6) Situational Awareness Tools, led by FOI. This work package was strategically planned to coincide partially with WP4 and WP5, ensuring the early initiation of computational tools and the Tactical Command tool development.

In line with this HLO 2, EU-RADION has developed a Tactical Command tool to serve as an access point to processed sensor data and computational functionalities such as data fusion and dispersion engine. This tool addresses the need highlighted by the ENCIRCLE catalogue [3] for real-time hazard data transmission to responders and visualization of detected threats across various system categories, namely:

- Lack of capabilities for real time threat assessment
- Rapid identification of hazardous agents and contaminants
- Joint Operational Picture and tactical command toolkit

In response to identified gaps, EU-RADION focused on unifying the data model for all components to maintain interoperability and enable near real-time data access through the situational awareness tool. The Sensor Integration Units (SIUs) were equipped with built-in data processing units to enable rapid threat assessment and real-time monitoring. These SIUs utilize wireless communication protocols for fast hazard data transmission to a central network controller, which then aggregates data and sends it to the Tactical Command tool. Additionally, the SIUs were designed for easy operation and maintenance, utilizing non-proprietary, replaceable power sources to ensure sufficient operational uptime. The networked approach maximizes sensor performance and reduces overall solution costs.

The Tactical Command tool serves as a dedicated system application, providing a comprehensive situational view to field command centers. It collects data from various system components, including sensors, computational tools, and Unmanned Ground Vehicles (UGVs), and visualizes processed sensor results and asset localizations. This visualization aids decision-making processes and enhances situational awareness by displaying crucial information and alerts. Overall, the project's response to identified gaps emphasizes optimization, functionality, and usability to effectively improve first responders' capabilities and decision-making processes in hazardous environments.

These tools were primarily designed to utilize information generated by the Sensor Integration Units (SIUs). Notably, the development of the Tactical Command Tool involved extensive collaboration with end-users and stakeholders to ensure optimal usability and user experience. This tool featured a computational layer responsible for data fusion and integration from all SIUs, enabling the creation of a comprehensive joint operational picture for first responders. The Situational Awareness Tools, under the leadership of FOI, encompassed the development of various tools aimed at enhancing practitioners' situational awareness. These tools included dispersion modelling, source estimation, network sensor control, and the development of the Tactical Command tool.

Key Performance Indicators (KPIs) Addressed by WP6:

- KPI 3: Design and development of communication and system interfaces to obtain processed sensor readouts in 1 second or less.
- KPI 5: Dispersion engine generates the first threat map model in 10 minutes.
- KPI 6: Dispersion engine estimates the approximate source of RN material in 20 minutes.

Overall, the work carried out within WP6 addressed the following Science and Technology (S&T) Objectives defined within the Proposal:

- S&T 5: Development of system functionality for estimating the dispersion and source of radioactive material.
- S&T 6: Development of data fusion algorithms for the effective use of all sensor data.
- S&T 7: Development of a Tactical Command tool to process and merge sensor data, including outputs from other computational modules, thereby building a joint operational picture for the command and control unit.

The comprehensive work plan, key milestones achieved, and the methodologies applied to meet the objectives of the project are thoroughly documented in the deliverables generated within Work Package 6 (WP6).

- Deposition Estimation (D6.1): This report outlined the outcomes of Task 6.1, focusing on the estimation of deposition [39].
- Improved Urban Deposition (D6.2): A summary report of Task 6.2, detailing the advancements in urban deposition models [40].
- Extended Threat Estimation Tool (D6.3): This software tool facilitates the estimation of dispersion for various threats (Deliverable RESTREINT UE/EU RESTRICTED).
- Tactical Command Tool - User Interface and Access Point (D6.4 & D6.5): These two deliverables provide the primary user interface for system visualization and control, with the exception of Unmanned Ground Vehicle (UGV) control. They serve as the main access points to the system [41] [42].
- Tactical Command Tool - Situational Awareness Engine (D6.6 & D6.7): Delivered in two parts, this software includes a logical service that aggregates and stores all necessary data to create an operational picture. It also coordinates data assimilation from various system components and computational tools [43] [44].
- Network of Sensors Controller (D6.8): A software module designed for the maintenance of sensor units, likely to support the integration and management of the sensor network within the tactical command tool [45].

Each deliverable represents a step towards a more integrated and sophisticated system for tactical command and control, with a strong emphasis on user interface design, situational awareness, and data management.

3.7.1 Dispersion Calculation

For the Dispersion Calculation, the team used atmospheric dispersion models to simulate the spread of radioactive materials in an urban setting, as detailed in the EU-RADION D6.2 document. These models provide spatially resolved deposition fields, taking into account the complexity of urban landscapes, including the variety of surface types and orientations. The accuracy of these models benefits significantly from specific knowledge of deposition velocities, thereby improving predictions of radioactive contamination levels. The models employed a Lagrangian particle tracking algorithm (Simplified Langevin Model) for atmospheric dispersion and modeled deposition as an averaging process, assigning particles a probability of deposition based on established deposition velocities. A notable achievement was the qualitative agreement of the model with real-world data from the Chernobyl accident, highlighting the model's potential utility in real scenarios.

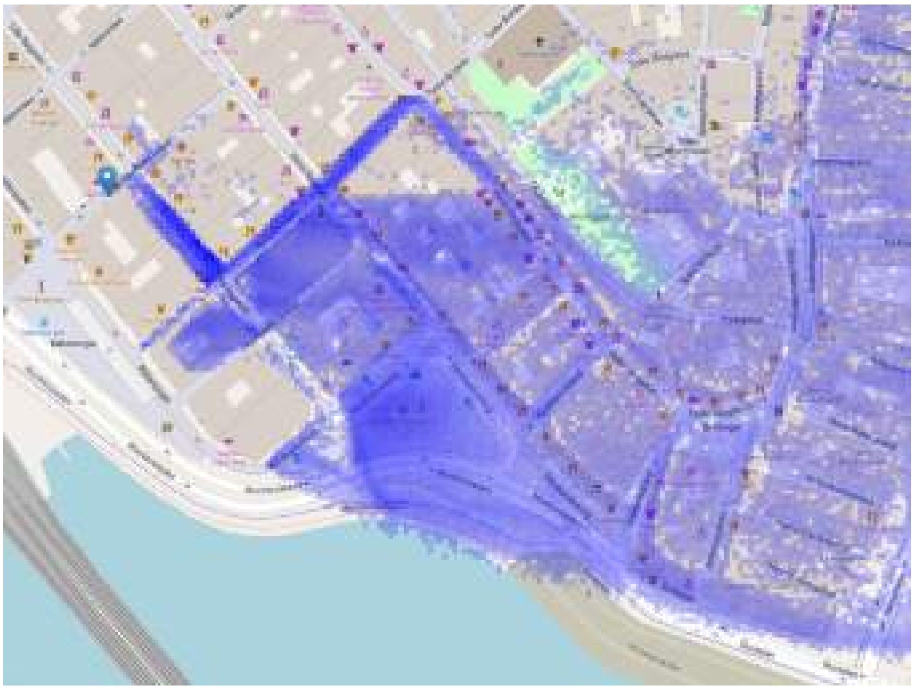

Figure 14 Hybrid Particle/Computational Fluid Dynamics Model Featuring Langevin Dynamics: UPELLO

3.7.2 Source Estimation

Source Estimation involved developing models to estimate the origins of detected radiation, as described in the EU-RADION D6.1 document. This process relied heavily on sensor system filter kernels (SSFKs), computed for specific geometries to represent early stages of radiological contamination. These SSFKs, developed for both spectrometer and GM-tube sensors, serve as calibration factors, converting sensor signals to deposition estimations. The project favoured local sensor measurements, particularly those from sensors mounted on Unmanned Ground Vehicles (UGVs), due to their direct applicability and relevance to first responders and the public. This approach underscores the integration of different sensor platforms, emphasizing the importance of localized, real-time data for accurate source estimation.

3.7.3 Hazard Prediction

Hazard Prediction focused on developing tools and models for predicting the potential impact of radiological dispersion, incorporating the findings from dispersion calculations and source estimations. The predictive models were designed to be part of a situational awareness tool, incorporating precomputed geometries and wind fields to enable real-time operation once the source location was determined. The discussion sections of the EU-RADION D6.2 document highlighted the need for further validation and refinement of these models, particularly in terms of deposition probability and the impact of urban geometry on particle dispersion and deposition. The aim was to enhance the accuracy and reliability of hazard predictions to better inform emergency response strategies.

