2025

Report on Rail

User Needs and Requirements

#EUSpace

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EXECUTIVE SUMMARY

This report sets out the current and emerging needs and requirements of the European rail sector for satellite-based positioning, navigation and timing (Galileo and EGNOS), Earth Observation (Copernicus), and secure satellite communications (GOVSATCOM and IRIS²). It is intended as a reference for end users, service providers and the EU Space Programme, capturing how rail digitalisation, the migration from GSM-R to the Future Railway Mobile Communication System (FRMCS), and climate adaptation are driving demand for space-based services.

Relative to the 2023 edition, this version sharpens the focus in three ways: it extends the GNSS chapter with safety-critical and freight applications now reaching demonstration maturity; it extends the EO chapter on data needs for climate resilience and adaptation, in line with the priorities expressed at the 2025 User Consultation Platform (UCP); and it introduces a dedicated SATCOM chapter aligned with the FRMCS multi-bearer architecture. Several application scenarios from the 2023 edition that have not been revisited in 2025 are retained for reference but not re-validated.

GNSS is already broadly deployed in non-safety-critical rail applications, supporting asset management, infrastructure monitoring, fleet management and passenger information across European networks. Safety-critical use has progressed from feasibility to demonstration: virtual balises and GNSS-aided ERTMS positioning are now being trialed with multi-sensor fusion, fault detection and exclusion (FDE) and redundant chains targeting SIL4 performance. A rail-specific version of EGNOS is under investigation, with work focused on defining the parameters required to meet rail safety requirements and on the corresponding certification approach.

Two areas stand out as emerging. First - freight applications, train composition detection and, longer term, automated shunting - create demand for low-cost, low-power GNSS receivers compatible with wagon maintenance cycles. Second, the high-accuracy and authentication services already provided by Galileo, namely the High Accuracy Service (HAS) and Open Service Navigation Message Authentication (OSNMA), remain largely under-exploited in rail; awareness and integration into rail equipment supply chains are the principal bottlenecks rather than service capability. Smart wagons, GNSS-anchored digital twins, and EGNSS-enabled drone inspection of bridges and overhead lines illustrate where the strongest near-term cost and safety benefits are expected.

Earth Observation (EO) through the EU's Copernicus programme already provides operational inputs to European rail infrastructure managers. Sentinel-1 data processed via the European Ground Motion Service (EGMS), detects millimetre-scale ground deformation using InSAR techniques and is used to identify unstable slopes, subsidence and settlement of rail earthworks. The Climate Change Service (C3S), Emergency Management Service (CEMS) and Land Monitoring Service (CLMS) supply complementary products for flood mapping, soil moisture, thermal hotspots and long-term climate reanalysis, with applications including spatial stress tests of national networks and historical flood mapping along TEN-T corridors.

Emerging uses centre on two directions: digital twins of rail networks that combine Copernicus background layers with GNSS positioning and in-situ sensors, and AI-enabled analytics for trackside vegetation classification, wildfire exposure and slope stability. Both move EO from one-off consulting studies towards recurring, subscription-based monitoring services delivering automated alerts and dashboards.

Adoption is, however, uneven. While the United Kingdom, Germany and Belgium are early adopters, most European infrastructure managers remain in an exploratory phase, treating EO as an innovation pilot rather than as a structurally integrated maintenance tool. The principal barriers identified at UCP 2025 are organisational (EO data confined to specialist teams, weak links to operational maintenance), data-related (lack of unified GIS platforms; the 10 m Sentinel-2 resolution is too coarse for narrow rail assets; 5–6 day revisit cycles are too slow for rapid-onset events) and procedural (slow rail procurement cycles, absence of a formal EO quality-label or certification framework recognised in safety contracts).

Satellite communications matter for rail because terrestrial mobile coverage along regional, freight and cross-border lines is uneven, and because FRMCS - replacing GSM-R from 2028 onwards - must support safety- and mission-critical services (ETCS signalling, MCPTT voice, ATO over radio, operational video, telemetry) with high availability. FRMCS is explicitly designed as a multi-bearer architecture that accommodates non-terrestrial networks (NTN), with LEO, MEO and GEO constellations providing complementary coverage, redundancy and resilience.

The current European posture combines two tracks. Commercial LEO high-throughput services (e.g. Starlink, OneWeb) offer low latency and high throughput suitable for video, passenger connectivity and non-safety operational data, while established MEO and GEO solutions are positioned as robust backup for safety-related communications. In parallel, GOVSATCOM and the IRIS² constellation are emerging as a sovereign EU complement, intended to provide secure governmental connectivity for signalling and freight security and to act as a resilience backbone in cross-border and remote operations. Ongoing work under EU-Rail Flagship Areas 2 to 6, together with the S5LECT project, is advancing field and laboratory testing of these hybrid configurations. Open issues highlighted at UCP 2025 include antenna form factors compatible with high-speed motion, NTN certification pathways for SIL4 services, and clarification of operating-cost models for sovereign versus commercial capacity.

Across the three technologies, the consultation pointed to six priority gaps that should guide service evolution and EU R&D programming:

- GNSS safety certification and EGNOS-for-rail. Maturation of certification methodologies and tools for GNSS-based safety-critical applications, and validation of a rail-specific EGNOS profile.
- Uptake of HAS and OSNMA. Targeted awareness, integration support and procurement guidance to bring authentication and high-accuracy Galileo services into rail receiver supply chains.
- EO spatial and temporal resolution for rail assets. Closing the gap between Copernicus baseline products and rail-specific needs - notably finer SAR resolution (3–5 m) with 1–3 day revisit, refined optical sensing, and access to a harmonised European Digital Elevation Model at 10 m or better.
- Integration of EO into asset-management workflows. Unified GIS platforms, predictive models and a recognised EO quality-label so that climate and ground-motion information reaches operational maintenance teams rather than staying inside specialist units.
- SATCOM integration into FRMCS. Continued alignment between SATCOM capabilities and railway requirements within a multi-bearer architecture, including certification of NTN for safety-critical services and clarity on commercial versus sovereign (IRIS² / GOVSATCOM) procurement options.
- Cross-technology coherence. Combined GNSS–EO–SATCOM solutions (for example, GNSS-positioned digital twins refreshed with Copernicus layers and exchanged over hybrid FRMCS bearers) require coordinated standards and procurement frameworks rather than separate technology silos.
- These gaps frame the detailed user requirements presented in the remainder of the report and inform the synthesis tables for GNSS, EO and SATCOM in the closing sections.

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1 SCOPE AND METHODOLOGY

1.1 Scope

The User Consultation

The User Consultation Platform (UCP) is a process developed at the European Union Agency for the Space Programme (EUSPA) to collect user needs and requirements and take them as inputs for the provision of user driven space data-based services by the EU Space Programme.

The objective of this report is to provide a reference for the EU Space Programme and for the RAIL segment community, reporting the most up-to-date user needs and requirements in the RAIL market segment for the use of Position, Navigation and Timing (PNT), Earth Observation (EO) and secure telecommunications (SATCOM) technologies. Its scope is to cover needs and requirements from the user perspective, considering the market conditions, regulations, and standards that influence them. The report serves as a reference for end users, service providers and the whole EO community in planning and decision-making activities for those concerned. The report is also intended to serve as an input to more technical discussions on systems engineering and to shape the evolution of the European Union s satellite navigation systems, Galileo and EGNOS and the Earth Observation system, Copernicus, and in the future Space Situational Awareness, GOVSATCOM and IRIS2.

The UCP process contains a regular event, where users from different market segments meet to discuss their needs and application-level requirements relevant for PNT, EO and SATCOM and the conclusions are presented in this document. This report is a living and evolving document that is regularly updated by EUSPA. It served as a key input to the UCP, that is continuous process to reflect the evolution of the user needs, market and technology captured during the event. The report does not represent any commitment of the EU Space Programme to address or satisfy the listed needs and requirements in the current or future versions of the services and/or data delivered by its different components.

This report is organized as follows:

- Section 1.1 defines the scope of the UCP.
- Section 1.2 outlines the methodology and overall consultation process followed under the UCP.
- Section 2.1 presents the role of the European Space Programme in addressing evolving user needs in the rail segment.
- Section 2.2 provides a summary of the Rail RUR 2023, including the main applications, operational scenarios, trends and innovations related to EO, GNSS and SATCOM.
- Section 2.3 presents the market overview and key trends in the rail segment, together with the main user communities and value chain actors.
- Section 2.4 describes the relevant policy, regulatory and standards framework affecting the rail segment.
- Section 2.5 presents the current use of GNSS and the associated requirements by application domain in the rail segment.
- Section 2.6 presents the user requirements specification for the rail segment.
- Section 2.7 provides a synthesis of the requirements relevant to GNSS across the application domains assessed in the report.

- Section 2.8 sets out the broader context for climate adaptation in the European rail sector, highlighting the main environmental and operational challenges affecting infrastructure resilience.
- Section 2.9 presents EO user needs and requirements related to climate adaptation in rail, including the analysis of relevant use cases and associated data and service needs.
- Section 2.10 provides the detailed user requirements specifications derived from the assessment of EO-related climate adaptation use cases.
- Section 3 contains the annexes, including definitions of key EO, GNSS and SATCOM performance parameters, additional terminology, acronyms, and reference documents.

1.2 Methodology

The UCP process follows systematic steps that are implemented in a continuous, repetitive manner. The logical steps allow transparency and continuous updates of the results, considering the new market developments and evolving user needs and requirements.

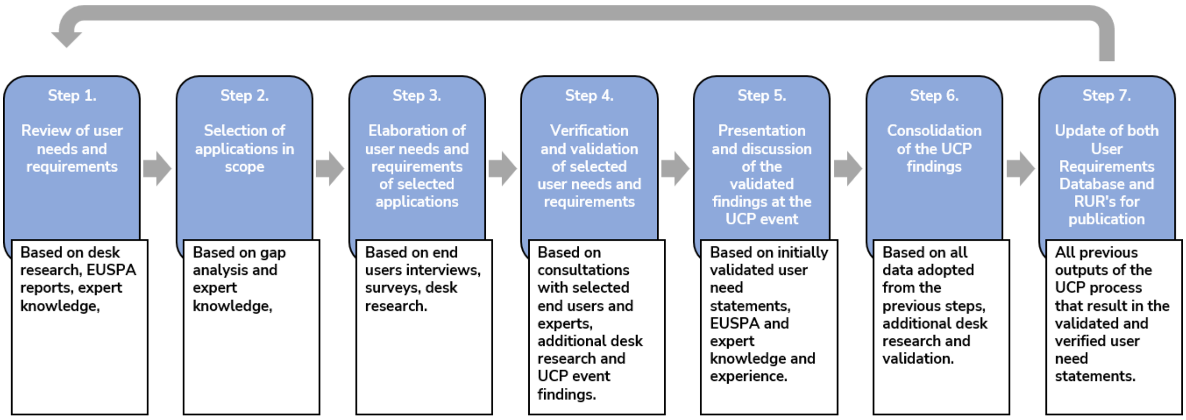

Figure 1: RAIL segment user requirements analysis methodology

Each Market Segment has its peculiar evolution due to the changes in legislation, standards, technological trends and so forth, therefore the update of the Report on User Need and Requirements can occur with a time distance of at least two years.

UCP user needs and requirements collection and analysis is based on one hand side on desk research and on the other, on stakeholders consultations and experts knowledge.

The UCP process starts with review and analysis of the most up-to-date sources related to the user needs and requirements in selected market segments. This step leverages on the previous UCP Reports on User Requirements, latest EUSPA EO and GNSS Market Report, Technology Reports and other expert publications and knowledge. The selection of relevant applications in each market segment is made based on the market analysis, the gap analysis from the earlier editions of the UCP and EUSPA, as well as external experts know-how.

After the initial desk research, the stakeholders consultations are carried out, both representing end users and intermediate users (service providers), in order to validate the findings and collect missing information (Step 3). Validation of user needs requires additional feedback from relevant users representatives that review the draft version of the Report on User Needs and Requirements, prepared in advance of the UCP event.

The UCP event is organized by EUSPA on an annual basis and offers a forum to present and discuss the finding, being additional layer of updates and gaps filling in the process. All the information and data gathered during the previous steps are consolidated in the segment-specific, presented here Report on User Needs and Requirements (RUR) and later on in the EUSPA User Requirements Database (Step 7).

2 RAIL MARKET SEGMENT

2.1 The role of the European Space Programme to meet the evolving user needs

The role of EUSPA

EUSPA (European Union Agency for the Space Programme) plays a pivotal role in the context of the EU Space Programme, acting as a key operational agency that is user-oriented and focused on promoting and maximizing the uptake of satellite-based services across various sectors, through the following activities:

1. User-Centric Approach

EUSPA adopts strategies that prioritize the needs and requirements of users. It aims to enhance the accessibility and integration of satellite services, ensuring that a broad spectrum of users, including governmental bodies, businesses, and citizens, can benefit from services related to Earth Observation, Satellite Navigation, and Connectivity.

2. Service Provisioning

EUSPA is responsible for providing state-of-the-art services in areas such as:

Positioning, Navigation, and Timing: Through the Galileo and EGNOS systems.

- Satellite Communications: It facilitates communication services for governmental applications through GOVSATCOM and is working on the new IRIS2 initiative.
- Space Surveillance: EUSPA manages Front Desk services for the EU Space Surveillance and Tracking program, ensuring safety and security in space operations.

3. Enhancing the European Space Ecosystem

EUSPA works to foster a robust European space ecosystem by:

- Providing market intelligence and technical expertise to innovators, SMEs, and academia.
- Leveraging EU funding programs such as Horizon Europe to stimulate innovation and research in space-related technologies.

Supporting startups and developing partnerships that enhance technological advancements.

4. Ensuring Security

- EUSPA plays a critical role in the security of the EU Space Programme. By operating the Galileo Security Monitoring Centre (GSMC), it implements and monitors the security of satellite services, thereby bolstering the overall security framework for EU Member States.

5. Stakeholder Engagement

EUSPA actively engages stakeholders from the entire space value chain, including industry leaders, academic institutions, and end-users. It facilitates feedback mechanisms where users can express their needs and satisfaction levels regarding EU satellite services. This engagement is crucial for the continuous evolution of the EU Space Programme.

EUSPA conducts various essential activities which include:

- User Consultation Processes: These are designed to gather insights and perceptions from users to improve service delivery.

Market and Technology Monitoring: EUSPA analyses trends and forecasts in the space industry to inform strategic decisions.

- Research and Development Funding: The agency identifies funding needs for R&D initiatives and ensures their implementation.
- Pilot Programs: EUSPA supports the testing and piloting of innovative applications to explore new possibilities in space services.
- Commercial Acceleration Programs: Through the CASSINI Programme, EUSPA promotes innovative commercial ideas and facilitates their growth in the marketplace.

In summary, EUSPA serves as a cornerstone of the EU Space Programme, bridging the gap between technological advancements and user needs. By providing innovative satellite services, fostering a collaborative space ecosystem, ensuring security, and engaging with a wide array of stakeholders, EUSPA is crucial in advancing the EU's strategic interests in space and enhancing the overall benefit of space technologies for society.

The role of COPERNICUS

Copernicus is the Earth Observation component of the European Union s space programme, looking at our planet to support the management of the environment, mitigate the effects of climate change and ensure safety and civil security across Europe. Copernicus delivers its data and services with a free and open policy. It consists of three main components:

Space Component, which delivers data from a fleet of dedicated observation satellites (the Sentinels) and other Copernicus Contributing Missions (CCM). Six Sentinel satellites families are designed to serve a wide range of users and are provided with a free and open access globally. They ensure an independent and autonomous Earth Observation capacity for Europe with global coverage. The satellites provide observations which serve a wide range of users for a multitude of applications in the areas of climate, land and ocean services, emergency management, atmosphere and air quality, among others.

- Sentinel-1 fleet of two operational satellites provides all-weather, day and night radar imagery for land and ocean services. The Sentinel-1C was launched on 5 December 2024 and Sentinel-1D in December 2025.
- Sentinel-2A, -2B and -2C provide optical imagery for land and emergency services.
- Sentinel-3A & -3B provide optical, radar and altimetry data for marine and land services.
- Sentinel-5P and -5 provide atmospheric composition data..

Sentinel-4 and Sentinel-5 are Copernicus atmospheric composition instruments hosted on EUMETSAT meteorological satellites: Sentinel-4 on geostationery Meteosat Third Generation Sounder satellite, and Sentinel-5 on polar orbiting MetOp Second Generation A-type satellites. Sentinel-4 provides hourly daytime monitoring of air quality, trace gases and aerosols over Europe and part of North Africa, while Sentinel-5 provides high-spatial-resolution daily global observations of atmospheric gases and aerosols. Sentinel-6 provides radar data to measure global sea surface height observations for climate monitoring and ocean and seasonal forecasts. It continues a time series of mean sea level rise measurements dating back to 1992.

CCMs complement the data portfolio in the Sentinel satellites missions with another layer of value to meet user needs, providing data from commercial data providers. There are around 30 existing or planned to contribute missions, encompassing various technologies like SAR, optical sensors, spectrometers and altimetry systems.

In-Situ Component collects data acquired by a multitude of sensors at air-, sea- and ground-level, and includes geospatial reference data.

Service Component of Copernicus programme transforms the various data into timely and actionable information products. The Copernicus Services deliver value-added information products in six thematic areas:

Atmosphere Monitoring Service (CAMS)	Climate Change Service (C3S)	Emergency Management Service (CEMS)	Land Monitoring Service (CLMS)	Marine Environment Monitoring Service (CMEMS)	Security Service (CSS)[1]

Figure 2: Copernicus services

Key takeaways for EO from the 2025 UCP Rail

The Rail panel of the User Consultation Platform (UCP) 2025 took place on 4th December 2025 as a mix on-site/online event in Prague. The event was divided in two main parts: the morning session, covering updates on recent projects: CLUG2, VICE4RAIL and EGNOS4RAIL for GNSS and S5LECT for satcom and 5G link. The afternoon was dedicated to the update of URD on GNSS, Copernicus and EU SATCOM respectively. The following include the outputs of the UCP consultation and desk research:

Early-stage adoption: While some nations (UK, Germany, Belgium) are early adopters, most European Infrastructure Managers (IMs) remain in the exploratory phase, treating EO as an innovation pilot rather than a structurally integrated maintenance tool.

Fragmented responsibility: A lack of centralized strategy with IMs often confines EO data to specialized departments, preventing valuable insights from reaching the operational maintenance crews responsible for safety and environment.

Data silos and integration: Disconnected systems for geotechnical reports, weather, and vegetation data prevent a holistic network view; IMs currently lack unified GIS platforms and predictive models required to transition from reactive to proactive maintenance.

Disaster management database: A significant gap exists in disaster reporting, as current databases lack the granular connectivity needed to correlate specific infrastructure damage and reconstruction costs with past extreme weather events.

Spatial mismatch: The 10m resolution provided by Copernicus Sentinel-2 is often too coarse for narrow rail assets like catenaries or tracks, while high-resolution commercial alternatives remain cost-prohibitive for network-wide use.

Temporal latency: The 5-to-6-day revisit cycle of Sentinel satellites makes it difficult to capture or respond to rapid-onset events like flash floods or fast landslides in real-time.

Topographic data needs: There is a critical requirement for a standardized, publicly available Digital Elevation Model (DEM) for Europe at 10m resolution (or better) to improve the accuracy of flood modeling and risk mapping.

Thermal and hyperspectral gaps: Current thermal sensors (e.g., Sentinel-3) are either too coarse (~1km) or with too low cadence (e.g. Landsat 8&9) to identify local and time critical anomalies, whereas

high-resolution hyperspectral data is needed to accurately classify vegetation species and soil conditions. **Enhanced SAR resolution:** To monitor smaller structural elements or earthworks deformation operators require SAR resolutions of 3–5m and more frequent revisit cycles of 1–3 days to pinpoint localized weak spots. Such data is available commercially. **Multi-Band frequency approach:** Slope, earthworks monitoring along rail corridors benefits from multi-frequency strategy: C-band for higher resolution over open terrain and large structures, **L-band** radar to penetrate trackside foliage and monitor deep-seated embankment movement, and **X-band** radar for millimeter-scale precision on structural elements of tracks and bridges. **Refined optical sensing:** Multispectral imagery at 5m resolution in Visible/NIR and 10–20m in SWIR, with a 2–3 day revisit cycle would better detect unauthorized track-side activity, but also improve vegetation health assessment.

Table 1: Takeaways for EO from the UCP

The role of Copernicus for climate resilience and adaptation

Copernicus data and services are increasingly useful for enhancing the climate resilience of European rail infrastructure, providing valuable inputs for risk assessment, operational decision-making, and long-term adaptation planning. By leveraging systematic and open data from the Sentinel constellations and Copernicus services, rail infrastructure managers can move beyond historical records to identify evolving hazards driven by climate change, such as intensifying floods, heatwaves, and wildfires.

The **Copernicus Climate Change Service (C3S)** and the **Climate Data Store (CDS)** support strategic, long-term resilience by providing historical reanalysis and future climate projections up to 2100. These datasets allow operators to quantify vulnerabilities and model the potential impacts of changing precipitation patterns and extreme temperatures on critical assets like tracks and embankments. For instance, national railway organizations like ProRail in the Netherlands utilize this data to conduct "spatial stress tests" to evaluate network-wide risks.

For immediate operational safety, the **Copernicus Emergency Management Service (CEMS)** and **Land Monitoring Service (CLMS)** provide tools for hazard mitigation and infrastructure integrity. Specifically:

- **Ground Stability:** The **European Ground Motion Service (EGMS)** uses Sentinel-1 radar data and MT-inSAR technique to detect millimeter-scale ground deformations, helping to identify creeping slopes or subsidence that could lead to landslides or track misalignments.

- **Flood and Moisture Management:** Data from **Sentinel-1** and **Sentinel-2** can be used to monitor soil moisture, drainage saturation, and river flooding. This supports the detection of heavy rain cells and enables historical flood mapping to eliminate blind spots in risk memory.

- **Environmental Monitoring:** Copernicus services can support environmental monitoring – track corridor habitat baseline mapping, change detection.

Integrating these services into asset management workflows allows for more targeted maintenance and the design of robust, "climate-proofed" infrastructure capable of withstanding the increasingly frequent simultaneous climate extremes.

The role of European Global Navigation Satellite System (EGNSS)

EGNSS is the European satellite navigation program designed to provide highly accurate and reliable positioning, navigation, and timing services on a global scale and ensuring Europe s technological autonomy. EGNSS offers high-precision and multi-constellation capability. There is a free positioning service available to the public, as well as encrypted services for government and commercial use, like the Public Regulated Service (PRS) for government-authorized users. EGNSS includes two main systems:

- **Galileo** is the European satellite navigation system that provides highly accurate global positioning and timing information. It offers several unique features, including higher accuracy (especially in urban areas), improved availability, and an authentication service to prevent signal spoofing. Numerous EU economic sectors rely on Galileo, from transport and agriculture to border management and search and rescue. Its 20cm accuracy makes Galileo a game changer for autonomous driving and commercial drones. Already more than 3.5 billion smartphones are Galileo-enabled.
- **EGNOS** (European Geostationary Navigation Overlay Service) is a satellite-based augmentation system (SBAS) that improves the accuracy, integrity, and reliability of the navigation services to aviation, maritime and land-based users in over 30+ countries.

Takeaways for GNSS from the 2025 UCP Rail
GNSS-based solutions for safety-critical applications are now at the level of demonstrations. They will need multi-sensor fusion, FDE and redundant chains to reach the SIL4 level of performance required. An important step under development is dedicated to the definition of methodologies and tools for certification
The EGNOS version dedicated to rail is under investigation; parameters needed to meet the safety requirements shall be validated, and the EGNOS certification approach defined.
Neither HAS, nor OSNMA are exploited, because of a lack of awareness and priorities in investments and developments. But most of the applications developed in rail will benefit from these new services.
New applications are identified as potential uses of GNSS in freight: for train composition detection, or later, in automated shunting operations. They will require low energy consumption to face wagon maintenance constraints and low cost.
While **Remote Train operations demonstrated feasibility** mainly based on perception sensors, the use of GNSS-based locomotive localization should allow a more complete and accurate perception of the situation.

Table 2: Takeaways for GNSS from the 2025 UCP Rail

European Secure SATCOM

The EU Secure Satellite Communication System, known as **GOVSATCOM** is an investment made by the EU, which aims to provide secure and cost-efficient communication capabilities to security and safety-critical missions and operations. **IRIS², ** the new multi-orbital constellation of 290 satellites will provide secure connectivity services to the EU and its Member States as well as broadband connectivity for governmental authorities, private companies and European citizens, while ensuring high-speed internet broadband to cope with connectivity dead zones**.** The program is part of the EU s broader strategy to strengthen its autonomy, security, and defence capabilities, especially in response to increasing geopolitical challenges and cybersecurity threats.

Takeaways for SATCOM from the UCP 2025 Rail
For communications, European railways are transitioning from GSM-R to FRMCS to support data-intensive, safety- and mission-critical applications (ETCS signalling, real-time monitoring, voice, operational data).
SATCOM functional organisation provides a clear role for IRIS² as a sovereign backbone for rail resilience and redundancy.
SATCOM integration is considered a key player to guarantee a cost-effective service, especially in rural, remote and cross-border areas for redundancy and global coverage.
Continuous alignment between SATCOM system capabilities and railway requirements will be essential to ensure smooth long-term use of SATCOM in railway operations. Relevant railway scenarios have already been successfully identified.
Satellite communication to be implemented as part of a hybrid solution within a **multi-bearer network approach.**
Current user needs and requirements for satellite communication remain valid, with additional technical aspects now taken into account.
Capital costs are mainly linked to space programs while operating costs will be clarified in the next steps.
Ongoing projects within FA2–FA6 of Europe's Rail Joint Undertaking (EU-Rail) and S5LECT are **showing strong advancement in the implementation of satellite communications for railways**, with technical solutions, field/laboratory tests and pilot projects already underway across several EU countries.

Table 3: Takeaways for SATCOM from the UCP 2025 Rail

2.2 Summary of Rail RUR 2023

The **Report on User Needs and Requirements (RUR) 2023** identified a suite of applications across GNSS, EO, and SATCOM technologies. It should be noted that several applications and operational scenarios detailed in the 2023 edition have not been carried forward or reviewed for the 2025 version. For further information regarding earlier use cases, please refer to the 2023 edition.

The following list presents the rail applications and operational scenarios as specified in the 2023 RUR.

2.2.1 GNSS-based applications

- **Safety Related**
  - **Enhanced Command & Control Systems:** Integration into signalling systems like ERTMS for high- and low-density lines.
  - **Trackside personnel protection systems:** Localization of work zones and moving equipment to protect personnel.
  - **Train Integrity and Train Length Monitoring:** Verification of train wholeness and length.
  - **Remote Train Operations:** controlling and operating trains from a remote location using advanced communication and control technologies. (added in the 2025 version of the document)
- **Maintenance Improvement**
  - **Condition-based maintenance:** Monitoring assets to intervene before defects become critical.
  - **Predictive maintenance:** Identifying potential issues early to optimize maintenance schedules.
- **Train Driving Optimisation**
  - **Asset management:** Tracking the location and status of rail assets.
  - **Fleet Management:** Real-time visibility of freight wagons and equipment.
  - **Driver Advisory Systems:** Providing guidance to drivers for energy and timing optimization.
- **Attractiveness Enhancement**
  - **Passenger information systems:** Providing real-time updates on arrivals and departures.
  - **Public Transport – Tram and Light Rail:** Enhancing urban rail operations and situational awareness. (not in-depth assessed in this document).
  - **Door control supervision:** to enable the opening of specific doors at particular stations (added in the 2025 version of the document)

- **Freight monitoring**
    - **Hazardous Cargo Monitoring:** Monitoring of hazardous goods like petroleum, flammable/corrosive/toxic chemicals etc. by the Rail freight operators (added in the 2025 version of the document).

2.2.2 EO applications and operational scenarios in 2023

The current edition of the RUR is focused exclusively on **the use of space for climate resilience and adaptation for rail, sections 2.7 and 2.8, as well as the annex**. The table below lists the EO applications analysed in the 2023 version of the RUR.

Application	Operational Scenarios
Railway Infrastructures Planning and Designing, Finance Planning	**Determination of surface ground movements:** Monitoring landslides, subsidence, uplifts, and seismic displacements.
	Determination of soil moisture: Analyzing water content for geotechnical risk assessments.
	Weather Impact Assessments and Adaptation to Climate Change: Long-term risk modeling and infrastructure resilience planning.
Railway Infrastructures Construction	**Geotechnical and structural monitoring during the construction:** Tracking ground shifts and material health during building or tunneling.
Railway Infrastructures Monitoring	**Vegetation monitoring:** Identifying diseased trees or overgrown branches near catenary lines.
	Monitoring for the construction of new buildings: Detecting unauthorized worksites or new buildings within restricted zones.
	Control of railway tracks located in places hard to reach: Remote inspection of tracks in mountainous or inaccessible areas.
	Condition and Predictive-based Maintenance: Using satellite data to forecast structural degradation.
Disaster Response to Floods	**Flood monitoring:** Near-real-time assessment of water levels on tracks for emergency response.

Table 4: EO Applications and Scenarios 2023

2.2.3 SATCOM applications

SATCOM is primarily addressed through its integration into the **Future Railway Mobile Communication System (FRMCS)**. The 2023 document details several specific communication-based scenarios:

- **Critical Communication Applications:**
  - On-train outgoing/incoming voice communication (driver to controller).
  - Multi-train voice communication for drivers including ground user(s).
  - Automatic train protection communication.
  - Automatic train operation communication.
  - Railway emergency communication and public emergency calls.
  - Train integrity monitoring data communication.
- **Remote/Rural Connectivity:** Providing service in areas where terrestrial coverage (GSM-R or 5G) is insufficient.

This document (2025 version) enhances the list by adding:

- **Additional FRMCS/SATCOM-relevant applications**
  - Remote control of locomotives and remote shunting operations, including future FRMCS remote driving use cases.
  - Communications for trackside maintenance and intervention teams (voice and operational data).
  - Remote monitoring and control of critical infrastructure (points, level crossings, signalling and power subsystems).
  - Operational video (e.g. driver view or trackside CCTV) to support situational awareness in defined FRMCS scenarios.
  - Rolling stock and asset condition monitoring, including predictive maintenance and freight wagon/cargo status.

2.2.4 Key Operational Trends

- **Smart Wagons:** Equipping freight wagons with telematics to monitor loading status, door/hatch conditions, and the health of bogies and braking systems.
- **Digital Twins:** Creating 3D digital representations of rail infrastructure for predictive modeling.
- **Drones and AI Integration:** Utilizing low-cost EGNSS-enabled drones for automated inspection of bridges and tracks.

2.3 Market overview & trends

2.3.1 Market Evolution

GNSS and EO serve the rail sector in many ways. First, GNSS plays a role in rail digitalization; from asset management to infrastructure monitoring and enhanced passenger information, GNSS is already largely deployed in non-safety critical applications. For safety critical application using GNSS, some of them are at the demonstration phase where the definition of the methodology and tools for certification are defined. An EGNOS version dedicated to rail is currently being investigated where the parameters are needed to meet the safety requirements are to be validated and certified according to the EGNOS certification approach.

New GNSS applications are emerging in the freight sector, including train composition detection and future automated shunting operations. These solutions will need to be low-cost and energy-efficient to meet wagon maintenance constraints. While remote train operations have so far relied mainly on perception sensors, incorporating GNSS-based locomotive localization can significantly enhance situational awareness and overall system accuracy.

Earth Observation and Copernicus data are becoming an increasingly important part of the European rail value chain, but the market is still emerging and fragmented compared with sectors such as agriculture or maritime. EO is used mainly as an enabling input to geospatial solutions and asset-management platforms, rather than as a stand-alone product, so most rail-specific activity sits inside the broader, fast-growing European satellite data and geospatial services market. Copernicus, as the EU's flagship EO programme, underpins many of these services by providing free, systematic data that can be integrated with GNSS, in-situ sensors and AI-based analytics for rail operators, infrastructure managers and public authorities. [RD44]

Across Europe, three main rail use cases are gaining traction: network and corridor monitoring, climate and environmental risk management, and support to planning and construction. Network monitoring applications combine Sentinel imagery with interferometric techniques to detect ground deformation, landslides and subsidence along tracks and in cuttings or embankments, allowing infrastructure managers to prioritise inspections and preventive maintenance at network scale. Copernicus data, particularly from Sentinel-1 and Sentinel-2, are also used to monitor flooding, soil moisture and slope stability, supporting operational decision-making during extreme weather as climate change increases the frequency and intensity of such events in Europe [RD45].

Another growing application area is strategic planning and capacity expansion, where EO supports route selection, environmental impact assessment and land use monitoring for new or upgraded rail corridors. High-resolution commercial imagery is often fused with Copernicus data to characterise urban growth, informal settlements, encroachments and biodiversity sensitive areas along planned alignments, helping project developers and authorities meet European Green Deal, TEN-T and national decarbonization objectives. EO based products also contribute to monitoring construction progress and compliance, for example by tracking earthworks, vegetation clearance and restoration over time. [RD46]

Several structural trends shape how EO and Copernicus will be used for rail in Europe. First, there is a clear move from one-off consulting studies towards recurring, subscription-based monitoring services that deliver automated alerts and dashboards to infrastructure managers, supported by cloud platforms and APIs. Second, policy and regulation are reinforcing demand: climate-adaptation requirements, resilience assessments, and EU-level sustainability reporting frameworks create incentives to use EO to evidence risk and performance of critical rail infrastructure. Third, technical evolution—denser satellite constellations, higher revisit rates, better spatial resolution and combined EO–GNSS solutions—improves the business case by reducing detection thresholds and increasing temporal coverage, which is valuable for assets that extend thousands of kilometers.

At the same time, the rail specific EO market faces several constraints. Procurement and digital transformation cycles in European rail are typically slow, with conservative risk postures and strong reliance on established engineering workflows, so integrating EO into asset management systems and standards can take years. Many infrastructure managers still see EO as complementary evidence rather than as a primary decision-making source, which limits contract size and depth of integration. Data policy and skills are also issues: while Copernicus provides free data, turning these into operational products requires specialized processing, domain knowledge and integration with existing systems; this favors intermediaries and consortia rather than direct uptake by rail operators.

The European rail use of EO and Copernicus is likely to deepen along two axes: resilience to climate change and digital-twin-driven asset management. As Europe invests in making rail the backbone of low-carbon transport, EO will be increasingly used to map and monitor climate exposure—heat stress, drought-related ground movement, flooding and extreme precipitation—over long asset lifetimes. In parallel, as geospatial and GNSS-enabled digital twins of rail networks mature, Copernicus data can provide regularly refreshed "background layers" and deformation products that keep these twins up to date, supporting predictive maintenance and integrated planning with other infrastructure such as roads, energy and utilities. Overall, the trend points to EO moving from pilot projects and niche studies toward being a standard component of geospatial and analytics platforms used by Europe's rail ecosystem [RD47].

Satellite communications (SATCOM) are emerging as a critical complement to terrestrial networks in the European rail ecosystem, particularly as the sector transitions to the Future Railway Mobile Communication System (FRMCS). While FRMCS is primarily based on 5G New Radio (NR) terrestrial infrastructure, its multi-access architecture explicitly accommodates non-terrestrial networks (NTN) to address coverage gaps on regional, freight and cross-border lines where deploying dense 5G cells is uneconomical or impractical. SATCOM bearers, spanning LEO, MEO and GEO constellations, offer ubiquitous coverage, redundancy and resilience, supporting FRMCS mission-critical services like ETCS train control, voice (MCPTT) and ATO over radio in challenging environments such as tunnels, cuttings and remote corridors.

Recent EU initiatives underscore SATCOM's strategic role in rail digitalization. The European Union Agency for Railways (ERA) has established expert groups to assess satellite integration within ERTMS/FRMCS, focusing on safety certification pathways and hybrid terrestrial-satellite handover protocols. Low Earth Orbit (LEO) High Throughput Satellites (HTS), such as those from Starlink and OneWeb, are gaining traction for their low latency (<50 ms) and high throughput (>100 Mbps), enabling real-time video surveillance, passenger connectivity and remote operations alongside GNSS positioning. Meanwhile, established MEO (e.g., SES O3b mPOWER) and GEO L-band solutions provide robust backup for safety-related communications, with ongoing 3GPP Release 17/18 NTN standardization ensuring seamless FRMCS interoperability.

The SATCOM-for-rail market mirrors EO's early-stage fragmentation but benefits from clearer regulatory momentum through GovSatCom and IRIS². These programmes position satellite capacity as a sovereign complement to commercial offerings, targeting secure governmental connectivity for rail signalling and freight security. Key applications include network-wide train localization (fusing SATCOM with GNSS), predictive maintenance telemetry from remote sensors, and climate-resilient operations during terrestrial outages. As FRMCS rollout accelerates post-2028, subscription-based SATCOM services are expected to bundle with 5G slicing, creating integrated "Rail-as-a-Service" platforms that lower total cost of ownership for infrastructure managers while meeting UIC performance classes for reliability and throughput. Challenges remain in antenna miniaturization for high-speed motion and certification of NTN for SIL4 safety levels, but pilot deployments across TEN-T corridors signal accelerating adoption by 2030.

2.3.2 Key trends

2.3.2.1 GNSS Key Market Trends

Infrastructure Cost Reduction

GNSS-based virtual balises and train positioning eliminate much of the traditional trackside infrastructure needed for fixed-block signalling. This cuts deployment costs for regional networks by up to 30-50% compared to conventional systems, while improving scalability across low-density lines. Reliability increases through satellite redundancy and hybrid fusion with inertial sensors, reducing single points of failure.

Automation and Autonomy advances

Europe's rail sector targets GoA3/GoA4 (semi-/fully autonomous) operations by 2030 under Shift2Rail/RAIL44 initiatives. GNSS provides the precise positioning (±1m accuracy with ERTMS/ETCS integration) essential for moving-block signalling and ATO over radio (ATOoR). Complementary tech like onboard LiDAR handles GNSS-denied tunnels, enabling seamless GBAS-augmented operations.

Predictive maintenance evolution

Satellite-enabled IoT sensors on rolling stock feed real-time data into AI platforms for condition-based maintenance. This predicts failures (e.g., wheel flats, pantograph wear) days in advance, cutting unplanned downtime by 20-30% and maintenance costs by 15%. EO-derived track geometry monitoring complements GNSS train location data for network-wide digital twins.

