IIMEO

Title	# State-of-the-art Update, Requirements and Use Cases Specifications
Project Name	IIMEO – Instantaneous Infrastructure Monitoring by Earth Observation
Project Number	101082410
Deliverable number	D1.1
Document Number	IIMEO-ATB-D-0003
Issue / internal Revision	02 / 03
Status/Release Date	Released / 13.11.2023
Dissemination Level	Public

Funded by the
European Union

1 PREFACE

In 2022, a European Consortium[1] has been selected by the European Commission to implement the project *"Instantaneous Infrastructure Monitoring by Earth Observation" (IIMEO)* [1] [2]. The project is funded by the European Union under the Horizon Europe program as an innovation action with €2.8 million and runs until 30 November 2025. It aims to develop and demonstrate key technologies for the global monitoring of critical infrastructures from space in near real time. A pilot application will be the monitoring of railway lines.[2]

"Energy supply, communications, transportation – our globalized society is highly dependent on functioning infrastructures. Typical examples are roads and railway lines, but also water pipelines, data cables and power lines," explains OHB project coordinator Daro Krummrich. "Just how critical these infrastructures are for daily life becomes particularly apparent when disruptions occur. These can be caused by natural disasters, extreme weather events or deliberate manipulation. In order to be able to restore the functionality of critical systems promptly after an incident, it is important to quickly gain an overview of the overall situation. This is why IIMEO is about detecting infrastructure malfunctions automatically, across large areas and in near real time, regardless of local weather and lighting conditions."
To this end, a satellite system is to be developed within the framework of the project. The intended use case calls for the principles of New Space: Since global coverage and revisit times of less than one hour are required for infrastructure monitoring, the project partners assume that a suitable constellation in low Earth orbit (500 to 900 kilometers altitude) will consist of at minimum 24 orbital planes with at least 2 small satellites each. Synthetic Aperture Radar (SAR) imaging radar instruments are to be used as payloads, which will be supplemented by sensors for the wavelength range of visible light (VIS). This will enable high-resolution images to be generated even at night and under heavy cloud cover. Another focus of the project is the development of algorithms.

Figure 1-1: Schematic of IIMEO's objectives

Since continuous global monitoring of infrastructure with SAR and VIS sensors produces gigantic amounts of data, it is necessary that these are already processed on board the satellites. This is to avoid the data downlink being a bottleneck in the system. Davide Di Domizio, Research Programme Administrator at the European Health and Digital Executive Agency (HaDEA) and in charge of IIMEO, explains: "In 2022, the Horizon Europe work program set the ambitious goal of demonstrating the performance of key technologies for future Earth observation systems by 2028. With the development of the planned on-board data processor, IIMEO is well positioned to make an important contribution to this mission." Once the development phase is complete, all relevant key technologies will initially be combined into an airborne technology demonstrator. The goal of the flight campaign planned for 2025 is to demonstrate the end-to-end prototype downstream service, including on-board data processing. The automated detection of obstacles on railway tracks is to serve as an example application. The national company for the management of railway infrastructure in Serbia was selected as a cooperation partner and pilot user. Slobodan Rosić, Serbian Railway Infrastructure Risk Manager, points out: "A satellite-based automatic monitoring system makes it possible to collect high-quality information about the condition of the infrastructure in real time without having to interrupt regular traffic and without the need for personnel on site." The next demonstration mission, currently planned for 2026 and 2027, will go one step further: it will demonstrate that the system developed in the course of IIMEO is also suitable for the global monitoring of railway lines from space.

---

[1] The project is being coordinated by *OHB Digital Connect GmbH* (OHBDC), a subsidiary of space and technology group OHB SE. *Antwerp Space N.V.* (AWS) brings its expertise to the on-board data processor. The *Institut für angewandte Systemtechnik Bremen GmbH* (ATB) brings its expertise in the implementation of european projects and the definition and management of requirements. The *Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V.* (Fraunhofer / FHR) brings ist expertise on SAR-data acquisition and processing. The *Fondazione Brunno Kessler* (FBK) brings its expertise on real-time capable fully automated detection methods based on AI. The *Univerzitet U Nis* (NIS) brings its expertise on railways and fully automated detection methods based on AI.

[2] LinkedIn: https://www.linkedin.com/company/iimeo-europe/

Table of Contents

List of Tables

List of Figures

2 INTRODUCTION

2.1 Document Purpose

This document comprises the results of tasks T1.1 *End-user requirements and use cases analysis* and T1.2 *Constellation and data transfer requirements analysis*. A set of pilot use cases for infrastructure monitoring has been defined and appropriate requirements collected, including requirements from the pilot's end users (section 3). An update of the state-of-the-art (from literature etc.) for the underlying technologies, such as on-board processing, particularly data compression and reduction, as well as a specification of evolving technical requirements is being provided (section 4).

Requirements Analysis Approach

The project approach is bottom up: starting from the analysis of the requirements from the pilot and on the data transfer, as well as analysis of the restrictions on the communication imposed by SmallSat LEO constellations (WP1).

We propose a common approach for categorizing relevant system requirements for later stages of the project (concept/specification & implementation phase), from which the overall workflow of the project will benefit for several reasons: Firstly, it allows for a systematic and comprehensive analysis of the various aspects that need to be considered when designing and implementing the targeted system components. By breaking down the requirements into distinct categories as shown below, it becomes easier to identify specific needs and prioritize them accordingly. Secondly, it helps to ensure that all stakeholders involved in the project have a clear understanding of what is required and can work together towards a common goal. The use of a common language and framework for discussing requirements, misunderstandings and miscommunications can be minimized, leading to a more efficient and effective project implementation. Moreover, the categorization of requirements allows for a more effective comparison of different monitoring solutions. By using the same set of criteria to assess different options, it becomes easier to identify the strengths and weaknesses of each solution and make informed decisions about which one best meets the needs of the project. Finally, this approach can be applied to both, the analysis of end user requirements of our main Serbian Railway infrastructure monitoring use case (section 3.1), as well as to the further system requirements analysis of potential other use cases (section 3.2).

Requirements categories

By using the following common set of categories for requirements analysis, it becomes easier to verify that the envisaged infrastructure monitoring system is tailored to the specific needs of the use cases presented in this document:

Table 2-1:Overview of requirement categories

Category	Variation	Comment
Type of Service operation	Continuous (autonomous) service	For this type of service, the satellite constellation collects data continuously and/or autonomously along predefined linear features or specific areas of interest without requiring external triggers or user-initiated requests
	On-demand service	The origin for the trigger of this service type is initiated directly by a user or an external entity, based on their specific needs or requirements. This can be in particular useful e.g. for planned (routine) inspections or investigations

	Trigger-based service	The origin of this trigger is initiated by predefined events or conditions, such as sensor readings or specific thresholds being met. This can be useful in particular for monitoring certain (unpredictable) events or weather phenomena, such as heavy rainfall or extreme temperatures
Spatial resolution/accuracy	High spatial resolution	for detecting small changes on the railway tracks or other infrastructure features
	Moderate spatial resolution	for monitoring changes over longer time periods across larger areas
	Fixed area of interest	for monitoring a specific geographic location or asset, such as a railway station or section of track exact information about the area of interest is provided (geographical location)
	Along a linear feature	for monitoring infrastructure along a railway line, pipeline, dike, road etc. no exact information about the area of interest is provided
Accuracy and precision	Sub-meter accuracy	for high-precision analysis of changes and anomalies in the infrastructure
	Meter-level accuracy	for detecting larger changes and trends over time
Temporal resolution	Near-real-time	the system updates the data periodically (frequency of signal update) appropriate to the rate the process to be observed evolves, e.g. every 20 minutes
	Response delay time	Delay time from change/anomaly detection to end-user notification
	Trigger event	A certain event triggers the change detection process (e.g. some extreme weather events)
Data format/interoperability	Standard data formats	for easy integration with existing systems and platforms
	Interoperability with other data sources	for combining earth observation data with other sources, such as ground-based sensors and geospatial data
Prioritization	Shall	indicates a mandatory requirement
	Should	indicates a recommendable requirement
	May	is used to indicate non-mandatory requirements that are nice-to-have, but not crucial for successful system operation

In addition to the end-user requirements analysis and the additional requirements gathered from the potential use cases (section 3.2), which are harmonised in the set of consolidated requirements, the Research and Technological Development (RTD) partners have created an **in-depth analysis of the state-of-the-art research activities** in the relevant areas, what was used, enriched by the expertise (of RTD partners), for a creation of a set of technical requirements (section 4). All participants in the activities described above (see Figure 2-1) have also provided **technical visions** and innovation ideas to complete the generic requirements.

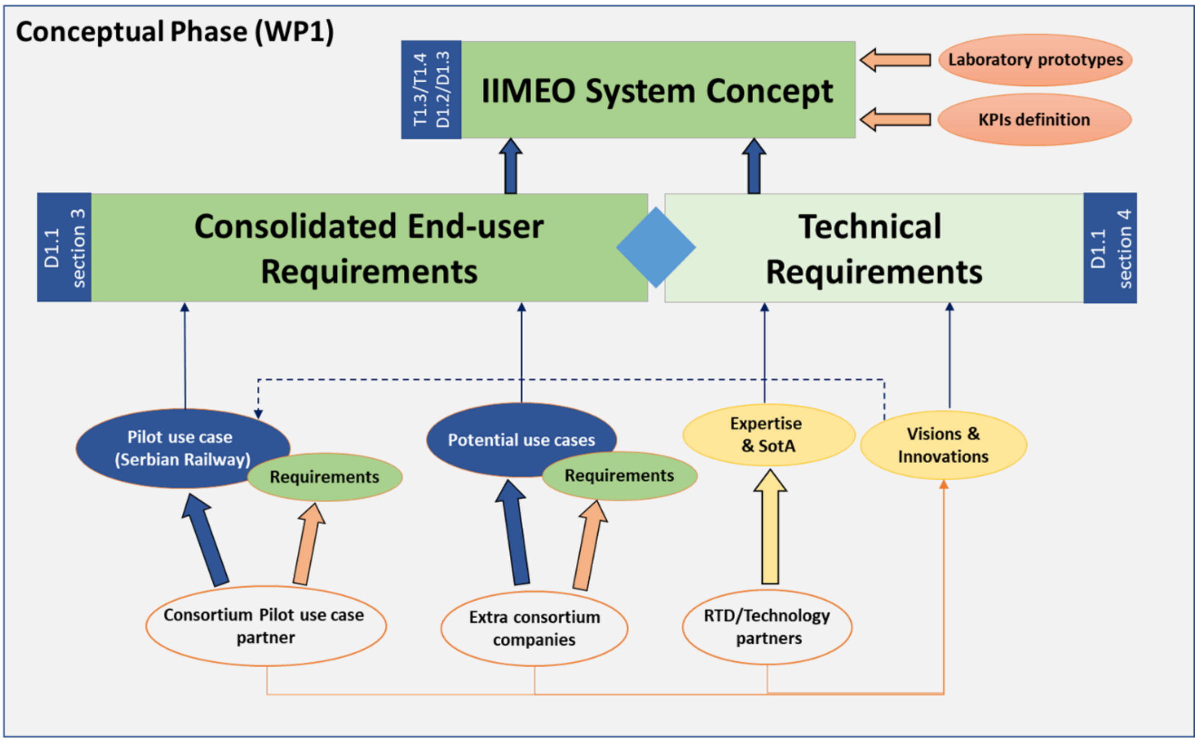


Figure 2-1: IIMEO Requirements Analysis & Concept Pathway

2.2 Document Structure

The document is outlined as follows:

- **Section 3** provides the results of the use cases analysis and the resulting end-user requirements (Task 1.1), with focus on the following key aspects:
    - collect (end-) user needs: the consortium will involve the end users (Serbian railways) of the future services, – e.g., requirements and problems encountered by the users in monitoring railway infrastructure etc. The objective is an analysis of user requirements to define use cases for real-time infrastructure monitoring. This includes both the analysis of key use cases in the area of rail infrastructure (**section 3.1**)
    - additional requirements: The other potential use cases and applications of the end-to-end earth observation technology to be developed in the project, will be analysed. An extension of the defined system to a wide range of applications with a focus on time-critical information to secure the operation of infrastructure services will be performed (**section 3.2**)

This will allow for definition of the requirements concerning the service to be developed (railway infrastructure monitoring) but also concerning further possible services

- **Section 4** covers the constellation and data transfer requirements analysis: i) The resulting requirements to the on-board processing, in particular to data compression and reduction, will be defined and compiled, ii) analysis of existing European EEE-parts. The technical requirements posed by SmallSat constellations operating in LEO are analysed with a focus on transfer rate limitations imposed by the data downlink

3 END USER REQUIREMENTS AND USE CASES ANALYSIS

This section will outline and provide the results of the use cases analysis and the resulting end-user requirements (Task 1.1). This includes the definition of the pilot use cases for infrastructure monitoring and analysis of the correlating requirements (resolution, timing, data products and processing steps) that are relevant to conceptualise the overall IIMEO solution. This section is split into two main parts:

1. Requirements analysis of IIMEOs main use case **Serbian Railway Infrastructure Monitoring**, which involves the actual end users (Serbian railways) of the future services, providing a thorough analysis of challenges, targets and needs encountered by the users in monitoring railway infrastructure
2. Requirements analysis of **other potential use cases and applications** of the end-to-end earth observation technology to be developed in the project. This will allow for definition of the requirements concerning the service to be developed (railway infrastructure monitoring) but also concerning further possible services.

As a result of the requirements analysis, a comprehensive list of consolidated system requirements with different aspects (such as spatial, temporal, type of service) will be provided (section 3.1.3).

3.1 Railway Infrastructure Monitoring Pilot Use Case

The following Table 3-1 summarizes some of the possible infrastructure damages or static obstacles which can cause severe consequences (catastrophic events in the railway system) or cause material damage and timetable disruption. The noted table also analyses the damages and static obstacles form the perspective of requirements categories. The possible infrastructure damages or static obstacles were identified based on results of Shift2Rail projects GoSAFE RAIL, SMART and SMART2. This comprehensive list of potential causes for railway failure is presented here to provide a summary and preview of the analysed scenarios discussed in sections 3.1.1 and 3.1.2. By including this table already in the current section, it allows for a concise overview of the different causes for railway failures and their associated requirements, before delving into the detailed analysis in subsequent sections. This approach aims to facilitate a clearer understanding of the scope and range of the main pilot use case, providing a comprehensive glimpse into the diverse challenges and scenarios that the IIMEO system aims to address.

As it can be seen from Table 3-1, the SRI pilot is mainly focusing on railway failures caused by extreme weather situations (e.g. landslide, flood, fallen trees etc.). A key reason for that is the increasing number of such weather events that, according to World Meteorological Organisation (WMO)[3], has increased by a factor of five over the 50-year period, driven by climate change. This leads also to an increased downtime of the railway network. For example, Research has shown that adverse weather conditions are responsible for 5 to 10 % of total failures and 60 % of delays on the railway infrastructure in Sweden[4]. In addition, the current inspection measures of the railway track network after such events (e.g. by helicopter, drones, manual inspection) are very expensive and time consuming and in the case of severe damages due to weather-related event, together with restoring the damages and return to normal operations can last up to several days.

By use of EO infrastructure monitoring services, SRI pilot expect a significant reduction of their current efforts (costs) and time needed for identification of railway failures caused by extreme weather situations. Reducing the time to one hour for the inspection of the spacious railways tracks, will significantly improve the operational railway availability and safe operation.

For the moment, SRI pilot neither see the possibility for an economic 24/7 monitoring of the whole railway infrastructure, nor for an economic implementing EO services requesting near-real time feedback (e.g. real time identification of vehicle/obstacle on tracks to avoid crashes), since such services would require a continuous operation and very short response time, with very high requirements on number of LEO satellites and technologies implemented.

---

[33] https://public.wmo.int/en/media/press-release/weather-related-disasters-increase-over-past-50-years-causing-more-damage-fewer#:~:text=The%20number%20of%20disasters%20has,deaths%20decreased%20almost%20three%2Dfold.

[4] https://www.diva-portal.org/smash/get/diva2:1584141/FULLTEXT01.pdf

During the concept phase of IIMEO (T1.3/1.4), a careful evaluation will be conducted to determine which specific causes for railway failure will be implemented as an actual IIMEO service (within WP4). As there may be numerous "Mandatory" Use Cases identified, it is understood that it may not be feasible or necessary to develop services for all of them. Therefore, a selection process will be carried out to identify the most relevant and impactful use cases that align with the project goals and objectives. This selection will be based on factors such as feasibility, technical considerations, stakeholder requirements, and potential impact on railway infrastructure monitoring. By carefully evaluating and prioritizing the use cases, the project team will focus efforts on developing those services, that offer the greatest value and address the critical challenges in the railway infrastructure monitoring.

