Title	# Specification of On- and Off-Board Algorithm
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1 PROJECT OBJECTIVE

In 2022, a European Consortium[1] has been selected by the European Commission to implement the project *"Instantaneous Infrastructure Monitoring by Earth Observation" (IIMEO)*. IIMEO 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."

Figure 1-1: Schematic of IIMEO's objectives

Infrastructure monitoring is an appropriate use case for satellite-based systems regarding the principles of "NewSpace: 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 least 24 small satellites.

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. 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 programme 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 integrated in an airborne technology demonstrator to verify the suitability of the technical solution before sending it into space as satellite payload. 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 won 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

[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/

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.

2 INTRODUCTION

2.1 Purpose of this Document

This document incorporates intermediate results of the tasks T2.2 *Preparation of sensor systems and evaluation datasets* and T2.3 *On- and off-board algorithm prototyping* of the IIMEO Grant Agreement [1].

Task T2.2 of the IIMEO project plan in [2] is concerned with the preparation of the sensor systems and evaluation data sets, so not directly with algorithm development and software prototyping. Nevertheless, the outputs of the sensor systems need to be understood by the programs implementing the algorithms. The same holds for training and evaluation data sets, whose types of content needs to be commensurate with the in- and outputs, respectively, of the algorithms.

Task T2.3 of [2], on the other hand, is concerned with developing prototypes of the actual algorithms. Those prototypes will be presented in [3] and publicly in [4], respectively. Although these prototypes are not finished yet, it is already clear that – in contrast to the laboratory prototypes documented in [5] – do not stand alone but have to work in a processing chain of multiple prototypes instead.

This implies that it needs to be known what each of the algorithms is doing, in particular each individual step of the processing chain must understand the output of the previous steps and format its own outputs in a way understandable to subsequent processing steps.

Moreover, the execution of and handover of data between the individual steps, which do computations on the data products, have to be organized somehow. To this end, we are developing software infrastructure and tooling to run the algorithms aboard the plane as well as on ground, and the implementations of the algorithms must interact with the respective infrastructure.

Thus, the purpose of this document is to specify the in- and outputs of the algorithms to the level of detail which is currently known, such that they will work together in a common processing chain using the infrastructure provided either on-ground or aboard the airplane platform approximating a potential satellite. The specifications take the infrastructure monitoring requirements into account, either by considering requirements from [6] or considering the system design update based on those requirements in [5].

For this it specifies the required on-board and on-ground algorithms as well as the corresponding software infrastructures for the processing chains.

2.2 Classification of Information

This document has been reviewed by the Security Advisory Board of the IIMEO project against the criteria set out in [7]. In particular, the criteria listed in chapter 4.3 (Critical infrastructure and utilities research) were considered. All information in this document can be published with the classification “Public” for the following reasons:

- The document describes a hypothetical construct that is yet to be proven through a demonstrator.
- The document does not include highly technical details.
- The technology described in the document is public information and can be subsumed from freely available sources.

2.3 Structure of this Document

Aside from preface (section 0), introduction (section 2) and the obligatory section 4 for references and appendices at the end, all the specifications are collected in section 3.

3 SPECIFICATIONS

Specifications concerning the various algorithms are covered in the subsections of this section. These do not have to be read in a particular order; however, they appear in an order which could also be an order of an actual processing chain. The sections on on-board infrastructure (section 3.1), on-board communication (section 3.2), on-ground infrastructure (section 3.13) and ground system communication (section 3.14) stand out a little as they are not concerned with immediate processing tasks but rather with enabling the immediately processing-related algorithms to do anything in the first place; either on the ground system or aboard the demonstrator plane.

The other sections consider the acquisition of data using our sensors or the computation of data products using such acquired data or other products computed previously. These are the regions of interest to be extracted from map data in section 3.3, followed by sections primarily concerned with SAR-related algorithms, namely SAR data acquisition and processing in section 3.4, acquisition of localization data and platform motion estimates in section 3.5, SAR masking and data pre-selection in section 3.6 as well as obstacle detection primarily using change detection on tiles of SAR images in section 3.7. Algorithms primarily related to acquisition and processing of VIS images start with the image acquisition in section 3.8, followed by their geo-referencing and masking in sections 3.9 and 3.11, respectively, using measurements of the platform's pose from section 3.9. Section 3.12 is concerned with anomaly detection. The geo-referencing algorithms may be extended to perform ortho-rectification which leads to slightly stricter requirements regarding the inputs as specified in section 3.15.

Finally, fusion of data derived both from SAR and VIS imagery is dealt with in section 3.16.

Most of the specifications are collected in tables which assign each individual specification a priority, either "shall" or "should". While all specifications should be respected, the idea is to allow the prototypes implementing the corresponding algorithm to deviate from the less critical specifications with "should" priorities.

Some of the specifications include remarks saying that message types of ROS2 will be used to pass data between different components and give the name of the message definition. This can be used to look up the message definition in ROS2's API [8] documentation. For instance, the definition of "sensor_msgs/msg/Image.msg" can be found at https://docs.ros2.org/latest/api/sensor_msgs/msg/Image.html.

3.1 On-Board Infrastructure

As described in greater detail in the deliverable on the system concept [5], the individual processing steps need a fair bit of infrastructure to be executed in a coordinated manner to jointly solve the observation tasks. This infrastructure will not be developed from scratch. Instead, ROS2 [9] will be used, which subsumes cross-cutting aspects such as message passing between individual components, logging as well as managing the processes' lifecycles.