These three facets of the project collectively contribute to a comprehensive approach for managing radiological threats, combining theoretical models with practical, sensor-based observations to enhance situational awareness and emergency response in urban environments.

3.7.4 Tactical Command Tool

The Tactical Command Tool (TCT) focuses on providing operators with a comprehensive view of the situation at hand through a map-centric display. It integrates assets, measurements, and calculation results to enhance situational awareness, offering functionalities for interaction, information enhancement, and operational planning. The design process involved close collaboration with end-users, ensuring the interface met technical and operational requirements effectively. The TCT is related to the S&T Objective 7, which covers the following aims:

- processing and merging all of the sensor data and the output of other computational modules including data fusion and dispersion engine
- build a joint operational picture for command and control unit.
- provide data in near real-time

3.7.4.1 TCT – User Interface

The paragraph outlines the User Interface (UI) aspect of the Tactical Command Tool (TCT) for the EU-RADION project. The UI is designed to work in conjunction with the Situational Awareness Engine, which forms the system's backend. The UI equips users with tools for visualizing and managing the EU-RADION system's assets and subsystems, enabling direct interaction for tasks like commanding measurements, enriching the Situation Display with additional data, and facilitating engagement with the Dispersion Calculation Tools.

The Tactical Command Tool (TCT, see: Figure 15) enhances situational awareness through a map-centric interface displaying sensor data and dispersion analysis. It helps first responders with visual cues on potential threat areas and supports mission planning with integrated tools. Essential information and alerts are readily accessible, streamlining the decision-making process.

Figure 15 Tactical Command Tool – Fundamental Interface Overview

Sensor Integration Units (SIUs) gather critical data for the EU-RADION system, presented on a map and in various data formats for analysis. This includes real-time measurements of dose rates, cps, and hydrogen concentration, which are immediately displayed and color-coded for quick visual assessment. Safety perimeters and danger zones are also highlighted, with alerts for elevated hydrogen levels, ensuring a rapid response to potential hazards (Figure 16).

Figure 16 Continuous Quantity Map Display for TCT with Configured Thresholds (Orange = Warning Level, Red = Severe Level)

Gamma spectrum data is represented by a marker on the map, which provides detailed measurement insights upon clicking, such as identified nuclides. Both continuous readings and gamma spectra are graphed, with updates for new data and interactive map points. The graphs highlight gamma peaks and can be zoomed or filtered for detailed temporal or spectral analysis.

Figure 17 Graph depicting continuous quantities

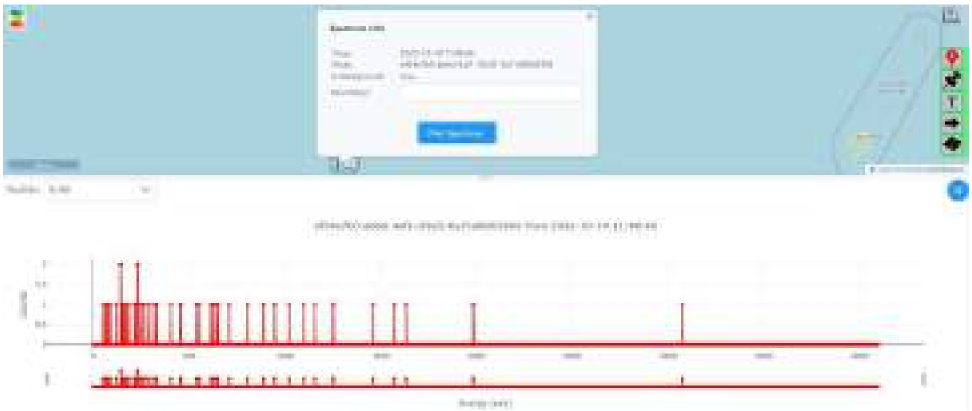

Figure 18 Gamma spectra presented on the TCT

The "data overview pane" provides a detailed analysis in a tabular format, allowing users to view, filter, and sort each measurement track or gamma spectrum. Individual measurement tracks can also be expanded to display every data point in a table for a comprehensive view (see: Figure 19 and Figure 20).

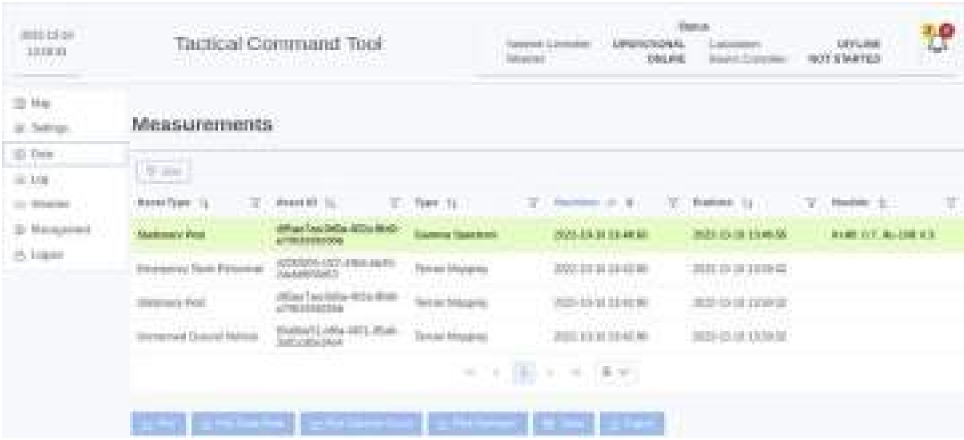

Figure 19 TCT – Measurement data view

Figure 20 TCT - Continuous quantities table view

3.7.4.2 TCT and DE

In the realm of EU-RADION, the Dispersion Engine (DE) emerges as a pivotal subsystem, meticulously crafted to conduct both foresighted dispersion simulations and reflective source estimations. This intricate process leverages sensor output and meteorological insights sourced from the Situational Awareness Engine, ensuring a robust analytical foundation. The Tactical Command Tool (TCT) serves as the user's portal to the DE's intelligence, allowing the strategic overlay of calculation outcomes upon geographical maps for enhanced visibility.

Initiating the DE's operations demands a meticulous setup via the TCT, where the user stipulates the parameters that govern the engine's complex algorithms. Once primed, the DE stands ready to process requests, be it for discerning the origins of a hazard or forecasting its trajectory. The map housed within the TCT becomes a dynamic display, charting the most current source estimations and offering a dedicated panel where hazard predictions are not only presented but can also be fine-tuned. This panel boasts temporal navigation capabilities, enriched by the integration of weather data, which can be streamed in real-time or fed manually.

Distilling the workflow between the Tactical Command Tool (TCT) and the Dispersion Engine (DE), we find:

1. Initialization: The DE springs to life through the TCT's interface, where users chart the course for the forthcoming simulations and estimations.
2. Data Integration (see: Figure 21): Drawing upon the sensor and meteorological data from the Situational Awareness Engine, the DE embarks on its analytical journey.
3. Dispersion Calculations: With a temporal sweep, the DE executes forward-looking dispersion simulations alongside retrospective source estimations.
4. Visualization: The TCT map comes alive with visual depictions of dispersion trends and pinpointed source locations.
5. Source Estimation (see: Figure 22): The DE diligently refreshes its source estimations, each new insight promptly materializing on the map.
6. Hazard Prediction (see: Figure 23): Engaging with the DE's foresight, users venture into hazard predictions, tweaking parameters as insights evolve.
7. Result Analysis (see: Figure 24): The fruits of hazard prediction are ripe for review in the results pane, where they can be draped over the map and scrutinized over time with the aid of a slider control.

