DIRS
Technology Roadmap

Space Defence Applications

September 2025

DIRS
Defence Industry & Research Strategy

ROYAL HIGHER INSTITUTE for DEFENCE

DEFENSIE
LA DÉFENSE

Colophon

This roadmap was commissioned by the Royal Higher Institute for Defence (RHID) under the Defence, Industry and Research Strategy (DIRS) to identify priority technology pathways in Space Defence Applications, align Belgian defence requirements with industrial and research capabilities, and guide future research, development and cooperation.

COORDINATION AND EDITING

The roadmap was coordinated and edited by Sirris, Belgium's industry-driven technology innovation centre, to ensure that defence priorities were translated into realistic industrial and research pathways. Lead editors were Pieter Kesteloot, Benjamin Denayer and Marc Bollen (Sirris), in partnership with Guido Maene (Agoria-BSDI). The Argonauts supported the facilitation of workshops.

CONTRIBUTORS

This roadmap reflects the contributions of a broad network of Belgian companies, research organisations, clusters and universities. We extend our sincere thanks to all stakeholders for their insights and commitment. A Technical Committee, comprising experts from defence, industry and academia, advised on the scope, priorities and alignment with DIRS objectives.

DESIGN

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EXECUTIVE SUMMARY

Belgium's strategic ambition is to secure a resilient, competitive Defence Technological and Industrial Base (DTIB) that supports national security and contributes to European strategic autonomy. The DIRS Space Defence Applications Technology Roadmap outlines clear RTD pathways to leverage Belgium's industrial strengths and research capabilities in the fast-evolving space sector. Belgium is a top ESA contributor and home to a robust space ecosystem including over 230 companies and tight academia–industry cooperation. This roadmap ensures targeted support for defence needs while consolidating Belgium's role as a trusted European partner.

PURPOSE AND SCOPE

The roadmap was developed through a structured participative process involving Belgian Defence, industry, and academia. It defines priority technology tracks aligned with defence capability goals and identifies focused challenges across key sub-domains. It establishes timelines and critical technology building blocks to guide future research and technological development (RTD) investments and project formation under DIRS.

THREE STRATEGIC TRACKS:

- The first track, **Earth Observation**, seeks to advance ultra-high-resolution payloads across EO, RF, SAR, IR and hyperspectral sensors; to integrate onboard, AI-enabled real-time data fusion and autonomous tasking; and to strengthen sovereign ground segments through smart data processing.

- The second track, **Space Situational Awareness**, focuses on the automated generation of near real-time space pictures using diverse sensors; the advancement of AESA radar, IR, RF localisation and telescopes; and the deployment of onboard edge processing with AI-based threat behaviour analysis.

- The third track, **Very Low Earth Orbit Platforms**, targets drag compensation through air-breathing and electric propulsion, advanced attitude control and platform optimisation, while also addressing challenges in power supply, environmental degradation and low-latency communications to support sovereign and autonomous operations.

BELGIAN DTIB PERSPECTIVE

Each challenge is assessed against Belgian DTIB strengths to prioritise high-potential technology building blocks for defence space applications. These include sensor miniaturisation, AI-enabled data pipelines, new propulsion concepts, and adaptive SSA sensors. The roadmap sets out collaborative R&D opportunities that match Belgian industry-research capabilities with strategic defence needs.

STRATEGIC IMPACT

The roadmap enhances Belgium's ability to respond swiftly to evolving threats in the space domain, to contribute actively to European capability programmes, and to develop dual-use technologies with significant spillover potential.

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Introduction: context and process

1.1. DEFENCE, INDUSTRY AND RESEARCH STRATEGY (DIRS)

The Defence, Industry and Research Strategy (DIRS[1]), led by the Royal Higher Institute for Defence (RHID), is Belgium's comprehensive initiative to develop the Belgian DTIB and as such to enhance national security and defence capabilities. It has identified "Space Defence Applications" as one of the key strategic technology domains.

DIRS aims to establish a resilient Belgian Defence Technological and Industrial Base (DTIB) that:

- Supports national security and defence policy and reinforces the EU's open strategic autonomy;
- Positions Belgium as a relevant, reliable, and competitive partner in European and transatlantic capability development;
- Secures essential national autonomy in critical areas of scientific, technological, and industrial expertise;
- Delivers tangible economic and societal benefits through knowledge, technology development, and job creation.

DIRS aims to develop a robust Belgian DTIB that supports national defence policies and contributes to European strategic autonomy. The Belgian DTIB encompasses all relevant public and private actors – from companies and research institutions to universities – that actively contribute to defence-related research and development activities, production and operational support.

In space, Belgium already hosts internationally integrated high-tech players for commercial and institutional missions. DIRS sets the ambition to build-up on this solid scientific and industrial base, to consolidate and expand this strategic positioning by adding necessary capabilities to develop a technological defence space ecosystem. By consolidating and expanding its strategic positioning, Belgium could confirm a reliable and credible role at Europe and Atlantic levels, ensuring long-term technological relevance in defence applications. The DTIB must therefore not only be scaled up, but also broadened and deepened in terms of defence capacity in order to be technologically and operationally self-sufficient in the long term.

The role of technology roadmapping within DIRS

Within DIRS, technology roadmaps play a key role in defining the Research, Technology, and Development (RTD) agenda for priority technology domains. They are essential to building a strong Belgian DTIB, aligned with Belgian and European strategic defence and autonomy goals. Roadmaps serve as crucial tools in aligning the RTD programming with clearly defined strategy, goals and objectives. They foster a focused, collaborative, and adaptable approach to innovation, ensuring research investments deliver maximum impact.

For each selected theme or flagship area, a structured roadmapping process establishes a long-term vision with clear capability goals and technology pathways. These roadmaps are translated into concrete projects, supported by relevant funding programmes. This approach unites industry, research institutions, and Defence around joint projects that strengthen both national defence capacity and Europe's strategic autonomy.

Roadmapping is a proven strategic tool to guide the development of technological value chains. DIRS technology roadmapping methodology clarifies the necessary technological and economic steps to achieve shared ambitions and long-term goals. The methodology addresses core strategic questions:

1. Defence, Industry and Research Strategy (DIRS) IRSD-KHID-RHID

- Where are we today? Where should we go? Where are we going?
- Is it real? Is it worth it? Can we win?

Roadmapping turns strategic visions into concrete actions. It creates a direct link between vision and implementation, fostering collaboration across ecosystems and parallel projects. From the outset, business dimensions such as market positioning, interaction with Belgian, European, and transatlantic defence markets, competition, and potential spillovers are integrated, ensuring sustainable and forward-looking choices.

This technology roadmap sets the scope, vision, and goals to guide DTIB development and steer future research, innovation, and industrial activities in the domain of space defence applications.

Core objectives of technology roadmaps within DIRS:

1. Strategic alignment: Link RTD projects to DIRS priorities within a long-term vision.
2. Prioritisation: Identify and focus on critical technologies and technology building blocks, setting priorities for resource allocation and project focus.
3. Guidance: Define clear timelines, milestones, and performance targets.
4. Collaboration: Foster cooperation among stakeholders, including defence, industry, and academia.
5. DTIB strengthening: Guide the DTIB development within an international framework.
6. Impact maximisation: Target research efforts on high-impact areas for greater efficiency and innovation outcomes.

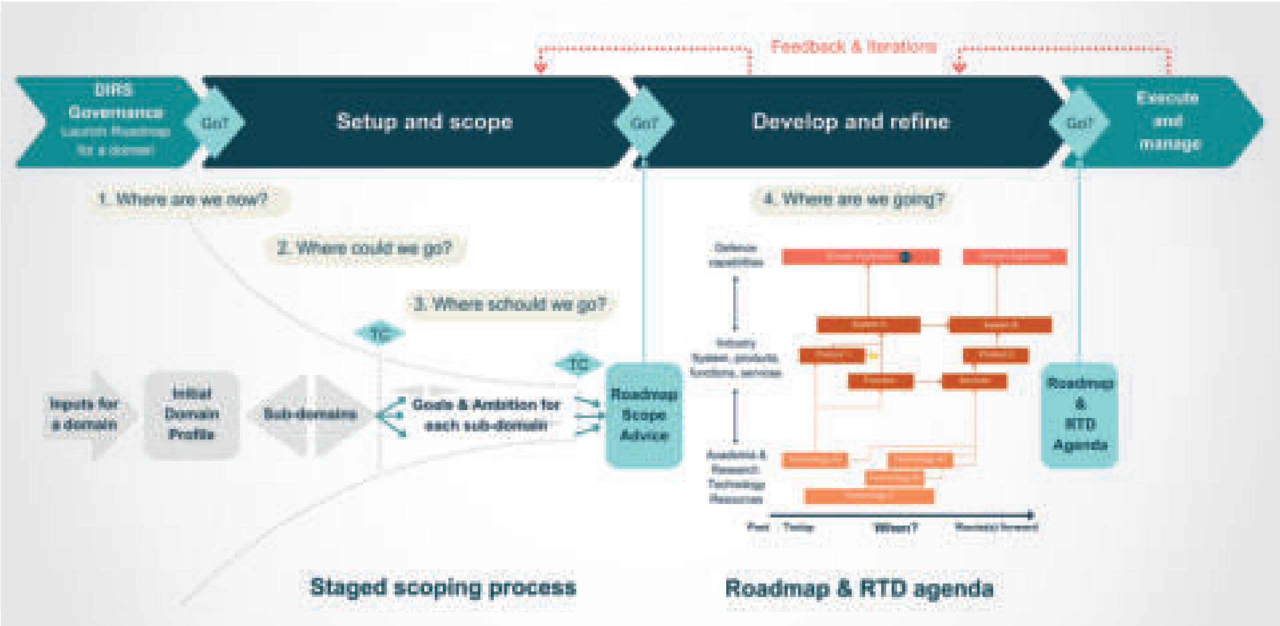
1.2. TECHNOLOGY ROADMAP DEVELOPMENT

This technology roadmap for "Space Defence Applications" was developed according to a methodology providing a structured framework for technology roadmapping tailored to the DIRS context and allowing to develop well structured and uniform technology roadmaps across all the domains. This makes it easier to compare different technology domains and helps decision-makers to prioritize and allocate resources effectively.

The participative approach integrates insights from the three key stakeholders in the process:

1. **Defence Stakeholders:** Provide insights into the future capability and capacity needs of the Belgian defence sector - the tools that enable defence to carry out its work - to ensure alignment with operational priorities. Defence also provided an understanding of the international DTIB landscape, the state of the art, and forward-thinking perspectives aligned with NATO priorities and European Defence Fund (EDF) initiatives.
2. **Industry Representatives:** Highlight opportunities for strategic collaboration and strengthening the Belgian Defence Technology Industrial Base to enhance competitiveness and resilience.
3. **Academia and Research Centres:** Offer expertise on forward-looking, beyond-state-of-the-art technology enablers that drive innovation and technological advancement.

The DIRS technology roadmapping methodology follows a **staged approach**, where diverse ideas and perspectives are initially explored (divergent), followed by a focused refinement and prioritization (convergent). The "setup and scope" phase determines in successive stages the sub-domains, goals and ambitions for a technology domain. The "develop and refine" phase defines the technology roadmap and a clear and focused RTD-agenda.



DIRS roadmapping methodology

The technology roadmapping for Space Defence Applications was undertaken in the period of February-September 2025. Choices were made through joint consultation to ensure that strategic priorities are defined to both meet the capability needs of Belgian Defence and contribute to strengthening European strategic autonomy. Some innovation goals target one or both objectives, while in other cases a balanced trade-off was required.

1) Scoping phase

The "setup and scope" phase determined supported by two workshops in successive stages the sub-domains, goals and ambitions for a technology domain

Step 1: Assessing the current state and identifying sub-domains

The first step answered the question **"where are we now"**. This question focuses on assessing the current state, including existing solutions, technologies, capabilities, and challenges, to understand the starting point for the roadmap.

Starting from 2 flagships identified by defence (Space-based Earth Observation and Space Situational Awareness), a first workshop aimed at identifying potential sub-domains in the space related applications domain. Based on 22 ideas for research were pitched by different stakeholders. Interactive sessions analysed the ideas, the interest of other participants to contribute to them and grouped them in potential sub-domains space defence applications for the Belgian DTIB. The outcomes were integrated in initial domain profiles for the identified sub-domains.

After the workshop, the scope and goals of the identified sub-domains were analysed on following criteria for scoping and prioritising the sub-domains. Belgian defence analysed the contribution to future defence capability/capacity needs and sovereignty. This identified sub-domains and topics that were out-of-scope, beyond the scope of the Flagships defined by defence, and of higher or lower interest. The sub-domain profiles were also confronted against international roadmaps to check their alignment with the European and transatlantic perspective.

The strength of the DTIB and seeds for collaboration between industry and academia were analysed. A preliminary exercise performed by BeMilSpace, a Belgian association from Agoria for the space industry, already provided insight in the Belgian DTIB. A questionnaire analysed how leading companies or research organisations and universities involved in the roadmapping exercise could contribute to specific technology building blocks within the defined sub-domains. Both provided insights into the interest, current skills, and R&D capabilities of 40 companies and research centres within the DTIB.

This provided feedback and input for the restructuring and further development of the sub-domains. Based on the feedback, the input related to the flagships was separated into what fits within the short-term focus for Belgian defence (2030) and what could fit in a longer-term focus (2035) or wider scope within a European defence perspective.

Step 2: Prioritizing the sub-domains for the roadmapping exercise

A 2nd workshop provided answers to the question "Where could we go?". Based on identified key-challenges and innovation goals for the retained sub-domains, research challenges were explored that enable to build-up relevant technology blocks for next generation solutions. This provided a more in-depth understanding of the innovation goals and the research and cooperation in the Belgian DTIB that could contribute to achieve them. Sub-domains were developed and analysed based on four key criteria: alignment with future Belgian Defence capability needs, potential to build a sustainable industrial ecosystem, use of existing technological and research strengths, and fit with European trends to ensure strong international positioning.

Results from workshop1 and 2, the analysis and questionnaire were integrated in the sub-domain profiles. By leveraging the domain profiles, an ad-hoc technical committee prioritized and scoped on May 19th the tracks to be included or further investigated in the roadmapping process. Six technology domains were identified in the technology roadmap for Space Defence Applications.

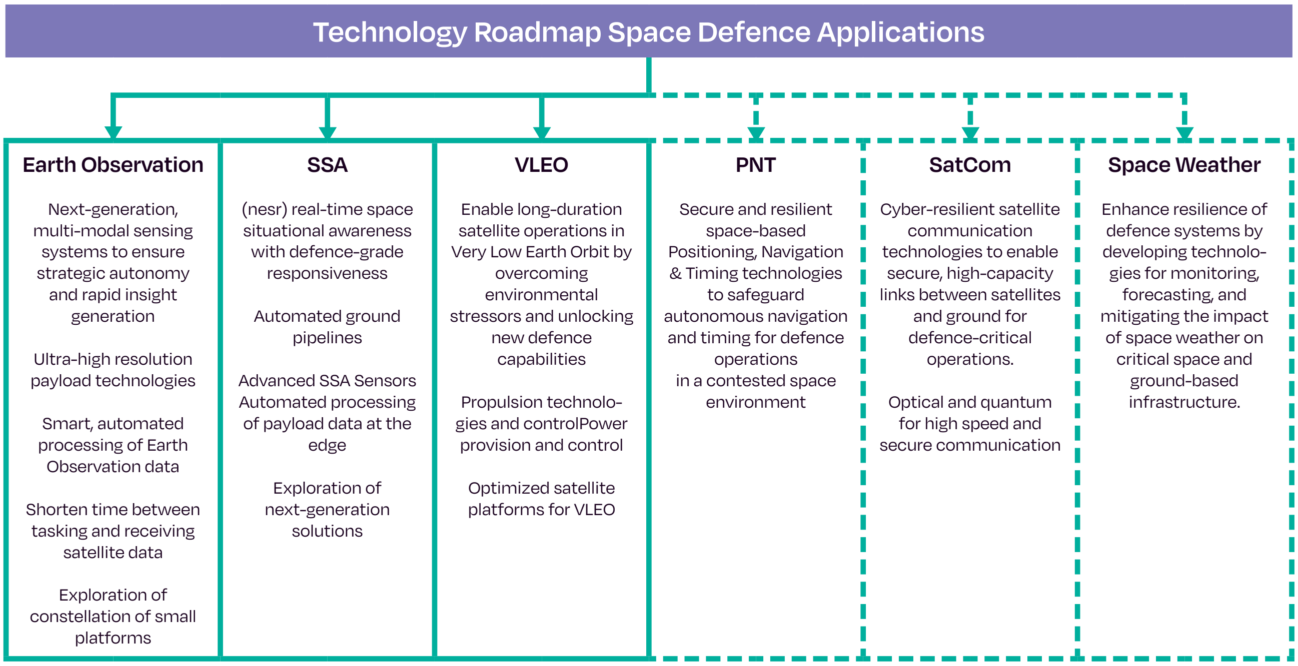
Step 3: Identification of sub-domains for space-based applications

Based on the roadmap-scope advice of the ad-hoc technical committee defined "Where should we go?". Six technology domains were identified in the technology roadmap for Space Defence Applications for the Belgian DTIB. Within the tracks challenges and innovation goals were evaluated to start structuring the roadmap around the most relevant identified challenges and innovation goals. These technology domains are integrated as separate tracks in one overarching technology roadmap.

Three tracks are already integrated in the current roadmap:

- Space Situational Awareness
- Space-based Earth Observation
- Very Low-Earth Orbit Technologies

Prior to structuring the three other roadmap tracks (Satellite Communication, Positioning Navigation and Timing, and Space Weather) it was decided to first further work-out and detail the most relevant identified challenge(s) and innovation goal(s) with aim to be able to decide if: a) the sub-domains challenges and innovation goals will be retained and b) the tracks can still be included in the timing of the 2025 exercise. These tracks are not yet integrated in the current roadmap.



Overview on the research tracks

2) Development phase

Step 4: Definition of the roadmap and RTD agenda

A third workshop addressed the question "Where are we going?" by developing a technology roadmap and an RTD agenda showing the way ahead to reach the future state. The innovation goals were further clarified by specifying the concrete outcomes to be achieved within the technology domain. These goals include measurable targets and key technology building blocks, covering the development of new solutions, the enhancement of existing capabilities, and the acquisition of new knowledge. The workshop also provided input to identify feasible pathways and timelines for an RTD agenda to overcome research gaps to reach the innovation goals.

1.3. STRUCTURE OF A TRACK FOR A TECHNOLOGY DOMAIN IN THE ROADMAP

The technology roadmap is composed of different tracks. Each track scopes and describes a technology sub-domain in Space Defence Applications. The track descriptions are structured as follows:

- An introduction for the technology domain provides a concise vision, the goal on short and longer term and the position of the Belgian DTIB to develop technology building blocks for next-generation solutions aligned with European defence needs.
- Each track is structured along key challenges for R&D to strengthen the Belgian DTIB. For these key challenges priorities, research gaps and innovation goals are identified that require close cooperation across the Belgian DTIB. The research to be undertaken to achieve a common innovation goal is further detailed by research challenges. These research challenges came out of the workshops with representatives from the Belgian DTIB and provide examples of research topics to be undertaken.
- An overall horizon and timeline provide insight in the timeline for the research on short term (2030) and longer term (2035).

1.4. THE BELGIAN DTIB

SWOT of the Belgian DTIB

Belgian industry plays a significant role within the European space sector. Belgium did not invest in an own Belgian space research institute, as many of our neighboring countries, but invested the full Belgian space budget for many years in ESA. As such, Belgium is since many decades the fifth/sixth-largest ESA contributor (last years about ~€296M/year). With more than 230 firms and a tight academia–industry collaboration involved in research and supply subcontracted by ESA to Belgian partners, Belgium invested strong in its space industry. Belspo took for many years a coordinating role with ESA, and Belgospace, VRI, Wallonie Espace aligned industry towards ESA. As the result of this effort for many decades, Belgium has strong niche competencies in multiple technology domains required within the roadmap of Space Defence Applications for defence.

Strengths	Weaknesses
• Competences in space developed by a strong ESA presence, supporting 230+ companies and institutes. • Broad end-to-end capability covering sensor-to-insight value chains, with critical strengths in photonics, AI, onboard processing, and integration. • High niche expertise & globally competitive miniaturised Earth observation sensors, advanced optics, data processing, space-qualified photonics and small satellites building. • Recognised leadership in AI/edge computing by Belgian industry and academia. • Strong role in EU strategic programs (EDF, European Union Space Surveillance and Tracking (EU SST), ESA Copernicus, Horizon Europe), aligning with European autonomy goals.	• Strong in components, but limited autonomy at system level, lacking sovereign capability and direct delivery of complete space systems to defence or (sub)systems to prime contractors. • No indigenous launcher capability, which constrains Belgium's strategic autonomy for rapid deployment. • Fragmented ecosystem with small critical mass, relying on European programs for scale and investment. • Dependency on non-EU critical components.

Opportunities	Threats
• High globally CAGR growth of defence-driven markets. • DIRS enabling first-mover advantages i.e. in VLEO, quantum sensing, and autonomous onboard processing • Leverage Belgium's strategic position in dual-use technologies to valorise civil space competences for defence applications and reduce dependence on tenders by building a competitive commercial portfolio. • Spin-ins and scale-ups from universities/research centres can accelerate Belgian autonomy. • EU strategic drive towards resilient supply chains and strategic autonomy aligns with Belgium's positioning. Opportunity to (sub) system suppliers for Belgian industry.	• Heightened global competition from major EU players (France, Germany, Italy); risk of Belgium being confined to subcontractor roles. • High dependence of some companies on ESA or similar RTD programs — shifts in funding mechanisms risk eroding the position of leading Belgian companies. • Risk of technological lock-in to niche subsystems without moving up the value chain to full system capability. • Supply chain vulnerability in critical raw materials or components.

Participation to the technology roadmapping exercise

During the technology roadmapping exercise, the tracks, challenges, innovation goals and research challenges were developed in close collaboration with the Belgian DTIB. Only those requiring and benefiting from cooperation within the Belgian DTIB were retained. The technological competences at academia, research institutes and companies were analysed to see if they provide a sufficient strong basis to develop the required technology building blocks at the basis of next-generation solutions and to scale their offering from components to (sub)system-level offerings.

During the technology roadmapping exercise names of organisations that could contribute were listed. However as DIRS will be open to other organisations – not listed or that have not actively participated to the roadmapping exercise, it was decided to describe the need for cooperation in the Belgian DTIB and the strength of the Belgian DTIB without naming specific organisations. A list of the contributors provides insight in the organisations having participated in the roadmapping exercise and workshops.

Cooperation with roadmap exercises in the regions

The regions also want to contribute to the further expansion of the Belgian DTIB[2, 3]. Flanders and Wallonia are developing strategic roadmaps for technologies in space-based defence applications. Both exercises are aligning with this DIRS technology roadmap for Space Defence Applications and examining the strengths of each region.