2.3.2.2 EO Key Market Trends

EO can support Europe's rail infrastructure become more climate-resilient, as operators and public authorities respond to EU climate, transport and adaptation policies that require systematic climate risk assessment of critical infrastructure. The core driver is the combination of more frequent extremes—heatwaves, intense rainfall, flooding, landslides and sea-level rise—with large EU investments in rail as a decarbonization backbone, which raises both the exposure of assets and the economic case for using EO-based climate and ground-motion intelligence throughout the asset life cycle [RD42].

From a policy and funding perspective, the European Green Deal, the EU Strategy on Adaptation to Climate Change and associated investment plans (including substantial EU-level rail infrastructure funding) push infrastructure owners to integrate climate resilience into planning, design and maintenance, which in turn increases demand for EO- and Copernicus-based services that can evidence climate risks and adaptation benefits. EO is also embedded in broader EU digital and green transition agendas, so Copernicus services are promoted not only as technical datasets but as part of a policy-ready "value chain" that starts from satellite observations and ends with decision-support indicators for asset managers and regulators. This is shifting the market from ad-hoc studies towards more standardized, policy-aligned climate services for infrastructure, including rail [RD43].

On the technical side, Copernicus can deliver several data layers that are directly relevant to rail climate resilience, including climate reanalysis and projections from the Copernicus Climate Change Service (C3S), land cover, land surface temperature and imperviousness products from the Copernicus Land Monitoring Service (CLMS), and ground deformation information from the European Ground Motion Service (EGMS). For rail, these data underpin use cases such as mapping heat exposed track sections, monitoring ground instability around embankments and tunnels, understanding changes in drainage basins affecting track bed flooding, and screening coastal or riverine segments exposed to sea-level rise and storm surges. The open and free nature of Copernicus data encourages both large engineering consultancies and specialized SMEs to develop tailored analytics, dashboards and early warning tools for infrastructure managers.

The main trends in Europe point toward deeper integration of EO into regulatory and financial frameworks, higher spatial and temporal resolution data tailored to operational needs, and closer coupling of climate, ground-motion and asset data into digital twins of rail infrastructure. There is a clear shift from focusing solely on physical hazards to constructing composite risk indicators that combine hazard, exposure and vulnerability, which is essential for prioritizing adaptation actions along complex, transboundary rail corridors. As EU adaptation screening and disclosure requirements tighten, EO-based climate services for rail are likely to move from optional add-ons to standard components of feasibility studies, design codes and long-term maintenance planning, consolidating a specialized market segment at the intersection of space, climate services and rail engineering in Europe.

2.3.2.3 SATCOM Key Market Trends

Migration from GSM-R to FRMCS within a multi-bearer architecture

The replacement of GSM-R by the Future Railway Mobile Communication System (FRMCS) is the dominant structural driver for SATCOM in European rail. FRMCS is based on 3GPP 5G New Radio, with the complete feature set targeted for Release 19, and it is explicitly designed as a multi-bearer system in which non-terrestrial networks (NTN) sit alongside terrestrial 5G as complementary bearers. With GSM-R and FRMCS expected to coexist until around 2035, the medium-term market is shaped less by SATCOM replacing terrestrial coverage than by SATCOM becoming a certified, interoperable bearer within a hybrid architecture — first for performance and business communications, and progressively for safety-critical services as certification frameworks mature.

IRIS² and GOVSATCOM positioning sovereign EU capacity alongside commercial constellations

The arrival of IRIS², the planned 290-satellite multi-orbital EU constellation, together with the existing GOVSATCOM / Secure Connectivity component, introduces a sovereign European layer to a market otherwise dominated by non-EU commercial LEO operators. For rail, this creates a two-track procurement environment: commercial LEO services for broadband, passenger and operational data; and sovereign EU capacity for secure, safety- and mission-critical traffic where data sovereignty, resilience against jamming, and cross-border interoperability matter. Clarifying the procurement and operating-cost models for the sovereign track is one of the open issues flagged at UCP 2025.

Convergence of satellite and terrestrial 5G through NTN standardisation

3GPP Release 17 and 18 NTN extensions, combined with the planned migration of SATCOM terminals from DVB-S2X to non-terrestrial 5G, are collapsing the technical gap between satellite and terrestrial bearers. This convergence simplifies seamless terrestrial-to-satellite handover, reduces the engineering cost of multi-modem onboard equipment, and allows SATCOM to inherit the wider 5G ecosystem (chipsets, network slicing, roaming). For rail, the practical consequence is that SATCOM is no longer a parallel system bolted onto FRMCS but increasingly an extension of the same radio architecture, lowering integration costs and accelerating the business case on regional and cross-border lines.

Pilot maturity ahead of certification: progress under EU-Rail and S5LECT

Field and laboratory validation is advancing faster than the certification framework. Projects under EU-Rail Flagship Areas 2 to 6, together with S5LECT, are demonstrating SATCOM integration for FRMCS scenarios across several Member States, while ERA expert groups are developing safety certification pathways and hybrid handover protocols. The 2025 UCP confirms that current user needs and requirements for satellite communication remain valid; the binding constraint on adoption by 2030 is therefore not technical feasibility but the absence of an established regulatory and certification framework authorising SATCOM bearers for SIL4 services, antenna form factors compatible with high-speed rolling stock and 25 kV catenary environments, and consolidated operating-cost models that can be defended in long-cycle rail procurement.

2.3.3 Main User Communities

The users community can express very different needs. Beyond train owners, operators, industries, construction and public works companies including civil engineering companies who leverage space enabled data to improve the safety, efficiency and comfort of the passengers and freight, there is a range of additional end users depending on the applications. Public authorities, logistics and insurance companies, research institutes and universities have specific needs fulfilled by different GNSS-EO enabled applications or by their integration. The industry is represented by the complex rail value chain, which, depending on the demand from train owners and operators, the train functions developed and the requirements of the associated operational scenario, develop requirements for positioning, timing and spatial information and decide on which information technologies to adopt to satisfy these.

In the rail industry, train manufacturers drive a value chain involving tier 1 suppliers and component suppliers in the manufacturing of trains. The industry has set up multiple working groups to proceed jointly on specifications and requirements, especially for safety relevant applications. Beyond the railway industry, the end user community includes the companies (generally private) including civil engineering companies involved in the designing and construction of rail infrastructure. The main user communities are listed below, which partly shape the rail users needs and requirements.

- **Passengers** (railway final users – passengers and freight) are indirectly benefiting from satellite data in most cases. Railway passengers rely on satellite data to improve the efficiency and safety of railway transportation.
- **Train owners / operators** can use satellite data, including navigation and earth observation, for a variety of purposes, including monitoring and controlling moving rail cars, tracking hazardous rail freight, and improving train scheduling and maintenance practices.
- **Construction and public works companies** including civil engineering companies. They correspond to the (generally private) companies contracted by railway infrastructure owners and/or operators to design and construct the above-mentioned infrastructures. A wide range of stakeholders are involved in infrastructure. Depending on the development stage, from planning until maintenance and even decommissioning, the roles, required expertise and responsibilities may greatly differ, and thus the usage and requirements for the use of space data.
- **Railway Undertakings and Infrastructure Managers** can use satellite data, including navigation and earth observation, for a variety of purposes, including monitoring railway infrastructure, improving maintenance practices, and enhancing safety and efficiency across the infrastructure lifecycle.
- **Public authorities,** including regulatory authorities, at local (e.g. municipalities), regional, national or European level. This includes authorities responsible for spatial planning and authorities entrusted with the verification that infrastructures comply with applicable legislation and regulations.
- **Infrastructure owners and/or operators**, referred to as "infrastructure managers" can be public or private entities.
- **International development organizations** (e.g. World Bank), when development projects involving the construction of large infrastructures such as transport networks are at stake.
- **Financial institutions** including large international development organizations are involved in the funding of railway infrastructures and are interested in the exposure to risk of the concerned infrastructures and in the progress of construction works.
- **Insurance companies** can be relevant from two standpoints. For GNSS, driving insurers offering telematics insurance schemes, for Earth Observation, insurance companies cover the risk related to issues to the railway infrastructure.
- **Standardization bodies** like ISO, ETSI and CEN/CENELEC, are active on GNSS performance criteria to better specify the positioning and timing in the standards. Moreover, ISO is active on standards for monitoring relevant for the use of Earth Observation. Since 2017, the Geoscience and Remote Sensing Society (GRSS) formed the Standards for Earth Observations (GSEO) Technical Committee to support the development and promotion of technical standards related to the generation, distribution, and utilization of interoperable data products from remote sensing systems.
- **Industry associations** are active in coordinating and shaping practices in the rail and infrastructure sectors.

Research institutes and universities active in the fields of navigation and positioning for rail industry with a particular focus on signal processing, to demonstrate the benefits of augmentation and multi-frequencies, in urban environment, to mitigate multipath effects.

European rail organizations:

- **Community of European Railway and Infrastructure Companies (CER)**
- **International Union of Railways (UIC)**
- **European Union Agency for Railways (ERA)**
- **PRIME Taskforce Climate Change (EU)**: Expert group pooling rail operator knowledge for adaptation, including earth observation.
- **Europe's Rail Joint Undertaking (EU-Rail)** is the European partnership on rail research and innovation established under the Horizon Europe programme (2020-2027) and the universal successor of the Shift2Rail Joint Undertaking.

National organizations:

- **SNCF Réseau (France)**:
- **Deutsche Bahn (Germany)** National railway company of Germany with subsidiary DB InfraGO managing rail infrastructure.
- **Network Rail (UK)**
- **ÖBB (Austria)**
- **ProRail (Netherlands)**

2.3.3.1 GNSS Key Users

GNSS-based solutions first rely on component and receiver manufacturers. Most of the chips embedded in GNSS-based railway solutions today rely on COTS components, most of them not specifically developed for the rail. They are integrated in rail systems by system integrators developing railway components. Some of the solutions developed for onboard systems can then be integrated by train manufacturers. These user communities also play an important role in the definition of user requirements: Component manufacturers, system integrators, and train manufacturers. As presented in the EO and GNSS EUSPA Market Report [RD1], the main market players in the GNSS value chain are:

- Components and receiver manufacturers
- System integrators: Tier 1 suppliers and train manufacturers
- Train manufactures
- Train operators that will use the service to offer better services to their clients and increase their efficiency and attractivity. Some examples: Fleet operators will offer customers a better view on their cargos such as temperature, pressure, estimate time of arrival as well as accurate information of the transport itself. Passenger information will benefit from revitalized capillary lines and regional rail services.
- Infrastructure managers to reduce costs and improve performance
- Users, beyond the railway industry, the end user community includes companies (generally private) such as civil engineering companies involved in the designing and construction infrastructure

The rail industry is concentrated in Europe and North America. European GNSS companies have a market share of roughly one-third among components and receivers and the top 3 companies in the continent are Septentrio, Hexagon (Leica Geosystems) and U-blox.

The main industry stakeholders in the Rail GNSS market value chain are system integrators, component manufacturers, train manufacturers, train owners and operators as well as Railway Undertakings and infrastructure managers.

- The main component manufacturers (receivers and others) are Hitachi Rail STS, Trimble, GMV, Glarun Technology, Sierra Wireless.
- System integrators are involved whenever key operators have strong exports both to North America and Asia. The top 3 companies are VTG, Alstom and CRRC, but this category also includes: Thales, Siemens, Hitachi.
- We can cite among train and rolling stock manufacturers: Siemens, Alstom, Hitachi, and China South Locomotive.
- Train owners and operators include train operating companies and freight operating companies, such as Deutsche Bahn, Trenitalia, SNCF, Arriva, Colas, Renfe, Stagecoach and urban transports operators. There are also rolling stock operating companies such as investment banks, consortia and national companies.
- The Railway Undertakings and infrastructure managers.

2.3.3.2 EO Key Users

The main users of EO for rail climate resilience and adaptation are infrastructure owners and managers, both public and private, who are responsible for national rail networks and corridors. These organizations can use EO- and Copernicus-based climate and ground motion information to map hotspots for possible flooding, landslides, subsidence, coastal erosion and heat stress along their assets, to prioritise adaptation investments and to justify them to regulators and funders. Within these organizations, asset management, engineering, risk and environmental or sustainability departments are typically the primary internal users, because they must integrate climate risk into long-term renewal plans, design standards and maintenance regimes.

A second major user group consists of transport and infrastructure ministries, safety authorities and regulators at national and EU level, who rely on EO-derived indicators and climate services to support compliance with adaptation strategies, TEN-T requirements and broader climate-risk disclosure and screening obligations. They use EO to obtain consistent, cross-border evidence on hazard exposure and to compare vulnerabilities across regions and modes, which feeds into policy, funding decisions and resilience guidelines that affect rail. Development and public finance institutions that support rail upgrades and extensions in Europe also increasingly consume EO-based climate analytics as part of their due-diligence and climate-risk assessments [RD48].

Engineering consultancies, geospatial and climate service SMEs, and research organizations form another key user group, because they transform raw Copernicus data into tailored products for the rail sector. These actors use EO to build models, risk maps, decision support tools and digital twins that can be embedded in rail clients 'processes, effectively acting as intermediaries between satellite data providers and operational users. Their role is critical in translating generic EO products into rail specific metrics such as expected damage, service disruption, or performance under different climate scenarios.

Local and regional authorities, as well as civil protection and disaster risk agencies, can use EO-based information on climate hazards that indirectly informs rail climate resilience, particularly where rail lines intersect with floodplains, unstable slopes, or along coastlines. While they may not manage the rail assets themselves, their climate risk assessments, land use plans and early warning systems can use EO and influence how rail infrastructure is planned, protected and operated in the face of climate extremes.

2.3.3.3 SATCOM Key Users

In the rail segment, SATCOM services serve a wide range of end-users and communities, each with unique characteristics and needs. These end-users can be grouped based on their roles in the sector. The main users identified are the following

- **Railway Undertakings (RUs)**: Operate passenger and freight train services on the network, managing rolling stock, onboard systems, train crews (drivers and onboard staff), and compliance with safety and operational rules. They use SATCOM for resilient train control and ETCS/FRMCS links, mission-critical voice and data for crews, real-time fleet tracking and predictive maintenance, and onboard passenger Wi-Fi/infotainment with cybersecurity protections.
- **Infrastructure Managers (IMs)**: Develop, operate, and maintain railway infrastructure, including tracks, signalling, control-command systems, capacity allocation, traffic management, and network safety. They use SATCOM to extend FRMCS/ETCS coverage in remote areas, support trackside worksite communications for maintenance crews, enable remote asset monitoring, and provide backup links for control centres during terrestrial outages.
- **Safety and standards organisations**: These organisations play a central role in the rail sector by developing, maintaining, and promoting technical standards, safety frameworks, and interoperability requirements. They define common specifications and best practices that ensure safe, reliable, and interoperable rail operations across national and cross-border networks, covering areas such as signalling, rolling stock, communications, and system integration. While instrumental in promoting SATCOM in the rail sector, authorities can also monitor and manage rail traffic more effectively, ensuring the safety and efficiency of port operations and navigational routes.
- **OEMs/system integrators**: They design, manufacture, and integrate railway components like signalling, onboard telecoms, and rolling stock systems. They leverage SATCOM during development, testing, and remote diagnostics to validate resilient connectivity, certify FRMCS-compliant integrations, and enable real-time data exchange for safety and performance enhancements.

End-users community	Key focus areas	Main organisations
RUs	• Train operations (freight and passenger) • Real-time train control and monitoring • Onboard communication systems • Telematics and predictive maintenance • Passenger services and infotainment • Compliance with operational and safety regulations	• SNCF Voyageurs/Fret (France) • Deutsche Bahn (Germany) • Trenitalia (Italy) • Renfe (Spain) • OBB (Austria) • SBB (Switzerland)
IMs	• Track and infrastructure management • Signalling and control-command systems • Traffic and capacity management • Maintenance and renewal of infrastructure • Safety and interoperability	• SNCF Réseau (France) • DB InfraGO (Germany) • Network Rail (UK) • RFI (Italy) • ADIF (Spain) • ProRail (NL) • Infrabel (Belgium)

End-users community	Key focus areas	Main organisations
OEMs/System integrators	• Design and manufacture of rolling stock and subsystems • Integration of trains, signalling, and communication systems • System-level testing and validation • Predictive maintenance and diagnostics support • Compliance with technical standards	• Alstom • Siemens Mobility • CAF • Hitachi Rail • Stadler Rail • Kontron • Indra
Safety and standards organisations	• Definition of technical and safety standards • Interoperability rules and best practices • Certification and compliance monitoring • Safety oversight and audits	• UIC (International Union of Railways) • ERA (European Union Agency for Railways) • ETSI (European Telecommunications Standards Institute)

Table 5: User mapping

2.4 Policy, Regulations and Standards

Applicable regulations

In addition to the rules described in legal texts (i.e., directives, decisions, regulations), the design and operating conditions of railway systems in Europe are today subject to a normative framework that requires the demonstration of the system's safety. This framework is composed of specific European standards derived from the generic functional safety standard IEC 61508: 2011 [RD3].

The railway sector is distinguished by the existence of three safety standards (EN 50126: 2017, EN 50128: 2011, and EN 50129: 2018]). Each of them addresses a particular safety aspect and can be applied depending on the considered subsystem.

- The EN 50126 standard describes a systematic RAMS management process (starting from the design phase until the system decommissioning) in order to specify and demonstrate reliability, availability, maintainability, and safety. Part 1 of this standard focuses on the generic RAMS process, while part 2 addresses the systems approach to safety.
- The EN 50128 standard specifies the process requirements and techniques applicable to the development of software for programmable electronic systems used in railway Control-Command and protection applications.
- The EN 50129 standard addresses safety-related electronic systems (including subsystems and equipment) for railway signalling applications.

Finally, the EU's rail transport policy is geared towards the creation of a single European railway area. The policy includes the harmonization of technical, administrative, and safety rules, which is essential for interoperability between national rail systems.

Critical Infrastructure protection policy

There is no regulatory authority dedicated to infrastructures in general but in the European Union, the European Commission plays an increasingly important transversal role with respect to Critical Infrastructure protection (see following section).

Telecommunications Regulations

In the specific case of telecommunications, the Body of European Regulators of Electronic Communications (BEREC) is the regulating agency of the telecommunication market in the European Union. Besides, each Member State has set up its own National Regulatory Authorities (NRA) in charge of regulating telecommunications. However, neither BEREC nor the NRAs are directly involved in the definition of the Timing & Synchronization architecture. Finally, spectrum regulation agencies (ITU-R world agreement, national agencies for enforcement) and telecom network regulation agencies (CCITT/ITU-T, national agencies for enforcement) are also involved in particular through their participation in Standardization forums [RD2].

Space Policy and Regulations

The Regulation (EU) 2021/696 of 28 April 2021 "*establishing the Union Space Programme and the European Union Agency for the Space Programme*" (EUSPA) ([RD3]) is the main Space policy document for the European Union. Although the regulation highlights the role that Copernicus should play in supporting the Union's capacity to achieve independent decision-making and actions in a certain number of fields, among which infrastructure monitoring, it does no impose any regulatory obligations with regard to the use of space-based systems for infrastructure management.

Except for "critical infrastructures", there is in general no EU policy or regulatory document which directly addresses the infrastructure market. There are however a number of policy or regulatory documents which may have an indirect impact on the infrastructure market. An overview of these documents is provided in the Annex.

European Rail User Requirements Specification – ERTMS/ ETCS RAM

Further specifications on ERTMS are provided by UNISIG on the design, certification and application of ERTMS equipment. Those considered to be more related to GNSS applications are commented in this section.

Railway requirement criteria are usually qualified in terms of reliability, availability, maintainability and safety (RAMS). They differ from the GNSS quality criteria. Railway definitions according to the EN 50126 standard are:

- Reliability: the probability that an item can perform a required function under given conditions for a given time interval.
- Availability: the ability of a product to be in state to perform a required function under given conditions at a given instant in time or over a given time interval assuming that the required external resources are provided.
- Maintainability: the probability that a given maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources. It means the ability of a system being maintained or restored after a failure to operational status over a given time interval assuming that the maintenance is made under given conditions with prescribed procedures and means.
- Safety integrity: the probability of a system satisfactory performing the required safety functions under all stated conditions within a stated period of time.

2.4.1.1 Performance requirements

This section contains an analysis of the required technical performances of ERTMS/ETCS equipment that could include a GNSS component inside.

Accuracy

- Position accuracy measured on-board: For every travelled distance s the accuracy shall be better or equal to ± (5m + 5% s). The fixed ± 5m tolerance is intended to cover the longitudinal uncertainty of the balise reader in detecting the balise reference location. Also, in case of malfunctioning, the on-board equipment shall evaluate a safe confidence interval.
- Accuracy of speed known on-board: ± 2km/h for speeds lower than 30km/h, then increasing linearly up to ± 12km/h at 500km/h.
- Age of location measurement for position report to trackside: The location of the train head indicated in a position report shall be estimated less than 1 sec before the beginning of sending of the corresponding position report.

Clock

- Safe clock drift: 0.1 %. This value is not only a performance but also a safety related requirement as it refers to clock information used for time-stamping of messages and for supervision of time-outs, the magnitude of which is a few minutes.

For more information about performance requirements, please refer to [RD5].

Performance Requirements for Interoperability define possible values for technical performance requirements of ERTMS on-board equipment.

Reliability requirements consist of quantitative requirements in terms of Mean Time Between Failures (MTBF); and differentiates in reason of the criticality (Immobilizing, Service or Minor) of such failures. They are also called ERTMS RAM (for Reliability, Availability and Maintenance) requirements and are stated as follows (these are all defined for on-board equipment).

- The MTB Immobilizing hardware Failures shall be not less than 2,7x106 hours.
- The MTB Service hardware Failures MTBF-SONB shall be not less than 3,0x105 hours.
- The MTB Minor hardware Failures MTBF-MONB shall be not less than 8,0x103 hours.

Availability must be not less than 99.973%, in order to assure compatibility with the ERTMS availability.

Maintainability is also standardized by European Standards. Apart being designed in order to minimize periodical maintenance and to control hazard levels, the equipment installation must not interfere with the access to other systems and devices on-board the train. The system supplier must specify the needed and forbidden maintenance procedures, it must also present auto test systems to verify periodically the correct operation and include a “maintenance mode” for the maintenance operation, including interfaces maintenance.

2.4.1.2 Safety requirements

According to [RD6], the Railway Safety philosophy is based on three main principles:

- Avoidance, and as far as possible exclusion, the transformation of the inherent human non-intended errors into wrong-side failures (= failures, technical or human, susceptible to develop into hazards, to produce harm). Prevention of imaginable non-intended failures of the human operator to become wrong-side failures => the railway system is not designed to protect against intended wrong-side human failures.

- The controlled reliability, mainly applicable to the vital components.

- Detection and identification of any possible random critical technical failure (= any technical non functionality which has the potential to produce a non-safe response) and immediate enforcement of a safe state.

The railway safety standards (EN 50126...EN 50129) clearly prescribe the methodology to be followed over the whole life cycle of a sub-system or component to assure that its safety integrity risk is controlled and maintained under the prescribed level.

The classification of the safety integrity is prescribed on 5 levels (from EN 50129):

Safety Integrity	On Demand Mode (Low demand mode)		Continuous Mode (High demand mode)	Consequence of a failure
Level	Availability	Probability of failure on Demand (failure/demand)	Tolerable Hazard Rate per hour and function	
SIL4	> 99.99%	$\geq 10^{-5}$ to $<10^{-4}$	$\geq 10^{-9}$ to $<10^{-8}$	Several possible dead people in surrounding community
SIL3	99.99%	$\geq 10^{-4}$ to $<10^{-3}$	$\geq 10^{-8}$ to $<10^{-7}$	Several possible dead people
SIL2	99% -99.99%	$\geq 10^{-3}$ to $<10^{-2}$	$\geq 10^{-7}$ to $<10^{-6}$	Possible serious wounded people or one dead person
SIL1	90% -99%	$\geq 10^{-2}$ to $<10^{-1}$	$\geq 10^{-6}$ to $<10^{-5}$	Possible minor wounds
SIL0	No requirement			N/A

Figure 3: Safety integrity classification (EN 50129)

This table indicates the probability of failure, the safety integrity risk allocated to each of the levels (the figures represent probabilities expressed in events/hour).

The classification of SIL makes a distinction between the continuous (high demand) mode of operation and the operation on demand. This distinction considers that the operation on demand shall be preceded by an initial check of the element’s fail-less state. In this study we will be interested exclusively in the continuous mode.

Note:

- The “on demand mode” is reserved for systems used in intermittent/sporadic way.
- The “continuous mode” concerns systems permanently used for a period of time.

In the framework of the generic high-level quantitative safety requirements for ETCS operating either in Level 1 or Level 2, requirements are presented here to illustrate the magnitude order of Tolerable Hazard Rates of the transmission systems. This information is important if we consider that, to replace balises by virtual balises, the GNSS-based equipment must provide a performance as good as the existing equipment.

A dangerous failure is an undetected failure of the positioning system leading to the position provided being out of the accuracy range.

The safety integrity level will be derived from the different tolerable hazard rates, taking into consideration the specified environment. For Hazard Rates of < 10-9 failures/hour, a SIL 4 process will be applicable. It is important to notice only failures that cause the ETCS hazard need to be considered.

Considering ETCS onboard equipment without the transmission system, the hazard rate for the ETCS onboard system excluding those parts forming part of the transmission paths shall be shown not to exceed a THR of 0.67x10-9 dangerous failures/hour. The process of confirmation that the train data is correctly stored on-board must be of a quality commensurate with a SIL 4 system.

For more information about safety requirements, please refer to [RD4].

2.4.1.3 Non-regulatory sources

The Green Deal is a set of initiatives proposed by the European Commission to make the European Union climate-neutral by 2050. The rail industry is expected to play a significant role in achieving this goal. Here are some relevant initiatives under the Green Deal that will impact the rail industry:

- Improving rail infrastructure management: The European Commission is proposing measures to make freight transport more efficient and sustainable by improving rail infrastructure management, optimizing the use of rail tracks, improving cross-border coordination, increasing punctuality and reliability, and ultimately attracting more freight companies to rail
- Supporting the expansion of zero-emission power sources: The Federal Railroad Administration (FRA) is committed to reducing rail's carbon footprint by supporting the expansion of zero-emission power sources, such as electric locomotives
- Reducing GHG emissions from rail operations, maintenance, and construction: The FRA is committed to reducing GHG emissions from the operations, maintenance, and construction of the rail system
- Decarbonizing rail operations: Railway companies are pursuing sustainability agendas, particularly surrounding decarbonizing operations
- Increasing efficiency within the sector: The European Commission aims to increase efficiency within the sector, helping it to contribute to the target of cutting transport emissions by 90% by 2050, as set out in the European Green Deal
- Enhancing railway security: Satellite data can be used to enhance railway security, improving safety and efficiency across the infrastructure lifecycle

2.4.1.4 Other (standards, practices, etc.)

Within the European Union, the following organisations are involved in the roll-out of standards, rules and practices:

- Product related standards are developed and published by the UIC on behalf of stakeholders that are constituents of the railway operating Community (ROC) in Europe, and also represented in UIC European regional Assembly

- UNIFE has been representing the European rail manufacturing industry since 1992. UNIFE and its members work on setting standards for the rail industry, including standards for rail vehicles, rail infrastructure, and rail operations.
- Europe's rail (ERJU), the European Committee for Standardization (CEN), and the European Committee for Electrotechnical Standardization (CENELEC) are the leading organisation providing standards and practices for the EU Rail sector. In 2021, ERJU, CEN and CENELEC have signed a Memorandum of Understanding (MoU) to accelerate European rail standardization work. The aim is to accelerate European rail standardization work and formalize the existing collaboration between the three organizations. The agreement is expected to foster innovation in the railway sector and maintain the EU's position as a world leader.

It is also worth noting that the **International Organization for Standardization (ISO)** is also the leading international organization focused on worldwide standards across practically every industry. It produces standards for the rail industry, including standards for rail vehicles, rail infrastructure, and rail operations.

The following list gathers a non-exhaustive list of relevant standardization bodies working groups, and related standards and initiatives in the field of GNSS positioning that influence implementation of GNSS and required performance, in particular for safety-critical applications.

2.4.1.5 Relevant Standards for GNSS

ETSI TC SES/SCN

TS 103 246-1 to TS 103 246-5: Satellite Earth Stations and Systems, GNSS based location systems. Setting out functional requirements, reference architecture, performance requirements, requirements for location data exchange protocols, and performance test specifications.

ISO

ISO TC204: The ISO's Technical Committee 204 is developing a new project titled "TS 21176 – Intelligent Transport Systems – Cooperative ITS – Position, Velocity and Time functionality in the ITS station". This is a collaboration between ISOTC204/WG18 (cooperative systems) and CEN TC5WG1.

ISO 5725 Accuracy of Measurements: On the accuracy (trueness and precision) of measurements methods and results, to establish practical estimations of the various measurements.

ISO/TC20/SC14 – WG8: *Downstream space services and space-based applications*: a dedicated WG established to cover downstream standards.

Other relevant working groups

IAG – WG 4.1.4.: The International Association of Geodesy has a commission (4) focussing on positioning and applications. Within this commission, WG 4.1.4. (Robust Positioning for Urban Traffic) is concerned with the specification and characterization of GNSS requirements, and performance analysis for vehicles and pedestrians in urban areas.

TISA: The Traveller Information Services Association (TISA) follows the development of the TPEG protocol family, covering the broadcast of traffic and transport information to end users. Recently, TISA has developed the TPEG2 Emergency Alerts and Warnings (EAW) technology, supporting the distribution of official Emergency Alerts and Warnings as issued by public authorities and/or authorized agencies, without language barriers.

OADF: The Open Auto Drive Forum is an initiative to harmonize the activities from NDS, TISA, ADASIS and SENSORIS created in 015. The overarching objective is to generate an ecosystem of production-ready automotive standards including navigation and positioning.

Cloud LSVA (Large Scale Video Analysis) project – Open Group: This project focusses on navigation data and maps and supports the development of suitable standards for video data sets and video annotation.

It aims to develop a standard on video content annotation to be published by an existing appropriate SDO.

2.4.1.6 Selection of applicable regulations, treaties and conventions

Techniques for observing the Earth are frequently criticized due to inconsistencies in various areas such as sensor calibration, data structure and formats, precision in terms, and pricing systems. This has led to slow adoption rates and challenges in ensuring the correct interpretation of these techniques. This sluggishness may be attributed to apparent inconsistencies and bewildering jargon. The implementation of international standards can provide effective solutions to these issues, and these guidelines are intended to enhance the accessibility of Earth Observation products and technologies.

At present, there is a noticeable lack of standards or regulatory documents in Earth Observation, regarding both data quality and processing or products. The internationally accepted data format and metadata standards for digital spatial data have been set by organizations such as ISO, IEEE, OGC, GRSS, and SEOAH. Appropriate Earth Observation standards for railway infrastructure can be categorized into various classes:

EO data standards

- The International Organization for Standardization (ISO); EO collection metadata: ISO 19115 Geographic Information - Metadata.
- The Open Geospatial Consortium (OGC) provides Standards and Schemas (XSD, JSON Schema, etc) for the geospatial information interoperability and implementation used by international organizations.
- EO product metadata: OGC's GML Application Schema for EO Products
- Collection and service discovery: OGC's Cataloguing of ISO Metadata using the ebRIM profile of CS-W.
- Catalogue Service: OGC's Catalogue Services Specification 2.0 Extension Package for ebRIM Application Profile: EO Products.
- Order: OGC's Ordering Services for EO Products
- Feasibility Analysis: OGC's Sensor Planning Service Application Profile for EO Sensors
- Online Data Access: OGC's WMS EO Extension
- Identity (User) Management: OGC's User Management Interfaces for EO Services.
- Geoscience and Remote Sensing Society (GRSS) created the Standards in Earth Observations (GSEO) Technical Committee to support the development and promotion of technical standards related to the generation, distribution, and utilization of interoperable data products from remote sensing systems.
- The Standards in Earth Observations Ad Hoc Committee (SEOAH) is the managing organizational unit within GRSS to handle standards development within the IEEE.

Standards for Geotechnical investigation

The Geotechnical Monitoring by Field Instrumentation Panel (ISO TC 182/WG2) is currently working on a draft document ISO/DIS 18674-9 that includes several annexes for new technologies, one of them being satellite InSAR.

Standards for Climate Risk assessment

The two key ISO standards for climate risk assessment are ISO 14090, which provides principles and guidance for adapting to climate change, and ISO 14091, which gives practical guidance for assessing climate-related risks, impacts, vulnerabilities and opportunities.

EU Strategies, Directives and Regulations

- Technical Specifications for Interoperability (TSI): Require climate-resilient design in rail subsystems, including standards for extreme weather (e.g., flooding, heat) under EU rail interoperability rules
- EU Strategy on Adaptation to Climate Change (2021): Aims for a climate-resilient Europe by 2050, directing rail operators to incorporate unavoidable climate impacts into infrastructure resilience
- European Climate Law (2021): Legally binds the EU to climate neutrality by 2050, with provisions for resilience in transport sectors like rail
- Regulation (EU) No 1025/2012: Covers standardization notifications, including lifecycle and climate resilience assessments for rail projects.

The Geotechnical investigation and testing, Geotechnical monitoring by field instrumentation, (ISO18674), establishes a set of methodologies for measuring pore water pressures and piezometric levels in saturated ground through the use of piezometers as part of geotechnical monitoring. These general monitoring rules are applicable to different geological scenarios, including ground levels, structures interacting with the ground, geotechnical fills, and geotechnical works as specified in ISO 18674-1. The guidelines are versatile, finding relevance in various scenarios including monitoring water pressures in and around geotechnical structures like dikes, excavation walls, foundations, dams, tunnels, and slopes.

2.5 Current GNSS use and requirements per application

2.5.1 Condition-based maintenance and predictive maintenance

Condition Based Maintenance is a maintenance strategy to monitor the real-time condition of tracks and trains. These results are large data sets that give key information to support decision-making and enable efficiency gains. If GNSS is not the main information to be collected, localization of the data is of main importance. The goal is to reduce maintenance costs significantly compared to today s corrective maintenance schemes.

GNSS user requirements for Condition-based maintenance		
Accuracy	Horizontal	10-20 m-level longitudinal
	Vertical	Non-applicable
Availability	Urban canyon	Yes
	Natural canyon	Yes
	Canopy	Yes
	Indoor	Yes
	Better than 95%	High
	Better than 99%	Medium
Robustness		Low
Integrity and reliability		Low
Size, weight, autonomy (when smartphone or handheld based)	Relevance	Yes
	Time a device can run	The device needs to run for long period but does not need to run full continuous time
TTFaF	In hot start	depending on the mode used for energy saving, hot start may be needed (if periods of short power on, long power off...)
Service area	Geographical coverage	Over the whole railway network
Update Rate		–From 1-30 min
TTA	Time between the occurrence of the failure and its presentation to the user	30s

Table 6: GNSS user requirements for Condition-based maintenance

2.5.2 Trackside personnel protection systems

The maintenance and upgrade of the infrastructure is a major activity involving movements of personnel, equipment and materials. Personnel working on or close to the track must be protected from trains using the network. Speed restrictions may apply, or the train may be prevented from entering the work zone completely. Alternatively, personnel working must be warned when a train is approaching the working area. Main applications related to protection and emergency management are described in this section.

GNSS applied to trackside personnel protection will improve current manual or semiautomatic procedures. This application can monitor the location of the working team, the assets (rail construction machinery, etc.) and the trains. The system, knowing the position of the elements, could issue warnings to the trains for slowing speed or event stop, and orders to the working equipment and teams to abandon working areas when trains are approaching.

GNSS user requirements for trackside personnel protection		
Accuracy	Horizontal	1 to 10 m-level The PNT shall provide a small relative accuracy
	Vertical	Non-applicable
Availability	Urban canyon	Yes
	Natural canyon	Yes
	Canopy	Yes
	Indoor	Yes
	Better than 95%	High
	Better than 99%	High
Robustness		Low
Integrity and reliability		High
Size, weight, autonomy (when smartphone or handheld based)	Relevance	Yes
	Time a device can run	8-10h (daily service of a worker)
TTFaF	In hot start	Some minutes
Service area	Geographical coverage	available over the whole EU Rail network
Update rate		5 - 10s

GNSS user requirements for trackside personnel protection		
TTA	Time between the occurrence of the failure and its presentation to the user	Not-applicable in a context where the system is for track workers and not for the train. If the system shall become safety-critical and ensure safety of the workers in the future: 10 - 30s
SIL		Not-applicable in a context where the system is for track workers and not for the train. If the system shall become safety-critical and ensure safety of the workers in the future: SIL2 corresponding to a failure rate of 10-7/hr

Table 7: GNSS user requirements for trackside personnel protection

2.5.3 Rail fleet management

The tracking of assets (rolling stock, wagons) is crucial to achieve an optimised use of the fleet. Fleet operators develop digital freight services and make wagons smart, that offer customers a better view on their cargos such as temperature, pressure, estimate time of arrival as well as accurate information of the transport itself: location of the cars, loading status, open/close condition of doors and hatches and health condition of bogies, braking system and wheelsets.

The technology has reached maturity with an increasing number of trains and wagons equipped but innovation is up and running for even more services.