Figure 21 Data Integration Overview: Dispersion calculation integration

Figure 22 Source Estimation

Figure 23 Hazard prediction

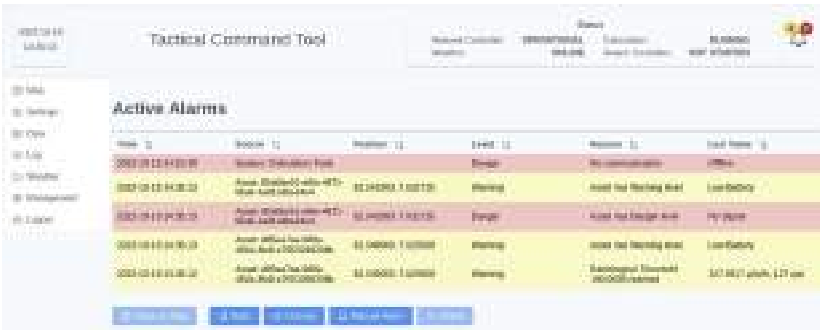

Figure 24 Alarming

The software, aligned with the system architecture from WP 4, comprises the Situational Awareness Engine and the User Interface & Access Point (UI & AP). The UI & AP, developed in Typescript using the Angular Framework, incorporates UI components from Prime-NG and the OpenLayers mapping library. It also integrates GeoServer for offline maps and geospatial data management, serving as the user-facing frontend with the Situational Awareness Engine functioning as the backend.

The User Interface & Access Point (UI & AP) underwent thorough testing, including unit tests for individual components and services, and end-to-end tests alongside the Situational Awareness Engine, using simplified simulators of other systems for comprehensive evaluation. User Acceptance Testing was conducted in a dedicated test environment. The UI's effectiveness was further validated through workshops and integrated tests in Oslo and Umeå, gathering valuable end-user feedback and real-world performance data during field trials with actual radiological samples (see: Figure 25 and Figure 26 for reference).

Figure 25 Figure captures the Gamma spectrum of a Cs-137 sample obtained during field trials in Umeå on 05/23, highlighting the UI's efficiency with actual radiological samples.

Figure 26 This figure showcases the outcome of dispersion calculations conducted in Umeå on 05/23, illustrating the projected spread of radiological materials under study

3.7.4.3 TCT – Situational Awareness Engine

The paragraph outlines the backend part of the Tactical Command Tool (TCT) for the EU-RADION project, known as the Situational Awareness Engine (Figure 27). It details functionalities such as managing and storing asset and measurement data, interfacing with other subsystems like the Network Controller and Dispersion Engine, and providing necessary data for UI visualization. Additionally, it incorporates weather forecasts and mapping information, with integration tests and technical requirements completion.

The Situational Awareness Engine (SA) within the Tactical Command Tool (TCT) acts as an intermediary, connecting the Network Controller and the Dispersion Engine with the User Interface & Access Point (UI & AP). It employs Apache Kafka for efficient communication among EU-RADION's subsystems, using named topics for tailored interactions. The SA-Engine enhances the system with integrated weather services and mapping capabilities for the UI & AP and ensures data persistence through an embedded database. All components leverage Docker for streamlined deployment across various infrastructures.

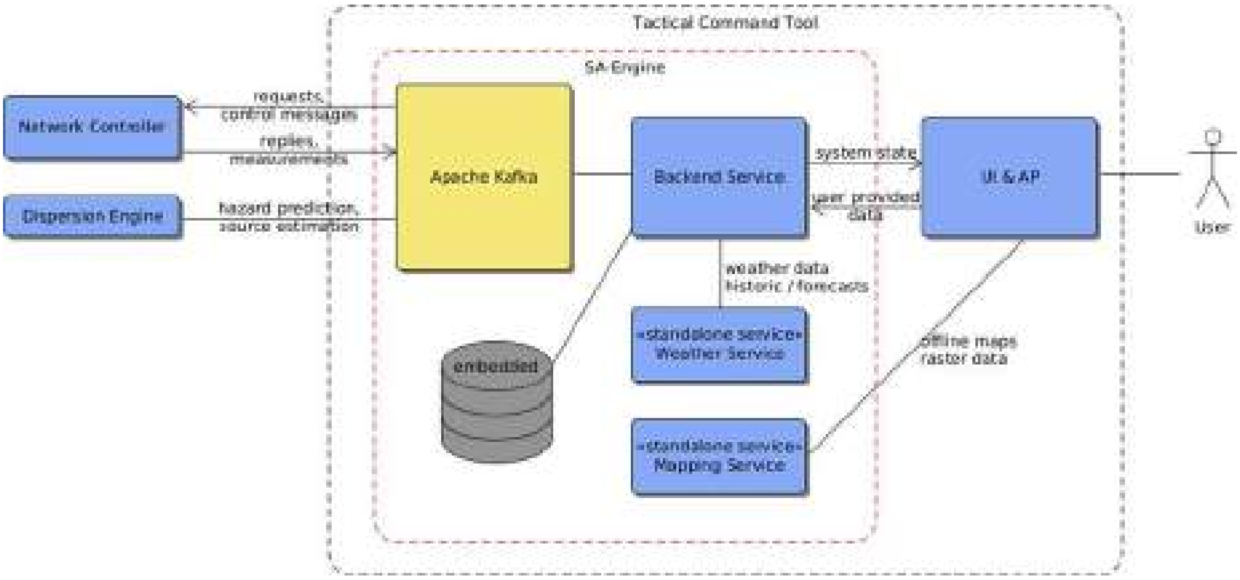

Figure 27 The architecture of Situational Awareness Engine

The Tactical Command Tool (TCT) interfaces seamlessly with the Network Controller and Dispersion Engine using well-defined protobuf messages, facilitating commands and data exchange. It integrates with a standalone Weather Service to access forecasts and employs a GeoServer for mapping, enhancing operational capabilities with real-time weather data and geospatial information. Comprehensive integration tests ensure robust communication and functionality, while the TCT meets all technical requirements, with ongoing efforts to address specific needs like alarm messaging to SIUs, ensuring readiness for system integration and operational deployment.

The Network Controller acts as a crucial intermediary, facilitating connectivity between sensor platforms and the broader system through MQTT protocols and interacting with key components like the Tactical Command Tool via Apache Kafka, ensuring seamless communication and integration within the operational infrastructure.

The Technical Requirements for this component are listed in the D3.1 Technical Requirements and D3.5 Architecture Report [13] [17].

The Network Controller incorporated internal nuclide library, initially comprising 10 radionuclides as recommended by CLOR. This library, integral to the RN Sensor Unit, expanded to contain 224 nuclides, surpassing initial expectations. It includes comprehensive data frames for each nuclide, featuring names, half-lives, and energy spectra peaks. An API facilitates access, allowing for the retrieval, creation, and updating of nuclide data. This enhancement significantly contributes to the consortium partners' software development efforts.

3.8 WP7 Field Tests and Data Collection

Work Package 7 (WP7) of EU-RADION project, titled "Field Tests and Data Collection" and led by FFI, has been instrumental in bridging the capability gaps identified for European first responders and CBRNe practitioners. The primary goal of WP7 was to conduct extensive field measurements using the Sensor Integration Unit (SIU) developed in WP4, "to ensure rapid identification of hazardous agents and contaminants" — a significant gap highlighted by IFAFRI.

With a focus on validating the SIU and its sub-components, WP7 successfully addressed High-Level Objective 1 (HLO1), which aimed to develop relevant technologies to fill the capability gaps cataloged by ENCIRCLE and IFAFRI [3] [4]. The SIU's efficacy in providing processed sensor readouts within the ambitious timeframe of 1 second was a critical Key Performance Indicator (KPI 3), which has been achieved, thereby enhancing the communication and system interfaces.

In the realm of Science and Technology Objectives, S&T 7 was fully realized with the development of the Tactical Command Tool. This application has proven pivotal in processing and merging sensor data, along with the outputs from other computational modules such as data fusion and the dispersion engine. It has created a comprehensive operational picture for command and control units, offering near real-time data.

The deliverables for WP7 are a series of reports and a database, all produced under the leadership of FFI, and they include the following:

- three iterations of the Data Collection Plan (D7.1, D7.2, D7.3), each detailing and refining the strategy for data gathering throughout the project [46] [47] [48];
- three Laboratory and Field Tests Reports (D7.4, D7.5, D7.6) documenting the outcomes of the tests conducted to validate the Sensor Integration Unit and its components [49] [50] [38],
- Measurements Database (D7.7) which has been created to store the results from field tests, which is classified as RESTREINT UE/EU RESTRICTED.