2. Vlaams Defensieplan, mededeling Vlaamse Regering van 4 april 2025

3. WSL - WOODI, une nouvelle alliance stratégique entre Thales, FN, John Cockerill et Ignity pour soutenir les start-up wallonnes de la défense

2

Track: Space-Based Earth Observation

2.1. INTRODUCTION: VISION AND GOAL

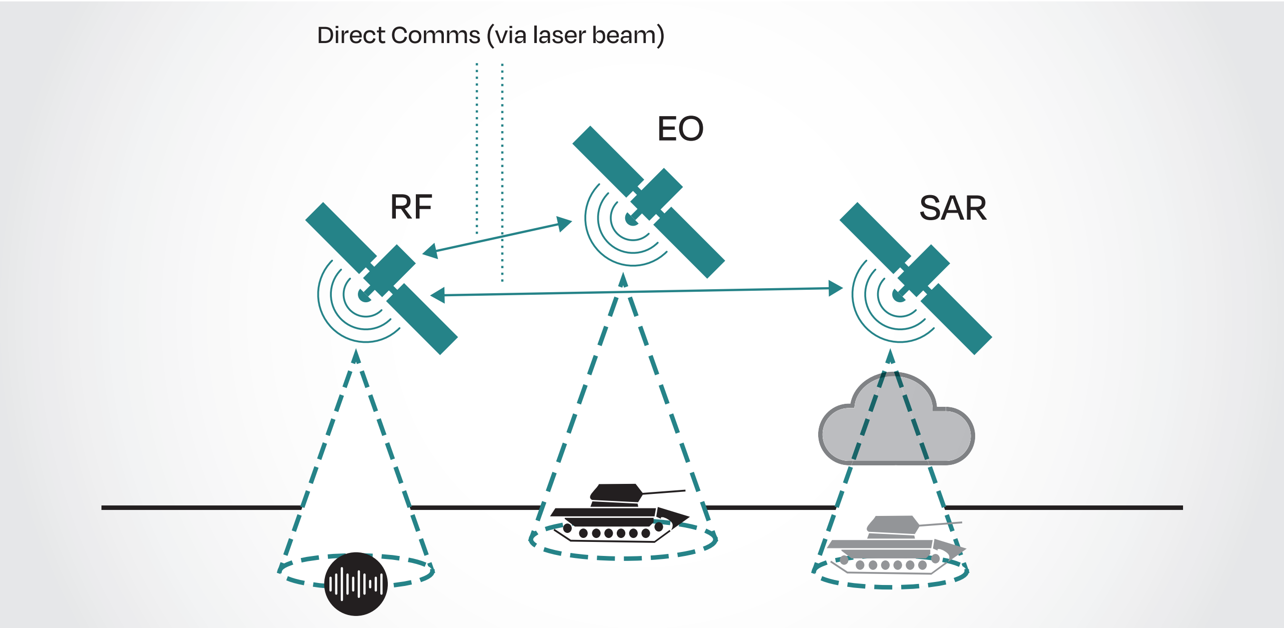
Space-based Earth Observation assets collect critical information on adversary activities, enabling informed decision-making and strategic planning. These systems support a range of missions, including monitoring compliance with international agreements, assessing battlefield conditions, and providing real-time intelligence to provide strategic insights and support tactical operations.

Solutions and technologies must equip Belgian/European defence with the right capabilities, the ability to achieve specific military objectives or perform particular tasks. Ensuring alignment with operational priorities requires identifying what defence must achieve, and the challenges involved at both strategic and tactical levels.

Specific lines of development and areas of priority are to be defined based on future evolution within scope of space, and/or other DIRS programmes/domains. All technological elements must consider low Earth orbit-based assets (LEO), assuming mini-Satellites (150 – 500kg) as a sweet spot between payload capability, launch flexibility and deployment cost as a baseline). The balance between cost and performance of proposed solutions must be carefully considered.

Short term focus

By 2030, within the GALO concept (Global coverage All weather LEO Observation) enabling defence operations to leverage an advanced and autonomous Low- Earth Orbit (LEO) satellite system, operating under the GALO framework. The system with several train of satellites integrates cutting-edge multi-sensor technology— Radio Frequency (RF) monitoring, Electro-Optical (EO), Synthetic Aperture Radar (SAR), and potentially multi/hyperspectral or infrared—into a resilient and adaptive network. Seamlessly interoperable with allied systems, it ensures persistent, all-weather surveillance and near-real-time data acquisition, providing a strategic edge for defence. All aspects of Earth Observation solutions increasingly rely on automation, with limited human intervention, reducing the time to deliver information to end users to (near) real-time.



The short term focus is on space-based Earth Observation (aspects between tasking a satellite and receiving data) to provide insights at a strategical level, not including intelligence, surveillance and reconnaissance (ISR, deriving insights and usages of the resulting data). Focus is on technology building blocks contributing to next generation solutions to GALO and the following innovation challenges:

- Ultra-high resolution payload technologies for continuous observation across visibility and weather conditions.
- Automation of processing, limiting the need on human intervention.
- Shorten time between tasking and receiving satellite data.

Longer term focus (medium term/long term)

Focus on increasingly disruptive technologies leading to new generation of payload solutions and ISR elements such as enhanced interoperability, direct-to-device, end-user tasking, and providing insights at tactical level.

The Belgian DTIB for Space-Based Earth Observation

Belgium combines mission-relevant R&D expertise, industrial capability, and space systems experience, placing it in a strong position to drive next-generation space-based Earth Observation solutions aligned with European defence needs:

- **Comprehensive Earth observation value chain from sensor to insight:** Belgian industry, academia, and research organisations collectively cover the full spectrum of Earth observation technology—from sensor innovation and platform integration to automated data processing and AI-based intelligence extraction. This enables end-to-end innovation across the Earth observation chain, tailored for defence operations.

- **Sensor excellence and miniaturisation:** Belgian research institutions lead in payload technologies (i.e. optics, calibration techniques, filter design, …) and photonics, supporting the miniaturisation and power efficiency critical for high-resolution, multi-modal Earth observation payloads deployed on compact LEO platforms.

- **Expertise in data handling, edge computing, and AI** Belgian actors specialise in (edge-ground) AI processing, sensor fusion, and payload data management. These strengths not only support more efficient payload operations but also enable automated processing pipelines and smart compression strategies—laying the groundwork for responsive, insight-driven Earth observation systems.

- **Integrated platform and ground segment development:** Belgium hosts satellite platform integrators and developers of autonomous ground segment solutions, supporting sovereign control and federated operation. These capabilities span mobile ground stations, AI-enhanced mission planning, and scalable infrastructure for tasking, downlink, and data dissemination.

- **Leadership in automation and context-driven intelligence:** Belgian RTOs and universities are at the forefront of contextual awareness, visual language modelling, and cross-domain AI. This enables systems that go beyond image capture to interpret scenes, infer mission-relevant context, and autonomously trigger tasking decisions—all aligned with defence intelligence cycles.

- **Strategic independence and European collaboration:** The Belgian DTIB supports European priorities in earth observation by contributing to European (e.g. EDA, EDF, ESA), international (NATO) and multilateral collaboration (e.g. BENELUX), while fostering supply chain independence through European initiatives focused on photonics, space-qualified microelectronics, and system-level integration. The DTIB is positioned to contribute both sovereign payloads and components for federated constellations.

Achieving the vision of GALO and future Earth observation capabilities requires continued collaboration between Belgian defence actors, academia, RTOs, and industry—from sensor R&D to constellation deployment—to meet demanding military needs in observation, responsiveness, and situational intelligence. Proposed solutions should prioritise the sovereignty of sourced components and contribute to strengthening the European industrial capability, ensuring critical technologies are developed, manufactured, and maintained within Belgium and the European Union.

2.2. CHALLENGE: ULTRA-HIGH RESOLUTION PAYLOAD TECHNOLOGIES

The challenge leverages a combination of different sensor technologies (by 2030 Radio Frequency (RF), Electro Optical (EO), Synthetic Aperture Radar (SAR), Infrared (IR), Hyperspectral) and sensor data from multiple data sources to provide for continuous observation across visibility and weather conditions and improved accuracy. Sensors will be deployed on several platforms, even if final design is not yet ready.

- By 2030, within the GALO framework, improve the resolution of payload technologies by development/upgrading of relevant data collection instruments, data and AI enabled improvements and support systems (Technology Readiness Level TRL 6-9)
- By 2035, research of disruptive technologies (i.e. quantum) and miniaturization, leading to new generations of sensors/instruments (starting from lower TRL).

Innovation goals within the challenge:

- Next-generation sensor technologies across electro-optical, radio-frequency, synthetic aperture radar, infrared, and hyperspectral payloads.
- Data & AI enabled improvements to enhance spatial detail and situational understanding.
- Next-generation support systems as critical enablers to enhance stability, accuracy, and autonomy of high-precision Earth observation.

Cooperation in the DTIB for sensor technologies

Next-generation Earth observation sensors require close cooperation across the DTIB:

- Academia and research organisations lead basic research on photonic systems, AI algorithms, spectral fusion, and calibration techniques.
- Industry drives the development, integration, and deployment of sensor systems by translating research into flight-ready hardware and software. Component suppliers produce miniaturised, space-qualified photonic, RF, IR, and hyperspectral elements, including cooling systems to enhance resolution; electronics manufacturers deliver low-power, radiation-hardened chips and signal processors; and system integrators assemble compact, multi-sensor payloads tailored for agile platforms. Belgium has today limited sovereign SAR payload development and integration experience. Platform providers ensure compatibility with satellite buses, while solution providers manage data flows, optimise latency, and support downstream exploitation.

Together, they ensure that sensor technologies meet defence-grade requirements for performance, reliability, and autonomy in orbit.

Three closely linked research challenges to be addressed jointly

The research challenges "Automation of the integration of data (and data sharing) from different sources and sensor types," "Latency in data processing for an operational space picture," and "Identify potential threat typology" share a strong interdependency and should be addressed as a coherent cluster.

These challenges all rely on a central model capable of real-time data fusion and interpretation across heterogeneous sources. A critical enabler for all three is the availability of sufficiently high-quality, standardized, and labelled datasets to support machine learning at scale. In particular, the development of an AI-based threat typology requires the output of integrated, real-time data to identify patterns, behaviours, and anomalies reliably. Joint research should prioritize the alignment of data pipelines and formats, processing timelines, and AI training protocols to reduce duplication and ensure consistent performance across operational and strategic levels.

2.2.1. SENSOR TECHNOLOGIES (EO – RF – SAR – IR – HYPERSPECTRAL)

The goal is to develop key technology building blocks that enable next-generation sensor systems across electro-optical, radio-frequency, synthetic aperture radar, infrared, and hyperspectral payloads—advancing spatial, spectral, and temporal resolution while minimising size, weight, and power requirements to support persistent, multi-sensor earth observation from compact satellite platforms.

On the longer term, this requires a strong emphasis on the miniaturization and power efficiency of photonic systems, as well as the integration of quantum-enabled sensor concepts. These disruptive technologies will enable new levels of sensitivity, spectral richness, and timing precision beyond current architectures. First in-orbit proof of concept for quantum or other disruptive building blocks are foreseen as a milestone toward adoption post-2030. On the longer term, systems must also evolve to support full in-orbit data fusion, deliver real-time situational insights to tactical users, and contribute to the creation of dynamic Earth observation Digital Twins.

Key priorities and innovation goals for the different payloads:

- **Electro-Optical (EO):**
  - By 2030, deliver ultra-high spatial resolution EO payloads (sub-meter level, ≤50 cm Ground Sample Distance (GSD) for dynamic environments and onboard data compression. Explore integration of photonic-based miniaturized optics for daylight operations.
  - By 2035, disruptive miniaturized EO systems with photonic-based wide-spectrum imagers enabling day/night operation and fusion with SAR/IR. Fully automated onboard tasking and image selection logic.

- **Radio-Frequency (RF):**
  - By 2030, RF payloads will feature multi-band, beam-steered antennas for persistent wide-spectrum coverage able to scan the entire RF spectrum (from Very High Frequency (VHF) to millimeter wave) and to provide an accurate RF signal localisation (~10 km).
  - By 2035, fully autonomous spectrum mapping systems with real-time spectrum analytics, resilient to contested electromagnetic environments. Fusion with EO/SAR assets.

- **Synthetic Aperture Radar (SAR):**
  - By 2030, SAR payloads will transition from large, power-intensive systems to compact, beam-steered units with a target average power consumption of 100 Watt. Achieving this will require short, intelligently managed duty cycles that balance power efficiency with operational needs, recognizing the trade-off between reduced observation time and system performance.
  - By 2035, advances in photonic beam steering and software-defined radar architectures will enable sub-meter resolution, dynamic reconfiguration, and efficient power usage. These SAR systems will be fully integrated into multi-sensor LEO constellations, supporting persistent, all-weather earth observation through mixed-modality data fusion across EO, RF, and IR domains.

- **Infrared (IR):**
  - By 2030 Infrared (thermal) sensors will evolve to support night-time earth observation with enhanced dynamic range and reduced noise (down to 2m GSD) and temperature resolution of 1 degree Celsius). Reduce pointing error/jitter to reduce motion blur for night-time sensors requiring longer exposure to accumulate enough signal.
  - By 2035, new infrared imagers with higher resolution (down to 1m GSD) will operate in synergy with Electro Optical and SAR systems.

- **Hyperspectral:**
  - By 2030, hyperspectral payloads will push spatial and spectral resolution beyond today's limits (GSD <10m, hundreds of bands).
  - By 2035, integrated with other sensor data. advanced photon-collection and real-time processing will enable persistent material characterization.

Complementary developments

These payload-specific developments are mutually complementary, each advancing technology building blocks for a distinct sensing modality while contributing to a coherent, integrated observation system. Together, they enable a new generation of persistent, multi-modal Earth observation architectures, where each sensor type enriches the overall system performance. The research challenges below for specific payloads serve primarily as illustrative examples of what is possible, rather than representing a coordinated, interdependent development trajectory as is the case for miniaturisation and quantum-enabled sensing.

2.2.1.1. Accommodate multiple antennas to scan the whole RF-spectrum

To observe, understand and respond to activities across the electromagnetic spectrum, future space-based platforms must be able to scan the entire RF spectrum (from VHF to millimeter wave) with high sensitivity, spatial resolution and agility. This requires multiple specialized antennas to cover diverse frequency bands effectively — no single antenna design can maintain optimal sensitivity across all bands. Additionally, accurate RF signal localisation demands Controlled Radiation Pattern Antennas (CRPA) and beamforming techniques, which introduce major integration, processing and power challenges.

For strategic and technological sovereignty, dependence on non-EU electronic components, must be avoided, particularly in the areas of field-programmable gate arrays (FPGAs) and application-specific chips for signal acquisition and real-time processing.

Key research gaps (short term, 2-3 years):

- **Miniaturisation and integration of multi-band antennas:** How can advanced materials, 3D manufacturing, and reconfigurable antenna concepts enable compact platforms capable of wideband scanning without sacrificing gain or sensitivity?

- **Real-time signal analysis algorithms:** Development of adaptive, AI-enhanced spectrum analysis algorithms to detect, classify, and localise signals in real-time, even in dense or contested RF environments.

- **Processing architectures:** Architectures (e.g. edge-AI, FPGA-accelerated pipelines, neuromorphic computing) to support the extreme compute demands of real-time spectrum analysis and beamforming onboard the satellite.

- **European FPGA and chip technology:** Development of high-performance, radiation-hardened FPGAs and signal processors within Europe to avoid critical dependence on United States/Asia.

2.2.1.2. Power-efficient, beam-steered SAR systems for compact platforms

Synthetic Aperture Radar (SAR) provides all-weather, day-night observation along with enabling unique applications related to assessment of soil composition, detection of camouflaged infrastructure (foliage penetration), moisture levels on ground and vegetation, and underground infrastructure monitoring, to name a few. However, SAR systems are traditionally power-hungry, large, and mechanically complex, making them ill-suited for small spacecraft and agile constellations. Reducing their power consumption while maintaining performance — and enabling beam steering without bulky mechanisms — is key to unlocking next-generation distributed SAR capabilities.

This challenge aims to develop the core technology building blocks for sovereign SAR payload solutions (e.g. photonic beam steering, compact software-defined radar electronics, low-power transmission chains) that enable affordable, scalable, power-efficient, and steerable SAR payloads for small satellites.

Key research gaps:

- **Antenna and photonic technologies for dynamic beam steering** to improve spatial resolution, signal-to-noise ratio, and interference suppression.

  - Replacing bulky mechanical gimbals with photonic beam steering (e.g. optical phase shifters, optical delay lines) is essential for reducing both power and mass.
  - Photonic Integrated Circuits (PICs) that are space-qualified and can operate across relevant radar bands. This also includes thermal stability, radiation hardening, and integration with antenna arrays.
  - Nextgen digital beamforming and electronically steerable arrays provide faster and more flexible reconfiguration for remote sensing satellites (SAR, hyperspectral).

- **Software-Defined Radar electronics:** SAR systems typically require high-speed signal generation, digitization, and processing — which draws significant power. The challenge is to design ultra-low-power software-defined radar electronics, combining reconfigurable signal chains, advanced power management, and FPGA-based control optimized for space-grade conditions.

- **Antenna integration with miniaturized platforms:** conformal, deployable, or printed antenna architectures that can work with active beam steering systems in a small satellite bus — without compromising effective aperture or thermal behaviour.

► **Compact, reconfigurable SAR monitoring payload** with on-board AI and real-time tasking capability.

2.2.1.3. Pushing the limits of sensors for night-time observation

Solutions pushing limits of sensitivity of current technologies (thermal IR, low-light optical, SAR) for night-time Earth observation to overcome the lack of observation data and low spatial resolution when natural illumination is absent or very low.

Challenges and technology building blocks:

- The minimum resolvable signal (e.g. temperature) difference of sensors to reliably distinguish between two adjacent pixels in a scene.
- Improving the dynamic range of sensors (the ratio between the brightest and darkest signal a sensor can capture simultaneously, without saturation or losing detail in noise), enabling to "see" hot objects and cold backgrounds — in one image — without losing contrast or detail.
- SAR and active sensors providing night-capable imagery without depending on ambient light
- Improving the sensitivity of scanning methods (signal to noise ratio, resolution, calibration, etc) or developing sensor solutions reducing/avoiding the need on scanning. E.g. time delay integration (TDI) - see also hyperspectral, backside illuminated imagers (for higher quantum efficiency)
- Advanced planar optics and filters at image device (and even individual pixel) level for lower mass, volume, cost and better performance.
- Detection and observation of movement (i.e. equipment) and night observation in forest or urban areas.
- Improving SIM (Synthetic Imaging Method) computational imaging, for low-light or photon-limited conditions.

Combination with other research challenges:

- Pushing the limits for hyperspectral resolution.
- Improved pointing stability and performance to avoid motion blur and jitter sensitivity.
- (onboard/on-ground) AI-image enhancement and correction to fix blur, interpolate missing data, or fuse sensor data (e.g. IR + SAR).

2.2.1.4. Pushing the limits for hyperspectral resolution

Hyperspectral Earth observation provides detailed spectral information across numerous narrow bands, enabling precise material identification and analysis. However, current space-based hyperspectral systems often suffer from coarse spatial resolution, limiting their effectiveness in defence applications such as urban monitoring, infrastructure assessment, and tactical surveillance. The primary challenge lies in overcoming the trade-off between spectral richness and spatial detail, particularly addressing the photon scarcity associated with smaller ground sample distances (i.e. GSDs <10m).

Key research gaps:

► **Photon Collection Efficiency:** Developing larger aperture telescopes to collect more photons, thereby enhancing signal strength for smaller GSDs.

- **Extended Integration Time:** Implementing technologies such as Time Delay Integration (TDI) and advanced pointing mechanisms to increase exposure time without compromising image quality.

- **Thin film optical filters:** enhanced filter response to improve signal to noise ratio and optimised geometric layout for improved performance in combination with time delayed integration sensor read-out within a compact instrument volume. Extension to longer wavelengths.

- **Sensor Innovation:** Designing sensors with low thermal noise, high sensitivity, and the capability to cover broader infrared ranges (NIR - Short-Wave Infrared (SWIR) spectrum), and small/medium pixel Full Well Capacity (FWC, maximum number of photoelectrons a pixel in an image sensor can store before it becomes saturated)

- **On-Board Processing:** Developing real-time data processing algorithms & Payload Data Handing Electronics (hardware and software components) to manage the increased data volume from higher resolution hyperspectral imaging.

- **Platform position, stability and control:** Improving the position of the platform and enhancing satellite manoeuvrability and stability to maintain precise imaging over targeted areas (Satellite and payload-level stability and agility solutions (see also 2.2.3. High precision and responsive support systems).

2.2.1.5. Enhancing Calibration Techniques for Space-Based Earth Observation Payloads

The performance of Earth observation payloads is critically dependent on precise pre-flight calibration to ensure higher sensitivity and resolution. Traditional calibration methods face limitations due to manufacturing constraints and the complexities of on-ground support equipment. This challenge focuses on developing advanced calibration techniques, including algorithmic corrections, to overcome these limitations and enhance payload performance. Position the co-design of sensor and calibration techniques as an integrated development path, from pre-flight calibration to in-orbit recalibration mechanisms to ensure end-to-end traceability, in-orbit stability, and long-term data consistency under real mission conditions.

Key research gaps:

- **Limitations of on-ground support equipment:** Investigate and mitigate the performance constraints of on-ground support equipment, particularly concerning stray light control and its impact on calibration accuracy.

- **Algorithmic correction techniques:** Develop sophisticated algorithms capable of compensating for manufacturing imperfections and enhancing calibration precision beyond physical limitations.

- **Understanding payload behaviour and origin of problems:** Conduct in-depth studies to distinguish and analyse the origins of performance issues, enabling targeted improvements in payload design and calibration processes.

2.2.1.6. Miniaturization and power efficiency of photonic systems

The objective is to advance and integrate space-qualified photonic technologies in support of miniaturised, high-performance sensors for earth observation. Photonic Integrated Circuits (PICs) combine compact design, low power requirements, and strong resistance to electromagnetic interference, making them a prime candidate for next-generation Earth observation payloads—across EO, RF, SAR, IR, and hyperspectral domains—deployed on small satellite platforms. Closing the gap between current PIC technologies and space-ready instruments is a key enabler of European autonomy in defence-focused Earth observation capabilities.

This work centres on application-driven research, aiming to transition photonic technologies into fully functional, next-generation space-grade payloads that meet the demanding environmental and operational requirements of Earth observation missions from compact satellite platforms. These solutions must be resilient in harsh orbital conditions and seamlessly integrable into defence-oriented applications. Central to this approach is the pursuit of European technological sovereignty. Maturing and qualifying PIC platforms must go hand in hand with establishing end-to-end value chains —from upstream component R&D to downstream system integration— ensuring strategic independence, robust supply chains, and responsiveness to defence requirements.

Key research gaps:

- **Space-grade photonic integration:** Existing PICs (silicon (Si), silicon nitride (SiN), indium phosphide (InP), and lithium niobate (LNO) platforms) are not fully qualified for the harsh radiation, temperature, and mechanical stress conditions in LEO. Develop and qualify radiation-hardened PIC platforms covering EO-relevant spectra. Integrate hybrid material systems (e.g. group III–V semiconductors (III/V), diamond, silicon carbide (SiC) to enhance bandwidth and thermal robustness.

- **Low-power, high-speed optical signal processing:** Develop ultra-broadband photonic signal processing chains tailored for onboard sensors. Combine passive and active photonic components in miniaturised, low-loss form factor.

- **Optical beamforming and flat optics for EO sensors:** Mature flat optics (metasurfaces, optical phased arrays) and lantern-based optical beamforming to enable beam-steered imaging or scanning in compact EO payloads. Ensure performance across wide spectral bands (short-wave infrared – visible) with thermal stability and high optical throughput.

- **Multi-sensor photonic integration:** Harmonise photonic architectures for use in hybrid sensing missions and cross-modality data synchronisation. Earth observation requires synergy across EO/SAR/IR/hyperspectral data layers, yet integrated photonic solutions for cross-domain fusion are rare. Design integrated platforms combining photonic components for imaging, spectral sensing, and RF signal processing.

- **Design, testing, and packaging for low-volume defence space applications:** Build a robust supply chain for low-volume, high-performance PICs tailored to defence-grade Earth observation missions (TRL 5–6). Develop test and packaging solutions for European sovereign PICs under space qualification processes.