GNSS user requirements for fleet management		
Accuracy	Horizontal	10 to 20 m-level longitudinal after track identification
	Vertical	Non-applicable
Availability	Urban canyon	Yes
	Natural canyon	Yes
	Canopy	Yes
	Indoor	Yes
	Better than 95%	High
	Better than 99%	High

GNSS user requirements for fleet management		
Robustness		Low
Integrity and reliability		Low
Size, weight, autonomy (when smartphone or handheld based)	Relevance	Yes
	Time a device can run	Long term
TTFaF	In hot start	depending on the mode used for energy saving, hot start may be needed (if periods of short power on, long power off…)
Service area	Geographical coverage	Over the whole EU rail network
Update Rate		60s or more
TTA	Time between the occurrence of the failure and its presentation to the user	30s

Table 8: GNSS user requirements for fleet management

2.5.4 Passenger information systems

Different applications can be included in the application bundle Passengers information”:

- On-train ticketing, retail & authentication
- On-train reservations
- On-train catering and services
- Train Crew information services
- Customer Information Systems
- On-board Passenger Information systems
- Personal Journey Assistant
- Location Based Services & Points of Interest
- Passenger Broadband (Internet Access Caching)

GNSS user requirements for Passenger information		
Accuracy	Horizontal	100 m-level
	Vertical	Non-applicable
Availability	Urban canyon	Yes, 95%
	Natural canyon	Yes, 95%
	Canopy	Yes, 95%

GNSS user requirements for Passenger information		
	Indoor	Yes, 95%
	Better than 95%	High
	Better than 99%	Medium
Robustness		Low
Integrity and reliability		Low
Size, weight, autonomy (when smartphone or handheld based)	Relevance	Yes when relying on tablets
	Time a device can run	1 day if tablet is used to collect positions
TTFaF	In hot start	Less than 10s
Service area	Geographical coverage	Over the whole EU network
Update rate		1s

Table 9: GNSS user requirements for Passenger information

2.5.5 Enhanced Command & Control Systems (CCS)

Control, command and signalling (CCS) refers to the on-board and trackside structures and equipment designed to ensure the safe operation and movement of trains, directing rail traffic, and keeping trains clear of each other. It includes lineside signals, but also a whole range of technology designed to control and manage the way train movements are managed. Control, command and signalling are at the core of railway operations – they essentially determine safety and performance of a network.

Automatic Train Protection aims to prevent a train proceeding beyond the point of danger and to prevent the speed of the train exceeding the permissible limit in the event of a driver error. It consists of the safe determination of position, speed and direction of train movement in order to supervise the safe movement of the train up to its stopping point (End of Movement Authority).

In Europe, the ERTMS, which stands for 'European Railway Traffic Management System', is the European standard for the Automatic Train Protection (ATP) and command and control systems. It is a single European signalling and speed control system that ensures interoperability of the national railway systems, reducing the purchasing and maintenance costs of the signalling systems as well as increasing the speed of trains, the capacity of infrastructure and the level of safety in rail transport. ERTMS comprises of the European Train Control System (ETCS), i.e. a cab-signalling system that incorporates automatic train protection (ATO), the Global System for Mobile communications for Railways (GSM-R) and operating rules.

Since 2012, EUSPA provides strong support to railway industry, infrastructure managers and railway operators to adopt EGNSS and EGNOS for the complex signalling applications and integrate GNSS within the evolution of European Rail Traffic Management System (ERTMS).

This application requires the combination of several functions (or lower-level applications) which in turn are strongly dependent of the accurate and safe determination of position and speed of the trains:

- Calculation of End of Movement Authority
- Calculation the emergency braking curve to protect a danger point
- Train Location / Train Position Report

- Speed profile calculation
- Train spacing
- Supervision to buffer stops (in particular Calculation on board the release speed for the approach to buffer stop)

There are many ATP applications where GNSS could be used, among them: Enhanced Odometry, Absolute Positioning, Cold Movement Detection, Train integrity and train length monitoring, Track Identification, Odometer Calibration, and Level Crossing Protection.

The use of GNSS for the following applications are still under definition at the EU level. Thus, the requirements proposed below are excluding the following use cases: Train integrity and train length monitoring, Odometer Calibration, and Level Crossing Protection that may require more maturity. The track identification function is also not analysed here as it is considered by the community that it will be addressed by other sensors. However, track identification is a prerequisite for some other functions addressed.

Most of the EU projects currently plan the use of an absolute position to be provided by a GNSS-based onboard localisation unit called ASTP (Absolute Safe Train Position) but agree that GNSS alone is not expected to fulfill safety requirements. Thus, the GNSS receiver is considered as one of the components of the ASTP solution but not as the sole solution. Some requirements are available in [RD2] but some more and refinements are under definition in the context of the X2R4 and R2DATO projects that will be delivered in the next months.

The table below is built based on the requirements expressed in the FP2 R2DATO project funded by the Europe s Rail program. The ASTP shall be modular and scalable and serve all CCS (and non-CCS) functions such as ATP, ATO, ATS/TMS, TCMS, applications of RU in train (e.g., DAS or travel-information) or on trackside. The table thus defines the ASTP requirements that are not direct GNSS requirements.

As safety is one of the main challenge for the ASTP, the position estimate will always be part of an integrity monitoring concept, that will associate a confidence interval (CI), which is the position, speed, acceleration interval within which the ASTP assumes the true train position, speed, acceleration is, with a defined probability (Tolerable Hazard Rate - THR). This CI will be compared to a Max Accepted Position Confidence Interval (MAPCI) which is the difference between the estimated train front end position and the min safe front end. When CI exceeds the MAPCI, the system becomes unavailable. For railway stakeholders, accuracy is defined in the 2D horizontal plan and 1D accuracy corresponds to the along-track dimension”. For the following, we consider that track identification will be defined and validated independently.

GNSS user requirements for ASTP		
Accuracy	Horizontal	1D 5m, 95% of time 3D 2.5m on the x y and z axis of the carriage reference frame, 95% of time
	Vertical	1D Non-applicable 3D 2.5m on the x y and z axis of the carriage reference frame, 95% of time
Availability	Urban canyon	Yes, 99.998%
	Natural canyon	Yes, 99.998%
	Canopy	Yes, 99.998%
	Indoor	Yes, 99.998%
	Better than 95%	High

GNSS user requirements for ASTP		
	Better than 99%	High
Robustness		
~~Integrity and~~ reliability		Minor failure: λ <1.25 * 10-4/h. Reduced service failure: λ < 3.3 * 10-6/h. Immobility failure: λ < 3.7 * 10-7/h.
Size, weight, autonomy (when smartphone or handheld based)	Relevance	No
	Time a device can run	Not relevant
TTFaF	In hot start	
Service area	Geographical coverage	Over the whole EU network
Update rate		0.25s – 1s TBC
TTA	Time between the occurrence of the failure and its presentation to the user	TBD
SIL	Safety Integrity level	SIL4

Table 10: ASTP requirements

The requirements presented in the following table result from previous discussions. The cold detector is expected to initiate operations once the train has halted and been turned off. Following this, it ought to verify that the train has remained stationary upon startup. These devices are therefore expected to operate without a battery within a certain period. During the UCP 2025 dialogue, doubts concerning the application's use case and the viability of a GNSS-based solution were brought to light. And the majority of the participants considered that the existing solutions will probably be preferred to a GNSS-based solution as these are validated to work and cost-effective. The table is however still proposed for further developments that could be developed as an alternative.

GNSS user requirements for Cold Movement Detection		
Accuracy	Horizontal	Longitudinal accuracy < 1m As long as track identification is ensured The PNT shall provide a relative accuracy < 1m
	Vertical	Non-applicable
Availability	Urban canyon	Yes, 99.99%
	Natural canyon	Yes, 99.99%
	Canopy	Yes, 99.99%
	Indoor	Yes, 99.99%

GNSS user requirements for Cold Movement Detection		
	Better than 95%	High
	Better than 99%	High
Robustness		High
Integrity and reliability		Very high
Size, weight, autonomy (when smartphone or handheld based)	Relevance	No
TTFaF	In hot start	5s
Service area	Geographical coverage	Over the whole EU network
Update rate		1s
TTA	Time between the occurrence of the failure and its presentation to the user	< 10s
SIL	Safety Integrity level	SIL 4 that corresponds to a failure rate of 10^{-9}/hr

Table 11: GNSS user requirements for Cold Movement Detection

The requirements for enhanced odometry are specified by the subset 41 [RD10] and [RD9].

GNSS user requirements for Enhanced Odometry		
Accuracy	Horizontal	Travelled distance 5m + 5% of the distance since the last balise
	Vertical	Non-applicable
Availability	Urban canyon	Yes, 95%
	Natural canyon	Yes, 95%
	Canopy	Yes, 95%
	Indoor	Yes, 95%
Robustness		High
Size, weight, autonomy (when smartphone or handheld based)	Relevance	No
	Time a device can run	Not relevant

GNSS user requirements for Enhanced Odometry		
Service area	Geographical coverage	Over the whole EU network
TTA	Time between the occurrence of the failure and its presentation to the user	< 5s

Table 12: GNSS user requirements for Enhanced Odometry

2.5.6 Driver Advisory Systems (DAS)

The DAS (Driver Advisory System) allows the exchange of information between the railway system and the human operator (the driver), with the purpose of optimizing the driving of the train. The on-train system calculates an energy efficient speed profile to achieve the pre-planned or dynamically updated train timings and generates detailed driver advice to follow the profile and achieve the timings. The control centre is responsible for conflict detection and calculation of new target train timings. GNSS is used as one of the sensors in the DAS equipment. The main applications targeted by the DAS system are:

- Real time location allowing traffic management by conflict detection and providing accurate location report.
- Speed management enabling low energy driving, increasing reliability on arrivals time and allowing proper management of braking before conflict.
- The DAS systems can be classified into two main categories:
- Standalone DAS (S-DAS) has all data downloaded to train at or prior to journey start. It realises a static exchange of information.
- Connected DAS (C-DAS) realises a communications link to the Control Centre (or Traffic Management Centre) in each controlled area in which the train operates. This enables the provision of schedule, routing and speed restriction updates to trains in near real time and also receipt of information from trains to the Infrastructure Manager control centre to improve regulation decisions. It aims to optimise the traffic flow of the railways as a whole by dynamic re-planning of the timetable to avoid conflicts.

Driver Advisory Systems (DAS) are a mean of reducing energy consumption in the rail freight sector. They provide train drivers with continuous or selective feedback on the most energy-efficient speeds to adopt while driving the train. They rely on timetable information and train characteristics as well as topographic data and, where possible, dynamic (real-time) traffic information (e.g. to prevent conflicts with passenger trains sharing the same line). By modifying the train drivers behaviour, DAS technology enables a smoother and more efficient rail traffic flow, thereby reducing the overall energy consumption. Users have reported an important notice regarding integrity and availability: it is suggested that the driver and infrastructure manager be informed when the solution is unavailable or unreliable. However, while there is no integrity risk for such an application, if availability is too low, drivers will stop relying on it and the system will be ignored.

GNSS user requirements for Driver Advisory System		
Accuracy	Horizontal	0,75-1m if track distinction is needed
	Vertical	Non-applicable

Availability	Urban canyon	Yes, but not fully mandatory
	Natural canyon	Yes, but not fully mandatory
	Canopy	Yes but not fully mandatory
	Indoor	Yes but not fully mandatory
	Better than 95%	High
	Better than 99%	High
Robustness	Susceptibility to interference	Low
	Susceptibility to spoofing	Low
Integrity and reliability		Low
Size, weight, autonomy (when smartphone or handheld based)	Relevance	Yes
	Time a device can run	8-10h (daily service of a driver)
TTFaF	In hot start	1 min
Service area	Geographical coverage	Over the whole EU network
Update rate		1s
TTA	Time between the occurrence of the failure and its presentation to the user	10s

Table 13: GNSS user requirements for Driver Advisory System

2.5.7 Hazardous Cargo monitoring

Some of the goods carried by Rail freight operators can damage the environment if they are spilt in transit and/or pose a threat to society if they are stolen. These include crude petroleum and petroleum products; compressed, liquefied and refrigerated gases; flammable/corrosive/toxic chemicals and chemical/nuclear hazardous wastes. GNSS can be used to provide an alarm and alert system when used in conjunction with satellite or terrestrial communications and geofencing technologies. This solution allows managers to remotely monitor, track and communicate with their cargoes in real-time. Furthermore, this application provides updates on location, speed, mapping directions, security, etc. It also helps in archiving of vital condition data and an ability to track stolen cargoes.

GNSS user requirements for Hazardous cargo monitoring		
Accuracy	Horizontal	1-10 m-level
	Vertical	Non-applicable
Availability	Urban canyon	Yes
	Natural canyon	Yes
	Canopy	Yes

	Indoor	Yes
	Better than 95%	High
	Better than 99%	Medium
Robustness		Low
Integrity and reliability		High
Size, weight, autonomy (when smartphone or handheld based)	Relevance	Yes
	Time a device can run	Years
TTFaF	In hot start	if power on/off for energy management, 1s
Service area	Geographical coverage	Over the whole EU network
Update rate		15 min
TTA	Time between the occurrence of the failure and its presentation to the user	10 - 30s

Table 14: GNSS user requirements for Hazardous cargo monitoring

2.5.8 Door control supervision

The purpose of this application is to enable the opening of specific doors at particular stations. GNSS is used to locate the train within a station. Some stations have short platforms or platforms on both sides, it is required that only the correct doors (i.e. those with a platform next to them) are opened when a train stops at a station. This application requires knowledge of the train location within the station and identification of the train at a specific platform. Location data can also be used by passenger information systems to alert passengers for the need to move to other vehicles, e.g. long trains at short platforms.

GNSS user requirements for Door Control Supervision		
Accuracy	Horizontal	1-10 m-level When using ATO: 1m
	Vertical	Non-applicable
Availability	Urban canyon	Yes
	Natural canyon	Yes
	Canopy	Yes
	Indoor	Yes
	Better than 95%	High

Robustness		Low
Integrity and reliability		High
Size, weight, autonomy (when smartphone or handheld based)	Relevance	No
	Time a device can run	Not relevant
Service area	Geographical coverage	Over the whole EU network
TTA	Time between the occurrence of the failure and its presentation to the user	10 - 30s

Table 14: GNSS user requirements for Door Control Supervision

2.5.9 Remote Train Operations

Remote train operation, also called teleoperation, consist in controlling and operating trains from a remote location using advanced communication and control technologies. It allows operators to manage trains without being physically present in the cab.

The objectives can be: to take control of the train in the event of a problem as a fallback solution to regain manual control of an driverless train; or as a way to enhance operational efficiency and safety of depot movements, reducing the risk of accidents, driver travel time and allowing an operator to control multiple trains simultaneously.

In Remote Train Operations, the operator sees the live transmission of the camera located in front of the train, providing the remote driver with the same kind of visibility the actual driver would have. This require low latency communications and video streaming. His actions are breaking or accelerating the train. The knowledge of the train s position will support operation and mainly increase awareness of the remote driver: to localise the train on the map and to enhance distance perception that are reported by demonstrators to be distorted by camera lenses. Safety is under the responsibility of the operator.

GNSS user requirements for Remote Train Operations		
Accuracy	Horizontal	<3m
	Vertical	Non-applicable
Availability	Urban canyon	Yes
	Natural canyon	Yes
	Canopy	Yes
	Indoor	Yes
	Better than 95%	TBD
	Better than 99%	TBD
Robustness	Susceptibility to interference	No
	Susceptibility to spoofing	No

Integrity and reliability	Risk	Low
Size, weight, autonomy (when smartphone or handheld based)	Relevance	No
	Time a device can run	Not relevant
TTFaF	In hot start	TBD
Service area	Geographical coverage	Over the whole EU network

Table 15: Remote Train Operations

2.5.10 Automated Shunting

Automated shunting refers to the use of autonomous or semi-autonomous technologies to move rail vehicles within rail yards, depots, or industrial sidings. Within the marshaling yards, manual operations encompass the tasks of breaking up freight trains, sorting wagons and forming new trains. In the recent projects, two different use cases have been identified:

- Automated shunting locomotive (towards autonomous trains). Automated shunting or hump locomotives aim to take over the tasks manually performed today, to improve the efficiency, safety and precision of locomotive movements in depots and yards, combining trains more efficiently for onward transportation. They can rely on lidar and cameras for perception and geolocation on the digital map.
- Automated freight train composition. The objective here is to develop digital tools to speed up freight train deployment, by simplifying the train preparation process, and thus contribute to their future automation. This solution is based on a set of on-board sensors installed on each carriage. These sensors provide precise knowledge of each train's position, enabling effective monitoring of train composition. The relative positions of each wagon in the train are utilised for this purpose.

The two dedicated tables are proposed.

The main difference will concern the SIL level that is required for the shunting locomotive but not so high for freight train composition.

GNSS user requirements for Automated shunting locomotives		
Accuracy	Horizontal	<0.5-1m
	Vertical	Non-applicable
Availability	Urban canyon	Yes
	Natural canyon	Yes
	Canopy	Yes
	Indoor	Yes
	Better than 95%	TBD
	Better than 99%	TBD
Robustness	Susceptibility to interference	High
	Susceptibility to spoofing	High

Integrity and reliability	Risk	High
Size, weight, autonomy (when smartphone or handheld based)	Relevance	Yes, equipment on wagons
	Time a device can run	5 years for wagons
TTFaF	In hot start	TBD
Service area	Geographical coverage	Over the whole EU network
SIL	Safety Integrity Level	TBD

Table 16: Automated shunting locomotives

GNSS user requirements for Automated freight train composition		
Accuracy	Horizontal	**<0.5-1m**
	Vertical	**Non-applicable**
Availability	Urban canyon	**Yes**
	Natural canyon	**Yes**
	Canopy	**Yes**
	Indoor	**Yes**
	Better than 95%	TBD
	Better than 99%	TBD
Robustness	Susceptibility to interference	**High**
	Susceptibility to spoofing	**High**
Integrity and reliability	Risk	**High**
Size, weight, autonomy (when smartphone or handheld based)	Relevance	Yes, equipment on wagons
	Time a device can run	5 years for wagons
TTFaF	In hot start	TBD
Service area	Geographical coverage	Over the whole EU network

Table 17: Automated freight train composition

2.5.11 Synthesis of Requirements Relevant to GNSS

Condition-based maintenance and predictive maintenance (based on previous requirements defined for cargo monitoring)

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0640	The PNT solution shall provide the train position with a longitudinal accuracy of 10-20m after track identification.	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0680	The PNT solution shall provide the train position with a horizontal accuracy of 10m or even more	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0650 and 0690	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0660 and 0700	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be Low.	Performance (Integrity)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0710 and 0670	The maximum allowable time between the occurrence of the failure in the PNT solution and its presentation to the user shall be 30s or even more.	Performance (Time To Alarm)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0991	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0992	The PNT solution shall be available in urban canyon with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0993	The PNT solution shall be available under canopy with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0994	The PNT solution shall be available indoors with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0995	The PNT solution shall have a TTFF that will depend on the mode used for energy saving (alternance of short power on/long power off periods). Hot start may be needed.	Performance (TTFF)	[RD19]
EUSPA-GN-UR-RAI-0996	The PNT solution shall have an update rate of 1-30 min	Performance (update rate)	[RD7] [RD8]

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1110	Size, weight and autonomy shall be considered.	Function (size, weight, autonomy, time a device can run)	[RD19]
EUSPA-GN-UR-RAI-0997	The robustness of the PNT solution to interference shall be Low.	Performance (Robustness)	[RD23]
EUSPA-GN-UR-RAI-0998	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be Low.	Performance (Integrity)	[RD23]

Table 18: Condition-based maintenance and predictive maintenance

Trackside Personnel Protection

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0360	The PNT solution shall provide the train position with a horizontal accuracy within a range of 1-10m.	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0365	The PNT solution shall provide a small relative accuracy.	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0370	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0380	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be High.	Performance (Integrity)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0921	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0922	The PNT solution shall be available in urban canyon with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0923	The PNT solution shall be available under canopy with a high probability	Performance (Availability)	[RD7] [RD8]

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0924	The PNT solution shall be available indoors with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0925	The PNT solution shall have a TTFF of some minutes.	Performance (TTFF)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0926	The PNT solution shall have an update rate of 5-10s	Performance (Update rate)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0390	The maximum allowable time between the occurrence of the failure in the PNT solution and its presentation to the user shall be between 10s and 30s if the system shall become safety-critical and ensure safety of the workers in the future.	Performance (Time To Alarm)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0391	The PNT solution shall achieve a Safety Integrity Level 2, that corresponds to a failure rate of 10-7/hr if the system shall become safety-critical and ensure safety of the workers in the future.	Performance (Safety Integrity Level)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1120	Size, weight and autonomy shall be considered.	Function (size, weight, autonomy, Time a device can run)	[RD19]
EUSPA-GN-UR-RAI-1121	The device shall run 8-10 hours (daily service of a driver)	Performance (size, weight, autonomy, Time a device can run)	[RD19]
EUSPA-GN-UR-RAI-1122	The robustness of the PNT solution to interference shall be Low.	Performance (Robustness)	[RD23]

Table 19: Trackside Personnel Protection

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0640	The PNT solution shall provide the train position with a longitudinal accuracy of 10-20m after track identification.	Performance (Accuracy)	[RD7] [RD8]

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0650	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0660	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be Low.	Performance (Integrity)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0981	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0982	The PNT solution shall be available in urban canyon with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0983	The PNT solution shall be available under canopy with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0984	The PNT solution shall be available indoors with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0985	The PNT solution shall have a TTFF that will depend on the mode used for energy saving (alternance of short power on/long power off periods). Hot start may be needed.	Performance (TTFF)	[RD19]
EUSPA-GN-UR-RAI-0986	The PNT solution shall have an update rate of 60s or more	Performance (Update rate)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0670	The maximum allowable time between the occurrence of the failure in the PNT solution and its presentation to the user shall be 30s.	Performance (Time To Alarm)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1130	Size, weight and autonomy shall be considered.	Function (size, weight, autonomy, Time a device can run)	[RD19]
EUSPA-GN-UR-RAI-1131	The robustness of the PNT solution to interference shall be Low.	Performance (Robustness)	[RD23]

Table 20: Rail fleet management

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0840	The PNT solution shall provide the train position with a horizontal accuracy of less than 100m.	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0850	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be of 95%.	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1031	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1032	The PNT solution shall be available in urban canyon with a 95% probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1033	The PNT solution shall be available under canopy with a 95% probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1034	The PNT solution shall be available indoors with a 95% probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1035	The PNT solution shall have a TTFF of less than 10s.	Performance (TTFF)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1036	The PNT solution shall have an update rate of 1s.	Performance (Update rate)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0830	The maximum allowable time between the occurrence of the failure in the PNT solution and its presentation to the user shall be less than 10s.	Performance (Time To Alarm)	[RD19]

Table 21: Passenger Information System

Enhanced Command & Control Systems (CCS) is a group of several functions with different requirements.

- Enhanced Command & Control Systems (CCS) – Cold Movement Detection

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0070	The PNT solution shall provide the train position with a longitudinal accuracy lower than 1m (as long as track identification is ensured).	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0075	The PNT solution shall provide a relative accuracy of less than 1m.	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0080	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0090	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be Very High.	Performance (Integrity)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0100	The PNT solution shall achieve a Safety Integrity Level 4, that corresponds to a failure rate of 10-9/hr.	Performance (Safety Integrity Level)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0861	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0862	The PNT solution shall be available in urban canyon with a 99.99% probability.	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0863	The PNT solution shall be available under canopy with a 99.99% probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0110	The maximum allowable time between the occurrence of the failure in the PNT solution and its presentation to the user shall be less than 10s.	Performance (Time To Alarm)	[RD7] [RD8]

Table 22: Enhanced Command & Control Systems (CCS) – Cold Movement Detection

Enhanced Command & Control Systems (CCS) – ASTP

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1200	The PNT solution shall provide the train position with a longitudinal accuracy lower than 1m (as long as track identification is ensured)	Performance (Accuracy)	[RD21] [RD22]
EUSPA-GN-UR-RAI-1210	The PNT solution shall provide the train position with a 3D accuracy lower than 2.5m on the x y and z axis of the carriage reference frame, 95% of time.	Performance (Accuracy)	[RD21] [RD22]
EUSPA-GN-UR-RAI-1220	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High (>99.998%).	Performance (Availability)	[RD21] [RD22]
EUSPA-GN-UR-RAI-1230	The PNT solution shall achieve a Safety Integrity Level 4, that corresponds to a failure rate of 10-9/hr.	Performance (Safety Integrity Level)	[RD21] [RD22]
EUSPA-GN-UR-RAI-1240	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD21] [RD22]
EUSPA-GN-UR-RAI-1241	The PNT solution shall be available in urban canyon with a 99.998% probability.	Performance (Availability)	[RD21] [RD22]
EUSPA-GN-UR-RAI-1242	The PNT solution shall be available under canopy with a 99.998% probability	Performance (Availability)	[RD21] [RD22]
EUSPA-GN-UR-RAI-1243	The PNT solution shall be available indoor with a 99.998% probability	Performance (Availability)	[RD21] [RD22]
EUSPA-GN-UR-RAI-1250	The PNT solution shall comply with the overall CCS on-board reliability as defined in [RD25 Chap 2]: Minor failure: λ <1.25 * 10-4/h. Reduced service failure: λ < 3.3 * 10-6/h. Immobility failure: λ < 3.7 * 10-7/h.	Performance (Reliability)	[RD21] [RD22] [RD25]

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1260	The PNT solution shall have an update rate of 0.25-1s	Performance (update rate)	[RD21] [RD22]

Table 23: Enhanced Command & Control Systems (CCS) – ASTP

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1140	The PNT solution shall provide an accuracy of 1m maximum if track identification is needed.	Performance (Accuracy)	[RD19]
EUSPA-GN-UR-RAI-1141	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD19]
EUSPA-GN-UR-RAI-1142	The PNT solution shall be available in urban canyon with a 95% probability	Performance (Availability)	[RD19]
EUSPA-GN-UR-RAI-1143	The PNT solution shall be available under canopy with a 95% probability	Performance (Availability)	[RD19]
EUSPA-GN-UR-RAI-1144	The PNT solution shall be available indoors with a 95% probability	Performance (Availability)	[RD19]
EUSPA-GN-UR-RAI-1145	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be Low.	Performance (Integrity)	[RD19]
EUSPA-GN-UR-RAI-1146	Size, weight and autonomy shall be considered if a handheld device is used to collect positions.	Function (Size, weight, autonomy, Time a device can run)	[RD19]
EUSPA-GN-UR-RAI-1152	The device shall run 8-10 hours (daily service of a driver)	Performance (Size, weight, autonomy, Time a device can run)	[RD19]
EUSPA-GN-UR-RAI-1147	The PNT solution shall have a TTFF of 1min	Performance (TTFF)	[RD19]

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1148	The PNT solution shall have an update rate of 1s	Performance (Update rate)	[RD19]
EUSPA-GN-UR-RAI-1149	The maximum allowable time between the occurrence of the failure in the PNT solution and its presentation to the user shall be 10s.	Performance (Time To Alarm)	[RD19]
EUSPA-GN-UR-RAI-1150	The susceptibility to interference of the PNT solution shall be Low	Robustness	[RD23]
EUSPA-GN-UR-RAI-1151	The susceptibility to spoofing of the PNT solution shall be Low	Robustness	[RD23]

Table 24: Driver Advisory System

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0800	The PNT solution shall provide an accuracy of 1-10m.	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0810	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0820	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be High.	Performance (Integrity)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1021	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1022	The PNT solution shall be available in urban canyon with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1023	The PNT solution shall be available under canopy with a high probability	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1024	The PNT solution shall be available indoors with a high probability	Performance (Availability)	[RD7] [RD8]

EUSPA-GN-UR-RAI-1025	The PNT solution shall have a TTFF 1s if If power is switched on/off for energy management	Performance (TTFF)	[RD19]
EUSPA-GN-UR-RAI-1026	The PNT solution shall have an update rate of 15min	Performance (Update rate)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0830	The maximum allowable time between the occurrence of the failure in the PNT solution and its presentation to the user shall be between 10s and 30s.	Performance (Time To Alarm)	[RD7] [RD8]
EUSPA-GN-UR-RAI-1150	Size, weight and autonomy shall be considered.	Function (Size, weight, autonomy, Time a device can run)	[RD19]
EUSPA-GN-UR-RAI-1151	The device shall run on long periods (years).	Performance (Size, weight, autonomy, Time a device can run)	[RD19]

Table 25: Hazardous Cargo Monitoring

Id	Description	Type	Source
EUSPA-GN-UR-RAI-0320	The PNT solution shall provide an accuracy of 1-10m.	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0321	When using ATO, The PNT solution shall provide the train position with a horizontal accuracy within a range of 1m.	Performance (Accuracy)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0330	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD7] [RD8]
EUSPA-GN-UR-RAI-0340	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be High.	Performance (Integrity)	[RD7] [RD8]

EUSPA-GN-UR-RAI-0350	The maximum allowable time between the occurrence of the failure in the PNT solution and its presentation to the user shall be between 10s and 30s.	Performance (Time To Alarm)	[RD7] [RD8]

Table 26: Door Control Supervision

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1300	The PNT solution shall provide an accuracy of 3m.	Performance (Accuracy)	[RD23]
EUSPA-GN-UR-RAI-1310	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1320	The PNT solution shall be available in urban canyon with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1330	The PNT solution shall be available under canopy with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1340	The PNT solution shall be available indoors with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1350	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1360	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be Low.	Performance (Integrity)	[RD23]

Table 27: Remote Train Operations

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1400	The PNT solution shall provide an accuracy of 0.5-1m.	Performance (Accuracy)	[RD23]

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1410	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1420	The PNT solution shall be available in urban canyon with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1421	The PNT solution shall be available under canopy with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1422	The PNT solution shall be available indoors with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1423	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1430	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be High.	Performance (Integrity)	[RD23]
EUSPA-GN-UR-RAI-1440	The susceptibility to interference of the PNT solution shall be High	Robustness	[RD23]
EUSPA-GN-UR-RAI-1450	The susceptibility to spoofing of the PNT solution shall be High	Robustness	[RD23]
EUSPA-GN-UR-RAI-1460	Size, weight and autonomy shall be considered as equipment is on the wagon.	Function (Size, weight, autonomy, Time a device can run)	[RD23]
EUSPA-GN-UR-RAI-1470	The device shall run on long periods (5 years for wagons).	Performance (Size, weight, autonomy, Time a device can run)	[RD23]

Table 28: Automated shunting

Id	Description	Type	Source
EUSPA-GN-UR-RAI-1500	The PNT solution shall provide an accuracy of 0.5-1m.	Performance (Accuracy)	[RD23]
EUSPA-GN-UR-RAI-1510	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be High.	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1520	The PNT solution shall be available in urban canyon with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1521	The PNT solution shall be available under canopy with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1522	The PNT solution shall be available indoors with a high probability	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1523	The PNT solution shall be available over the whole EU Rail network	Performance (Availability)	[RD23]
EUSPA-GN-UR-RAI-1530	The ability of the PNT solution to provide timely warnings to the user when data provided by the solution should not be used shall be High.	Performance (Integrity)	[RD23]
EUSPA-GN-UR-RAI-1540	The susceptibility to interference of the PNT solution shall be High	Robustness	[RD23]
EUSPA-GN-UR-RAI-1550	The susceptibility to spoofing of the PNT solution shall be High	Robustness	[RD23]
EUSPA-GN-UR-RAI-1560	Size, weight and autonomy shall be considered as equipment is on the wagon.	Function (Size, weight, autonomy, Time a device can run)	[RD23]
EUSPA-GN-UR-RAI-1570	The device shall run on long periods (5 years for wagons).	Performance (Size, weight, autonomy, Time a device can run)	[RD23]

Table 29: Automated freight train composition

2.6 EO user needs and requirements, 2023

EO applications for rail focus on three primary pillars:

- **Structural Health & Safety:** Continuous monitoring of ground movement, asset degradation, and structural integrity to transition from reactive to **predictive maintenance.**
- **Environmental Stewardship:** Identifying ecological risks, optimizing sustainable site selection, and mitigating damage to biodiversity during construction.
- **Climate Resilience:** Using data to safeguard tracks against extreme weather events like floods, landslides, and avalanches.

EO-based applications can be categorized into five distinct stages:

- **Planning & Finance:** Focuses on site selection, environmental impact assessments, and economic trade-off analysis.
- **Construction:** Focuses on monitoring ground shifts and tracking real-time building progress.
- **Asset Monitoring:** Focuses on managing track conditions, vegetation growth (identifying diseased trees), and encroachment of nearby buildings.
- **Disaster Response:** Focuses on tracking flood evolution to manage safe railway closures and reopenings.
- **Risk Assessment:** Focuses on evaluating the long-term vulnerability of assets to climate change and geohazards.

Beyond technical monitoring, EO facilitates **stakeholder engagement** by providing transparent data to local communities and government agencies. This ensures that sustainability principles—such as energy efficiency and green infrastructure—are embedded into the project from the design phase through to long-term operation. The following applications have been considered in the 2023 report:

User needs	EO Applications
Infrastructures Planning and Designing, Finance Planning	• Determination of surface ground movements • Weather Impact Assessments and Adaptation to Climate Change • Determination of soil moisture
Infrastructure construction	• Geotechnical and structural monitoring during the construction
Infrastructure monitoring	• Determination of surface ground movements • Vegetation monitoring • Monitoring for the construction of new buildings • Control of railway tracks located in places hard to reach
Flood monitoring	• Flood monitoring for disaster response

User needs	EO Applications
Risk and vulnerability assessments	• Weather Impact Assessments and Adaptation to Climate Change

Table 31: User needs and EO Applications

To effectively monitor railway infrastructure via EO, several user requirements and technical challenges must be addressed:

- **Spatial and Temporal Resolution:** Monitoring narrow, linear assets like tracks requires high-resolution imagery to capture fine details. While traditional satellites often lack this precision, acquiring higher-quality data frequently remains a significant expense.
- **Long-Term Continuity:** Railway projects operate over decades, making long-term monitoring difficult. Challenges include the need to maintain data consistency across evolving sensor technologies.
- **Cost Management:** The cost of high-resolution, commercial satellite imagery can restrict the accessibility for many rail operators.
- **Accuracy and Calibration:** Reliable monitoring depends on perfectly calibrated instruments. However, maintaining and verifying these sensors is complex, especially when the infrastructure spans remote or inaccessible geographic regions.
- **Multi-Sensor Integration:** Utilizing various Synthetic Aperture Radar (SAR) bands (C, X, and L) is needed for comprehensive coverage. For example, while C-band is standard, the L-band is superior for penetrating vegetated areas, and X-band is needed for resolving finer details.
- **Data Latency:** For near-real-time safety monitoring, the time gap between image acquisition and data availability must be minimized.

2.6.1 Infrastructure planning and design, finance planning

The planning phase is focused on the surveying of the areas to understand the site characteristics, which include site topography, geology, land cover/land use on the site and its vicinity, terrain stability, exposure to risks and exposure to climate change impacts.

The phase includes the evaluation of environmental and economic trade-off and provides all the information for the identification of the route and infrastructures elements to be build.

After the planning phase of an infrastructure, the design phase is performed with the scope to establish to identify construction techniques and provide the determination of the costs useful for the financial planning of the railway infrastructures.

The main site characteristics requested by the users are the following ones:

- **Topography**: determine the elevation and slope of the site to assess if it is well-adapted to the type of infrastructure to be built;
- **Geology**: analyse soil characteristics (e.g. density, depth of bedrock) to identify possible complications and design plans to remediate these complications ([RD19]);
- **Land cover/land use**: be informed about the natural and manmade characteristics of the site land cover and land use characteristics of the potential site and of its surroundings (e.g., presence of built areas, agricultural lands, natural areas, rivers, railways, railways, etc.);
- **Terrain stability**: be informed about the extent to which the potential site is subject to ground deformation and if so, be informed about the associated subsidence risk;

- **Exposure to risks**: be informed about the natural risks the potential site is exposed to , such as floods, landslides, subsidence, wildfires, avalanches, earthquakes, tsunami;
- **Exposure to climate change impacts**: be informed about the long-term impacts of climate change the potential site will be exposed to (e.g., higher risk of exposure to droughts).
- **Environmental impact assessment:** be informed about the potential environmental effects of a proposed project, development, or policy before it is implemented.

The planning phase mainly consists in surveying activities, which as mentioned in the previous Reports on User Needs and Requirements on surveying ([RD2]) involve the staking out of reference points and markers that will guide the execution of the construction project. These activities include establishing basic lines, grade control and principal points, positioning for corners, delineating the working areas, determining ground profiles and the placement of utilities, and preparing large-scale topographic maps for drainage and site design. The establishment of the coordinate framework for a construction site involves both high-order control surveys and low-order control surveys. During this phase, users (inc. engineering and construction companies, public land authorities, etc.) need to perform the construction surveying activities with a sufficient level of accuracy to guarantee that construction operations benefit from a high-quality reference framework.

The infrastructure designing phase is a critical stage in the development of any infrastructure project and it is essential for ensuring financial viability and securing funding for the project. Typically, the design phase involves several key steps and considerations:

Project Definition**:** Clearly defining the objectives, scope, and requirements of the infrastructure project. This includes identifying the purpose of the infrastructure, target users, expected capacity, and performance criteria.

Site Selection and Analysis: Assessing potential sites for the infrastructure project, considering factors such as geographical features, land use, environmental sensitivity, accessibility, and existing infrastructure networks.

Feasibility Studies: Conducting feasibility studies to evaluate the technical, economic, environmental, and social viability of the proposed infrastructure project. This involves analysing costs, benefits, risks, and potential impacts to determine whether the project is feasible and worth pursuing.

Design Concept Development: Developing conceptual designs and layouts for the infrastructure project, considering factors such as functionality, safety, efficiency, aesthetics, and sustainability. This may involve brainstorming sessions, workshops, and consultations with stakeholders to explore different design options.

Engineering Design: Detailed engineering design of the infrastructure project, including structural design, civil engineering, electrical systems, mechanical systems, and other technical aspects. This phase involves creating detailed drawings, specifications, and plans that will guide the construction and implementation of the project.

Environmental Assessment: Conducting environmental assessments to identify and mitigate potential environmental impacts of the infrastructure project. This may involve Environmental Impact Assessments (EIAs), as discussed earlier, as well as other studies and analyses to ensure compliance with environmental regulations and standards.

Stakeholder Engagement: Engaging with stakeholders, including government agencies, local communities, businesses, and other relevant parties, to gather input, address concerns, and build support for the infrastructure project. Effective stakeholder engagement is essential for ensuring the project's success and minimizing conflicts.

Regulatory Approvals: Obtaining necessary permits, licenses, and approvals from regulatory authorities for the infrastructure project. This may include obtaining planning permissions, environmental permits, zoning approvals, and other regulatory clearances required for construction and operation.

Risk Management: Identifying and managing risks associated with the infrastructure project, including technical, financial, environmental, and social risks. This involves developing risk management plans and strategies to mitigate or address potential threats to project success.

Cost Estimation and Budgeting: Estimating the total cost of the infrastructure project, including design, construction, land acquisition, permits, contingencies, and other expenses. Establishing a realistic budget is essential for ensuring financial viability and securing funding for the project.

Value Engineering: Evaluating design options and construction methods to optimize project performance, quality, and cost-effectiveness. Value engineering involves finding ways to maximize value and minimize waste while meeting project objectives.