Table 3-1: Mapping of causes for railway failure to system requirements

Causes for railway failure	Type of Service operation	Spatial resolution/accuracy	Temporal resolution	(Trigger Event)	Prioritisation[5]
Landslide	On-demand service Continuous (autonomous) monitoring under specific conditions/event-based	Along a linear feature with meter-level accuracy Moderate spatial resolution with meter-level accuracy	Near-real-time Continuous service Trigger-based service	User on-demand User-defined fixed area of interest and service start/end Extreme weather events	Mandatory
Rockfall	On-demand service Continuous (autonomous) monitoring under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Continuous service Trigger-based service	User on-demand User defined fixed area of interest and service start/end Extreme weather events	Mandatory
Flood	On-demand service Autonomous under specific conditions/event-based	Along a linear feature with meter-level accuracy Moderate spatial resolution with meter-level accuracy	Near-real-time Trigger-based service	User on-demand Extreme weather events	Mandatory
Snow	On-demand service Autonomous under specific conditions/event-based	Along a linear feature with meter-level accuracy	Near-real-time Trigger-based service	User on-demand Extreme weather events	Mandatory
Trees	On-demand service	Along a linear feature with sub-meter accuracy	Near-real-time	User on-demand	Mandatory

---

[5] Prioritisation with respect to the end user requirements

Causes for railway failure	Type of Service operation	Spatial resolution/accuracy	Temporal resolution	(Trigger Event)	Prioritisation[5]
	Autonomous under specific conditions/event-based		Trigger-based service	Extreme weather events	
Rail parts and Maintenance equipment (e.g. sleepers)	On-demand service Autonomous under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Trigger-based service	User on-demand After maintenance operations along the line in the process of commissioning	Recommended
Stalled (large) vehicles	On-demand service Autonomous under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Trigger-based service	User on-demand Reported vehicle accidents (crashes, braking-downs)	Recommended
Contact line masts	On-demand service Autonomous under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Trigger-based service	User on-demand Extreme weather events After maintenance operations along the line in the process of commissioning	Recommended
Bridge collapse	On-demand service Continuous (autonomous) monitoring under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Continuous service Trigger-based service	User on-demand User defined fixed area of interest and service start/end Extreme weather events After maintenance operations along the line in the process of commissioning	Mandatory

Causes for railway failure	Type of Service operation	Spatial resolution/accuracy	Temporal resolution	(Trigger Event)	Prioritisation[5]
Lateral Buckling	On-demand service Continuous (autonomous) monitoring under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Continuous service Trigger-based service	User on-demand User defined fixed area of interest and service start/end Extreme weather events	Mandatory
Rotational Failure	On-demand service Continuous (autonomous) monitoring under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Continuous service Trigger-based service	User on-demand User defined fixed area of interest and service start/end Extreme weather events	Mandatory
Embankment	On-demand service Continuous (autonomous) monitoring under specific conditions/event-based	Along a linear feature with sub-meter accuracy Moderate spatial resolution with meter-level accuracy	Near-real-time Continuous service Trigger-based service	User on-demand User defined fixed area of interest and service start/end Extreme weather events	Mandatory
Wall/defence damage	On-demand service Continuous (autonomous) monitoring under specific conditions/event-based	Along a linear feature with sub-meter accuracy Moderate spatial resolution with meter-level accuracy	Near-real-time Continuous service Trigger-based service	User on-demand User defined fixed area of interest and service start/end Extreme weather events	Recommended

3.1.1 Pilot Use Case Description

Reliable transport infrastructure is one of the backbones of a prosperous economy, providing access to markets, jobs, and social services [3]. Two main means of transport over land are road and rail transport. It is generally acknowledged that railways are a comparatively safe mode of transport. There are nonetheless each year many recorded safety critical accidents caused by derailments and collisions between trains and obstacles on or adjacent to the railway tracks, so rail operations could be made even more safe if the number of collisions could be reduced (Project GoSAFE RAIL). Besides the more frequent obstacles such as people trespassing the railway tracks, there are obstacles such maintenance equipment left on the rail tracks and stalled cars on the track. An example of the train accident caused by the maintenance equipment on the tracks is the fatal accident happened in Netherland on 4th April 2023. A freight train collided with a construction crane on the tracks at Voorschoten. The wreckage of the crane ended up on another track, where a passenger intercity crashed into it and derailed. A passenger train derailed in after colliding with a maintenance crane can be seen in Figure 3-1[6] (left side). A DB Freight train that struck the crane first can be seen in the background. An example of the accident caused by stalled vehicle on the track is the accident happened near Gothenburg, Sweden, in March 2021, when a passenger train has smashed into a broken-down bus which was on a level crossing (Figure 3-1 right side).

Figure 3-1: Scenes of train accidents caused by different obstacles on the tracks. (left) Maintenance equipment left on the tracks. (right) Stalled bus on the level cross

Particularly hazardous railway obstacles are consequence of geological and natural hazards such as landslides, flooding and extreme weather conditions causing railway bridges damages/collapses and blocking the rail tracks due to fallen trees. Example of such an obstacle, fallen tree is given in Figure 3-2[7] and a scene of the train accident when a freight train was derailed by a landslide in Kentucky, USA, in February 2020 is shown in Figure 3-2[8].

Figure 3-2: (left) Storm Arwen rail chaos captured by helicopter team as fallen trees block Scots train tracks. (right) The aftermath of the rail accident outside Elkhorn City in Kentucky, caused by a shallow landslide

Besides the derailments caused by train collision with obstacles on and near the rail tracks, often derailments are these caused by rail tracks deformations due to earthquakes or extreme heat. Hot weather can affect the rails, which can expand, bend, and even break in the heat, which are the effects known as “buckling rails” (Figure 3-3 left). Heat was a factor in the derailment of a freight train in Lincolnshire on 30th June 2015 (Figure 3-3 right).

---

[6] https://www.prorail.nl/nieuws/treinongeval-bij-voorschoten
[7] https://www.dailyrecord.co.uk/news/scottish-news/storm-arwen-rail-chaos-captured-25560520
[8] Elkhorn City, Kentucky: a fiery train derailment by a landslide - The Landslide Blog - AGU Blogosphere.

Figure 3-3: (left) Typical example of track buckle, Australia. (right) Train derailment due to heat induced buckling in Lincolnshire, UK

In last decades, significant efforts have been put in development of trackside and on-board systems for autonomous detection of rail tracks and the obstacles on and near the rail tracks with the goal of both risk reduction to personnel, as no personnel walking along the line is required, and railway safety increase [4]. Examples of projects that dealt with the topic of advanced on-board obstacle detection in railways are Shift2Rail (Europe's Rail) projects SMART and SMART2.

As a result of developments of aerial and remote sensing technologies, in recent years, there has been also a rapid expansion of R&D of railway infrastructure monitoring using these technologies. The possible benefits have been identified such as enormous economic advantage, cost reduction and safety increase as the railway tracks could be monitored at a larger scale than by, for example, on-board systems. For example, project SMART2 proposed using of UAV remote sensing to complement on-board obstacle detection and so to achieve holistic approach to rail tracks detection and obstacle detection in railways.

Besides the aerial and UAV-based remote sensing technologies, in last years, there have been initiatives for using the space assets for railway monitoring. Space4Rail is an ESA initiative (SPACE4RAIL initiative[9], n.d.) to support the railway community by raising awareness of the added value that space-based assets can bring to railway applications. Different types of projects have been supported within this initiative and some of them are related to monitoring of hazards as sources of potential damaging of railway infrastructure/rail tracks. The feasibility study on satellite monitoring to enrich the analysis/prediction of track/terrain settlement behaviour including the identification of possible 'hotspots' in the network that are under threat (substructure stability and terrain deformation, e.g. due to existing geohazards such as mining or slow-moving landslides) was performed in the RailSAT project (RailSAT feasibility study[10]). However, no technical correlation between satellite data and relevant in-situ events could be established during the RailSAT project, so that due to this lack of technical feasibility, a viable business case could not be elaborated and the feasibility study was closed. The objective of the MATIST feasibility study[11] was to evaluate the technical feasibility, economic viability as well as the sustainability of services to the Alpine transportation infrastructure operators that are based on the integration of the space techniques radar interferometry and satellite navigation. The space assets mobilized for this project were:

Satellite SAR interferometry for surface displacement mapping and monitoring and satellite positioning for accurately measurement of surface displacement. Although the MATIST project demonstrated the overall feasibility of the intended solution for the provision of ground-motion information to operators of transport infrastructure, no demonstration project was proposed.

The LiveLand demonstration project[12] developed and demonstrated a number of solutions based on integrated data from Earth observation satellites and GNSS, complemented by geology, geomorphology and landslide

---

[9] https://space4rail.esa.int/

[10] https://business.esa.int/projects/railsat

[11] https://business.esa.int/projects/matist

[12] https://business.esa.int/projects/liveland

susceptibility from the BGS GeoSure dataset, for detecting, monitoring and forecasting landslide and subsidence hazards to support UK transport networks owners and operators. The LiveLand was not investigated for monitoring of other possible hazards for the rail transport different from landslides.

Besides the above-mentioned ESA initiative, other initiatives also recognised the need to support the R&D in remote sensing of railway infrastructure such as Shift2Rail Joint Undertaking (Shift2Rail Joint Undertaking). Shift2Rail H2020 project MOMIT (Project MOMIT- Multi-scale observation and monitoring of railway infrastructure threats[13]) demonstrated a new use of remote sensing technologies – such as drones and satellites – for railway infrastructure monitoring. MOMIT solutions were mainly aimed at supporting the maintenance and prevention processes within the infrastructure management lifecycle. The overall concept underpinning MOMIT project was the demonstration of the benefits brought by Earth Observation and Remote Sensing to the monitoring of railways networks both in terms of the infrastructure and of the surrounding environment, where activities and phenomena that could impacting the infrastructure such as ground movements near the infrastructure, vegetation elements that could affect trains operation along the corridor of interest, and hydraulic activities near the track could be present [5]. However, MOMIT project did not consider detection of the changes on the rail tracks such as obstacles (undesired objects) that would be possible consequences of natural hazards as (storm)-related conditions that could happen even in spite of the prevention measures. Such changes on the rail tracks (railway obstacles) are of interest in IIMEO.

Only a spaceborne approach is able to monitor infrastructure continuously and at large-scale. Other means such as airborne-based solutions can allow high-precision monitoring of small regions-of-interest, yet they become too costly when scaling up to larger areas. Furthermore, the airborne solutions are prone to environmental conditions that impede their usage in severe weather conditions, which are usually a trigger for railway infrastructure damages and occurrence of obstacles on the railroads that are envisioned to be detected by IIMEO technologies.

3.1.2 User Needs, Challenges and targeted Services

The IIMEO service prototype will be used in relevant railway environment to demonstrate and validate the overall end-to-end service as it could be operational in space, as well as the near-real-time service operation. The demonstration will be conducted with the involvement of the pilot end user – Infrastructure of Serbian Railways (ISR) – that is a member of IIMEO Advisory Board as a stakeholder. Necessary regulatory approvals for airborne-based demonstration in real-world railway environment will be issued by ISR upon provision of all necessary documentation by IIMEO partner NIS. The procedure for assuring the regulatory approvals adopted and implemented by ISR and NIS in ongoing H2020 Shift2Rail Project SMART2[14], dealing with development of system for on-board autonomous obstacle detection in railways, will be followed in IIMEO. The IIMEO Airborne-demonstration scenarios will be defined in cooperation with ISR and they will define the timing of the IIMEO flight campaign actions, service performance and acceptance criteria as well as position and the size of the obstacles which should be identified by IIMEO by anomaly and change detection algorithms. That is, the infrastructure itself, e.g. railway lines, will be detected and deviations from expected detections – anomalies – will be flagged, and measurements taken above the current infrastructure will be checked for significant changes against measurements of the same infrastructure when it was known to be healthy. The acquisition of SAR and VIS data, as well as on-board processing will be performed during the airborne flight campaign, also exploiting the availability of the data previously acquired during the flight campaigns aimed at gathering of reference data (WP2). The flight campaign aircraft will be equipped with communication system capable of real-time transmission of data to the IIMEO cloud-based service platform. A near-real-time transmission of pre-selected data with already existing infrastructure using wide-band data link or the LTE network is envisaged. To simulate instantaneous satellite-based service, for the duration of the aircraft's flying over the demonstration railway location defined in the demonstration scenario, the pilot end user will issue a request for inspection of that part of the railway network through the IIMEO web-based service interface. The demonstration location, i.e. the part of the railway network under the management of pilot end-user, will be previously "prepared" by NIS so that obstacles defined in the demonstration scenarios, which should be detected by IIMEO services,

---

[13] https://www.momit-project.eu/

[14] https://smart2rail-project.net

will be brought to strategic pre-defined locations. Based on the issued request, the SAR and VIS data of the demonstration part of the railway network will be gathered, processed both on-board and, if time permits and greater detail is obtainable by on-ground processing, also off-board, and the processed results will be made available to the pilot end user ISR through the IIMEO service web-based interface. The performance of the service will be monitored during the execution of the demonstration and will be evaluated against the performance and acceptance criteria defined by the demonstration scenario.

IIMEO focusses with a resolution below 0.5 m on hazardous events/obstacles that are of static nature (i.e. in the time frame of one to few hours) and that could endanger the safety of the rail operation. Such static obstacles could cause direct train crash if the rail transport was not timely stopped (e.g. before the announced extreme weather conditions), or could cause significant delays in case of stopped rail transport to perform the inspection of the effected rail track. Using IIMEO services has potential to reduce delay and track down times, as well as reduction of inspection effort/costs for track monitoring after occurrence of an extreme weather event.

With the airborne-based demonstration, we intend to demonstrate the overall end-to-end service as it could be operational in space. The demonstration includes the following steps:

- Acquisition of SAR and VIS data on-board of the airplane
- Real-time on-board processing and AI-based pre-selection of interesting regions containing hazardous events/obstacles with means of anomaly and change detection
- We envisage a real-time transmission of pre-selected data with already existing infrastructure
- Cloud-based service platform for off-board, high-resolution processing and visualisation of the results

3.1.3 Pilot Use Case Requirements

The following table outlines a set of requirements for the envisaged IIMEO system, related to the Railway Infrastructure Monitoring Pilot Use Case. These requirements were defined in cooperation with the end-user, Serbian Railway Infrastructure, based on their experience and current procedures. Note, that the requirements subset to be fulfilled by the pilot use case demonstrator will be defined in more detail within the corresponding WP4.

Table 3-2: Consolidated Pilot Use Case Requirements

Requirement#	Requirement description	Priority
IIMEO-FR-01	IIMEO service shall provide geo-localized information about changes in railway environment which are the consequences of damages/failures of infrastructure and occurrences of static objects (potential obstacles) in the free profile of the railway line. The targeted damages/failures are all infrastructure changes that can cause catastrophic events in the railway system. The IIMEO service should also detect pre-selected damages/failures which can lead to material damages or timetable disruptions. The targeted static objects are all static objects found on or near the tracks that are not part of the railway infrastructure.	Shall
IIMEO-FR-02	IIMEO service shall be able to provide information on-demand, continuously or autonomously based on the user defined triggers.	Shall
IIMEO-FR-03	The IIMEO service user shall be able to define multiple continuous or autonomous subservices (e.g. for rockfall, buckling detection etc.) for change detection in railway environment.	Shall
IIMEO-FR-04	The IIMEO on-demand service shall provide a result response no later than 60 min after the user demand.	Shall

Requirement#	Requirement description	Priority
IIMEO-FR-05	The IIMEO on-demand service may provide a result response no later than 30 min after the user demand.	May
IIMEO-FR-06	The IIMEO continuous service shall provide information about changes in targeted infrastructure at least every 60 min.	Shall
IIMEO-FR-07	The user of IIMEO continuous service shall be able to define the frequency of information update.	Shall
IIMEO-FR-08	The user of IIMEO continuous service shall be able to define the service start and end time.	Shall
IIMEO-FR-09	The user of IIMEO autonomous service should be able to define conditions or events which will start the autonomous service.	Should
IIMEO-FR-10	The IIMEO autonomous service shall provide information about changes in railway environment with a delay less than 60 min	Shall
IIMEO-FR-11	The IIMEO autonomous service may provide information about changes in railway environment with a delay less than 30 min.	May
IIMEO-FR-12	The IIMEO service shall be able to provide sub-meter accuracy for the change detection in railway environment.	Shall
IIMEO-FR-13	The user of IIMEO service shall be able to independently set up the accuracy of the service for on-demand, continuous and autonomous subservices.	Shall
IIMEO-FR-14	The user of IIMEO service shall be able to define change detection along a linear feature with the predefined width of 12 m	Shall
IIMEO-FR-15	The user of IIMEO service shall be able to define a fixed area of interest for change detection in the user interface.	Shall
IIMEO-FR-16	IIMEO service shall be able to load into the system and to show in the user interface geospatial data in appropriate format (such as CSV, Xls, Shpefiles, JSON, SQLite, GPGK or GML)	Shall
IIMEO-FR-17	IIMEO service should be able to communicate over standardized interfaces with the user selected platforms which are supplying the geospatial data in standard formats.	Should
IIMEO-FR-18	IIMEO service shall be able to receive geo-localized severe weather alerts from the sources defined by user.	Shall
IIMEO-FR-19	IIMEO service shall be able to communicate the results to other connected systems over standardized interfaces.	Shall
IIMEO-FR-20	The IIMEO service shall encrypt the results output from the system for communication. The communicated encrypted outputs shall be able to be decrypted by other connected systems.	Shall

Requirement#	Requirement description	Priority
IIMEO-FR-21	The report of a defect detection shall include a measure of the detector's confidence in the detection, e.g. the probability of the existence of the defect given the observations used by the detector. The output of the location of a detected defect shall include a measure of the location's uncertainty.	Shall

3.2 Analysis of other potential Use Cases and Applications

During the last decades, the Synthetic Aperture Radar (SAR) imagery market has traditionally been dominated by government operating large and expensive satellites. According to NSR, a global leader in satellite & space market research, smaller and more manoeuvrable satellites with flexible delivery methods by new and emerging market players are paving the way for operators to gain a foothold in the market.