2.2.1.7. Quantum-Enabled Technology Building Blocks

Quantum sensing leverages quantum properties to measure physical features with unprecedented sensitivity and precision, significantly surpassing classical sensor capabilities. It has an enormous potential across many diverse fields, i.e. for space-based gravimetres for Earth observation purposes. The goal is to develop in-orbit proof of concept for quantum-based next-generation technology building blocks that enhance the performance, resilience, or versatility of space-based Earth observation systems. The goal is to strengthen the quantum ecosystem by validating core quantum-enabled functionalities—such as ultra-sensitive imaging, enhanced spectral discrimination, or autonomous calibration—under real orbital conditions, targeting TRL 5-6.

This effort includes maturing the selected quantum technology from laboratory readiness, adapting it for space through miniaturization, radiation hardening, and system integration, and deploying it ready for a compact in-orbit demonstrator in LEO. The demonstrator will provide critical insight into system behaviour, environmental robustness, and mission relevance, and will serve as a key enabler for future multi-sensor Earth observation architectures supporting defence, intelligence, and environmental security applications. The specific quantum building block (e.g. photon-based calibration source, quantum-enhanced imager, or inertial component) will be selected through pre-feasibility analysis and stakeholder alignment within the roadmap framework.

2.2.2. DATA & AI ENABLED IMPROVEMENTS

This innovation goal aims to enhance spatial detail and situational understanding by leveraging machine learning, contextual reasoning, and cross-modality data fusion. Rather than relying solely on hardware resolution, new approaches will extract sub-pixel insights from multi-source, multi-pass, and time-series data, while dynamically adapting observation strategies based on the evolving mission context. Together, these capabilities will enable defence systems to detect smaller targets, interpret scenes more accurately, and prioritise observations with greater intelligence—transforming raw imagery into actionable awareness under all conditions.

First solution already might fit within GALO, more advanced solution can go beyond the 2030 timeframe.

Cooperation in the Belgian DTIB

Cooperation combines industrial expertise in application requirements, ground stations, sensor techniques, alignment and fusion with academic strengths in AI-enhanced methods and processing infrastructure and platforms to enhance for i.e. super resolution techniques, sub-pixel object detection, data augmentation techniques, edge processing or scene understanding.

2.2.2.1. Super resolution and image improvement

Space-based sensors are fundamentally limited by optics, platform altitude, and bandwidth — constraining the size of detectable features to the sensor's native pixel resolution. Yet critical targets (vehicles, assets, anomalies) are often smaller than one pixel.

The aim is to develop approaches to detect, enhance, and interpret sub-pixel objects, not by increasing hardware resolution, but by enriching interpretation through fusion and inference:

AI-driven methods that go beyond the native resolution of the sensor — by leveraging:

- Data from other sensors (e.g. thermal, SAR, hyperspectral).
- Temporal or angular variation (multi-pass, multi-view).
- Contextual reasoning (patterns, shadows, surroundings) within the main image.

On the longer term, the potential of quantum computing should be explored to accelerate complex fusion, inference, and reconstruction tasks beyond the capabilities of classical onboard or ground-based systems.

Key research gaps:

- **Unified geospatial reference system:** Develop a coordinate and alignment framework where data from multiple sensors and modalities (with varying resolution, viewing angles, and timestamps) can be consistently fused.

- **Cross-image enrichment algorithms:** Create robust computer vision techniques that use approximately aligned images (e.g. from previous or adjacent passes) to fill in detail, correct blur, or refine edges in the primary image.

- **Sub-pixel object prediction from context:** ML-models that learn to infer the likely presence of sub-pixel features based on patterns in shadows, texture transitions, or correlated spectral features — akin to how humans "see" faint hints in noisy images.

- **Sensor-level onboard data compression:** Develop intelligent compression approaches directly at sensor output, optimised for AI-driven interpretation, to reduce downlink volume without compromising critical spatial or spectral information.

- **Data augmentation and synthetic image generation:** Create advanced data augmentation pipelines to simulate various scenes, reconstruct missing backgrounds, or enrich training datasets—improving model generalisation and robustness in edge cases.

2.2.2.2. Enhancing contextual awareness in space-based Earth observation

Contextual awareness in Earth observation systems refers to the capability to interpret observed data in relation to environmental context, historical events, and specific mission objectives. This involves integrating various data sources and analytical methods to move beyond mere data collection towards meaningful situational understanding. For defence applications, this means Earth observation systems can prioritize observations, detect anomalies, and support decision-making processes more effectively.

Contextual awareness refers to an Earth observation system's ability to interpret what it sees in relation to its surroundings, past events, and mission objectives. It's the difference between passively capturing pixels... and actively understanding the situation. It involves fusing:

- Scene understanding (e.g. urban vs. forest, peace vs. conflict) to support target detection.
- Temporal patterns for change detection (what has changed to prior baselines, flag anomalies with meaning).
- Tasking prioritization based on evolving context (e.g. weather window opens, previously spotted aspects).
- Mission intent, to incorporate what do we care about now.
- External signals (weather, alerts, terrain, previous passes, threat intelligence...)

Key research gaps:

- **Digital Twins for contextual modelling:** Creating dynamic digital replicas of Earth's systems that integrate Earth observation data with in-situ measurements and simulations to provide a comprehensive contextual framework.

- **Visual Language Modeling:** Designing AI models capable of interpreting visual data in conjunction with contextual information to enhance scene understanding and semantic analysis.

- **Integration of mission intent and external signals:** Developing systems that can incorporate mission-specific objectives and external data (e.g., weather, alerts) to adapt observation strategies in real-time.

- **Simulation Environments for Predictive Contextual Analysis:** Establishing simulated environments that can predict contextual circumstances, aiding in proactive decision-making and tasking prioritization.

- **Advanced data fusion techniques:** Create robust algorithms to fuse multi-source, multi-temporal, and multi-resolution data into coherent, actionable layers—enabling consistent situational awareness across sensor types and missions.

- **Automation of context-driven workflows:** Develop end-to-end automated pipelines—from data ingestion to alert generation—that reduce human workload while maintaining situational relevance and traceability.

- **Satellite-agnostic data access and distribution:** a secure, flexible data distribution architecture that decouples analysis and visualisation from specific satellite platforms, enabling seamless access to context-rich Earth observation data across missions and systems.

2.2.3. HIGH PRECISION AND RESPONSIVE SUPPORT SYSTEMS

Support systems are critical enablers of high-precision Earth observation, ensuring that sensor payloads operate with the stability, accuracy, and autonomy needed to deliver timely and actionable data—especially under operational constraints such as poor visibility, limited ground control, or contested environments. This innovation goal focuses on two research challenges:

- Achieving high-performance, agile pointing to maintain line-of-sight and optimise target acquisition on compact, dynamic platforms.
- Ensuring accurate, autonomous geolocation through the development of ultra-stable inertial reference systems that reduce dependence on external references.

Collaboration in the DTIB

Both areas require a collaboration in the DTIB to realise breakthroughs in control architectures, sensor technologies, and validation infrastructure to meet the demands of next-generation defence Earth observation missions. This can be strengthened by i.e. contributions from high-precision mechanical equipment for micro-electronics sector.

2.2.3.1. High performance, agile pointing of the payloads

Achieving precise and responsive pointing is critical for next-generation Earth observation missions—especially on compact and agile platforms where both the spacecraft and its payload must adapt dynamically to observation demands. The challenge lies in optimising the trade-off between satellite-level attitude control and sensor-level agility, ensuring that sensors remain accurately locked onto targets, even during rapid reorientation or in the presence of vibrations and disturbances.

This requires advances in high-performance pointing technologies that enable:

- Higher pointing accuracy to maintain line-of-sight on small, moving or distant targets.
- Improved stability to support long integration times and high image quality.

- Greater observation agility for rapid re-targeting, efficient orbital use, and the tracking of time-sensitive or mobile phenomena.
- For multi-sensor alignment improving pointing consistency to ensure spatial alignment, data correlation, and fusion accuracy.

Dual-stage control systems—combining coarse spacecraft orientation with fine, fast payload steering—are essential to meet these needs, alongside supporting infrastructure for testing and validation under representative conditions. Expected accuracy is in the range of arcsec and ½ pixel accuracy in integration time. Results will enable in-orbit demonstration to validate the proof of the technology (from TRL 4/5 to 7).

Key research gaps:

- **Dual-stage control systems:** Integrated control architectures that manage low-frequency spacecraft pointing and high-frequency instrument steering. These systems must address increasing complexity as platform size decreases, while ensuring tight synchronisation between satellite and sensor.

- **Advanced ADCS technologies:** New mechanisms and control algorithms within the Attitude Determination and Control System to reduce jitter and enhance fine-pointing performance—enabling stable data capture under real-world orbital dynamics.

- **High-performance instrument platforms:** Mechatronic or electromechanical payload platforms capable of rapid and precise reorientation. These must ensure flexibility, speed, and fine control to optimise scene acquisition within each orbit segment.

- **Fine guidance and actuator integration:** Integrate high-resolution fine guidance sensors with responsive actuators to continuously adjust the sensor's line-of-sight, maintaining target lock within the stringent constraints of high-resolution imaging.

- **Hardware-software breadboard validation:** Develop and test representative breadboard systems that couple inertial sensors and embedded control logic to validate dynamic performance, accuracy, and responsiveness under simulated mission conditions.

- **3-axis pointing test platforms:** Extend existing lab setups to 3-degree-of-freedom (3 DOF) platforms to enable realistic ground testing of full control loop performance in low-vibration environments, supporting early validation before space deployment.

2.3. CHALLENGE: SMART, AUTOMATED PROCESSING OF EARTH OBSERVATION DATA

Achieving smart, automated processing of Earth observation data is identified as a short-term priority for defence. Rapid access to relevant, post-processed information is essential to ensure data is available in real-time or near real-time. This effort focuses on application-driven research rooted in defence-relevant use cases, with the aim of transitioning Earth observation data processing to meet the demanding operational needs of compact satellite platforms. The objective is to move from traditional processing workflows toward highly automated, distributed architectures—on the ground and in orbit—to meet the speed, performance, and reliability expectations of future defence Earth observation operations.

Key bottlenecks:

- Minimize as much as possible the human treatment of raw data, limiting work of specialized analyst to high-value analysis.
- Onboard AI/ML and edge processing identifying key features, anomalies, and automatically recognizing targets, enabling to only downlink the meaningful information, to tackle data deluge and reduce latency.
  - High performance edge processing systems.
  - Ensuring real-time image enhancement, noise reduction, and super-resolution processing with limited computational resources
  - Implementing onboard AI and deep learning models for autonomous object detection, classification, and anomaly tracking.
- Automate identification and characterization of sensor output. Currently this requires too much manual effort. Automated, limiting human intervention to high adding-value analysis.
- Accelerate the process and delivering of information (increase speed to acquire data).
- Managing high volume of data with minimum of infrastructure, filtering high amount of data and addressing priority targets, possibly (partially) in orbit.
- Real-Time Data Processing and AI Integration

Innovation goals within the challenge:

- Autonomous onboard intelligence for multi-sensor fusion and mission-driven data handling
- Nextgen sovereign ground segment for Earth observation

2.3.1. AUTONOMOUS ONBOARD INTELLIGENCE FOR MULTI-SENSOR FUSION AND MISSION-DRIVEN DATA HANDLING

2.3.1.1. Edge processing and automation

To meet the demands of increasing data volume from high-resolution multispectral, hyperspectral, SAR, and RF sensors, this challenge focuses on developing AI-enhanced, on-board data fusion and interpretation capabilities. The goal is to enable satellites to autonomously process and prioritise Earth observation data in orbit—detecting features of interest, classifying targets, and making tasking decisions in real-time—thus reducing downlink load, accelerating responsiveness, and improving operational efficiency.

This requires fusing multi-sensor inputs (EO, SAR, RF) directly on board to support contextual awareness, change detection, and autonomous decision-making, while operating within the power, thermal, and computational constraints of the space environment. These also connect with enhanced contextual awareness and multi-variable tasking.

Key research gaps:

► **AI algorithms for in-orbit interpretation and decision-making**

  - Robust AI models for real-time cloud masking, feature detection, target recognition, and change detection under space constraints (limited compute, radiation, thermal variability).
  - Autonomous feature extraction and prioritisation to downlink only mission-relevant data.
  - Fault and anomaly detection in Earth observation workflows to improve in-orbit quality control and mission reliability.
  - AI models for multi-sensor fusion (optical, SAR, RF) to support contextual understanding and autonomous tasking decisions.

- Neuromorphic or brain-inspired computing techniques for energy-efficient, high-speed pattern recognition.

- **Low-power, high-performance hardware architectures**
  - Radiation-hardened AI accelerators: FPGAs, ASICs, and co-processors optimised for space-based AI workloads.
  - Innovative low-power AI architectures that ensure optimal balance between performance and satellite power budgets.

- **Payload data handling and system integration**
  - Integrated payload data handling units (PDHUs) combining real-time co-processing, high-throughput interfaces, and onboard tasking logic.
  - End-to-end payload data architecture optimisation, addressing data/power/processing bottlenecks across sensors, memory, and computing modules.
  - High-speed, resilient mass memory systems to buffer and manage high-resolution sensor data in real-time.
  - Efficient data compression and mining techniques for onboard storage and transmission under bandwidth limitations.
  - Reliable, high-throughput data transfer and communications interfaces, both intra-satellite and satellite-to-ground.

2.3.1.2. High-efficiency, SWaP-optimized onboard data storage

Modern Earth observation missions — particularly those involving hyperspectral, high-resolution multispectral, and persistent monitoring — generate massive data volumes. However, downlink windows are limited by bandwidth, line-of-sight, and contested spectrum. This bottleneck makes on-board data storage and management a strategic capability: enabling satellites to store, prioritize, and delay transmission without loss of data or performance.

The challenge lies in developing storage systems that are high-capacity, low-power, and volume-efficient, and that can survive the harsh radiation and temperature conditions of space. These systems must scale with future payloads and fit within the strict low SWaP (Size, Weight, and Power) constraints of small or agile platforms.

Key research gaps:

- **Electronics vs SWaP trade-offs:** Advanced storage electronics (e.g. high-speed flash, Solid-State Drive (SSD) controllers) often introduce size, heat, shielding, or mass issues. There is a need to co-design radiation-hardened storage systems that deliver high throughput while fitting within SWaP envelopes — especially for constellations or deployable Earth observation platforms.

- **Data growth from evolving sensors:** New sensors (e.g. hyperspectral imagers, video payloads, multi-angle optics) generate far more data per orbit than legacy systems. There's a growing mismatch between sensor output and existing storage architectures, requiring novel solutions like compression-aware storage, tiered memory, or selective archiving.

- **Flight-qualified components and thermal control:** Space-grade storage options require component hardening, thermal optimization, and lifetime assurance to handle long-duration missions and frequent read/write cycles — without driving mass and volume too high.

2.3.2. NEXT-GEN SOVEREIGN GROUND SEGMENT FOR EARTH OBSERVATION

The ground segment is a critical enabler of operational Earth observation missions, particularly in the short term, where sovereign control and responsiveness are essential. Modern ground station capability is a key component of a resilient Earth observation system. It requires specialized knowledge and the development of dedicated hardware. A lot more data is generated on the satellites - even with new techniques allowing for data processing to be done on board of the satellite.

2.3.2.1. Secure and federated ground segment for sovereign and responsive Earth observation

The goal is to develop the technology building blocks for a next-generation resilient, scalable, and AI-enabled ground segment that guarantees national autonomy while supporting federated integration with allied and commercial partners.

The TBBs for the ground segment:

- Support dynamic tasking and rapid delivery of Earth observation products (see also next challenge).
- Integrate AI to streamline operations, processing, and analysis.
- Enable real-time Earth observation data access through secure, autonomous ground infrastructure.
- The ability to acquire high- and standard-resolution images from different sources (national or privately owned Earth observation satellite constellations), based on user-defined criteria such as resolution, revisit time, and cost.
- Compatibility to share and use Earth observation capabilities with allied partner systems through the adoption of universal data formats, standardised communication protocols, encryption extending beyond the handling of sensitive data in compliance with homologation and classification procedures, and modular architectures for multi-platform integration. This enables seamless multi-source collaboration across systems while maintaining Belgian sovereign control over Belgian Earth observation assets.

Key research gaps:

► **Interoperability and data integration:**

- Harmonisation of Earth observation data models and metadata standards for multi-partner operations/integration.
- Standardised, extensible protocols (e.g. Consultative Committee for Space Data Systems (CCSDS), Open Geospatial Consortium (OGC) for cross-platform communication and tasking.
- Compatibility beyond ESA's European Ground Systems – Common Core (EGS-CC) to support small and responsive missions.

► **Secure and sovereign operations**

- Advanced encryption and secure software/hardware for satellite communications.
- ISO 27001 (International Organization for Standardization) based security governance for end-to-end operations.
- Data traceability and auditability mechanisms for sensitive, multi-party Earth observation use.

- **Distributed and autonomous control**
  - Distributed on-premise/cloud/edge processing for rapid, decentralised product generation.
  - Scalable infrastructure for autonomous coordination of large satellite constellations (>25 spacecrafts).
  - AI-enhanced operations support for anomaly detection, prioritisation, and decision support.

- **Resilience and mission continuity**
  - Redundancy, failover mechanisms, and cyber-resilience in sovereign ground assets.
  - Modular architectures allowing scalable upgrades and flexible partner integration.
  - Continuous operation under hybrid public-private constellation management models.

2.3.2.2. Deployable mobile ground stations for space-based Earth observation

In modern defence scenarios, the ability to rapidly deploy and operate mobile ground stations capable of acquiring, tracking, and transferring data from LEO/GEO (Geostationary orbit) satellites is crucial. These stations, whether mounted on vehicles or vessels, must function reliably under varying environmental conditions and mobility constraints. The challenge lies in developing technologies that ensure robust communication links (optical/RF), precise pointing, acquisition, and tracking (PAT) capabilities, and efficient data handling, all within the constraints of a mobile and often unpredictable operational environment.

Key research gaps:

- **Environmental Resilience:** Mobile ground stations must operate under diverse and harsh environmental conditions, including extreme temperatures, humidity, dust, and electromagnetic interference. Research is needed to develop materials and systems that maintain performance and reliability in such conditions, ensuring uninterrupted operations.

- **Motion Compensation Techniques:** Operating from moving platforms introduces challenges in maintaining stable communication links. Advanced motion compensation algorithms and stabilization mechanisms are required to counteract the effects of platform movement, ensuring accurate satellite tracking and data acquisition.

- **Optimized Communication Systems:** Ensuring reliable data transfer during both daytime and nighttime operations necessitates the development of communication systems that can adapt to varying light conditions and potential obstructions. Research into hybrid optical/RF systems and adaptive modulation techniques can enhance data throughput and link stability.

- **Advanced Pointing, Acquisition, and Tracking (PAT) Systems:** Precise PAT systems are essential for establishing and maintaining communication links with satellites. Innovations in sensor technologies, control algorithms, and real-time feedback mechanisms are needed to improve the accuracy and responsiveness of these systems, especially in dynamic environments.

2.4. CHALLENGE: SHORTEN TIME BETWEEN TASKING AND RECEIVING SATELLITE DATA

To reduce end-to-end latency in LEO-based Earth observation, each step in the LEO-based Earth observation chain—from tasking request to user delivery—must be streamlined and tightly integrated. This challenge focuses on enabling intelligent, automated operations that minimize delays across planning, satellite acquisition, downlink, and data dissemination. A key priority is the use of AI-driven systems for dynamic tasking both into ground and on-board data processing, allowing satellites to respond autonomously to mission needs and trigger follow-up observations in real-time.

Smart, AI-enabled systems will dynamically prioritize and coordinate satellite tasking across heterogeneous constellations, balancing urgency, resource constraints, and mission context to deliver rapid and conflict-free responses. At the same time, advanced on-board processing capabilities will fuse and interpret multi-sensor data (EO, SAR, RF, etc.) in real-time, enabling satellites to autonomously trigger follow-up observations without waiting for ground input. Together, these capabilities aim to create a scalable, responsive Earth observation infrastructure that supports both strategic monitoring and time-critical operations with minimal human intervention.

These advances aim for:

- By 2030, smart tasking will reduce latency by allowing satellites to autonomously prioritise and execute observation requests in real-time, replacing static planning and limiting reliance on human intervention.
- By 2035, fully autonomous data fusion (RF, EO, SAR, IR, hyperspectral) will support dynamic re-tasking based on real-time triggers.

Note: End-to-end latency in (LEO based) Earth observation is closely linked to the smart, automated processing of Earth observation data, both in the ground segment and at the edge in orbit. This challenge focuses on the "Data & AI enabled improvements". Improvements in ground segment/stations and edge processing capability are taken-up in the smart, automated processing of Earth observation data challenge.

Key research challenges and gaps to overcome bottlenecks for rapid response:

- **Limited satellite agility and on-board autonomy** slowing reaction time to new tasking and dependence on manual updates.

- **A long wait between uplinks/downlinks**, i.e. caused by a fixed and sparse ground segment.

- L**ack of dynamic re-tasking and mission context**, due to absent Inter-satellite link capabilities that could enable "Always-on" tasking feature.

- **Automation to reduce heavy reliance on human-in-the-loop operations** introducing unnecessary lag in tasking, approval, and data pre-processing to augment quality (i.e. radiometric, geometric corrections) and access.

- **No prioritization of urgent users** - data is observed and queued regardless of mission importance or urgency.

- **Mission Planning through flexible integration with Ground Station providers:** Integration with multiple ground stations—including ESA's European Space Tracking (ESTRACK) network, Belgian assets, and commercial ground networks—supports mission planning by streamlining satellite manoeuvre computation, tasking, and data delivery workflows.

- **Imagery Ordering management. Overall management** and optimization of tasking orders processes. Including user facing interfaces for tasking, tracking the progress of delivery, and potentially invoice processing. Integrated processes with complementary imagery sources, such as allied imagery catalogues and tasking interfaces.

2.4.1. MULTI-VARIABLE SATELLITE TASKING OPTIMIZATION

This research challenge addresses the development of AI-enabled smart tasking systems for time-critical and resource-aware Earth observation that can dynamically direct satellites to capture data at precise times and locations, while autonomously triggering follow-on payloads for complementary or higher-resolution observations. Replacing static schedules with event-driven optimization, these systems must ensure timely collection of high-priority data while efficiently using satellite resources and resolving conflicts. The focus is on scalable multi-objective optimization approaches for coordinating tasking across heterogeneous LEO constellations, directly contributing to latency reduction across the Earth observation chain. The goal is to ensure that high-priority or time-sensitive targets are captured with minimal delay, while also optimizing the use of satellite resources and network capacity.

Key research areas include:

- **Formalisation of tasking as a multi-objective optimization problem** to capture the complex trade-offs between urgency, resource constraints, revisit frequency, and imaging quality and combining competing priorities (e.g. rapid response vs. persistent monitoring) into a mathematically grounded framework.

- **Resource-aware satellite modelling (agility, power, link constraints).** Detailed modelling considering real-world satellite constraints of each satellite's agility (slew time, pointing limits), power budget, onboard data storage, and available communication links (GEO/LEO relay access, bandwidth) to ensure the system can make implementable decisions.

- **Priority management under uncertainty:** Real-world observation planning rarely happens under perfect information. Cloud cover, sensor availability, geopolitical events, or user requests may change rapidly. A robust tasking system must handle uncertainty in both the environment and the mission objectives, using probabilistic models or adaptive strategies.

- **Integration of real-time triggers and AI-based event detection** by onboard AI or ground-based analytics to dynamically/autonomously re-plan and re-task satellites based on situational awareness in response to these triggers, balancing pre-scheduled observations with urgent new targets.

- **Fairness and explainability in tasking decisions:** fair, transparent, and explainable decision-making mechanisms that justify why certain tasks are selected over others.