User needs	Description
Determination of surface ground movements	Determination of surface ground movements derived by geological processes such as landslides, subsidence, ground failures, sinkholes, uplifts, faults and seismic displacements poses significant challenges for the planning and projecting of new infrastructures.
Determination of soil moisture	Determination of soil moisture, the total amount of water, including the water vapor in a land surface provides a basic information for the geotechnical engineering
Weather Impact Assessments and Adaptation to Climate Change	Climate change and extreme weather events such as flooding, severe storms, landslides, rock fall, avalanches can have a devastating impact on the safety and the expected lifetime of infrastructures which may become unreliable, unpredictable, inadequate, and unsafe.

Table 30: User needs for Railway Infrastructures Planning and Designing, Finance Planning

ID	EUSPA-EO-UR-RAI-0001
Application	Determination of surface ground movements
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Railways tracks can be affected by any movement taking place on the ground such as landslides, subsidence, uplifts, sinkholes, faults and seismic displacements. Avoiding or mitigating the consequences of such events poses significant challenges for planning, building and maintenance of railways infrastructures.
Size of area of interest	In general, a buffer of 500 m around the rail infrastructure is sufficient but it can be incremented depending on the geomorphology of the area to monitor and by the origin of ground movements.
Scale	From local to national
Frequency of information	From weekly to monthly
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	Provide information on ground displacements in the surroundings of the infrastructure. The risk assessment can take different forms depending on what users need (e.g. map, reports)
How does the service work	The service uses the MT-InSAR technique to determine time series of the surface ground displacements, velocities, accelerations and strains.

	The variation of the velocity (acceleration) and the strain rate identify areas affected by active surface ground movements.
Service Provider Satellite EO Requirements	
Spatial resolution	From 1 m up to 100 m
Temporal resolution	Weekly
Data type / Spectral range	SAR (C, X, L bands)
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1, TerraSAR X, ALOS, Cosmo SkyMed
Other data sources	GNSS and precise levelling measurements for the determination of the movements of ground reference points. Piezometers for the determination of the level of ground water and pluviometers. Historical archives.

Table 31: EO requirements for "Determination of surface ground movements"

ID	EUSPA-EO-UR-RAI-0002
Application	Determination of soil moisture
Users	Infrastructure owners and/or operators.
User Needs	
Operational scenario	Determination of soil moisture, the total amount of water, including the water vapor in a land surface provides a basic information for the geotechnical engineering.
Size of area of interest	A buffer until 2000m around the railway infrastructure
Scale	From local to regional scale
Frequency of information	Ad-hoc
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	Information provision
How does the service work	The service analyses InSAR and optical images to determine the soil moisture.
Service Provider Satellite EO Requirements	
Spatial resolution	From 10 m up to 100 m
Temporal resolution	From daily to weekly
Data type / Spectral range	SAR (C, X, L bands), multi and hyper spectral images
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1 and 2, TerraSAR-X, ALOS, Cosmo SkyMed
Other data sources	In-situ inspection and sensors such as piezometers.

Table 32: EO requirements for "Determination of soil moisture"

ID	EUSPA-EO-UR-RAI-0003
Application	Weather Impact Assessments and Adaptation to Climate Change
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Determination of the risk and of the vulnerability for the planning of safety, durable and resilient infrastructures and to minimizes damage to

	railway infrastructure assets. Climate change and extreme weather events such as flooding, severe storms, landslides, rock fall, avalanches can have a devastating impact on the safety and the expected lifetime of infrastructures. The assessment is based with natural hazard management under today's weather conditions and develop solutions and strategies to prepare for the changed weather and climate conditions of the future.
Size of area of interest	The whole railway network
Scale	From regional to national
Frequency of information	Ad-hoc
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	The service develops predictive models and maps of risks, to support the identification of solutions and strategies to prepare for the changed weather and climate conditions of the future and prioritize key actions to reduce asset exposure to damage and disruption.
How does the service work	The service combines EO observations, atmospheric, geomorphological and geographical data and models to develop predictive models and maps of risks.
Service Provider Satellite EO Requirements	
Spatial resolution	From 10 m up to 100 m
Temporal resolution	From weekly to monthly
Data type / Spectral range	SAR (C, X, L) Multi and hyper spectral, Meteosat
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1 and 2, TerraSAR-X, ALOS, Cosmo SkyMed
Other data sources	Atmospheric, geomorphological and geographical data and models. Historical archives.

Table 33: EO requirements for "Weather Impact Assessments and Adaptation to Climate Change"

2.6.2 Infrastructure construction

Construction operations cover the activities carried out between the end of the "site selection and planning" phase and the time at which the infrastructure enters its operational phase. They include activities such as earth-moving, excavation, concrete work, installation work, etc. Depending on the type of infrastructure, they may also include activities such as tunnelling and boring.

The monitoring of construction progress aims at verifying that construction operations are progressing in line with the foreseen schedule and with design plans. Users need to identify delays and deviations as soon as possible in the process while minimising inspection costs.

User needs	Description
Geotechnical and structural monitoring during the construction	Continuous geotechnical and structural monitoring to control slopes and works to be built during the construction of a railway infrastructure such as the excavation of tunnels, the construction of viaducts, bridges, and railway sections.

Table 34: User needs for “Railway Infrastructures Construction”

ID	EUSPA-EO-UR-RAI-0004
Application	Geotechnical and structural monitoring during the construction
Users	Railway infrastructure owners and/or operators, construction and public works companies, financial institutions financing the construction that can include international organisations.
User Needs	
Operational scenario	Geotechnical and structural monitoring as part of the completion of a rail section. Continuous geotechnical and structural monitoring to control slopes and works to be built during the excavation of tunnels and the construction of railways.
Size of area of interest	The entire area susceptible to ground shifts caused by the construction or excavation of an infrastructure project.
Scale	Local
Frequency of information	From daily to weekly
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	Provide information on ground displacements in the surroundings of the infrastructure. The risk assessment can take different forms depending on what users need (e.g. map, reports)
How does the service work	The service uses the MT-InSAR technique to determine time series of the surface ground displacements, velocities, accelerations, and strains. The variation of the velocity (acceleration) and the strain rate identify areas affected by active surface ground movements
Service Provider Satellite EO Requirements	
Spatial resolution	From 1 m up to 100 m
Temporal resolution	From daily to weekly
Data type / Spectral range	SAR (C, X, L bands), Multi and hyper spectral
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1 and 2, ALOS, TerraSAR-X, Cosmo SkyMed
Other data sources	GNSS and precise levelling measurements for the determination of the movements of ground reference points. Piezometers for the determination of the level of ground water and pluviometers.

Table 35: EO requirements for “Geotechnical and structural monitoring during the construction”

2.6.3 Infrastructure monitoring

Built infrastructures can suffer from natural phenomena (e.g. ground deformation, vegetation encroachment, extreme weather events, natural hazard) or anthropogenic activities (e.g. construction works in the vicinity of existing infrastructures). In this document, post-construction operations refer to the monitoring of the state (mainly the structural health) of existing infrastructures once their construction is completed.

Users need to ensure the protection of their infrastructures, to optimise maintenance operations and possibly to extend the infrastructure lifecycle within safety margin. To achieve this, they need to monitor aging damages, to improve maintenance effectiveness in terms of planning and cost reduction, reduce risks notably from more frequent extreme weather events and predict possible failures ([RD8], [RD13][RD14]).

GNSS contribution and related requirements

Concerning GNSS, the stability of built infrastructure can be monitored via high-precision GNSS methods, e.g. by post-processing of static relative GNSS observations at field control points (established directly into or in the vicinity of the object) with station data from local or global CORS networks. In addition, GNSS data may be utilised to feed various smart sensors, mounted into the infrastructure body for real-time stability monitoring (see [RD1]).

EO contribution and related requirements

As far as EO is concerned, it is considered very cost-effective for monitoring infrastructure on a large scale and with high frequency ([RD9]). For the infrastructure monitoring, several user needs have been considered and are described in the table below.

User needs	Description
Determination of surface ground movements	Determination of surface ground movements derived by geological processes such as landslides, subsidence, ground failures, sinkholes, uplifts, faults, and seismic displacements poses significant challenges for the for the maintenance and mitigation of existing ones. A continuous monitoring is almost requests for the identification of new geological processes and for controlling their evolution.
Vegetation monitoring	The monitoring of vegetation growth and the identification of diseased trees surrounding the railways can be useful to the maintenance of railway infrastructures and avoid incidents.
Monitoring for the construction of new buildings, quaries and the broader environment of the railway tracks	Monitoring the construction of new buildings within a certain distance from a railway track is crucial for safety and regulatory compliance. Satellite imagery can contribute to the identification of new buildings close the railways can create problems with the trains. In addition, users have reported the use of EO data to monitor quaries and other elements surrounding the railway tracks to better assess the impact of human surrounding activities on railway tracks. Automated alerts and notifications to inform relevant stakeholders, including railway operators, local authorities, and regulatory agencies, when new construction is detected within the restricted area. Regulatory guidelines and safety standards regarding the distance between railways and buildings may vary from one jurisdiction to another.
Control of railway tracks located in places hard to reach	Controlling railway tracks located in hard-to-reach places presents unique challenges due to the remote and sometimes harsh environments in which they are situated. Effective control of deformation of tracks and maintenance are essential to ensure the safety, efficiency of rail transportation and avoid incidents to the trains in these areas.
Condition and Predictive-based Maintenance	Condition and predictive-based maintenance are a strategy that implies a proactive approach to maintenance, achievable through continuous monitoring of an asset's conditions of tracks and trains, which allows triggering maintenance activities only when potential asset degradation is detected in the case of condition-based maintenance. On the other hand, Predictive Maintenance uses condition-based monitoring to optimize equipment performance and lifespan by continually assessing its health in real time.

Table 36: User needs for "Railway Infrastructures Monitoring"

ID	EUSPA-EO-UR-RAI-0005
Application	Vegetation monitoring
Users	Railway infrastructure owners and/or operators
User Needs	
Operational scenario	The presence of vegetation along and close to the railway tracks can create obstacles and impact the trains. The monitoring of the status and growth of vegetation along the railway corridor can prevent hazards such as fallen trees or overgrown branches that can disrupt rail operations. The goal is the determination of the distance between vegetations and tracks. Identification of the types of vegetation, and determination of height and volume of trees.
Size of area of interest	In general, a buffer of 100 m around the railway infrastructure is sufficient but it can be incremented depending on the geomorphology of the area to monitor. In the case of slope stability monitoring a wider buffer could be needed (>100m) to effectively monitor the surroundings.
Scale	From local to national
Frequency of information	Monthly
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	Information provision and alert in case of presence of diseased and dead trees that can fall on the railway tracks.
How does the service work	The service analyses InSAR and optical images to determine the presence of vegetation and identify diseased and dead trees.
Service Provider Satellite EO Requirements	
Spatial resolution	From 1 m up to 100 m
Temporal resolution	Weekly
Data type / Spectral range	SAR (C, X, L bands), Multi and hyper spectral
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1 and 2, ALOS, TerraSAR-X, Cosmo SkyMed
Other data sources	Aerial and drone imagery

Table 37: EO requirements for “Vegetation monitoring”

ID	EUSPA-EO-UR-RAI-0006
Application	Monitoring for the construction of new buildings
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Monitoring construction activities, especially related to earthworks activities, of new and existing buildings within a certain distance from a railway track is crucial for safety and regulatory compliance. Satellite imagery can contribute to the identification of new buildings close the railways can create problems with the trains. Automated alerts and notifications to inform relevant stakeholders, including railway operators, local authorities, and regulatory agencies, when new construction is detected within the restricted area. Regulatory guidelines and safety standards regarding the distance between railways and buildings may vary from one jurisdiction to another.

Size of area of interest	In general, a buffer of 100 m around the railway infrastructure is sufficient but it can be incremented depending on the geomorphology of the area to monitor.
Scale	From local to national
Frequency of information	Monthly
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	Information provision and alert in case of the identification of new buildings
How does the service work	The service analyses InSAR and optical images to determine the presence of new buildings.
Service Provider Satellite EO Requirements	
Spatial resolution	From 1 m up to 100 m
Temporal resolution	Weekly
Data type / Spectral range	SAR (C, X, L bands), Multi and hyper spectral
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1 and 2, ALOS, TerraSAR X, Cosmo SkyMed, Planet
Other data sources	Aerial and drone imagery.

Table 38: EO requirements for "Monitoring for the construction of new buildings"

ID	EUSPA-EO-UR-RAI-0007
Application	Control of railway tracks located in places hard to reach"
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Controlling railway tracks located in hard-to-reach places presents unique challenges due to the remote and sometimes harsh environments in which they are situated. Managing the deformation of rail tracks and regular maintenance are crucial to maintain the safety and efficiency of rail transportation, and to prevent train incidents. These practices are key to keeping rail infrastructure functioning at its highest level.
Size of area of interest	The entire area susceptible to geohazards.
Scale	From local to national
Frequency of information	From weekly to monthly
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	Provide information on ground displacements in the surroundings of the infrastructure, focusing on places difficult to reach (e.g. mountain environment, sea-side, etc.). The risk assessment can take different forms depending on what users need (e.g. map, reports).
How does the service work	The service uses the MT-InSAR technique to determine time series of the surface ground displacements, velocities, accelerations and strains. The variation of the velocity (acceleration) and the strain rate identify areas affected by active surface ground movements. The service is integrated with the optical and SAR images for change detection.
Service Provider Satellite EO Requirements	
Spatial resolution	From 1 m up to 100 m

Temporal resolution	Weekly
Data type / Spectral range	SAR (C, X, L bands)
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1, TerraSAR-X, ALOS, Cosmo SkyMed
Other data sources	Aerial and drone surveys.

Table 39: EO requirements for "Control of railway tracks located in places hard to reach"

ID	EUSPA-EO-UR-RAI-0008
Application	Condition and Predictive-based Maintenance
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Controlling the real-time condition of railway tracks and trains for detecting potential asset degradation and provide a pointed maintenance. CBM is a proactive approach to maintenance that uses condition-based monitoring to optimize equipment performance and lifespan by continually assessing its health in real time.
Size of area of interest	The entire railway networks
Scale	From local to national
Frequency of information	From weekly to monthly
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	Provide information on asset degradation of railway tracks and trains.
How does the service work	The service is an integrated system that analyses optical, SAR images both from satellites, drones and on-board train cameras, and sensors.
Service Provider Satellite EO Requirements	
Spatial resolution	From 1 m up to 100 m
Temporal resolution	Weekly
Data type / Spectral range	SAR (C, X, L bands), Multi and hyper spectral
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1, TerraSAR-X, ALOS, Cosmo SkyMed
Other data sources	Aerial, drone surveys and on-board train cameras and sensors.

Table 40: EO requirements for "Condition and Predictive-based Maintenance"

2.6.4 Flood monitoring

Flood monitoring is typically performed using a combination of technologies, data sources, and processes to detect, track, and respond to potential or ongoing flooding events. This specific application is covered under the Report on User Requirement related to Emergency Management, however it was deemed relevant to include a snapshot of this application under the Rail Report on User Requirement considering the interest of end-users for this application.

The key components of flood monitoring are:

- **Remote Sensing**: Remote sensing technologies, including satellites, are used to monitor weather patterns, precipitation levels, and changes in water bodies such as rivers and lakes. This data can help predict and monitor potential flood events.
- **Radar Systems:** Weather radars are used to detect heavy rainfall and storm systems. Doppler radar, for instance, can measure the speed and direction of precipitation, helping forecasters determine if a weather event may lead to flooding.
- **Aerial and Drone Surveillance:** Drones and aerial surveys can be used to assess the extent of flooding and damage in real-time. They are particularly valuable for accessing areas that are difficult to reach.
- **Weather Forecasting:** Meteorological data and computer models are used to predict weather conditions and potential rainfall amounts. These forecasts can help authorities anticipate flood events and take preventative measures.
- **Flood Modelling**: Computer models are used to simulate potential flooding scenarios based on various factors, such as rainfall, snowmelt, topography, and land use. These models can help predict the extent and impact of floods.
- **GIS** (Geographic Information Systems): GIS technology is used to create floodplain maps, which show areas prone to flooding. These maps help in planning and response efforts.
- **River Gauges:** River gauges are instruments placed in rivers and streams to monitor water levels. They provide real-time data on water height and can trigger flood warnings if levels rise significantly.
- **Ground Sensors:** Ground-based sensors can monitor various environmental parameters, such as soil moisture and water quality, which can provide early warning signs of potential flooding.

Several user needs have been considered and are described in the table below.

User needs	Description
Flood monitoring	During floods it is necessary to identify the area and the railways that are involved in the flood, helping the authorities to monitor the evolution of the situation, and in the management of the closing or reopening of the railways.

Table 41: User needs for Disaster Respond to Floods

ID	EUSPA-EO-UR-RAI-0009
Application	Flood monitoring
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	During floods can be useful to identify railways that are involved in flood, helping the authorities to monitor the evolution of the situation, and in the management of the closing or reopening of the railways. Creation of flood maps to identify the areas to be checked before the re-activation of the railways.
Size of area of interest	Section of the railway infrastructure network involved in the flood
Scale	From local to regional
Frequency of information	Ad-hoc, continuous monitoring
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	Map of flooded areas and alert provision

How does the service work	The service analyses InSAR and optical images to determine the areas affected by flood or disaster.
Service Provider Satellite EO Requirements	
Spatial resolution	100 m
Temporal resolution	From daily to weekly
Data type / Spectral range	SAR (C, X, L bands) Multi and hyper spectral
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel-1 and 2, ALOS, TerraSAR-X, Cosmo SkyMed
Other data sources	Aerial and drone imagery.

Table 42: EO requirements for "Flood monitoring"

2.6.5 Risk and vulnerability assessments

Risk and vulnerability assessments related to climate change are essential tools for understanding the potential impacts of climate change on infrastructures and help to develop strategies for adaptation and mitigation and reduce the economic impact. Continuous monitoring and review of climate risks and vulnerabilities are critical to assess the effectiveness of adaptation and mitigation strategies and adjust as needed.

The main types of risks to be considered include:

- Flooding
- Extreme temperatures and theirs impact on tracks and railway infrastructures. In high temperature conditions, railway tracks can experience "sun kinks" or buckling because heat causes the steel to expand.
- Extreme forest fires: particularly relevant for energy grids in countries such as Chile. This has a direct impact on infrastructures.
- Sea level rising and quality of water (most important for the desalinization plants).
- Sea level and the temperature of water (relevant for desalinization plants and the physical resilience of the infrastructure itself). Also, water temperature, has an impact on the chemical process of the desalinization. The higher the temperature the more expensive the process.

Key components of risk and vulnerability assessments monitoring are climate data collection and analysis: Assessors gather historical climate data and future climate projections to understand temperature changes, precipitation patterns, sea-level rise, and extreme weather events in the region.

User needs	Description
Weather Impact Assessments and Adaptation to Climate Change	Natural hazard management related weather and climate such as flooding, severe storms, landslides, rock fall, avalanches etc in a way that keeps and improves railway infrastructure performance and avoids or minimizes damage to railway infrastructure assets. It starts with natural hazard management under today's weather conditions and develops solutions and strategies to prepare for the changed weather and climate conditions of the future.

Table 43: User needs for "Weather Impact Assessments and Adaptation to Climate Change"

ID	EUSPA-EO-UR-RAI-0010
Application	Weather Impact Assessments and Adaptation to Climate Change
Users	Railway infrastructure owners and/or operators.

User Needs	
Operational scenario	Natural hazard management related weather and climate such as flooding, severe storms, landslides, rock fall, avalanches etc in a way that keeps and improves railway infrastructure performance and avoids or minimizes damage to railway infrastructure assets. It starts with natural hazard management under today's weather conditions and develops solutions and strategies to prepare for the changed weather and climate conditions of the future.
Size of area of interest	Mainly the whole railway network
Scale	From regional to national
Frequency of information	Ad-hoc
Other (if applicable)	Not applicable
Service Provider Offer	
What the service does	The service develops predictive models and maps of risks, to support the identification of solutions and strategies to prepare for the changed weather and climate conditions of the future and prioritize key actions to reduce asset exposure to damage and disruption.
How does the service work	The service combines EO observations, atmospheric, geomorphological and geographical data and models to develop predictive models and maps of risks.
Service Provider Satellite EO Requirements	
Spatial resolution	From 10 m up to 100 m
Temporal resolution	From weekly to monthly
Data type / Spectral range	SAR (C, X, L), multi and hyper spectral, Meteosat
Other (if applicable)	Not applicable
Service Inputs	
Satellite data sources	Sentinel 1 and 2, TerraSAR-X, ALOS, Cosmo SkyMed
Other data sources	Atmospheric, geomorphological and geographical data and models. Historical archives.

Table 44: EO requirements for "Weather Impact Assessments and Adaptation to Climate Change"

2.6.6 EO limitations

2.6.6.1 Technology limitations

The limitations of using EO for the rail industry stem from a combination of atmospheric, geometric, and technical constraints. While optical imagery is highly intuitive, its primary weakness is its inability to penetrate cloud cover. In regions like Europe, where average cloud coverage reaches 70%, obtaining a clear view of infrastructure requires satellites with high revisit frequencies to capitalize on brief windows of clear weather. Furthermore, optical sensors are obstructed by physical barriers such as dense tree canopies, which render tracks "invisible" in heavily forested areas. While SAR provides a solution by penetrating clouds and operating at night, it introduces its own set of complexities related to how radar waves interact with the earth's surface.

Topography presents a significant challenge for radar-based monitoring, particularly in mountainous or hilly terrain. Because SAR is a side-looking technology, it is prone to geometric distortions known as shadowing and layover. Shadowing occurs when steep slopes block the radar signal, leaving the infrastructure behind them in a data "blind spot." Conversely, layover occurs when the top of a feature, such as a mountain peak, is closer to the satellite than its base, causing the signals to overlap and distort the spatial accuracy of the rail tracks below. These issues are further compounded in "urban canyons," where tall buildings reflect signals and create multipath interference, making it difficult to achieve a clean line-of-sight to urban rail networks.

Environmental factors like snow, ice, and rapid vegetation growth also interfere with data reliability. While SAR can detect snow, heavy accumulation can change the "backscatter" signal, making it difficult for automated systems to distinguish between the rail bed and the surrounding frozen ground. Additionally, a technical phenomenon called signal decorrelation occurs when the ground surface changes too rapidly between satellite passes—often due to heavy rain or aggressive vegetation—which breaks the phase consistency needed for Interferometric SAR. When this happens, it becomes impossible to measure the millimetric ground displacements for predicting landslides or track subsidence.

Finally, the rail industry faces economic and operational hurdles regarding the resolution and latency of satellite data. Most rail components, such as fasteners or small cracks, are far smaller than the resolution provided by standard satellites. While sub-meter high-resolution data exists, it is often prohibitively expensive to apply across an entire national rail network. Furthermore, the latency—or the delay between image acquisition and data processing—can be a major bottleneck. For emergency disaster response, the hours or days required to download and analyse satellite imagery may be too slow to prevent an accident, necessitating a more seamless integration between space-based data and real-time ground sensors.

Contrary to optical imagery, SAR imagery can be obtained night and day and is not affected by the cloud coverage. Nevertheless, it also suffers limitations [RD11] among which a few are mentioned:

Depending on the frequency used, vegetation can limit data acquisition. For instance, the C-band SAR used in Sentinel-1 cannot capture image of the ground in vegetated areas while L-band SAR (e.g. the ALOS mission) can penetrate vegetation. SAR interferometry is based on measurements of the phase difference between the signal emitted by the sensor and the signal backscattered by “objects” on the surface. The distribution of measurement points is therefore depending on land cover and on the presence of natural or man-made “objects”, generally referred to as “reflectors”, able to reflect the radar signal (such as rocks, buildings, rail, etc.). In case of unsuitable land cover (e.g. dense vegetation, insufficient number of natural or man-made reflectors) the use of SAR interferometry requires that dedicated artificial reflectors are installed on site to enable measurements;

SAR interferometry measures movements in the line-of-sight of the satellite and cannot measure displacement parallel to the orbit of the satellite (i.e. in the North-South direction in the case of near-polar, sun-synchronous orbits like for Sentinel-1)). The discrimination between vertical and horizontal (West-East) movements is only possible if several geometries (ascending and descending orbits) are used (see [RD12]). The actual technical features of SAR sensors and constellations permit the detection only of slow ground movements that do not exceed few cm/year.

2.6.6.2 Performance/Cost balance of EO data

The performance of satellite missions varies significantly across different constellations, creating a distinct divide between public and commercial data. Public missions generally provide data relevant to infrastructure monitoring at no cost, but they often lag behind commercial missions in terms of spatial resolution and revisit frequency. Currently, the highest-tier commercial imagery offers a spatial resolution of approximately 30cm with updates every 12 to 24 hours. However, the industry is shifting toward high-revisit architectures. New constellations, such as Planet’s Pelican and Capella Space’s Whitney, are designed to maintain high resolutions—ranging from 30cm to 50cm—while drastically increasing the frequency of data collection to every 1 to 4 hours.

The primary challenge for rail operators lies in balancing cost with performance. While high-frequency, high-resolution data is technically superior, the price of imagery becomes a significant financial burden for linear infrastructure that spans hundreds of kilometers or requires constant updates. Beyond the raw data cost, the value of an EO service is heavily dictated by accessibility and "timeliness." This includes the reduction of cut-off times and the rapid delivery of both the images themselves, and the precise orbital data required for advanced analytics, such as InSAR. These premium service features are essential for moving EO from a research tool into a functional, near-real-time monitoring asset.

Finally, a notable non-technical barrier is the specialized language and scientific complexity inherent in EO. The terminology required to describe data processing, sensor physics, and underlying scientific principles can be daunting for those outside the field. This is particularly true for SAR, where concepts like phase coherence and backscatter are far less intuitive than traditional optical photography. This "language gap" often makes it difficult for infrastructure managers to fully grasp the nuances of the data, highlighting a need for better translation between EO experts and end-users in the rail sector.

2.6.6.3 EO key challenges

The effective monitoring of railway infrastructure through EO demands a highly multidisciplinary framework, bridging the gap between remote sensing experts, data scientists, civil engineers, and policymakers. A primary technical hurdle lies in the sheer volume and complexity of data processing, particularly regarding SAR imagery. Because the parameters used in SAR time-series analysis—such as the selection of stable "persistent scatterers"—can significantly alter the resulting displacement measurements, the analysis cannot rely on automation alone. It requires expert supervision to interpret results within the specific geotechnical and geomorphological context of the monitored rail corridor.

Beyond the processing algorithms, environmental and integration challenges play a major role. While optical sensors are frequently hampered by cloud cover—necessitating a shift toward radar—the real value of EO is only realized when it is fused with other data sources. Integrating satellite imagery with aerial photography and ground-based IoT sensors is essential for accuracy, yet maintaining system compatibility and data synchronization across these different platforms remains a significant engineering challenge. Furthermore, although EO data is increasingly abundant, it often requires specialized software and high-level technical expertise that may not be readily available within traditional rail maintenance teams.

Finally, the transition to EO-based monitoring is governed by complex human and legal factors. The sensitivity of railway network data introduces security concerns regarding data ownership and the potential for misuse of high-resolution infrastructure maps. These issues are compounded by a lack of standardized international regulations for satellite data use. Moreover, because manual interpretation is still prone to human error, there is an urgent industry push toward machine learning and automation. These technologies are intended not to replace experts, but to provide a consistent, objective baseline for identifying infrastructure anomalies before they escalate into safety risks.

2.6.7 Drivers for EO-related user requirements

The primary technical requirements for EO in the rail sector are driven by the need for high-resolution optical, multispectral, and SAR imagery. Most applications demand meter-level or sub-meter precision to monitor narrow tracks, alongside extensive historical archives that allow for long-term change detection and trend analysis. Because rail networks are linear and span vast distances, the ability to capture hundreds of square kilometers in a single pass is essential. While the frequency of data updates is often less critical for structural monitoring—with monthly intervals being sufficient—higher frequencies remain needed for tracking construction progress and managing environmental hazards.

Beyond technical performance, the adoption of EO is heavily influenced by the regulatory landscape and the drive for operational efficiency. Infrastructure managers typically integrate satellite monitoring when it aligns with legal obligations to verify the structural integrity of bridges, tunnels, and embankments. Furthermore, there is a strong economic incentive to optimize maintenance budgets by reducing the frequency of hazardous on-site inspections, thereby enhancing worker safety. This transition would be further accelerated by robust cost-benefit analyses and the establishment of industry-wide best practices. As networks age and ESG (Environmental, Social, and Governance) requirements become more stringent, the market pressure to replace traditional in-situ measurements with scalable EO data will continue to grow.

2.7 EO for Climate Resilience and Adaptation, 2025

Context

Extreme weather events present an escalating challenge to European railway systems. Floods, landslides, strong winds, and heatwaves, are intensifying in both frequency and severity leading to profound disruptions, significant physical damage to critical infrastructure, and substantial economic losses across the continent's rail networks [RD25]. The European Union Agency for Railways (ERA) highlights that extreme weather events are becoming more frequent, exerting significant impacts on both rail infrastructure and daily operations. Under a medium-high emissions scenario (RCP6.0), the exposure of critical European transport infrastructure to heatwaves is projected to increase up to 70 times by mid-century (2024–2075) compared to historical conditions (1954–2005). Similarly, railways and roads are projected to face up to 42 times as many wildfires by the end of the century (2049–2100) [RD26]. All European regions are expected to experience increasing climatic risk drivers, including heatwaves, heavy precipitation, and drought. Train delays directly attributable to extreme weather events are estimated to result in an annual loss of 3 to 7 years across the European rail network [RD37]. Beyond delays, economic ramifications are substantial. Single extreme weather events have already caused billions of euros in damages [RD27].

Heavy rainfall is a primary driver of climate-related risk for railway networks in Europe. These events can lead to severe consequences, including track washouts, landslides, and even bridge collapses. The resulting operational disruptions and increased maintenance demands can be significant. Heavy rainfall-related incidents account for a large portion of disruptions, with impacts such as [RD25]:

- Landslides: 47% of heavy rainfall impacts
- Water on tracks: 40% of cases
- Settlement on platforms: 13% of cases
- Bridge collapses: 7% of cases

In the UK, there have been widespread rail disruptions [RD28], while countries like Italy, Slovenia, Czechia, Poland, Austria, and Spain have also faced major challenges [RD29]. The impact of heavy rain is evident:

- **Italy:** Over 480,000 landslides have been recorded since 1999, frequently impacting railway lines [RD30].
- **Germany:** A train derailment in 2025 was caused by a landslide following heavy rain [RD36]. The 2021 floods destroyed 15 railway bridges, leading to new, more resilient designs without central pillars [RD31].
- **Austria:** Significant infrastructure damage is attributed to floods and rain [RD32].
- **Belgium:** During severe floods, significant erosion of railway embankments and damage to older bridges, which were not designed for current extreme precipitation levels, was reported.

High temperatures and heatwaves pose a major threat to railway networks, causing a range of infrastructure failures and operational problems. High temperatures can lead to rail buckling, sagging overhead power lines, and malfunctions in electrical and signalling systems. As an example, a heatwave in the UK in 2022 caused a 40-50% drop in train performance and a £30 million loss in one week [RD33].

Strong winds and storms pose a significant risk to railways, causing objects like trees and roofs to be blown on the tracks. This can lead to severe track blockages and damage to trains and overhead line equipment (OLE). These destructive events are also becoming more frequent [RD34]. Wind is the costliest weather risk for the UK rail network, with costs of £382.8m.

Ground instability, which includes landslides, rock falls, and avalanches, can be a major hazard for railways. These events, often triggered by heavy rainfall, can cause earth to spill onto tracks or the ground to crumble beneath them. This leads to railway closures and the risk of derailments. In the UK, landslips and similar subsidence events have cost an estimated £144 million. Landslides alone account for 47% of all damage caused by heavy rainfall.

Coastal erosion and sea level rise are long-term hazards that threaten railway infrastructure by causing flooding and loss of land. These issues can render coastal tracks inoperable and lead to debris and water overtopping the railway line. In the UK, Network Rail has made a significant investment in the Dawlish sea wall to protect its coastal lines from these threats.

The Directorate-General for Mobility and Transport (DG-MOVE) published a study in 2024 [RD52] that addresses the climate-related concerns in the context of the Trans-European Transport (TEN-T) network, with the objectives to identify past climate impacts and their costs, as well as future climate risks on the TEN-T network, adaptation measures needed, and corresponding investment needs, and to identify cross-border investment gaps on the network [RD51]. The study examined the necessity of completing the Trans-European Transport Network (TEN-T) and making it resilient to the increasing threat of climate extremes. The climate risk analysis, focusing on hazards like heatwaves, river floods, droughts, and wildfires, projects a dramatic increase in exposure for all TEN-T transport modes relative to the present day. The study shows the following predictions for the Rail network.

Heatwaves are the hazard predicted to have the highest increase in occurrence by a factor of 18.1, with around 16% of the network exposed for the first time. Heatwaves escalate to affect most of the TEN-T network, with some parts of the network to experience up to 50-60 times as may heatwaves by mid-century, with the Mediterranean region being the most affected. **River floods** will increase by around 20% to affect the rail network, including newly exposed areas. Railways will face increases in **drought exposure** by a factor of 14.3, with 47.3% of the infrastructure becoming newly exposed. Railways will experience 80% more **wildfires** by the end of the century. Many European coastlines are experiencing heightened **extreme sea levels**, primarily driven by rising local sea levels. This trend is expected to escalate the occurrence of historically extreme sea levels, such as those with a one-in-100-year frequency. Without improved coastal protection, projections indicate an increase in frequency of extreme **high coastal water levels** across most European coastlines by 2050.

There is an **increased probability for the European transport network to experience multiple climate extremes simultaneously**, the same extreme covering a larger area, and different extremes affecting different parts of the network at the same time. This suggests that these climate extremes may cause impacts that practitioners are currently not prepared for since in the present situation their transport infrastructure is not experiencing them. Additionally, climate-related events are site-specific, and detailed localized analyses are necessary to provide advice for specific locations.

Copernicus can provide essential support for climate risk assessment and adaptation planning across the rail sector. Through its Climate Change Service (C3S) and Emergency Management Service (CEMS), Copernicus delivers multiple datasets derived from satellite observations and reanalysis products. These datasets can enable the observation of long-term climate trends, the quantification of exposure and vulnerability to compound hazards, and the development of spatially explicit impact models. By integrating Copernicus data into infrastructure planning and risk analysis workflows, users can enhance predictive modelling, improve the accuracy of localized hazard assessments, and design targeted adaptation measures to increase the resilience of the TEN-T network under future climate scenarios.

National Initiatives for Climate Adaptation by Rail Infrastructure managers in Europe (excerpt)

Deutsche Bahn (DB) in Germany is intensifying its efforts to prepare rail technology for increasing weather extremes. DB acknowledges its significant exposure to climate-related risks and operates a specialized "natural dangers management" unit and has implemented a monitoring system for tree health along its extensive railway network. Their climate-resilient rail technology program utilizes expanded climate indicators—comprising over 80 parameters with a high geographical resolution of 5x5 km for various future periods—to conduct comprehensive climate risk analyses [RD39]. DB's approach is informed by scientific studies from the Potsdam Institute for Climate Impact Research (PIK). These studies analyse climatic changes in Germany up to 2060, predicting a significant increase in heat days, fewer harsh winters, and more frequent heavy rains and intense storms. To gain detailed regional insights, DB expanded its climate indicator dataset in 2024 to over 80 parameters, providing high geographical resolution (5x5 km) for past, near-future, and distant-future periods.

SNCF, France's railway company, is proactively adapting its network and infrastructure, responding to a projected temperature rise of +4°C by 2100. The company acknowledges that climate change is an immediate challenge, evidenced by a 20% increase in torrential rainfall over the past two decades. SNCF Réseau, responsible for 28,000 km of track, is focused on building a more robust and climate-resilient network. SNCF Réseau utilizes satellite imagery combined with machine learning algorithms for pixel-based classification of vegetation, assessing tree health, and developing a "Vegetation Threat Index for Railways" (VTIR) [RD38] [RD39]. SNCF Gares & Connexions has identified eight major climate hazards for its 3,000 stations—including flooding, soil instability (shrinking/swelling of clayey soils), extreme heat, vegetation fires, and landslides—projected for 2030, 2050, and 2100. A comprehensive roadmap has been developed to adapt these stations, aligning with SNCF Réseau's broader strategy to build climate resilience across the entire rail infrastructure [RD35] [RD36] [RD37] [RD38] [RD39]. Keolis, SNCF subsidiary, has conducted climate and risk audits at over 1,000 sites, including those in high-risk areas [RD40]. SNCF Voyageurs conducts vulnerability studies to assess how climate change impacts its operations, addressing issues such as heat-induced rail warping, system malfunctions, fallen trees, and floods. The company collaborates globally to develop innovative and effective solutions for climate resilience [RD35].

Network Rail, the UK's rail infrastructure owner, acknowledges climate hazards are the "biggest challenge" facing British railways and is undertaking significant investments to enhance resilience. Network Rail has developed specific Weather Resilience and Climate Change Adaptation Plans for each of its regions for the 2024-2029 period. These plans identify asset risks and outline targeted interventions, encompassing both "pure weather resilience activity" and "business as usual activities with weather resilience benefits" [RD41]. The UK's Department for Environment, Food and Rural Affairs publishes adaptation reports to summarize its progress on climate change impacts and adaptation measures. Their 4th Adaptation Report, released in December 2024, highlights the development of "bespoke climate change hazard and vulnerability geospatial mapping tools." This initiative covering the 2024-2029 period implicitly uses EO data to enhance risk assessment and planning.

Climate resilience across European rail networks is far from uniform, creating a patchwork of preparedness that often reflects regional geography and economic history. Southern European nations, such as Spain and Italy, have long-standing experience with high temperatures but are now hitting the "hard limits" of their infrastructure as heatwaves exceed the thermal thresholds for which their tracks were originally stressed. In contrast, Northern and Nordic countries, historically the masters of snow and ice management, find themselves increasingly vulnerable to "new" hazards like summer track buckling and the destabilization of embankments due to thawing permafrost. Meanwhile, Central and Western Europe—home to some of the world's densest networks—face a high-stakes battle against fluvial flooding and intense storms that threaten aging assets. The most significant "resilience gap," however, appears in Eastern Europe and the Balkans, where a combination of fragmented governance and limited funding for modernization can leave critical corridors exposed to multiple climate extremes without the localized risk assessments common in the West.