Further, the NSR "Satellite Based Earth Observation Report Edition 14" [6] shows "a total revenue opportunity of $16.9 Billion from 2021-2031 for SAR markets, which amounts to 24% of the total EO market, growing from $821 Million in 2021 to $2.4 Billion in 2031 at an 11% CAGR." NSR also forecasts that "revenues are expected to grow the most for Information Products (IP) and Big Data segments."

These market trends and projections not only underscore the growing importance of SAR imagery but also highlight the significant opportunities it presents in various application scenarios for infrastructure monitoring, offering yet unprecedented capabilities to capture detailed and timely information about critical infrastructure assets and the surrounding environment. This enables end-users to have a comprehensive understanding of asset conditions, detect anomalies, and proactively plan maintenance and response activities, thereby enhancing the resilience, safety, and efficiency of infrastructure networks.

Building upon the Railway Infrastructure Monitoring Pilot Use Case discussed before, in this section we will dive into some other potential application scenarios for infrastructure monitoring, exploring how IIMEO technology can be used to address specific challenges and deliver valuable insights in other relevant domains such as power line monitoring, road network management, dike surveillance, and response to natural disasters. These use cases will serve as additional valuable sources for collecting IIMEO system requirements (see also Figure 2-1), enabling us to create an extensive and robust system design that aligns with the diverse demands of infrastructure monitoring across different application domains.

The Table 3-3 below provides a comprehensive list of the further potential use cases for infrastructure monitoring and is presented here to provide already a summary and preview of the analysed scenarios discussed in the following sections 3.2.1 - 3.2.6.

Table 3-3: High-level system requirements of potential use cases

	Application scenario	Type of Service operation	Spatial resolution/accuracy	Temporal resolution	(Trigger Event)
Natural Disasters	See Landslide, Flooding, Snow for railway infrastructure (see section 3.2.1).				

Pipeline Inspection	Leaks	Continuous / Permanent	Along a linear feature with low resolution. Requires greater spectral resolution than IIMEO prototype.	Daily	
	Pipeline Deformations	Continuous / Permanent	Along a linear feature with sub-meter resolution.	Daily	
	Ground Property Changes (e.g. Permafrost Thaw)	Continuous / Permanent	Along a linear feature with low resolution.	Daily	
Power Lines	Pole Monitoring	On-demand service Autonomous under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Trigger-based service	User on-demand Extreme weather events
	Vegetation Encroachment	Continuous / Permanent	Along a linear feature with low resolution.	Near-real-time (on a vegetation-growth-time scale, so very low)	
Dike Monitoring	Water level monitoring to infer pressure.	Continuous (acute dike failure) / On-demand service (early warning)	Moderate spatial resolution / Area of interest	Trigger-based service Near-real-time (acute dike failure)	extreme weather event water level threshold
	Monitoring of deformation / moisture	Continuous /Permanent (acute dike failure) / On-demand service (early warning)	High spatial Resolution Along a linear feature or persistent scatterer with sub-meter up to centimetre-scale height accuracy	Trigger-based service Near-real-time (acute dike failure) by evaluation of previously acquired multitemporal data sets	extreme weather event water level threshold, annual inspection intervals

Road Monitoring	Road Condition	Permanent/continuous monitoring Autonomous under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Continuous service Trigger-based service	User on-demand Extreme weather events
	Environment	On-demand	Along a linear feature with (sub)-meter accuracy	Near-real-time Trigger-based service	User on-demand Extreme weather events User defined fixed area of interest and service start/end
Waterway Monitoring	Infrastructure /Assets	Permanent/continuous monitoring Autonomous under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Continuous service Trigger-based service	User on-demand Extreme weather events User defined fixed area of interest and service start/end
	Environment (e.g. erosion/vegetation	On-demand	Along a linear feature with (sub)-meter accuracy	Near-real-time Trigger-based service	User on-demand Extreme weather events User defined fixed area of interest and service start/end
	Infrastructure /Assets	Permanent/continuous monitoring Autonomous under specific conditions/event-based	Along a linear feature with sub-meter accuracy	Near-real-time Continuous service Trigger-based service	User on-demand Extreme weather events User defined fixed area of interest and service start/end

3.2.1 Natural disasters: early warning and prevention, monitoring, response

Climate change is a major factor promoting desertification and natural disasters worldwide, but also in the EU with 50 million people affected between 1980 and 2020, and with over €12 billion in economic losses per year. This includes, but is not limited to, forest fires, landslides due to deforestation, or flooding events similar to the 2021 floods that caused severe damages to people and infrastructures in several European countries. Rapid availability of high-resolution data is crucial for coordinating an effective response to such events. IIMEO has the capability to provide data suitable for prevention and early detection/warning, as well as for monitoring the evolution of natural disasters on a short timescale and coordinating the responses accordingly. In addition to routine monitoring of risk areas for prevention purposes, tools intended for pre-selection enable prioritized data availability upon request for situational awareness and to direct first responders. Change-detection tools can assist with the identification of compromised structures.

Natural disasters are one class of causes of railway infrastructure failures, e.g. landslides, flooding, or excessive snow. Such events are not disasters per se, but because they break things, such as railways but, of course, also buildings, bridges or other structures. Given the population and industry density in Europe, at least in Europe those are also geographically very dispersed. If one of the events causing disaster happens, only a fraction of such structures, i.e. those near the event, are of interest for real-time monitoring. Thus, we expect requirements for these tasks to be similar to the requirements related to the corresponding events regarding railway infrastructure.

Thus, we expect the technology and services to be of interest to local and transregional public bodies (e.g. European Disaster Risk Management) as well as to private organizations including, for instance, insurance providers.

3.2.2 Pipeline Inspection

To become climate-neutral by 2050, Europe needs to transform its energy system. The Energy System accounts for 75 % of the EU’s greenhouse gas emissions. The EU Strategy for Energy System Integration will provide the framework for this green energy transition. This strategy has three main pillars: A more 'circular' energy system, a greater direct electrification and clean fuels.

The results from IIMEO for the monitoring of railways can also be applied to the monitoring of overground pipelines. Therefore, IIMEO will contribute to the third pillar, clean fuels, of the EU Strategy for Energy System Integration. For those sectors where electrification is difficult, the strategy promotes clean fuels, including renewable hydrogen and sustainable biofuels and biogas. One of the means to transport these liquids and gases over long distances will be existing and new pipelines. Such pipelines need to be maintained and monitored, which could be done from space.

Pipeline defects may be detected from different types of observations. Pipelines may start to leak, which could be detected by their spectral absorption patterns using multi- or hyperspectral imagers mounted on a satellite. Doing so with on-board processing on a satellite constellation with very low revisit times seems to be particularly attractive for oil pipelines to shorten response times to minimize environmental hazards due to the leak. Multi- and hyperspectral imagers are decidedly not part of the IIMEO platform be demonstrated during this project, however, one would expect the computational demands to be fairly similar.

When a pipeline leaks, defects already occurred. An indicator of impending damage may be deformations of the pipeline which are likely detectable via VIS and in particular SAR sensors. Similarly, deformations on the ground supporting the pipeline may also indicate risks for the pipeline. The latter will likely get worse in the near future for pipelines built on permafrost ground, which are likely to thaw as global warming continues. Such changes most likely evolve slowly, such that IIMEO may be able to exploit synergies with approaches like MATIST and MOMIT, which were mentioned in Sect. 3.1.1.

3.2.3 High Voltage Power Lines

Power line and power line corridor monitoring has been done using remote sensing, including using SAR in the past. [7] Power lines are similar to railway infrastructure in that they are large, geographically dispersed structures. We expect that the usage of power lines will further increase in the near future, in particular to transport electricity over very long distances, as the location of power production increasingly moves away from the location of consumption with the shift to renewable energy, e.g. from an industrial area to off-shore wind parks, while the consumption still happens in the industrial area.

Power lines are not only similar to railways with respect to its geographic dispersion, but also in the components used. After all, one of the distinct features of electrified railways are overhead wires mounted on some catenary, which essentially are power lines.

Thus, we expect some of the requirements regarding railways to be directly transferable to power lines. For instance, requirements regarding contact line masts of railways likely apply also to masts holding power lines. Requirements with respect to the detection of flooding and landslides will likely also be similar. For power lines vegetation encroachment should be monitored in order to avoid trees from potentially striking the power line or, in case of badly maintained power lines, even catching fire, which is likely similar to monitoring vegetation encroachment at overhead railway wires. Regarding timeliness requirements vegetation monitoring will be less demanding than regarding the spatial resolution, so this may be a use case for the acquisition of imagery on a satellite, compression and processing on ground.

Monitoring an individual power line itself will most likely be infeasible and even if it turned out to be feasible, at least if monitored using SAR, strongly dependent on the orientation of the power line with respect to the SAR, so this would probably not be worth pursuing.

In summary, IIMEO for railway infrastructure will probably be useful to for power lines, too, even without changes to the system, so parties interested in power line monitoring should be considered stakeholders for IIMEO as well.

3.2.4 Dike Monitoring

Dikes are structures that are built to prevent water from flooding nearby areas. These structures are typically made of earth, stone, or concrete, and their integrity is critical in preventing catastrophic floods that can result in loss of life and property damage. Typical known failure mechanisms are water overflow, overtopping, piping, settlements or erosion. Infrastructure monitoring of dikes involves continuously assessing the condition of the dike, such as the height, width, slope, moisture, vegetation and the presence of cracks or erosion. Monitoring also involves tracking the water levels in the rivers or lakes adjacent to the dike, as well as the water pressure on the dike itself. Changes in any of these parameters can indicate potential problems with the dike's stability and integrity, which may require immediate attention and maintenance. Early warning systems for coastal protection, e.g. in Germany, are based on water level measurements and forecasts but information of the internal condition of dikes that play an important role in safety issues are completely lacking [8]. Thereby, coastal protection via dikes in e.g. Germany alone covers a distance of 1200 km [9] while there are about 17.000 km in the Netherlands [10] and 150.000 km in the USA [11]. Inspections of these large areas on foot is obviously a costly, and time-consuming process. Therefore, the use of remote sensing techniques is still an active research field, envisaged to complement traditional visual inspections. A relatively recent study investigating the application of optical remote sensing for monitoring dikes can be found in [12].

Specific requirements or uniform guidelines for dike monitoring, for e.g. Germany, do not exist but the procedure can nevertheless be summarized from [8]. In Lower Saxony, for example, a visual inspection of the dike surface is required twice a year and after each extreme event to check for visible damage and the condition of the vegetation. In addition, height measurements are carried out every 10 years to record any subsidence or settling. To assess the stability of the dike after extreme events, additional further indicators are recorded visually: These include freeboard, erosion damage, and slope slides, as well as increased seepage, ground lifting, and large cracks on the inland side. Thus, visual inspection by trained personnel remains the primary tool for dike monitoring. Continuous and reliable monitoring of the dikes is currently not possible, especially due to the length of the dikes, and not all indicators can be determined by visual inspection [8].SAR technology can be used for dike monitoring to detect changes and anomalies in the dike's surface structure, such as larger cracks, deformations or changes in vegetation. This technology can also be used to measure and monitor the dike's height and width, which can provide important information about its stability. The research focus so far has been on deformation detection from SAR image stacks, and slide detection and soil moisture detection with Polarimetric SAR [12].

A very promising approach to observe the deformation of the dike, especially the heave and subsidence, are InSAR techniques, especially Persistent Scatterer Interferometry (PSI) [13] that work well in urban areas. However, current ongoing research approaches in rural areas still show difficulties in evaluating the backscatter objects of a dike (distributed scatterers), which are usually not coherent over a longer time interval [14].

IIMEO could contribute to provide early warning of potential dike failures. By continuously monitoring the dike and its nearby surroundings, potential signs of impending failure, such as changes in the water levels or ground movement could be detected, and authorities be alerted to take action. High-resolution multi-temporal image stacks could also be built and methodologies such as PSI could be integrated in the future. However, these applications would not generally require instantaneous evaluation.

Another area of application for IIMEO would certainly be in acute catastrophic cases after extreme events to quickly evaluate the condition of vegetation or locate dike areas that have already broken or are overflowing with water. Here, an instantaneous and time-critical evaluation of a potential large dike area would be required.

3.2.5 Road Monitoring

Infrastructure monitoring of roads and highways is an essential task that ensures the safety and efficiency of transportation systems. This is important especially in regions where alternative monitoring methods, such as UAV, are limited or not feasible[15]. Road networks are subject to various forms of degradation, including potholes, cracks, and structural damage, which can lead to accidents, congestion, and increased maintenance costs. By using satellite data, it is possible to monitor the condition of road infrastructure over a wide area and detect potential issues before they become severe.

These are some exemplary application scenarios where IIMEO could be applied to:

- Road condition monitoring: monitor road conditions, such as potholes, cracks, and other forms of wear and tear. This information can be used to schedule maintenance and repairs, which can help to prevent accidents and extend the lifespan of the road
- Environmental monitoring: monitor environmental factors that affect road conditions, such as rainfall and temperature, in order to predict changes in road conditions and schedule maintenance accordingly
- Asset management: monitor the condition of road assets, such as bridges and tunnels, helping to identify areas where maintenance is needed and schedule repairs [15] [16].

In order to fulfil such kind of services, the following lists some initial requirements for an infrastructure monitoring system using satellite data for roads/highways [17]:

- Spatial resolution: The system should be able to provide high-resolution imagery to identify cracks, potholes, and other forms of degradation at the scale of individual lanes or segments of the road. The resolution should be high enough to detect features of interest and enable accurate measurements of their dimensions.
- Temporal resolution: The system should provide frequent updates of the road condition to detect changes and monitor degradation over time. The update frequency should be determined based on the rate of degradation and the required response time.
- Probability of occurrence: The system should take into account the probability of occurrence of events that could damage the road infrastructure, such as floods, landslides, or earthquakes. This information should be used to prioritize monitoring efforts and allocate resources effectively.
- Type of service operation: The system should support continuous monitoring of the road infrastructure, with on-demand updates and event-triggered notifications (e.g. when extreme weather event occurs). In the event of a significant degradation or damage, the system should provide real-time alerts to enable prompt response and prevent accidents.
- Data analysis/processing: The system should include advanced data analysis and processing capabilities, such as image segmentation and classification, to detect and identify features of interest automatically. The system should also be able to generate reports and visualizations of the road condition and trends over time, and ensure high data quality and reliability by using validated and calibrated satellite data and implementing quality control procedures.

3.2.6 Waterway Monitoring

Satellite-based infrastructure monitoring provides a viable solution for waterways in regions, where alternative monitoring methods (e.g. UAV) may be limited or impractical. These regions might include remote or inaccessible areas, expansive waterway networks, or underdeveloped regions lacking adequate infrastructure

---

[15] e.g. Australia with its vast land area is maintaining an extensive road network across the country (approx. 80% of the 877.000km wide network is of rural nature (https://www.piarc.org/ressources/documents/90,australie.pdf)), where satellited-based monitoring could play a vital role, especially in remote regions where UAV operations may be challenging due to harsh weather conditions or limited infrastructure

as satellites offer extensive coverage and can capture data over large geographic areas, including remote and challenging terrains[16].