- **Scalable optimization from a satellite to a few satellites,** and to across large(r) constellations.

2.4.2. SMART ON-BOARD DATA FUSION AND INTERPRETATION FOR REAL-TIME INTELLIGENT TASKING

To support near-instantaneous, autonomous decision-making in Earth observation missions, satellites must be capable of fusing and interpreting raw sensor data—EO, SAR, RF, or others—directly on board. This research challenge targets the development of smart, automated on-board processing systems that enable satellites to analyse acquired data in real-time and autonomously trigger follow-on tasking decisions without relying on delayed ground intervention. The ability to perform in-orbit data interpretation will be critical for reducing latency in time-sensitive scenarios such as surveillance, threat detection, and dynamic monitoring operations.

Key research gaps include:

- **AI-based data fusion algorithms** for multi-sensor interpretation (e.g. target detection, classification, change detection) that operate efficiently in on-board environments.

- **Increase edge processing capability:**

  - **Radiation-hardened, power-efficient processing hardware**, such as AI accelerators, FPGAs, or dedicated co-processors, tailored for real-time satellite applications.
  - **Integrated payload data handling units** combining high-throughput processing and storage with mission control interfaces.
  - **High-speed, reliable mass memory systems** for buffering, accessing, and transferring multi-sensor data streams under real-time constraints.
  - **Low-latency, secure data transfer architectures**, supporting intra-satellite communication as well as potential inter-satellite or downlink links for prioritised information.

2.5. CHALLENGE: CONSTELLATION OF SMALL PLATFORMS (BEYOND)

Develop concepts for satellite constellation for Earth observation and research the feasibility and opportunities of a enabling resilient, scalable and cost-effective Earth observation, leveraging mass production techniques, enhanced autonomous capabilities, and rapid in-orbit replacement concepts to enable persistent and adaptable space-based services, even in contested environments.

Key features:

- **Mass production and standardization:** Embrace modular, standardized satellite designs that allow for rapid, low-cost assembly and integration, and enable cost-effective scaling and low lifecycle costs. A modular approach to support multiple payload types and adapt quickly to evolving mission needs. Implement rapid technology insertion techniques to keep up with emerging technology needs, balancing affordability and innovation.

- **Operational resilience:** Develop a concept for satellites and supporting infrastructure to maintain functionality in degraded or contested environments. Develop strategies for autonomous, cooperative operation and tasking within constellations, reducing dependence on ground control and enabling faster responsiveness. Constellation nodes should autonomously reassign observation and downlink tasks based on changing operational priorities. Leverage edge AI and inter-satellite communication to enhance responsiveness and maintain functionality in contested or denied environments. Include autonomous collision avoidance capabilities and secure inter-satellite coordination to prevent conjunctions in increasingly crowded orbits.

- **Rapid replacement and scalability:** Incorporate approaches for swift replacement of failed or outdated satellites to ensure mission continuity and resilience. Investigate the feasibility of "responsive launch" concepts to quickly replenish or expand constellation capacity as required.

- **Phased approach and concept validation:** This phase is limited to concept study and initial validation. In a later phase, based on the investigation of various (mini)satellite constellation concepts, the most promising concept(s) might be invited for the next R&D step. Goals for subsequent R&D phases will be defined after comprehensive validation of selected concepts to ensure alignment with strategic needs and operational requirements from their application.

Cooperation in the DTIB

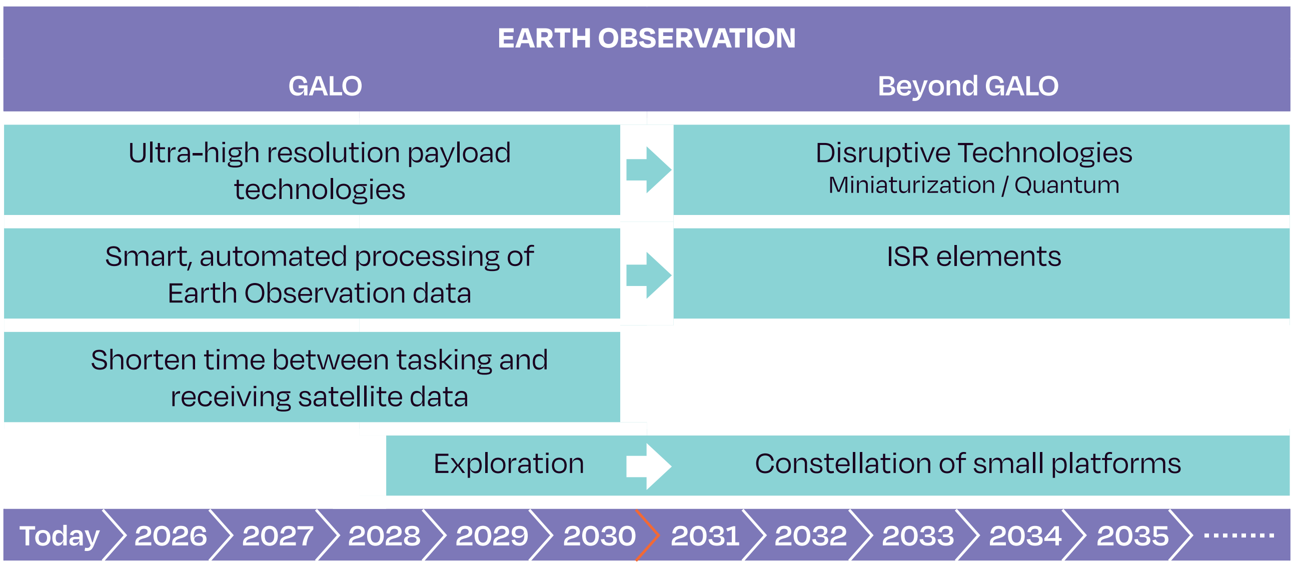
The presence of Belgian satellite integrators can play a central role in building a national ecosystem capable of developing scalable, resilient, and modular Earth observation constellations—combining academic research on autonomy, communication, and mission concepts with industrial capacity for rapid integration, standardisation, and deployment.

2.6. OVERALL HORIZON AND TIMELINE

By 2027, an in-orbit demonstrator is planned to support sovereignty in Earth observation through improved tasking and testing of EO-SAR payloads, using state-of-the-art technologies, with performance enhancement being secondary to strategic autonomy.

- **By 2030,** the focus is on launching a first-generation constellation integrating high-TRL payloads—including Electro-Optical, Synthetic Aperture Radar, and Hyperspectral sensors—building on next-generation solutions form DIRS research suitable for integration within the GALO concept.

- **By 2035,** the objective shifts to deploy a second-generation constellation based on more disruptive, lower-TRL technologies that require longer R&D cycles, enabling innovation goals that go beyond the current GALO framework. Based on the outcome of the exploration, the roadmap might envision constellations for Earth observation, enabled by rapid launch, plug-and-play standardisation, and continuous technology insertion.



Overview on the timeline for the Earth Observation track

3

Track SSA: Space Situational Awareness

3.1. INTRODUCTION: VISION AND GOAL

By 2030, the space domain will be even more congested, contested, and competitive, with near-Earth orbits hosting tens of thousands of active satellites and an exponentially growing debris population. By 2030–2035, congestion and debris proliferation will greatly complicate safe military space operations and space will also be increasingly contested by adversaries. As military reliance on space-based capabilities continues to grow, the ability to protect, understand, and actively respond within the space domain has become essential for operational superiority and strategic autonomy.

Flagship focus: SSA in a congested environment

Space Situational Awareness (SSA) focuses on monitoring and protecting space assets against threats caused by debris and spacecraft. SSA tracks objects in space and enables access to vital information on the location, movement, and status of objects in space. SSA capability is crucial for maintaining the safety of space operations and for protecting assets from potential collisions with debris or another spacecraft. Space Situational Awareness (SSA) provides knowledge of the space environment, ensuring the safety and functionality of vital assets. The rapid growth of the number of satellites and debris overwhelms current tracking systems and increases collision risks. Incomplete global coverage and sensor gaps, limit the ability to track all relevant objects, especially small or covert satellites.

Beyond flagship: persistent SSA and defensive response in a contested environment

This expands SSA by integrating intelligence and characterisation of behaviours to inform space operations in a congested and contested environment. The focus is on providing continuous awareness of the space environment (incl. environmental hazards) and understanding behaviours in space and attributing intent to ensure security and freedom to operate in the space domain. It integrates sensor data and strategic intelligence to build a detailed, real-time picture of space activities, actors, and capabilities. Beyond tracking, identifying, and characterizing cataloguing objects, it enables: characterisation of space systems, recognition of operational patterns, and attribution of potentially hostile actions. It provides actionable insights about the operating environment, including identification of threats, emerging risks, and adversary intent. This enables timely responses across military operations, space policy, and defence and resilience strategies.

Cyber resilience: secure data exchange at all stages of the functional chain

Cyber resilience must be embedded as a core design principle from the very start of any research on space-based Earth Observation and Space Situational Awareness (SSA). Since both domains share similar technological and operational needs, cyber solutions that ensure secure, trusted data exchange across the entire functional chain from data acquisition to decision-making should be applied. This includes enabling secure and resilient access, transmission, and data availability. Solutions will rely on secure architectures and include protection concepts for sensors, space and ground segments. A collaborative, encrypted framework must allow controlled sharing of sensitive data with partners, while enforcing national, NATO and EU-level data protection rules. Ensuring that data remains protected and governed—across military, institutional, and industrial stakeholders—is vital to operational sovereignty and alliance trust.

The Belgian DTIB

Belgium combines strategic capabilities, institutional expertise, and industrial maturity across both space and AI domains, making it particularly well placed to address this innovation challenge:

- **Strong multidisciplinary DTIB ecosystem across the full value chain:**
  - Belgian universities and academic labs are recognised for their applied research in machine learning, AI model efficiency, orbit dynamics, all of which are essential for developing onboard autonomy and edge and ground processing.
  - RTOs have deep expertise in sensor calibration, data fusion, and AI algorithm validation for remote sensing and Earth Observation, technologies directly translatable to SSA contexts.
  - Industry: Belgian industry plays a recognised role in Europe across the full SSA value chain, including sensor and payload development, onboard processing, AOCS systems, ground segment command and control, advanced manufacturing for structures and thermal control, data handling and mass memory systems, compact satellites, and platform integration. The DTIB brings together system integrators, specialised component manufacturers, SSA software and automation providers, propulsion and AOCS developers, and leading research institutes, forming a strong industrial base for SSA-related capabilities.

- **Proven experience with operational space systems:** Belgian organisations are already active in developing space-qualified electronics, AI-based Earth observation platforms, and contributing to European SSA initiatives (e.g. EU SST, ESA, and EDF-funded projects).

- **Cross-domain data and AI expertise:** Belgium is a leader in cross-sector AI applications, bringing reusable methods for low-power AI models, smart filtering, and distributed learning—key enablers for onboard SSA analytics. The capabilities in photonic and electronic miniaturisation further support the development of compact, power-efficient edge hardware.

Delivering the next generation, advanced SSA solutions requires strong cooperation between industry, academia, and research organisations to reach the SSA goals and to scale from components to system-level offerings. Proposed solutions should prioritise the sovereignty of sourced components and contribute to strengthening the European industrial capability, ensuring critical technologies are developed, manufactured, and maintained within Belgium and the European Union.

The landscape of Space Situational Awareness (SSA) will evolve rapidly, with new players entering the market and introducing novel services. This diversification will increase the complexity of monitoring the space domain. Belgium will address this challenge by strengthening its national capacity while simultaneously embedding these efforts within wider international cooperation networks. In this way, national initiatives will directly support collective resilience and contribute to European strategic autonomy.

3.2. CHALLENGE: AUTOMATED PIPELINES FOR NEAR REAL-TIME SPACE SITUATIONAL AWARENESS

Near real-time awareness is essential for threat response, but many SSA systems rely on delayed or intermittent data feeds and require human intervention. This innovation goal is to develop technology building blocks for an automated, AI-enhanced system for fusing, analyzing, and providing near-real-time, secure, and coherent information and operational picture on the location, movement, and status of debris and objects in space, minimizing human intervention and enabling quick threat response.

This will enable a standardized and integrated data stream feeding a scalable platform capable of identifying and classifying potential threats in real-time. The system will support automated detection, correlation, and interpretation of multi-sensor inputs (optical, radar, RF, space-based), enabling a persistent, high-confidence space situational awareness picture. This integrated approach will significantly reduce time-to-decision and enhance the defence posture across all operational domains.

Key priorities:

1. Full automation of data collection, fusion, and interpretation across multiple data sources and various sensor types into a coherent, accurate, and secure operational picture.
2. AI-enhanced data analytics to identify, classify, and track objects with minimal human oversight.
3. Integration of multi-platform data (ground-based and space-based, commercial and allied sensor data) into a single, secure operational picture.
4. Near-real-time awareness of objects in space to enable faster decision-making and response to threats.
5. Enhanced security and reliability to ensure the operational picture is accurate and resistant to cyber threats or misinformation.
6. Reduction of human workload (and dependence on humans) in data handling, interpretation, and decision-making.

3 closely linked research challenges to be addressed jointly:

The research challenges "Automation of the integration of data (and data sharing) from different sources and sensor types," "Latency in data processing for an operational space picture," and "Identify potential threat typology" share a strong interdependency and should be addressed as a coherent cluster.

These challenges all rely on a central AI model capable of real-time data fusion and interpretation across heterogeneous sources. A critical enabler for all three is the availability of sufficiently high-quality, standardized, and labelled datasets to support machine learning at scale. In particular, the development of an AI-based threat typology requires the output of integrated, real-time data to identify patterns, behaviours, and anomalies reliably. Joint research should prioritize the alignment of data pipeline and formats, processing timelines, and AI training protocols to reduce duplication and ensure consistent performance across operational and strategic levels.

Technology readiness and development timeline

This challenge cluster is well-suited to be tackled jointly starting from TRL 2, with a coordinated effort to achieve proof-of-concept maturity (TRL 6) by 2030. This implies targeted research into data standardization, model training, sensor data integration, and AI-enhanced support.

Beyond 2030, the focus must shift toward extending and refining the training datasets and operationalizing the AI engine to reach full operational quality. This will require continuous learning cycles, fed by validated, diverse, and increasingly real-time data streams, ensuring adaptability to evolving threat signatures and environmental contexts.

Cooperation in DTIB

Strong cooperation between industry, academia, and research organisations is essential. This challenge requires expertise from sensor-level detection to mission-level data fusion and interpretation. In example:

- Academia contributes long-standing knowledge in celestial mechanics and applied mathematics for modelling uncertainties.

- Research organisations bring advanced capabilities in AI-driven data fusion and automated object classification, especially across heterogeneous sensor types.
- Industry manages and produces large volumes of data and develops operational systems.

Collaboration is also needed to build robust models that can handle the wide variety of object signatures and behaviours encountered in space. Only by integrating these complementary strengths can automated, scalable, and trustworthy solutions be developed for defence applications.

3.2.1. AUTOMATION OF THE INTEGRATION AND SHARING OF DATA FROM DIFFERENT SOURCES AND SENSOR TYPES

Automate the integration and sharing of heterogeneous data streams from space-based, ground-based, commercial, and allied sensors, in order to generate unified, reliable, and real-time Space Situational Awareness (SSA) information for defence operations, and to increase traceability. Automation of the Integration of heterogeneous data from various sensor types (e.g. radar, optical, RF). Management of the data trustworthiness and quality assessment. This includes federated intelligence-sharing platforms integrating military and commercial SSA data (within the EU-SST Space Surveillance Track).

Key research gaps:

- **Heterogeneous data model standardisation:** define interoperable schemas to fuse data from dissimilar sensors (space, ground, radar, optical, RF) in a common operational picture.
- **Automated data ingestion and pre-processing pipelines:** AI-driven systems to clean, normalize, and synchronize inputs from different sources with minimal human intervention.
- **Design secure, distributed platforms that allow selective, policy-driven sharing of sensitive SSA data** across national, commercial, and allied domains (in EU-SST Space Surveillance Track a Federated intelligence-sharing platforms integrating military and commercial SSA data).
- **Standardization to enable automated integration:** The magnitude or brightness data of an object can reveal of an object is spinning, tumbling, lost control, or has solar panel extension capability. The main challenge here is standardization before automated integration can be considered.
- **AI-enhanced automated cross-sensor object correlation and track association** to avoid human bottlenecks in identifying and tracking objects across sensor types.
- **Data trustworthiness and quality:** A correct methodology to model uncertainty in data before data fusion. Create algorithms that assess reliability and accuracy of data inputs (esp. when mixing commercial, allied, and defence data and data from different sensors).
- **Latency and scalability optimisation:** Ensure integration frameworks operate in near-real-time and scale with the growing number of sensors and tracked objects.
- **Maintain and keep a scoring validation of the sources** in terms of quality but also at a geopolitical level.
- **Consider policies and compliance** (e.g. is an object registered in the UN database? What was the purpose description? Has ownership been claimed? Etc.).

3.2.2. ACCELERATE DATA PROCESSING TOWARDS AN OPERATIONAL SPACE PICTURE

Reduce latency between multi-source sensor data acquisition (raw sensor data, previous research challenge) and the creation of a reliable, operational space picture. In an increasingly congested and contested space environment, near-real-time awareness is critical to detect, identify, characterize and respond to objects, anomalies, or threats. This assures low latency, reduces human bottlenecks, and improves scalability across growing sensor networks.

While the underlying data processing architecture and AI-models can be largely standardized, specific adaptations will be required to accommodate the unique characteristics of different payloads (e.g., radar, optical, RF), particularly in terms of signal pre-processing, feature extraction, and fusion logic.

Key research gaps:

- Make SSA smarter and faster — use AI and automation to turn raw sensor data into an operational picture in real-time. Overcome processing and data fusion latency in SSA systems by using AI-based automated processing, to generate near-real-time, actionable space domain awareness for rapid threat detection and response.

- Automate detection and characterisation of objects, events or threats in space.

- Advanced sensing and data fusion beyond basic orbit tracking to overcome current limitations real-time analysis by current onboard and ground processing capabilities (e.g., active vs inactive, benign vs threatening) by advanced sensing and data fusion beyond basic orbit tracking.

- Use case Algorithms tailored to detect and characterize objects, events or threats in space. Algorithms able to deal with heterogeneous data.

- Adaptation of star tracker data for the detection and identification of other objects in orbit (such as other spacecraft and also debris).

3.2.3. IDENTIFY POTENTIAL THREAT TYPOLOGY

Develop a dynamic threat typology of objects, behaviours and signatures to systematically distinguish between different types of objects and activities in space. By combining AI-enhanced methods with typology data and real-time sensor inputs — including imaging from space-to-space sensors and dedicated on-orbit payloads — it becomes possible to capture the cues required for timely and reliable identification of actors in space and the behaviours that may represent potential threats. The solution supports edge–ground loops: on-board AI-enabled models flag manoeuvres, separations, jamming/spoofing cues or unusual behaviours; while ground pipelines validate, retrain and fuse this data with allied and commercial sources to maintain a trusted threat picture. Investment in new sensor modalities is critical, as the typology must be based on observable features rather than data correlation alone.

Key research gaps:

- A threat typology and database with potential threats and related typical characteristics on which one can distinguish from other threats. Build further on previous studies in threat classification at EU/US/NATO level and take future interoperability into account.

- Make a correlation between the characteristics and the corresponding detection/identification technology/sensor.

- Define typical observable characteristics (motion, spectrum, emissions, manoeuvre patterns) and link them to threat categories. Develop and validate AI/ML models for real-time detection, behavioural pattern recognition and manoeuvre intent classification.

- Integrate space environmental data and RF spectrum monitoring to enhance detection of non-kinetic threats (jamming, spoofing).

- Develop a framework that involves worldwide detection capabilities based on a wide range of possible sensors such as radar, in orbit detection capabilities etc.

- Novel sensor modalities — including space-to-space imaging payloads, and spectral sensors — to ensure that the typology is underpinned by enhanced observable features.

3.3. CHALLENGE: ADVANCED SSA SENSORS OVERCOMING CURRENT SENSOR LIMITATIONS

Create a new generation of advanced SSA sensors that overcome current sensor limitations through high-resolution, adaptive ground-based systems, miniaturized and multifunctional co-passenger sensors, and long-range on-orbit sensors. These sensors must deliver superior observation and characterization capabilities while addressing key operational gaps, including resilience, latency, observation blind spots, and cost-effectiveness. Sensor developments should explicitly assess their contribution to SSA concepts based on multi-sensor architectures, in which payloads have complementary roles, rather than focusing solely on stand-alone payload technologies. In parallel, data processing capabilities should be advanced alongside the sensors, particularly where on-board or edge processing can enhance detection accuracy, reduce false positives and optimise bandwidth usage. The joint optimisation of sensing and processing is essential to improving system performance under real operational conditions.

Key priorities:

- **High-resolution, adaptive ground-based sensors** providing high-resolution observations capabilities and adaptive optics for SSA identification and characterization. Develop algorithms to identify observation blind spots and enable rapid next-available observations, reducing latency and improving data timeliness.

- **Small, robust sensors as a co-passenger to new missions** enabling to add small, dedicated SSA sensors as secondary payloads limiting the mass increase by the payloads on satellites whose primary mission is not SSA. This includes expanding the functionality of sensors beyond their traditional roles (i.e. a star tracker beyond the traditional attitude sensing).

- **High-resolution, long-range on-orbit SSA sensors:** Spacecraft sensors that can detect, track, and characterize objects in space from a significant distance while operating in orbit.

- **Explore creative alternative concepts** to address current detection limitations in (V)LEO regimes, leveraging novel sensing methods and hybrid data fusion approaches.

► **Joint optimisation of sensing and processing:** develop onboard and edge processing capabilities that work alongside the sensors to enhance detection accuracy, reduce false positives and optimise bandwidth usage.

Research should carefully assess cost-benefit trade-offs to ensure that high-cost sensor solutions provide tangible operational advantages. Sensor development must be grounded in real operational challenges. A critical question is: "What signatures should the sensors be looking for?" This requires early and continuous input from end-users and operational analysts to define the observable behaviours, features, or events of interest. Sensor design should not proceed in isolation but be informed by scenarios such as threat object detection, RPO (rendezvous and proximity operations), debris fragmentation, or stealth techniques. In parallel, data processing capabilities should be developed alongside the sensors, especially where onboard or edge processing can enhance detection accuracy, reduce false positives, and optimise bandwidth usage. Joint optimisation of sensing and processing will improve system performance under real-world constraints.

While test infrastructure already exists to validate sensor performance under realistic conditions, these facilities might need adaptations to match the increasing complexity, resolution, and sensitivity of next-generation sensors. This includes adapting test setups for higher angular precision, spectral fidelity, and dynamic response simulation. Calibration standards and performance benchmarks must also be updated to reflect the technological advances and to ensure comparability across sensor classes and platforms.

Technology readiness and development timeline

Sensor development will follow a staggered roadmap, with short-term enhancements pursued in parallel with long-term breakthroughs, ensuring operational relevance while investing in disruptive capabilities. The maturity level of the technology building blocks for advanced SSA sensors will depend strongly on the type of sensor and its intended operational role.

- In many cases, sensors can evolve from existing technologies—with upgrades in resolution, robustness, or integration—for demonstration and initial deployment by 2030 (TRL 6).
- For next-generation concepts, including entirely new sensor classes or high-performance space-qualified versions, proof of concept should be targeted by 2030 (TRL 3–4), with further development and validation beyond 2030 to reach TRL 7–9 by 2035.