2.8 EO user needs and requirements, 2025

This section outlines extends the needs and requirements elicited in 2023 issue of this report by expanding on data and information needs to assess and adapt to risks of changing climate to rail. As a reference and guidance for challenges and tasks that Infrastructure managers face within climate risk assessment and adaptation planning, we use UIC's RERA-Rain [RD38] and RERA-Temp frameworks published in 2025. Major European Infrastructure managers contributed to it: CEMOSA (partner to ADIF), National French Railways (SNCF), Italian Railway Network (RFI), Finnish Transport Infrastructure Agency (FTIA), Swiss National Railways (SBB) Network Rail UK, Deutsche Bahn (DB), Polskie Koleje Panstwone (PKP).Hence it provides broad representation across European climatic zones, infrastructure design and management practices.

Climate risk assessments and adaptations touch many aspects of 'regular' rail infrastructure and rolling stock operations. Hence for some of the elicited information needs, we may see a partial overlap with those elicited in previous user consultation.

Resilient Railways (RERA) program is practical guidance for railway infrastructure managers while ISO 14090 and ISO 14091 provide a generally agreed foundational framework. RERA studies cover two primary climate threats: extreme precipitation and flooding (covered by RERA-Rain) and intense heat events (covered by RERA-Temp). The Annex also presents ways how the Copernicus program can contribute to the frameworks.

2.8.1 Rail facing extreme rain

The **Resilient Railways facing Heavy Rains (RERA-Rain)** project is a global initiative dedicated to boosting the resilience of railway systems against heavy rainfall and climate change-driven precipitation. Collaborating with railway infrastructure managers worldwide, the project focused on developing adaptive strategies to maintain the safety and functionality of railways despite shifting rain patterns. It highlights that relying solely on historic climate patterns is inadequate for addressing the structural damage, operational delays, and safety hazards caused by increasingly severe heavy rain events. To address this challenge, the project delivered the RERA-Rain Framework, a structured methodology designed to help infrastructure managers enhance resilience. This framework is organized into **three interconnected phases**, and we will investigate the possibilities of EO contributing to each:

- **Climate Impact Analysis:** Gathering and analysing future precipitation data under various climate scenarios to understand changing rainfall trends.
- **Vulnerability, Risk and Criticality Assessment:** Systematically evaluating the vulnerabilities of railway assets to heavy rains, assessing associated risks, and identifying critical sections.
- **Adaptation Planning:** Selecting and implementing targeted adaptation measures to ensure the railway network remains functional, safe, and reliable long-term.

Principal **external cause** for weather-related incidents is identified as:

Weather exceeding expectations (EUSPA-EO-UR-RAI-0011): This occurs when precipitation exceeds forecasts or when no weather forecast tool is in place, meaning no alerts are triggered. This highlights the need to integrate the latest forecasting capabilities into railway management.

User Need: *The Operations Manager needs the ability to proactively adjust rail services and infrastructure readiness because unexpectedly high precipitation can cause derailments and flooding when alerts aren't triggered, in the context of rapidly changing regional weather patterns.*

User Requirement: *The system needs to enable users to receive and visualize real-time high-intensity precipitation alerts under all weather conditions (including those exceeding historical norms), such that mitigation protocols are initiated prior to the weather event impacting the tracks.*

ID	EUSPA-EO-UR-RAI-0011
Application	Weather exceeding expectations
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Management of rail infrastructure during extreme precipitation events. Focuses on integrating real-time data (nowcasting) and probabilistic forecasting to trigger mitigation protocols (speed restrictions, crew pre-positioning) before flooding or soil instability impacts the tracks.
Size of area of interest	**Regional to Continental.** Specific monitoring of small basins and rail corridors across the European transport network.
Scale	**Local/Catchment Scale.** Data must be granular enough to resolve individual rail segments and small hydrological catchments (flash flood risk zones).
Frequency of information	**Variable/Trigger-based.** 6-hourly for standard monitoring; **< 5 minutes** "nowcasting" when precipitation exceeds 20mm/hour or deviates >15% from forecasts.
Other	Integration of SAR for flood extent, multispectral imagery for land cover/soil moisture, and water vapor atmospheric profiles. Radar backscatter (SAR), Gridded Meteorological Maps (EMO-5), Probabilistic Ensemble Forecasts, and Water Vapor profiles (CAMS).
Service Provider Satellite EO Requirements	
Spatial resolution	**1 km² (Atmospheric/Hydrological)** for regional alerts; **10m - 30m (Surface)** for impact mapping (via Sentinel-1/2), and DEMs.
Temporal resolution	**Real-time (Nowcasting):** < 5–30 min. **Short-range:** 6-hourly updates. **Medium-range:** 5–10 day probabilistic forecasts (EFAS).
Data type / Spectral range	**C-band SAR** (for all-weather/night imaging) and **VNIR/SWIR** (Visible to Short-Wave Infrared) for soil moisture and vegetation monitoring.
Service Inputs	
Satellite data sources	**Sentinel-1** (GFM/Flood monitoring), **Sentinel-2** (Land/Infrastructure), **Sentinel-3** (Atmospheric/Water Vapor), and **Meteosat (MTG)** for rapid scan high-intensity rain.
Other sources	**In-situ:** Local weather radar, ground-based river discharge gauges, and SYNOP meteorological stations. **Models:** AIFS (AI-integrated forecasting) and ERIC (European Runoff Index).

Table 45: EO requirements for "Weather exceeding expectations"

2.8.1.1 Infrastructure Integrity against geohazards, Land Service (EUSPA-EO-UR-RAI-0012)

To address the integrity of rail infrastructure against geohazards like landslides and subsidence, the data and system must bridge the gap between geological monitoring and operational safety.

Pre-Event Predictive Monitoring: Identifying creeping slopes and embankment vulnerabilities.

User Need: *Geotechnical engineers need the ability to identify accelerating slope displacement because undetected soil creep often precedes catastrophic failure during heavy rain, in the context of routine maintenance and seasonal storm preparation.*

***User Requirement**: The data and the system used shall enable maintenance teams to visualize high-precision (i.e. mm-level) ground deformation maps under dry-weather baseline conditions, such that high-risk "hotspots" are prioritized for stabilization.*

***System Requirement:** The system shall deliver ground deformation maps.*

The system requires a multi-layered data approach:

- **Primary Displacement Data (InSAR):** Historical and current satellite-based SAR data to calculate "Line of Sight" displacement.
- **Topographic Baseline:** DEM to understand the slope's geometry and catchment areas.
- **Geotechnical:** Soil composition, moisture content history, and historical failure records.
- **Asset Geometry:** Precise mapping of the railway centerline and embankment boundaries.
- **Ground Truth:** Data from physical sensors at known unstable sites to calibrate the EO data.

Post-event stability verification: evaluating the conditions of the soil after a flooding event.

***User Need**: Rail operators need the ability to verify embankment structural integrity post-saturation because receding floodwaters can leave behind hidden voids or weakened soil foundations, in the context of re-opening tracks after a major weather event.*

***User Requirement**: The system shall enable safety inspectors to detect subsurface moisture pockets and vertical subsidence under post-flood recovery conditions, such that trains can resume full-speed operations without risk of track geometry failure.*

***System Requirement:** The system shall trigger automated alerts for any vertical displacement exceeding user-defined values when on-track sensors detect a deviation from the baseline.*

Additional information can be found in section 2.6.3, “Infrastructure monitoring.”

ID	EUSPA-EO-UR-RAI-0012
Application	Infrastructure integrity against geohazards
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Monitor rail infrastructure for geohazards (landslides, subsidence, and soil creep). The scenario covers **Pre-Event Predictive Monitoring** to identify slope instabilities and **Post-Event Stability Verification** to detect subsurface voids or "soft spots" following extreme weather events.
Size of area of interest	**Regional to Continental scale.** Specifically targeting the European rail network (~200,000 km) with a buffer zone (typically 50m–100m) around track centerlines.
Scale	**Local to Asset-level.** While the coverage is broad, the data must focus on specific embankments and individual track segments to distinguish asset movement from natural terrain.
Frequency of information	**Routine Monitoring:** Weekly to bi-weekly (6–12 days). **Post-Event/Emergency:** Hourly (in-situ) to immediate post-cloud-clearance (satellite).

Other (if applicable)	**InSAR displacement:** Millimeter-scale ground motion (Line-of-Sight). **Multispectral:** High-resolution optical imagery for erosion and scour detection. **Topographic:** Digital Elevation Models for slope geometry.
Service Provider Satellite EO Requirements	
Spatial resolution	**Sentinel-1/EGMS:** 20m x 5m (Basic) or 100m (Ortho). **High-Res (Commercial):** 1m to 3m per pixel for specific embankment analysis. **Post-event Optical:** 0.3m to 0.5m for structural visual inspection.
Temporal resolution	**Baseline/Pre-event:** 6 to 12 days (Sentinel-1 revisit). **Post-event:** Rapid response (within 24-48 hours post-event). **Historical:** 3 to 5 years of archive data for baseline behaviour.
Data type / Spectral range	**Radar:** C-band (Sentinel-1) or X-band for finer precision. **Optical:** Visible (RGB) and Near-Infrared (NIR) for Soil Moisture Indices and vegetation health. **Multispectral/Optical:** 400nm to 2500nm (Erosion, moisture, and vegetation).
Service Inputs	
Satellite data sources	**Copernicus Sentinel-1:** Primary source for EGMS (InSAR). **Copernicus Sentinel-2:** Soil moisture and erosion monitoring. **VHR SAR missions:** (e.g., COSMO-SkyMed, TerraSAR-X, Iceye) for sub-meter resolution.
Other sources	**In-situ sensors:** Piezometers (pore water pressure), GNSS stations (calibration), and moisture probes. **Asset Data:** GIS layers of rail centerlines and geometry. **Climate Data:** Copernicus C3S historical rainfall and ERA5-Land reanalysis.

Table 46: EO requirements for “Infrastructure integrity against geohazards”

2.8.1.2 River Flooding (EUSPA-EO-UR-RAI-0013)

User Need: *The Rail Network Operator needs the ability to receive timely hydrological alerts and flood depth projections because rising river levels can lead to track washouts or bridge instability, in the context of extreme weather events and seasonal runoff.*

User Requirement: *The system shall enable maintenance teams to assess the structural integrity of river-adjacent assets under active flooding conditions, such that no train enters a section of track where water levels exceed the safe operating threshold of 50mm above the rail head.*

System Requirement: *The system shall integrate external river gauge data and topography data with a refresh rate that meets user acceptable requirements (e.g. no less than once every 15 minutes when local precipitation exceeds 20mm/hour or upstream gauges hit "Action Stage" levels).*

Additional information can also be found in section 2.6.4 “Flood Monitoring.”

ID	EUSPA-EO-UR-RAI-0013

Application	River flooding
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Monitoring and forecasting river flood levels and flood extents to prevent track washouts and bridge instability. Integrating real-time hydrological gauges with EO-derived flood mapping and InSAR displacement monitoring to ensure water levels remain below the **50mm above rail head** safety threshold.
Size of area of interest	Localized corridors (100m–500m width) for specific assets/bridges, extending to regional catchment basins (1,000–50,000 sqkm) for discharge forecasting.
Scale	High-precision local scale for asset integrity (1:1,000) and regional/basin scale for hydrological modelling (1:25,000).
Frequency of information	**Emergency:** 5–15 minutes (Gauges/Radar); **Situational:** 1–3 days (Flood mapping); **Strategic:** 6–12 days (Bridge displacement).
Other (if applicable)	High-revisit SAR for flood extent, InSAR for structural deformation, and high-resolution DEMs for depth modelling.
Service Provider Satellite EO Requirements	
Spatial resolution	**VHR SAR:** 3m–10m (Flood extent); **InSAR:** mm-scale displacement; **Topography:** <1m grid (LiDAR-derived).
Temporal resolution	**Dynamic:** 1–3 days (via SAR constellations like Sentinel-1 or commercial VHR); **Long-term:** 6–12 days (Sentinel-1 orbit cycle).
Data type / Spectral range	C-band/X-band microwave frequencies for all-weather penetration and phase stability. C-band (Sentinel) or X-band (TerraSAR-X/COSMO-SkyMed, Iceye) for water detection through clouds and night.
Service Inputs	
Satellite data sources	**Copernicus Sentinel-1:** Primary source for EGMS (InSAR). **Copernicus Sentinel-2:** Soil moisture and erosion monitoring. **VHR Missions:** (e.g., COSMO-SkyMed, TerraSAR-X) for sub-meter resolution.
Other sources	**In-situ:** Ultrasonic/Radar river gauges; **Meteorological:** Ground-based Radar rainfall (nowcasting); **Asset:** BIM models and rail-head elevation surveys; **Topographic:** LiDAR and Bathymetry.

Table 47: EO requirements for "River flooding"

2.8.1.3 Increased Runoff (EUSPA-EO-UR-RAI-0014)

Extreme precipitation leads to higher-than-expected water flows, causing instability in railway surroundings (e.g., drainage systems overtopping, landslides) when the ground cannot absorb water quickly enough. This is also considered "external" as it occurs in the surroundings rather than directly on the rail infrastructure.

User need: *Maintenance Engineers need to anticipate and mitigate soil and drainage saturation levels because extreme runoff can cause embankment instability and culvert failure, in the context of rapid-onset extreme precipitation events.*

User requirement: *The system shall enable users to receive alerts regarding localized runoff risks under all weather conditions, such that preventative speed restrictions or site inspections can be initiated in due time (e.g. at least 60 minutes prior to predicted infrastructure overtopping).*

System requirement: *The system shall calculate hydraulic load and soil saturation indices with predictive accuracy (e.g. of +/-10%) when integrated sensor data exceeds the agreed baseline (e.g. 50-year flood threshold).*

ID	EUSPA-EO-UR-RAI-0014
Application	Increased runoff
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Monitoring of rapid-onset extreme precipitation and resulting soil/drainage saturation in railway surroundings. The goal is to provide maintenance engineers with a **60-minute lead time** to issue speed restrictions or initiate inspections before infrastructure overtopping or embankment failure occurs.
Size of area of interest	**Regional to Local:** Typically, 5–10 km buffer zones around critical rail corridors, covering specific catchments that drain toward rail assets (e.g., culverts, bridges).
Scale	**Multi-scale:** Catchment-level hydrology (1:50,000) for routing, paired with hyper-local asset resolution (1:500 or better) for drainage geometry and embankment stability.
Frequency of information	Near-Real-Time (NRT) every **5–15 minutes** during active precipitation events; daily to weekly for baseline soil moisture and land-use trends.
Other (if applicable)	High-cadence meteorological forcing, surface soil moisture indices, snow water equivalent (SWE), and multispectral water quality indicators (turbidity).
Service Provider Satellite EO Requirements	
Spatial resolution	**500m** for meteorological radar; **10m–20m** for soil moisture (Sentinel-1) and runoff coefficients (Sentinel-2); **0.5m** for topographic LiDAR.
Temporal resolution	**5 minutes** (Nowcasting/Radar); **1–3 days** (satellite data).
Data type / Spectral range	**Microwave (C-band/L-band)** for moisture; **Visible/NIR/SWIR** (Bands 2, 3, 4, 8, 11) for Land Use/Runoff coefficients and NDTI (Turbidity); **Thermal** for snowmelt proxies.
Service Inputs	

Satellite data sources	**Copernicus Sentinel-1** (Soil Moisture/Flood Extent), **Sentinel-2** (Land Use/Turbidity), **Sentinel-3** (Altimetry/Water Level), and **CLMS/CEMS** (Lisflood/Soil Water Index).
Other sources	Airborne LiDAR (DTM), In-situ Piezometers (Pore Water Pressure), Ground Weather Stations, X-band Weather Radar, and Asset Management Databases (Culvert as-builts).

Table 48: EO requirements for "Increased runoff"

The analysis of incidents in the RERA-Rain report identified an **internal cause** that can benefit from EO:

2.8.1.4 Lack of Awareness of a Site Being at Risk (EUSPA-EO-UR-RAI-0015)

User need: *The Rail Operator needs the ability to identify high-risk sites (flood zones, landslide susceptibility areas) that have not been previously identified and mapped because relying solely on historical event data could fails to account for changing environmental patterns and "hidden" vulnerabilities, in the context of network-wide risk assessment and climate adaptation planning.*

User requirement: *The system shall enable geotechnical engineers and operators to discover and visualize sites potentially at risk.*

System requirement: *The system will overlay topographic, hydrological, and geological datasets under normal operational and planning conditions, such that the rail corridor is mapped against a standardized risk-rating scale.*

Additional information can be found in sections 2.6.3 and 2.6.5.

ID	EUSPA-EO-UR-RAI-0015
Application	Lack of awareness of a site being at risk
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Identification of railway vulnerabilities (flood zones and landslide susceptibility) by integrating topographic, geological, and climate data. This scenario moves beyond historical incident records to a proactive, network-wide risk assessment that accounts for changing environmental patterns, urbanization, and micro-topographic traps.
Size of area of interest	Regional to Continental; typically covering the entire national or cross-border rail network corridor (buffer zones of 500m to 5km surrounding the tracks).
Scale	Local/Site-specific for engineering interventions (1:2,000 to 1:10,000) and Regional for catchment and runoff modeling (1:25,000 to 1:50,000).
Frequency of information	**Strategic:** Every 3–5 years for DTM/Land Cover updates. **Monitoring:** Seasonal/Monthly for soil saturation. **Retrospective:** Once (archival analysis) for historical flood mapping.

Other (if applicable)	High-resolution Digital Elevation Models, Surface Soil Moisture (SSM), Land Cover/Impermeability layers, and Surface Displacement (InSAR).
Service Provider Satellite EO Requirements	
Spatial resolution	**High:** 1–3m (DTM, InSAR, Slopes); **Medium:** 10m (Land Cover, Flood Delineation); **Coarse:** 100m–500m (Soil Saturation).
Temporal resolution	**6–12 days** (Sentinel-1/2 revisit) for dynamic variables; **Long-term archives** (10+ years) for historical trend analysis.
Data type / Spectral range	Multispectral (for vegetation and soil) C-band/X-band SAR (for flood mapping and displacement).
Service Inputs	
Satellite data sources	**Copernicus:** Sentinel-1 (SAR), Sentinel-2 (Optical), Copernicus DEM (GLO-30), CLMS (Land Monitoring Service), and EFAS (Emergency Management Service).
Other sources	Airborne LiDAR (10cm vertical accuracy), In-situ borehole data (groundwater), Meteorological stations (IFD curves), Lithological maps, and Seismic fault records.

Table 49: EO requirements for "lack of awareness of a site being at risk"

2.8.1.5 Climate Impact Analysis (EUSPA-EO-UR-RAI-0016)

The first phase of the RERA-Rain Framework provides guidelines for analysing future precipitation patterns based on climate models and scenarios. The goal is to generate useful data that feeds directly into subsequent vulnerability and risk assessments. Understanding potential changes in rainfall under various climate change scenarios is useful for proactive planning, enabling rail infrastructure managers to identify potential weak points in the network and implement risk mitigation strategies. A survey of infrastructure managers from various railway organizations provided valuable insights into the types of precipitation data they currently use, their analytical approaches to precipitation patterns, and the challenges they face in assessing infrastructure vulnerability.

User need: *The Rail Infrastructure managers needs to identify high-risk sites (flood zones, landslide susceptibility areas) that have not been previously identified because historical records alone do not capture the evolving risk profile driven by climate change.*

User requirement: *The system shall enable operators to discover and visualize sites potentially at risk (i.e. flooding, landslides) due to extreme weather events.*

System requirement: *The system shall integrate observed station data (1970–present) with simulated climate model outputs (present–2100) to generate localized precipitation anomalies when performing a vulnerability scan of the rail corridor. The system will compare precipitation trends 1970–2100 against current topography within a GIS environment, such that future flood zones are categorized by risk level.*

ID	EUSPA-EO-UR-RAI-0016
Application	Climate impact analysis
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Perform vulnerability scans of rail corridors. This scenario can integrate historical reanalysis (ERA5), topographic models (DEMs), and climate projections (CMIP6/CORDEX) to identify high-risk sites for flooding and landslides that historical records alone cannot capture due to evolving climate change profiles.
Size of area of interest	Continental scale with focused analysis on specific rail corridors, mountain passes, and coastal sections.
Scale	**Regional to Local:** Data must bridge global climate models (100km) down to infrastructure-scale assessments (sub-10km to 30m for topography).
Frequency of information	**Strategic/Periodic:** Annual updates for long-term adaptation planning; climate projections (decadal horizons to 2100); 6-yearly for land cover updates; and sub-daily (6-hourly) for hydraulic load modeling.
Other (if applicable)	Precipitation indices (Total, Mean, Max 1-day/5-day, frequency/intensity), digital elevation models, land cover classification (for friction/runoff coefficients), and hydrological discharge data.
Service Provider Satellite EO Requirements	
Spatial resolution	**Variable:** 9km (ERA5-Land reanalysis), 12km (EURO-CORDEX projections), 30m (Copernicus DEM GLO-30), and 100m (Corine Land Cover).
Temporal resolution	**Historical:** Hourly/Daily (1950/1970–Present); **Future:** Daily/Monthly projections (Present–2100)
Data type / Spectral range	Gridded climate data (GRIB/NetCDF), Raster (DEM/Land Cover), and Vector (Rail GIS layers). Microwave (for precipitation/soil moisture) and Optical/SAR (for topography).
Service Inputs	
Satellite data sources	**Copernicus Services:** C3S (ERA5, CMIP6), CLMS (Corine Land Cover, Copernicus DEM), and CEMS (EFAS/GloFAS). **Missions:** Sentinel-1 (SAR for DEM/Floods), Sentinel-2 (Land Cover).
Other sources	Local in-situ weather stations (rain gauges), national topographic surveys, railway infrastructure GIS layers (track geometry, drainage assets), and SSP (Shared Socioeconomic Pathways) scenario parameters.

Table 50: EO requirements for “Climate impact analysis”

2.8.1.6 Vulnerability, Risk and Criticality Assessments

Second phase in the RERA-Rain framework deals with **evaluating the railway system's exposure and sensitivity** to precipitation-related hazards, thereby **determining the severity of risks.** It is also mandatory for **identifying the criticality of specific railway sections** to properly prioritize interventions. By executing this phase, infrastructure managers can pinpoint the assets or railway segments most vulnerable to extreme precipitation, assess the network-wide effects of potential disruptions, and effectively prioritize necessary intervention needs.

The objective of this phase is to **identify which parts of the railway system are susceptible to damage** from adverse precipitation events, considering both current conditions and future climate scenarios. This requires a high-level internal evaluation of the railway system's exposure and sensitivity. Key questions addressed are whether the railway is vulnerable due to its geographical location or its physical characteristics, and if existing adaptation measures are adequate. The implementation procedure relies on knowledge of the railway's geographical location, any history of flooding, the properties and condition of its assets, and the future rainfall projections generated in the RERA-Rain Phase 1.

Geographic Location assesses the railway's exposure based on its geographical setting and historical weather conditions, and includes the following criteria and recommended data sources to provide a clear picture of the railway's vulnerability to historic and current weather events:

2.8.1.7 Topography: Elevation, slope, and aspect of the railway's geographical location (EUSPA-EO-UR-RAI-0017)

User Need: *The Rail Infrastructure Manager needs to assess the railway's exposure based on its geographical setting and historic weather conditions because elevation and slope gradients significantly dictate how precipitation transforms into flood or landslide risks.*

User Requirement: *The system shall enable operators to identify high-exposure segments and flag them for further inspection.*

System Requirement: *The system shall enable users to overlay railway asset locations with topographic layers (elevation, slope, and aspect) and historical weather station data under risk-assessment workflows, such that geographically high-exposure segments are identified and flagged.*

ID	EUSPA-EO-UR-RAI-0017
Application	Topography, elevation, slope and aspect of railway's geographic location
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Assessment of the railway's exposure to climate-induced risks (flooding, landslides, buckling, and icing) by integrating railway asset locations with high-resolution topographic layers (elevation, slope, aspect) and historical weather data. Identify and flag high-exposure track segments to support maintenance and inspection workflows.
Size of area of interest	Continental to regional. Focuses on the "Zone of Influence" (typically a buffer of **50m–500m** flanking the track centerline) across trans-European rail corridors.
Scale	**Local / Asset-level.** Data must be granular enough to distinguish between the track-bed, drainage ditches, and adjacent embankments.
Frequency of information	**Low to Static.** Topographic baselines are typically updated every **1–3 years** or following extreme weather events/construction. Risk flagging workflows are triggered seasonally or during specific weather alerts.

Other (if applicable)	High-precision Digital Elevation Models and Digital Terrain Models capable of deriving slope and aspect with high vertical accuracy.
Service Provider Satellite EO Requirements	
Spatial resolution	**<5m** (standard requirement); **1m or better** for high-speed corridors and asset-specific exposure mapping.
Temporal resolution	Baseline mapping: Multi-year. Monitoring (InSAR-based): **6–12 days** (e.g., Sentinel-1) to detect active slope deformation.
Data type / Spectral range	Topographic models (derived from structural/geometric data). If using optical proxies for land cover, multispectral (4–8 bands) is required. C-band or X-band SAR (InSAR) and LiDAR for 3D geometric modeling and vegetation penetration.
Service Inputs	
Satellite data sources	**Copernicus Sentinel-1** (InSAR for stability), **Copernicus DEM** (European/Global), **TerraSAR-X / TanDEM-X** (High-res DEM), and **Pleiades Neo** (Stereo-photogrammetry).
Other sources	**In-situ:** Historical weather station data (precipitation/temp), LiDAR-equipped maintenance trains. **Standards:** INSPIRE-compliant GML/GeoPackage, ETRS89/EVRS datum, Eurocode 7, and EN 15273.

Table 51: EO requirements for “Topography: Elevation, Slope, Aspect of the railway’s geographic location”

2.8.1.8 Proximity to water: Distance from rivers, lakes, and coastlines, proximity to flood-prone areas (EUSPA-EO-UR-RAI-0018)

User need: *The Rail Infrastructure Manager needs to quantify the spatial relationship between rail assets and nearby hydrological features because assets located in the proximity of water bodies or historical floodplains are inherently more sensitive to the extreme precipitation events.*

User Requirement: *The system shall enable operators to calculate and visualize the distance of rail segments from rivers, lakes, coastlines, and designated flood-prone zones under risk-assessment workflows, such that assets within high-risk proximity buffers are flagged.*

System Requirement: *The system shall assign railway database assets a proximity-risk value (e.g., distance < 50m, 100m, 500m) when mapped assets against the projected flood extent layers.*

ID	EUSPA-EO-UR-RAI-0018
Application	Proximity to water
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Assessment of rail asset vulnerability to hydrological hazards by quantifying spatial proximity to water bodies (rivers, lakes, coastlines) and flood-prone zones. The scenario can utilize EO-derived flood extents and hydrological vectors to flag high-risk segments sensitive to extreme precipitation and sea-level rise.
Size of area of interest	Regional to Continental (TEN-T scale), focusing on specific rail corridors and their immediate 500m buffer zones.
Scale	Local/Asset level (1:5,000 to 1:25,000) for precise infrastructure buffering and vertical offset calculations.
Frequency of information	Annual updates for baseline risk assessment, supplemented by "On-demand" updates following major flood events or significant river morphology changes.

Other (if applicable)	High-resolution DEMs, SAR for flood mapping, and Multispectral imagery for coastline and riparian vegetation monitoring.
Service Provider Satellite EO Requirements	
Spatial resolution	**High to Very High Resolution:** 0.5m to 10m. Assets require <5m for precise buffer flagging, while flood extents can utilize 10m.
Temporal resolution	5 to 12 days (Sentinel-1/2 revisit) to capture seasonal peaks, with archive data spanning decades to model 20, 100, and 500-year return periods.
Data type / Spectral range	SAR (C-band/X-band) for all-weather flood detection; VNIR (Visible/Near-Infrared) and SWIR for water indices (e.g., NDWI) and coastline delineation.
Service Inputs	
Satellite data sources	**Copernicus Sentinel-1** (SAR), **Sentinel-2** (Optical), **Sentinel-3** (Altimetry/SLR), and Third-Party Missions (e.g., ICEYE, TerraSAR-X, or WorldView-2/3) for sub-meter infrastructure detail.
Other sources	National Hydrographic datasets (Strahler Stream Order), In-situ gauge stations, LiDAR-derived DEMs (for 0.5m accuracy), and Climate Projection Models (CMIP6).

Table 52: EO requirements for "Proximity to water"

2.8.1.9 Flood zones: Presence in areas officially designated as flood-prone. (EUSPA-EO-UR-RAI-0019)

User Need: *The Rail Infrastructure Manager needs to identify assets at risk of inundation from coastal storm surges and riverine proximity because sea-level rise and increasing peak discharge in European basins directly threaten low-lying coastal and riparian rail corridors.*

User Requirement: *The system shall enable operators to filter rail assets based on their horizontal and vertical distance from sea-level baselines and major European river basins (e.g., Rhine, Danube, Po) under current and predicted climate scenarios.*

System Requirement: *The system shall attribute a Flood Risk Category to each asset based on its geographic intersection with National/Regional Flood Hazard Maps (FHM) when the asset's spatial coordinates fall within the specified (e.g. T=10, T=100, T=500) year return period polygons.*

ID	EUSPA-EO-UR-RAI-0019
Application	Flood zones
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Mapping and monitoring of European rail assets at risk of inundation from coastal storm surges and riverine flooding. This involves intersecting rail geometry with dynamic flood hazard polygons (Return Periods T=10 to 500) and extreme sea-level (ESL) models.
Size of area of interest	**Continental/Regional:** railway corridors, specifically low-lying coastal regions and major European river basins (e.g. Rhine, Danube, Po).
Scale	**Local to Regional (1:5,000 to 1:25,000):** High-precision mapping required to distinguish between track bed elevation and surrounding floodplains.
Frequency of information	**Static/Strategic:** Annual updates for climate adaptation planning. **Dynamic/Operational:** Real-time to daily updates during extreme weather events.

Other (if applicable)	High-resolution Digital Elevation Models, Synthetic Aperture Radar for flood extent mapping, and Multispectral imagery for land cover/permeability analysis.
Service Provider Satellite EO Requirements	
Spatial resolution	**Very High Resolution (VHR):** 1m to 5m for rail asset identification and vertical accuracy; 10m to 30m for regional catchment modeling.
Temporal resolution	**Revisit time:** 1–6 days (Sentinel-1/2 constellation) or sub-daily via commercial VHR providers during emergency activation.
Data type / Spectral range	SAR (backscatter intensity for water detection), Optical (Multispectral), and Altimetry (Sea surface height). Radar (C-band/X-band): Essential for cloud-penetration during flood events. Optical: Visible (RGB) and Near-Infrared (NIR) for identifying saturated soils and vegetation.
Service Inputs	
Satellite data sources	**Copernicus Sentinels (1, 2, and 3)**, Jason-3/Sentinel-6 (Sea level), and VHR Contributing Missions (e.g., ICEYE, TerraSAR-X, or Cosmo-SkyMed) for precise infrastructure monitoring.
Other sources	EU-Hydro, EVRS (European Vertical Reference System), EFAS (European Flood Awareness System), EMODnet (Bathymetry), National Flood Hazard Maps (FHM), and in-situ river gauge telemetry.

Table 53: EO requirements for "Flood zones"

2.8.1.10 Historical weather patterns: Analysis of past weather events such as heavy rainfall and floods. (EUSPA-EO-UR-RAI-0020)

User Need: *The Rail Infrastructure Manager needs to analyse historical weather patterns (heavy rainfall, flood events, and storm surges) because understanding the frequency and magnitude of past disruptions is essential to calibrating risk thresholds for existing assets, in the context of validating climate models against real-world historical performance.*

User Requirement: *The system shall enable operators to query and correlate historical precipitation and hydraulic data (1970–present) with recorded infrastructure failure events such that the correlation between specific weather intensities and asset damage is statistically established.*

System Requirement*: The system shall ingest and harmonize in-situ weather station observations and ERA5-Land data to generate Intensity-Duration-Frequency (IDF) curves for the rail corridor.*

ID	EUSPA-EO-UR-RAI-0020
Application	Historical weather patterns
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Statistical correlation of historical weather extremes (1970–present) with rail infrastructure failure events. Harmonize in-situ and ERA5-Land data to establish Intensity-Duration-Frequency (IDF) curves, enabling infrastructure managers to calibrate risk thresholds and validate climate models against historical asset performance (e.g., ballast scour, washouts).
Size of area of interest	Regional to Continental rail network corridors, typically focusing on a 5km to 50km buffer zone around specific rail alignments.
Scale	Localized (Asset level) to Macro-scale (Catchment level) to understand hydraulic impacts on bridges and culverts.

Frequency of information	On-demand/Retrospective: One-time deep historical baseline per asset, updated every 1–5 years to incorporate new extreme events.
Other (if applicable)	Historical precipitation estimates, soil moisture proxies, and surface water extent for flood validation.
Service Provider Satellite EO Requirements	
Spatial resolution	**ERA5-Land:** ~9 km; **Downscaled/In-situ:** 100m to 1km; **Infrastructure Damage Mapping:** 0.5m to 10m (High Resolution/Very High Resolution).
Temporal resolution	Hourly to Daily (required to capture the "bursts" of intensity
Data type / Spectral range	Passive Microwave (for precipitation), C-band/L-band SAR (for soil moisture and historical flooding), Multi-spectral (VIS/NIR/SWIR). Reanalysis data (Gridded), SAR (for flood mapping).
Service Inputs	
Satellite data sources	**Copernicus Sentinel-1** (Flood mapping), **Sentinel-2** (Land cover/Vegetation), **GPM** (Global Precipitation Measurement), and **SMOS** (Soil Moisture).
Other sources	**ERA5-Land** reanalysis, **E-OBS** gridded datasets, In-situ weather stations, River gauges (Hydrometric data), and Infrastructure Maintenance Logs (Failure/Damage timestamps).

Table 54: EO requirements for "Historical weather patterns"

2.8.1.11 Climate Projections (EUSPA-EO-UR-RAI-0021)

Climate projections evaluate how the railway is likely to be affected by future climate scenarios, focusing on changes in precipitation patterns, temperature, and extreme weather events. The assessment helps to project future vulnerabilities, based on climate change trends.

User Need: *The Rail Infrastructure Manager needs to evaluate how the railway system will be affected by future climate scenarios (up to 2100) because relying on historical data alone underestimates the risk of unprecedented rainfall, heat-induced soil instability, and sea-level rise, in the context of long-term capital investment and climate adaptation planning.*

User Requirement*: The system shall enable strategic planners to visualize projected shifts in precipitation, temperature, and sea levels under multiple RCP scenarios, such that vulnerable assets are identified based on their threshold sensitivity to future extreme weather events.*

System Requirement*: The system shall ingest and downscale ensemble climate projections (e.g., CORDEX-EUR-11) to a required spatial resolution (e.g. 12.5 km/0.11°) to calculate future return periods for precipitation and temperature extremes when performing a 2050 or 2100 horizon risk simulation.*

ID	EUSPA-EO-UR-RAI-0021
Application	Climate projections
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Strategic assessment of railway infrastructure resilience against future climate scenarios (up to 2100). The scenario utilizes downscaled ensemble climate projections and Copernicus EO data to identify asset vulnerabilities to extreme heat, flooding, and sea-level rise, enabling long-term capital investment planning and adaptive infrastructure engineering.
Size of area of interest	**Continental to Local:** Covers TEN-T corridors, spanning thousands of kilometers of linear infrastructure across diverse European climatic zones.

Scale	**Multi-scale:** Regional climate modeling (12.5 km) for strategic planning, downscaled to local/asset level (1 km to 10m) for site-specific sensitivity analysis (e.g., specific bridges, coastal segments, or embankments).
Frequency of information	**Periodic/Epoch-based:** Updates every 5–10 years aligned with IPCC/CMIP release cycles. However, simulations require **Daily to 3-Hourly** temporal slices to model convective storm peaks and heatwave durations.
Other (if applicable)	Historical baselines for precipitation/temperature, land cover/use classification (soil permeability), ground motion monitoring (InSAR), and sea-level/storm surge modeling.
Service Provider Satellite EO Requirements	
Spatial resolution	**Variable:** 9–12.5 km for climate modeling (EURO-CORDEX/ERA5-Land); 10–100m for land cover (CLMS); and up to 1m for local risk mapping using VHR (Very High Resolution) data.
Temporal resolution	**Hindcast/Baseline:** 1970–present (daily). **Projections:** 3-hourly/daily timesteps for horizons 2030, 2050, and 2100.
Data type / Spectral range	**Multispectral:** Required for identifying vegetation health (NDVI) and soil moisture; **SAR:** Required for InSAR displacement monitoring and all-weather flood mapping; **Thermal:** For monitoring urban heat island effects on rail tracks. Numeric model output (NetCDF/GRIB),
Service Inputs	
Satellite data sources	**Copernicus Sentinels:** Sentinel-1 (Subsidence/Floods), Sentinel-2 (Land Use/Permeability), Sentinel-3 (Sea Surface Temp/Altimetry). **Contributing Missions:** VHR optical satellites for asset-level detail.
Other sources	**EURO-CORDEX** ensemble projections, **IPCC AR6** Sea Level Data, **C3S Climate Data Store**, **EFAS/GLOFAS** hydrological models, and In-situ weather stations/tide gauges for validation.

Table 55: EO requirements for "Climate projections"

Sensitivity of Railway, Land Use. Another important factor when analyzing the sensitivity of railway infrastructure to precipitation-related stresses is the land use of the surrounding areas. Land with effective natural drainage conditions can reduce surface runoff, mitigating the risk of flooding or water accumulation near the infrastructure. In contrast, areas with poor drainage or extensive surfaces of an impervious nature, such as asphalt or concrete, can generate high levels of runoff, increasing the railway system's vulnerability to heavy rain events. The following land uses in this section need to be analysed:

- **Impervious surfaces:** The extent of impervious surfaces (e.g., roads, car parks, buildings) that prevent water from being absorbed into the ground thereby increasing surface runoff.

- **Human-made or modified porous surfaces:** Surfaces such as permeable paving or agricultural areas (bare soil, open crops, pasture) that allows some water absorption but may still contribute to runoff depending on land-use practices.