3.8.1 Data Collection

The EU-RADION project's data collection process, as outlined in the deliverables D7.1, D7.2, and D7.3 [46] [47] [48], involves a meticulously planned and executed series of laboratory and field tests. Initially, the project established a comprehensive plan detailing both laboratory and field test methodologies for system components. This included radionuclide dosimetry radiation detection and hydrogen gas detection, with tests conducted locally and then integrated onto unmanned ground vehicles (UGVs) for comprehensive field assessments in environments like underground tunnels. The culmination of these efforts resulted in an expanded database, significantly exceeding initial expectations by documenting information on 224 nuclides. This robust dataset, supported by an API for efficient data management, now serves as a foundational resource for ongoing and future research within the consortium, enhancing the system's reliability and efficacy in real-world applications.

3.8.1.1 Laboratory tests

The laboratory tests for the EU-RADION project encompassed comprehensive assessments across multiple components:

Dosimetric calibration: CLOR undertook comprehensive radiometric evaluations on the Sensor Integration Unit (SIU) and its Geiger-Müller counter to ensure their precision and applicability for in-situ radiation measurements. This encompassed calibrating against various gamma and X-ray sources, assessing responses across a wide dose range, and evaluating the linearity and angular sensitivity of measurements. These efforts were aimed at enhancing the SIU's capabilities to meet specific user demands, ensuring its effectiveness in accurately detecting and measuring radiation levels in diverse environments.

The calibration of dosimetric components in the Sensor Integration Unit (SIU) was meticulously conducted at CLOR's accredited calibration laboratory, adhering to the ISO/IEC 17025:2018-02 [51] standard. The process encompassed a range of tests across gamma radiation beams using specified sources to ensure the SIU's efficacy for the project and future research. These tests included functional checks, background indication verifications, alarm assessments, high dose responses, linearity of response evaluations, energy dependence assessments, and directional dependence determinations, all contributing to the comprehensive validation of the SIU's performance.

Hamamatsu/Kromek Gamma Spectrometry Module: This module underwent a series of tests to evaluate its identification capabilities and temperature stability, utilizing various radionuclides and ambient temperatures. Tests aimed at energy calibration, resolution, identification capabilities, temperature stability, and angular response were conducted to ensure the module's precision and reliability.

The testing and calibration process for the Hamamatsu/Kromek gamma spectrometry module involved several key steps:

1. Identification Capabilities: Initially, the module's ability to identify different radionuclides was tested using sources like 137Cs, 60Co, and 241Am, with acquisition times set at 10, 30, and 60 minutes.

2. Temperature Stability: The module underwent temperature stability tests in a climatic chamber at temperatures of 0°C, 10°C, 20°C, and 30°C using 60Co and 137Cs sources to study the gamma radiation spectrum's changes with ambient temperature.

3. Energy Calibration: The module was calibrated in the presence of well-defined radionuclide samples, establishing an energy calibration function from the detected peak channel numbers and the discrete energy of each peak, covering a range from 30 keV to 2 MeV.

4. Energy Resolution: The Full Width Half Maximum (FWHM) for the 662 keV gamma photon peak from a 137Cs source was determined to measure energy resolution.

5. Comprehensive Testing: The module's response to high doses, energy response, linearity, angular response, response time, and build-up time were evaluated to ensure its accuracy and reliability in various conditions.

These meticulous laboratory tests aimed to refine the spectrometry module's performance, with all measurements set to be repeated in final testing to validate the enhancements and ensure the module's readiness for deployment.

The testing and calibration of the CdZnTe (CZT) radiation detector involved comprehensive laboratory evaluations and Monte Carlo simulations to assess its efficiency across a range of energies, angular dependency, and Full Width Half Maximum (FWHM). These tests, conducted using gamma calibration point sources like 210Pb, 241Am, and 152Eu, aimed to establish an efficiency calibration curve and assess the detector's performance at varying angles and distances from radiation sources. Monte Carlo simulations further supported this process by creating a virtual model of the detector to simulate its response in varied radiation fields, aiding in the calibration and ensuring the detector's accuracy for nuclide identification and ground deposition estimates.

The testing of the CdZnTe radiation detector encompassed laboratory evaluations and Monte Carlo simulations to ascertain its fitness for purpose and validate the Monte Carlo model of the detector. The laboratory tests aimed to establish the detector's efficiency across various photon energies and its angular dependency. These efforts were instrumental in ensuring the detector's readiness for deployment in scenarios involving UGV surroundings and elevated radiation fields, highlighting the utility of Monte Carlo simulations as a practical alternative for calibrating the system in the absence of actual field tests with dispersed radioactivity.

The **Gas Sensor Unit**, crucial to the Sensor Integration Unit (SIU), underwent thorough testing in Airsense laboratory facilities, focusing on its responsiveness to varying hydrogen concentrations. This involved recording both dynamic and final static responses, leading to the establishment of a calibration curve. These findings are documented in deliverable D4.9. Further tests are planned following the completion of the SIU development, including evaluations of handheld and stationary/UGV units, to ensure the Gas Sensor Unit's precision and reliability across different operational configurations.

3.8.1.2 Field tests

The EU-RADION field tests in Norway initially planned for a firefighter training facility were redirected to tunnels near Oslo due to logistical advantages. Initial tests were successfully conducted in the VEAS tunnel system at Slemmestad in October 2022, with further testing anticipated in spring 2023. Challenges were noted in simulating a radiological dispersal device's airborne radioactive cloud for validating dispersion models, leading to a preference for synthetic data and existing experiment validations. The VEAS facility offered two potential test sites, the Slemmestad-tunnel and the Holmen-tunnel, each with unique characteristics and logistical considerations for future testing.

3.9 WP8 EU-RADION System Integration, Verification and Validation

In WP8 EU-RADION System Integration, Verification, and Validation, led by ITTI, the components developed within WP4, 5, and 6 were integrated, tested, and validated. Work Package 8 resembled all of the Capability Gaps identified by IFAFRI and ENCIRCLE [3] [4], and it was directly related to the High-Level Objectives 1 and 3:

- High-Level Objective 1 - To cover selected capability gaps of European first responders and CBRNe practitioners indicated in ENCIRCLE catalogue and IFAFRI study by development of relevant technologies,
- High-Level Objective 3 - To boost European CBRNe market innovativeness and support its competitiveness.

The primary focus was on integrating all components into a complete operational system. This integration process followed three iterations, mirroring the development process of the sub-components. The first integration phase focused on interface testing and mock-up solutions. The second provided the first operational components, while the third focused on the solutions' refinement. Alongside system integration, validation activities were conducted to ensure the functionality and reliability of the EU-RADION system. The outcome of WP8 was a fully integrated and validated EU-RADION system, prepared for demonstration. Additionally, WP7 Field Tests and Data Collection, dedicated to data collection and lab measurements, supported the validation process.

The EU-RADION project's integration process involved a meticulous methodology focusing on both hardware and software components to enhance emergency response capabilities against radiological threats. This involved iterative testing to identify and rectify issues, ensuring seamless interoperability between components like the Sensor Integration Unit, Stationary Sensor Platform, and others. The integration plan outlined a structured approach to testing each component's functionality and compatibility within the system, leading to a comprehensive evaluation of the integrated system's performance in real-time data gathering and analysis. This approach was crucial for validating the system's effectiveness in improving situational awareness and decision-making for first responders in radiological emergency scenarios.

The EU-RADION project's integration process for both hardware and software components were methodically approached to ensure the seamless operation of the system intended for enhancing emergency responses to radiological threats. WP8 delivered a comprehensive suite of reports and hardware aimed at integrating and validating the system. Key deliverables included:

- Integration Testing Results (D8.1, D8.2, D8.3): A series of reports detailing the integration and functional testing of EU-RADION, providing foundational guidelines for subsequent modifications and development of components [52] [53] [54].
- Validation Results (D8.4, D8.5, D8.6): Three reports focusing on the validation of the EU-RADION system [55] [56] [57] [58].
- Integrated Hardware - Sensor Platforms (D8.7, D8.8, D8.9): Demonstrators consisting of an integrated hardware sensor platform which includes UGV Units, Stationary Sensors, and Handheld Devices [59] [60] [61] [62].