Need for cooperation in the DTIB

Delivering the next generation of advanced SSA sensors demands structured cooperation between academia, research organisations, and industry. In example:

- Academia contributes to emerging sensor concepts and technologies, modelling orbital behaviours, and providing the mathematical foundations for handling uncertainty in sensor data.
- Research organisations focus on the development, validation, and qualification of advanced sensor technologies and AI-based data processing, enabling high-resolution sensing, autonomous object tracking, and multi-sensor fusion across platforms.
- Industry brings operational insights into sensor requirements based on real-world challenges and evolving threat signatures. It transforms innovation into deployable, space-qualified systems—developing robust sensors, integrating them into operational payloads, and managing system performance, scalability, and lifecycle support.

This collaboration is essential to cover the full spectrum of sensing environments—from ground-based adaptive optics to integrated, space-based multi-sensor platforms—and to ensure that SSA sensor development remains aligned with mission priorities and technological timelines.

3.3.1. ADAPTING AESA RADAR TECHNOLOGY FOR (V)LEO SATELLITE DETECTION

Radar systems offer the advantage of all-weather, day-and-night detection, independent of illumination conditions. Advanced Electronically Scanned Array (AESA) radar, originally developed for air surveillance at medium ranges and near-horizontal scanning (~460 km), must be adapted to reliably detect and track (V)LEO satellites. Unlike aircraft, satellites in these regimes travel at hypersonic speeds, follow steep trajectories across the sky and remain in view for only a few minutes. These characteristics require rapid 3D beam steering, wide angular coverage and advanced Doppler processing. To ensure defence relevance, the technology building blocks for adapted AESA radars must not only detect but also characterise satellites with small radar cross-sections, maintain custody across successive passes and feed data into federated SSA networks. Solutions should minimise power requirements and optimise thermal efficiency, ensuring that AESA radars remain operable even in mobile or remote deployments with limited energy supply.

Key research gaps:

- Adaptive 3D beam steering with full-elevation and azimuth control to capture near-zenith passes and maintain track on high-inclination, fast-moving satellites across the full sky.
- AI-enhanced signal processing and data compression algorithms for fast-moving satellite targets detection and to distinguish satellites from clutter and classify manoeuvres.
- Seamless handover algorithms between radars to maintain continuous tracking across short visibility windows.
- Systems must be smart and self-managing (calibration, tasking) to operate in remote places with minimal human interaction.
- Enhance AESA performance through advanced semiconductor technologies (e.g. GaN and other wide-bandgap materials) that can significantly increase the power (up to 10x), while developing efficient thermal management to handle heat loads, reduce overall power consumption, and secure European supply chains.
- Develop multi-band configurations (e.g. combining radar in the lower-frequency L-band or S-band with higher-frequency X-band) to improve the detection and classification of objects with low radar cross-sections or stealth features.

3.3.2. SPACE-BASED SPACE SURVEILLANCE (SBSS)

Develop technology building blocks for Space-Based Space Surveillance (SBSS) providing persistent, atmosphere-free monitoring of satellites and debris by deploying dedicated sensors in orbit. Unlike ground-based systems, SBSS should enable continuous coverage of high-value orbital regions, enabling early detection of manoeuvres, attribution of hostile activities and resilience against sensor gaps.

SBSS missions may serve as wide-area surveyors from LEO scanning GEO, as close-up patrols in GEO monitoring neighbouring satellites, or as high-ground sentinels in GEO observing activity in lower orbits. These roles complement one another but demand different sensor designs, autonomy levels and integration pathways to deliver a resilient defence architecture. Research must move beyond stand-alone technologies towards mission-relevant building blocks that are designed for integration and can be progressively validated.

Key research gaps:

- LEO-to-GEO wide-area coverage:
  - High-frame-rate imaging and agile tracking to counter fast relative motion.
  - Compact optics with wide field-of-view and low false-alarm filtering.
  - Onboard autonomy to pre-select detections before downlink.
- GEO-to-GEO close custody
  - Milli-arcsecond pointing stability and jitter suppression for long integrations.
  - Stray-light management and thermal stability for faint-object detection.
  - Advanced detectors and AI-enhanced light-curve/spectral analysis for characterisation.
- GEO-to-LEO threat monitoring:
  - Wide field-of-view sensors for rapid detection of fast, incoming objects.
  - On-board event detection logic for immediate alerting.
  - Algorithms to discriminate natural events (e.g. debris) from deliberate threats (e.g. inspector satellites).
- Cross-cutting gaps:
  - AI-enhanced fusion of SBSS data with ground-based and allied sensors for custody and characterisation.
  - Secure crosslinks and tasking frameworks for SBSS constellations.
  - Ensure interoperability within European and NATO frameworks.

3.3.3. RF-BASED LOCALISATION AND IDENTIFICATION OF SATELLITES AS POTENTIAL THREATS

Deploy and network RF sensors as a complement to optical and radar systems to detect satellites and other emitters based on their radio frequency transmissions or reflections, thereby identifying and characterising potential hostile actions such as Global Navigation Satellite System (GNSS) jamming, spoofing or satcom interference. Accuracy can be increased, latency reduced and coverage broadened by applying and combining proven geolocation techniques (e.g. angle of arrival, time difference of arrival, frequency difference of arrival) across ground sites and LEO satellites. The objective is an integrated solution that brings together advanced geolocation algorithms, AI-supported signal fingerprinting, resilient coverage through mobile units or LEO-hosted sensors, and a comprehensive database of RF signatures.

Key research gaps:

- A network of RF receivers/dishes that can triangulate radio emitters (or reflect radar signals)
- Develop algorithms for real-time localisation of emitters with improved accuracy and low latency, even under dynamic conditions.

- ► Autonomous real-time signal characterization, fingerprinting, anomaly detection, and classification of hostile interference attempts leveraging unsupervised AI-enhanced models for compression and signature characterization.
- ► Detect and localise emitters using frequency-hopping, spread-spectrum, or low-power covert transmissions.
- ► Build and maintain a secure repository of RF signal fingerprints, inspired by community concepts such as the RF Libre Space Network but ensuring sovereign, reliable, and defence-grade data instead of relying on open or non-EU sources.
- ► Expand capabilities where you have black spots or areas where you want to put down more higher power RF detection.

3.3.4. AESA FOR ONBOARD SATELLITE USE

Develop space-qualified AESA radar systems capable of operating on board satellites to enable long-range detection of non-cooperative objects beyond close LEO approaches (i.e. beyond 450 km), providing autonomous space object tracking and threat detection without reliance on ground-based sensors. Key on-board constraints include the miniaturisation and space qualification of AESA modules, reliable deployment mechanisms, and advanced power and thermal management to balance performance with the limited energy supply and heat rejection capacity available in orbit. Beyond detection, these systems require trustworthy on-board autonomy, with AI-based algorithms for detection, classification and prioritisation, as well as seamless integration into satellite mission systems and fault detection, isolation and recovery. Research must deliver building blocks that enable progress from component technologies to integrated (sub-)systems, validated in a progressive manner.

Key research gaps:

- ► Develop scalable and modular AESA architectures. Compact, space qualified AESA modules suitable for satellite integration under mass and volume constraints and ensuring long-term reliability solutions.
- ► High-efficiency AESA architectures with advanced thermal management to balance performance with limited on-board power and space heat rejection capacity.
- ► Signal processing algorithms for orbital dynamics to detect objects from a moving platform, compensating for own movement.
- ► High reliable antenna deployment and pointing/reorientation mechanisms for AESA arrays
- ► Autonomous detection and classification algorithms (without a human in the loop), enabling the development of trustworthy on-board decision-support and tasking capabilities.
- ► Advanced on-board compression (reducing data transmission)
- ► Integration with onboard SSA, FDIR, and mission systems (avoid isolated system design)
- ► Ensure operation and counter measures under jamming or contested RF environments.

3.3.5. NIGHT-VISION SENSORS FOR SSA

LIDAR (Light Detection and Ranging) offers unmatched capability for measuring range, velocity and the 3D characterisation of resident space objects — even in zero-light conditions. LIDAR can evolve from ground-based debris laser ranging to space-based concepts that deliver centimetre-level orbit refinement and object characterisation. While mid-wave infrared (MWIR) and long-wave infrared (LWIR) sensors remain valuable for wide-area passive detection, particularly of objects in Earth's shadow, narrow-beam LIDAR provides the precision layer essential for high-confidence tracking and classification. LIDAR sensors and MWIR/LWIR systems are complementary technologies, together supporting continuous, all-condition SSA.

Key research gaps:

- Advance frequency-modulated continuous-wave (FMCW) LIDAR to enable reliable long-range detection of small or distant resident space objects (RSO) at ranges of 10^3–10^4 kilometres.
- Achieve robust daylight operations by improving filtering, adaptive optics (AO), and background suppression techniques to counteract high sky radiance.
- Develop low-SWaP, radiation-tolerant lasers and detectors with long-life reliability for on-orbit LIDAR missions.
- Integrate LIDAR ranging with complementary optical photometry, MWIR and LWIR measurements to improve inference of size, attitude and material properties. Generate datasets to support AI-enhancements.
- Ensure compliance with international norms and implement technical safeguards when using laser beams to illuminate satellites.

3.3.6. SENSORS FOR SMALL OBJECT DETECTION IN SPACE

Small space debris is hard to detect but still dangerous. Make satellites see the small stuff — detect invisible threats with on-orbit smart sensors. Develop cost-effective sensor systems capable of detecting and tracking very small objects from a certain distance in space, overcoming current technological limitations and budget constraints, to ensure comprehensive space domain awareness.

Key research gaps:

- Optical or hybrid sensors small and light enough for satellite hosting, yet sensitive enough to detect low-signature small objects
- New scanning concepts balancing narrow FOV (high resolution) vs wide FOV (better statistical coverage)
- Smart onboard detection and filtering essential to reduce false positives and confirm detections of small objects (low signal-to-noise).
- Validation of detection capabilities.

3.3.7. OPTICAL PAYLOAD FOR DETECTION, CHARACTERISATION, AND TRACKING OF THREATS

Dedicated optical payloads in space will be essential for detecting, tracking and understanding objects and events in orbit with speed and reliability. Recent advances in AI enable automated wide-field detection, event characterisation (e.g. rendezvous and proximity operations, fragmentation) and close-range pose estimation. On-board AI processing reduces latency and downlink requirements, while ground-based retraining ensures continuous improvement. Pairing traditional imagers with event-based sensors, and fusing their outputs with LIDAR and MWIR/LWIR, strengthens detection under all conditions. AI-enhanced optical payloads reinforce SSA by providing early warning, detailed characterisation and persistent custody of threats.

Key research gaps:

- Develop payload systems and AI-enhanced methods to detect faint or fast-moving resident space objects (RSO) under diverse conditions.
- Design AI/ML pipelines to fuse optical imagery, light-curves, and complementary data for object characterisation.
- Use AI-enhanced methods to connect observation tracks, calculate orbits, and spot unusual behaviour.
- Build reliable datasets and set clear testing and validation methods aligned with EU and NATO practices to make AI-enhanced methods to make SSA trustworthy.

3.3.8. SCIENTIFIC SENSORS THAT DETECT CHANGES IN THE ATMOSPHERE OR MAGNETIC FIELD

Develop next-generation scientific sensors capable of detecting subtle changes in the atmosphere or magnetic field to enhance space situational awareness through indirect observation methods. These sensors must be miniaturized, power-efficient, and integrable as co-passenger payloads or components of distributed on-orbit systems. The challenge is to advance sensor sensitivity, temporal resolution, and environmental robustness to enable the detection of space object interactions, plasma events, or geomagnetic disturbances that may indicate untracked activity or system anomalies.

Key research gaps:

- High sensitivity, resolution, and dynamic range of compact sensors to detect subtle atmospheric or magnetic anomalies associated with space events.
- AI-based signal processing and fusion algorithms to link environmental fluctuations with object behaviour or unknown activity in orbit in real-time or near-real-time.
- Define signature databases and develop classification algorithms to isolate SSA-relevant anomalies from background variations to distinguish between natural phenomena (e.g. solar storms, atmospheric tides) and anthropogenic signals (e.g. satellite propulsion plumes or active emissions).
- Advance onboard preprocessing and event-driven data compression to reduce latency and prioritize critical data for SSA systems to overcome latency and data throughput limitations.

3.3.9. ONLINE RADIO SYSTEMS FOR FAST-MOVING OBJECTS PASSING THROUGH THE UPPER ATMOSPHERE

Online radio systems to automatically detect when and where fast-moving objects are passing through the upper atmosphere (between 30 and 300 km high). If the object is heading toward Earth, also predict where and when it will land.

3.4. CHALLENGE: AUTOMATED PROCESSING OF PAYLOAD DATA AT THE EDGE

The innovation challenge aims at technology building blocks for a fully automated, edge driven processing system for SSA sensor data that fuses inputs from multiple onboard sensors, leverages nonspecific data for SSA insights, and ensures autonomous operation under contested or degraded conditions.

The challenge is closely aligned with the goal of "Automated ground pipelines for near real-time space situational awareness", as both rely on shared architectures for automated data processing, fusion, and interpretation. However, automated processing at the edge—on board the spacecraft—introduces specific system-level constraints, including limited power budgets, processor and memory size/weight, and the need for real-time responsiveness in contested or communication-degraded environments.

To ensure robust and scalable SSA capability, edge and ground processing must be co-designed as complementary layers. On-board processing enables real-time detection and reaction, but on-ground processing remains essential—both as a fallback when limited on-orbit capacity cannot deliver required SSA insights, and to support model training, refinement, and validation using large datasets that exceed in-orbit storage and processing capabilities. The architecture must enable smart distribution of tasks, with critical decisions handled on board, and learning loops, heavy computation, or data correlation handled on ground—ensuring resilient, adaptive, and continuously improving SSA performance across missions.

Key features:

- **Onboard autonomy:** Implement AI/ML algorithms onboard spacecraft for real-time satellite identification, characterization, and motion analysis. Enable data fusion from multiple onboard sensors to generate an integrated operational picture of the space environment.

- **Smart data use:** Harness nonspecific sensor data (not originally intended for SSA) to extract relevant insights and contribute to SSA awareness. Develop data correlation and fusion algorithms to maximize information value from existing onboard data sources.

- **Operational resilience:** Ensure that processing capabilities are robust against contested and degraded environments, maintaining SSA functionality even when ground-based support or external data feeds are compromised. Incorporate secure, tamper-resistant processing for resilient operations.

Three closely linked research challenges to be addressed jointly:

The research challenges — opportunistic use of non-SSA sensors, AI-based behavioural analysis of unknown objects, and automated onboard processing for resilient SSA operations — share a common architecture and should be pursued jointly. All rely on edge AI-enhanced capabilities to extract actionable SSA insights from diverse onboard sensors, under strict resource constraints and operational uncertainty. While each addresses a different entry point (sensor source, behaviour classification, execution architecture), they converge on the need for robust, autonomous, and efficient models that balance onboard autonomy with ground-based support for training, refinement, and fallback processing. Joint development will accelerate cross-cutting capabilities such as sensor fusion, threat identification, and real-time decision-making in degraded or adversarial space environments.

Cooperation in DTIB

The development of an integrated edge-AI framework for space-based SSA requires close cooperation across the Belgian DTIB. In example:

- Academic institutions provide essential contributions in machine learning, orbital mechanics, and algorithm design, particularly under the constraints of limited onboard resources.
- Research organisations can drive the development of sensor fusion techniques, calibration models, behavioural analytics, and synthetic training data generation—ensuring that AI models are robust, explainable, and suitable for deployment under contested conditions.
- Industry plays a crucial role in translating these models into hardware-constrained environments by integrating edge-AI into space-grade processors, mass memory units, and onboard data handling systems. They also bridge the gap to operations through platform integration, mission design, and validation in real-world satellite constellations.

Given Belgium's strengths in both space systems and data innovation, this cooperation is key to ensuring that sovereign capabilities in autonomous SSA are developed, matured, and aligned with future European and allied requirements.

3.4.1. COMBINING DIFFERENT SENSORS ON THE SAME PLATFORM

To improve object detection, characterization, and continuous tracking, future SSA platforms should combine multiple sensor types (e.g. optical, radar, infrared, RF) on the same satellite platform:

- ensuring that all sensors stay aligned on the same target, especially in dynamic tracking of fast or manoeuvring objects.
- achieving a permanent 360° situational awareness, which requires careful sensor field-of-view coordination, coupling of multiple sensors around the platform, and onboard fusion to maintain a consistent object track.

Key research gaps:

► Multi-sensor co-alignment and cooperative tracking algorithms to maintain focus on the same object despite sensor-specific pointing constraints.

► Platform-level design for full-sphere coverage, with overlapping fields of view and sensor coordination logic.

► Synchronised data fusion from heterogeneous sensors to support unified object classification and threat assessment.

3.4.2. OPPORTUNISTIC SPACE-BASED SSA

Every satellite is a potential cost-effective space observer and can deliver back allot of interesting SSA opportunities and data. Exploit existing onboard satellite sensors, not originally designed for SSA, to generate valuable situational awareness data, enabling enhanced detection and characterization of space objects and events without requiring new hardware / hardware changes.

Key research gaps:

- Determine suitable non-SSA sensor data types on existing satellites (optical imagers, star trackers, sun sensors, GNSS, RF receivers) to provide useful SSA data (i.e. star trackers and sun sensors to determine attitude determination, or optical cameras for imaging Earth, moon or deep space to detect space debris or uncooperative satellites).

- Develop AI/ML-enhanced methods to extract space object detections, trajectories, and behaviour indicators from non-SSA data.

- Calibration and cross-referencing techniques: align and synchronize opportunistic observations with dedicated SSA sensors for validation and track association.

- Understand detection thresholds, revisit rates, accuracy.

- Develop operational doctrines and automated tasking for when/how to use non-SSA sensors without disrupting primary missions.

3.4.3. BEHAVIOURAL ANALYSIS OF UNKNOWN SPACE OBJECTS USING ORBITAL DATA

This research challenge aims to develop AI-enhanced methods for detecting, classifying, and interpreting the behaviour of unknown or uncooperative space objects based on satellite orbit data and complementary sensor inputs. The objective is to enable automated recognition of anomalous or deceptive behaviours—such as covert manoeuvres, separation events, or spoofing—by analysing changes in trajectory, velocity, and event timing across various orbital regimes.

Robust detection capabilities must cover a wide range of manoeuvre types, including:

- Small manoeuvres (0.1–1.0 m/s), often used for station-keeping or subtle orbit tuning,
- Medium manoeuvres (1.0–5 m/s), possibly indicating orbital adjustment or stealthy repositioning,
- Large manoeuvres (5–20 m/s), typically related to active operational changes or evasive actions,
- Aggressive manoeuvres (>20 m/s), associated with high-energy activities such as rapid avoidance or threat posturing,
- Manoeuvres characterised by short durations (0–10 minutes) or longer sustained actions (>10 minutes), which may signal differing tactical intent.
- **Separation events**, including **sub-satellite deployments** (which may indicate inspection, servicing, or RPO activity) and **debris-generating events** (such as mechanical failure, shedding, explosion, or impact). Models should distinguish these by analysing relative motion, fragment dispersion, and timing characteristics.

To ensure robustness, the system must also identify objects attempting to evade detection—those using tactics such as irregular motion, low observability profiles, or avoiding traditional radar/telescope tracking geometries. AI models should be trained to infer plausible orbital paths and detect discontinuities or mismatches in expected movement.

Foundation models adapted to SSA applications must fuse orbital data with other sensor modalities (e.g. EO, RF, radar) to enable behaviour recognition, intent estimation, and threat classification in near-real-time.

Key research gaps:

- Develop algorithms to automatically detect and classify manoeuvres, separation events, and trajectory anomalies. Performant AI-models with limited power consumption and processor capacity.
- Develop and build training datasets (including synthetic orbital scenarios) to adapt foundation models for space domain behaviour recognition.
- Fuse orbital data with other sensor types to improve detection accuracy and reduce false positives.
- Define onboard vs ground-based processing roles for event detection, initial flagging, and model refinement.
- Ensure system robustness to data uncertainty, degraded conditions, low-observability tactics, and incomplete tracking.

RTD aims to advance technology building blocks from basic research to applied research. Target TRL: TRL 3–4 by 2030; TRL 6–7 beyond 2030.

3.4.4. AUTOMATED ON-BOARD PROCESSING OF SENSOR DATA FOR RESILIENT SSA OPERATIONS

Develop automated and efficient sensor AI-enhanced data processing capabilities enabling resilient and autonomous space situational awareness, balancing onboard autonomy and ground-based processing to ensure fast, reliable, and intelligent decision-making in the face of threats and contested space environments.

Key research gaps:

- Develop AI/ML algorithms optimized for threat identification able to be executed on-board (with limited resources), creating robust, autonomous AI-enhanced chains (what events/actions can satellites handle onboard vs escalate to ground).
- Synthetic data to create large dataset for ML training.
- Efficient image and signal processing algorithms, pushing advanced detection, enhancement, and classification processing onboard and avoiding downlink bottlenecks.

3.5. CHALLENGE: EXPLORATION NEXT-GENERATION SOLUTIONS

Explore next-generation solutions that extend beyond the original focus areas defined by Belgian Defence for the SSA Flagship.

3.5.1. PERSISTENT TRACKING AND BEHAVIOURAL ANALYSIS OF SPACECRAFT

Innovation goal

Develop a set of foundational and enabling technologies for persistent, intelligent monitoring of space objects, enabling continuous tracking and behavioural interpretation in complex, congested, and contested orbital environments. This solution combines real-time analytics, multi-sensor fusion, intelligent tasking, and active tracking strategies to understand object capabilities, predict intent, and support threat attribution.

Key features:

- **Advanced real-time analytics:** Integrate machine-learning algorithms for real-time pattern recognition and behavioural analysis of space objects. Characterize spacecraft attitude, rotational rates, and precise shape reconstruction to better understand capabilities and potential actions. Use historical patterns, mission profiling, and anomaly detection to support attribution and intent analysis.
- **Expanded sensor use:** Enable multi-spacecraft observation and data fusion to build a persistent, comprehensive, real-time picture of space activities and intent. Incorporate low-light and thermal optical tracking for detecting and tracking stealthy or obscured space objects.
- **Sensor and data fusion with external assets:** Integrate onboard tracking capabilities with ground-based telescopes, radar networks, and partner systems to maintain a shared tracking picture. Develop standards and interfaces for secure, latency-aware data sharing and task delegation.
- **Cyber and functional anomaly detection:** Extend behavioural analysis to detect cyber or functional anomalies (e.g. spoofing, loss-of-function, shadow activity) and support automated threat attribution through sensor and intelligence fusion. Support automated function recognition of spacecraft, leveraging sensor data and intelligence fusion.
- **Attribution and decision-making:** Go beyond cataloguing to enable attribution of potentially hostile actions and recognition of adversary operational patterns. Provide actionable insights to inform military operations, policy decisions, and deterrence strategies.

TRL status: Cyber anomaly detection in SSA is TRL 3–4; integrated systems could reach TRL 6 by 2030, improved accuracy and operational validation by 2035.

3.5.2. SATELLITE CONSTELLATION CONCEPT

Enable coordinated observation of a single object from multiple satellites, supporting continuous handover, angle diversity, and resilience against blind spots. Develop concepts for satellite constellation for SSA and research the feasibility and opportunities of a enabling resilient and cost-effective SSA, leveraging mass production techniques, enhanced autonomous capabilities, and rapid in-orbit replacement concepts to enable persistent and adaptable space-based services, even in contested environments.

Key features:

- **Mass production and standardization:** Embrace modular, standardized nanosatellite designs that allow for rapid, low-cost assembly and integration. Implement rapid technology insertion techniques to keep up with emerging technology needs, balancing affordability and innovation.

- **Operational resilience:** Develop a concept for (nano)satellites and supporting infrastructure to maintain functionality in degraded or contested environments. Develop strategies for autonomous, cooperative operation within large-scale constellations, reducing dependence on ground control.