By applying IIMEO in regions with limited alternative options, decision-makers can gain valuable insights into the condition of critical water roads and canals. This information can inform maintenance and repair activities, aid in disaster response planning, facilitate efficient resource allocation, and ultimately contribute to the effective management and preservation of vital waterway infrastructure. In the following some exemplary application scenarios of infrastructure monitoring for waterways are presented:

- Erosion monitoring: Identify erosion-prone areas along riverbanks and canals to prevent infrastructure damage and ensure stability; monitor sedimentation rates to optimize dredging activities and maintain navigability.
- Vegetation monitoring: Detect excessive vegetation growth, such as aquatic weeds, to prevent obstruction of waterways and maintain water flow; monitor vegetation patterns in wetlands and river deltas to assess ecological health and potential impacts on waterway conditions.
- Infrastructure condition monitoring: Assess the condition of locks, dams, and other waterway infrastructure (e.g. bridges) to ensure safe and efficient navigation; monitor erosion or structural weaknesses in canal banks to mitigate risks and plan necessary maintenance or repairs [18] [19].

In order to fulfil such kind of services, the following lists some initial requirements for an infrastructure monitoring system using satellite data for waterways:

- High-resolution imaging capabilities to detect and monitor erosion-prone areas along waterway banks, as well as for assessing the condition of locks, dams, and other waterway infrastructure.
- Temporal resolution sufficient to capture changes in erosion patterns over time. If applicable: integration with topographic data to assess erosion rates accurately.
- Ability to differentiate between various types of aquatic vegetation and terrestrial vegetation near waterways, including seasonal monitoring capabilities to capture vegetation dynamics.

3.2.7 Other potential use case requirements

The following Table 3-4 provides an indication of applicability of the requirements for the railway use case, as provided in Table 3-2 to the other potential use cases as described in sections 3.2.1 - 3.2.6.

Table 3-4: Applicability of requirements from Railway use case for other potential use cases

Requirement#	Natural Disasters	Pipeline Inspection	High Voltage Power Lines	Dike Monitoring	Road Monitoring	Waterway Monitoring
IIMEO-FR-01	-	-	-	-	-	-
IIMEO-FR-02	X	X	X	X	X	X
IIMEO-FR-03	see IIMEO-ER-01 in Table 3-5					
IIMEO-FR-04	X	X	X	X	X	X
IIMEO-FR-05						
IIMEO-FR-06	X	X	X	X	X	X

---

[16] Brazil's Amazon River system is one of the most extensive and important waterway networks in the world. It serves as a vital transportation route for goods and people, particularly in the Amazon rainforest region

Requirement#	Natural Disasters	Pipeline Inspection	High Voltage Power Lines	Dike Monitoring	Road Monitoring	Waterway Monitoring
IIMEO-FR-07	X	X	X	X	X	X
IIMEO-FR-08	X	X	X	X	X	X
IIMEO-FR-09	X	X	X	X	X	X
IIMEO-FR-10	see IIMEO-ER-02 in Table 3-5					
IIMEO-FR-11	see IIMEO-ER-03 in Table 3-5					
IIMEO-FR-12	see IIMEO-ER-04 in Table 3-5					
IIMEO-FR-13	X	X	X	X	X	X
IIMEO-FR-14	see IIMEO-ER-05 in Table 3-5					
IIMEO-FR-15	X	X	X	X	X	X
IIMEO-FR-16	X	X	X	X	X	X
IIMEO-FR-17	X	X	X	X	X	X
IIMEO-FR-18	X	X	X	X	X	X
IIMEO-FR-19	X	X	X	X	X	X
IIMEO-FR-20	X	X	X	X	X	X
IIMEO-FR-21	X	X	X	X	X	X

The following Table 3-5 provides extra requirements (IIMEO-ER-X) derived from the requirements for the railway use case (Table 3-2) to the IIMEO system derived from the other potential use cases as described in sections 3.2.1 - 3.2.6.

Table 3-5: Extra requirements from other potential use cases

Requirement#	Additional Requirement description	Priority	Use cases
IIMEO-ER-01	The IIMEO service user shall be able to define multiple continuous or autonomous subservices (e.g. for rockfall, buckling detection etc.) for change detection in the use case environment (generalization of IIMEO-FR-03)	Shall	All
IIMEO-ER-02	The IIMEO autonomous service shall provide information about changes in the use case environment with a delay less than 60 min (generalization of IIMEO-FR-03) (generalization of IIMEO-FR-10)	Shall	All

Requirement#	Additional Requirement description	Priority	Use cases
IIMEO-ER-03	The IIMEO autonomous service may provide information about changes in the use case environment with a delay less than 30 min (generalization of IIMEO-FR-11)	May	All
IIMEO-ER-04	The IIMEO service shall be able to provide sub-meter accuracy for the change detection in the use case environment (generalization of IIMEO-FR-12)	Shall	All
IIMEO-ER-05	The user of IIMEO service shall be able to define change detection along a linear feature (dike) with the predefined width of 200m (generalization of IIMEO-FR-14)	Shall	Dike Monitoring

4 CONSTELLATION AND DATA TRANSFER REQUIREMENTS ANALYSIS

The project IIMEO originally proposed in [1] the architecture displayed in Figure 4-1. By now, the architecture is outdated and will be updated during task T1.4, but is nevertheless instructive to get the idea of what is to be developed: An airborne prototype for a space-based real-time infrastructure monitoring service.

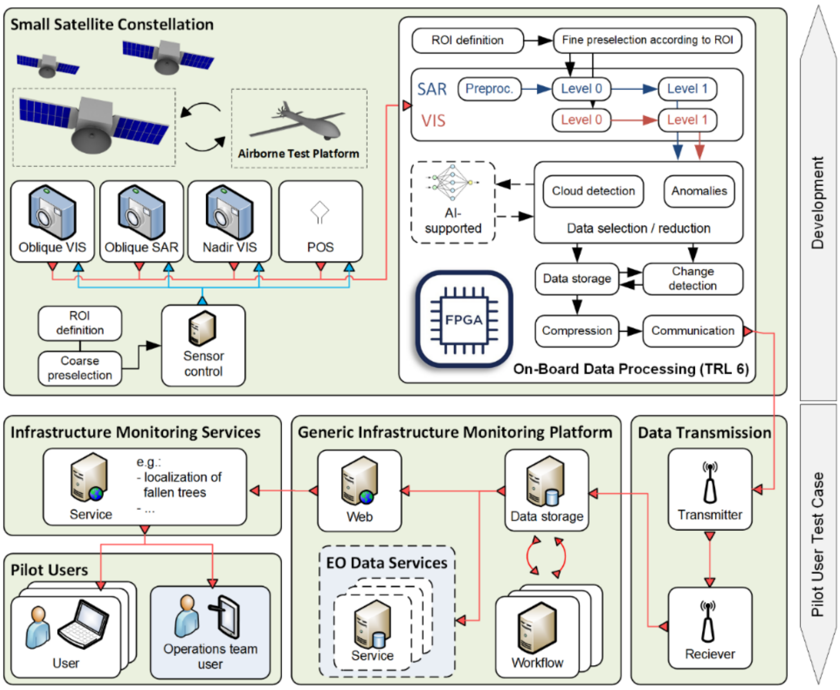


Figure 4-1: Original architecture proposed for IIMEO in [1]. Details of the architecture are outdated and will be updated during task T1.4.

As displayed in the top half of Figure 4-1, the system will use both SAR and VIS sensors to acquire the data to monitor infrastructure and perform at least part process of the necessary data processing, e.g. pre-processing, anomaly and change detection as well as data compression, on board, before the intermediate processing results are transferred (in the bottom half of Figure 4-1) to ground for further processing and presentation to a user. This is to avoid the transmission of large amounts of raw sensor in order to save time, such that infrastructure defects can be reported to the user in time in order to enable the user to react to such defects in a timely manner. Once the specifics of the (on-board) processing, communication, storage, etc. will have been worked out, implemented and demonstrated, the idea is to substitute a satellite constellation for the airborne test platform to create a useful space-based service.

To make sure switching from an airborne platform to satellites remains possible, the consequence for this project is that requirements imposed by a satellite constellation on both data processing aboard a satellite and communication including what can be reasonably expected from data compression need to be considered, while updating the system concept to satisfy the user requirements, selecting the algorithms to use for payload data processing and deciding which part of the processing can be done on-ground and which parts on board.

While the previous section considered requirements from a use-case point of view, this section takes a more technical perspective. Since the project IIMEO aims to develop a prototype for a future, satellite-based service, the concepts, procedures and hardware to be developed for the prototype are supposed to be feasible on satellites, too. To prevent the developments of the coming work packages WP2 and WP3 from going against that feasibility, we carried out task T1.2, i.e., we estimated properties of a satellite constellation for IIMEO, figured out the constraints of what we could reasonably develop on our airborne prototype which follow from those properties, and checked the state of the art of both hardware and methods to satisfy the requirements specified in section 3 under these constraints. The results of task T1.2, which will guide the development of the system concept (T1.4) and algorithm selection (T1.3), which in turn will affect the prototype development in the coming work packages, are documented in this section.

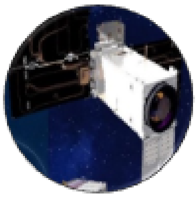
Satellites, particularly “SmallSat”, impose restrictions with respect to the size, power and weight of the payload it may carry, as well as limits to the data volume which is possible to transmit to ground. Thus, this section briefly discusses satellite platforms which will most likely be available to a future, space-based IIMEO project in subsection 4.1, before considering the transmission of payload data from the satellite in low earth orbit (LEO) to ground in subsection 4.2. This includes that downlink itself as well as its availability from LEO in subsections 4.2.1 and 4.2.2, before different compression techniques to keep the amount of data to be transferred small are discussed in subsection 4.2.3. Subsection 4.3 concludes the communication topics by very briefly considering the communication of control and telemetry data. The computational aspects are started in subsection 4.4 with a description with focus on European components of the computational resources likely to be available on the on-board processing unit to be used in IIMEO, as well as the space, power and weight the satellite platform would have to provide to carry the processing unit. Subsections 4.5 and 4.6 consider the state of the art with respect to SAR data processing and change detection, respectively.

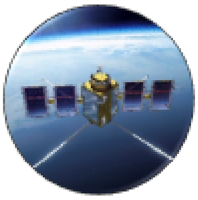
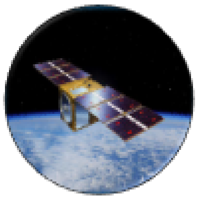
From sections 4.1 to 4.6, section 4.7 extracts some ramifications to be considered while designing the airborne IIMEO prototype to keep the resulting infrastructure monitoring components to be as compatible to flying in space as possible.

4.1 Satellite Platforms

There are a few European satellites which approximately fit the conditions, which were already stated in the grant agreement, to make space-based IIMEO economically viable, i.e., less than 200 kg in mass and single-digit years lifetime. From the OHB group alone there the satellites mentioned in Table 4-1.

Table 4-1: OHB satellites with up to 200 kg mass



	Multi Mission Microsatellite M3	InnoSat SML Series	Triton	Triton-X
Launch Mass	25 – 35 kg	40 – 300 kg	25 – 100 kg	up to 250 kg
Payload Mass	8 – 20 kg	20 kg (S) 20 – 30 kg (M) 30 – 80 kg (L)	up to 35 kg	up to 90 kg
Lifetime	3 years	5 years	3 – 5 years	5 years
Typical Applications	Navigation, Earth Observation, Communications, Technology development, Science	Earth Observation, Communications, Technology demonstration, Science	Earth Observation, Communications, Situational Awareness, Technology Demonstration	Earth Observation, Communications, Situational Awareness, Technology Demonstration

Additionally, relatively inexpensive satellites, so-called “CubeSats”, may be an options for space-based IIMEO. Payload is mounted on CubeSats in standardized [20] units, $(10\ cm)^3$ cubes weighing $1\ kg$ each. Such payload units may be stacked to form the payload of the satellite. If the IIMEO payload can be partitioned in sized units, a constellation of CubeSats may be a feasible, low-cost option to deploy IIMEO in space quickly with standard components. Concepts for Ka-Band SAR on CubeSat platforms have been developed previously. [21]

As mentioned in the IIMEO Grant Agreement [1], the target for the revisit time of a location to be observed is somewhere below one hour from a satellite constellation flying in LEO, somewhere between $500\ \mathrm{km}$ and $900\ \mathrm{km}$ above ground. Depending on the height, the round trip time of a single satellite in such an orbit would be between $94\ \mathrm{minutes}$ and $103\ \mathrm{minutes}$. Thus, at least 2 satellites per orbital plane would be necessary to fulfil the revisit time target. This may be scaled to up to 6 to achieve, neglecting earth rotation, revisit times of about 17 minutes. The number of orbital planes will largely depend on the field of regard of the sensors and the pointing equipment to be mounted on the satellites. To provide a ballpark figure, assuming a field of regard of 16 degrees and polar orbit at 900 km altitude, the IIMEO constellation would have about 24 orbital planes. Nevertheless, the specifics depend on quantities, particularly the field of regard, which are unknown at this point, so we defer more details regarding the constellation to the roadmap [22] to space.

Right now, it is also not clear whether some orbits would be preferable to others concerning the orbit’s direction with respect to the directions of the tracks to be observed. In VIS camera images, the tracks will likely look the same from all relative directions. Since SAR is actively illuminated, the reflection to be received will looks dramatically different depending on the relative direction of the track. If a track is observed and thus illuminated perpendicular to the track’s direction, almost all the reflection will come from the individual rails, since the rail’s web and foot are approximately orthogonal. In the other extreme case, i.e. the observation being along the track, almost all the reflection will come from the sleepers, looking very different from the rail reflections. Both, however, are likely to produce fairly regular patterns. We also do not expect that there is a preferred direction of the railways, so considering the viewing geometry, we assume that no orbit would be better than the others.

4.2 Payload Data Downlink

The primary means to detect infrastructure deterioration will be anomaly detection and change detection against SAR and VIS images – or features detected in such images – of healthy infrastructure. The corresponding reference data can be stored on each of the satellites separately and may be periodically updated from ground station. Thus, high-bandwidth satellite-to-satellite communication will not be necessary.

Depending on the satellite platform, there are different communication options to choose from for the data downlink of the satellite’s payload. The communication band to be used hints towards the ballpark figure of the downlink bandwidth to be expected, as in Table 4-2.

Table 4-2: Communication Bands' Bandwidth Magnitudes

Band	Bandwidth
S-Band	Tens of Mbit/s
X-Band	Hundreds of Mbit/s
Ka-Band	Less than 10 Gbit/s
Optical	Tens of Gbit/s

The range of possible downlink bandwidths is very large, however, optical communication is relatively new and rare on satellites. Small satellite platforms, i.e. the currently intended target for IIMEO, usually use X-Band downlinks, allowing us to expect to be able to use about 100 Mbit/s for the communication of all data from the satellite to ground combined.

This fits well the grant agreement's suggestion for the data link between ground and plane, LTE, which, while being able to provide very large bandwidths in theory, typically transmits data at a few tens of Mbit/s, which would be matched by even the slowest of the satellite datalinks.

4.2.1 Downlink Availability

Downlink data rate requirements are further influenced by availability, locations and number of suitable ground stations and by the time a satellite can make contact with a station. An estimate for the latter time window, termed here 'overpass time' can be given for LEO satellites based on orbit radius and minimal elevation of the ground station. For direct overpasses, this is indicated in Figure 4-2.

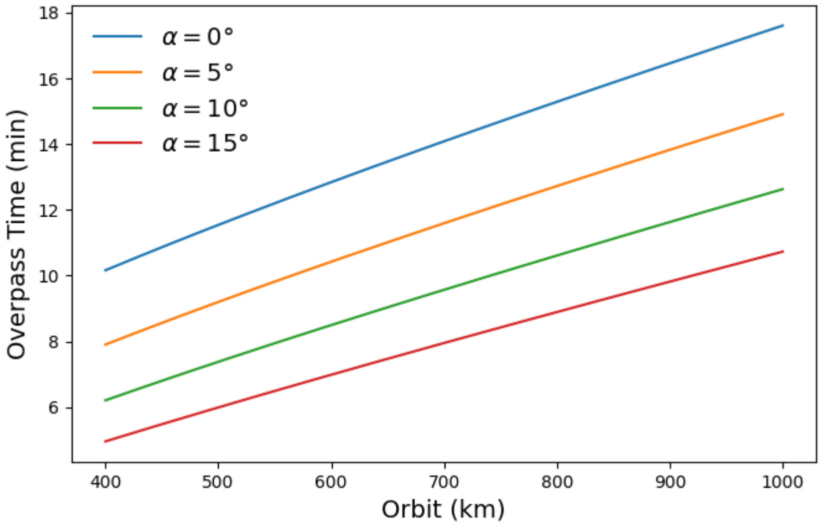


Figure 4-2: Duration of direct over overpasses dependent on minimal elevation and orbit

The estimate given in Figure 4-2 does not account for elevation-dependent data rates. Further, since only direct overpasses are considered, the estimation must be interpreted as an upper limit.