- Integrated EU-RADION System (D8.10, D8.11, D8.12): A tripartite series delivering the integrated EU-RADION system in progressive iterations, from an early prototype enabling measurement sessions to a fully functional system utilized during demonstrations [63] [64] [65].

3.9.1 Hardware Integration Methodology

The hardware integration methodology adopted an iterative process, allowing for the quick identification and resolution of potential issues, thereby minimizing their impact on the overall development. The process commenced with planning integration tests, which involved all consortium experts to create a comprehensive concept for integration testing. This concept remained flexible throughout the project, allowing for necessary adjustments or extensions. Each hardware component, upon completion, was individually tested to confirm readiness for further integration. This approach was applied to all hardware components, including the Sensor Integration Unit (SIU) and its subcomponents, as well as various platforms like the Unmanned Ground Vehicle (UGV), which was among the most extensively integrated platforms. The iterations focused on connecting components, testing interfaces, and incorporating functionalities, with the final iteration preparing the system for the demonstration event, integrating all operational components and software.

3.9.2 Software Integration Methodology

The software integration methodology mirrored the hardware approach, starting with planning and conceptualizing integration tests. The methodology emphasized the readiness of each software component before proceeding with integration, ensuring all non-hardware system components could effectively communicate and collaborate. This approach aimed at integrating the software seamlessly with the hardware to produce a fully operational system for the final demonstration. Key software components included the Network Controller, Dispersion Engine, UGV Swarm Controller, and the Tactical Command Tool, with the latter being crucial for controlling the entire EU-RADION system. The integration process for software also involved iterative phases focusing on interfaces, communication, specific functionalities, and final optimization.

This structured and flexible integration methodology facilitated the effective assembly of the EU-RADION system's complex hardware and software components, ensuring the system's readiness to enhance the situational awareness and decision-making capabilities of first responders in radiological emergencies.

3.9.3 Integration Tests Summary

The EU-RADION project underwent extensive integration testing to ensure the seamless operation of its components within the system. This chapter provides a detailed summary of how each component was integrated and tested.

The SIU integration tests focused on the integration of various sensors including the CZT spectrometer, NaI spectrometer, Geiger Muller tube, and gas sensors with the SIU computing platform. Each sensor integration test ensured data acquisition and stable operation of the devices. Additionally, the power supply integration ensured that the SIU and its components were adequately powered, while the adaptable navigation unit integration confirmed the acquisition of navigation data by the SIU.

The Stationary Sensor Platform underwent tests to ensure the platform's casing was selected and used effectively for SIU protection, addressing operational and overheating concerns. The integration with the power supply was tested to confirm the platform's power functionality. Communication tests with the Network Controller (NC) ensured seamless data transmission and reception, contributing to the platform's operational efficacy.

Similar to the Stationary Sensor Platform, the Handheld Sensor Platform was tested for casing selection and integration with the power supply, ensuring operational stability and addressing potential overheating issues. Communication tests with the NC verified the platform's ability to send and receive data, ensuring its functionality within the EU-RADION system.

The UGV integration tests encompassed various components, including the chassis, power supply, onboard computer, motor controller, and main control unit, ensuring their preparedness for connector and mechanical holder integration. The telemetry integration confirmed the UGV's status and internal component communication capabilities, enhancing the UGV's operational readiness for field deployment.

The UGV Swarm tests focused on Apache Kafka Broker Communication, ensuring the sending and receiving of messages for effective swarm communication. The tests confirmed the NC's ability to receive data from the broker and send messages to specific topics, validating the swarm's communication framework.

The Navigation Unit underwent general functionality tests, GNSS tests for signal reception and accuracy, and housing selection tests to ensure operational stability. Communication tests between the SIU and the navigation unit were conducted to verify data acquisition and command reception, ensuring the unit's integration within the system.

The Network Controller (NC) tests included MQTT and Apache Kafka Broker Communication tests to verify the NC's ability to send and receive messages. Additional tests confirmed the NC's integration with a universal sensor platform and its capability to manage sensor platforms, ensuring network stability and data channel functionality.

The Tactical Command Tool (TCT) tests encompassed various functionalities including asset listing, control, self-testing, spectrometer measurement workflow, and configuration management. These tests ensured the TCT's capability to manage system assets, perform measurements, and configure system settings effectively.

The Dispersion Engine (DE) initial tests focused on Kafka communication, ensuring the DE's ability to connect to the Kafka broker and exchange information with the TCT and NC. Additional tests verified the DE's operational state management, confirming its readiness to switch between idle and running states based on system commands.

This comprehensive integration testing phase was pivotal in confirming the operational readiness of the EU-RADION system's components, ensuring their effective collaboration within the system to enhance emergency response capabilities in the face of radiological threats.

The validation process's outcome was documented, detailing whether the system met each requirement. In instances of interrelated requirements, the fulfilment of one could be compromised in subsequent versions if it facilitated meeting another related requirement, thereby aiding in process sub-optimization. Such instances were noted in the evaluations.

In situations where the system failed to meet a requirement, deviations were classified as either crucial or non-crucial. Crucial deviations, which threatened the achievement of the project's overarching requirements, necessitated additional actions to ensure compliance. Conversely, for non-crucial deviations, further action was optional and aimed at realizing specific, non-essential features to demonstrate the project's overall Science and Technology objectives fulfilment.

The validation criteria were grounded in the D2.2 User Requirements Specification, developed in collaboration with end-users and industry experts. These requirements represented the standards the developed system needed to meet to achieve the highest technology readiness level (TRL 9). However, the project's ambition was to reach TRL 6 by its conclusion, prompting the consortium to establish a set of technical requirements (documented in D3.1 Technical Requirements Specification) based on D2.2, which were then used to assess and validate the development outcomes.

3.10 WP9 EU-RADION Dissemination, Exploitation and Demonstration

In WP9 EU-RADION Dissemination, Exploitation, and Demonstration, led by UW, the focus was on disseminating project results through scientific channels such as conferences and journals, press releases, and awareness-raising campaigns. Additionally, plans for exploitation and commercialization were developed, with extensive analysis of business scenarios and opportunities. This work package played a crucial role in identifying potential target groups and preparing for commercialization. One of the key activities was the final demonstration of the system under realistic conditions.

Commercializing project results presents significant challenges, which were addressed through the development of an exploitation plan and a business model within WP9. Success in commercialization requires a deep understanding of the target market, demand for proposed solutions, and the needs of end users. To ensure this understanding, the project consortium included representatives from industry/SMEs (ITTI, tms, AIRSENSE) with expertise in commercialization and established networks within the market.

The EU-RADION project, encompassing Work Package 9, implemented a multifaceted approach for Exploitation and Dissemination. The following deliverables were prepared within this work package:

- Communication Plan (D9.1) outlined a comprehensive strategy for communication and dissemination activities within the EU-RADION project [66].
- Dissemination Report (D9.2, D9.3, D9.4) a series of reports documenting the dissemination efforts conducted throughout the project's duration. Generated annually by UNIWARSAW, these public reports chronicle the various dissemination activities carried out [67] [68] [69].
- Exploitation Plan (D9.5) is a confidential document intended solely for consortium members, including the Commission Services. It is a strategic report that maps out the potential markets, business opportunities, and commercial viability of the project's outputs [70].
- Demonstration Report (D9.6) offers a comprehensive account of the demonstration activities, including the preparatory steps, execution, outcomes, and feedback from end-users. Prepared by ITTI, this public report provides valuable insights into the practical application and effectiveness of the project's results [71].

Communication Plan: The project's communication strategy was focused on maximizing visibility and engaging stakeholders. Diverse channels such as academic publications, social media, and specialized forums were utilized. Emphasis was on disseminating research findings, raising awareness, and fostering collaborations. Special events and workshops also played a key role in reaching out to the community and stakeholders, ensuring continuous engagement and dissemination of project advancements.

Dissemination Efforts: Dissemination activities were extensive, targeting both scientific communities and industry practitioners. Key activities included presentations at international conferences, publication of research papers, and participation in industry expos. This multi-channel approach ensured broad dissemination of project results, fostering an environment for collaboration, knowledge sharing, and future exploitation of the project’s outputs. Partnerships with educational institutions also facilitated the integration of project findings into academic curricula, further extending the project's reach.