- **Rapid replacement and scalability:** Incorporate approaches for swift replacement of failed or outdated satellites to ensure mission continuity and resilience. Investigate the feasibility of "responsive launch" concepts to quickly replenish or expand constellation capacity as required.

Phased approach and concept validation

This phase is limited to concept study and initial validation. In a later phase, based on the investigation of various (nano)satellite constellation concepts, the most promising concept(s) might be invited for the next R&D step. Goals for subsequent R&D phases will be defined after comprehensive validation of selected concepts to ensure alignment with strategic needs and operational requirements.

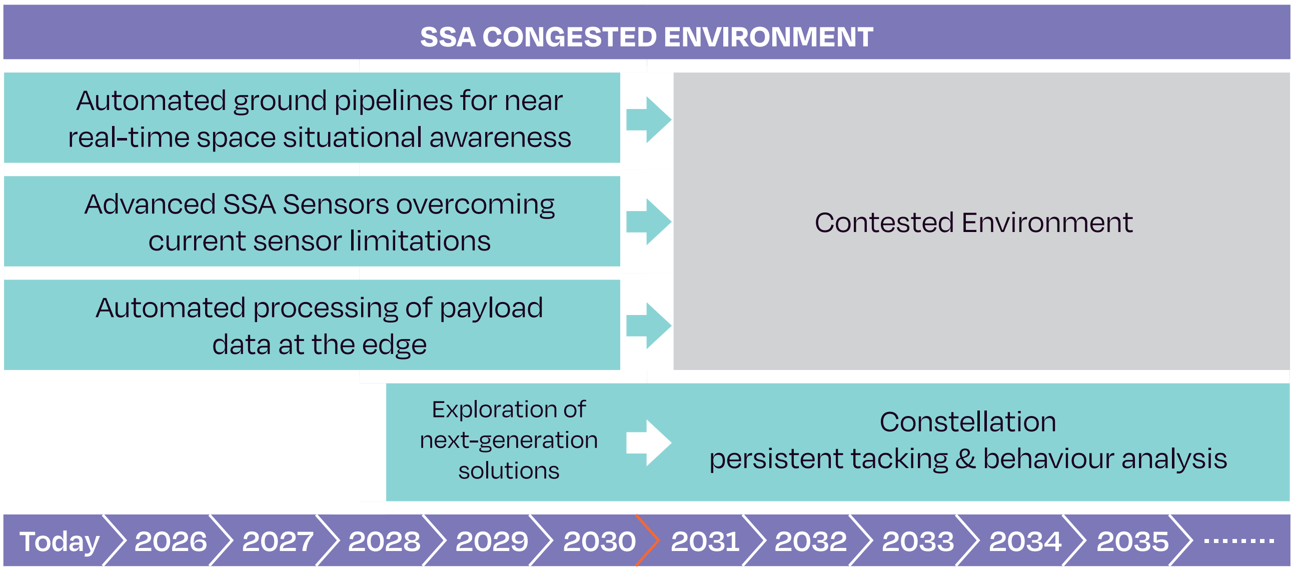
- Constellation-based concepts at TRL 4–5 today;
    - coordinated SSA-tracking constellations could reach TRL 6 by 2030 (software layer),
    - TRL 7–8 by maximum 2035 with hardware in orbit.

3.6. TIMELINE OVERVIEW

- **By 2030,** the focus of SSA RTD is on enabling operational, real-time situational awareness in a congested environment. Technology building blocks, including adaptive optics, AI-enhanced detection, and low-power radar or optical payloads, are expected to reach TRL 6, enabling first deployments and mission-level demonstrations.

- **By 2035,** DIRS targets the transition to persistent SSA in a contested environment with enhanced behavioural analysis, space-to-space tracking, and hostile intent attribution. These advanced, space-qualified systems integrated with strategic intelligence and edge autonomy support defence operations in contested space environments.

Based on the outcome of the exploration of next-generation solutions, the roadmap might envision a fully sovereign, modular SSA constellation, enabled by rapid launch, plug-and-play standardisation, and continuous technology insertion.



Overview on SSA-track timeline

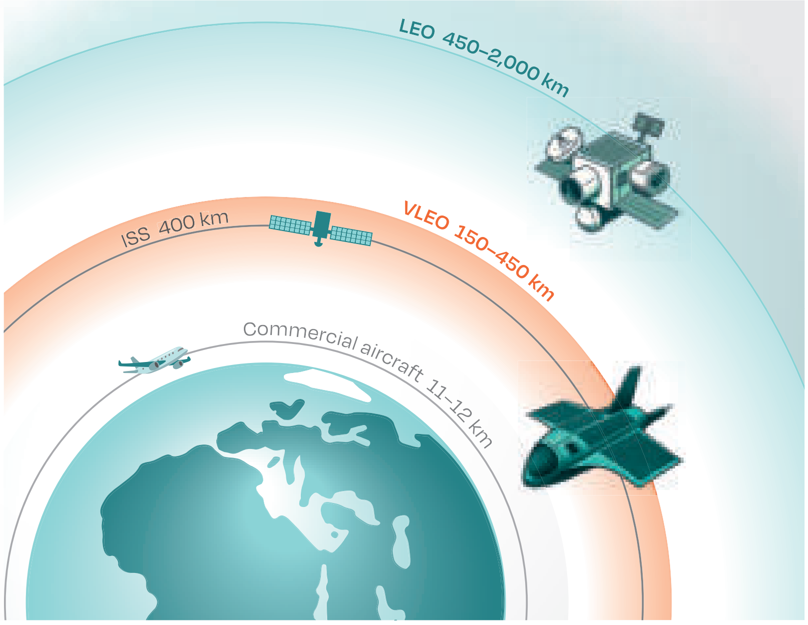
4

Track: VLEO Very Low-Earth Orbit Technologies

4.1. INTRODUCTION: VISION AND GOAL

Very Low Earth Orbit (VLEO) is generally recognized by the scientific and industry community as a subset of Low Earth Orbit (LEO) confined to altitudes below 450 km.

Traditional Satellites struggle with this regime due to the increase atmospheric density which induces significant technical challenges. For this reason, this same region remains the least explored area of our atmosphere, and whilst most satellites transition through this region as part of their decommissioning (MEO and GEO satellites are currently not required to re-enter at end of life), only a handful has been purposely deployed in this region. Fewer even have managed to remain for periods longer than a few months.



An operationally capable multi-mission VLEO platform requires research and integration of multiple key technological areas. R&D must take into account the specific requirements and must purposely designed for the nature of the operational environment.

Vision

By 2030, the DIRS research track will resolve key technological gaps in propulsion, power, control, and satellite platform design to make long-term operations in Very Low-Earth Orbit a reality. Like a "moonshot for VLEO," it will unite the most promising innovations enabling an integrated demonstration mission, validating and verifying full-system performance on an operational satellite in VLEO orbit — proving Belgium's capability to master technologies for sustained, agile, and autonomous operations in the most demanding orbital environment.

At start of the developments, VLEO system-level objectives must be set by combining performance-driven requirements across propulsion, power provision and control, and platform. This enables a structured progression for the different innovation goals for systems and sub-systems supported by on ground and subsystem validation (TRL5-6). At end of the first development phase an integration of the most promising results for enabling components ensures an in-orbit platform-level demonstration and validation (TRL7, 2030).

A new horizon for applications (2035)

VLEO technologies present a new horizon for capability development. Operating so close to Earth offers unique strategic advantages for defence applications, if technical challenges can be overcome. Until 2030, the focus lies on developing and validating the key technology building blocks required to sustain long-term operations in VLEO under its specific environmental stressors—significantly more demanding than those in traditional LEO. Based on these results, post-2030 efforts will shift towards defence application uptake and demonstration using fully operational VLEO satellite platforms.

- **Enhanced observation:** Operating at lower altitudes, VLEO satellites can, with smaller payloads, achieve comparable performance to larger satellites at higher orbits. Thus enabling key capabilities, such as sub-metric resolution imagery (particularly when looking after <0.5m resolutions), and operation superiority when considering space-to-space operation and SSA. at the same time, some optical surfaces and materials can be negatively impacted by the Atomic-oxygen rich environment without the necessary protection.

- **Lower latency** in communication for (near) real-time applications, related to an operational, strategic or tactical need.

- **Reduced space debris risks** (versus LEO), higher atmospheric drag leading to shorter orbital lifespans and natural deorbiting reduceing long-term space debris concerns make this type of orbit of particular interest in the frame of future constellations.

- **More challenging to track** due to higher speeds, limited ground station contacts and higher angular momentum requirement to keep contact, ...

- **Maneuverability for tactical flexibility:** Their propulsion systems enable VLEO satellites to adjust their orbits dynamically, allowing them to evade threats, reposition rapidly, or enhance surveillance over a specific area. This manoeuvrability makes them more resilient against space-to-space operations, anti-satellite weapons and jamming attempts. Increased drag regime presents a set of new challenges and opportunities linked to the spacecraft dynamics and operations. Specifically, the possibility to use atmospheric drag to undertake "aerobraking" manoeuvres to modify the orbit of the spacecraft, does provide with extended capabilities for manoeuvrability without the need to use propellant during the "breaking" part of the manoeuvre and instead limiting propellant use to only the orbit raising part of the operations. This can provide operators with higher resiliency against tracking (by inadvertively changing the altitude and period of the orbit). Similarly the capability of operating efficiently in such a regime provides the asset with a certain "natural" resiliency against unsanctioned RPOD and jamming attempts.

- **The implementation of more challenging operations** involving flight in and out of VLEO. Deployment of an asset in LEO for short-notice enhanced operations support throught reduction of operating altitude (LEO to VLEO). Air breathing missions presenting virtually limitless possibilities for orbital maneuvers without the need to rely on on-board fuel.

- **SSA of LEO from VLEO:** SSA needs to constantly catalogue and maintain an up-to-date registry of operational as well as non-operational threats to critical infrastructure and assets in Space. In this sense, VLEO provides yet another alternative "vantage point in terms of its physical location and long-term monitoring potential with respect to other assets in space. **Stealth**-like Ops: By flying lower than other assets, Spacecraft in VLEO can benefit from a "back-light" effect caused by Earth's Albedo effect which can induced blinding on optical systems such as star trackers, allowing them to observe assets flying "overhead" whilst maintaining a certain cover from "prying eyes".

The VLEO context challenges LEO solutions

Reducing orbital altitude from LEO to VLEO introduces significant challenges for existing technologies, spacecraft dynamics and operations. Technology building blocks and solutions should specifically address the impacts these changes have on current LEO-based systems.

- **Atmospheric drag:** At these altitudes, even the thin upper atmosphere slows down satellites, requiring highly efficient propulsion systems to maintain orbit (aimed at overcoming short operational lifespan, increasing replacement frequency and launch costs).

- **The harsh effects of atomic oxygen** causing material degradation, affecting optics & sensors, requiring a durable material protection, resistant coatings and of components, systems and structures.

- **Coverage** (smaller field of view on Earth covered per satellite) requires larger constellation, tasking to schedule imaging on priority areas, hybrid approaches, … Alternatively to multiplying the amount of satellites (high CAPEX), one can also increase the optical payload performance, specifically increase the sweep rate while using Time-Delay Integration (virtual or physical) to avoid losing signal to noise ratio. In parallel, foresee high agility ADCS to rapidly change orientation for the next targets and/or range of targets (e.g. multiple strips); This is developed by US companies (e.g. Albedo) to push the state of the art of Ultra-high Resolution imagery. It should be worth exploring.

- **Thermal and power management:** the thermal environment of VLEO poses challenges for thermal control systems, and the increased drag limits the size of deployable solar panels, impacting power generation.

- **High-efficient power provision:** Driven by need for electric propulsion for extended orbital operations and adjustments, raises a need for SWAP-efficient power subsystems Atomic Oxygen-resistant panels

- **Revisit Time & Short(er) ground contact time**, requiring robust ground station coverage for timely data relay and higher momentum requirement to keep satellite pointed on target. Rapid change of orientation is necessary to avoid losing time acquiring high rate and slowing down. Alternatively, use single or dual gimbal with high throughput antenna.

- **Extend operational life:** The shorter operational life of systems increases the need to preserve rare resources and critical components. NATO, for example, has observed that one way to mitigate the scarcity of such resources is to extend the service life of platforms — broadly, not only in the space domain. VLEO platforms are, by definition, subject to additional constraints and face the added challenge of extending their operational life as far as possible.

Altitude based challenges

Due to the above-mentioned challenges being linked to the altitude of the envisaged orbit, this VLEO track within the roadmap uses altitude as a key dimension to map and rank the challenges alongside each other. In general, going from higher altitudes (e.g., 450 km) to lower orbits (e.g., 150 km), the number and severity of challenges increase due to the rising presence of atomic oxygen and greater atmospheric density. At the end of the development phase, the target altitude for in-orbit validation must be defined based on the performance and limitations of the developed technologies under representative environmental conditions.

Belgian DTIB – Supporting VLEO Research and Innovation

VLEO developments are gaining traction across Europe (esp. Germany), and Belgium is well positioned to also contribute to and lead in this emerging field. The Belgian ecosystem brings together multidisciplinary industrial capabilities, academic excellence, and advanced test infrastructure, offering a comprehensive base to accelerate R&D and address the integrated system demands of VLEO.

- **Full value chain coverage:** The Belgian DTIB includes key players across the entire VLEO technology chain—propulsion, power provision and control, and satellite platforms—combining system-level integration capacity with insights in VLEO-stressors and leadership in critical enabling technologies. Established Belgian system integrators can play a key role in defining platform-level VLEO missions.
    - **Propulsion and control:** Propulsion innovators, thrusters and micro-thrusters, attitude and orbit control system specialists, mechatronic control experts (e.g. for precision steering, model predictive control) and atmospheric drag research.
    - **Power provision and control:** Capabilities in high-efficiency solar materials (Ge layer), re-usable substrate concept, cheaper solar cell processing, compact power management systems, and thermal control (incl. advanced coatings and flexible structures), power electronics, batteries cells, and expertise on effect of VLEO on commercial off-the-shelf components (COTS).
    - **Platform and environment:** Developers of novel environmental-resistant materials, coatings, and microstructures; aerodynamic design and modelling for drag control; advanced deployable mechanisms and structures; additive manufacturing and laser texturing; and partners for VLEO-capable ground segment and tracking systems.

- **Digital subsystems:** Belgian companies offer cutting-edge on-board software, autonomous mission control, secure satellite-ground communications, and high-performance ruggedised edge computing platforms for AI-enhanced data processing under extreme conditions in orbit.

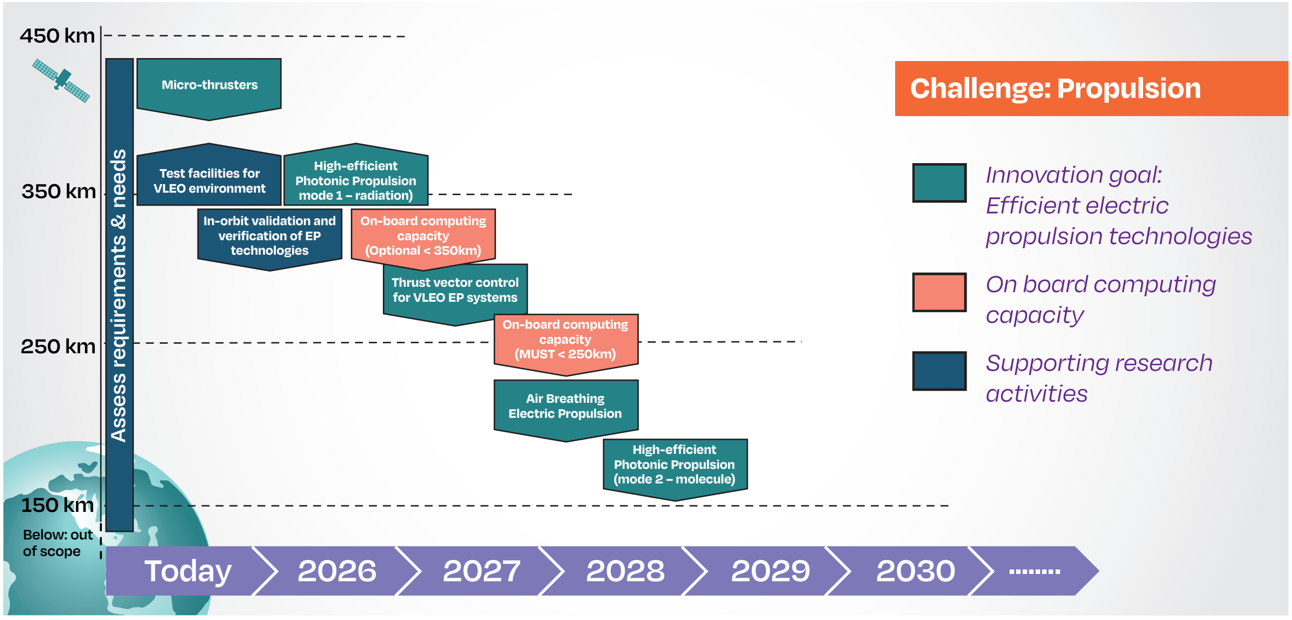
- **Research and cross-sector collaboration:** This industrial capability is reinforced by Belgium's strong academic and RTO base — e.g. IMEC, VKI, VITO, KU Leuven, University of Antwerp, CENAERO, CSL, CRM, MateriaNova, ULB, Sirris, BIRA and ROB — which ensures knowledge transfer, long-term innovation, and interdomain collaboration.

- **Test and validation infrastructure:** VLEO-specific development can be supported by expanding the world-class simulation tools and test infrastructure (e.g. at VKI, CSL, Cenaero and other actors), including rarefied gas dynamics, aerothermodynamics/plasma testing, and high-temperature material evaluation. These facilities are essential to enable validation up to TRL 6 on ground and constant loops between simulation, experimental validation and iterative design improvement.

The DIRS VLEO track leverages this solid national base to coordinate focused RTD efforts—across propulsion, platform, power, and environmental resilience—laying the groundwork for long-duration operational VLEO systems, validated in orbit and supported by a resilient, sovereign industrial ecosystem. The roadmap reinforces sovereign industrial capabilities ensuring that critical technologies are developed, manufactured, and maintained within the EU. The use of COTS will enable spin-ins and spin-offs of non-space companies into space applications.

4.2. CHALLENGE: PROPULSION TECHNOLOGIES AND CONTROL

Propulsion is the #1 enabling tech for sustained VLEO operations. At altitudes of 200–350 km, continuous atmospheric drag would deorbit a satellite in days to months if uncountered. Thus, VLEO satellites need efficient electric propulsion to provide frequent "drag compensating" thrust and orbit adjustments. Additionally, propulsion allows manoeuvring for collision avoidance and quick orbital changes – leveraging VLEO's drag for agility.



4.2.1. EFFICIENT ELECTRIC PROPULSION TECHNOLOGIES

Efficient electric propulsion technologies are essential to the long-duration survivability and operations of VLEO missions and reducing the need for onboard fuel. There are already some electric propulsion technologies available for the deployment of satellites in VLEO. Two main approaches are used:

- **Air-Breathing Electric Propulsion (ABEP)** – an emerging concept (TRL 3-4) where the satellite inhales atmospheric gases, ionizing them and ejecting at high speeds. ABEP promises theoretical indefinite station-keeping capabilities by ingesting atmospheric particles for fuel (5 year+ missions). The need to flight lower where atmospheric gases are present, creates more constraints in terms of control, recovery and survivability. Similarly, the use of atmospheric gases over conventional propellants such as Xenon or Krypton greatly hinder engine efficiency. proof of concept and prototypes of new "building block" technologies such as ABEP intakes and ground-based testing of EP systems using other gas sources have already been performed. Ground-based testing exists, but no operational missions with high-performance payloads[4]. Early examples of in-orbit demonstrators are also expected to fly before the end of this decade, however, there are no known (public) examples of these technologies being successfully applied to operational missions in combination with high-performance payloads. Full deployment and industrialization on these technologies at larger scale is expected to materialize in the 5-to-10-year timeframe.

- **Conventional electric propulsion** (fairly mature, e.g. Hall-effect thrusters[5], electrospray, Gridded Ion, and other types of ion-based thruster engines). On-board propellant ultimately limits a satellite's lifetime of a VLEO satellite (limited propulsion budget), on the other hand, use of Xenon as propellant typically results in much higher thrust efficiency when compared with other types of fuel. In parallel to ABEP, high thrust (chemical propulsion) might see a role for rapid orbital shifts from LEO to VLEO (for example, to quickly increase/lower a satellite's orbit, or change planes). This last kind of technology leads to a much lower operational lifetime when operating in VLEO.

Depending on the chosen propulsion technology, an efficient and compact power processing unit (PPU) has to be developed. PPUs are responsible for handling power conversion, distribution,

4. DISCOVERER EU Project https://discoverer.space/our-findings/discoverer-public-deliverables
5. https://www.exotrail.com/product/spaceware

and management, ensuring that the system operates efficiently and effectively. PPUs with space heritage exist today for the common thruster technologies (e.g. Hall-effect-thruster (HET), High Efficiency Multistage Plasma Thruster (HEMPT), Gridded ion engine (GIE). For the new thruster technologies under development, it is important to ensure adapted designs to minimize overall power consumption. For small platforms it is important that the overall platform integration is compact & minimal in weight.

Future research and development is focused on improving availability, cost, performance, lifetime, efficiency and reliability of the systems used. Expected outcome are system/subsystems demonstrated and their performance validated in a relevant environment (based on the research challenge from lab at TRL 2-3 to TRL5-6 under operational orbital dynamics ready for further validation in operational environment in orbit on a satellite TRL7).

4.2.1.1. Air Breathing Electric Propulsion

Design, integration, and testing of an efficient air-breathing electric propulsion (ABEP) system enabling sustainable, long-duration, and guilt-free manoeuvrability for Very Low- Earth Orbit (VLEO) satellites, while preserving payload capacity and maintaining material integrity against atmospheric interactions throughout the mission lifespan. Research targets at a thrust-to-power ratio $\geq$ 1 mN/W for sustained drag compensation at VLEO and an intake efficiency $\geq$50% with mixed atmospheric gases.

Key elements:

- Efficient atmospheric intake design and storage system targeting mixed atmospheric compositions (fuel capture and storage solutions).
- Advanced material microstructures and protective coatings.
- Propulsion integration optimised at platform level without compromising payload capacity.
- Resilience against atmospheric drag and erosion effects.

Key research gaps:

- **Efficient atmospheric intake design:** Developing collectors that capture enough particles at orbital speeds with minimal losses and drag.
- **Integration with specific electric propulsion technologies:** Harmonizing air intake flow with specific EP types (Hall-effect, Helicon Plasma, Gridded Ion thrusters), optimized for very light and reactive gases like oxygen and nitrogen at VLEO.
- **Material science for coatings:** improving thermo-mechanical resilience and thermal management at intake-thruster interfaces, including high heat-flux coatings, and preventing erosion and molecular scattering within the collector for material "guiding"; understanding how propulsion systems and their plasma plumes interact with VLEO particles and induce accelerated erosion, contamination, or severe thermal gradients.
- **Advanced aerodynamic magneto-fluid dynamic modelling:** Simulating high-temperature gas dynamics, atmospheric modelling, gas-surface interactions, plasma behaviour, and surface charging effects at VLEO altitudes.

- **Full ABEP platform integration:** creating compact systems that combine propulsion, intake, energy supply and thrust vector control, without compromising payload mass or volume.