4.2.2 Data Rate from Low Earth Orbit

The typical downstream bandwidths of a satellite appear to be rather promising, however, a satellite in Low Earth Orbit (LEO) travels substantially faster than a plane. The round trip time of a LEO satellite at 500 km altitude is approximately 90 minutes. With the earth's radius being about 6375 km, the speed of its projection on the earth's surface is approximately $^{2\,\pi}/_{90\ minutes}\ 6375\ km \approx 7.4\frac{km}{s}$, which is about 100 times faster than the speed the plane will fly at.

Since the width of the fields of view of both the SAR and VIS sensors is constant, the area observed by the sensors per unit time increases linearly with the platform's speed and thus, omitting other factors also affecting the data rate, the volume of data generated approximately increases linearly with the platform's speed as well.

The factor of 100 between satellite speed and demonstrator airplane speed suggests that, if the demonstrator communication payload fitted into single-digit Mbit/s, the on-board processing could be moved from demonstrator to satellite platform more or less unmodified to put the communication requirements into the X-band bandwidth ballpark.

The fields of view themselves, however, will also change as the sensors are moved from the airborne platform to a satellite. Thus, there is a (yet unknown) factor by with the communication requirements would increase if all the data from the area passed by the fields of view were transferred. A preliminary estimation for the SAR case is given in subsection 4.5.2.1, suggesting that data covering the complete field of view cannot be transferred to ground. To mitigate this, aside from compression of the data, only data regarding the area of actual interest should be transferred and the rest of the field of view discarded. In the case of our prototype application, the areas of interest are immediately around railway lines and can be identified from existing and almost static maps such as the Open Railway Map [23].

4.2.3 Data Compression

The data which will have to be transferred between one of the constellation's satellites and the ground will be command and control data from ground to satellite, telemetry data regarding the state of the satellite from satellite to ground and, of course, the payload data also from the satellite to ground. The payload data will be imagery acquired using VIS cameras and SAR data. Probably for all and surely at least for the (near) real-time applications, the SAR data will be processed into imagery prior to transmission to ground, so the most important data type regarding data compression will be images, because those will be the bulk of the data.

One of the motivations for computations with payload on-board the satellite is to reduce the amount of data necessary to transmit from satellite to ground which ensuring that the information the user on ground cares about, e.g. information as to how the observed infrastructure is broken, is not lost. Thus, transmitting an image whose pixels contain whether the infrastructure at the projection on ground of the pixel changed, or a series of indications of defect types annotated with coordinates, instead of the original images, may be interpreted as some sort of very lossy compression, where the parts that are lost happen to be the parts unimportant for the application.

More generic image compression systems may also be lossy to varying degrees with some control over the information which can not be reconstructed from the compressed representation, e.g. very high spatial frequencies. Compressions which allow the exact reconstruction of the image are termed lossless.

A review of the state of image compression in 2011 geared towards satellite imagery was done by Faria et al. [24] using the scenes imaged by five-channel CCD camera on board the Brazilian-Chinese CBERS-2B satellite. Each channel carried 8-bit-per-pixel 5812x5812 images, which were used to test the compression ratio and, for lossy compressors, image reconstruction fidelity in terms of peak signal to noise ratio (PSNR) and (mean) structural similarity ([M]SSIM).

In [24], the former is defined as $\mathrm{PSNR} = 10\left[\log_{10}(2^B - 1)^2 - \log_{10}(\mathrm{MSE} + 1/12)\right]$, where MSE is the mean of the squared differences of the original and reconstructed image and B is the number of bits to encode a single pixel. The $1/12$ is to avoid an undefined PSNR in case of perfect reconstruction, i.e. zero MSE from lossless compression. For two identical 8-bit-per-pixel images, the PSNR as defined in [24] is thus $58.9\,dB$. The structural similarity, $\mathrm{SSIM}(x,y) = (2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)/\left[\left(\mu_x^2 + \mu_y^2 + C_1\right)\left(\sigma_x^2 + \sigma_y^2 + C_2\right)\right]$, is 1 if two regions, x and y, are identical and zero if they are not correlated at all.

They looked at both transform-based compressors prediction-based compressors, the latter being Differential Pulse Code Modulation (DPCM) and, in particular, JPEG-LS.

4.2.3.1 Transform-Based Compression

The compression pipeline of compressors using basis transforms usually starts with dividing the image to be compressed into blocks to be compressed, and then for each block transforming from the pixel-basis to the new frequency-domain-like basis, quantization and ordering of the new coefficients and finally encoding the ordered and quantized coefficients using run-length coding and entropy-based codes, e.g. using the fewest bits for coefficients appearing the most often. For instance, to compress images according to the still ubiquitous JPEG standard, the image is divided into 8x8 pixel blocks, each block is transformed using the Discrete Cosine Transform (DCT) to coefficients of the 64 DCT basis functions who are then quantized. To understand why one would want to compute the coefficients of the DCT basis, it is instructive to look at the 1-dimensional case, e.g. the matrix to compute second-differences of the pixel values of a single image line:

$$D^2 = \begin{bmatrix} 1 & -1 & 0 & 0 & \cdots & 0 \\ -1 & 2 & -1 & 0 & \cdots & 0 \\ 0 & -1 & 2 & -1 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & -1 & 2 & -1 \\ 0 & \cdots & 0 & 0 & -1 & 1 \end{bmatrix}$$

The DCT basis vectors are just the eigenvectors of D^2, thus spanning the different ways in which the pixels of the image line might change. This is very closely related to the Discrete Fourier Transform (DFT), which would decompose a periodic vector into its frequency components.

The transform just swaps one set of coefficients to an equally large set of coefficients, so by itself it does not compress anything, however, since it represents the image in the different directions in which the image can change, the directions can be quantized differently, e.g. the coefficient for average brightness may be quantized very finely and coefficients for high-frequency changes rather coarsely, saving Bits regarding the component we might not care so much about. JPEG does just that, quantizing high-frequency changes more coarsely than low-frequency components, which might not be ideal for SAR imagery or VIS image, in particular if we do not want to lose information regarding sharp edges in the images.

Additionally, transforming 8x8 blocks of an image leads to blocking artifacts in the reconstruction of that image.

Such blocking artifacts may be avoided by using a Discrete Wavelet Transform (DWT), representing the image using a sum of wavelets (instead of blocks of sums of cosines), which are parameterized both by frequency and location. This is what both JPEG2000 as well as the CCSDS-IDC, i.e. the compressor recommended by the CCSDS, do. [25] Another strategy is to combine a block-wise transform with a second transform centred on the boundaries of the first transform to consider correlations across the boundaries of those blocks. This strategy is implemented for JPEG-XR. [24]

4.2.3.2 Prediction-Based Compression

Prediction-based compressors are attractive because they substitute both conceptually and computationally complicated transforms from spatial to frequency domain by a predictor, which computes the value of some pixel from its surrounding pixels, such that only the difference between prediction and actual image needs to be encoded and transmitted.

A simple variant of DPCM for the CBERS satellites mentioned above was looked at in [24], however, that variant, while being attractive for its simple implementation, has a fixed compression ratio of 2, which is relatively small compared to the transform-based compressors and also compared to JPEG-LS, which predicts the value of that pixel from the values of its neighbours which also precede it.

4.2.3.3 How to choose a compressor?

We obviously want a compressor with a high compression ratio and a compressed image which contains the information necessary to tell deteriorated infrastructure from healthy infrastructure. What information that is exactly is not known yet, so we aim for high mean SSIM and PSNR as mentioned above. JPEG-LS yields an average compression ratio of 3.6 on the dataset used in [24] when doing lossless compression.

When little errors are acceptable, JPEG-XR achieves an average compression ratio of 6.1 while maintaining an average PSNR of $50.4\ \mathrm{d}B$. The CCSDS-IDC implementation has also been looked at in [24], achieving an average PSNR of $50.9\ dB$ using 2 Bits per pixel, i.e. compression ratio 4, and $46.1\ dB$ using 1 Bit per pixel, i.e. compression ratio 8, respectively. Using the more common definition of the PSNR, without the $1/12$ smoothing term to define a PSNR for lossless compressed images, i.e. $\mathrm{PSNR} = 10\left[\log_{10}(2^B - 1)^2 - \log_{10}(\mathrm{MSE})\right]$ as used for evaluation of the CCSDS recommendation [25], the results would be $51.06\ db$ for JPEG-XR and $51.65\ dB$ for 2-bits-per-pixel- as well $46.33\ dB$ for 1-bit-per-pixel-CCSDS-IDC, respectively, which is even a little better than the mean performance of CCSDS compression on the 8-bits-per-pixel test images in [25].

The constant bitrate of CCSDS-IDC is attractive since it allows to estimate very accurately the data volume to be transmitted for an observation of a region of known extent. However, at comparable image quality, the average compression ratio of CCSDS-IDC appears to be significantly worse than JPEG XR's, and, given the anticipated on-board processing unit, the reduced complexity of CCSDS-IDC might be less of an advantage. Software support for JPEG XR is not as widespread as one might expect after reading the four familiar letters JPEG, however, there are open source implementations available today [26] as well as the reference implementation [27] with a free license for use in derivative works.

4.2.3.4 Likely Compression Systems to be used in airborne IIMEO

In the IIMEO airborne system alongside the SAR system, high resolution RGB cameras from Phase One will be used. These come with two different types of proprietary compression formats, the lossy IIQ (Intelligent Image Quality) RAW S and the lossless IIQ RAW L format. This supports the 16-bit bit-depth of the Phase One Images [28].

For a convenient use of the images open and widespread formats might be the better option. In the last years two formats that are spin offs of the video encoding formats HEVC and AV1 named HEIC/HEIF and AVIF were established and already have reached a certain spread. These are very good at low bit rates and compete with the successor of JPEG, JPEG-XL. In general, the performance in quality and speed of encoding and decoding is very similar. JPEG-XL has the advantage that it is already optimized for usage on standard hardware and does not need special hardware encoders like HEIF and AVIF and with that is faster in most cases. Furthermore, for scientific applications high bit rates (16-bit unsigned integers) or floating-point values for pixel, as much as the support for more than 4 channels can be important. Unfortunately, HEIF and AVIF only support 16-bit or 12-bit unsigned integer and 4 Channels (RGBA) more supported as images in video container.

The software support for JPEG-XL is not very wide yet as it was released in 2020, unfortunately the good alternatives for that as mentioned before, JPEG2000 and JPEG-XR, are also not supported by a lot of standard software. One very important library is GDAL for GIS applications, there JPEG-XL will be supported and JPEG2000 is used for years.

In conclusion, for lossless compression the dedicated JPEG-LS, but also JPEG-XL and JPEG-2000 are good options. In case of the Phase One camera a very good lossless compression with bit rates of up to 7.83 bits-per-pixel for a 14-bit RGB Image could reached using IIQ L, which corresponds to a compression ratio of 5.35, on an average image a ratio of 3.56 could be achieved. As there is more redundancy in the high-resolution Phase One images, higher ratios can be achieved, this is a good reason to stay with that for a raw data archive.

For lossy compression JPEG2000 seems to be a good option for now as it has a little more Software support, even though JPEG-XR is a bit faster. As soon as JPEG-XL is available in more software and operating systems it should be used, as it is faster in some cases and supports a wide variety of data types with the same or better compression ratios. [29]

An outlook to learning-based codecs might be worth a look in the future an initial overview can be found in [30].

Similar techniques might work for SAR images as well, however, in subsection 4.5.2.2 much bigger compression ratios for images process from SAR data have been reported. Additionally, it might turn out that grayscale imagery will suffice to detect infrastructure defects, such that only a single channel would have to be transmitted per image. Similarly, it might turn out that lower bitrates or lower image quality, respectively would still be good enough. In both cases, the reductions in data volume might even exceed the compression ratios.

4.3 Satellite to Ground Communication: Packet Utilisation Standard (PUS)

Beyond the payload data communication, an IIMEO satellite would transmit maintenance and telemetry data to ground and receive tasking commands from ground, e.g. to comply with requirements such as on-demand-processing (IIMEO-FR-02) in subsection 3.1.3. Because parts of this functionality will also be demonstrated during this project and do keep the barrier between the demonstrator and space-based IIMEO as low as possible, the demonstrator should stick to the corresponding standard.

The telemetry and telecommand packet utilization standard [31] defines a set of services for individual projects to choose from to satisfy their requirements with respect to control and monitoring of a spacecraft, e.g. satellite platform, as well as its on-board components. It also defines packet structures for both telemetry and request messages in order to transport the monitoring and control data, respectively. Notably, it does not deal with payload data, however, the rules imposed by the standard, i.e. the PUS foundation model, may help with the definition of the “payload” infrastructure-monitoring-specific services as well.

The PUS is very large standard. Even missions which so not use a 'satellite approximation platform' are not expected to implement the standard in its entirety but rather pick and choose the services which are useful to the particular mission. For IIMEO this applies even more, however, sticking to the foundation model in particular might ease the transition from a demonstration prototype to an actual space-based service.

4.4 On-Board Processing Unit

This section presents an overview of available onboard processing platforms, and a description of the likely configuration used, pending the subsystem requirements.

4.4.1 OBP unit platform overview

Multiple on board processing frameworks exist for space applications, which are presented in Table 4-3. None are based exclusively on European EEE components. Opting for a European supplier, support for a well-established AI accelerator IC, and autonomous/flexible OS based CPU processing, the powerful Unibap iX10-100 is selected as basis. The core AMD component provides flexible and fast OS based development, is very mature and has good availability (contrary to a hypothetical NanoXplore FPGA solution).

Table 4-3: Overview of onboard processors platforms

	Leopard DPU **KPlabs** ***Poland***	**Lion DPU (Under development)** **KPLabs** ***Poland***	**SpaceCloud® iX5-100** **Unibap** ***Sweden***	**SpaceCloud® iX10-100 (Under development)** **Unibap** ***Sweden***	**CogniSAT-XE1** **Ubotica** ***Ireland***	**Q8S Processor** **Xiphos Technologies** ***Canada***
Form factor	< 1U	< 3U	< 1U	< 1U	< 1U (PC/104 form factor)	< 1 U
Power	7.5-40W	up to 15 W (for KU035)	10-30W	12-25W (only SoC)	2W (targets sub 5W)	4 W – 25 W
Mainboard						
Model	ZU6EG, ZU9EG, ZU15EG	KU035, KU060, KU095	AMD G-Series GX-412HC	AMD Ryzen™ Embedded V1605B	Intel Myriad 2	XCZU7EG
Type	MPSoC (CPU, GPU, FPGA)	FPGA based	Module with SoC (CPU, GPU, VPU, FPGA)	Module with SoC (CPU, GPU, VPU, FPGA)	SoC with vision accelerators (VPU)	MPSoC (CPU, GPU, FPGA)
CPU						
CPU	Quad ARM Cortex-A53 Dual ARM Cortex-R5F	Not present	Integrated with SoC	Integrated with SoC	LEON4	Quad ARM Cortex-A53 Dual ARM Cortex-R5F
OS	64-bit Linux (Yocto build)		64-bit Linux	64-bit Linux	No information found	Linux 4.14 LTS Robot Operating System
GPU						
GPU	Arm Mali™-400	Not present	Radeon™ R3E	Radeon™ Vega 8	Not present	Arm Mali™-400
API	OpenVG 1.1, OpenGL ES 1.1/2.0		DirectX 11.1, OpenCL 1.2, OpenGL 4.2, Vulcan 1.0	DirectX 12.1, OpenCL 2.1, OpenGL 4.6, Vulcan 1.2 ROCm to compile CUDA		OpenVG 1.1, OpenGL ES 1.1/2.0
FPGA						

FPGA	Xilinx Zynq UltraScale ZU15EG	Xilinx Kintex UltraScale KU095	Microsemi SmartFusion2	Microsemi PolarFire	**Not present**	Xilinx Zynq UltraScale XCZU7EG
AI-accelerator						
Model	[Irrelevant]	[Irrelevant]	Intel Movidius Myriad X with 16 SHAVE-cores	Intel Movidius Myriad X with 16 SHAVE-cores	Intel Movidius Myriad 2 with 12 SHAVE-cores	[Irrelevant]
Theoretical Compute	3 TOPS	No information found	4 TOPS	4 TOPS	1 TOPS	No information found

The less powerful Unibap iX5 (Unibap heritage) has been used in space: launched into space in 2021 as part of the WILD RIDE mission and it is also included in NASA's Hyti mission which was delayed but will be launched in 2023.