3.10.1 Final Demonstration

The Final Demonstration of the EU-RADION project, an integral component of Work Package 9 (WP9) led by Warsaw University (UW), aimed to exhibit the system's functionality in a realistic setting, adhering to pre-established scenarios. This approach intended to bolster the system's reliability and user-friendliness, addressing three Key Performance Parameters (KPIs): operational continuity, reflecting multinational interdisciplinary needs, and achieving a high acceptance level among stakeholders and end-users.

The demonstration highlighted a tunnel scenario, demonstrating the EU-RADION system's capability in managing incidents in constrained environments such as road tunnels, where hazards like RN substance contamination and access limitations due to smoke or structural challenges may occur. The scenario showcased the deployment of Unmanned Ground Vehicles (UGVs) equipped with Sensor Integration Units for reconnaissance, with data integration facilitated through the Tactical Command tool, enhancing situational awareness and response efficiency.

Figure 28 Pre-Demonstration Setup: Entrance to the tunnel (left), ITTI representative preparing the system (right)

Conducted on February 7th and 8th, 2024, in Åndalsnes, Norway, at the Runehamar Test Tunnel, the event commenced with onsite preparations by consortium partners, research institutes, military services, and other stakeholders. The two-day event included a conference discussing CBRN detection advancements and a field demonstration illustrating the system's practical application in a tunnel scenario.

Figure 29 The picturesque surrounding of the Runehamar Test Tunnel

The first day focused on theoretical aspects, emphasizing the EU-RADION system's innovation, particularly its use of machine learning and dispersion modeling for radioactive substance detection. The discussions extended to project dissemination and exploitation strategies, engaging a diverse audience of military personnel, researchers, and end-users.

Figure 30 The first Day of the Final Demonstration held in the Conference Hall, pictured are the project representatives during their presentations.

The second day transitioned to a practical demonstration at the Runehamar Test Tunnel. Participants were given a tour, followed by a desk exercise and a field test simulating a traffic accident involving radioactive substances. This exercise displayed the UGV's capabilities in establishing safe zones and localizing radioactive sources, with live feeds providing a visual account of the operation. The successful demonstration of the Sensor Integration Unit and the Tactical Command Tool highlighted the project's advanced technological solutions and its potential to enhance emergency response strategies.

Figure 31 The Day 2 of the Demonstration – the Desk Exercise

This final demonstration not only showcased the EU-RADION project's state-of-the-art technology but also underscored the collaborative effort behind its development, marking a significant achievement in advancing unmanned operational technologies for safety and emergency responses.

4 Critical Implementation Risks and Mitigation Actions

Critical risks are a fundamental aspect of every project, with their prompt identification being essential for proactive management and prevention. The oversight of a project involves the diligent monitoring of various risks, both from within and external sources, which could impede its successful completion.

At the project proposal submission phase, we meticulously identified and catalogued potential risks, laying out preventive strategies for their mitigation. These risks spanned several categories, including cooperation and management challenges, such as the risk of subpar deliverables or project delays, and technological hurdles, like designs failing to meet user expectations or the Sensor Integration Unit not fitting its designated role. To counter these risks, we implemented several mitigation strategies: conducting regular internal audits, cultivating a culture of collaboration through continuous information exchange and meetings, directly involving critical end-users in the design phase, and employing an iterative design and development methodology. Additionally, we anticipated demonstration phase risks, such as the potential unavailability of the demo site, for which we arranged early verification and booking.

Below is an exhaustive list of critical risks identified at the outset of the project, along with the mitigation actions undertaken to address them throughout the project's duration. This list reflects the dynamic challenges encountered and the adaptive strategies employed to ensure the project's objectives were met.

Description of risk	Work package(s) involved	Proposed risk-mitigation measures	Probability	Impact
Management risks:				
MR1: Problems with internal communication and cooperation and conflicting goals among project multi-disciplinary team	WP1	Most of the EU-RADION partners have already worked together on various occasions (e.g. H2020 EU-SENSE, EDA CENSIT projects). A collaborative atmosphere was fostered through regular sharing of information and deepening the mutual understanding of the scope of the project through technical meetings and progress meetings.	1	3
MR2: Deliverables from a given WP are not available on time, which delays the impact of another WP.	WP1	Regular contacts between WP leaders were ensured. Project timeline and deliverable releases have been agreed by all WP leaders taking into account work to be done in particular work packages and its influence on other tasks.	2	3
MR3: Underestimation of resources for a given task/WP.	All	Project was regularly monitored in context of available resources for particular tasks.	1	3
Cooperation risks:				
CR1: Deliverables are of poor quality or they are delayed.	WP1	Internal review process was scheduled. There were frequent internal management reportsscheduled that would support monitoring of the project progress. Any potential delay risks shouldbe easy to spot and respond to with corrective solutions.	1	3
CR2: End users are no longer committed to supporting the project or their priorities have changed over time.	WP3	There were 2 internal project end-users, who were fully devoted and committed to the successfulrealization of the project. In addition, there is an open group of Stakeholders.	1	5
Technological risks:				
TR1: End users find the project design and goals in disharmony with their expectations.	WP3	Key end users have been identified in theproposal phase and they were also involved at the latter stages of the project, including requirements collection workshop, etc. They had real influence in the final look of the developed system.	3	4

TR2: Use cases implementations do not perform as desired / meet user expectations / add value.	WP3	Any organizational problems with the demo sites were solved ahead of the planned demonstration. The demo site was selected and thoroughly discussed with project end users, who were also responsible for leading the demonstration.	2	3
TR3: The designed interfaces do not include all of the necessary methods/functionalities and does not allow for robust communication between the components.	WP3,4	The project assumed an iterative design and development process. This approach allowed for interfaces modifications, extensions and corrections between the iterations.	4	2
TR4: The SensorIntegration Unit is not suited for the deployment on UGV/hand- held platform or as a stationary unit.	WP4,5	The iterative approach for the development allowed modifications of UGV, stationary and hand-held platforms as well as Sensor Integration Unit in order to ensure that they were compatible.	3	3
TR5: Navigation unit functionality provides toolow accuracy to track first responders effectively.	WP4	Navigation unit combined inertial navigation system as well as GNSS in order to increase the effectiveness of the positioning as deliver accurate data.	2	4
TR6: Raw datastream is too large to be transmitted to central node.	WP8	Data compression was applied whenever necessary.	2	3
TR7: Fusion of the several technologies cause Interface or fusion problems	WP4,8	Common Interface will be provided within WP4 for Sensor Integration Unit.	1	3
TR8: Dispersion modelling components require additional data/input.	WP6	Required input was included in the technical documentation and the tool's specification was delivered in the early stage of the project (asa part of technical requirements). Moreover, the iterative approach provided initial feedbackand possibility to adjust the tool design in case of any issues.	2	4
TR9: System performance is lower than required by the end-users	WP8	The project plan assumed several iterations ofthe development activities. Tests and validation results (including feedback from end users) made impact on the following iterations.	2	4
TR10: The complexity of the developed devices results in poor performance and/or high cost.For example, the necessity to install additional computing power results will increase the overall cost of the solution	WP9	The main technological partners are very experienced in building IT systems. Furthermore, innovations proposed in EU-RADION were based on existing platforms and tools. Higher performance hardware or reduced number of features were used as needed.	2	3

Demonstration risk:				
DR1: Unavailability of demonstration site.	WP9	Availability of the demo site (Runehamar tunnel site) was verified at the proposal stage. Further verification and booking were done in the early stage of the project. Moreover, an inspection of the venue was conducted 6 months before the demonstration, ensuring its availability for the planned activities. Over the subsequent six months, dedicated efforts were focused on the execution of the event. This proactive approach not only ensured the venue's availability but also allowed ample time for thorough preparation and implementation of the event activities.	1	4

Table 2 The list of Risks defined at the beginning of the project

During the lifetime of the EU-RADION project, the consortium faced unforeseen critical risks, primarily due to the COVID-19 pandemic. This global crisis led to an unprecedented level of supply chain disruption, affecting the electronic market significantly. The scarcity of electronic components became a substantial hurdle for the project, notably delaying the production of several hardware prototypes crucial for the project's advancement. These included the Adaptable Navigation Unit, Sensor Integration Unit, and a Swarm of Unmanned Ground Vehicles (UGV), all of which are integral to the project's objectives.