- **Natural drainage conditions:** The capacity of the surrounding land to naturally manage water flows, including natural watercourses, wetlands, the soil type, and overall drainage capacity.

2.8.1.12 Impervious Surfaces (artificial sealing) (EUSPA-EO-UR-RAI-0022)

These parameters define zones where the water infiltration is zero, leading to maximum runoff velocity and volume.

User Need: *The Rail Drainage Engineer needs to map artificially sealed (impervious) zones within the rail catchment because surfaces with zero infiltration generate maximum runoff velocity and volume, in the context of calculating peak discharge requirements for culverts and track-side gutters.*

User Requirement*: The system shall enable operators to identify and quantify impervious areas with a spatial precision that distinguishes between the rail track-bed and adjacent urban infrastructure under flood-modeling conditions, such that runoff volume calculations account for 100% of the sealed area.*

System Requirement*: The system will provide the impervious surfaces around the rail corridor in GIS.*

ID	EUSPA-EO-UR-RAI-0022
Application	Impervious surfaces
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Mapping and quantification of artificially sealed (impervious) surfaces within rail catchments to calculate peak runoff velocity and volume. This ensures hydraulic structures like culverts and track-side gutters are sized correctly to prevent track flooding and ballast washout under extreme weather conditions.
Size of area of interest	Linear corridors extending **50m to 500m** on either side of the track centreline, encompassing the immediate rail embankment and the surrounding hydrological catchment area.
Scale	**Local to Regional scale**; requires high-precision mapping to distinguish between the porous track-bed (ballast) and non-porous adjacent urban infrastructure or paved surfaces.
Frequency of information	**3-year update cycle** (standard) for general infrastructure planning, or **Ad-hoc/On-demand** following significant land-use changes or new urban developments near the rail line.
Other (if applicable)	High-accuracy land cover classification and soil sealing density layers capable of identifying "sealed" pixels with a thematic accuracy of 90%.
Service Provider Satellite EO Requirements	
Spatial resolution	**10m (Standard)** for catchment-level modelling; **2m or sub-meter (High)** for precise differentiation between rail infrastructure components and adjacent buildings.
Temporal resolution	**Seasonal/Annual** snapshots to account for urban expansion, though the specific product update cycle is typically every 3 years.
Data type / Spectral range	**Multispectral**; requires Visible (RGB), Near-Infrared (NIR), and Short-Wave Infrared (SWIR) bands to distinguish between various artificial materials and vegetation. Optical imagery (Visible to SWIR) and derived indices (e.g., NDVI, NDBI) for imperviousness density mapping.
Service Inputs	
Satellite data sources	**Copernicus Sentinel-2** (10m), **CLMS High Resolution Layer (HRL) Imperviousness**, and Very High Resolution (VHR) commercial missions (e.g., Pléiades, WorldView-2/3) for 2m requirements.
Other sources	**Digital Elevation Model** (e.g., Copernicus DEM 10m) for slope calculation, **Land Use/Land Cover (LULC)** maps for roughness coefficients, and **In-situ survey data** for verification.

Table 56: EO requirements for "Impervious surfaces"

2.8.1.13 Human-made or modified porous surfaces (EUSPA-EO-UR-RAI-0023)

These parameters account for surfaces with restricted infiltration. In the RERA-Rain Phase 2, these are important for identifying where agricultural "crusting" or partial paving causes unexpected runoff.

User Need: *The Rail Infrastructure Manager needs to account for surfaces with restricted or variable infiltration (e.g. agricultural land and semi-permeable paving) because natural soil crusting or man-made modifications can cause unexpected runoff volumes that bypass standard drainage designs, in the context of identifying hidden vulnerabilities in rural or semi-urban rail corridors.*

User Requirement: *The system shall enable operators to identify and categorize surfaces with restricted porosity under seasonal or extreme weather simulations, such that runoff coefficients are adjusted to account for agricultural soil crusting and partial soil sealing.*

System Requirement: *The system shall apply a dynamic runoff coefficient to agricultural and modified porous pixels when the antecedent precipitation index (API) indicates a high-intensity storm following a prolonged dry period.*

ID	EUSPA-EO-UR-RAI-0023
Application	Human-made or modified porous surfaces
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Monitoring and categorizing surfaces with restricted or variable infiltration (e.g., agricultural soil crusting, semi-permeable paving) along rural/semi-urban rail corridors. The goal is to apply dynamic runoff coefficients during extreme weather simulations to identify hidden drainage vulnerabilities and prevent track washouts caused by unexpected runoff volumes.
Size of area of interest	Linear corridors extending **50m to 500m** on either side of the rail centerline, covering catchment areas that drain directly toward the permanent way.
Scale	**Local to Regional:** High-precision mapping at the asset level (individual rail segments) aggregated across national or cross-border rail networks.
Frequency of information	**Weekly to Seasonal:** Near-real-time updates during high-risk seasons (e.g., peak agricultural activity or transition from dry to wet seasons) to update Antecedent Precipitation Index (API) models.
Other (if applicable)	Multi-spectral imagery capable of distinguishing between bare soil, managed vegetation, and artificial sealing; must support the derivation of soil moisture and porosity indices.
Service Provider Satellite EO Requirements	
Spatial resolution	**5m to 10m:** Necessary to resolve field boundaries, access roads, and small-scale land-use modifications adjacent to the infrastructure.
Temporal resolution	**5-6 day revisit:** Aligned with Sentinel-2 to capture rapid land-cover changes such as ploughing, harvesting, or crusting post-dry spells.
Data type / Spectral range	**Red, NIR, SWIR:** Used for calculating NDVI/SAVI for vegetation fraction and SWIR-based indices for soil moisture and mineral composition. C-band SAR (from Sentinel-1) can be integrated for surface roughness and soil moisture independent of cloud cover.
Service Inputs	

Satellite data sources	**Copernicus Sentinel-2**; **Sentinel-1** (Surface moisture/roughness); **Landsat 8/9** (Thermal/SWIR continuity); **VHR Commercial Imagery** (e.g., Pléiades or WorldView-2/3) for specific urban-fringe "hotspots."
Other sources	**European Soil Data Centre (ESDAC):** Clay/Silt/Sand fractions (250m/1km); **In-situ Meteorological Stations:** For real-time API calculation; **Digital Elevation Models:** Copernicus GLO-30 or local LiDAR for flow path analysis.

Table 57: EO requirements for "Human-made or modified porous surfaces"

2.8.1.14 Natural drainage conditions (infiltration capacity) (EUSPA-EO-UR-RAI-0024)

These parameters evaluate the land s inherent capacity to mitigate heavy rain through interception and storage.

User Need*: The Rail Infrastructure Manager needs to evaluate the land s capacity to mitigate heavy rain through interception and storage because natural ecosystems (e.g. forests, wetlands, undisturbed soils) act as a primary flood defence by absorbing water before it reaches the tracks, in the context of identifying natural "safety zones" and protecting critical environmental assets within the rail corridor.*

User Requirement*: The system shall enable operators to assess the natural infiltration and storage capacity of the surrounding landscape under peak precipitation scenarios, such that the mitigating effects of soil type, vegetation interception, and natural watercourses are factored into the net risk score for the railway corridors under consideration.*

System Requirement*: The system shall calculate the Net Infiltration Rate when executing the rainfall-runoff transformation model for the rail catchment area.*

ID	EUSPA-EO-UR-RAI-0024
Application	Natural drainage conditions
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Evaluation of the land's natural capacity (soil infiltration, vegetation interception, and storage) to mitigate heavy rainfall-runoff before it reaches rail assets. This scenario identifies "safety zones" that act as natural flood defenses to protect tracks and critical infrastructure.
Size of area of interest	**Regional to Corridor Level.** Typically covers the rail catchment area extending **1 km to 5 km** on either side of the track centreline, depending on local topography and hydrological connectivity.
Scale	**Local/Asset Scale.** Mapping must be precise enough to factor into the net risk score of specific railway segments while maintaining a regional context for catchment modelling.
Frequency of information	**Seasonal/Dynamic.** Baseline updates are required quarterly or seasonally to account for phenological changes (e.g., leaf-off in winter). Rapid updates (daily/weekly) are needed for antecedent moisture conditions (AMC) during high-risk weather seasons.
Other (if applicable)	High-resolution land cover/use (to identify impervious vs. natural surfaces), vegetation density (Canopy/LAI), soil moisture indicators (SWI), and high-precision DEMs for flow direction.
Service Provider Satellite EO Requirements	
Spatial resolution	**10m – 20m:** For vegetation (Sentinel-2) and surface roughness.

	250m – 1km: For deep soil parameters and saturated hydraulic conductivity (K_sat). **2m – 10m:** For track-side topography and hydrological connectivity (EU-Hydro/DEM).
Temporal resolution	**5 to 10 days** (revisit time of Sentinel-1 and Sentinel-2) to capture dynamic soil moisture and rapid vegetation growth/senescence.
Data type / Spectral range	**Visible/NIR/SWIR:** (e.g., Sentinel-2) for NDVI, LAI, and phenology. **C-band SAR:** (e.g., Sentinel-1) for Soil Water Index (SWI) and moisture monitoring regardless of cloud cover. Digital Elevation data (linear/raster) for slope and drainage networks.
Service Inputs	
Satellite data sources	**Copernicus Sentinels:** Sentinel-2 (L2A), Sentinel-1 (GRD/SLC). **Copernicus Services:** CLMS (Tree Cover Density, High Resolution Layers), EU-DEM, Copernicus Global Land Service (CGLS).
Other sources	**In-situ / Geospatial Databases:** ESDAC/LUCAS (Topsoil), SoilGrids (Root zone), EU-Hydro (Watercourses), and local weather station data for peak precipitation validation.

Table 58: EO requirements for "Natural drainage conditions"

2.8.1.15 Geomorphology (EUSPA-EO-UR-RAI-0025).

Geomorphology plays an important role in determining the sensitivity of railway infrastructure, as soil type, stability, and behaviour under varying water conditions can significantly influence the system's vulnerability to precipitation events. Certain soil types, particularly those prone to erosion or landslides, may weaken during heavy rainfall, posing risks to the integrity of the infrastructure. Additionally, the surrounding areas' slope and terrain characteristics impact how water flows and accumulates around the railway system. Assessing this factor requires a comprehensive understanding of the geological and soil conditions in proximity to the railway.

User Need: *The Rail Geotechnical Engineer needs to evaluate the geological and topographical stability of the rail corridor because specific soil types and steep slope geometries are prone to failures (landslides, washouts, subsidence) when saturated, in the context of preventing structural integrity loss during extreme precipitation events.*

User Requirement: *The system shall enable operators to characterize the geotechnical risk profile of the terrain under heavy rainfall and saturation scenarios, such that assets located on unstable soil types or high-gradient slopes are prioritized for stabilization and monitoring.*

System Requirement: *The system shall generate a Landslide Susceptibility Index (LSI) for each track segment based on soil shear strength, slope gradient, and pore water pressure estimates when cumulative precipitation exceeds the geotechnical failure threshold.*

More information can be found in section 2.6.1, "Infrastructure planning and design, finance planning."

ID	EUSPA-EO-UR-RAI-0025
Application	Geomorphology
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Geotechnical risk assessment for rail infrastructure focused on the **Landslide Susceptibility Index (LSI)**. Integrating EO data (InSAR, spectral indices) with topographical models (LiDAR) to identify vulnerabilities to landslides, washouts, and subsidence triggered by heavy rainfall and soil saturation.
Size of area of interest	Linear rail corridors with a lateral buffer of **500m** from the track centreline (1km total width) across the European rail network.
Scale	**Local to Regional:** Requires high-precision point data for stability monitoring (local) and medium-resolution mapping for soil texture and drainage (regional).
Frequency of information	**Dynamic/Update-driven:** Monthly updates for ground deformation; near real-time (< 24 hours) synchronization between rainfall events and soil state updates.
Other (if applicable)	Ground deformation (velocity), soil mineral indices (clay/sand), surface roughness, dielectric constants (permeability), and historical failure footprints.
Service Provider Satellite EO Requirements	
Spatial resolution	**Variable by parameter:** 2m or better for Slope/Flow; 5m–10m for InSAR/Drainage; 10m–100m for Soil Type. Positional accuracy must be < 2.0m RMSE.
Temporal resolution	**Monthly** for Copernicus EGMS (InSAR) and seasonal/archive-based for geomorphological baselines; event-based for emergency mapping.
Data type / Spectral range	Multispectral (VNIR/SWIR) for mineral identification and soil indices; C-band SAR for interferometry, surface dielectric properties and soil moisture. Digital Elevation Models.
Service Inputs	
Satellite data sources	**Copernicus Sentinel-1** (InSAR/Radar), **Sentinel-2** (Multispectral), **European Ground Motion Service (EGMS)**, and **Copernicus Emergency Management Service (EMS)**.
Other sources	**LiDAR DTM** (for 2m Slope/Flow); **Eurocode 7/ISO 14688-1** geotechnical data; **EU-Hydro**; In-situ physical sensors (1 per 10km); and historical geotechnical logs.

Table 59: EO requirements for "Geomorphology"

Step 2 – Risk Assessment

The objective of this phase is to **assess the probability of adverse events occurring** and **determine the severity of their impact** on both infrastructure and services. This is achieved by answering key questions such as: What is the probability of specific events occurring? What are the potential consequences of such events on operations and infrastructure? The implementation procedure involves a **detailed analysis that combines event severity and probability** for both current and future scenarios.

User Need: *The Rail Asset Manager and Strategic Planner need to quantify the probability and impact of climate-related disruptions because limited maintenance budgets must be prioritized toward the highest-risk segments to ensure network resilience, in the context of balancing current operational safety with long-term infrastructure investment.*

User Requirement: *The system shall enable operators to generate a localized Risk Matrix (Severity × Probability) for any rail segment or asset under historic, current, and future climate scenarios, such that mitigation strategies can be justified based on projected reduction in service downtime and repair costs.*

System Requirement: *The system shall calculate a Risk Score for the railway corridors under investigation and display these results for visualization and analysis via an interactive GIS heatmap.*

2.8.1.16 Environmental Impact (EUSPA-EO-UR-RAI-0026)

This scenario assesses the negative consequences of an event (e.g. flood, landslide) on the surrounding natural environment, focusing on both the short and long-term effect on ecosystems, wildlife, and natural resources. It examines how the event disrupts natural processes and causes pollution or habitat destruction.

User need: *The Rail Environmental Compliance Officer needs to quantify the ecological and hydrological consequences of a climate-related asset failure because breaches in infrastructure (e.g., bridge collapses or embankment washouts) can discharge pollutants into protected watercourses and destroy natural habitats.*

User requirement: *The system shall enable operators to assess the vulnerability of surrounding ecosystems and water bodies to contamination and physical disruption under diverse failure scenarios, such that high-sensitivity environmental zones (e.g. Natura 2000) are prioritized for preventative action.*

System requirement*: The system will calculate an Environmental Impact Score when the probability of a structural breach or hazardous material spill exceeds the defined risk threshold.*

ID	EUSPA-EO-UR-RAI-0026
Application	Environmental impact
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Assessment of consequences of climate-related rail asset failures (e.g., floods, landslides) on surrounding ecosystems and water resources. The scenario quantifies ecological and hydrological damage, focusing on pollutant discharge into protected zones and habitat disruption.
Size of area of interest	A focused **500m buffer zone** on both sides of the rail track, with specific emphasis on adjacent narrow watercourses (streams >5m wide) and legally protected **Natura 2000** sites.
Scale	**Local to Regional:** Precision is required to identify small structural rills (gullies) and sediment plumes in narrow streams, while maintaining compliance with EU-wide ecological mapping standards (1 ha MMU).
Frequency of information	Variable by phase: **Seasonal/Annual** for baseline habitat mapping; **Daily to 5 days** for water quality monitoring; and **<24 hours (Near Real-Time)** for emergency pollutant spill response.
Other (if applicable)	High-resolution multispectral and radar data capable of identifying turbidity, vegetation health (chlorophyll/moisture), and structural soil changes (erosion).
Service Provider Satellite EO Requirements	
Spatial resolution	**High to Very High Resolution:** <5m for erosion/gully detection; 10m for pollutant drift and habitat extent; 10m–20m for water quality in narrow watercourses.
Temporal resolution	**Dynamic Revisit:** 5 days (nominal Sentinel-2) reaching **<24 hours** during emergencies via CEMS and Contributing Missions.
Data type / Spectral range	**Multispectral:** Minimum of 13 bands (VNIR to SWIR) to distinguish between actual pollution/algae and atmospheric haze; requires **Level 2A**

	(Atmospherically Corrected) consistency. **Optical (VNIR, SWIR):** For water turbidity and vegetation indices. **Radar (SAR):** For flood delineation and soil moisture during cloud cover.
Service Inputs	
Satellite data sources	**Sentinel-2** (Primary for WQ and Land Cover), **Sentinel-1** (Flood mapping/SAR), **Sentinel-3** (Regional WQ), and **Copernicus Contributing Missions** (VHR for <5m gully detection).
Other sources	Digital Elevation Models for runoff modelling; **Natura 2000** vector databases; Hydrological maps; and **In-situ** sensors for water quality validation.

Table 60: EO requirements for "Environmental impact"

Step 3 – Criticality Assessment

The objective of this final step is to **determine the importance of the railway section or network** currently under analysis, which is essential for effectively **prioritizing intervention needs.** The key question the railway infrastructure manager also needs to answer is: How critical is the infrastructure?

2.8.1.17 Adaptation Planning

The final phase of the RERA-Rain Framework centres on creating tailored **adaptation strategies** to minimize the impacts of extreme weather events, directly addressing the risks and vulnerabilities identified earlier. These strategies enhance the resilience of railway systems through several key measures. These include boosting **infrastructure robustness** by reinforcing critical elements like tracks, bridges, and tunnels against floods, heatwaves, and storms. Furthermore, adopting **climate-proofing designs** ensures new infrastructure is built to cope with future climate projections. Specific protective measures, such as installing enhanced **flood management systems** like better drainage and flood barriers, safeguard railway lines. Finally, implementing advanced **monitoring and early warning systems** allows for prompt detection and response to extreme weather, minimizing service disruptions and damage. Since the needs of each railway system vary, all adaptation measures must be customized to the specific location, infrastructure type, and relevant hazards.

2.8.2 Rail facing high temperatures

UIC RERA-Temp (Resilient Railways facing High Temperatures) is a strategic initiative by the UIC designed to safeguard global infrastructure against the escalating threats of extreme heat and desert environments. Major European rail infrastructure managers contributed to these (SBB, Network Rail, ADIF (via CEMOSA), RFI etc. These guidelines offer railway engineers and decision-makers a practical framework for assessing risks and planning adaptations assuring heat-resilient rail networks. The following section reviews the data needs and shows how EO can contribute to identifying thermal risks and implementing precision solutions.

Risk Assessment Methodology

This section introduces a methodology for assessing the risks posed by high temperatures on railway systems. It outlines a three-phase process, beginning with data elaboration to define the scope and climate context, followed by prioritization of assets based on temperature risk, and concludes with guidelines for the implementation and monitoring of adaptation measures.

Data preparation and analysis: The process begins by defining the geographical and technical scope of the assessment. This involves gathering granular climate data and long-term temperature projections to establish the environmental context in which the railway must operate.

User Need: *The Railway Infrastructure Manager needs a method to visualize and assess spatial temperature of rail variations across the rail network and identify assets at risk of failure due to extreme heat to issue operational restrictions or plan maintenance.*

User Requirement: *The user shall have the capability to know historical and predict near future temperature of rail track and identify high-risk thermal zones based on specific geographical extents and defined timeframes.*

System Requirement: *The system shall generate visual temperature maps by integrating contextual imagery and historical/predictive climate data for any defined geographical area and temporal range.*

Vulnerability and risk assessment of identified assets: Once the climate context is set, the infrastructure is analysed to identify the most vulnerable components. The Railway Network Operator needs to identify and prioritize infrastructure assets most susceptible to extreme heat to ensure that maintenance and mitigation resources are allocated efficiently to prevent operational failures.

Implementation and monitoring of adaptation measures: The final stage provides a roadmap for deploying adaptation measures, such as technical upgrades or revised operational protocols. This phase emphasizes continuous monitoring to evaluate the effectiveness of these solutions and to refine the system's resilience over time.

To evaluate the exposure of the assets to heat, the temperature maps help to identify high-risk areas, including urban hot-spots, heatwave-prone regions or zones with consistently above-average temperatures. These areas can then be prioritised for further risk assessments to evaluate the severity of the impacts. Additionally, prioritisation could be refined by incorporating factors such as population density, critical infrastructure, and ecosystems particularly vulnerable to temperature changes.

2.8.2.1 Climate data and projections (EUSPA-EO-UR-RAI-0027)

User Need*: The Railway Infrastructure Manager requires historical and projected temperature distribution to identify segments vulnerable to track buckling, equipment failure, and heat-related operational delays.*

User Requirement: *The methodology used shall utilize standardized climate indicators—including daily extremes, frequency of warm nights, and heatwave durations—derived from globally consistent and locally downscaled climate datasets to support long-term infrastructure resilience planning.*

System Requirement: *The system shall integrate multiple data sources at various granularity levels, merging historical records from local weather stations with simulated projections that model future climate change impacts.*

ID	EUSPA-EO-UR-RAI-0027
Application	Climate data and projections
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Integration of high-resolution historical climate reanalysis and future projections to identify rail segments vulnerable to heat-induced risks such as track buckling, equipment failure, and operational delays. The scenario focuses on standardizing climate indicators (e.g., heatwave duration, thermal amplitude) for long-term infrastructure resilience.
Size of area of interest	**Regional to Continental.** Coverage spans national rail networks across Europe, including trans-border corridors (TEN-T).
Scale	**Local to Regional.** Data must be granular enough to assess specific track segments and assets while maintaining a consistent methodology across the entire European rail network.

Frequency of information	**Annual Updates for Planning; Hourly for Analysis.** Historical baselines require hourly/daily consistency, while resilience planning assessments are typically updated annually or bi-annually as new CMIP6 models/ensembles are released.
Other (if applicable)	High-resolution Land Surface Temperature (LST), air temperature at 2m, and integrated climate indices derived from satellite-based reanalysis and atmospheric modelling.
Service Provider Satellite EO Requirements	
Spatial resolution	**High Resolution (100m to 9km).** ERA5-Land provides ~9km resolution; however, scaling via Copernicus Regional Climate Models (RCMs) or local station blending is required to reach sub-kilometre scales for specific track assets.
Temporal resolution	**Hourly (Historical) to Decadal (Projections).** Hourly data for historical extremes (ERA5-Land); daily/monthly averages for future projections (CMIP6) looking at 2050 and 2080 horizons.
Data type / Spectral range	**Multispectral & Thermal.** Specifically focused on Thermal Infrared (TIR) for surface temperature monitoring and microwave/infrared sounding for atmospheric temperature profiles. Gridded numerical data representing temperature. Spectral range primarily involves Thermal Infrared (8–14 µm) for land surface observations.
Service Inputs	
Satellite data sources	**Copernicus Sentinels & Core Services.** Sentinel-3 (SLSTR for LST), ERA5-Land (C3S), CMIP6 (C3S Climate Data Store), and C3S Agrometeorological/Thermal Assessment indicators.
Other sources	**In-situ & Infrastructure Data.** Local weather station records (for bias correction), GIS layers of rail track geometry/material, historical maintenance logs of heat-related failures, and Digital Elevation Models.

Table 61: EO requirements for "Climate data and projections"

2.8.2.2 Soil Stability and Moisture Content (EUSPA-EO-UR-RAI-0028)

Earthworks in railway infrastructure encompass embankments, slopes and cuttings, which are engineered to provide a stable foundation for tracks and manage the surrounding terrain. Earthworks have limited inherent resilience and are highly susceptible to failure, including landslides, under certain weather conditions. Embankments in particular play a critical role as they form the foundation of railway infrastructure, ensuring track stability and maintaining structural integrity. High temperatures can trigger a range of direct and cascading effects on earthworks, leading to soil degradation, reduced stability, increased maintenance demands, and significant safety and operational challenges.

User Need: *The Railway Infrastructure Manager needs to ensure the structural stability and operational safety of earthworks (embankments, slopes, and cuttings) by identifying and mitigating heat-induced soil degradation, such as desiccation, shrinkage, and differential settlement.*

User Requirement: *The system shall provide continuous monitoring of the geotechnical health of railway earthworks to detect early indicators of failure caused by high temperatures and Soil Moisture Deficit (SMD).*

System Requirements: *The monitoring system shall meet the following technical requirements:*

- ***Soil Moisture Deficit:*** *The system shall calculate SMD by integrating evapotranspiration and precipitation data to identify high-risk desiccation zones.*
- ***Shrinkage & Cracking:*** *The system shall detect surface anomalies and vegetation stress indicators that correlate with deep-seated clay shrinkage and soil cracking.*

- ***Settlement & Displacement:*** *The system shall monitor millimetric changes in embankment height and slope stability to identify differential settlement.*
- ***Thermal Loading:*** *The system shall map Land Surface Temperature across the network to identify "heat hotspots" where earthworks are most exposed.*

ID	EUSPA-EO-UR-RAI-0028
Application	Soil stability and moisture content
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Continuous geotechnical health monitoring of railway earthworks (embankments, slopes, and cuttings) to mitigate heat-induced degradation. The system needs to detect **Soil Moisture Deficit (SMD)**, clay shrinkage/cracking, and millimetric settlement caused by extreme thermal loading and desiccation.
Size of area of interest	**Corridor-wide to Continental:** Individual railway segments (5–20 km) up to entire national/European networks (~10,000+ km of track).
Scale	**Local to Regional:** High-precision monitoring at the asset level (individual embankments) nested within regional climate and thermal hotspot mapping.
Frequency of information	**Strategic & Operational:** Daily updates for thermal/moisture indices; weekly to bi-weekly (6–12 days) for displacement; seasonal/annual for long-term subsidence trends.
Other (if applicable)	**Multimodal:** Integration of SAR for displacement, Thermal Infrared for hotspots, and Multispectral imaging for vegetation/surface moisture.
Service Provider Satellite EO Requirements	
Spatial resolution	**Variable:** 5m to 20m for ground movement (EGMS); 10m for vegetation health (Sentinel-2); 1km for LST and Surface Moisture (Sentinel-3).
Temporal resolution	**Daily to 12-day:** Daily for LST/SMD; 5-day for vegetation (NDVI/NDMI); 6–12 day repeat cycles for InSAR.
Data type / Spectral range	**High Multi-domain:** C-band SAR; Thermal Infrared; Multispectral (Red, NIR, and SWIR for moisture/stress indices).
Service Inputs	
Satellite data sources	**Copernicus Sentinels:** Sentinel-1 (InSAR/EGMS), Sentinel-2 (NDVI/NDMI), Sentinel-3 (SLSTR for LST/SSM); C3S (CDS).
Other sources	**In-situ & Infrastructure:** Track geometry records, geotechnical boreholes, local weather stations, Digital Elevation Models, and Fiber Optic Sensing (DAS/DTS) for real-time strain.

Table 62: EO requirements for “Soil stability and moisture content”

2.8.2.3 Impact on Vegetation Cover (EUSPA-EO-UR-RAI-0029)

Extreme heat can compromise the stability of railway surroundings by disrupting the natural lifecycle and water-retention properties of trackside vegetation. High temperatures dehydrate plants, weakening root systems that are essential for stabilizing slopes. As vegetation dies off, the underlying soil is left exposed. Without this protective cover, embankments become highly susceptible to wind and water erosion—a risk that is intensified when heatwaves are followed by sudden, intense rainfall. During periods of drought and high heat, large trees require significantly more water. They extract moisture from deep within clay-based embankments, causing the soil to shrink and crack. This process, known as desiccation, can lead to uneven settlement of the embankment and misalignment of the track above.

User Need: *The Railway Infrastructure Manager requires a detailed geolocated inventory of vegetation along the tracks to identify hazards (such as falling trees, rail-line encroachment, and invasive species) to transition from reactive maintenance to a dynamic, risk-based mitigation strategy.*

User Requirement: *The system shall provide a continuous, multi-parameter assessment of all large flora within the railway corridor, within a specified buffer zone, to prioritize interventions based on tree health, species vulnerability, and proximity to rail infrastructure.*

System Requirements: *The system must operate based on the following operational requirements:*

- ***Inventory and Geometry:*** *The system shall geolocate all trees and delineate canopy/crown shapes within the railway corridor and map them in a GIS environment.*
- ***Species Identification****: The system shall classify tree species and identify invasive flora (e.g. Japanese knotweed).*
- ***Health Assessment:*** *The system shall quantify dieback and physiological stress levels to identify trees at risk of structural failure.*
- ***Proximity Analytics:*** *The system shall flag any tree with a specific height-to-distance ratio indicating a strike risk (e.g. proximity < 6m).*
- ***Dynamic Frequency****: The system shall update risk profiles continuously, with high-threat segments (based on weather and tree health) refreshed on a regular basis.*

ID	EUSPA-EO-UR-RAI-0029
Application	Impact on vegetation cover
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Monitoring and managing trackside vegetation to mitigate climate-induced risks such as embankment desiccation, slope instability, and possible "strike" hazards (falling trees). Transition from reactive maintenance to a dynamic, risk-based strategy by identifying hazardous flora, assessing physiological health, and mapping invasive species.
Size of area of interest	Linear corridors across European rail networks (thousands of kilometers), including a specific lateral buffer zone (typically **10m to 50m**) from the track centreline.
Scale	**Local/Micro-scale:** Individual tree level for structural geometry and proximity analytics. **Regional-scale:** Landscape-level monitoring for drought-induced stress and species distribution.
Frequency of information	**Dynamic/Variable:** Annual updates for baseline geometry; 5-day intervals for health monitoring (during growing seasons/heatwaves); and bi-weekly updates for invasive species detection during bloom phases.
Other (if applicable)	Multi-source integration of VHR stereoscopic imagery for 3D modelling and high-revisit multispectral imagery for biological health assessment.
Service Provider Satellite EO Requirements	
Spatial resolution	**0.1m – 0.5m** for geometric precision, crown segmentation, and strike-risk modelling; **10m or better** for regional health indices (NDVI/NDRE) and phenological tracking.
Temporal resolution	**5 days** (Sentinel-2 revisit time) for continuous health monitoring; **Seasonal** for species classification; **Annual or Event-based** for structural height and proximity updates.
Data type / Spectral range	Multispectral including **Panchromatic**, **R**, **G, B, NIR, Red-Edge** (for chlorophyll stress), and **SWIR** (for water content and species "fingerprinting"). Synthetic Aperture Radar for roughness mapping; Digital Surface Models derived from stereo-photogrammetry or LiDAR.

Service Inputs	
Satellite data sources	**Copernicus:** Sentinel-2 (MSI), Sentinel-1 (SAR). **Commercial Missions:** Pléiades Neo, WorldView-3/4, SPOT, or Planet Scope for VHR data and high-revisit capacity.
Other sources	**Infrastructure Data:** Rail GIS layers (track geometry), catenary locations. **Environmental Data:** Soil maps (clay-content for desiccation risk), high-accuracy airborne LiDAR (for vertical calibration), and weather station feeds (temperature/wind).

Table 63: EO requirements for "Impact on vegetation cover"

2.8.2.4 Increased Risk of Wildfire (EUSPA-EO-UR-RAI-0030)

High temperatures dry out vegetation, reducing moisture content and increasing its flammability. Sparks from passing trains, overheated equipment or external sources can ignite dry vegetation, leading to wildfires that threaten rail infrastructure and surrounding areas. Smoke from fires can reduce visibility for train operators and disrupt services due to safety concerns.

User Need: *The Railway Infrastructure Manager requires a system to identify, monitor, and mitigate wildfire risks along the rail corridor to prevent damage to infrastructure, ensure operator visibility, and minimize service disruptions caused by trackside ignitions.*

User Requirement: *The system shall continuously assess the flammability of trackside vegetation and provide real-time alerts for active fire proximity or smoke-induced visibility reductions to ensure the safety of rail assets and operations.*

System requirements. *The system shall map the Fuel Moisture Content of trackside vegetation to identify high-ignition-risk zones during heatwaves; shall detect and geolocate thermal anomalies (hotspots) within a specified buffer zone from the track centreline; shall provide data to forecast visibility degradation along specific rail segment; shall predict the fire spread direction relative to railway assets.*

ID	EUSPA-EO-UR-RAI-0030
Application	Increased risk of wildfire
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Mitigation of wildfire risks triggered by climate-induced high temperatures and dry vegetation. Focusing on preventing trackside ignitions (from train sparks or equipment), protecting infrastructure from thermal damage, and managing operational safety issues such as smoke-induced visibility loss and service disruptions.
Size of area of interest	Linear rail corridors across the European network, typically extending to a **500m to 1km buffer zone** for fire spread monitoring and a broader regional extent for smoke (aerosol) dispersion.
Scale	**Local/Corridor Scale** for fuel moisture and hotspot detection; **Regional/Atmospheric Scale** for smoke density (AOD) and wind field modelling.
Frequency of information	**Dynamic/Real-Time:** Hourly updates for smoke and wind; Daily (day/night) for active hotspot detection; and every 5 days for vegetation flammability (fuel moisture) baseline updates.

Other (if applicable)	Integration of high-resolution multispectral imagery for fuel mapping and medium-to-low resolution thermal and atmospheric data for active fire/smoke monitoring.
Service Provider Satellite EO Requirements	
Spatial resolution	**10m – 20m** (Fuel moisture/LFM); **100m – 1km** (Thermal anomalies/FRP/Surface Temp); **10km – 40km** (Aerosol Optical Depth/Smoke).
Temporal resolution	**Hourly** (CAMS/C3S) for smoke and wind; **Daily** (Sentinel-3) for hotspots; **5 days** (Sentinel-2) for vegetation lifecycle and moisture trends.
Data type / Spectral range	**Multispectral** for indices NDWI, SAVI. **Thermal Infrared:** (S7-S9, 10.8μm–12μm) for brightness temperature, and dedicated fire channels (F1, F2) for high-temperature anomalies. **Atmospheric Modeling:** PM2.5/PM10 particulate matter and wind vectors (U/V components).
Service Inputs	
Satellite data sources	**Copernicus Sentinel-2** (MSI), **Sentinel-3** (SLSTR), **Sentinel-5P** (TROPOMI - for smoke precursors), and **Landsat-8/9** (for higher-res thermal monitoring).
Other sources	**Copernicus Services:** CAMS (Atmosphere) and C3S (Climate Change). **Ancillary Data:** Rail GIS (asset locations), digital elevation models (for fire spread physics), and local weather station data for real-time wind gusts.

Table 64: EO requirements for "Increased risk of wildfire"

2.8.2.5 Rapid Vegetation Growth (EUSPA-EO-UR-RAI-0031)

In regions where high temperatures coincide with sufficient rainfall, environmental conditions often trigger excessive vegetation growth, leading to significant operational and ecological challenges. This accelerated growth is frequently dominated by fast-growing invasive species that outcompete native flora, thus destabilizing local ecosystems and placing a heavier burden on infrastructure maintenance programs. For railway networks, the consequences are particularly acute as overgrown plants encroach upon the tracks, potentially obstructing driver sightlines, interfering with critical signalling systems, and reducing the necessary physical clearance for safe train passage.

User Need: *The Railway Infrastructure Manager requires to identify and quantify excessive vegetation growth and invasive species encroachment to maintain safety clearances, preserve signal visibility, and prevent structural destabilization of the rail corridor.*

User Requirement: *The system needs to detect and geolocate all vegetation within the defined railway clearance zone that poses a threat to signal sightlines, track stability, and infrastructure integrity.*

System Requirements: *The system shall detect any vegetation encroaching within the minimum safe clearance envelope. The system shall differentiate between native, and priority invasive species (e.g., Japanese knotweed) based on unique growth characteristics. The system shall identify vegetation that obstructs the visual cone of any lineside signal or safety signage. The system shall calculate biomass accumulation rates to predict when a track segment will breach safety thresholds.*

Additional information can be found in section 2.6.3. "Infrastructure monitoring."

ID	EUSPA-EO-UR-RAI-0031
Application	Rapid vegetation growth
Users	Railway infrastructure owners and/or operators
User Needs	

Operational scenario	Managing accelerated vegetation growth and invasive species encroachment (e.g., Japanese Knotweed) triggered by high heat and rainfall. The scenario focuses on maintaining the "clearance envelope," ensuring signal visibility, and preventing structural destabilization of rail corridors through a transition from reactive cutting to predictive, risk-based maintenance.
Size of area of interest	Linear railway corridors across regional or national networks (potentially thousands of km), focusing on a lateral buffer typically **5m to 20m** from the track centreline.
Scale	**Local/object-scale:** Precision required to identify individual branches or signal obstructions. **Regional-scale:** Monitoring biomass growth across entire climate-affected zones.
Frequency of information	**Dynamic/High-Frequency:** Every **5 to 10 days** for growth surges and biomass monitoring; **Weekly** for invasive species vigour; **Annual/Seasonal** for structural 3D clearance and sightline audits.
Other (if applicable)	Integration of high-revisit multispectral data for biological activity and Very High Resolution 3D data for geometric clearance modelling.
Service Provider Satellite EO Requirements	
Spatial resolution	**Geometric:** < 0.25m for signal sightlines and < 0.5m for 3D clearance. **Biological:** 3m to 10m for biomass density and chlorophyll activity tracking.
Temporal resolution	**5-day revisit** (revisit time of Sentinel-2) to capture rapid growth following rainfall; **Seasonal** updates for height-based risk assessment.
Data type / Spectral range	Multispectral including **Visible (RGB) and Near-Infrared (NIR)** for NDVI, **Red-Edge** (700-740 nm) for vigour/species identification; **Short-Wave Infrared (SWIR)** for water content/biomass. **Structural:** 3D Point Clouds, Digital Surface Models, and Vector Polygons (XYZ). **Radar:** C-band SAR for moisture/ground stability monitoring.
Service Inputs	
Satellite data sources	**Copernicus:** Sentinel-2 (MSI) and Sentinel-1 (SAR). **Commercial:** VHR missions (e.g., Pléiades Neo, WorldView, Planet SkySat) for stereo-imagery and 0.5m DSMs.
Other sources	**Infrastructure Data:** Signal/signage geocoordinates, track centreline GIS, and dynamic train clearance envelope specs. Copernicus Climate Change Service (C3S) / ERA5-Land for rainfall/temperature correlations; airborne LiDAR for high-precision baseline mapping.