4.4.2 Intended OBP platform description

The intended hardware for onboard data processing is build around a UniBap iX10 computing unit, and will consist of a SoC including CPU and GPU, two VPUs and >1TB SSD storage :

- The **CPU** (AMD 1605b) runs a (recent) linux Ubuntu 20.04LTS based OS to execute the algorithms and processing, control the interfaces to the outside world (such as the SAR and VIS sensors), and to interface with the internal GPU and the VPUs.
- The **GPU** (AMD 1605b) can be used to accelerate optional (semisupervised) retraining of the AI algorithm or to execute CUDA accelerated data processing. Alternatively, the CPU can be used for this task.
- Dual **VPUs** (Vision Processing Unit) (Intel Myriad X) are added to the unit. These are dedicated AI accelerator microprocessors from Intel, to speed up AI model execution. Alternatively, the CPU can be used for this task. Each VPU consumes approximately 1.5W .
- 16GB **RAM** is expected
- The **SSD** storage can be used to store a reference dataset for the algorithms, buffer input data, buffer results, and allow storage of labelled and unlabelled dataset for optional AI model semi-supervised retraining.

An AI algorithm can be deployed using Tensorflow, Python3, and the Myriad VPU OpenVINO interfacing libraries. A similar platform has been used in the past for wireless RF signal interference detection, but is now adapted and optimised to support change and anomaly detection algorithms based on sensor data from a SAR and VIS sensor.

The estimated SWaP of the intended configuration is:

- The **power** consumption is dependent on the exact hardware configuration and will be measured after integration. A configuration with CPU, active GPU and single VPU consumes approximately 40W with peak power consumption up to 50W.
- The **volume** of the platform is 103x87x66.9 mm, exceeding the typical 1U formfactor in 1 dimension unless a hardware modification is made (removing a connector). These dimensions exclude additional mechanical housing of the processing unit. Exceeding the 1U formfactor in 1 dimension is typically acceptable in smallsats/cubesats.
- The estimated **mass** of the unit is <600g.

For this project, the unit's 1xEthernet, 2xUSB3 and 2xUSB2, and HDMI connection are expected to be used for interfacing with the data sensors, the user, and the data downlink.

In this project, depending on the AI model complexity and latency requirement, 2 (or even 4) instead of 1 VPU can be used to interleave multiple instances of the AI model (for example using the 'AI CORE XM 2280' module).

This classical Von Neumann implementation is first made operational to reduce functional risk of the demonstrator. Next, if the remaining project resources permit it, a Neuromorphic Akida Chip from Brainchip can be connected to the unit, to enable experimentation and comparison with this relevant and new technology.

The unit is to be applied with a single 12Vdc supply.

4.4.3 Latency analysis

In case of a targeted 60 minute user-request-result delay (section 3.1.3), a satellite revisit time of 17 minutes (section 4.1), and 10ms round-trip delay for a 900km LEO altitude (section 4.1), the onboard delay (including sensors, processing, algorithms, and scheduling for transmission) should be below $60 * 60 - 17 * 60 - 0.01 = 2580\ seconds$. For the nice-to-have 30 minute user-request-result delay (section 3.1.3), the on board delay constraint decreases to $780\ seconds$. This estimation assumes the satellite is in range of a ground station (or has access to an inter-satellite link) when the output data can be transmitted, and neglects on-earth connectivity delay.

A <10min delay is likely achievable, yet to be determined more accurately during design phase since depends heavily on the algorithm complexity and SAR processing delay.

4.5 SAR Image Formation

Within the last decades, a large number of operational and well known SAR satellites have been in service in space, most of them still providing data. These SAR sensors were mainly financed and operated by government operators and work mainly in the C, S, L or especially X-band. These imaging sensors include e.g. Sentinel-1 (A and B) (Copernicus Program of the European Union), COSMO-SkyMed (Italy), PAZ (Spain), Kompsat-5 (Korea), RADARSAT (Canada) and TerraSAR-X and TanDEM-X (Germany).

4.5.1 Comparison of several *SAR-Microsatellites constellations in "New Space"*

Numerous commercial companies have stepped up their activities and innovations in the field of "New Space" during the last years. Among the many activities, satellite-based SAR plays a significant role [32]. The emergence of numerous potential applications has changed technological approaches, leading to rapid development of new space systems through the application of agile concepts and the use of the latest commercial off-the-shelf (COTS) technologies.

A comparison in terms of resolution and mass of some spaceborne SAR systems is shown in Figure 4-3 from [33]. The listed microsatellite SAR constellations such as ICEYE and Capella SAR can provide low-cost SAR images with resolution comparable to medium/large SAR satellites such as KOMPSAT-5.

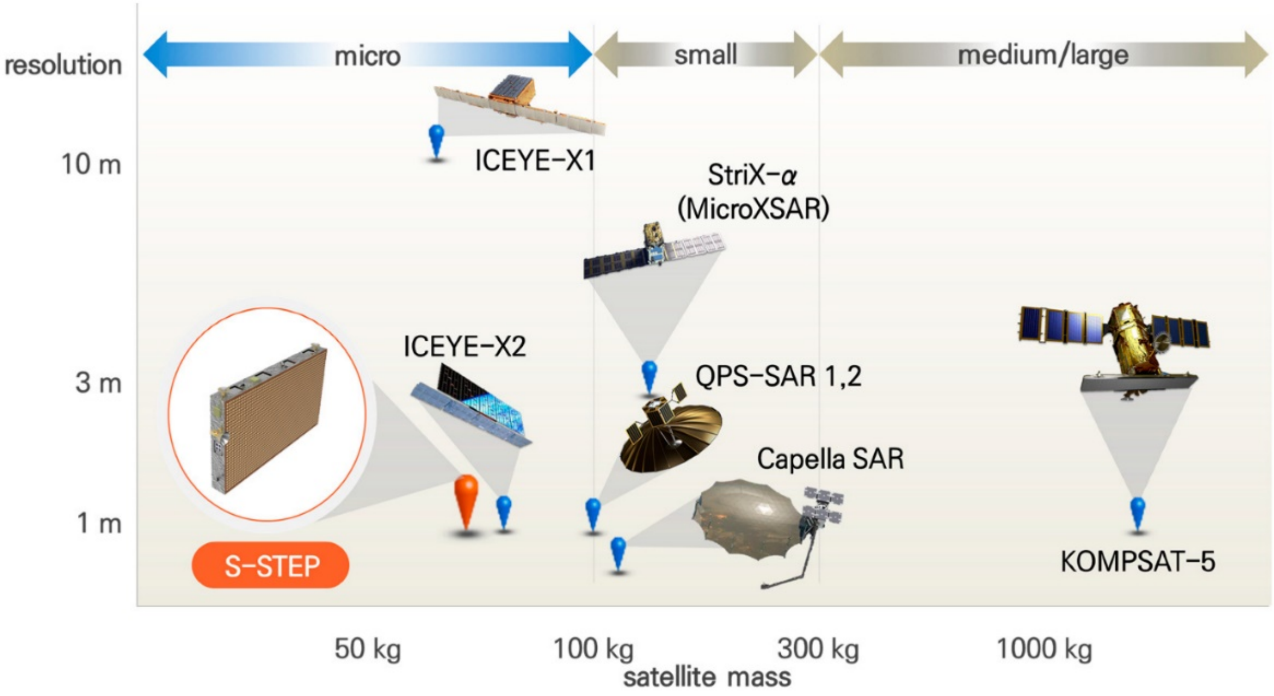


Figure 4-3: Comparison of satellite masses vs. SAR image resolutions [33].

ICEYE-X2, with a mass of 92 kg, is probably the first commercial SAR satellite in the microsatellite class [34] [35]. It can acquire SAR images in stripmap, spotlight, and ScanSAR modes and operates in the X-band. A phased array SAR antenna with 320 transmit/receive modules is used (3.2 m × 0.4 m microstrip patch array). Thereby, the time span from the request to the delivery of processed image data is estimated to be 32-48 h on average (https://www.iceye.com).

Capella SAR is a 107 kg microsatellite that was successfully launched in 2020 [36] [37] [38] [39]. The satellite has an X-band SAR sensor that acquires SAR images in spotlight mode with a ground resolution of 0.5 m. The satellite is equipped with a reflector antenna with a diameter of 3.6 m to minimize the transmit power. The effective area of the Capella SAR antenna is 8 m^2 compared to 1.3 m^2 for ICEYE. Therefore, Capella achieves a higher SAR image quality than ICEYE, e.g. for the Noise Equivalent Sigma Zero (NESZ).

StriX-α is an X-band SAR microsatellite constellation consisting of 25 satellites [40]. Each one weighs 130 kg and provides SAR images with a ground resolution of 1 to 3 m. Strix-α features a passive phased-array antenna with 4.9 m x 0.7 m honeycomb panels of a slotted waveguide array with solar panels mounted on its rear.

QPS-SAR is an X-band SAR microsatellite constellation with a total of 36 launches planned [41]. Each satellite weighs 100 kg and has a parabolic reflector antenna with a diameter of 3.6 m, which provides a resolution of 1 m in spotlight mode and a resolution of 1.8 m in stripmap mode.

The NOCTUA project aims at monitoring ground infrastructure and natural hazards by means of an X band SAR satellite designed for repeat pass Differential SAR interferometry [42].

However, besides conceptual studies like [43], the IIMEO consortium is not currently aware of any operational Ka-band SAR microsatellite constellation with (near) real-time SAR capability and spatial resolution of 50 cm.

4.5.2 SAR Image Formation in context of IIMEO

The basic methodology and the main discussion about the literature for the real-time Ka-band SAR image formation is presented in [2], that includes the real-time SAR processing aspects in Part B, section 1.2.1.2 and the SAR sensor aspects in Part B, section 1.2.1.3.

IIMEO aims to focus and process SAR raw data in the Ka-band at a frequency of 35 GHz in near real time (with a final expected spatial resolution of <50cm) from railroad tracks and railroad infrastructure acquired on an airborne platform with similar acquisition geometry as from a satellite in LEO and then to feed this generated SAR image data via suitable interfaces to further change and anomaly detection processing. This is to research and evaluate the procedures and algorithms for a later use of a Ka-band SAR sensor operated on a satellite.

In the course of the project, it is intended to realize the real-time SAR image formation based on the discussion in [2] by implementing the schematic concept illustrated in Figure 4-4.

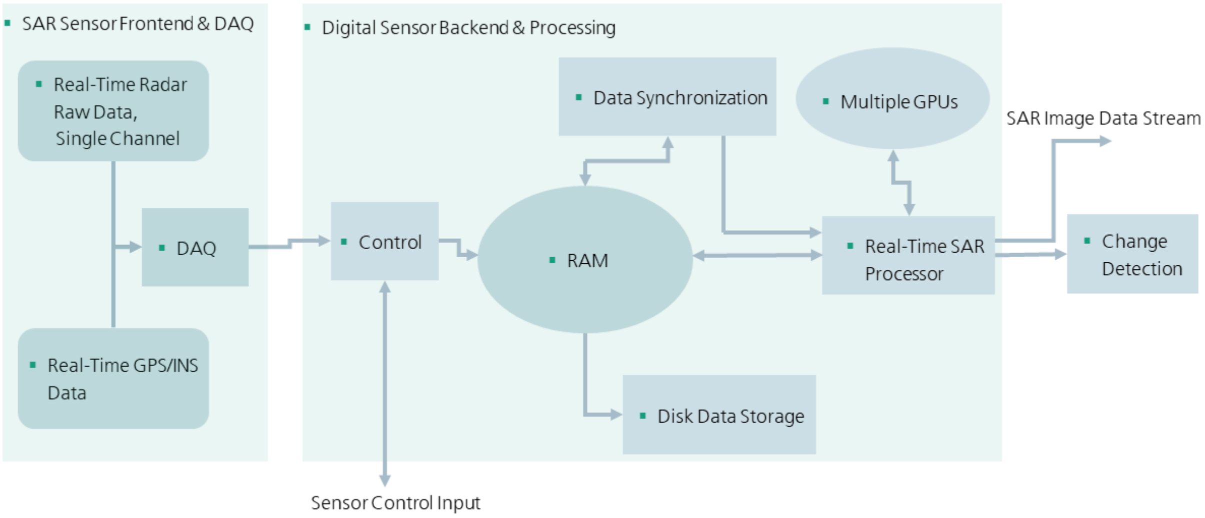


Figure 4-4: Schematic concept of the intended real-time SAR image formation process.

This involves the simultaneous collection and processing of SAR raw data and navigational data (GPS/INS), the synchronization of the data and the real-time SAR focusing by parallel processing of consecutive synthetic apertures or subapertures using multiple graphics cards. Therefore, several processes must simultaneously share a certain part of the background memory (RAM), which contains the currently acquired radar raw data and navigational data. Thus, a high level of inter-process communication (IPC) is required, which can e.g. be realized in the form of a shared memory.

4.5.2.1 First estimations concerning the SAR data rate

To obtain a range resolution (slant range) of $\delta_r =$ 50 cm with a possible satellite SAR sensor configuration, an RF signal bandwidth B_{RF} of at least $B_{Rf} = \frac{c_0}{2 \cdot \delta_r}$ has to be transmitted with c_0 the speed of light. Considering the resolution projected onto the illuminated ground area, this deteriorates at increasingly steeper elevation angles ϑ, requiring a signal bandwidth $B_{RF} = \frac{c_0}{2 \cdot \delta_r \cdot \cos(\vartheta)}$. For a typical elevation angle ϑ of 50°, equivalent to an inclination angle of 40°, this corresponds to a required bandwidth B_{RF} of about 460 MHz.

In the airborne case with a platform speed of 54 m/s and a desired azimuth resolution of 0.5 m, this corresponds in Ka-band to an azimuth angle of 0.5° that needs to be coherently processed at the minimum. At a flight altitude of 1500 m and a depression angle of 50°, a single subaperture would then correspond to about 18 m in length. With highly directional antennas of 0.5 degrees aperture angle this would correspond to a pulse repetition frequency (PRF) of < 200 Hz, however, if the less directional antennas of 3° aperture angle from the existing Ka-band sensor are used and small drift angles during flight are taken into account, a PRF of at least 1 kHz is more realistic. If then a strip width in range of 500 m is illuminated and 3 subapertures per second are recorded, this results in a data rate of about 16 Mbit/sec raw data (complex samples). After SAR processing, an area of 54 m * 500 m is illuminated per second, which results in 432000 pixels if a 0.25 m^2 pixel spacing is applied. With a pixel encoding of only one Byte, 432 KByte image data would be generated. Further considering meta data for each subaperture such as GPS and IMU data and georeferencing parameters, the generated data is estimated to be below 1 Mbyte/sec, but can grow significantly if a different pixel spacing or encoding of the image pixels is required.

Transferred to the satellite case, a significantly larger area will be illuminated and processed per unit time. Assuming a flight speed of 7500 m/s and an assumed strip width of 20 km in range, about $\frac{7500\frac{m}{s}\cdot 20.000m}{(0.25m)^2}\cdot 1\,Byte$ = 2.4 GByte/sec of processed image data would be generated taken into account a pixel spacing of 0.25 m². To reduce the data rate, however, smaller strip widths in range have to be considered or a focus exclusively on the target area - the area around the railroad tracks. With a given margin of 12 m on each side along a railway track with a supposed width of 6 m, this would correspond to an area of interest to be focused of 30 m. In such a constellation, about $\frac{7500\frac{m}{s}\cdot 30m}{(0.25m)^2}\cdot 1\,Byte = 3.6$ MByte/sec of processed image data would be generated.

4.5.2.2 Onboard Real-time SAR Processing Benefits

As discussed, one challenge for SAR remote sensing systems is the large amounts of data that often exceed the downlink capacity of satellite communications. This means that critical data and information may not be available in real time on the ground. One way to increase data throughput is to compress the raw SAR data, which is difficult due to the nature of the raw data. The most effective techniques such as block adaptive quantization (BAQ) result in a compression factor of 4 [44] [45] [46]. Another option is to process the raw SAR data onboard and then compress the generated SAR images (Multilook or Single Look Magnitude), since SAR images are much easier to compress. Table 4-4 by [47] provides a comparison of compression factors for raw SAR data and images and clearly shows the advantages of processing and compressing onboard. For a more general discussion of image compression, see section 4.2.3.

Table 4-4: SAR Compression Factors [47]

Parameter	SAR Raw Data	SAR Image
Compression Factor	Up to 4 x	Up to 50 x
Data Processing	None	Multilook Image Processing
Compression Technique	FFT Block Adaptive Quantization	Wavelet Compression
Downlinked Data Format	Complex	Magnitude

4.5.2.3 Recent research towards real-time satellite SAR processing

Besides the work already reviewed in [2], there has recently been increased research for real-time spaceborne SAR imaging systems especially in China. In [48], the authors designed a real-time SAR processing platform hardware based on multiple FPGAs and supplemented by high-performance DSP processors supporting high-speed floating point processing. Evaluation was further performed by processing airborne data.