Despite early identification and mitigation efforts, the impact of these challenges was profound. The consortium's proactive steps included detailed discussions during the first periodic review and constant communication with the Project Officer and reviewers. However, the severity of the global supply chain disruption made it nearly impossible to circumvent these issues without affecting the project negatively.

In response to these challenges, the consortium employed several strategies to mitigate the impact and adapt to the situation. For the Adaptable Navigation Unit, the difficulty in obtaining motion sensors led to delays and necessitated changes in development plans. Similarly, for the Sensor Integration Unit, the shortage of electronic parts, such as the µController chips, resulted in significant delays in purchasing and testing, with some chips being non-functional upon delivery. The development of the Swarm of Unmanned Ground Vehicles also encountered delays due to chip shortages affecting essential components for the mesh communication system.

To address these unforeseen critical risks, the consortium applied for a six-month extension of the EU-RADION project. This additional time was deemed essential to compensate for the delays and ensure the delivery of the project's full scope and objectives within the contracted budget. The consortium's ability to navigate these challenges demonstrates resilience and adaptability in the face of global supply chain disruptions, ultimately ensuring that the project remains on track to achieve its goals despite unprecedented external pressures.

5 Lessons learned

The EU-RADION project faced unforeseen challenges due to the COVID-19 pandemic, notably in supply chain disruptions affecting the availability of electronic components essential for hardware prototype development. This significantly delayed progress, particularly in the development of the Adaptable Navigation Unit, Sensor Integration Unit, and Swarm of Unmanned Ground Vehicles. Despite these obstacles, the consortium's proactive approach, including adapting project timelines, searching globally for component suppliers, and iterative development processes, allowed for the successful completion of project objectives. These experiences underscored the importance of flexibility, thorough testing, and quality data analysis in project management, especially in unpredictable circumstances. The consortium's ability to navigate these challenges, with support from the European Commission, highlighted the strength of collaboration and the critical nature of allocating sufficient time and resources for testing and data analysis. This situation also revealed the complexity of equipment transportation between partners, especially across EU borders, emphasizing the need for planning and cooperation in future projects.

Throughout the project, the consortium remained committed to its objectives and adapted to changing circumstances, demonstrating resilience and adaptability. These "lessons learned" reflect the importance of flexibility, preparedness, and a strong collaborative spirit in managing the administrative and technical complexities of an ambitious project like EU-RADION.

The main conclusions drawn from the challenges encountered during the project execution are outlined below and divided into categories:

Insights from Technical Challenges:

- Network Flexibility: The integration necessity of novel sensor technologies underscored the significance of adaptable data processing and fusion approaches. Rigidly specialized methods limited the network's extensibility and adaptability.
- Sensor Platform Durability: The resilience of our Unmanned Ground Vehicle (UGV) platforms was underscored by their performance in challenging environments. Tested across harsh outdoor landscapes and low-light conditions, the UGVs demonstrated exceptional durability.
- Energy Efficiency: Employing lithium-polymer batteries, known for their high current output and energy density, was crucial. For extended operations, the platforms included connectors for additional power sources, greatly enhancing their endurance.
- Communication and Coordination: The importance of robust and flexible communication networks became clear. Utilizing mesh network technologies enabled the formation of a coordinated UGV swarm, allowing for efficient area coverage and task fulfillment.
- Autonomous Navigation: The deployment of SLAM (Simultaneous Localization and Mapping) technology was crucial for navigating uncharted environments autonomously. The integration of diverse sensors, such as lidars and depth cameras, along with sophisticated data fusion techniques, enabled UGVs to navigate accurately and perform tasks in GPS-denied areas.
- Sensor Sensitivity - Gamma spectrometers are notably susceptible to environments with high dose rates. Integrating these spectrometers with GM tube-based dosimeters enabled the adjustment of measurements to fit the environmental conditions encountered, by fine-tuning the measurement points of the spectrometer.
- Modular System Design and Black Box Approach - The system was structured modularly, facilitating more efficient integration testing. This was achieved in part by minimizing the number of active components involved.

Inisghts related to Managerial Challenges:

- Adaptability to Unforeseen Challenges: The COVID-19 pandemic highlighted the critical need for adaptability, as supply chain disruptions severely impacted the availability of essential components for hardware development. This underscored the importance of flexibility in project timelines and strategies.
- Global Search for Solutions: Faced with component shortages, the consortium's proactive global search for suppliers and an iterative development approach were key to overcoming obstacles and ensuring project continuity.
- Importance of Thorough Testing and Analysis: The project emphasized the need for rigorous testing and quality data analysis to manage technical complexities effectively, particularly in unpredictable situations.

- Collaboration and Support: The strong collaborative efforts within the consortium and the support from the European Commission were instrumental in navigating the project's challenges, highlighting the value of teamwork in achieving objectives.
- Resource Allocation for Testing and Analysis: Allocating sufficient time and resources for testing and data analysis emerged as a crucial strategy, enabling the consortium to address technical issues and validate project outcomes efficiently.
- Logistical Considerations for Equipment Transportation: The complexities of transporting equipment between partners, especially across EU borders, revealed the necessity for detailed planning and cooperation to ensure smooth project execution.

Overall, the EU-RADION project's experience reinforces the significance of flexibility, preparedness, and a collaborative approach in managing large-scale projects, offering valuable insights for future endeavors in similar domains.

6 Summary/Conclusion

The EU-RADION project's final report encapsulates the culmination of extensive efforts toward improving radiological hazard detection and identification. Through innovative research and development, the consortium effectively addressed the challenges posed by the dynamic threat landscape, leveraging advanced sensor technology, computational tools, and user-centric design methodologies. The project was marked by successful milestones across all work packages, from system architecture development to field testing and system validation. Notably, the project navigated unforeseen challenges, such as the COVID-19 pandemic, demonstrating resilience and adaptability. The collaborative spirit among consortium members, coupled with European Commission support, was pivotal in overcoming obstacles. Key lessons underscored the importance of thorough testing, data analysis, and the strategic allocation of time and resources. This report not only documents the project's achievements and lessons learned but also reinforces the EU's commitment to enhancing CBRNe preparedness and response capabilities.

Final demonstration video available under:

https://www.youtube.com/watch?v=o6N21eTfoVI

References

[1] Europol (2018). EU Terrorism Situation and Trend Report 2018. https://www.europol.europa.eu/cms/sites/default/files/documents/tesat_2018_1.pdf

[2] European Commision (2017). Action Plan to enhance preparedness against chemical, biological, radiological and nuclear security risks. https://home-affairs.ec.europa.eu/system/files/2020-09/20171018_action_plan_to_enhance_preparedness_against_chemical_biological_radiological_and_nuclear_security_risks_en.pdf

[3] Jankiewicz, B. (2017). ENCIRCLE D3.10 Needs and Gaps Update. https://encircle-cbrn.eu/wp-content/uploads/2017/05/ENCIRCLE-WP3-WAT-D3.10-Needs-and-Gaps-Update.pdf

[4] IFAFRI (2018). Capability Gaps. https://www.internationalresponderforum.org/services/capability-gaps

[5] Szklarski, Ł., & Oleś, M. (2020). D1.1 Project Handbook. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[6] Oleś, M., Szklarski, Ł., & Walczyk, W. (2020). D1.2 Project Website. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[7] Szklarski, Ł., & Smoliński, A. (2021a). D1.3 Annual Report (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[8] Szklarski, Ł., & Smoliński, A. (2022). D1.4 Annual Report (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[9] Lipinski, P. (2020). D2.1 Suite of adapted scenarios. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[10] Lipinski, P. (2021a). D2.2 User Requirements Specification. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[11] Lipinski, P. (2021b). D2.3 Key Performance Parameters. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[12] ISO, IEC, (2018). 29148:2018 Systems and software engineering. Life cycle processes. Requirements engineering. https://www.iso.org/standard/72089.html