That and additional requirements regarding the on-board infrastructure are collected in Table 3-1.

Table 3-1 On-board infrastructure SW requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-Onboard-IN-01	The onboard system provides ROS2 (Humble Hawksbill or newer)	Shall		[5]
IIMEO-SW-RQ-Onboard-IN-02	Individual processing steps shall be implemented as ROS2 nodes.	Shall		[6]

IIMEO-SW-RQ-Onboard-IN-03	Handover of data for communication to ground shall happen using (from the on-board perspective) terminal nodes.	Shall	Such a terminal node only subscribes to ROS2 topics, collects data and then sends the data collection to ground.	[5]
IIMEO-SW-RQ-Onboard-IN-04	Tasks from ground shall also be accepted by terminal ROS2 nodes, which in turn trigger the corresponding ROS2 services or actions of other on-board nodes.	Shall		[5]
IIMEO-SW-RQ-Onboard-IN-05	The processing chains made of ROS2 nodes are fed using ROS2 nodes driving the individual sensors and publishing either raw sensor data or derived products, subscribing nothing.	Shall		[5]
IIMEO-SW-RQ-Onboard-IN-06	The acquisition computers as well as the on-board processing unit should provide storage to save intermediate on-board processing results.	Should	In particular data for the first few minutes of data acquisition should be stored.	
IIMEO-SW-RQ-Onboard-IN-07	The on-board system shall be able to store intermediate results for developer-specified periods.	Shall	This is to enable troubleshooting of issues occurring during data acquisition.	

3.2 On-Board Communication

On-Board communication is described in greater detail with the system concept in [5]. Corresponding requirements are collected in Table 3-2.

Table 3-2 On-board communication SW requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-Onboard-Com-01	The on-board system shall be capable to process and transfer the complete processing-chain results within a fixed time window.	Shall	The time window has to determined individually for the space system and the demonstrator.	IIMEO-RQ-Com-02 of [6]
IIMEO-SW-RQ-Onboard-Com-02	The on-board system shall be capable of receiving and processing telecommands from ground.	Shall		IIMEO-RQ-Com-05 of [6]
IIMEO-SW-RQ-Onboard-Com-03	The on-board system shall be commanded using corresponding PUS services.	Shall		IIMEO-RQ-Com-06 of [6]
IIMEO-SW-RQ-Onboard-Com-04	The on-board system shall be capable of sending status telemetries to ground.	Shall		IIMEO-RQ-Com-05 of [6]
IIMEO-SW-RQ-Onboard-Com-05	The on-board system shall report its status telemetries using corresponding PUS services.	Shall		IIMEO-RQ-Com-06 of [6]

3.3 Regions of Interest Extraction

To restrict processing and storage of data the regions which actually contain infrastructure, regions of interest (ROI) are extracted before the actual data acquisition. The computation of the regions is thus not part of the actual processing chains themselves, however, the results are used as static data both on-board and potentially on ground. Requirements with respect to the ROI computation are collected in Table 3-3.

Table 3-3: Requirements for the extraction regions of interest from map data.

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-ROI-01	Users shall be able to restrict the ROIs to user-defined areas.	Shall	This is to further restrict the ROIs in addition to the ROI extraction from map data.	[5]
IIMEO-SW-RQ-ROI-02	Regions of interest shall be determined from map data such that regions without infrastructure are not regions of interest.	Shall		[5]

IIMEO-SW-RQ-ROI-03	Regions of interest shall be automatically from vector maps of railway tracks.	Shall	“Vector” as opposed to already rasterized tiles.	[5]
IIMEO-SW-RQ-ROI-04	Regions of interest shall be extracted automatically from OpenRailwayMap files in PBF format.	Shall	PBF is the “Protocol Buffer Format” [10] of OpenStreetMap.	[5]
IIMEO-SW-RQ-ROI-05	Extracted regions of shall be stored in GeoJSON [11] files.	Shall		[5]
IIMEO-SW-RQ-ROI-06	Regions of interest shall be represented as multiple polygons.	Shall		[5]
IIMEO-SW-RQ-ROI-07	The ROI extraction step shall specify the coordinate system in which its outputs are represented with the same GeoJSON file.	Shall	The specific coordinate system is still under discussion, although it will likely be WGS84 or coordinates in the corresponding UTM tile.	[5]
IIMEO-SW-RQ-ROI-08	User-selected ROIs should be stored separately from automatically extracted ROIs.	Should	ROIs extracted from map data will probably stay static over longer time periods; user selections might change even between individual tasks.	[5]

3.4 SAR acquisition and processing

The general intention is to ensure that only the illuminated area of the radar footprint that covers an area of interest is continuously processed during on-board SAR processing. After each synthetic aperture processing, this focused data set is then assigned to its previously defined tiles and made available to the change detection process in the defined format in the form of a cropped and rotated SAR amplitude image. Table 3-5 lists the derived requirements for the on-board SAR acquisition and processing.