Table 65: EO requirements for “Rapid vegetation growth”

2.8.2.6 Impact on Soil and Root Systems (EUSPA-EO-UR-RAI-0032)

Soil contraction due to dehydration may lead to ground movement, increasing the risk of embankment failures or track misalignment. Loss of vegetation due to heat stress can exacerbate soil erosion during subsequent rainfall events.

User need: *The Railway Infrastructure Manager needs to detect sub-surface soil contraction (desiccation) and surface vegetation loss to prevent embankment failures, track misalignments, and rainfall-induced erosion.*

User Requirement: *The system shall identify millimetric ground movements and changes in vegetation density that correlate with soil dehydration and increased erosion vulnerability.*

System Requirements: *The system shall detect vertical and horizontal ground displacement caused by soil dehydration; shall identify segments where clay-rich soils are undergoing volumetric shrinkage; shall flag areas where vegetation loss exposes bare soil to erosion; shall cross-reference soil moisture deficit with ground movement to predict track misalignment.*

ID	EUSPA-EO-UR-RAI-0032
Application	Impact on soil and root system
Users	Railway infrastructure owners and/or operators.
User Needs	
Operational scenario	Detection of sub-surface soil desiccation and surface vegetation loss to prevent embankment failures and track misalignment. The focus is on monitoring millimetric ground displacement in clay-rich soils and identifying erosion-prone segments where heat stress has depleted protective vegetation cover.
Size of area of interest	Linear corridors covering trans-European rail networks, focused on specific geotechnical hotspots characterized by high clay content and steep embankment gradients.
Scale	**Local to Regional:** Millimetric precision for track-side displacement (local) integrated with regional soil moisture trends and geological mapping.
Frequency of information	**Continuous/High Frequency:** Daily to weekly updates for soil moisture and vegetation health; monthly cumulative reporting for ground displacement trends.
Other (if applicable)	Integration of InSAR for displacement, multispectral imaging for vegetation/soil composition, and microwave radiometry for moisture.
Service Provider Satellite EO Requirements	
Spatial resolution	• **Ground Displacement:** 10m – 20m (InSAR) • **Vegetation Cover (FCover):** 10m – 20m • **Soil Moisture (SWI):** 0.1km – 1km • **Geology/Elevation:** 30m – 100m
Temporal resolution	**Daily to 12-day revisit:** 5-day revisit for Sentinel-2 (Optical); 6–12 day revisit for Sentinel-1 (Radar); Daily for Sentinel-3/SMOS (Moisture).
Data type / Spectral range	**Radar:** C-band or X-band (for InSAR). **Optical:** Red, NIR (for FCover), and SWIR (for Clay Content/Mineralogy). **Microwave:** L-band or C-band (for Soil Water Index). **Active Microwave:** Phase-shift measurement (SAR). **Passive Microwave:** Brightness temperature (Soil moisture).

	Multispectral: VNIR and SWIR (400nm – 2500nm).
Service Inputs	
Satellite data sources	**Copernicus:** Sentinel-1 (InSAR), Sentinel-2 (FCover), Sentinel-3 (Soil Water Index). **Contributing Missions:** SMOS (Soil Moisture), TerraSAR-X or COSMO-SkyMed (for higher resolution 2mm displacement).
Other sources	**Geological Maps:** Cation Exchange Capacity (CEC) and lithological maps for clay identification. **Topographic Data:** High-resolution Digital Elevation Models for slope gradient analysis. **In-situ:** Piezometers (groundwater levels) and track geometry cars (alignment verification).

Table 66: EO requirements for "Impact on soil and root systems"

2.8.2.7 Sparta Project – Case Study

High rail temperatures present a critical risk to railway infrastructure, often leading to track buckling and significant operational downtime. The Horizon Europe project **SPATRA (Satellite-based Prediction for Rail Track Risk Assessment)** explores how EO and AI can provide a scalable, cost-effective alternative to traditional monitoring, optimizing safety and scheduling for infrastructure managers [RD49].

The Challenge: Thermal Stress and Infrastructure Risk

When rail temperatures reach or exceed **60°C**, the steel expands significantly, leading to **lateral displacement** or "buckling." This phenomenon poses severe threats to the rail ecosystem:

- **Safety Hazards:** High risk of derailments and catastrophic failure of signalling/control systems.
- **Operational Delays:** Thermal issues account for approximately 240 days of train delays in EU annually.
- **Economic Impact:** Increased maintenance costs, energy inefficiencies, and massive financial losses due to schedule disruptions.

Current monitoring of rail track temperature relies on weather forecasts that introduce a varying sptial and temporal bias) or sparse in-situ sensors. This leaves infrastructure managers with a "blind spot" between localized data and network-wide reality. Uncertainty around rail track temperature and buckling risk leads managers to both introduce unnecessary conservative operational restrictions while at the same time taking on unacknowledged risk.

The Solution: The SPATRA Approach

SPATRA utilizes satellite-derived Land Surface Temperature (LST) data combined with AI to create a predictive digital twin of track conditions. The solution is structured into three integrated modules:

Real-Time Estimation: Translating LST data into precise rail temperature readings.

Forecasting (RTTP Model): Predicting future rail temperatures to allow for proactive planning.

Buckling Prediction: Analysing potential lateral displacement to identify high-risk zones.

By providing more granular data than traditional forecasting, SPATRA has demonstrated superior precision in real-world applications, leading to the following improvements:

- **Optimized Evening Efficiency:** The system successfully shortened restriction periods by approximately four hours in the evenings, allowing for a faster return to normal service speeds.

- **Enhanced Morning Planning:** Infrastructure managers can now identify earlier windows for introducing speed restrictions, ensuring safety measures are in place before peak thermal stress occurs.

- **Data-Driven Decision Support:** The model enables the timely imposition of "low-speed orders," replacing guesswork with data-driven safety protocols to mitigate derailment risks.

- **Network-Wide Scalability:** Unlike physical sensors, the satellite-based approach allows for comprehensive monitoring across entire rail networks without the prohibitive costs of hardware installation and maintenance.

To transition from a validated prototype to a global standard, the SPATRA project is focused on:

- **Model Refinement:** Incorporating additional datasets to retrain and sharpen AI predictive accuracy.

- **Operational Validation:** Partnering with stakeholders for preliminary field use.

- **Feedback Loops:** Collecting continuous user data to improve the interface and reliability before broad deployment.

SPATRA transforms Earth Observation data into actionable safety intelligence, ensuring that rail networks remain resilient in an era of increasing extreme heat events. [RD50]

Table 67: SPATRA PROJECT – CASE STUDY

2.9 EO User Requirements Specifications

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
EUSPA-EO-UR-RAIL-0011	Weather exceeding expectations	*The Operations Manager needs the ability to proactively adjust rail services and infrastructure readiness because unexpectedly high precipitation can cause derailments and flooding when alerts aren't triggered, in the context of rapidly changing regional weather patterns.*	Regional rail networks and small catchments/basins adjacent to tracks that lack ground-based sensors.	Dynamic Refresh Rate: Near-real-time "nowcasting" (< 5 minutes) when precipitation exceeds 20mm/hour; otherwise, daily probabilistic forecasting (up to 10 days in advance).	High-Granularity: $1km^2$ for localized precipitation cells and ERIC flash flood indicators	Multi-Tiered: < 5-minute refresh for active alerts; 5 to 10-day lead times for EFAS probabilistic forecasting; and 5-day lead times for ERIC flash flood surges.	Data Fusion Approach: Radar (Sentinel-1): Global Flood Monitoring (GFM) to confirm locations through cloud cover. Atmospheric (CAMS): Water vapor tracking to identify "super-charged" air masses. Predictive AI (AIFS): Machine learning models for "low probability/high impact" scenarios. Hydrological Models: EFAS/GloFAS for probabilistic ensemble forecasting.
EUSPA-EO-UR-RAIL-0012	Infrastructure integrity, geohazards, land service	*Geotechnical engineers need the ability to identify accelerating slope displacement because undetected soil creep often precedes catastrophic failure during heavy rain, in the context of routine maintenance and seasonal storm preparation.*	Linear railway corridors, specifically embankments and surrounding natural terrain prone to landslides/subsidence.	Dynamic (Real-time to Weekly): Continuous 15-minute to hourly monitoring for in-situ sensors; 6–12 day updates for satellite-based displacement maps; and weekly/monthly Soil Moisture Index updates.	High Precision (0.3m to 10m): 0.3m–0.5m for post-event erosion/scour detection; 1m–3m for embankment-scale SAR displacement; and 10m for regional soil moisture mapping.	Revisit & Archive: 6–12 day revisit cycles (standard for SAR constellations like Sentinel-1); supported by a 3 to 5-year historical archive to establish seasonal baselines.	SAR (InSAR): Multi-temporal InSAR (Ascending/Descending orbits) for mm-level Line-of-Sight (LoS) displacement. Optical/Multispectral: High-resolution VHR imagery for erosion and scour mapping. Topographic: Digital Elevation Models (DEM) for slope geometry. In-situ/Ground Truth: Integrated pore water pressure, VWC (Volumetric Water Content), and track-side sensors.

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
EUSPA-EO-UR-RAIL-0013	River flooding	*The Rail Network Operator needs the ability to receive timely hydrological alerts and flood depth projections because rising river levels can lead to track washouts or bridge instability, in the context of extreme weather events and seasonal runoff.*	River-adjacent assets, bridge crossings, and flood-prone track sections (catchment-scale monitoring with asset-specific focus).	High-Frequency/Real-Time: 5–15 minute updates for hydrological gauges and meteorological radar during "Action Stage" levels; 10-day lead times for forecasting; and 1–3 day updates for flood extent mapping.	Variable Multi-Scale: <1m for topographic DEMs and asset elevations; 3m–10m for SAR flood extent; 1km for gridded precipitation; and mm-scale for InSAR-based bridge displacement.	Event-Driven: 5-minute sampling for active flood stages; 5-day to 12-day revisits for satellite-based displacement and recovery mapping; and static baseline updates for topography/BIM data post-major events.	Synthetic Aperture Radar (SAR): Sentinel-1 (GFM) for all-weather flood extent and depth mapping. InSAR: For mm-scale monitoring of bridge/pier displacement trends. Meteorological Satellite/Radar: For precipitation nowcasting and gridded rainfall. Copernicus Services: EFAS/GloFAS for discharge forecasting and EMS Risk & Recovery for damage grading.
EUSPA-EO-UR-RAIL-0014	Increased runoff	*Maintenance Engineers need to anticipate and mitigate soil and drainage saturation levels because extreme runoff can cause embankment instability and culvert failure, in the context of rapid-onset extreme precipitation events.*	Catchment-scale monitoring (The specific land area draining into rail assets, often extending several kilometers from the track).	High-Frequency/Real-Time: 5-minute intervals for rainfall nowcasting (QPF) and 15-minute intervals for in-situ geotechnical triggers. Daily/Weekly: For soil saturation trends and snow water equivalent (SWE).	Variable/Multi-Scale: <0.5m to 1m for topographic DTMs and asset geometry; 10m to 30m for land use and soil moisture; and 500m grid for meteorological rainfall intensity.	Dynamic Revisit: 5-minute refresh for precipitation; 1–3 day revisit for SAR-based moisture; Monthly updates for land use/runoff coefficients; Static/Baseline for topography and drainage geometry.	Radar (SAR & X-Band): InSAR/SAR for Soil Saturation Index (SSI) and X-band ground-based radar for Rainfall Intensity (QPF). Multispectral: Sentinel-2/Landsat for Land Use (Runoff Coefficient 'C') and monitoring river turbidity as a proxy for sediment-heavy runoff. Altimetry: Sentinel-3 for measuring water surface height/river discharge volumes. Topographic/LiDAR: Airborne LiDAR for high-precision Digital Terrain Models (DTM) to map hydraulic flow paths.
EUSPA-EO-UR-	Lack of awareness of a site	*The Rail Operator needs the ability to identify high-*	Network-wide / Catchment Scale	Hybrid Frequency: Periodic baseline updates every 3–5 years for	High Precision to Regional: 1m–3m for to-	Variable: Static for geological/topographic features; 5min	SAR (Synthetic Aperture Radar): Sentinel-1 archive for flood history and InSAR for "Slow Creep" displacement (+/- 2mm/year).

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
RAIL-0015	being at risk	*risk sites (flood zones, landslide susceptibility areas) that have not been previously identified and mapped because relying solely on historical event data could fails to account for changing environmental patterns and "hidden" vulnerabilities, in the context of network-wide risk assessment and climate adaptation planning.*	(including upstream areas affecting the rail corridor).	DTM/Lithology; Continuous monitoring for dynamic factors like land cover (seasonal) and soil saturation (near real-time).	pography and displacement; 10m–30m for land cover/DEM; and 100m–500m for regional soil saturation. Scale of 1:10,000 for geological mapping.	to 72h durations for climate (IFD curves); and historical archive analysis (Sentinel-1/2) spanning several years to reconstruct "Risk Memory."	Multispectral: Sentinel-2 for land cover, impermeability maps, and runoff coefficients. Airborne LiDAR: High-res DTM for slope, aspect, and curvature. Climatic/Hydrological Models: Copernicus EFAS/LISFLOOD for flash flood indicators.
EUSPA-EO-UR-RAIL-0016	Climate impact analysis	*The Rail Operator needs to identify high-risk sites (flood zones, landslide susceptibility areas) that have not been previously identified because historical records alone do not capture the evolving risk profile driven by climate change.*	Regional to National rail networks; specifically high-vulnerability "weak points" like mountain passes, coastal lines, and embankments.	Strategic & Operational: Daily to 6-hourly for historical reanalysis (to establish baselines); 6-yearly for land cover updates; and decadal increments (e.g., 2030, 2050, 2100) for long-term climate projections.	Multi-Scalar: <4m (Vertical) for DEM topography; 1.5km to 9km for local hydrology (EFAS/ERA5-Land); and 10km to 12km for downscaled climate projections (EURO-CORDEX).	Historical to Future (1950–2100): Continuous 6-hourly/daily archives from 1950/1970 to present (ERA5); and future simulated daily/monthly projections reaching up to the year 2100.	Climate Reanalysis & Projections: Reanalysis: ERA5/ERA5-Land (merged satellite and station data). Climate Models: CMIP6 and EURO-CORDEX (Simulated precipitation/SSP scenarios). Topographic/Hydrological: Copernicus GLO-30 DEM and EFAS discharge models. Thematic: Corine Land Cover (CLC) for surface friction/runoff analysis
EUSPA-EO-UR-RAIL-0017	Topography: Elevation, slope, and aspect of	*The Rail Infrastructure Manager needs to assess the railway's exposure based on its geographical setting and historic weather*	The "Zone of Influence" surrounding the railway infrastructure (requires	Static to Periodic: Primarily a baseline dataset (Static). Updates are required post-major geohazard events (e.g., landslides) or after significant	High Precision (≤5m): Specifically requiring 1m precision for asset-level exposure to distinguish between	Low Update Cadence: Baseline topographical mapping with "Post-event" verification. Must support risk-assessment	Digital Elevation Models (DEM/DTM): Derived from LiDAR (standard for 1m vertical accuracy) or high-resolution InSAR point clouds. Data must be delivered in INSPIRE-

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
	the railway's geographical location	*conditions because elevation and slope gradients significantly dictate how precipitation transforms into flood or landslide risks.*	100% spatial coverage of the corridor and adjacent terrain).	infrastructure earthworks to maintain 1m precision.	the track-bed and drainage ditches.	workflows by aligning with historical weather station data intervals.	compliant formats (GML/GeoPackage) using ETRS89/EVRS datums.
EUSPA-EO-UR-RAIL-0018	Proximity to water: Distance from rivers, lakes, and coastlines, proximity to flood-prone areas	*The Rail Infrastructure Manager needs to quantify the spatial relationship between rail assets and nearby hydrological features because assets located in the proximity of water bodies or historical floodplains are inherently more sensitive to the extreme precipitation events.*	Linear Catchment Buffers: Focus on 0–500m horizontal distance from track center-lines intersecting with hydrological features and floodplains.	Low to Event-Driven: Updated annually to reflect morphological changes in riverbeds/coastlines, or immediately following major flood/storm surge events.	High Precision: Requires < 10m horizontal resolution for proximity buffering (10m increments) and < 0.5m vertical accuracy for Freeboard Height/Mean High Water (MHW) assessments.	Static/Annual Baseline: Consistent with long-term return periods (T=20, 100, 500 years) and annual updates for hydrological vector changes.	VHR Digital Elevation Models (DEM): LiDAR-derived or Stereo-optical (e.g., WorldView) for vertical offsets and freeboard height. Synthetic Aperture Radar (SAR): For flood extent mapping (e.g., Sentinel-1) and coastal baseline detection. Multispectral Imagery: For delineating water bodies and Strahler Stream Order classification. Altimetry: Satellite altimetry (e.g., SWOT mission) for monitoring water surface elevations and MHW.
EUSPA-EO-UR-RAIL-0019	Flood zones: Presence in areas officially designated as flood-prone.	*The Rail Infrastructure Manager needs to identify assets at risk of inundation from coastal storm surges and riverine proximity because sea-level rise and increasing peak discharge in European basins directly threaten low-lying coastal and riparian rail corridors, in the context of EU Climate Adaptation strategy and*	Corridor & Catchment Scale: Specific focus on low-lying coastal areas (within 1km of EU-Hydro coastline) and riparian buffers (50m, 100m, 250m) along major European river basins	Cyclical & Event-Driven: Strategic updates aligned with the EU Floods Directive (typically 6-year cycles) supplemented by "Post-event" updates and real-time alerts from EFAS during extreme weather.	High Precision: Vertical accuracy strictly tied to the EVRS (European Vertical Reference System); Horizontal resolution matching EMODnet High-Res Grids and National/Regional Flood Hazard Maps	Static Baseline with Dynamic Modeling: Multi-decadal climate scenarios for sea-level rise; Daily/Seasonal for river discharge and storm surge modeling; 5–100 year return period probabilities.	Altimetry & Bathymetry: Satellite altimetry for Mean Sea Level; EMODnet High-Res Grid for wave modeling. Synthetic Aperture Radar (SAR): Sentinel-1 for flood extent mapping (Copernicus EMS). Digital Elevation Models (DEM): High-accuracy TanDEM-X or LiDAR-derived Copernicus DEMs for vertical flood-risk filtering.

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
		Trans-European Transport Network (TEN-T) resilience.	(Rhine, Danube, Po).		(FHM) for return periods (T=5 to T=500).		
EUSPA-EO-UR-RAIL-0020	Historical weather patterns: Analysis of past weather events such as heavy rainfall and floods.	*The Rail Infrastructure Manager needs to analyse historical weather patterns (heavy rainfall, flood events, and storm surges) because understanding the frequency and magnitude of past disruptions is essential to calibrating risk thresholds for existing assets, in the context of validating climate models against real-world historical performance.*	Regional to National (Rail corridors and associated hydrological catchments).	High-Frequency Historical Reanalysis: Hourly for precipitation "bursts" (washouts); Daily for cumulative antecedent rainfall (soil saturation); and Event-based for peak river gauge heights.	Variable/Hybrid: 9km for ERA5-Land reanalysis; Point-specific for in-situ weather stations and river gauges; and <30m for localized hydraulic mapping at bridges/crossings.	Long-term Archive (1970–Present): Hourly intervals for Intensity-Duration-Frequency (IDF) curve generation; 5-day and 30-day windows for antecedent moisture analysis.	Climate Reanalysis: ERA5-Land (ECMWF) for harmonized global/regional weather history. Hydrometric Data: In-situ river gauge height and discharge records. Satellite Precipitation: GPM (Global Precipitation Measurement) or TRMM for verifying ungauged areas. Historical Imagery: Archive SAR or Optical data to delineate past flood extents (e.g., Landsat/Sentinel-1)
EUSPA-EO-UR-RAIL-0021	Climate Projections	*The Rail Infrastructure Manager needs to evaluate how the railway system will be affected by future climate scenarios (up to 2100) because relying on historical data alone underestimates the risk of unprecedented rainfall, heat-induced soil instability, and sea-level rise, in the context of long-term capital investment and climate adaptation planning.*	Regional to Local: National or regional rail networks, with high-resolution downscaling applied to vulnerable segments (e.g., coastal lines, flood-prone embankments).	Epochal / Planning Cycles: Focused on key horizons—2030, 2050, and 2100. Data ingestion involves continuous updates as new IPCC/CMIP6 cycles are released, with daily/3-hourly slices used for storm modeling.	Multi-Scale Downscaling: Regional ensembles at 12.5 km (0.11°) (CORDEX-EUR-11) downscaled to 1 km or finer for local asset-level vulnerability mapping.	High-Frequency Intervals: Daily to 3-hourly intervals are required to capture convective storm peaks and extreme T-max thresholds (e.g., >35°C), summarized into 20-30 year climatological averages.	Climate Reanalysis & Projections: Historical baselines (ERA5-Land), Regional Climate Models (RCMs) for precipitation/temp, and sea-level rise projections (CMIP6). Auxiliary EO Layers: Land Cover (CLMS) for runoff modeling, InSAR (EGMS) for current subsidence baselines, and VHR DEMs for flood risk.

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
EUSPA-EO-UR-RAIL-0022	Impervious Surfaces (artificial sealing)	*The Rail Drainage Engineer needs to map artificially sealed (impervious) zones within the rail catchment because surfaces with zero infiltration generate maximum runoff velocity and volume, in the context of calculating peak discharge requirements for culverts and track-side gutters.*	Catchment-scale (Rail trackbed and adjacent urban infrastructure contributing to track-side drainage).	Low to Medium (3-year cycle): Updates must align with the Copernicus HRL update frequency to capture new urban development or infrastructure changes.	High (2m to 10m): 10m standard for general catchment modeling; 2m high-resolution for distinguishing the specific rail trackbed from adjacent urban sealing.	Triennial (3-Year Baseline): Minimum 3-year update cycle for the High Resolution Layer (HRL), supplemented by post-construction aerial or satellite imagery updates.	Optical/Multispectral Imagery: Used for LULC (Land Use/Land Cover) classification and Imperviousness Density (0-100%). Digital Elevation Models (DEM): 10m resolution for calculating runoff velocity (v) as a function of slope. GIS-Integrated CLMS Layers: Specifically the High Resolution Layer (HRL) for Soil Sealing.
EUSPA-EO-UR-RAIL-0023	Human-made or modified porous surfaces	*The Rail Infrastructure Manager needs to account for surfaces with restricted or variable infiltration (e.g. agricultural land and semi-permeable paving) because natural soil crusting or man-made modifications can cause unexpected run-off volumes that bypass standard drainage designs, in the context of identifying hidden vulnerabilities in rural or semi-urban rail corridors.*	Rural and semi-urban rail corridors (including adjacent agricultural catchments affecting track drainage).	High Frequency (5-Day Revisit): Critical for capturing rapid land-use changes such as ploughing, harvesting, or vegetation growth stages that influence soil crusting and infiltration capacity (10 to 25 mm/hr).	High to Coarse (10m to 1km): 10m–20m resolution is required to delineate field boundaries and access roads; 250m–1km resolution is utilized for regional soil texture (Clay/Silt/Sand) baselines.	Seasonal & Event-Based: Regular 5-day monitoring of vegetation indices (NDVI/SAVI) to determine "Porous Surface Fraction," supplemented by static soil texture data from the European Soil Data Centre.	Multispectral (Red, NIR, SWIR): Essential for moisture detection and bare soil exposure. Optical Indices: NDVI (Normalized Difference Vegetation Index) and SAVI (Soil Adjusted Vegetation Index). Thematic Soil Data: Gridded datasets (ESDAC) for textural composition.
EUSPA-EO-UR-RAIL-0024	Natural drainage conditions (infiltration capacity)	*The Rail Infrastructure Manager needs to evaluate the land's capacity to mitigate heavy rain through interception and storage because natural ecosystems*	Catchment-wide: Extension beyond the immediate track to the full rail catchment	Monthly to Seasonal: Required to capture deciduous "leaf-off" periods in winter and seasonal variations in Soil Water Index	Multi-tiered: High (10m–20m): For vegetation canopy (Sentinel-2), impervious surface mapping, and urban atlas classes Medium (250m–1km):	Dynamic & Seasonal: Monthly updates for biomass/LAI and phenology; daily to weekly monitoring for Soil Water Index (SWI) to determine	Multispectral (Optical): Sentinel-2 (NDVI/LAI) for vegetation interception and surface roughness (Manning's n). Radar (SAR): Sentinel-1 for Soil Water Index (0–100 saturation scale).

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
		(e.g. forests, wetlands, undisturbed soils) act as a primary flood defence by absorbing water before it reaches the tracks, in the context of identifying natural "safety zones" and protecting critical environmental assets within the rail corridor.	area (Hydrological Connectivity).	(SWI) and antecedent moisture conditions.	For regional soil parameters (SoilGrids) and Saturated Hydraulic Conductivity (K_sat}). Vertical/Topographic: 1:30,000 scale or finer for hydrological connectivity (EU-DEM).	Antecedent Moisture Condition (AMC) before peak precipitation events.	Topographic/Hydrological: EU-DEM and EU-Hydro for mapping drainage flow paths and connectivity. Thematic Products: Copernicus HRL (High Resolution Layers) for Imperviousness and Tree Cover Density.
EUSPA-EO-UR-RAIL-0025	Geomorphology	*The Rail Geotechnical Engineer needs to evaluate the geological and topographical stability of the rail corridor because specific soil types and steep slope geometries are prone to failures (landslides, washouts, subsidence) when saturated, in the context of preventing structural integrity loss during extreme precipitation events.*	Track centerline plus a 500m lateral buffer to capture up-slope flow accumulation and surrounding terrain characteristics	Variable/Hybrid: Monthly: Updates for ground deformation (EGMS/InSAR) to track creep. Near Real-Time (<24 hrs): Synchronization between rainfall events and soil state updates. Static/Baseline: Geological soil type and slope gradient mapping (updated post-event).	High-Precision Multiscale: <2m: For Slope Gradient and Flow Accumulation (LiDAR-derived DTM). 10m: For Ground Deformation (InSAR), drainage capacity, and water flow paths. 10m to 100m: For regional soil texture and mineral indices.	High Recurrence: Monthly updates for displacement time-series; 5-day revisit for Sentinel-2 spectral indices; and <24-hour latency for triggering Landslide Susceptibility Index (LSI) alerts during precipitation events.	Radar (SAR/InSAR): Sentinel-1 and European Ground Motion Service (EGMS) for millimeter-level monitoring of slope creep and subsidence. Optical/Multispectral: Sentinel-2 for mineral indices (clay/sand) and moisture-driven drainage detection. Topographic (DEM/DTM): LiDAR-derived Digital Terrain Models for slope/aspect and EU-Hydro for connectivity. Derived Products: Copernicus EMS for historical failure footprints and Landslide Susceptibility Indices (LSI).
(EUSPA-EO-UR-RAIL-0026)	Environmental impact	*The Rail Environmental Compliance Officer needs to quantify the ecological and hydrological consequences of a climate-related asset failure because breaches in infrastructure*	Linear track corridors including a 500m buffer on both sides to cap-	Variable & Event-Driven: Daily to 5-day monitoring for water quality; Near Real-Time (<24 hours) for pollutant drift during emergencies; Seasonal/Annual for habitat	High Precision (<5m to 20m): <5m for gully detection/erosion; 10m for pollutant drift and habitat mapping (aligning with 1ha MMU); and 10m–20m	Dynamic Revisit: High-frequency (Daily/5-day) for water/vegetation; Near Real-Time (NRT) for spill response; and	Multispectral (Level 2A): Atmospherically corrected optical data (e.g., Sentinel-2) for water greenness, turbidity, and habitat extent.

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
		(e.g., bridge collapses or embankment washouts) can discharge pollutants into protected watercourses and destroy natural habitats.	ture sedimentation and pollutant runoff.	mapping; and Post-event assessments within 48 hours.	for capturing sediment plumes in narrow watercourses (e.g., 5m wide streams).	Static/Seasonal baselines for "Riparian Zones" and "Natura 2000" site intersections.	Copernicus Land (CLMS): Riparian Zones (RZ) and Natura 2000 (N2K) products for ecological buffering. Emergency Mapping (CEMS): Delineation maps for flood/habitat submergence. Climate Data (C3S): Soil moisture for pollutant "flushing" potential. VHR Optical/Radar: For gully/erosion detection (<5m resolution)
(EUSPA-EO-UR-RAIL-0027)	Climate data and projections	*The Railway Infrastructure Manager requires a standardized, high-resolution evidence base of historical and projected temperature extremes to identify segments vulnerable to track buckling, equipment failure, and heat-related operational delays.*	Regional to National (Track-level granularity along the entire rail network).	Daily to Multi-Decadal: Daily updates for recent historical monitoring (ERA5-Land); Decadal updates for long-term climate projections (CMIP6) spanning to 2050 and 2080.	High-Resolution Reanalysis (9km): ERA5-Land provides 0.1° (~9km) horizontal resolution. Projections (CMIP6) are typically at 25km–100km, often requiring Local Downscaling to match track-level needs (<1km).	Hourly to Seasonal/Long-term: Hourly data for calculating thermal amplitude and extreme maximums; Daily counts for threshold indicators (e.g., Tmin > 20°C); and Annual/Decadal slices for future-proofing.	Climate Reanalysis & Projections: Historical: ERA5-Land (Merged Satellite & In-situ Reanalysis). Projected: CMIP6 Global Climate Models (GCMs). Indicators: C3S Agrometeorological and Thermal Assessment indices
(EUSPA-EO-UR-RAIL-0028)	Soil stability and moisture content	*The Railway Infrastructure Manager needs to ensure the structural stability and operational safety of earthworks (embankments, slopes, and cuttings) by identifying and mitigating heat-induced soil degradation, such as desiccation,*	Linear Network-Wide: Specifically focused on embankments, slopes, and cuttings along the track corridors, including localized "heat hotspots."	High-Frequency (Daily to Weekly): Daily monitoring for Thermal Stress (LST) and Surface Moisture (SSM); 5-day intervals for Vegetation Health (NDVI/NDMI); and 6–12 day cycles for structural displacement.	Multi-Tiered Resolution: High (5m – 20m): Ground displacement and vegetation stress indices.	Continuous & Dynamic: Real-time daily updates for moisture and temperature variables; 5–12 day repeat cycles for physical deformation and vegetation status; and 8–10 day synthesis	Radar (SAR): Sentinel-1 (Level-1 SLC) for millimetric displacement (EGMS) and soil wetness. Optical/Multispectral: Sentinel-2 (Red/NIR/SWIR) for NDVI/NDMI to detect vegetation moisture stress.

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
		shrinkage, and differential settlement.			Medium (30m – 100m): General embankment land cover. Coarse (1km – 10km): Regional Land Surface Temperature (LST) and Soil Water Index (SWI).	for root-zone moisture (SWI).	Thermal Infrared: Sentinel-3 for radiometric Land Surface Temperature (LST). Modeled/Geophysical Products: Copernicus Land Monitoring Service (CLMS) for Soil Water Index (SWI).
(EUSPA-EO-UR-RAIL-0029)	Impact on vegetation cover	*The Railway Infrastructure Manager requires a detailed geolocated inventory of vegetation along the tracks to identify hazards (such as falling trees, rail-line encroachment, and invasive species) to transition from reactive maintenance to a dynamic, risk-based mitigation strategy.*	Linear railway corridors, specifically focusing on a buffer zone defined by the tree height-to-distance "Strike Risk" ratio (e.g., proximity < 6m).	Dynamic/Multi-layered: High-frequency (5-day to bi-weekly) updates for health stress and invasive species during bloom phases; Seasonal updates for species identification; Annual or post-event updates for structural geometry/height.	Very High Resolution (VHR): 0.3m to 0.5m for geometry, crown segmentation, and proximity modeling; 10m or better for regional health indices (NDVI/NDRE) and species classification.	Variable Revisit: 5-day cycle for physiological stress (Sentinel-2); Bi-weekly for invasive species "fingerprinting"; Annual baseline for 3D Digital Surface Models (DSM).	VHR Optical (Panchromatic/Multispectral): For 0.3m–0.5m geometry and strike-risk modeling. Stereo-Photogrammetry & LiDAR: For 3D Digital Surface Models (DSM) and tree height. Multispectral (Red-Edge/NIR/SWIR): Sentinel-2 and commercial missions for health indices (NDVI/NDRE) and spectral fingerprinting of invasive species. SAR (Sentinel-1): For terrain roughness and wind exposure indexing.
(EUSPA-EO-UR-RAIL-0030)	Increased risk of wildfire	*The Railway Infrastructure Manager requires a system to identify, monitor, and mitigate wildfire risks along the rail corridor to prevent damage to infrastructure, ensure operator visibility,*	Linear Rail Corridor: Specifically the track centerline with a variable buffer (typically 50m–500m for ignition risk	Near Real-Time (NRT) to Weekly: Hourly updates for atmospheric conditions (smoke/wind); Daily for hotspot detection and surface temperature;	Multi-resolution (10m to 10km): High-resolution (10m–20m) for trackside fuel mapping; Medium-resolution (100m–1km) for thermal hotspots;	High Frequency Revisit: 5-day cycle for Sentinel-2 (vegetation stress); Daily (day/night) for Sentinel-3 (thermal anomalies); Hourly for	Optical/Multispectral: NIR and SWIR bands (Sentinel-2) for NDWI/SAVI to map Live Fuel Moisture. Thermal Infrared (TIR): Brightness temperature and Fire Radiative Power (FRP) from

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
		and minimize service disruptions caused by trackside ignitions.	and up to 10km for fire spread/smoke proximity).	Every 5 days for vegetation fuel moisture (LFM) assessment.	Coarse-resolution (10km) for regional smoke/aerosol dispersion and wind fields.	CAMS and C3S (smoke density and wind direction).	Sentinel-3/Landsat for active hotspot detection. Atmospheric Modeling: Aerosol Optical Depth (AOD) and Particulate Matter (PM2.5/10) from CAMS for visibility assessment. Climatic Reanalysis: U/V Wind components at 10m height (C3S/ECMWF) for fire spread forecasting.
(EUSPA-EO-UR-RAIL-0031)	Rapid vegetation growth	*The Railway Infrastructure Manager requires to identify and quantify excessive vegetation growth and invasive species encroachment to maintain safety clearances, preserve signal visibility, and prevent structural destabilization of the rail corridor.*	Along the tracks corridors (Specifically targeting the minimum safe clearance envelope and signal visual cones).	High-Frequency & Seasonal: Weekly to 5-day intervals for growth surges and biomass monitoring; Seasonal to Annual for 3D height and structural encroachment mapping.	Variable (0.25m to 10m): <0.25m for visual line-of-sight/occlusion; 0.5m–1.0m for vegetation height (DSM); and 3m–10m for spectral indices (NDVI/Red-Edge).	Dynamic Monitoring: 5–10 day revisit for biomass/vigor (Sentinel-2); Annual or risk-based for 3D vector/encroachment mapping; and Long-term/Projected for climate correlation.	Multispectral (Optical): Sentinel-2 (MSI) for NDVI, LAI, and Red-Edge spectral fingerprints to identify invasive species vigor. 3D / Geometric Data: Airborne or VHR Satellite LiDAR and Stereo-imagery for Digital Surface Models (DSM) and 3D point clouds. SAR (Radar): Sentinel-1 for monitoring ground stability and moisture beneath dense canopy cover. Climatic Data: C3S (ERA5-Land) for rainfall and temperature correlations to predict "vegetation explosions."
(EUSPA-EO-UR-RAIL-0032)	Impact on soil and root system	*The Railway Infrastructure Manager requires a methodology to detect sub-surface soil contraction (desic-*	Linear track corridors (typically buffered 50m–100m from center-line).	High-Frequency & Seasonal: Monitoring ranges from Daily/Weekly (Soil Water Index) and Every 5 Days (Vegetation/FCover)	High to Medium (1m to 20m): High vertical resolution (<1m) for slope modeling; 10m–20m for displacement	Variable (Static to 5-Day Revisit): Constant monitoring for vegetation (5-day cycle) and soil moisture	SAR & Optical Fusion: SAR (InSAR): C-band or X-band radar for millimetric displacement (Line-of-Sight velocity).

ID	Application	Abstract of the Need & Requirement	Size of the area of interest	Frequency of information needed	Spatial resolution	Temporal resolution	Type of EO data
		cation) and surface vegetation loss to prevent embankment failures, track misalignments, and rainfall-induced erosion.		to Monthly (Cumulative Ground Displacement).	and vegetation; and 0.1km–1km for regional soil moisture (SWI).	(Daily/Weekly); Monthly reporting for displacement; and Static/Baseline for geological clay content and elevation models.	Multispectral: NIR/SWIR bands for FCover and Clay Content (Cation Exchange Capacity mapping). Microwave Radiometry: For subsurface Soil Water Index (SWI). VHR DEM: From LiDAR or Stereo-imaging for <1m vertical slope gradients.

Table 68: Synthesis of Requirements Relevant to EO

2.10 SATCOM user needs and requirements

Satellite communication is being used in the railway industry, and its use is expected to increase in the future, especially considering that the railway sector has been characterized by important innovations regarding digital technologies for train-to-ground communications [RD14]. In addition, satellite communication can provide reliable and secure communication for rail operations, including train control, signalling, and safety-critical applications [RD15]. Most demanding criteria for SATCOM solutions are 1) Reliability for critical applications, 2) Transfer delay between SATCOM remote terminals and 3) The use of handhelds (when needed). High-capacity NGSO Ka-band services are provided from MEO by an EU-headquartered operator, with capabilities being progressively enhanced from the mid-2020s onward. Furthermore, the multi-orbit constellation IRIS² is intended to complement and integrate existing and future secure satellite communication capacities under the European Union Space Programme, including the GovSATCOM/Secure Connectivity component, for the provision of secure satellite communications. From a preliminary technical and business-related analysis, if only safety-critical data and voice services are considered, the most competitive value propositions are narrowband solutions, whereas broadband solutions expand the possibility to open new markets for the rail users generating multiple sources of revenue and being able to recover the strong initial investments required to provide the service.