Authors in [49] designed and constructed a prototype real-time SAR imaging chip for spaceborne SAR constellations based on 4 ARM cortex 53 CPUs, optimised for applying the Fast-Factorized Backprojection (FFBP) algorithm to focus the SAR data. They state that a single chip has an expected power consumption of 30 watt while a complete real-time SAR imaging setup consisting of multiple parallel chips requires 800 Watt.

4.6 Change Detection

The main discussion about the related literature for the change detection problem is presented in [2], Part B, Section 1.2.1.2. We discuss here the recent findings that emerged from the literature review.

IIMEO algorithms must deal with SAR images of railways in the Ka-band, therefore at the unprecedented wavelength of ~1cm (with a final expected spatial resolution of <50cm) for the application of change detection. This poses a challenge and requires ad-hoc techniques to deal with the high spatial detail of the images. In [2], we discussed the implementation of both fast-thresholding techniques and deep neural networks for the identification and recognition of high-level features like rails, sleepers, embankment stones, etc. A recent document by the Railtec Illinois proposes a workflow for automated change detection of railway components [50]. The approach described therein discusses an integrated workflow with co-registration, intensity-based and thematic-based change detection and cluster processing applied to optical cameras images. Although in a different application context (in situ monitoring of rail track changes by flying over the track with unmanned vehicles) the analysis gives important elements for the definition of the methodological structure of the IIMEO SAR obstacle-change detection approach. Of particular interest, there are:

- A thematic approach based on automatic recognition of elements in the image.
- An effective ontology of relevant and non-relevant changes and their impact on the performance and the outcome of the algorithms.
- A semantic interpretation of a set of railway-related changes and their relationship with the track conditions.

In the project we aim at empowering the mentioned framework with integration of neural networks technology to boost the object recognition task. Besides the works already reviewed in [2], another work emerged in the literature analysis that applies neural networks for change detection and inspection of railways, with focus on plug defects [51]. Although this work focuses on optical imagery, it is of interest how the image alignment and similarity measurements are included in the network for better performance of the change detection algorithm.

Regarding VIS data, labelled data sets are readily available for several change detection scenarios. These do not necessarily contain railway infrastructure, but contain core features also expected to be present in IIMEO VIS data that need to be correctly accounted for. For instance, apparent changes due to off-nadir viewing angles are an ongoing topic in the building change detection task [52], [53], which is a popular benchmark for change detection methods. For these, we find that neural networks, such as [54], produce state of the art results in high-resolution optical data and are capable of accounting for numerous adverse effects such as the aforementioned, or those dependent on the time of day, i.e. variant illumination and shadow.

4.7 VIS and Anomaly Detection

In addition to SAR, the IIMEO demonstrator and the potential future IIMEO space-based prototype will carry a VIS camera whose field of view will overlap the field of view of the SAR. The demonstrator to be built in the scope of this project will also carry a nadir-looking camera, whose field of view will be distinct of the SAR's field of view.

The resulting imagery is to be used to find defects on railway tracks by the detection of anomalies. Additionally, the sensor data of the VIS camera is to be fused with the SAR measurements in order to improve the defect detection accuracy.

Being at the beginning of the project, it is not entirely clear what camera performance parameters are needed to perform anomaly detections, however, a few assumptions to pick cameras to determine the parameters actually required is made in the following.

Doing anomaly detection using imagery essentially amounts to establishing a belief as to which parts of the image are supposed to show a railway track, classifying parts of the image as "railway track" and "not a railway track" using the image content and then computing the likelihood of finding "not a railway track"-regions at the so-classified regions given the belief established previously. Aside from complications such as buildings obstructing the view onto the railway tracks or a train driving on that track, the main difficulty appears to detect unobstructed railway tracks in the images in the first place.

The track gauge in most parts of the world – including Serbia – is 1435 mm. Using a ground sampling distance of about 50 cm as we will for SAR (see section 4.5) would result in less than 3 pixels being between the two rails of the track. This appears to be very little to carry out the detection task, so at last for the IIMEO demonstrator, we will require at least double that resolution, i.e. a ground sampling distance of at most 25 cm.

In addition to the sensor's resolution, the optics and the altitude, the ground sampling distance also depends on the angle the camera is mounted within the wing pod. Since one of the cameras looks in the direction of the SAR which must look in an oblique direction, the ground sampling distance of the farthest pixels is to be used to check compliance with the ground resolution requirement.

Although we assume that – given enough pixels per track – we will be able to detect railway tracks in panchromatic images, we are not entirely certain about that either, so we require the VIS cameras on the IIMEO demonstration plane to have at least three (red, green, blue) colour channels. Computing an approximately panchromatic image from an RGB image is possible, down sampling a relatively high-resolution image is possible as well, so using such imagery it is still possible to determine whether panchromatic with 50 cm ground sampling distance would be sufficient; the other way around, however, would obviously be impossible.

4.8 SAR and VIS Fusion

IIMEO will find evidence for defects of railway tracks at least using change detection on SAR data (see sections 4.5 and 4.6) and, if daylight and weather permit, using anomaly detection on VIS image (see section 4.7).

We will also fuse both sources of evidence in order to provide a map of defects which shall be at least as good as the map of defects estimated using only one of the individual sources. There are a few situations in which this will be trivially the case, e.g. without daylight or complete cloud-cover and thus a blind VIS camera, or over areas only observed by the VIS camera and not by SAR due to the larger field of view of the two cameras on the demonstrator plane. The interesting are is the intersection of the fields of view of the oblique camera and the SAR.

For locations with actual defects on the railway track, the probability of a defect detection using both SAR und VIS shall be greater than or equal to the detection probability using only one of the instruments exclusively. Similarly, the probability of defect detections for locations with no actual defects shall be less than or equal to the corresponding probability using SAR or VIS exclusively.

In most cases, we also expect the estimator's confidence in its own estimate to increase, however, it may be that the data from the individual instruments provide conflicting evidence. In such a case, the estimator shall still report its best guess, however, it also shall put out that its confidence in the result is low, thus essentially report that it does not know what's going on at the respective location.

One approach to the data fusion problem would be to process the data of both VIS and SAR independently at first, e.g. into ortho-rectified images, collect large volumes of reference imagery over areas for which the locations of defects are known and then to train a more or less generic model, such as a neural network, to detect the known defects, expecting to capture the features of SAR and VIS data which are useful to detect defects in the model's parameters. Such a setup may be varied in a number of ways, e.g. using a model to compute an intermediate representation from which the actual defect detections are computed.

An alternative approach is to handcraft a statistical model with fewer parameters which fuses data generated from SAR and VIS, such as the change detection and anomaly detection results, into a map of defects. The best-possible performance in terms of true- and false-positive detections of such an approach would likely be worse than the best-possible performance of a larger, trained model, however, its results would be much easier to explain and the required amount and required diversity of reference imagery would like be a lot smaller, which are both very desirable properties. Additionally, we aim to use the simpler method to compute the SAR and VIS fusion on-board to provide extents and locations of defects on rail tracks from fused data.

In IIMEO, we will follow the second, more transparent, approach first to reach a high TRL quickly with relatively small amounts of imagery. Once that works, we will try approaches using neural networks, using the then-existing VIS+SAR-fusion as a baseline.

4.9 IIMEO Requirements and Space Platform Constraints

As discussed in section 3.1, the requirements for Railway Monitoring depend on the type of defect to be found.

Some need **continuous monitoring** with a limited resolution, others – those rendering a segment of track dangerous to use – need the potential satellite constellation to frequently monitor a very limited geographic area with great spatial resolution, i.e. **around 50 cm ground sampling distance**. Such defects, which suddenly change a healthy track into a dangerous one, usually have external triggers, e.g. heavy rainfall or storm.

The latter requires, even from low earth orbit, multiple satellites to achieve revisit rates greater than 1 visit per 60 minutes. Since we expect defect detection to be done using change detection with respect to reference data of healthy railways or using anomaly detection, there does not have to be direct satellite-to-satellite communication. However, IIMEO has to support **bi-directional communication with the ground station**, both to communicate the payload results and telemetry data (satellite-to-ground) as well as **tasking** (ground-to-satellite) to make the constellation's satellites observe the regions affected by events which lead to relatively frequent occurrence of dangerous defects.

One of the primary motivations to satellite (constellation) requirements is to keep the gap between this IIMEO project and a potential space-based service small. Thus, even in this IIMEO project, **telemetry and tasking communication is to be implemented using services as in the PUS** mentioned in subsection 4.3.

It is relatively hard to come up with definite requirements concerning the data downlink since there is considerable variability in the available data rate a satellite downlink might offer, as discussed in Section 4.2. In addition to the data rate induced by the ground sampling distance and the speed at which the satellite moves across the earth's surface, the satellite also needs to see a ground station with its communication link in order to transfer data. How long this is depends on the concrete orbit as well as the ground station elevation but, as briefly discussed in section 4.2.1, the duration is in the 10 minutes to 15 minutes ballpark. Assuming an X-band link with >100 Mbit/s, this would allow a satellite to **transfer** $\mathbf{100 * 60 * 10/8/1000 = 7.5}\ \text{GByte}$ **per ground station overpass**. This should be kept in mind when choosing or designing algorithms requiring the transfer of image data. Additionally, as discussed in section 4.2.2, the data rate of a satellite is drastically larger than that of our 'satellite approximation plane', simply due to the difference in speed. As argued above, the design to be developed in this project will probably be satellite-constellation-compatible in terms of data downlink requirements as long as it restricts itself to single-digit Mbit/s.

The largest part of the data volume is made up of image data, the compression of which was discussed in section 4.2.3. The take-home message regarding compression is that we can **expect a compression rate of about 6** without any major loss of image quality in terms of PSNR and without blocking artefacts. So as a guideline, the **data rate of the IIMEO demonstrator should not exceed single-digit Mbit/s or "single-digit times 6" without image compression**. For SAR images, significantly greater compression factors have been mentioned in subsection 4.5.2.2, if those are to be relied on the corresponding image quality has to be evaluated as well.

There appear to be surprisingly little constraints due to the satellite platforms itself. To keep costs low, it would certainly be beneficial if the potential IIMEO payload would remain bearable for a CubeSat satellite, however, as mentioned in section 4.1, there are LEO satellites in the up-to-5-years lifetime category which support up to 90 kg payload, which we assume to be the maximum acceptable mass. So we should aim for **less than 15 kg payload mass to fit on CubeSats and limit us at 90 kg**. This is the same payload mass magnitude as the pod under the wing of the demonstration plane can carry. We expect the choice of satellite platform to be narrows down in the scope of the roadmap to space in D5.9 [22].

4.9.1 IIMEO System requirements

The following tables specify the intended IIMEO system as described in the previous sections.

The column "Relevance" denotes the applicability for the satellite constellation and/or the demonstrator.

Table 4-5 Satellite constellation requirements

Requirement#	Requirement description	Priority	Remark	Relevance	Reference
IIMEO-RQ-Sat-01	The IIMEO system shall be based on a satellite	Shall	LEO: between 500 and 900 km above ground	Space	4.1

	constellation flying in low earth orbit (LEO).				
IIMEO-RQ-Sat-02	The IIMEO system shall use a satellite platform with mass < 200 kg and single digit years lifetime (SmallSat).	Shall	Optionally, so-called CubeSats may be used.	Space	4.1
IIMEO-RQ-Sat-03	The revisit time of the IIMEO system shall be less than one hour.	Shall	Details, such as field of regard, orbit, number of satellites etc., will be given in the roadmap to space (WP5).	Space	4.1

Table 4-6 Data transfer requirements

Requirement#	Requirement description	Priority	Remark	Relevance	Reference
IIMEO-RQ-Com-01	The IIMEO system shall provide a payload data downlink bandwidth of at least 100 Mbit/s.	Shall	X-Band	Space	4.2
IIMEO-RQ-Com-02	The IIMEO system shall be capable to transfer a complete response from satellite to ground within the corresponding overpass time.	Shall	The overpass time depends on the satellite orbit and the related ground station elevation. The overpass time is estimated with 10-15 minutes, allowing a transfer of 7.5 Gbyte per overpass.	Space	4.2.1
IIMEO-RQ-Com-03	The downlink data rate for the IIMEO demonstrator shall be scaled down with respect to - the ratio between airplane speed and estimated satellite speed - the airplane's field of view size and the estimated satellite's field of view size.	Shall	The ratio between airplane speed and satellite speed is estimated with 1:100.	Demonstrator	4.2.2
IIMEO-RQ-Com-04	The data rate of the IIMEO demonstrator should not exceed 10 Mbit/s (compressed data) or 60 Mbit/s (uncompressed data), respectively.	Should		Demonstrator	4.9

IIMEO-RQ-Com-05	The IIMEO system shall be capable of bi-directional communication with the ground station.	Shall		Demonstrator Space	4.3
IIMEO-RQ-Com-06	The communication between the IIMEO system and the ground station shall be based on or be similar to PUS services.	Shall		Demonstrator Space	4.3

Table 4-7 On-board data processing requirements

Requirement#	Requirement description	Priority	Remark	Relevance	Reference
IIMEO-RQ-Proc-01	The IIMEO system should be capable of fusing SAR data and image data prior to transmission to ground.	Should		Demonstrator Space	4.8
IIMEO-RQ-Proc-02	The IIMEO system shall provide VIS image data compression at a high compression rate that preserves the information, required to distinguish damaged infrastructure from healthy infrastructure.	Shall		Demonstrator Space	4.2.3.3
IIMEO-RQ-Proc-03	The applied VIS image data compression shall be capable of processing high resolution RGB images with 16 bit depth.	Shall		Demonstrator Space	4.2.3.4
IIMEO-RQ-Proc-04	The applied VIS image data compression should be based on an open and widespread format.	Should		Demonstrator Space	4.2.3.4
IIMEO-RQ-Proc-05	The applied VIS image data compression should provide a compression ratio of about 6 or greater.	Should		Demonstrator Space	4.9
IIMEO-RQ-Proc-06	The data processing shall be executed on a dedicated on-board processing (OBP) unit.	Shall	Data processing includes fusion of SAR and image data, processing of algorithms and data compression	Demonstrator Space	4.4

IIMEO-RQ-Proc-07	The OPB unit shall consist of a SoC including CPU and GPU, two VPUs, 16GB RAM and >1TB SSD storage.	Shall	The Unibap iX10-100 system is selected as basis in IIMEO.	Demonstrator Space	4.4.2
IIMEO-RQ-Proc-08	The OBP unit shall provide interfaces to the SAR and VIS sensors, the data downlink and the user.	Shall		Demonstrator Space	4.4.2
IIMEO-RQ-Proc-09	The power consumption of the OBP unit (not including SAR raw data processing) shall not exceed 50W.	Shall	40W nominally with peak power consumption up to 50W	Demonstrator Space	4.4.2
IIMEO-RQ-Proc-10	The volume of the OBP unit shall not exceed the 1U form factor in more than one dimension.	Shall		Demonstrator Space	4.4.2
IIMEO-RQ-Proc-11	The overall payload mass shall be less than 90 kg.	Shall	Goal: less than 15 kg payload mass to fit on CubeSats.	Demonstrator Space	4.9
IIMEO-RQ-Proc-12	The unit is to be applied with a single 12Vdc supply.	Shall		Demonstrator Space	4.4.2
IIMEO-RQ-Proc-13	The onboard delay (including sensors, processing, algorithms, and scheduling for transmission) should be below 2580 seconds.	Should		Demonstrator Space	4.4.3

Table 4-8 SAR instrument requirements

Requirement#	Requirement description	Priority	Remark	Relevance	Reference
IIMEO-RQ-SAR-01	The IIMEO system shall be capable of processing SAR raw data in the Ka-band at a frequency of 35 GHz in near real time.	Shall		Space Demonstrator	4.5.2
IIMEO-RQ-SAR-02	The IIMEO system shall provide a spatial resolution of ≤ 0.5 m.	Shall		Space Demonstrator	3.1.2 4.5.2.1
IIMEO-RQ-SAR-03	The IIMEO system shall provide an RF signal bandwidth of about 460 MHz.	Shall		Space Demonstrator	4.5.2.1

IIMEO-RQ-SAR-04	The IIMEO system shall provide a Pulse Repetition Frequency (PRF) of at least 1 kHz.	Shall		Demonstrator	4.5.2.1
IIMEO-RQ-SAR-05	The IIMEO system shall be capable of processing SAR raw data of at least 2 Mbyte/sec	Shall		Demonstrator	4.5.2.1
IIMEO-RQ-SAR-06	The IIMEO system shall be capable of processing focused SAR data of at least 1 Mbyte/sec.	Shall	Taking pixel spacing of 0.25 m^2 into account	Demonstrator	4.5.2.1
IIMEO-RQ-SAR-07	The IIMEO system shall be capable of processing focused SAR data of at least 3.6 MByte/sec.	Shall	Taking pixel spacing of 0.25 m^2 into account, further assuming that only the relevant area of a single railway track is focused	Space	4.5.2.1
IIMEO-RQ-SAR-08	The IIMEO system shall be capable of processing raw SAR data onboard.	Shall		Space Demonstrator	4.5.2.2

Table 4-9 VIS instrument requirements

Requirement#	Requirement description	Priority	Remark	Relevance	Reference
IIMEO-RQ-VIS-01	The IIMEO demonstrator shall have a nadir-looking camera.	Shall		Demonstrator	4.7
IIMEO-RQ-VIS-02	The IIMEO system shall have an oblique camera whose field of view overlaps the SAR's field of view.	Shall		Space Demonstrator	4.7
IIMEO-RQ-VIS-03	The ground sampling distance of the IIMEO cameras shall be less than or equal to 25 cm.	Shall		Space Demonstrator	4.7
IIMEO-RQ-VIS-04	The IIMEO cameras of the demonstrator shall record color channels for red, green and blue.	Shall		Demonstrator	4.7
IIMEO-RQ-VIS-05	The field of view of an image shall overlap the field of view of the image acquired immediately before by the same camera.	Shall		Space Demonstrator	4.7

Table 4-10: SAR+VIS fusion requirements

Requirement#	Requirement description	Priority	Remark	Relevance	Reference

IIMEO-RQ-SVF-01	The true-positive detection rate shall be equal to or greater than the true-positive rate obtained using the individual sensors alone.	Shall		Space Demonstrator	4.8
IIMEO-RQ-SVF-02	The false-positive detection rate shall be equal to or less than the false-positive rate obtained using the individual sensors alone.	Shall		Space Demonstrator	4.8
IIMEO-RQ-SVF-03	The detection results obtained using fused SAR and VIS measurements should be explainable using features of those measurements.	Should		Space Demonstrator	4.8

5 CONCLUSION

In conclusion, the D1.1 document has provided a sound analysis of the requirements, providing the baseline for the upcoming IIMEO algorithms and sensor synergy concept (task T1.3), where we will come up with a preliminary selection of algorithms to use and also a preliminary decision on what to compute on-board/on-ground, as well as for the overall system design update (task T1.4), where we will elaborate the demonstration scenario, define KPIs and measurements within the pilot and specify the data to be collected as we will update the system concept. At the same time this document prepares the ground for the subsequent implementation phase (performed within WP2-4). The use of a common approach by categorizing requirements has provided a structured framework for conducting the analysis, enabling a systematic and comprehensive understanding of the end user needs, helping to identify the key aspects that need to be considered in the development of an effective infrastructure monitoring system.