Table 3-4 On-board SAR acquisition and processing requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-Onboard-SARA-01	The SAR algorithm shall be able to work with raw input data of type integer.	Shall		
IIMEO-SW-RQ-Onboard-SARA-02	The SAR algorithm shall be able to handle an input data rate of up to 16 Mbit/s.	Shall		[6] Section 4.5.2.1
IIMEO-SW-RQ-Onboard-SARA-03	The SAR algorithm shall be able to process input data with a PRF of at least 635 Hz.	Shall		[6] Section 6.3.7
IIMEO-SW-RQ-Onboard-SARA-04	The SAR algorithm shall be able to parse, process and use data from an GPS/IMU unit.	Shall	See Table 3-5 for the IMU data format.	[1] Section 1.2.1.3
IIMEO-SW-RQ-Onboard-SARA-05	The SAR algorithm shall be able to process input data with a center frequency of 35 GHz.	Shall		[1] Section 1.2.1.3
IIMEO-SW-RQ-Onboard-SARA-06	The SAR algorithm shall be able to process input data with a bandwidth of at least 460 MHz.	Shall		[6] Section 4.5.2.1
IIMEO-SW-RQ-Onboard-SARA 07	The spatial resolution of the focused SAR data should be approx. 50 cm in range and azimuth.	Shall		[6] Section 4.5.2.1
IIMEO-SW-RQ-Onboard-SARA 08	The pixel spacing in the SAR image shall be of size 0.25 m.	Shall		
IIMEO-SW-RQ-Onboard-SARA-09	The pixels of a processed SAR image shall be amplitude values of type float32.	Shall		
IIMEO-SW-RQ-Onboard-SARA-10	Focused pixels should be assigned to their corresponding tiles.	Shall	See Table 3-6	[5] Section 5.2.2
IIMEO-SW-RQ-Onboard-SARA-11	Processed SAR images shall be rotated and cropped according to the alignment of their assigned tile.	Should	See Table 3-6	

IIMEO-SW-RQ-Onboard-SARA-12	SAR focusing of a single tile shall be performed in less than 3 minutes after acquisition.	Shall		
IIMEO-SW-RQ-Onboard-SARA-13	A processed SAR image shall be transferred to the Change Detection module using a ROS2 message.	Shall		
IIMEO-SW-RQ-Onboard-SARA-14	The ROS2 message containing the SAR image shall contain the following information: →Cropped SAR image →Metadata: • Metadata of the tile • GPS time • Aspect acquisition angle • Flight altitude • Depression angle	Shall		

3.5 GPS / IMU raw data structure for SAR processing

The GPS/IMU raw data of the SAR sensor are embedded in the header of the radar raw data for each record with an update rate of 256 Hz and have the following format as described in Table 3-5.

Table 3-5: On board and off board GPS/IMU data structure

Name	Data type	Unit	Remark
Sync	uint8[3]		Value: 0x1144AA
Checksum	uint8		XOR over whole packet excluding checksum
Message ID	uint32		Value: 0xAEC00501
Packet length	uint32	Byte	Value: 66
GPS Time	float	GPS week seconds	
Mode	uint8		0 = idle, 1 = initial, 2 = align, 3 = normal, 4 = unaugmented
Status	uint8		Bit7 = Online/Offline Bit6 = GNSS Error Bit5 = No ini file Bit4 = Card error Bit3 = Drive error

			Bit2 = Card full Bit1:0 = IMU error
Latitude	double	rad	WGS84
Longitude	double	rad	WGS84
Altitude	float	m	WGS84
Velocity North	float	m/s	
Velocity East	float	m/s	
Velocity Up	float	m/s	
Roll	float	rad	Range: -pi to +pi
Pitch	float	rad	Range: -pi/2 to +pi/2
Heading	float	rad	Range: -pi to +pi

3.6 SAR Masking & Pre-Selection

To save processing time and to prevent the change detection algorithm from working on irrelevant areas, only the relevant parts around the railway track are processed by the SAR algorithm. Therefore, the whole railway map is divided into individual tiles that define the relevant areas as described in [5].

Table 3-6 On-board SAR masking and pre-selection requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-Onboard-SARM-01	Instead of the whole antenna footprint, only a specific area of interest (tiles) around the railway shall be focused.	Should		[5] Section 5.2.2
IIMEO-SW-RQ-Onboard-SARM-02	All tile information is stored in a GeoJSON file, accessible to the on-board SAR processor.	Shall		
IIMEO-SW-RQ-Onboard-SARM-03	Each tile shall have an unique identifier.	Shall		
IIMEO-SW-RQ-Onboard-SARM-04	Each tile shall have a center coordinate provided in WGS84 format (lat/lon).	Shall		
IIMEO-SW-RQ-Onboard-SARM-05	A tile shall have a rectangular shape in the metric system. The four corner coordinates shall be provided in WGS84 format (lat/lon).	Shall		[5] Section 5.2.3

IIMEO-SW-RQ-Onboard-SARM-06	Each tile shall have assigned a mean topography height above the WGS84 ellipsoid.	Shall		[5] Section 5.2.3
IIMEO-SW-RQ-Onboard-SARM-07	Each tile shall have listed the unique identifiers of those tiles that have an overlap of pixels with the connected tile.	Shall		
IIMEO-SW-RQ-Onboard-SARM-08	Only the tiles relevant to the flight campaign, ideally sorted in a specific sequence, should be stored in the GeoJSON file.	Should	The sequence could correspond to the flight route	
IIMEO-SW-RQ-Onboard-SARM-09	Every SAR image shall be converted from radar reflectivity to physical unit σ_0, the radar cross-section where the area normalization is aligned with ground plane.	Should		
IIMEO-SW-RQ-Onboard-SARM-10	Every SAR image corresponding to a tile shall be within georeferencing accuracy as from the DEM and the accuracy of the real-time GPS data.	Shall	It follows from the altitude from DEM accuracy and the accuracy of the real-time GPS data.	