[13] Maik, P., Smoliński, A., & Oleś, M. (2021). D3.1 Technical Requirements Specification. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[14] Szklarski, Ł., Zalas, M., Michoń, K., & Maik, P. (2021). D3.2 Concept of Operation. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[15] Maik, P., Zalas, M., Michoń, K., & Szklarski, Ł. (2021). D3.3 Architecture Report (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[16] Szklarski, Ł., Maik, P., Koch-Eschweiler, H., Vågberg, D., & Ungethüm, B. (2022). D3.4 Architecture Report (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[17] Szklarski, Ł., Maik, P., Koch- Eschweiler, H., Vågberg, D., & Ungethüm, B. (2022). D3.5 Architecture Report (III). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[18] Ungethüm, B. (2021a). D4.4 Radio-Nuclide Sensor Unit. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[19] Ungethüm, B. (2022a). D4.5 Radio-Nuclide Sensor Unit (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[20] Ungethüm, B. (2022b). D4.6 Radio-Nuclide Sensor Unit. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[21] Ungethüm, B. (2021b). D4.7 Gas Sensor Unit. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[22] Ungethüm, B. (2022c). D4.8 Gas Sensor Unit (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[23] Ungethüm, B. (2022d). D4.9 Gas Sensor Unit. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[24] Kaiser, D. (2021). D4.10 Adaptable Navigation Unit. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[25] Kaiser, D. (2022). D4.11 Adaptable Navigation Unit (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[26] Kaiser, D., Koch-Eschweiler, H., Wieczorek, A., & Szklarski, Ł. (2023). D4.12 Adaptable Navigation Unit. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[27] Ungethüm, B. (2021c). D4.13 Integrated SIU (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[28] Ungethüm, B. (2022e). D4.14 Integrated SIU (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[29] Ungethüm, B. (2023a). D4.15 Integrated SIU (III). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[30] Ungethüm, B. (2022f). D5.1 Sensor Platforms (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[31] Ungethüm, B. (2023b). D5.2 Sensor Platforms (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[32] Ungethüm, B. (2022g). D5.3 Handheld Sensor Platform (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[33] Ungethüm, B. (2023c). D5.4 Handheld Sensor Platform (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[34] Ungethüm, B. (2022h). D5.5 Stationary Sensor Platform (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[35] Ungethüm, B. (2023d). D5.6 Stationary Sensor Platform (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[36] Michoń, K., Zalas, M., Maik, P., & Szklarski, Ł. (2022). D5.7 UGV Swarm (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[37] Oleś, M., Zalas, M., Folejewska, W., Nowaczyk, M., Maik, P., Wieczorek, A., & Szklarski, Ł. (2023). D5.8 UGV Swarm (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[38] Wiborg Hagen, T., Ungethüm, B., Forsberg, A., Granström, M., Norenberg, M., Jakubowska, A., & Wołoszczuk K. (2023). D7.6 Laboratory and Field Test Report (III). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[39] Forsberg, A., Persson, L., & Granström, M. (2023). D6.1 Deposition estimation. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[40] Elfverson, D., & Lejon, C. (2023). D6.2 Improved Urban Deposition. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[41] Lewalder, S. (2022a). D6.4-TCT-User Interface and Access Point (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[42] Lewalder, S., & Szklarski, Ł. (2023a). D6.5 – TCT – User Interface and Access Point (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[43] Lewalder, S. (2022b). D6.6-TCT-Situational Awareness Engine (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[44] Lewalder, S., & Szklarski, Ł. (2023b). D6.7 – TCT – Situational Awareness Engine (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[45] Maik, P., Wieczorek, A., Folejewska, W., Oleś, M., & Szklarski, Ł. (2023). D6.8 Network of Sensors Controller. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[46] Høibråten, S., Granström, M., Kliś, B., & Ungethum, B. (2021). D7.1 Data Collection Plan (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[47] Høibråten, S., Forsberg, A., Granström, M., Persson, L., Kliś, B., Lipinski, P., & Ungethüm, B. (2022). D7.2 Data Collection Plan (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[48] Wiborg-Hagen, T., Høibråten, S., Ungethum, B., Granstrom, M., Forsberg, A., Larsson, A., Persson, L., Norenberg, M., Jakubowska, A., Wieczorek, A., Maik, P., & Szklarski, Ł. (2023). D7.3 Data Collection Plan (III)

[49] Høibråten, S., Ungethum, B., Granstrom, M., Lipiński, P., & Szklarski, Ł. (2022). D7.4 Laboratory and Field Test Report (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[50] Høibråten, S., Ungethüm, B., Forsberg, A., Granström, M., Jakubowska, A., & Lipinski, P. (2022). D7.5 Laboratory and Field Test Report (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[51] ISO, IEC, (2018). 17025:2018-02 Technical Requirements. https://sklep.pkn.pl/pn-en-iso-iec-17025-2018-02p.html

[52] Maik, P., & Szklarski, Ł. (2022a). D8.1 Integration Testing Results (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[53] Vågberg, D., Kaiser, D., Koch-Eschweiler, H., Ungethüm, B., Wieczorek, A., Maik, P., & Szklarski, Ł. (2023). D8.2 Integration Testing Results (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[54] Kaiser, D., Koch-Eschweiler, H., Vagnberg, D., Maik, P., Szklarski, Ł., & Wieczorek, A. (2023). D8.3 Integration Testing Results (III). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[55] Maik, P., & Szklarski, Ł. (2022b). D8.4 Validation results (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[56] Maik, P., Folejewska, W., Lewalder, S., Vågberg, D., Ungethüm, B., Wieczorek, A., & Szklarski, Ł. (2023). D8.5 Validation results (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[57] Maik, P., Folejewska, W., Lewalder, S., Kaiser, D., Vagberg, D., Ungethum, B., Wieczorek, A., Szklarski, Ł., Lipiński, P., Wołoszczuk, K., Jakubowska, A., & Norenberg, M. (2023a). D8.6 Validation results (III). CLOR. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[58] Maik, P., Folejewska, W., Lewalder, S., Kaiser, D., Vagberg, D., Ungethum, B., Wieczorek, A., Szklarski, Ł., Lipiński, P., Wołoszczuk, K., Jakubowska, A., & Norenberg, M. (2023b). D8.6 Validation results (III). CLOR.

https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[59] Maik, P., & Szklarski, Ł. (2022c). D8.7 Integrated Hardware-Sensor Platforms (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[60] Zalas, M., Urbański, J., Wieczorek, A., Oleś, M., Ungethum, B., Kaiser, D., Maik, P., & Szklarski, Ł. (2023a). D8.8 Integrated Hardware-Sensor Platforms (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[61] Zalas, M., Urbański, J., Wieczorek, A., Oleś, M., Ungethum, B., Kaiser, D., Maik, P., & Szklarski, Ł. (2023b). D8.8 Integrated Hardware-Sensor Platforms (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[62] Zalas, M., Urbański, J., Ungethum, B., Kaiser, D., & Szklarski, Ł. (2023). D8.9 Integrated Hardware-Sensor Platforms (III). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[63] Maik, P., & Szklarski, Ł. (2022d). D8.10 Integrated EU-RADION System (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[64] Maik, P., Lewalder, S., Vågberg, D., Folejewska, W., Nowaczyk, M., Bolek, M., Wieczorek, A., & Szklarski, Ł. (2023). D8.11 Integrated EU-RADION System (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[65] Maik, P., Lewalder, S., Vågberg, D., Folejewska, W., Nowaczyk, M., & Bolek, M. (2023). D8.12 Integrated EU-RADION System (III). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[66] Gudzbeler, G., Stefanowski, K., & Tomaszewska-Michalak, M. (2021a). D9.1 Communication Plan Dissemination level. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[67] Gudzbeler, G., Stefanowski, K., & Tomaszewska-Michalak, M. (2021b). D9.2 Dissemination Report (I). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[68] Gudzbeler, G., Stefanowski, K., & Tomaszewska-Michalak, M. (2022). D9.3 Dissemination Report (II). https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[69] Gudzlbeler, G., Oblinska, K., Zbroszczyk A., Szklarski, Ł., & Wieczorek, A. (2024). D9.4 Dissemination Report. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[70] Gudzlbeler, G., Oblinska, K., Zbroszczyk A., Szklarski, Ł., & Wieczorek, A. (2024). D9.5 Exploitation Plan. https://ittispzoo-my.sharepoint.com/personal/anna_wieczorek_itti_com_pl/Documents/Projekty/EU-RADION/Deliverables - drafts/www.eu-radion.eu

[71] Wieczorek A., Maik P., & Szklarski Ł. (2024). D9.6 Demonstration Report.