- **High-voltage power supply for ionised gas acceleration.**

4.2.1.2. Micro-thrusters – Pulsed Detonation Engines

Design, integration, and testing of efficient, compact micro-thruster systems using pulsed detonation engine technology (PDE i.e. with hydrogen propellant) for responsive manoeuvring, fine orbit adjustments, and attitude control of VLEO satellites. The challenge aims to exploit the high energy density and clean combustion properties of hydrogen to enable rapid orbital changes while maintaining platform compactness, low system mass, and compatibility with extended mission durations in high-drag environments. Research targets at a more efficient use of propellant (high specific impulse in range 500-800 s) and a high energy conversion efficiency.

Key research gaps:

- Miniaturisation by adaptation of PDE systems to micro-thruster scale with consistent detonation initiation, stable repetitive firing, and low cycle-to-cycle variability, suitable for space applications in VLEO orbits.

- Ensuring compact integration of detonation chambers, valves, ignition systems, and thermal management within mass-limited platforms without degrading payload capacity.

- High-life cycle resilient materials and protective coatings resistant to shock loading, high thermal gradients, and combustion byproducts at high repetition rates.

- High-fidelity models for detonation dynamics, thrust impulse characterisation, plume effects, and their interaction with spacecraft structures at micro-thrust scales.

- Exploration of low-energy, rapid-response ignition mechanisms compatible with pulsed hydrogen detonation in a vacuum or rarefied environments.

4.2.1.3. High-efficient Photonic Propulsion

Develop photonic propulsion systems that are real, efficient, and precise enough for use on defence satellites operating in VLEO. The goal is to ensure performance that meets current and future VLEO mission demands, including a realistic thrust-to-weight ratio, precise thrust vectoring control, and compact integration suitable for small platforms. As an ultra-low-thrust solution, research targets a thrust-to-power ratio of **≥ 10 μN/W** along with high pointing accuracy and stability.

Key research gaps:

- Compact, lightweight, and powerful lasers or photon sources that fit tight space budgets and survive VLEO radiation/thermal conditions.

- Dynamic beam steering and pointing mechanisms that offer micro-adjustments for manoeuvrability.

- System integration for small platforms aiming at minimal energy consumption, cooling, and structural loads.

- ► Efficiency optimization under real VLEO conditions (microdrag, plasma, residual gases) must be factored in.
- ► Develop dual-mode thrusters combining ABEP with limited onboard propellant reserves for mission flexibility.
- ► Material and coating resilience.
- ► Validate performance of photonic propulsion under operational orbital dynamics.

4.2.2. THRUST VECTORING, AERODYNAMIC CONTROL SURFACES AND OTHER ATTITUDE AND ORBIT CONTROL TECHNIQUES

Propulsion, attitude and orbit control techniques for controlling the spacecraft's movement and orientation to deal with unpredictable changes in the surrounding environment (atmospheric drag, variable density, and aerodynamic torques) to maintain orbit, allow manoeuvrability and ensure long-duration survivability and operations and reducing the need for onboard fuel. More exotic operations could involve flight in and out of VLEO / LEO.

This includes:

- Unlike higher orbits, aerodynamics matter in VLEO control. Control techniques using atmospheric drag for increased manoeuvrability of the satellite for tactical flexibility without the need to use propellant (i.e. "aerobraking" manoeuvres to modify the orbit of the spacecraft, stealth and resilience for tracking or unauthorized rendezvous attempts).
- Mecha(tro)nical systems for direction control of electric thrusters allowing precise, real-time adjustments. Control moment gyroscope to provide fine attitude control for stabilizing optical payloads while offering:
  - The better momentum envelop (compared to reaction wheels) to accumulate disturbance torques (from engine or drag) and allowing high rates for ground station contact (due to high speed).
  - The ability to change orientation quickly if need be (collision avoidance, change from low-drag orientation to nadir imaging orientation and back, or ground station acquisition with high roll & pitch rates and back to low drag orientation).
- Exploration of synergies or conflicts between control techniques based on electric/photonic propulsion and aerodynamic control surfaces.

4.2.2.1. Thrust vector control for VLEO EP systems

Development of compact, resilient mechatronic systems and integrated propulsion solution, to enable precise attitude and orbit control for VLEO satellites. Primary aim is to enhance manoeuvrability, attitude control, and orbit maintenance in a dynamic atmospheric environment. This can also include combining electric propulsion steering with aerodynamic surface adjustment for manoeuvrability based on atmospheric drag (next research challenge).

Key research gaps:

- ► Development of thrust vectoring adapted to electric thrusters for VLEO. Beam steering for precision thrust vectoring and dual gimbal or tri-pod for coarse thrust vectoring + steering laws to control the overall system. Evaluate possibility to play with electric potentials or magnetic field to influence the direction of the ejected beam combined with the use of asymmetrical gas injection

- Adapt electric propulsion thrusters to VLEO if needed, based on findings of challenge "In-orbit validation and verification of EP technologies" while taking into account optimal thruster sizing: the ideal size/thrust range for effective manoeuvrability in VLEO (too large = energy drain; too small = ineffective.)

- How does VLEO affect the materials & mechanisms (long-term exposure to atomic oxygen…)

- SWAP optimization: Actuation systems have to be miniaturized, efficient miniaturized electronics

- Combined attitude and orbit control using thrusters

4.2.2.2. Using atmospheric drag for manoeuvrability for tactical flexibility

Use atmospheric drag for increased propellant-free manoeuvrability through controlled aerodynamic surfaces (i.e. "aerobraking" manoeuvres to modify the orbit of the spacecraft, stealth and resilience for tracking or unauthorized rendezvous attempts).

In order to use the atmospheric drag for manoeuvrability, the control surfaces is closely connected to the design of active, orientable aerodynamic structures – such as moveable aero-surfaces or differential drag panels to steer –to generate lift to keep a satellite aloft or to adjust ground track by banking like an aircraft.

Key research gaps:

- Analyse the feasibility to use atmospheric drag to assist manoeuvrability.

- Analyse the impact of the environment on the satellite and its equipment (Radiation, free oxygen, temperatures, temperature cycles, vibrations, shock,…)

- Assess suitable surface types (flaps, fins, morphing skins), their optimal materials resistant to atomic oxygen, radiation, and thermal cycling; and number and placement optimization.

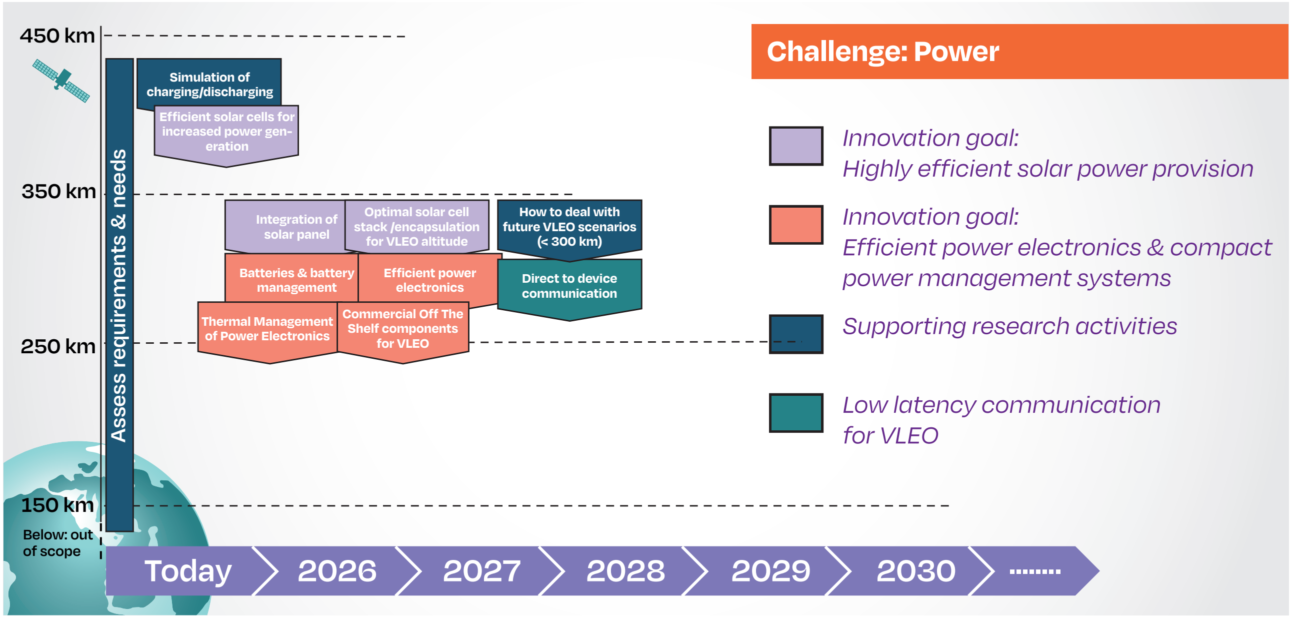
- Analyse the steering mechanisms needed to control these surfaces (miniaturization, power density, power efficiency)

- Exploit the potential of additive manufacturing for power density.

- Optimize power density & efficiency of the power propulsion supply unit (PPU).

4.3. CHALLENGE: POWER PROVISION AND CONTROL

Power is a fundamental subsystem – satellites need reliable power (typically solar panels + batteries) to run payloads, propulsion, and computing. Efficient solar power provision, electronics, and management resistant to degradation and adapted to the dynamic power requirements (i.e. for drag compensation) and communication adapted for the shorter visibility windows in VLEO.



4.3.1. HIGH EFFICIENT SOLAR POWER PROVISION

High efficient solar power provision based on efficient (germanium) substrates for solar cells are used worldwide, to keep systems running esp. electric propulsion. This requires high efficient panels, support structures, shielded/coated to protect against environment (Atomic Oxygen proof), and safe/stable deployment.

KPIs to guide the technology building blocks research at VLEO, focusing on indicative ranges and target directions under VLEO-specific stressors impacting high-efficiency solar arrays:

- Solar Cell Efficiency Loss: ≤15% degradation (from erosion by atomic oxygen) after 3 years
- Specific Power of Solar Array: ≥250 W/kg end-of-life, including encapsulation to limit mass of a compact platform.
- Power Density: ≥200 W/m².
- Operational Lifetime: ≥3 years continuous operation .
- Thermal Operating Range Stability: Maintain nominal power output between -80°C to +120°C to account for severe thermal cycling.

4.3.1.1. Efficient solar cells for increased power generation

High efficient space solar cells are grown on Ge substrates. Germanium is a minor metal used in strategic markets like optical fibre, infrared optics, micro-electronics, space solar cells amongst others. With no significant primary source in Europe or US, it is listed among the critical raw materials. Moreover, its scarcity and limited production (130 – 150T annually) make the Ge market susceptible to economic and geopolitical manipulations. A recent example is the export control implemented by the Chinese government on Ge starting in August 2023 and the Chinese stockpiling programme in 2024. With 60% of the world's Ge supply originating from China, these measures did the Ge market price triple in a couple of weeks from 1000$/kg to 3000$/kg on the Western markets. Currently, the space market accounts for 10% of the total Ge demand. Given the rapid growth of the space sector, reducing reliance on Ge supply is crucial to enhance the attractiveness of high efficient multi-junction solar cells and to maintain European sovereignty in the field of space power generation.

These considerations have led to the development of engineered Ge substrates, comprising of a thin layer of Ge weakly attached to its mother substrate. After solar cell processing, the top Ge layer can be easily unzipped from its mother substrate, allowing re-use of the latter. Umicore has been at the forefront of developing these engineered Ge substrates. Compared to multi junction solar cells developed on traditional bulk Ge substrates, those developed on engineered Ge substrates offer several advantages:

- Lower cost per Watt and higher throughput.
- Improved resource efficiency, as only a fraction of the Ge substrate is used, reducing reliance on resource availability. For this reason, the European Commission recognizes this approach as a Strategic Project under Regulation 2024/1252 of the Critical Raw Materials Act[6].
- Greater flexibility, enabling the development of flexible modules.
- Smaller and lighter solar arrays, lowering launch costs.

In that respect, this technology is ideally suited for VLEO missions, which will require high efficient, lightweight, flexible solar cells.

Key research gaps:

► Current development track does not allow for a Ge bottom junction. Development of Ge epi as a capability block is missing.

4.3.1.2. Optimal solar cell stack for VLEO altitude

VLEO satellites will require high power with limited wing surface areas. In such case, the use of high-efficient multi junction (MJ) solar cells is preferred over Si cells. Indeed, the latter have about half the efficiency of MJ cells. MJ cells typically consist of 2 up to 3 solar cells monolithically stacked onto a Ge substrate, which may or not form the bottom solar cell. In order to have the best cell for VLEO satellites, the solar cell stack architecture may need to be tweaked, ie. the thickness and exact composition of the different cells may need to be tailored to the solar spectrum present at the envisaged altitude.

Key research gaps:

► Understand solar irradiation at VLEO

► Understand angle of arrays with respect to sun (e.g., key in use for energy control)

► Calculate optimal solar cell stack structure: 2-junction, 3-junction or 4-junctions?
4- (or-3) junctions is a-priori preferred as this results in highest power capability per kg.

► Growth and performance testing of such stacks on re-usable Ge substrates

4.3.1.3. Solar Cell Encapsulation for VLEO Operation

Atomic oxygen (ATOX), micrometeoroids and temperature swings can cause glass cracking, adhesive failure, optical loss, and structural fatigue. Develop VLEO-optimized encapsulation solutions for advanced solar cell architectures that withstand atomic oxygen, thermal cycling, and plasma exposure, while maintaining high optical performance, structural integrity, and full compatibility with new multi-junction stack designs of new cells architectures.

6. See Selected projects - European Commission for a list of selected strategic projects. ReGAIN, project 39, refers to the re-usable Ge substrate approach by using engineered wafers.

Key research gaps:

- Solar cell cover glass coatings adapted to the VLEO environment and specific cell design
- Cover glass adhesive compatibility with the VLEO environment (bond durability, thermal stability and performance)
- Full integrated fabrication/assembly chain (co-engineered fabrication steps from cell to coating to adhesive to integration of photovoltaic assembly (PVA)with wing structures)
- Solar-cell assembly interconnector design – adapted to atox & temperature environment
- Modelling of output power depending on environmental conditions

4.3.1.4. Integration of photovoltaic assembly (PVA)

Analyse how to design, deploy, and integrate high-efficiency, lightweight solar panels onto VLEO satellites, ensuring aerodynamic compatibility, systems for reliable unfolding, and resilience against the harsh atmospheric environment, while optimizing for limited aerodynamic surface areas and structural constraints.

Key research gaps:

- Flawless deployment mechanisms
- Integration of solar cells on aerodynamic surfaces in the VLEO environment
- Working out concept of re-usable Ge substrates for this application, resulting in lightweight cells
- Working on highly thin, flexible solar sheets equipped with high efficient solar cells
- PVA for VLEO environment
  - Selection/characterization of materials & components to resist VLEO ATOX environment.
  - Development of processes to protect critical components & materials e.g. 3E (diodes – thermal sensors), cables, and interconnections.
  - Take into account charging constraints & ESD requirements in VLEO conditions, as well as avoid accumulation of charged particles due both to plasma in orbit and coming from the electric propulsion system plume
  - Study of potential failure mechanisms (by accelerated testing)
  - PVA design for VLEO, complying with required lifetime & power expectations

4.3.1.5. Integrated Solar Tracking for Power-Efficient and Aerodynamically Stable VLEO Platforms

Unlike higher orbits, VLEO missions face a direct trade-off between optimal solar orientation and minimised atmospheric drag. Solar tracking systems must therefore be designed not only for maximum energy capture, but also to limit drag penalties, avoid destabilising aerodynamic torques, and support continuous electric propulsion demands. Integrated solar tracking approaches are needed which ensure efficient power generation while maintaining aerodynamic stability and attitude control in VLEO.

Key research gaps:

- Integration of solar trackers in solar panels are still at very low maturity level (TRL 2) and need to be further developed.
- Aerodynamic–power trade-off modelling quantifying the impact of solar panel orientation on drag, aerodynamic torque, and power efficiency in VLEO conditions.
- No mature concepts for constrained or limited-motion solar tracking balancing power gain with drag and stability impacts.
- Framework for cooperative solar tracking and attitude control loops, ensuring stability while enabling power optimisation.
- Limited data on solar tracking behaviour and dynamic performance under continuous propulsion modes and during sunlight–eclipse transitions.
- Mechanisms to extend the deployable systems.

4.3.2. EFFICIENT POWER ELECTRONICS & COMPACT POWER MANAGEMENT SYSTEMS

Efficient power electronics & compact power management systems are essential for managing the higher energy density demands of VLEO satellite platforms. The central subsystem enabling this is the Power Control and Distribution Unit (PCDU), which ensures the generation, storage, distribution, and efficient usage of power while also managing thermal effects and providing fault detection, isolation, and recovery. In the VLEO environment, reduced radiation opens up opportunities for the integration of commercial off-the-shelf components, provided these are screened for resilience to atomic oxygen, plasma exposure, and thermal cycling. Leveraging COTS could significantly lower costs and allow spin-ins from the non-space sector, but requires rigorous evaluation.

4.3.2.1. Efficient and Cost-Effective Power Electronics and Power Management Systems

This research aims to develop a compact, efficient, and reliable PCDU tailored to the unique environmental and operational conditions of VLEO satellites. The goal is to combine high system-level performance with cost efficiency by exploring two complementary technology pathways:

- **COTS Integration Pathway:** Identify and qualify Commercial Off-The-Shelf (COTS) components suitable for VLEO applications by applying dedicated screening and accelerated life testing under atomic oxygen exposure, plasma interactions, and thermal cycling (–80°C to +120°C). This track focuses on reducing costs and increasing supply chain flexibility while ensuring system reliability.
- **Advanced Power Electronics Pathway:** Develop novel power electronics architectures including high-efficiency converters (e.g., GaN-based systems), intelligent energy management, integrated batteries, and advanced thermal management solutions. The focus is on achieving higher energy density, improved conversion efficiency, and robust performance under VLEO stressors.

This integrated approach aims at scalable, modular, and cost-effective power systems optimised for the demanding VLEO environment while fostering both innovation and affordability within the European industrial base. For both pathways the goal is to go from a TRL 3–4 to a TRL 6, ready for in VLEO-orbit demonstration and validation by 2030. KPIs to guide the technology building blocks research at VLEO under VLEO stressors impacting high-efficiency solar arrays and power electronics:

- Efficient Power Electronics losses: ≤5% power conversion losses at full load.
- COTS component survivability: ≥3 years operation with ≤10% performance drift.
- Thermal management efficiency: maintain <15°C temperature variation during peak load.
- Specific power electronics mass: ≤5 kg/kW installed electrical capacity.

Key research gaps:

- Evaluation and integration of COTS components, including up-screening and qualification under VLEO-specific conditions (e.g. radiation, AO, plasma). Accelerated lifetime tests to predict long-term COTS and system performance under VLEO stressors.

- Design of compact, lightweight PCDU architectures optimised for high power density and constrained volume and integrating COTS and high-efficiency components. Advance low-loss, high-efficiency power converters suitable for dynamic VLEO power demands.

- Smart, algorithm-driven energy management systems capable of handling variable power generation and adaptive load balancing across subsystems.

- Incorporation of redundancy and failure recovery logic to ensure continued operation in case of subsystem degradation.

- Advanced thermal management solutions for stable operation under high power density. Adoption of wide bandgap materials (e.g., GaN, SiC) to improve thermal performance and power conversion efficiency.

4.3.2.2. Batteries and battery management

Batteries and battery management systems must address the unique VLEO operational needs, including frequent high-power demand for electric propulsion during eclipses, simultaneous payload operation, and thermal management in a highly variable environment. Research should focus on high cycle-life, thermally robust, and lightweight batteries, coupled with intelligent battery management systems capable of handling frequent charge/discharge cycles, rapid load changes, and VLEO-specific degradation effects, including exposure to atomic oxygen and plasma. This includes developing compact high-efficiency storage systems, with target performance in the range of ≥5000 cycles, <20% capacity degradation over 3 ears, and specific energy ≥200 Wh/kg end-of-life.

Key research gaps:

- Development and validation of battery cells with of high-cycle-life and high specific energy storage, resistant to structural and vibrational stresses.

- Identification or development of cell chemistries compatible with rapid recharge and frequent cycling under VLEO stressors (low TRL).

- Intelligent Battery Management Systems (BMS) capable of managing dynamic power profiles and switching between propulsion and payload operations.

- Evaluation and implementation of COTS-based cell balancing schemes to extend operational lifetime.

- Improved thermal resilience, maintaining nominal performance between –80°C to +120°C and including management of thermal loads from variable albedo and plasma interaction.
- Optimised packaging design to ensure mechanical and thermal compatibility with compact and drag-minimised VLEO platforms.

4.3.2.3. Fault Detection, Isolation, and Recovery (FDIR) to deal with failure scenarios in VLEO

In VLEO, satellites are exposed to unique failure drivers compared to LEO, including accelerated mechanical degradation and fatigue from atmospheric drag and atomic oxygen erosion, increased risks from plasma charging, more frequent thermal cycling, and high reliance on propulsion for orbital maintenance. This research aims to develop VLEO-specific Fault Detection, Isolation, and Recovery (FDIR) systems that enable satellites to detect, diagnose, and autonomously recover from failures before they lead to mission loss, ensuring operational continuity despite these harsher conditions.

Key research gaps:

- Refining VLEO-specific failure scenarios, covering mechanical fatigue, drag-related anomalies, plasma-induced electrical issues, and propulsion failure impacts.
- Defining recovery envelopes, esp. optimised for high-drag environments with rapid orbit degradation risks and limited energy margins.
- Developing onboard health monitoring systems based on AI, machine learning, and digital twin concepts, enabling predictive fault avoidance and autonomous reconfiguration.
- Validating high-fidelity degradation models for thermal cycling, AO erosion, and plasma effects.

These target demonstration of TRL 6 by 2030, validated under relevant VLEO environmental stressors.

Key research gaps:

- Hardware and software-based FDIR solutions tailored to VLEO failure scenarios, combining real-time onboard fault detection with adaptive software-driven recovery.
- Redundancy concepts optimised for mass and power-limited VLEO satellites, including function-level redundancy and architectural resilience without overburdening system mass.
- Use of COTS components within FDIR systems, balancing low-cost hardware with qualified screening for VLEO operational conditions.
- Criticality assessment linked to orbital altitude, defining response priorities and autonomous recovery logic based on how quickly failures lead to irreversible mission degradation in VLEO.
- Inclusion of remote failure scenario reproduction tools, allowing high-fidelity ground-based testing and verification of onboard fault management strategies.
- High-fidelity digital models of VLEO operational conditions, including atmospheric, plasma, and thermal influences, to support simulation-driven FDIR design and validation.

4.3.2.4. Thermal management of power electronics

Thermal management systems for VLEO satellites must address high internal heat loads from continuous electric propulsion, reduced heat rejection capacity due to drag-constrained surfaces, and surface degradation from atomic oxygen and plasma exposure.

Thermal management in VLEO requires a shift towards drag-aware, atomic oxygen(ATOX)-resistant, and power-dense solutions, integrating new materials and compact designs beyond typical LEO standards. This research focuses on developing compact, erosion-resistant, and efficient thermal control solutions, using:

- High-performance, drag-minimised heat exchangers with optimised geometries;
- ATOX-resistant, high-emissivity coatings ensuring long-term thermal stability;
- Advanced materials and integrated structural thermal solutions;
- Phase changing techniques;
- 3D-printed thermal components for complex, weight-optimised designs;
- Robust thermal systems supporting continuous peak loads and rapid cycling in VLEO.