3.7 Obstacle Detection (SAR)

Given that each SAR image is acquired over a tile tightly placed over a railway segment, images need not to be georeferenced as geographic information can be retrieved from the tile vector file. However, by intrinsic properties of multi-temporal processing, images acquired over the same tile shall be within acceptable spatial tolerance. Given their relatively small size, SAR images can be stored onboard in floats, therefore it is optimal to store pixel values that already encode the radar cross-section, to avoid useless processing time in doing the conversion in the obstacle detection module. Output requirements for the obstacle detection module are listed below.

Table 3-7 On-board SAR obstacle detection requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-SAROD-01	Obstacle detection algorithm based on change detection should detect obstructing objects with size greater than 1.5x1.5 m (3x3 pixels at the spatial resolution of 0.5 m).	Should		
IIMEO-SW-RQ-SAROD-02	Obstacle detection algorithm shall perform in less than 30 min for each tile.	Shall		

IIMEO-SW-RQ-SAROD-03	Output shall be the tile identification number (and associated attribute values from the corresponding tile feature) where an anomaly has been detected.	Shall		
IIMEO-SW-RQ-SAROD-04	Output shall be provided as a ROS2 message.	Shall		

3.8 VIS Acquisition

Except for the frame rate of the cameras and the acquisition frequency, the acquisition process is identical for both the nadir-looking and obliquely looking cameras, whose setup is described in D2.1 [12].

Table 3-8 On-board VIS acquisition requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-VIS-Acquisition-01	Images are provided via a ROS2 topic as ROS2 images with a sequence number.	Shall	A ROS2 message type will be defined containing the sequence number and wrapping the usual image message. (See sensor_msgs/msg/Image.msg.)	
IIMEO-SW-RQ-VIS-Acquisition-02	The image shall include information of its encoding.	Shall	See sensor_msgs/msg/Image.msg.	
IIMEO-SW-RQ-VIS-Acquisition-03	The image acquisition program shall be able to report calibration and operational parameters of the camera(s) it uses to acquire images.	Shall	As of now, the preferred way to implement this would be a service responding with a camera info message. (See sensor_msgs/msg/CameraInfo.)	
IIMEO-SW-RQ-VIS-Acquisition-04	The image acquisition processes shall put out images at 0.1 Hz or the image acquisition frequency if that is lower.	Shall		See [12] for the sensor system specification.
IIMEO-SW-RQ-VIS-Acquisition-05	The image acquisition processes shall be able to accept images at 1 Hz.	Shall	This will be relevant for the obliquely looking camera only due to different triggering as described in [12].	See also [12].

3.9 GPS / IMU acquisition for VIS processing

In contrast to SAR data processing, VIS images are formed without quasi-continuous estimates of the platform's motion, however, the poses of the platform at the image acquisition times are required to compute the geo-referencing and the ortho-rectification of the images, respectively.

Thus, the GPS+IMU data in the pod carrying a VIS camera has different, less strict requirements, listed in Table 3-9, than the acquisition of platform motion data in the pod also carrying the SAR in section 3.9.

Table 3-9: Plane localization requirements for VIS processing

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-INSGPS-01	The position of the plane shall be provided as latitude and longitude in degrees using the WGS84 ellipsoid.	Shall	See ROS2's geographic_msgs/GeoPoint.msg message definition.	
IIMEO-SW-RQ-INSGPS-02	The altitude shall be provided in meters above the WGS84 ellipsoid.	Shall		
IIMEO-SW-RQ-INSGPS-03	The attitude of the platform shall be given in east-north-up-coordinates (ENU) at the position of the same platform pose.	Shall		
IIMEO-SW-RQ-INSGPS-04	The attitude shall be represented by a rotation matrix or quaternion.	Shall	Particularly not using three (Euler-)angles.	
IIMEO-SW-RQ-INSGPS-05	Localization outputs shall be timestamped.	Shall		
IIMEO-SW-RQ-INSGPS-06	The frequency of localization data outputs shall be greater than or equal 50 Hz and constant.	Shall		
IIMEO-SW-RQ-INSGPS-07	Localisation data outout via a ROS2 topic as ROS2 time-stamped geo-pose with covariance.	Shall	See ROS2's geographic_msgs/ GeoPoseWithCovarianceStamped. We may change the reference frame in which the covariance is expressed to be the tangent space at the respective geo-pose in the plane-local coordinates.	

3.10 Geo-Referencing (VIS)

Geo-Referencing will be implemented in a ROS2 node and will communicate with the other components via ROS2 topics. How in- and output data are supposed to look like is specified in Table 3-10. References to ".msg"-files in the "Remark"-column of Table 3-10 are to message definition files which are shipped as part of ROS2.

Note that during geo-referencing, the image is only annotated using localization data – it's bounding box – but the actual image contents to not change.