The results of the requirements analysis will serve as the basis for the design and development of the overall infrastructure monitoring system. It will guide the selection of appropriate satellite constellations, data processing techniques, and service delivery models to meet the specific needs of the end users.

As a next step, following the identification of requirements, the consortium will define the overall innovation concept and the plan for the implementation (to be done in WP2- WP4). Moreover, laboratory prototypes of the technologies to be developed will be prepared and appropriate KPIs and methods for their performance measurements will be defined in detail.

6 REFERENCES

[1] European Health and Digital Executive Agency (HaDEA), *Instantaeous Infrastructure Monitoring by Earth Obeservation (101082410 - IIMEO), IIMEO-EC-CTR-0001, 01,* 2022.

[2] IIMEO Consortium, *Consortium Agreement, IIMEO-OHBDC-CTR-0002, 01,* 2022.

[3] E. Koks, J. Rozenberg, C. Zorn and others, “A global multi-hazard risk analysis of road and railway infrastructure assets.,” *Nat Commun 10, 2677,* 2019.

[4] D. Ristić-Durrant, M. Franke and K. A. Michels, “Review of Vision-Based On-Board Obstacle Detection and Distance Estimation in Railways”.*Sensors 2021, 21, 3452.*

[5] MOMIT Consortium, “Deliverable D4.2-Technical Report: Application Cases Outcomes,” 2020. [Online]. Available: https://projects.shift2rail.org/download.aspx?id=c6d301d0-3143-4487-8738-fd9faee361ca.

[6] NSR, An Analysis Mason Company, „https://www.nsr.com/?research=satellite-based-earth-observation-14th-edition,“ [Online]. Available: https://www.nsr.com/?research=satellite-based-earth-observation-14th-edition.

[7] L. Matikainen, M. Lehtomäki, E. Ahokas, J. Hyyppä, M. Karjalainen, A. Jaakkola, A. Kukko und T. Heinonen, „Remote sensing methods for power line corridor surveys,“ *ISPRS Journal of Photogrammetry and Remote sensing,* Bd. 119, pp. 10-31, 2016.

[8] V. Krebs und H. Schuettrumpf, „Entwicklung eines sensorbasierten Deichmonitorings,“ *Die Kueste,* Bd. 90, pp. 79-130, 2021.

[9] H. Schuettrumpf und H. Oumeraci, „Sea Dikes in Germany,“ *Die Kueste,* Bd. 74, pp. 189-199, 2008.

[10] J. Knoeff, E. Vastenburg und E. Tromp, „Rational risk assessment of dikes by using a stochastic subsurface model,“ in *4th International Symposium on Flood Defence: Managing Flood Risk, Reliability and Vulnerability*, Toronto, Canada, 2008.

[11] J. Aanstoos, K. Hasan, C. O'Hara, L. Dabbiru, M. Mahrooghy, R. Nobrega und M. Lee, „Detection of slump slides on earthen levees using polarimetric SAR imagery,“ in *IEEE Applied Imagery Pattern Recognition Workshop (AIPR)*, 2012.

[12] S. Cundill, „Investigation of remote sensing for dike inspection,“ *PhD Thesis, Faculty of Geo-Information Science and Earth Observation, University of Twente,* 2016.

[13] S. Gernhardt und R. Bamler, „Deformation monitoring of single buildings using meter-resolution SAR data in PSI,“ *ISPRS Journal of Photogrammetry and Remote Sensing,* Bd. 73, pp. 68-79, 2012.

[14] J. Driebergen, „The detection of deformation on vegetated dikes using InSAR,“ *Master Thesis, TU Delft - Geoscience and Remote Sensing,* 2019.

[15] M. Soilán, A. Sánchez-Rodríguez, P. del Río-Barral, C. Perez-Collazo, P. Arias and B. Riveiro, “Review of Laser Scanning Technologies and Their Applications for Road and Railway Infrastructure Monitoring,” *Infrastructures 2019, 4, 58,* 2019.

[16] F. Outay, H. A. Mengash and M. Adnan, “Applications of unmanned aerial vehicle (UAV) in road safety, traffic and highway infrastructure management: Recent advances and challenges,” *Transp Res Part A Policy Pract.;141,* pp. 116-129, 2020.

[17] F. Orellana, J. Delgado Blasco, M. Foumelis, P. D’Aranno, M. Marsella and P. Di Mascio, “DInSAR for Road Infrastructure Monitoring: Case Study Highway Network of Rome Metropolitan (Italy),” *Remote Sens. 2020, 12, 3697,* 2020.

[18] M. Khatun, S. Rahaman, S. Garai, P. Das and S. Tiwari, “Assessing River Bank Erosion in the Ganges Using Remote Sensing and GIS. 10.1007/978-3-030-75197-5_22,” 2022.

[19] L. Longoni, M. Papini, D. Brambilla, L. Barazzetti, F. Roncoroni, M. Scaioni and V. Ivanov, “Monitoring Riverbank Erosion in Mountain Catchments Using Terrestrial Laser Scanning,” *Remote Sens. 2016, 8, 241,* 2016.

[20] A. Mehrparvar, D. Pignatelli, J. Carnahan, R. Munakat, W. Lan, A. Toorian, A. Hutputanasin und S. Lee, „Cubesat Design Specification,“ *The CubeSat Program, Cal Poly San Luis Obispo, US,* Bd. 1, Nr. 2, 2014.

[21] A. Freeman, „Design Principles for Smallsat SARs,“ in *Small Satellites Conference (SmallSat 2018)*, 2018.

[22] IIMEO Consortium, *D5.9: Roadmap to Space and for future Earth Observation Services,* 2024 (to appear).

[23] „Open Railway Map,“ [Online]. Available: https://www.openrailwaymap.org/. [Zugriff am May 2023].

[24] L. N. Faria, L. M. G. Fonseca und M. H. M. Costa, „Performance evaluation of data compression systems applied to satellite imagery.,“ *Journal of Electrical and Computer Engineering,* 2012.

[25] Consultative Committee for Space Data Systems, „Report Concerning Space Data System Standards: Image Data Compression (CCSDS 120.1-G-3),“ CCSDS Secretariat, NASA, Washington, DC, USA, 2021.

[26] C. Gohlke, *Imagecodecs,* DOI: 10.5281/zenodo.6915978, 2023.

[27] JPEG, „Software for JPEG XR,“ [Online]. Available: https://jpeg.org/jpegxr/software.html. [Zugriff am 04 05 2023].

[28] [Online]. Available: https://support.captureone.com/hc/en-us/articles/360002564358-Phase-One-RAW-files-option.

[29] E. Öztürk und M. Altan, „Performance evaluation of jpeg standards, webp and png in terms of compression ratio and time for lossless encoding,“ *2021 6th International Conference on Computer Science and Engineering (UBMK),* 2021.

[30] M. Testolina, E. Upenik und T. Ebrahimi, „Comprehensive assessment of image compression algorithms,“ *Applications of Digital Image Processing XLIII,* 2020.

[31] ECSS, “ECSS-E-ST-70-41C – Telemetry and telecommand packet utilization,” 15 April 2016. [Online]. Available: https://ecss.nl/standard/ecss-e-st-70-41c-space-engineering-telemetry-and-telecommand-packet-utilization-15-april-2016/.

[32] S. Paek, S. Balasubramanian, S. Kim und O. De Weck, „Small-Satellite Synthetic Aperture Radar for Continuous Global Biospheric Monitoring,“ *Remote Sensing,* p. 2546, 12 2020.

[33] S. Kim, C.-M. Song, S.-H. Lee, S.-C. Song und H.-U. Oh, „Design and Performance of X-Band Payload for 80 kg Class Flat-Panel-Type Microsatellite Based on Active Phased Array Antennas,“ p. 213, 9(4) 2022.

[34] V. Ignatenko, P. Laurila, A. Radius, L. Lamentowski, O. Antropov und D. Muff, „ICEYE Microsatellite SAR Consteallation Status Update: Evaluation of First Commercial Imaging Modes,“ *Proceedings of the IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium,* pp. 3581-3584, 10 2020.

[35] J. Korczyk, „Reliable on Board Data Processing System for the ICEEYE-1 Satellite,“ in *KTH Royal Institute of Technology*, Stockholm,Sweden, 2016.

[36] D. Castelleti, G. Farquharson, C. Stringham und D. Eddy, „Operational Readiness of the Capella Space SAR System,“ *Proceedings of the IGARSS 2020 IEEE International Geoscience and Remote Sensing Symposium, Waikoloa, USA,* pp. 3571-3573, 2020.

[37] G. Castelletti, G. Farquharson, C. Stringham, M. Duersch und D. Eddy, „Capella Space First Operational SAR Satellite,“ in *Proceedings of the 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*, Brussels, Belgium, 2021.

[38] G. Farquharson, W. Woods, C. Stringham, N. Sankarambadi und L. Riggi, „The Capella Synthetic Aperture Radar Constellation,“ in *Proceedings of the IGARSS 2018 IEEE International Geoscience and Remote Sensing Symposium*, Valencia, Spain, 2018.

[39] C. Stringham, G. Farquharson, D. Castelletti, E. Quist, L. Riggi, D. Eddy und S. Soenen, „The Capella X-band SAR Constellation for Rapid Imaging,“ in *Proceedings of the IGARSS 2019 IEEE International Geoscience and Remote Sensing Symposium*, Yokohama, Japan, 2019.

[40] B. Pyne, H. Saito, P. Akbar, J. Hirokawa, T. Tomura und K. Tanaka, „Development and Performance Evaluation of Small SAR System for 100-kg Class Satellite,“ *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.,* Bd. 13, pp. 3879-3891, 2020.

[41] D. Faizullin, „Attitude Determination and Control System for the First SAR Satellite in a Constellation of iQPS,“ in *Proceedings of the 71st International Astronautical Congress (IAC)*, Dubai, United Arab Emirates, 2020.

[42] A. Meta und F. Speziali, „Design and performance analysis of the MetaSensing StarSAR-X, the phased array SAR payload of the NOCTUA project,“ in *13th European Conference on Synthetic Aperture Radar EUSAR* , 2021.

[43] M. Ludwig, D. D'Addio und P. Saameno-Perez, „Ka-Band SAR for Spaceborne Applications based on Scan-on-Receive Techniques,“ in *7th European Conference on Synthetic Aperture Radar*, Friedrichshafen, Germany, 2008.

[44] S. Bhattacharya, T. Blumensath, B. Mulgrew und M. Davies, „Fast Encoding of Synthetic Aperture Radar Raw Data using Compressed Sensing,“ in *IEEE SSP'07*, 2007.

[45] M. Suess, C. Schaefer und R. Zahn, „Discussion of the introduction of on-board SAR data processing to spaceborne SAR instruments,“ in *IGARSS 2000*, 2000.

[46] S. Parkes und H. Clifton, „The compression of raw SAR and SAR image data," *Int. J. Remote Sensing,* Bd. 20, pp. 3563-3581, 1999.

[47] A. Bergeron, M. Doucet, B. Harnisch, M. Suess und et al., „Satellite on-board real-time SAR processor prototype," *Proc. International Conference on Space Optics - ICSO,* 2010.

[48] Q. Liu, F. Wang, H. Yu, H. Li und J. Zhao, „Design of High Reliable Spaceborne SAR Real-time Processing Platform," in *2nd China International SAR Symposium (CISS)*, Shanghai, China, 2021.

[49] Y. Li, L. Chen, F. Liu, T. Qiao, M. Xu und Y. Xie, „Design of High-performance Super-resolution Spaceborne SAR Real-time Imaging Chip," in *3rd China International SAR Symposium (CISS)*, Shanghai, China, 2022.

[50] C. Stuart, E. Sherrock, J. Griebel und A. Borsholm, „railtec.illinois.edu," 2018. [Online]. Available: http://railtec.illinois.edu/wp/wp-content/uploads/pdf-archive/8.1_Stuart.pdf.

[51] X. Y. C. a. Z. G. Du, „Change detection: the framework of visual inspection system for railway plug defects," *IEEE Access,* Bd. 8, pp. 152161-152172, 2020.

[52] L. Shen, Y. Lu, H. Chen, H. Wei, D. Xie, J. Yue, R. Chen, S. Lv und B. Jiang, „S2Looking: A Satellite Side-Looking Dataset for Building Change Detection," *Remote Sensing,* Bd. 13, Nr. 24, 2021.

[53] C. Pang, J. Wu, J. Ding, C. Song und G. Xia, „Detecting building changes with off-nadir aerial images," *Science China Information Sciences,* 2023.

[54] S. Fang, K. Li, J. Shao und Z. Li, „SNUNet-CD: A Densely Connected Siamese Network for Change Detection of VHR Images," *IEEE Geoscience and Remote Sensing Letters,* Bd. 19, pp. 1-5, 2022.

[55] "Project GoSAFE RAIL," [Online]. Available: http://www.gosaferail.eu.

[56] "SPACE4RAIL initiative," [Online]. Available: https://space4rail.esa.int/about-space4rail.

[57] "RailSAT feasibility study," [Online]. Available: https://business.esa.int/projects/railsat.

[58] "MATIST feasibility study," [Online]. Available: https://business.esa.int/projects/matist.

[59] "LiveLand Demonstration Project," [Online]. Available: https://business.esa.int/projects/liveland.

[60] "Shift2Rail Joint Undertaking," [Online]. Available: https://shift2rail.org/about-shift2rail/mission-and-objectives/.

[61] "Project MOMIT- Multi-scale observation and monitoring of railway infrastructure threats," [Online]. Available: https://www.momit-project.eu/.

Appendix A Abbreviations & Nomenclature

For all terms, definitions and conventions used, if available.

Abbreviation	Meaning
AD	Applicable Documents
CI	Configuration Item
CIP	Continuous improvement process
ECSS	European Cooperation for Space Standardization
ISO	International Organization for Standardization
LLI	Long-Lead Item
NC	Non-Conformance
NCR	Non-Conformance-Report
NCTS	Non-Conformance Tracking System
NRB	Non-Conformance Review Board
OHB DC	OHB Digital Connect GmbH
PA	Product Assurance
QA	Quality Assurance
QM	Quality Management
RD	Reference Documents
RFW	Request for Waiver
TRR	Test Readiness Review
RTD	Research and Technology Development
IIMEO	Instantaneous Infrastructure Monitoring by Earth Observation
SAR	Synthetic Aperture Radar
LEO	Low Earth Orbit
WP	Work Package