Accordingly, potential solutions identified in the Satcom4Rail study span GEO systems in several bands (Ka-, L-, S-, C- and X-band) and MEO options. In that study's timeframe, MEO S-band capacity was associated with existing MSS systems approaching end of life, while a MEO C-band solution was treated as a theoretical option that was not under development or in a planning phase, but nonetheless analysed because it appeared technically attractive for railway requirements [RD20]. In particular, Low Earth Orbit (LEO) High Throughput Satellites (HTS) can play a significant role in the adaptable communication system for train-to-ground communication. This technology can provide continuous communication for train control, voice communication (including railway emergency communications), passenger information systems, and real-time video capabilities. LEO satellite connectivity offers faster speeds, real-time conversations, and reliable connections even over remote regions. The use of satellites and other space-based technologies is helping railway operators to improve their services, increase safety, security, reliability, and enhance their overall efficiency. From improving train scheduling to enhancing maintenance practices, space technology is providing solutions that were previously unimaginable. Overall, satellite communication has the potential to revolutionize the rail sector by providing reliable and secure communication, optimizing logistics, and enhancing overall efficiency and safety for both passenger and freight trains. The potential of SATCOM in regional railway lines should be further explored, it might be playing a crucial role in proffering cost-efficient strategies for digitalization and modernization. In addition, the utilization and seamless integration of SATCOM into intelligent rail infrastructure elements such as capacity management, energy management, and maintenance should also be considered. This integration conveys how SATCOM can significantly accelerate the advancement of rail systems, thereby transforming the railway industry toward greater efficiency and sustainability. SATCOM has significant potential to support the Future Railway Mobile Communication System (FRMCS), as FRMCS is being designed to leverage satellite communication as a complementary bearer where appropriate [RD16]. The transition to FRMCS is expected to require a substantial increase in data capacity and bandwidth, driven by advanced operational and passenger services, and satellite communication can contribute to meeting these needs in areas where terrestrial 5G is limited. FRMCS will also require interoperability between different communication technologies, including satellite and terrestrial networks, to ensure seamless communication across the railway network. [RD17] The technical specifications of the FRMCS are defined in several documents and standards. The FRMCS is based on 3GPP building blocks and will provide overall technical conditions for the successor of GSM-R. The UIC has already structured and gather user requirements related to the FRMCS by classifying applications in the following three different groups [RD18]:

- Critical Communication Applications, for example: On-train outgoing voice communication from the driver towards the controller(s) of the train, Trackside maintenance voice communication, Automatic train control communication, Data recording and access, etc. The UIC lists 36 applications in the critical category.

- Performance Communication Applications, for example: On-train voice communication, Station public address, On-train telemetry communications, Non-critical Real time video, Wireless on train data communication for train staff, etc. The UIC lists 23 applications in the critical category.
- Business communication applications, for example: help points for public, internet for passengers, billing information, etc. The UIC lists 4 applications in the critical category.
- Critical Support Applications, for example: Multi-user talker control, Location service, Safety application key management communication, etc.

FRMCS relies on terrestrial 5G NR/5GC as standardized in 3GPP (with the complete FRMCS feature set finalized in Release 19). Regardless, it is still uncertain if these 3GPP standards will be designed or compatible with IRIS2. The UIC's Functional Requirement Specification for FRMCS [RD18] identifies main communication attributes for the above-mentioned categories, where:

1. Link type could be:
    1. Bi-directional voice: like a user-to-user communication
    2. Uni-directional voice: like a "broadcast" communication (e.g. PA)
    3. Bi-directional data: like an application sending and receiving data
    4. Uni-directional data: like an application sending or receiving data
2. Latency, i. e. the delay between action and reaction could be classified as:
    1. Normal: there is no explicit requirement from the user, there is no need for immediate and the delay does not harm the use of the application by the user. UIC defines a maximum end-to-end latency of ≤ 300 ms for critical communications, with more stringent expectations for voice and real-time services.
    2. Low: immediate action (order of seconds)
3. Throughput i.e. an indication of the anticipated rate of data transfer when using the application which could be:
    1. High (order of > 10Mbps)
    2. Medium (order of 1-10 Mbps)
    3. Low (less than 1Mbps)
4. Reliability: a qualitative indication of the reliability required of the communications system when the application is in use which could be:
    1. High
    2. Normal
5. Setup: a qualitative indication of the time to establish a voice or data communication session with the application that would be acceptable to a user, and is sufficient to perform the railway operation:
    1. Normal: there is no explicit requirement from the user, there is no need for immediate and the delay does not harm the use of the application by the user
    2. Immediate (order of hours)
6. Speed: the speed that a user is travelling in, maximum value:
    1. Low ≤40 Km/h, including stationary users
    2. Normal >40 Km/h,
    3. High ≥250 Km/h, ≤500 Km/h

Accordingly, the following table provides a first iteration of high-level requirements at the level of the sections. Note: due to the high level of discrepancy between the numerous applications defined by the UIC a range has been included:

	Link type	Latency	Throughput	Reliability	Session setup time	Speed
Critical Communication Applications	Bi-directional and Uni- directional voice/data	Normal-Low	Low	High	Normal-Immediate	High-Normal
Performance Communication Applications	Bi-directional and Uni-directional voice/data	Low-Normal	Medium-Low	High-Normal	Normal	High-Normal-Low
Business Communication Applications	Bi-directional data	Normal	Low	High-Low	Normal	High-Low

Table 69: Average requirements for the FRMCS applications per category

On top of the functional requirements specified above, additional requirements were identified such as Service Requirements and User Equipment needs:

- **Service Requirements:** The rail sector requires tailored satellite communication solutions for various applications, including train control systems, predictive maintenance, and passenger information systems. However, FRMCS specifies the minimum performance and reliability requirements for safety-critical railway applications, including signalling and communication. Satellite communication systems, where used as a bearer for such services, are required to meet these minimum requirements:[1]
    - **Operational Constraints**: SATCOM plays a vital role in ensuring connectivity for rail operations where terrestrial networks fall short, particularly in remote or low-density areas. However, it comes with its own operational constraints as it requires a clear line of sight to satellites, which can be disrupted in tunnels, dense forests, urban canyons, or mountainous regions. These challenges are amplified in cross-border rail operations, where interoperability issues arise from navigating multiple regulatory environments and transitioning between national networks.
    - **Network reliability (uptime and availability):** Rail users require strong assurance that communication services are available whenever needed. High service availability is particularly critical for mission-critical applications such as emergency communications and automated train operations. An uptime of ≥ 99.99% is required for critical FRMCS functions.
    - **Latency:** When SATCOM is employed as a primary communication bearer, including for critical applications such as train control and monitoring systems, latency becomes a key performance parameter. UIC defines a maximum end-to-end latency of ≤ 300 ms for

[1] Consultations - All

critical communications, with more stringent expectations for voice and real-time services. Satellite solutions—particularly LEO constellations—are expected to be capable of meeting these latency requirements. [2]

  - **Service continuity:** Seamless handover between all coverage areas, including tunnels and cross-border segments. Significant development efforts are currently underway to achieve seamless connectivity between terrestrial networks and SATCOM. While progress is steady, full integration has not yet been achieved.[3]

- **User Equipment Needs:** User equipment preferences vary across different environments, such as urban, rural, and trackside settings. Ensuring compatibility with the operational contexts in which satellite communication services will be deployed is important. Compact and aerodynamic satellite antennas must be integrated into rolling stock without affecting train design or aerodynamics, or other antennas. The antennas must also be resistant against locomotive vibrations and proximity of high voltage (catenary).[4]

Identification of limitations for the use of SatCom in Rail

FRMCS will be introduced alongside GSM-R, with both systems expected to coexist until roughly 2035. Given this long transition, the stringent GSM-R voice requirements on availability, latency and call setup remain a major barrier for using SATCOM as a full replacement bearer at European scale, as no current SATCOM solution fully satisfies these safety-critical specifications. It is therefore important to define and assess dedicated safety cases in which SATCOM could operate in a stand-alone or complementary role, particularly in remote or rural areas.

When only safety data applications (i. e. ETCS) are considered, most of the SATCOM solutions become technically feasible. This is because of more challenging criteria for SATCOM are easier to reach when applications data rates are lower, and when the most demanding type of terminal (i. e. the handheld) is not required anymore (since pedestrian users do not use ETCS data applications). When voice applications are not considered, data rate decreases and, therefore, link reliability and latency are largely increased. Moreover, SATCOM communications will only consist of single hop connections (between ground stations and on-board SATCOM terminals). In this way, the transfer delay is reduced compared to with that of the double hop connectivity required for user-to-user (voice) connections. In the long term, the concept of operation in railways could change and voice services could be replaced by data applications, making possible the use of SATCOM solutions to support services currently provided by voice and data applications using only data.

There is still no fully established regulatory and certification framework allowing SATCOM solutions to be authorised for safety-critical railway applications, even though SATCOM is a good candidate bearer within the multi-bearer FRMCS concept. As a result, solutions that are technically compliant with railway requirements will need to be upgraded once the relevant regulations and certification schemes are defined. Given the stringent requirements of safety-related railway applications, the future communication architecture is expected to rely on multiple complementary communication systems (multilink), in line with next-generation network concepts. To successfully introduce SATCOM as part of this multi-technology architecture, key aspects must be addressed, including the regulatory framework, railway certifications, use of standardised communication technologies, geographical constraints and the technical implications of integrating SATCOM into the railway domain.

From the economic point of view of satellite solutions compared with terrestrial ones, it is worth mentioning that two main scenarios can be analysed: Brownfield (when considering terrestrial solutions deployed re-using current GSM-R infrastructure) and Greenfield (when deploying future terrestrial solutions

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[2] https://uic.org/IMG/pdf/frmcs-t_v1_0_.pdf

[3] https://uic.org/IMG/pdf/uic_frmcs_srs_at-7800_v2.1_0.pdf

[4] Iridium Communications Inc. (2025). Rail systems and satellite networks. Retrieved from https://www.iridium.com/markets/rail/

from scratch). In this sense, SATCOM economic feasibility raises when deploying a railway communication system in a new line (Greenfield), since it is much cheaper (in terms of CAPEX) and faster to deploy than terrestrial solutions. This is because of ground infrastructure is not required in SATCOM solutions (except for those areas to be covered by alternatives terrestrial solutions due to the lack of satellite coverage).

Identification of the prospective use of Satcom in Rail

The main key technological factor to support the usage of SATCOM technology in rail domain refers to the interoperability 5G communication protocol. The landscape of radio protocols in satellite communication encompasses several key standards and technologies. In commercial SATCOM, two primary protocols are widely used: 5G and DVB-S2X. The DVB-S2X standard currently serves as a prevalent choice for commercial satellite communication. DVB-S2X is mainly used as a current standard in commercial SATCOM, however over the long term, it could be anticipated that the upcoming non-terrestrial 5G (which will be updated soon) is estimated to pave the way and become another important standard. Indeed, it will benefit from the 5G terrestrial eco-system. Interoperability between satellite gateways and user terminals including terrestrial networks) enabling roaming and full mobility and dynamic tracking. Non-terrestrial 5G terminals is a relatively new concept which is expected to still evolve in the coming years. This evolution is likely to prompt SATCOM terminal manufacturers to transition from DVB-S2X to 5G, driven by the advantages offered by non-terrestrial 5G's integration with the terrestrial 5G ecosystem. Although there are differences in the air interfaces, the efficiency disparity from a radio efficiency standpoint is relatively small. The key benefit of non-terrestrial 5G lies in its ability to facilitate seamless integration between non-terrestrial 5G SATCOM terminals and the terrestrial 5G infrastructure. Terrestrial 5G modem chipsets will have to be modified to accommodate SATCOM links. Nevertheless, it is expected that the integration of non-terrestrial 5G will enable some cost saving, ease of roaming capabilities for mobile terminals among different geographical regions, and easier handover from terrestrial network to SATCOM network (some mobile terminals already offer this feature, but the engineering is rather complex as the air interface is not the same, e.g.: 4G to DVB-S2X etc.).

Indeed, Key stakeholders in the railway industry have a clear preference for utilizing 5G technology in FRMCS up to version 3. 5G's capability to fully address the mission-critical communication needs essential for rail operations to replace GSM-R. 5G MNOs (Mobile Network Operator) are considered in FRMCS version 3. According to the FRMCS roadmap, the potential utilization of SATCOM could be considered in a later version of FRMCS.

2.11 Synthesis of Requirements Relevant to SATCOM

This section provides *the* general requirement for the railway telecom signal application called FRMCS, as defined by the UIC. Any system, regardless of its components and distribution architecture, aimed to support applications based on the following requirements will have to fulfil these requirements. These requirements could potentially be supported by any communication modes, whether terrestrial, mobile or satellite (examples of radio access technology includes LTE, UMTS, Wi-Fi, GSM-R, Satellite, etc.).

Application	Sub-Application	Distribution	Latency	Throughput	Reliability	Setup	Speed
Critical Communication Applications	Generic voice communication	User-to-User/ Multi-user	Low	Low	Medium	Normal	
	Generic Data communication	User-to-User/ Multi-user	Normal	Medium	Normal	Normal	
	Generic video communication	To be defined in a later version of the specification					
	Role management and presence	Not specified	Normal	Low	Normal	Normal	
	On-train outgoing voice communication from the driver towards the controller(s) of the train	User-to-User/ Multi-user	Low	Low	Medium	Normal	High
	On-train incoming voice communication from the controller towards a train driver	User-to-User	Low	Low	Medium	Normal	High
	Multi-train voice communication for drivers including ground user(s)	Multi-user	Low	Low	High	Normal	High
	Banking voice communication	User-to-User/Multi-user	Low	Low	Medium	Normal	Normal
	Trackside maintenance voice communication	User-to-User/Multi-user	Low	Low	Medium	Normal	Normal

Application	Sub-Application	Distribution	Latency	Throughput	Reliability	Setup	Speed
	Shunting voice communication	User-to-User/Multi-user	Low	Low	Medium	Immediate	Low
	Public emergency call	To be defined in a later version of the specification.					
	Ground to ground voice communications	User-to-User	No specific requirements. It is assumed that a ground user will not change domain.				
	REC-alert		Low	Low	Medium	Immediate	High
	REC-data		Normal	Medium	Normal	Normal	High
	REC-voice		Low	Low	Medium	Normal	High
	Automatic train protection communication	User-to-User/Multi-user	Low	Low	High	Immediate	High
	Automatic train operation communication	User-to-User/Multi-user	Low	Low	High	Immediate	High
	Data communication for Possession Management	User-to-User	Normal	Low	High	Normal	Low
	Trackside maintenance warning system communication	User-to-User/Multi-user	Low	Low	High	Immediate	Normal
	Remote control of engines communication	User-to-User	Low	Low	High	Normal	Normal
	Monitoring and control of critical infrastructure	User-to-User	Low	Low	High	Normal	Normal
	Railway emergency communication	User-to-User/Multi-user	Low	Low	High	Immediate	High
	On-train safety device to ground communication	User-to-User	Low	Low	High	Immediate	High

Application	Sub-Application	Distribution	Latency	Throughput	Reliability	Setup	Speed
	Platform train interface alert	User-to-User/Multi-user	Low	Low	High	Immediate	Normal
	Working alone	User-to-User	To be defined in a later version of the specification.				
	Voice Recording and access to the recorded data	N/A	N/A	N/A	Normal	N/A	Low
	Data recording and access	N/A	N/A	N/A	Normal	N/A	Low
	Shunting data communication	User-to-User/Multi-user	Low	Low	High	Normal	Low
	Train integrity monitoring data communication	User-to-User/Multi-user	Normal	Low	High	Immediate	High
	Public emergency warning	Multi-user	To be defined in a later version of the specification.				
	On-train outgoing voice communication from train staff towards a ground user	User-to-User/Multi-user	To be defined in a later version of the specification.				
	On-train incoming voice communication from a ground user towards train staff	User-to-User/Multi-user	To be defined in a later version of the specification.				
	Railway staff emergency communication	User-to-User/Multi-user	To be defined in a later version of the specification.				
	Critical real time video	User-to-User/Multi-user	Low	High	High	Normal	High
	Critical Advisory Messaging services- safety related	User-to-User/Multi-user	Normal	Low	High	Immediate	High
	Virtual Coupling data communication	User-to-User/Multi-user	Low	Low	High	Normal	High

Application	Sub-Application	Distribution	Latency	Throughput	Reliability	Setup	Speed
	Train parking protection	User-to-User	Normal	Low	High	Normal	Normal
	Safety application key management communication	User-to-User	Normal	Low	High	Immediate	High
Performance Communication Applications	Multi-Train voice communication for drivers excluding ground user(s)	Multi-user	Low	µLow	High	Normal	High
	On-train voice communication	User-to-User/Multi-user	Low	Low	Normal	Normal	High
	Lineside fixed telephony	User-to-User	Low	Low	High	Normal	Low
	On-train voice communication towards passengers (Public Address)	User-to-User/Multi-user	Low	Low	Normal	Normal	High
	Station public address	User-to-User/Multi-user	Low	Low	Normal	Normal	Low
	Communication at stations and depots	User-to-User/Multi-user	Low	Low	Normal	Normal	Low
	On-train telemetry communications	User-to-User	Normal	Low	High	Normal	Low
	Infrastructure telemetry communications	User-to-User	Normal	Low	High	Normal	Low
	On-train remote equipment control	User-to-User	Normal	Low	Normal	Normal	High
	Monitoring and control of non-critical infrastructure	User-to-User	Normal	Low	Normal	Normal	Low
	Non-critical real time video	User-to-User	Low	High	Normal	Normal	High

Application	Sub-Application	Distribution	Latency	Throughput	Reliability	Setup	Speed
	Wireless on-train data communication for train staff	User-to-User	Normal	Low	High	Normal	Low
	Wireless on-train data communication for train staff	User-to-User	Normal	Low	High	Normal	Low
	Train driver advisory train performance	User-to-User	Normal	Low	High	Normal	Low
	Train departure data communications (voice and data)	User-to-User	Normal	Low	Normal	Normal	Low
	Messaging services	User-to-User/Multi-user	Normal	Low	Normal	Normal	High
	Transfer of data	User-to-User	Normal	Medium	Normal	Normal	High
	Record and broadcast – controller to driver(s)	User-to-User/Multi-user	Normal	Medium	Normal	Normal	High
	Transfer of CCTV archives	User-to-User	Normal	High	Normal	Normal	Low
	Non-critical real time video communication	User-to-User/Multi-user	Low	Medium	Normal	Normal	High
	Augmented reality data communication	User-to-User	Low	Medium	Normal	Normal	High
	Real time translation of languages data communication	User-to-User	Low	Medium	Normal	Normal	High
Business Communication Applications	Information help point for public	User-to-User	Low	Low	Normal	Normal	Low
	Emergency help point for public	User-to-User	Low	Low	Normal	Normal	Low

Application	Sub-Application	Distribution	Latency	Throughput	Reliability	Setup	Speed
	Wireless internet on-train for passengers	User-to-User	Normal	High	Normal	Normal	High
	Wireless internet for passengers on platforms	User-to-User	Normal	High	Normal	Normal	High
Critical Support Applications	Assured Voice Communication (voice and data)	User-to-User/Multi-user	Low / Normal	Low	High	Normal	Normal
	Multi user talker control	User-to-User/Multi-user	Low	Low	High	Normal	High
	Role management and presence	User-to-User/Multi-user	Normal	Low	High	Normal	High
	Location services	User-to-User/Multi-user	Low	Low	High	Normal	High
	Authorisation of communication	User-to-User	Low	Low	High	N/A	High
	Authorisation of application	User-to-User	Normal	Low	High	Normal	High
	QoS and priority	User-to-User	Normal	Low	High	N/A	High
	Assured data communication	User-to-User/Multi-user	Normal	Low	High	Normal	Normal
	Inviting-a-user messaging	User-to-User	Normal	Low	Normal	Normal	High
	Authorisation of application	User-to-User	Normal	Low	High	N/A	High
	Distribution of synchronised time	User-to-User/Multi-user	High	Low	High	N/A	High

Table 70: Synthesis of Requirements Relevant to SatCom

3 ANNEX

A.1 Definition of key EO performance parameters

This annex provides a definition of the most used EO performance parameters and includes additional details which are relevant for Rail community.

Spatial resolution refers to the level of detail and clarity in the images, specifically the size of the smallest discernible ground features. It is determined by the pixel size, which is the smallest unit in the image that represents a spatial area on the Earth's surface. Spatial resolution is usually measured in terms of meters per pixel. Thus, a spatial resolution of 1 meter means that each pixel represents a 1 by 1 meter area on the ground.

Spectral resolution refers to the ability of a sensor to differentiate electromagnetic radiation of different wavelengths. In other words, it refers to the number and size" of wavelength intervals that the sensor is able to measure. The finer the spectral resolution, the narrower the wavelength range for a particular channel or band. In remote sensing, features (e.g. water, vegetation) can be characterised by comparing their response" in different spectral bands.

Radiometric resolution expresses the sensitivity of the sensor, that is to say its ability to differentiate between different magnitudes of the electromagnetic energy. The finer the radiometric resolution, the more sensitive it is to small differences in the energy emitted or reflected by an object. The radiometric resolution is generally expressed in bit, e.g. an 8-bit image has a scale of 2^8=256 nuances.

Temporal resolution relates to the time elapsed between two consecutive observations of the same area on the ground. The higher the temporal resolution, the shorter the time between the acquisitions of two consecutive observations of the same area. In absolute terms, the temporal resolution of a remote sensing system corresponds to the time elapsed between two consecutive passes of the satellite over the exact same point on the ground (generally referred to as revisit time" or orbit cycle"). However, several parameters like the overlap between the swaths of adjacent passes, the agility of the satellites and in case of a constellation, the number of satellites mean that some areas of the Earth can be reimaged more frequently. For a given system, the temporal resolution can therefore be better than the revisit time of the satellite(s).

Geolocation accuracy refers to the ability of an EO remote sensing platform to assign an accurate geographic position on the ground to the features captured in a scene. An accurate geolocation makes easier the combination of several images (e.g. combination of a Synthetic Aperture Radar image with a cadastral map and a vegetation map).

Spectral range refers to the wavelength range of a particular channel or band over in which remote sensing data must be collected.

Latency is the difference between the reference time of the satellite measurement and the time the final product is made available to the user (here the service provider).

A.2 Additional EO definitions

Ground deformation monitoring is the process which consists in tracking the vertical and horizontal movements of the land surface and their dynamics, whatever these movements are caused by natural phenomena (e.g. volcanic activity) or by human activities (e.g. aquifer exploitation).

Change detection is the process which aims at identifying difference in the state of objects" (e.g. bridges, constructions, urban areas) or of a phenomenon (e.g. deforestation, soil sealing) by comparing snapshots of the situation at different times. In Earth Observation, change detection is extensively based on satellite imagery obtained through a wide variety of sensors (e.g. optical, radar, infrared, microwave, etc.

Geodesy (see [RD2]) is the earth science of accurately measuring and understanding three of Earth s fundamental properties: its geometric shape, orientation in space, and gravitational field. The field also studies of how these properties change over time. Today, geodesy goes beyond that, being the geoscience that deals among other with the monitoring the solid Earth (which includes the monitoring of displacement, subsidence or deformation of the ground and structures due to tectonic, volcanic, and other natural phenomena as well as human activity.

Interferometric Synthetic Aperture Radar (InSAR) is a technique enabling to generate surface deformation maps based on the processing of SAR images captured at different moments in time. The processing uses the fact that if the ground has moved between the times of two SAR images of the same area, a slightly different portion of the wavelength is reflected to the satellite resulting in a measurable phase shift that is proportional to displacement. The processing therefore consists in obtaining information about the vertical movements of the ground surface by calculating the phase difference between the emitted radar signal and the signal backscattered by the surface for successive images. InSAR can potentially measure deformations of millimetre-scale during periods ranging from days to years.

Near-Real-Time (NRT) refers, when used in the context of EO applications, to applications/services/products for which the time delay between the occurrence of a given event and the availability of the outcomes of the processing of the Earth observation data corresponding to that event is considered as being not significant from a user perspective. The notion of "near real-time" is therefore depending on user requirements. For Earth observation, the corresponding time delays may range from a few hours to a few days depending on the application/service/product.

A.3 Definition of key GNSS performance parameters

This annex provides a definition of the most commonly used GNSS performance parameters and includes additional details which are relevant for Rail community.

Availability: the percentage of time the position, navigation or timing solution can be computed by the user. Values vary greatly according to the specific application and services used, but typically range from 95-99.9%. There are two classes of availability:

- System availability: the percentage of time the system allows the user to compute a position - this is what GNSS Interface Control Documents (ICDs) refer to.
- Overall availability: considers the receiver performance and the user's environment. Values vary greatly according to the specific use cases and services used.

Accuracy is the difference between true and computed solution (position or time). This is expressed as the value within which a specified proportion – usually 95% – of samples would fall if measured. This report refers to positioning accuracy using the following convention: centimetre-level: 0-10cm; decimetre level: 10-100cm; metre-level: 1-10 metres.

Continuity is the ability of a system to perform its function (deliver PNT services with the required performance levels) without interruption once the operation has started. It is usually expressed as the risk of discontinuity and depends entirely on the timeframe of the application. A typical value is around 1*10-4 over the course of the procedure where the system is in use.

Indoor penetration is the ability of a signal to penetrate inside buildings (e.g. through windows). Indoor penetration does not have an agreed or typical means for expression. In GNSS this parameter is dictated by the sensitivity of the receiver, whereas for other positioning technologies there are vastly different factors that determine performance (for example, availability of Wi-Fi base stations for Wi-Fi-based positioning).

Integrity is a term used to express the ability of the system to provide warnings to users when it should not be used. It is the probability of a user being exposed to an error larger than the alert limits without timely warning. The way integrity is ensured and assessed, and the means of delivering integrity-related information to users are highly application dependent. Throughout this report, the integrity concept" is to be understood at large, i.e. not restricted to safety-critical or civil aviation definitions but also encompassing concepts of quality assurance/quality control as used in other applications and sectors.

Latency is the difference between the reference time of the solution and the time this solution is made available to the end user or application (i.e. including all delays). Latency is typically accounted for in a receiver but presents a potential problem for integration (fusion) of multiple positioning solutions, or for high dynamics mobile devices.

Robustness relates to spoofing and jamming and how the system can cope with these issues. It is a more qualitative than quantitative parameter and depends on the type of attack or interference the receiver is capable of mitigating. Robustness can be improved by authentication information and services.

Authentication gives a level of assurance that the data provided by a positioning system has been derived from real signals. Radio frequency spoofing may affect the positioning system, resulting in false data as output of the system itself.

Power consumption is the amount of power a device uses to provide a position. It will vary depending on the available signals and data. For example, GNSS chips will use more power when scanning to identify signals (cold start) than when computing a position. Typical values are in the order of tens of milliwatts (for smartphone chipsets).

Probability of false alarm refers to the likelihood of the receiver to indicate the presence of a signal when no signal is present.

Probability of detection refers to the likelihood of a receiver to detect the presence of a GNSS signal when a signal is indeed present.

Time To First Fix (TTFF) is a measure of time between activation of a receiver and the availability of a solution, including any power on self-test, acquisition of satellite signals and navigation data and computation of the solution. It mainly depends on data that the receiver has access to before activation: cold start (the receiver has no knowledge of the current situation and must thus systematically search for and identify signals before processing them – a process that can take up to several minutes.); warm start (the receiver has estimates of the current situation – typically taking tens of seconds) or hot start (the receiver understands the current situation – typically taking a few seconds).

Time To First accurate Fix (TTFaF) is a measure of a receiver s/solution's performance covering the time between activation and output of a position within the required accuracy bounds.

A.4 Definition of key SATCOM performance parameters

Link type refers to the type of communication link used for transmitting voice or data.

Availability is qualitative indication of the reliability and uptime of the communications system. It refers to the percentage of time the communication system is operational and meets the required quality of service when the application is in use.

Latency refers to the delay between the transmission of a signal and the reception of the response. This is the time it takes for a signal to travel from the sender to the receiver and back.

Bandwidth (bit rate) is a qualitative indication of the anticipated rate of data transfer when using the application. It is the amount of data that can be transmitted over the communication link in a given amount of time, usually measured in bits per second (bps).

Coverage is an indication of the geographical area that can be reached by the service. It defines the regions where the satellite signal is available and can provide communication services.

Symmetry Up/Down is the ratio between the uplink traffic (data sent from the ground to the satellite) and the downlink traffic (data sent from the satellite to the ground). This ratio indicates whether the communication link is symmetric (equal uplink and downlink capacity) or asymmetric (different uplink and downlink capacities).

Distribution refers to the method and extent to which the communication service is distributed across different regions or users. It can include the distribution of signal strength, service availability, and user access.

Setup refers to a qualitative indication of the time required to establish a voice or data communication session with the application. It refers to the acceptable duration for setting up a communication link that is sufficient to perform the intended operation, such as railway operations.

Speed: the speed at which a user is traveling, with a maximum value specified. In satellite communication, this can affect the ability to maintain a stable communication link, especially for mobile users.

Security protection refers to the measures and protocols implemented to ensure the security of the communication link. This includes protecting the data from unauthorized access, interception, and ensuring the integrity and confidentiality of the transmitted information

A.5 Other performance parameters

EO

Agility corresponds to the ability of a satellite to modify its attitude and to point rapidly in any direction to observe areas of interest outside its ground trace. High agility can improve the temporal resolution compared with the revisit time of the satellite.

Swath corresponds to width of the portion of the ground that the satellite sees" at each pass. The larger the swath, the bigger the observed area at each pass.

Off-nadir angle corresponds to the angle at which images are acquired compared with the nadir", i.e. looking straight down at the target. In practice, objects located directly below the sensor only have their tops visible, thus making it impossible to represent the three-dimensional surface of the Earth. High resolution images are therefore generally not collected at nadir but at an angle. A large off-nadir angle enables a wider ground coverage at each pass and the identification of features not visible at nadir, but it reduces the spatial resolution. For optical imagery, typical off-nadir angles are in the range of 25-30 degrees.

Sun-elevation angle corresponds to the angle of the sun above the horizon at the time an image is collected. High elevation angles can lead to bright spots on the imagery while low elevation angles lead to darker images and longer shadows. The most appropriate angle depends on the type of application: a high sun elevation is appropriate for spectral analysis since the objects to be observed are well illuminated while a lower elevation angle is better suited to interpretation of surface morphology (e.g. the projected shadows can enable a better image interpretation).

GNSS

Size, weight, autonomy, and power consumption. Power consumption and size are not strictly GNSS performance parameters, however they are also considered in this analysis, especially for GIS and Mapping-related applications.

- **Autonomy**. Power consumption is the amount of power a device uses to provide a position. The power consumption of the positioning technology will vary depending on the available signals and data. For example, GNSS chips will use more power when scanning to identify signals (cold start) than when computing a position. Typical values are in the order of tens of mW (for smartphone chipsets). GNSS is considered one of the heaviest drains on smartphones batteries
- **Size, weight**. Most GIS devices used by NGOs are handheld or rugged tablets/phones, which implies that they must remain small and lightweight.

Resiliency is the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions; including the ability to recover from deliberate attacks, accidents, or naturally occurring threats or incidents. A resilient system will change its way of operations while continuing to function under stress, while a robust (but non-resilient) system will reach a failure state at the end, without being able to recover.

Connectivity refers to the need for a communication and/or connectivity link of an application to be able to receive and communicate data to third parties. Connectivity relies on the integration with both satellite and terrestrial networks, such as 5G, LEO satellites, or LPWANs.

Interoperability refers to the characteristic of a product or system, whose interfaces are completely understood, to work with other products or systems, in either implementation or access, without any restrictions (e.g. ability of GNSS devices to be combined with other technologies and the possibility to merge the GNSS output with the output coming from different sources).

Traceability is the ability to relate a measurement to national or international standards using an unbroken chain of measurements, each of which has a stated uncertainty. For Finance applications, knowledge of the traceability of the time signal to UTC is essential to ensure regulatory compliance of the timestamp.

A.6 List of Acronyms

Acronym	Definition
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CCS	Command and Control System
CI	Confidence Interval
CMD	Cold Movement Detection
DAS	Driver Advisory System
EC	European Commission
EGNOS	European Geostationary Navigation Overlay Service
EGNSS	European Global Navigation Satellite System
EO	Earth Observation
EOA	End of Movement Authority
ERA	European Union Agency for Railways
ETCS	European Train Control System
ERTMS	European Rail Traffic Management System
ESA	European Space Agency
EU	European Union
EUSPA	European Agency for the Space Programme
FRMCS	Future Railway Mobile Communication System
GNSS	Global Navigation Satellite System
HAS	High Accuracy Service
MR	Market Report
EUSPA	European Union Agency for the Space Programme
OSNMA	Open Service Navigation Message Authentication
PNT	Positioning, Navigation and Timing
RAIM	Receiver Autonomous Integrity Monitoring
RAMS	Reliability Availability Maintainability Safety
R&D	Research and development
RUR	Report on User needs and Requirements
R&I	Research and Innovation
SATCOM	Satellite communications
SME	Small and Medium-sized Enterprise
SIL	Safety Integrity Level

Acronym	Definition
ATO	Automatic Train Operation
ATP	Automatic Train Protection
SoL	Safety of Life Service
SST	Space Surveillance and Tracking
UCP	User Consultation Platform
UNISIG	UNion Industry of SIGnalling

Table 71: Acronyms

A.7 Reference Documents

Id	Reference	Title	Date
RD1	EUSPA Market Report	EUSPA EO and GNSS Market Report (Issue 1)	2022
RD2	GRAIL-2 D4.2	Safety approval process	2013
RD3	Himrane PhD Thesis	Contribution to safety and operational performance evaluation of GNSS-based railway localization systems	2022
RD4	IEEE Access journal paper	A Review of the Evolution of the Integrity Methods Applied in GNSS	2020
RD5	ESSP-TN-11715 v01-00	Report on the use of EGNOS V2 for Railway safety and non-safety applications	2014
RD6	SATLOC	Impact of EGNOS and Galileo integrity on railway fail-safe positioning equipment	2008
RD7	GSA-MKD-RL-UREQ 250286	Report on User Needs and Requirements (UCP outcome)	2021
RD8	EUSPA-MKD-RL UREQ-A11383	Annex 7 – User Needs and Requirements for Rail	2021
RD9	GRAIL-WP3	GNSS Subsystem Requirements Specification for Enhanced Odometry	2008
RD10	SUBSET-041	Performance Requirements for Interoperability	2015
RD11	ITAtech	Guidelines for Remote Measurements Monitoring Systems	2015
RD12	UN SPIDER Portal	Land Deformation Mapping Using DInSAR	2023
RD13	EUSPA URD Infra 2022	Infrastructure User Needs and Requirements	2022
RD14	Vizzari	Future Technologies for Train Communication (LEO HTS Satellites)	2023
RD15	ERA – SatCom	Feasibility of SATCOM for railway communication	2017
RD16	UNIFE	Transition to FRMCS – Position Paper	2021
RD17	UIC	FRMCS – Transition Guidelines for 4G networks	2024
RD18	UIC	FRMCS Functional Requirement Specification	2025
RD19	EUSPA UCP 2023	Rail Market Segment Panel Minutes of Meeting	2023
RD20	ESA – SATCOM4rail	Certification Framework for SATCOM in Railway Safety Applications	2014
RD21	Interviews A	Interviews A	–
RD22	Interviews B	Interviews B	–
RD23	Interviews C	Interviews C	–
RD24	Interviews D	Interviews D	–
RD25	ERA	Conference on Rail Resilience to Climate Change	2025
RD26	EGUsphere	Is Europe's transport infrastructure ready for climate change	2025
RD27	Berkmans	Climate change risks for rail in Europe	2025
RD28	Network Rail	Weather Resilience and Climate Change Adaptation Plans	2024
RD29	RailFreight	Strategies to combat heavy rain impacts on rail	2025
RD30	ResearchGate	Landslide susceptibility map of Italy	2013
RD31	ResearchGate	Damages and morphological changes (Ahr valley railway)	2022
RD32	Climate-ADAPT	Railway resilience to Alpine hazards in Austria	–
RD33	Network Rail	Responding to weather impacts on the railway	–
RD34	Network Rail	Storms and flooding impacts on railway	–
RD35	SNCF	Adapting to Climate Change	–
RD36	Wikipedia	Riedlingen derailment	–
RD37	ERA	Rail Resilience Study	2025
RD38	UIC	RERA Rain	–

RD39	UIC	RERA Temp	–
RD40	SNCF Réseau	Innovating for sustainable mobility	–
RD41	CMCC	Coastal railways and rising sea levels	2024
RD42	Frontiers in Climate	Climate change adaptation in infrastructure	2022
RD43	Copernicus	Support to urban climate adaptation	–
RD44	The Insight Partners	Europe Satellite Data Services Market Forecast	–
RD45	Innovation News Network	European Earth Observation market analysis	2022
RD46	EARSC	Copernicus Evolution Position Paper	2022
RD47	Market Data Forecast	Europe Geospatial Solutions Market Report	–
RD48	EGU	European climate resilience insights for policymakers	–
RD49	IEEE Xplore	Technical document on railway monitoring	2024
RD50	SPATRA Project	SPATRA Project Home Page	–
RD51	EGUsphere	Infrastructure and climate change preprint	2025
RD52	European Union	Publication on rail resilience	2024

Table 72: Reference documents

EUSPA Mission Statement

The mission of the Agency is defined by the EU Space Programme Regulation.

EUSPA's mission is to be the user-oriented operational Agency of the EU Space Programme, contributing to sustainable growth, security and safety of the EU. In the execution of its mission, EUSPA counts on strong partnerships with the European Commission, European Parliament, Member States, European Space Agency, and private actors across the EU.

EUSPA:

- Provides state-of-the-art, safe and secure positioning, navigation and timing services based on Galileo and EGNOS, cost-effective satellite communications services for EU GOVSATCOM and soon IRIS² and Front Desk services of the EU Space Surveillance Tracking whilst ensuring the systems' service continuity and robustness.

- Promotes and maximises the use of data and services offered by Galileo, EGNOS, Copernicus, EU GOVSATCOM and soon IRIS² across a broad range of domains.

- Fosters the development of a vibrant European space ecosystem by providing market intelligence, and technical know-how to innovators, academia, start-ups, and SMEs. The Agency leverages Horizon Europe, other EU funding, and innovative procurement mechanisms.

- Implements and monitors the security of the EU Space Programme components in space and on the ground with the aim to enhance the security of the Union and its Member States. To do so, EUSPA operates the Galileo Security Monitoring Centre (GSMC).

- The EU Space Programme Security Accreditation Board is established within the Agency, representing the security accreditation authority for all of the EU Space Programme's components.

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