Table 3-10: On-board geo-referencing requirements

Requirement#	Requirement description	Priority	Remark	Reference

IIMEO-SW-RQ-Onboard-Geo-01	Images are accepted via a ROS2 topic as ROS2 images with a sequence number.	Shall	A ROS2 message type will be defined containing the sequence number and wrapping the usual image message. (See sensor_msgs/msg/Image.msg.)	See section 3.8.
IIMEO-SW-RQ-Onboard-Geo-02	Successive images are required to overlap by at least one third.	Shall	The current plan is to determine the approximate ground plane from triangulated image points. If we can do without triangulation, this requirement may be dropped.	
IIMEO-SW-RQ-Onboard-Geo-03	Localisation data is accepted via a ROS2 topic as ROS2 time-stamped geo-pose with covariance.	Shall	See geographic_msgs/GeoPoseWithCovarianceStamped. We may change the reference frame in which the covariance is expressed to be the tangent space at the respective geo-pose in the plane-local coordinates.	See section 3.9.
IIMEO-SW-RQ-Onboard-Geo-04	Output is published via a ROS2 topic and is the bounding box of the image in WGS84-coordinates.	Shall	A ROS2 message type has to be defined containing the sequence number of the geo-referenced image and wrapping the usual bounding box message (geographic_msgs/BoundingBox.msg)	
IIMEO-SW-RQ-Onboard-Geo-05	The bounding box should be computed by computing the approximate ground plane from triangulated image points of successive images.	Should	This is described in greater detail in [5].	

3.11 VIS Masking & Pre-Selection

The regions of interest from section 3.3 used to clip the contents of geo-referenced or ortho-rectified images to regions which may contain infrastructure and remove the rest. The requirements regarding this processing step are collected in Table 3-11 in subsection 3.11.1.

The resulting images will be relatively sparse, with only relatively small regions left with actual image data. To avoid wasting storage space and communication bandwidth, the not every pixel of the masked images will be encoded individually but as described briefly in subsection 3.11.2.

3.11.1 Requirements

Table 3-11 On-board VIS masking and pre-selection requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-VISMASK-01	Images are accepted via a ROS2 topic as ROS2 images with a sequence number.	Shall		See also section 3.8

IIMEO-SW-RQ-VISMASK-02	Geo-Reference information is accepted as the images bounding box in WGS84-coordinates.	Shall		See also section 3.10.
IIMEO-SW-RQ-VISMASK-03	Region-of-Interests are accepted as a set of polygons loaded from static configuration data.	Shall	The regions of interest will be stored in a single GeoJSON file.	
IIMEO-SW-RQ-VISMASK-04	The masked image is put out as a ROS2 image of the same dimensions and with the same sequence number as the input, with the masked part of the image set to a specific value indicating "no data".	Shall		
IIMEO-SW-RQ-VISMASK-04	The masked image is put out in a custom format where the no-data values are stored using run-length encoding.	Should	See section 3.11.2.	

3.11.2 Encoding of Masked Images

Images after masking will have a significant number of pixels – more than half in most cases – containing the "no data"-value. In order to transfer those on-board between processing nodes, a simple run-length-encoding shall be applied. The image representation of images before masking is a contiguous block of memory in which the values for the image channels are stored in row-major order.

For masked images, consecutive "no data"-values are stored using a signal word of two bytes, where the most-significant bit is zero indicating "no data" and the remaining 15 bits encoding the number of consecutive "no data"-pixels. Pixels which have not been masked out, the most significant bit of the signal word is one followed by the number of bytes of image data behind that signal word.

There should be a dedicated message type for images encoded using that scheme and a short conversion library to encode and decode there run-length-encoded messages into normal ROS2 image representations.

3.12 Anomaly Detection (VIS)

As most of the other on-board processing steps, anomaly detection on VIS images will be implemented in a ROS2 node and will communicate with the other components via ROS2 topics. How in- and output data are supposed to look like is specified in Table 3-12 below.

Table 3-12 On-board VIS anomaly detection requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-Anomaly-01	Images are accepted via a ROS2 topic as ROS2 images with a sequence number.	Shall	A ROS2 message type will be defined containing the sequence number and wrapping the usual image message. (See sensor_msgs/msg/Image.msg.)	See also section 3.8 on VIS Acquisition

IIMEO-SW-RQ-Anomaly-02	Geo-reference information regarding the image is accepted via a ROS2 topic as the image's bounding box in WGS84-coordinates.	Shall		See also section 3.10.
IIMEO-SW-RQ-Anomaly-03	One output shall be a grid of binary "rail"/"not a rail" classifications.	Shall	ROS2 already has a message type for gridded, geo-referenced data, OccupancyGrid (nav_msgs/OccupancyGrid.msg), which could be wrapped in another message with a sequence number.	
IIMEO-SW-RQ-Anomaly-04	The anomaly detector shall load vector map data containing railway tracks.	Shall	There already is a vector representation of track data in GeoJSON [11] and OSM PBF [10] format, which should be used for this.	
IIMEO-SW-RQ-Anomaly-05	Register to map to improve geo-reference.	Should	The intermediate rail detection results should be used register the VIS image onto the rail track map to improve registration accuracy.	
IIMEO-SW-RQ-Anomaly-06	One output shall be a grid of binary "anomaly"/"not an anomaly" labels.	Shall	For larger scale anomalies, this is to be based on the absence of tracks at locations where there should be track according to map data.	

Anomaly detection may be recomputed on-ground to create a data product of greater resolution and using ortho-rectified instead of just geo-referenced images. To simplify this, the anomaly detection step should also conform to the additional specifications in Table 3-13 below.

Table 3-13: Additional on-ground VIS anomaly detection requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-Anomaly-07	(Geo-references) images can additionally be accepted as GeoTIFF files.	Should	The image file contains both the coordinate annotation as well as the actual image data.	
IIMEO-SW-RQ-Anomaly-08	Gridded outputs of IIMEO-SW-RQ-Anomaly-03 and IIMEO-SW-RQ-Anomaly-06 should also be writable as GeoTIFF files.	Should		IIMEO-SW-RQ-Anomaly-03, IIMEO-SW-RQ-Anomaly-06

3.13 On-Ground Infrastructure

3.13.1 Overview

As outlined in [6], the on-ground processing of the SAR and VIS images shall be implemented by two respective processing chains, each consisting of individual containers with specific functionality. Intermediate and final processing results shall be exchanged using a global data storage. The on-ground processing chains will be applied for both, the airborne demonstrator and a later satellite constellation.

Figure 3-1 shows the planned setup for the SAR and VIS processing chains (see also section 6.1 in [5]).

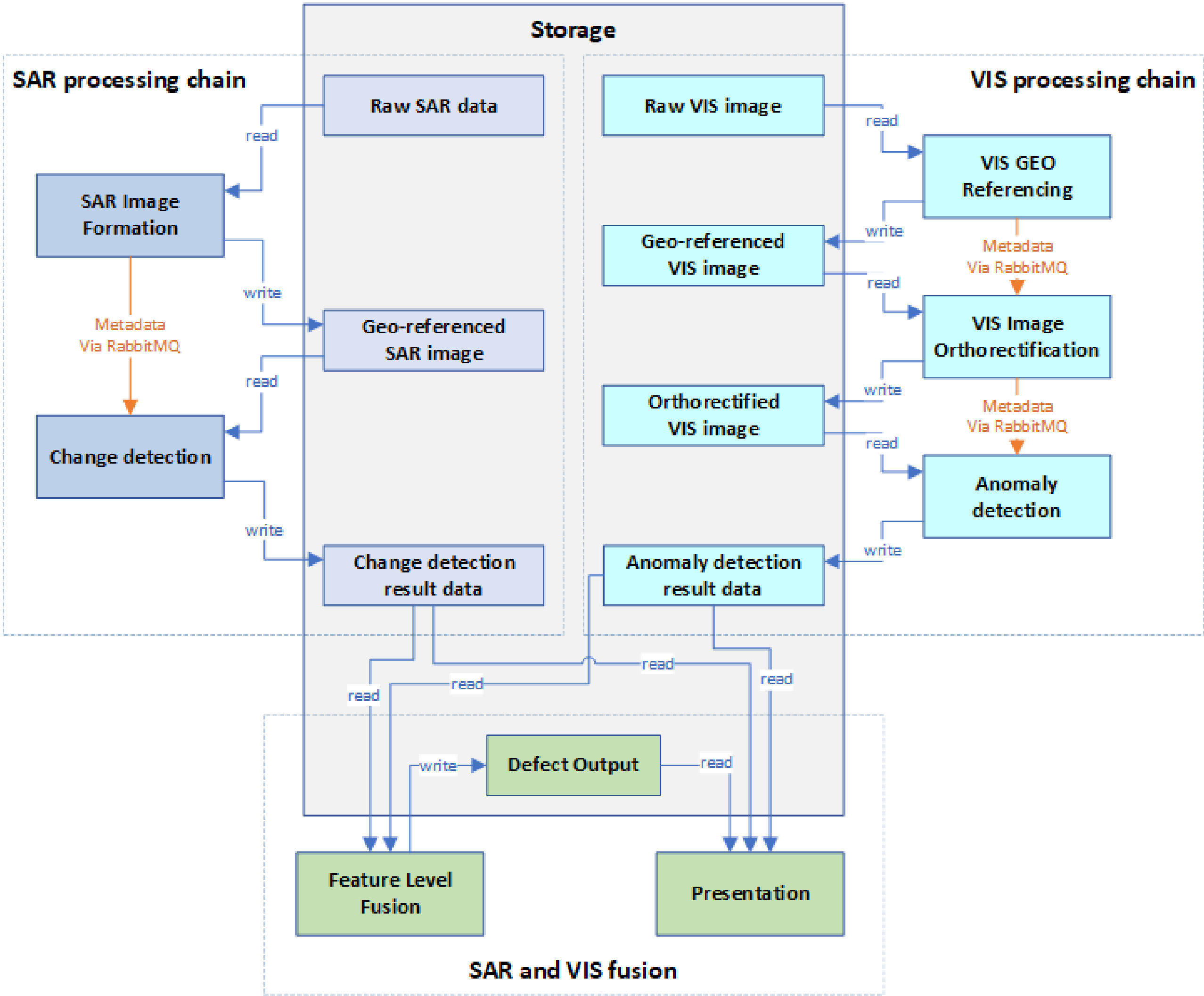

Figure 3-1 On-ground processing chains

The specification of the on-ground infrastructure and processing chain elements are provided in the following subsections.

3.13.2 Storage, Message Passing, Containerization

This section collects the software-related requirements for the on-ground processing chains for SAR and VIS related to the overall infrastructure. Requirements concerning the specific algorithms are provide in the next sections. References to the related descriptions in [5] are given wherever possible.

Table 3-14 On-ground infrastructure SW requirements

Requirement#	Requirement description	Priority	Remark	References in [5]
IIMEO-SW-RQ-Onground-Infra-01	The on-ground system shall enable containerization.	Shall	'*Containerization*' is defined as OS-level virtualisation that allows software applications to run in isolated user spaces called *containers*.	Section 4.3 Section 6.1
IIMEO-SW-RQ-Onground-Infra-02	Each step of the processing chains (SAR, VIS) shall be implemented as a container.	Shall		Section 4.3 Section 6.1
IIMEO-SW-RQ-Onground-Infra-03	All on-ground data shall be saved on a global S3 compatible storage.	Shall	On-ground data incorporate SAR and VIS images, intermediate and final processing results. 'Global storage' means that all processing chain elements use the same storage device.	Section 6.1
IIMEO-SW-RQ-Onground-Infra-04	The on-ground system shall incorporate a message broker.	Shall	It is intended to use the open-source message-broker software *RabbitMq*.	Section 4.3 Section 6.1
IIMEO-SW-RQ-Onground-Infra-05	Each element of the processing chains shall implement the corresponding message broker functionality to • Receive messages that are addressed to this element. • Perform the action related to this message (callback function) • Publish messages to the next element of the processing chain	Shall		Section 4.3 Section 6.1
IIMEO-SW-RQ-Onground-Infra-06	Each element of the processing chain must have a unique key by which it can be addressed.	Shall		Section 4.3
IIMEO-SW-RQ-Onground-Infra-07	The message format shall be determined. The message shall include at least the path to the associated image data.	Shall	So-called "IIMEO Product Descriptors", see subsection 3.13.3.	Section 4.3

IIMEO-SW-RQ-Onground-Infra-07	Each element of the processing chain shall be configured at start-up via a respective configuration file.	Shall		Section 4.3

3.13.3 Product Descriptor

During on-ground processing, data products are handed over from one step to the next by passing the corresponding Product Descriptor, a data structure describing the product itself as well as the location of its data, via RabbitMQ message queues. The fields of the descriptor are given in Table 3-15, the descriptor itself is encoded as (machine- and human-readable) text using JSON.

Table 3-15: Fields of the IIMEO Product Descriptor

IIMEO Product Descriptor	
Field	**Description**
Identifier	Unique identifier of the data product.
Flight Identifier	Unique identifier of the flight during which the data product has been acquired. If the data product has been computed from other data products, this field lists the "parent" products' identifiers.
Processing Level	Enumeration of processing level. Indicates whether the product corresponding to the identifier is raw data, image, geo-referenced image or further processed data.
Project	Tasks from ground shall also be accepted by terminal ROS2 nodes, which in turn trigger the corresponding ROS2 services or actions of other on-board nodes.
Product Data Type	E.g. GeoTIFF, GeoJSON, etc.
Date and Time	Timestamp (ISO 8601) of the creation of the corresponding product.
Position	If the product has been computed from data from a single point in time, this is the platform's (i.e. plane's) pose at the acquisition time. May be left empty if such pose cannot be given, e.g. if then product is computed from data captured at different poses.
Geometry	Describes the viewing geometry at acquisition time, e.g. in case of the VIS camera image, the identifier as well as the internal and external parameters of the camera.
Data	List of paths to all files comprising this product to be loaded from storage.

3.14 Ground System Communication

This section collects the software-related requirements of the on-ground system concerning the communication with the on-board system (space system resp. airborne demonstrator). References to the use case requirements in [6] are given, wherever possible.

Table 3-16 On-ground communication SW requirements

Requirement#	**Requirement description**	**Priority**	**Remark**	**Related requirements in [6]**

IIMEO-SW-RQ-Onground-Com-01	The on-ground system shall be capable to receive and process incoming data with data rates of at least 100 Mbit/s.	Shall	100 Mbit/s is expected for the space system. For the demonstrator it will be scaled down.	IIMEO-RQ-Com-01 IIMEO-RQ-Com-03
IIMEO-SW-RQ-Onground-Com-02	The on-ground system shall command the space system resp. the airborne demonstrator by sending telecommands.	Shall		IIMEO-RQ-Com-05
IIMEO-SW-RQ-Onground-Com-03	The telecommands shall be based on corresponding PUS services.	Shall		IIMEO-RQ-Com-06
IIMEO-SW-RQ-Onground-Com-04	The on-ground system shall be capable to receive status telemetries from the space system resp. the airborne demonstrator.	Shall		IIMEO-RQ-Com-05
IIMEO-SW-RQ-Onground-Com-05	The on-ground system shall process the telemetries using the associated PUS services.	Shall		IIMEO-RQ-Com-06
IIMEO-SW-RQ-Onground-Com-05	The on-ground system shall be capable to decompress image data that has been compressed on-board	Shall	The same compression format has to be applied on-board (compression) and on-ground (decompression).	IIMEO-RQ-Proc-02 IIMEO-RQ-Proc-03 IIMEO-RQ-Proc-04 IIMEO-RQ-Proc-05

3.15 Ortho-Rectification (VIS)

Ortho-Rectification of VIS images is similar to geo-referencing (see section 3.9). Like geo-referencing, images points found in successive images are triangulated, however, here not only the bounding box on the approximated ground plane is computed, but a height profile of the ground is interpolated and used to resample the image to the actual ground coordinates. That is, in contrast to the geo-referencing step, the image's contents change here.

Table 3-17 On-ground VIS ortho-rectification requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-VIS-OR-01	Images shall be accepted as geo-referenced GeoTIFF files.	Shall		
IIMEO-SW-RQ-VIS-OR-02	Successive images shall overlap by more than half.	Shall		
IIMEO-SW-RQ-VIS-OR-03	Localisation data is corresponding to an image shall be accepted via the IIMEO Product Descriptor.	Shall		

IIMEO-SW-RQ-VIS-OR-04	Localization data shall include the plane's pose at image acquisition time.	Shall		
IIMEO-SW-RQ-VIS-OR-05	Both internal and external (e.g. pose w.r.t. the platform) parameters of the camera shall be loaded from the same files as for the onboard system.	Shall		
IIMEO-SW-RQ-VIS-OR-06	Output shall be formatted like the input, e.g. as geo-referenced GeoTIFF files.	Shall		
IIMEO-SW-RQ-VIS-OR-07	The height profile of the ground in the camera's field of view should be interpolated from triangulated image points of successive images.	Should	Alternatively, a DEM with sufficient resolution (similar to the sensor's GSD) may be used.	
IIMEO-SW-RQ-VIS-OR-08	The image should be resampled using the height profile computed previously using the image to be resampled and the neighbouring images.	Should		

Ortho-Rectification may also be computed on-board. In that case, accepting inputs and formatting outputs should be a little different, because during on-board processing the individual data products are not stored as files but handed over between the different components of the processing chain directly. So for on-board processing, there are the additional specifications of Table 3-18 below.

Table 3-18: Additional on-board VIS ortho-rectification requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-VIS-OR-09	Images are accepted via a ROS2 topic as ROS2 images with a sequence number.	Should		IIMEO-SW-RQ-VIS-OR-01
IIMEO-SW-RQ-VIS-OR-10	Localisation data is accepted via a ROS2 topic as ROS2 time-stamped geo-pose with covariance.	Should	Like IIMEO-SW-RQ-Onboard-Geo-03.	IIMEO-SW-RQ-VIS-OR-03
IIMEO-SW-RQ-VIS-OR-11	Output is published via a ROS2 topic and is the bounding box of the image in WGS84-coordinates.	Should	Like IIMEO-SW-RQ-Onboard-Geo-04.	IIMEO-SW-RQ-VIS-OR-06

3.16 SAR+VIS Fusion

The both the algorithm and laboratory prototype of the SAR+VIS Fusion is described in [5]. The idea is to use intermediate results of both the anomaly detection on VIS images as well as the change detection on SAR images, and to compute a map of defective track parts which is aligned with the tiling of the SAR imagery for change detection, which is also described in [5].

The in- and outputs of the corresponding step of the processing chain are collected in Table 3-19 below.

Table 3-19 On-ground SAR-VIS fusion requirements

Requirement#	Requirement description	Priority	Remark	Reference
IIMEO-SW-RQ-Fusion-01	Accept rectangular change detection grid.	Shall	Number of rows and columns are not the same of all grids but depend on the tiling.	[5]
IIMEO-SW-RQ-Fusion-02	Accept rectangular anomaly detection grid.	Shall	See IIMEO-SW-RQ-Fusion-01.	[5]
IIMEO-SW-RQ-Fusion-03	Put out grids of railway defects of the same dimension as the input grids of IIMEO-SW-RQ-Fusion-02 and IIMEO-SW-RQ-Fusion-03.	Shall		[5]
IIMEO-SW-RQ-Fusion-04	Each cell of the output grid is the assignment of a binary random variable. There is one grid where the possible values of the cells mean “defective track” or “no/good track”.	Shall		[5]

4 REFERENCES

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Appendix A Abbreviations & Nomenclature

Abbreviation	Meaning
AD	Applicable Documents
ATB	Institut Für Angewandte Systemtechnik Bremen GmbH
AWS	Antwerp Space N.V.
CA	Consortium Agreement
CI	Configuration Item
CIP	Continuous improvement process
EB	Executive Boards
EC	European Commission
ECSS	European Cooperation for Space Standardization
FBK	Fondazione Bruno Kessler
FHR	Fraunhofer-Institut für Hochfrequenzphysik und Radartechnik FHR
FRAUNHOFER	Fraunhofer-Institut für Hochfrequenzphysik und Radartechnik FHR
GA	Grant Agreement
IIMEO	Instantaneous Infrastructure Monitoring by Earth Observation
IPR	Intellectual Property Rights
ISO	International Organization for Standardization
LEO	Low Earth Orbit
LLI	Long-Lead-Item
NC	Non-Conformance
NCR	Non-Conformance-Report
NCTS	Non-Conformance Tracking System
NIS	University of Nis
NRB	Non-Conformance-Review-Board
OHB DC	OHB Digital Connect GmbH
PA	Product Assurance

Abbreviation	Meaning
PC	Project Coordinator
PU	Public
QA	Quality Assurance
QM	Quality Management
RD	Reference Documents
RES	Classified R-UE/EU-R – EU RESTRICTED under the Commission Decision No2015/444
RTD	Research and Technology Development
S&T	Science and Technology
SAB	Security Board
SAR	Synthetic Aperture Radar
SEN	Sensitive
TRR	Test Readiness Review
WP	Work Package