Key research gaps:

- High-efficiency, drag-minimised heat exchangers with complex internal geometries suitable for confined satellite volumes in VLEO.
- Durable coatings and/or micro-structures that maintain high emissivity and thermal stability under prolonged AO exposure while resisting erosion.
- Identify lightweight, high-conductivity materials that withstand plasma and AO degradation.
- Removing concentrated heat from high-performance power electronics in small VLEO satellites.
- 3D printing and precision manufacturing to realise optimised thermal components with complex flow channels and reduced weight, while ensuring long-term durability in the VLEO environment.
- Robust thermal stability during rapid thermal cycling (~90-minute orbit hot/cold cycles).

4.3.3. LOW LATENCY COMMUNICATION FOR VLEO

Low-latency communication, adapted to the shorter visibility windows of VLEO through frequent handovers and inter-satellite links, is recognised as a promising application area for VLEO systems. While not yet widely implemented, early commercial initiatives targeting direct-to-device communication (e.g., Starlink, Apple) demonstrate the potential of these concepts.

This research focuses on exploring low-latency communication concepts for VLEO satellites, specifically addressing communication between satellites and efficient data links between satellites and ground stations. The goal is to investigate how existing and emerging technology building blocks—such as inter-satellite links, high-data-rate downlinks, and advanced handover mechanisms—can be combined to overcome the challenges of short visibility windows and frequent ground contact interruptions typical of VLEO. The research will also identify gaps in key enabling technologies, including compact, power-efficient communication hardware and precision pointing systems. The objective is to develop system-level solutions optimised for timely and reliable data transfer in VLEO, while supporting persistent coverage through a space-based communication architecture. Direct-to-device tactical communication towards ground users – to deal with future scenario's - is out of scope at this stage.

KPIs to guide the technology building blocks research at VLEO under VLEO stressors impacting communication:

- End-to-end communication latency: ≤100 ms round trip for tactical use cases
- Data throughput (peak link): ≥1 Gbps for optical terminals; ≥500 Mbps for RF links
- Ground contact duty cycle: ≥25% orbital period in contact, including ISL relay.
- Antenna/terminal pointing accuracy: ≤0.1° dynamic pointing error for optical links.

RTD aims at bringing technology building blocks from TRL3-5 to reach TRL 6, enabling and supporting the overall in-orbit validation and system-level demonstration under VLEO conditions.

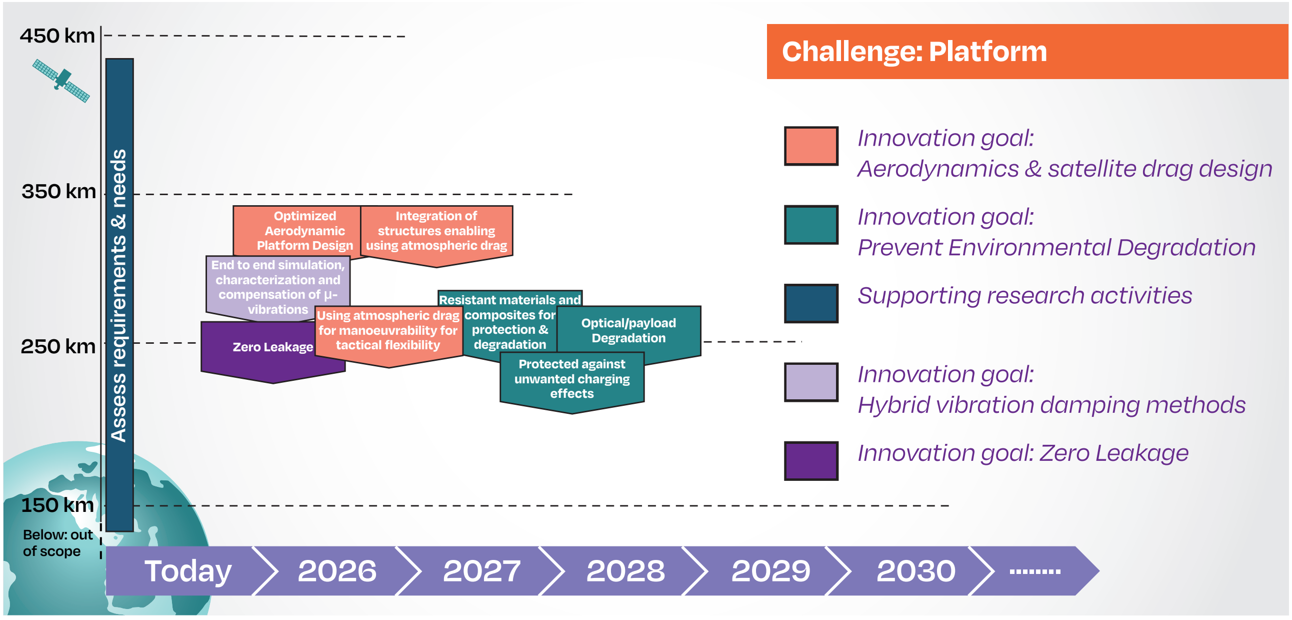
Key research gaps:

- Optimising data transfer during short ground contact windows through advanced handover and scheduling strategies.
- On-board data processing and prioritisation to maximise transmission efficiency under VLEO constraints.
- Power-efficient, compact communication hardware tailored to the limited energy budgets of VLEO platforms.
- Miniaturised high-gain antennas and optical terminals with precise pointing for high-data-rate links.
- Thermally stable, high-throughput internal link solutions, including flexible cabling and deployment mechanisms.
- Inter-satellite link (ISL) configurations to maintain continuous data relay despite rapid orbital dynamics.

4.4. CHALLENGE: OPTIMIZED SATELLITE PLATFORMS FOR VLEO

Design VLEO satellite platforms to withstand high atmospheric drag, atomic oxygen erosion, and plasma exposure. Integrate aerodynamic shaping, mechatronic systems, resistant materials, protective coatings, and leakage prevention technologies. Use topological optimisation of composite and metallic structures to achieve lighter, stronger platforms.

Advanced 3D printing techniques to enable the creation of optimised, aerodynamic satellite frames that minimize drag and mass, while maintaining structural resilience under VLEO conditions.



4.4.1. AERODYNAMICS & SATELLITE DRAG DESIGN

In VLEO, satellites experience significantly stronger and more variable aerodynamic forces than in higher orbits due to rarefied flow conditions and atmospheric composition changes. This makes aerodynamic design, characterisation, and validated modelling essential to reduce overall drag, enhance orbital stability, and minimise propulsion requirements.

This research focuses on:

- **Passive aerodynamic shaping** to reduce drag and generate lift, optimising satellite longevity and fuel consumption.
- **Active aerodynamic structures**, such as moveable surfaces or differential drag panels, to enable atmospheric drag-based manoeuvring for tactical flexibility, including orbit raising, ground track adjustment, and controlled re-entry.
- **Coupling of aerodynamic forces with attitude control**, exploiting aerodynamic torques for stability or actively managing disturbances. Active aerodynamic structures are closely linker dot Links to attitude and orbit control techniques 6.2.2 esp. "6.2.2.2 Using atmospheric drag for manoeuvrability for tactical flexibility".

The design approach considers the entire platform, including shape, panel configuration, mass distribution, and component integration, with attention to drag reduction efficiency and system behaviour across mission phases (orbit acquisition, operational mode, safe mode).

Key research gaps:

- Development of optimised aerodynamic designs adapted to VLEO's rarefied flow, plasma interactions, and variable atmospheric conditions (composition, temperature, density).

- Validated aerodynamic models for drag, lift, and aerodynamic torques, including rare gas-surface interactions.

- In-orbit aerodynamic measurement payloads to generate validation data for simulation models, with links to wind tunnel testing.

- ► Ensure cost-feasible manufacturability and scaling of the production of the platform.

A phased approach ensures progressive validation: starting from simulation validation (TRL 3–4) to ground test validation (TRL 5–6) ready for flight demonstration. The production cost and ability to scale production should be evaluated.

4.4.2. PREVENT ENVIRONMENTAL DEGRADATION

VLEO satellites are exposed to intensified degradation from atomic oxygen, plasma, UV, thermal cycling, and micrometeoroids. This research focuses on developing multifunctional protective materials and coatings, as well as high-performance optical surfaces, that combine durability, ease of processing, and straightforward integration into satellite structures and payloads, validated under combined VLEO environmental stressors to ensure long-term mission reliability and reduce operational risks.

The question remains if adapted design guidelines are required for VLEO or if LEO practices are sufficient. The difference between LEO and VLEO should be verified (e.g. via modelling) and quantified to assess the need for adapted design guidelines and environmental monitoring.

4.4.2.1. Multifunctional Protective Materials and Composites

Develop and validate multifunctional, VLEO-resistant materials, coatings and microstructures suitable for structural, thermal, and electronic applications, ensuring durability under mechanical loads and aiming at minimising drag, reducing charging risks, and extending operational lifetimes.

- Materials should demonstrate sustained resistance to erosion and degradation under VLEO-specific environmental conditions with minimal performance loss over mission-relevant timescales.
- Surfaces should effectively limit the build-up of differential charging and reduce the risk of electrostatic discharge, contributing to overall satellite stability.
- Protective materials should maintain structural integrity under repeated thermal and mechanical stresses typical of VLEO missions.
- Materials and coatings should be compatible with standard space manufacturing processes, allowing for straightforward application on complex satellite geometries. Solutions should enable easy incorporation into existing satellite designs without major system-level modifications.
- Material performance should be confirmed through a combination of ground-based simulation and testing, ready in-orbit demonstration and validation.

Key research gaps:

- ► Extend operational life to preserve scarce resources and critical components.
- ► Limited information on atmospheric composition across VLEO region to verify the performance gap between LEO and VLEO protective materials and measures. Current simulations rely on analytical models and approximations.
- ► Develop multi-layered materials resistant to VLEO stressors.
- ► Explore micro-textures and advanced coatings (e.g. carbon nanotubes) to improve durability and reduce drag. Demonstrate and validate their stability (and adhesion) under thermal and mechanical stress cycles.
- ► Design surfaces that mitigate differential charging and limit plasma-induced degradation.

- Validate scalable, manufacturable materials suitable for small satellite platforms.
- Gather real degradation data to provide insight in stressors in VLEO orbit.
- Development of more accurate predictive models, supported by experiments, for material degradation under VLEO conditions to help in material selection and design.

4.4.2.2. Optical Surface Durability and Performance

Preserve the optical performance of payload instruments, solar arrays, and thermal management surfaces by developing coatings and materials resistant to AO erosion, plasma abrasion, and UV-induced degradation. Solutions must meet typical payload integration constraints.Manufacturability of coatings and micro-structures and suitability for integration in high-throughput satellite production should be assessed.

Key research gaps:

- Characterise optical degradation mechanisms under combined VLEO conditions.
- Define contamination thresholds and optical performance limits (reflectivity, transmittance).
- Develop coating architectures and micro-textures optimised for optical stability and environmental resistance.
- Advance process engineering for high-stability thermo-optical surfaces compatible with satellite integration.
- Validate optical performance through environmental simulation and testing, prior to confirmation in-flight during VLEO mission phases.

The question remains if adapted design guidelines are required for VLEO or if LEO practices are sufficient. Quantification of the differences can support the decision which improvements for VLEO are necessary.

4.4.2.3. Protected against unwanted charging effects & environmental monitoring

Protect against unwanted charging effects. Unwanted charging due to denser atmosphere and more aggressive plasma interactions is expected to increase in VLEO. The difference with LEO should be verified via modelling to assess the need for adapted design guidelines and environmental monitoring.

Key research gaps:

- Limited information on atmospheric composition across VLEO region: Unknown conditions associated to environment-induced charging. Potential risks related to plume particle (re-)incidence, gas-surface interactions, increased material degradation and drag due to electro-static differential.
- Current simulations rely on analytical models and approximations.
- Further research needed to develop effective mitigation strategies such as the use of specialized materials, grounding techniques, and advanced plasma shielding.

The question remains if adapted design guidelines are required for VLEO or if LEO practices are sufficient. Quantification of the differences can support the decision which improvements for VLEO are necessary.

4.4.3. HYBRID VIBRATION DAMPING METHODS

In VLEO, satellites are exposed to stronger and more variable disturbances than in higher orbits due to continuous atmospheric drag, density fluctuations, and more frequent thermal cycling. These factors, combined with near-continuous operation of electric propulsion systems, create persistent micro vibrations and structural stresses. Effective vibration damping is essential to protect sensitive payloads, ensure pointing stability, prevent fatigue-related failures, and maintain overall system performance in the highly dynamic and compact VLEO satellite environment.

4.4.3.1. End to end simulation, characterisation and compensation of (micro) vibrations

Development and validation of hybrid vibration damping methods through passive and semi-active laws (use of sensors for live monitoring of vibration properties and accurate response), enabling:

- Vibration mitigation / shock protection of hardware during launch
- Isolation of sensitive payloads in-orbit

Key research gaps:

- Assess the effect of VLEO on vibrations, investigate difference with other orbits to define the additional needs required for VLEO

- Optimization of active control methods

- Development of an intelligent vibration damper which adapts in real-time during on-orbit operation

- Multi-physics constrained topology optimization of some components taking into account vibration constraints.

4.5. CHALLENGE: PREDICTIVE MODELLING AND VALIDATION INFRASTRUCTURE

The unique VLEO environment imposes new challenges that current LEO validation infrastructure cannot address. At the start of the VLEO track, research should assess atmospheric density to determine to what extent developments are feasible.

To further guide and de-risk VLEO research throughout the VLEO-track, the deployment of real-time environmental prediction models should provide continuous insight into atmospheric conditions, while dedicated ground test infrastructure and in-orbit testing capabilities must be established to validate technologies under real VLEO operational stressors. This approach should enable validation in a relevant VLEO environment at TRL 5-6 during development phases, progressing to in-orbit demonstration and performance validation of most promising outcomes on a satellite in VLEO-orbit (TRL 7) by the end of the VLEO development track.

4.5.1. ATMOSPHERIC DENSITY VARIABILITY & PREDICTION

Develop low-cost, reliable, and real-time atmospheric density models tailored to VLEO environments (150–450 km). These models must provide short-term forecasts (on the order of satellite orbit cycles) with high accuracy (≤10% error), supporting operational mission planning and in-orbit thrust management. Research includes the development of in-situ atmospheric density sensing solutions suitable for integration on small satellites and demonstrators, as well as the creation of data-assimilation techniques combining space weather inputs, satellite measurements, and physical modelling to enhance real-time operational forecasts.

Key research gaps:

Advance the current academic understanding of atmospheric density variability towards the development of practical, operational models suitable for real-time applications.

- Real-time, low-complexity density forecasting tools for on-board applications.
- Operational-grade, validated atmospheric density models addressing short-term variations driven by solar, geomagnetic, and thermospheric effects.
- Compact, low-cost, in-situ density sensors suitable for VLEO missions.
- Model-data fusion techniques integrating satellite measurements and space weather data.
- Assessment methodologies to quantify the operational impact of density fluctuations on drag-assisted propulsion and manoeuvrability.

4.5.2. VLEO-SPECIFIC ENVIRONMENTAL TEST FACILITIES

The VLEO environment poses specific challenges in terms of rarefied winds, charging, or particle radiation. Design and establish technology building blocks to extend/develop test infrastructure that accurately replicates the VLEO environment, integrating rarefied gas flows (N_2/O_2 mix), atomic oxygen exposure, plasma interactions, and/or high-energy particle radiation. VLEO-specific test infrastructure must support the validation and qualification of key outcomes, such as propulsion systems, satellite materials, coatings, and control systems under representative environmental stressors. The goal is to de-risk operational deployments by closing the TRL gap from laboratory prototypes to systems ready for further in VLEO-orbit demonstration and validation.

The research aims at building blocks extending current infrastructure for a LEO environment available in Belgium at research institutes and universities, towards additional VLEO stressors. Examples of required expansions might include combining rarefied atmospheric flows with atomic oxygen and plasma exposure, integrating propulsion-plasma interaction testing, and enabling long-duration material and optical surface degradation studies under realistic VLEO environmental conditions. Where for critical aspects access to test infrastructure is currently lacking in Belgium research can aim at new test-infrastructure.

4.5.3. IN-ORBIT VALIDATION AND VERIFICATION OF EP TECHNOLOGIES

In-orbit demonstration, performance validation, and verification of propulsion, power provision and control and satellite platform for VLEO ensures operational viability, long-term survivability, and adaptability across different propulsion principles and regimes, power, and fuels used under realistic VLEO-orbit space conditions. The technologies and technology building blocks are not fully understood. A structured VLEO-validation in-orbit should provide insights in:

- Real-world survivability and performance in VLEO (atomic oxygen, drag, thermal stress).
- Efficiency benchmarking under operational conditions.
- Cross-validation of multiple EP types (Hall-effect, Helicon).
- Refinement of analytical and numerical models for simulation tools and future use

The development of in-orbit test procedures and capabilities must enable comprehensive validation of the complete system outcome, progressing from integrated component testing in relevant environments on Earth to full system qualification (TRL5-6) and in-orbit demonstration under operational VLEO conditions (TRL7).

Key research gaps:

- Design of a (standardized) testing platform and protocols for monitoring and validating performance and evaluate degradation effects in VLEO-orbit.

- Develop real-time sensing and analytics to detect erosion, sputtering, and coating breakdown in subsystems.

- Understand how EP power needs can be dynamically balanced with satellite energy budgets in VLEO.

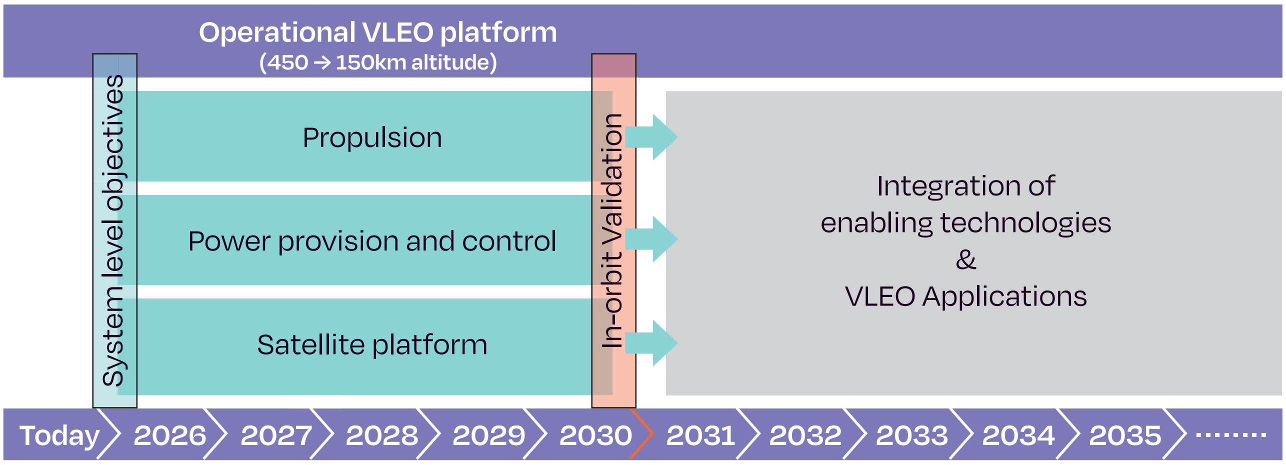
- Access to in VLEO-orbit measurements and test data to build predictive models for thruster lifetime and failure patterns under VLEO-specific conditions (including plasma interactions with residual atmosphere).

4.6. HORIZON OVERVIEW

To support deployment and industrialization on larger scale, in a 10-year timeframe two timeframe horizons for fundamental and applied R&D are proposed.

- **By 2030, environmental, specification and key-enabling technologies definition and validation for a VLEO platform,** resolve key-technological gaps for enabling a long-term operational VLEO (propulsion, power provision and control and platform). Integrate need for test, measure and in-orbit validation and verification of the most promising technologies.

- **By 2035, integration of enabling technologies and defence applications for the MoD,** expand and integrate technological capabilities and initiate R&D for payloads linked to identified applications for defence based on 2030 outcomes (i.e. optimized Earth observation sensors for high-resolution imaging, miniaturized AI-driven onboard processing for near-instant intelligence analysis).



Overview on the timeline of the VLEO track.

5
Annex

5.1. SOURCES

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5.2. ACRONYMS

Acronym	Full text
ADCS	Attitude determination and control system
AESA	Active electronically scanned array
AI	Artificial intelligence
AKE	Adaptive Kalman estimator
CCSDS	Consultative Committee for Space Data Systems
COTS	Commercial off-the-shelf
CRPA	Controlled reception pattern antenna
DIRS	Defence, Industry and Research Strategy
DOF	Degree of freedom
DTIB	Defence Technological and Industrial Base
EDF	European Defence Fund
EGS-CC	European Ground Systems – Common Core
EO	Electro-optical
ESA	European Space Agency
ESTRACK	European Space Tracking (ESA network)
EU	European Union
EU SST	European Union Space Surveillance and Tracking
FPGA	Field-programmable gate array
FWC	Full Well Capacity
GALO	Global coverage All weather LEO Observation
GEO	Geostationary orbit
GNSS	Global Navigation Satellite System
GSD	Ground Sample Distance
IMU	inertial measurement unit
InP	indium phosphide
IR	Infrared
ISO	International Organization for Standardization
ISR	Intelligence, surveillance and reconnaissance
LEO	low Earth orbit
LIDAR	Light Detection and Ranging
LNO	lithium niobate
ML	Machine Learning
NATO	North Atlantic Treaty Organization
NIR	Near infrared
OGC	Open Geospatial Consortium

Acronym	Full text
PAT	Pointing, acquisition and tracking
PCDU	Power Control and Distribution Unit
PIC	Photonic integrated circuit
RF	Radio frequency
RHID	Royal Higher Institute for Defence
RHIS	Royal Higher Institute for Security
RTD	Research and technological development
SAR	Synthetic aperture radar
Si	Silicon
SiC	Silicon Carbide
SIM	Synthetic Imaging Method
SSA	Space situational awareness
SSD	Solid-state drive
SWaP	Size, Weight and Power
SWIR	Short-wave infrared
SWOT	Strengths, weaknesses, opportunities, threats
TDI	Time delay integration
TRL	Technology readiness level (e.g. TRL 5-6 Technology readiness level 5 to 6).
US	United States
VHF	Very high frequency
VLEO	Very low Earth orbit

5.3. STAKEHOLDERS INVOLVED IN THE ROADMAPPING PROCESS AND ECOSYSTEM

Contributors

We would like to sincerely thank all stakeholders for their valuable contributions, insights, and active engagement in shaping this technology roadmap, ensuring it reflects both national defence priorities and the strengths of Belgium's industrial and research ecosystem.

Ecosystem

The Belgian DTIB for space-based defence applications reaches beyond the direct contributors to this roadmap, encompassing a wider network of innovative companies, research centers, and public actors that collectively strengthen national and European resilience.

1. Companies:

Company (official site)	Space link
Absolem (https://www.absolem.be)	Enabler – mechatronics & robotics for satellite factories
ACB (https://acb.be)	Upstream – high-reliability PCB boards for satellites
Advionics (https://advionics.be)	Upstream – avionics & telemetry
Aerospacelab (https://www.aerospacelab.com)	Upstream – small-sat bus & EO constellations
Aldoria Belgium (https://www.aldoria.com)	Downstream – space-situational-awareness data
AMOS (https://www.amos.be)	Upstream – precision opto-mechanics & telescopes
Antwerp Space (https://www.antwerpspace.be)	Upstream – on-board & ground TT&C
APO-GEE (https://www.apo-gee.tech)	Enabler – Bearings for propulsion systems, altitude control and high-precision sensors
Any-Shape (https://www.any-shape.com)	Enabler – 3-D printed metal parts, ESA flight heritage
Arcsec (https://www.arcsec.space)	Upstream – star-tracker software
Bracquené (https://www.bracquene.be)	Enabler – Legal IP consulting
Cactus-now (https://cactus-now.com) Cactussoft (https://cactussoft.biz)	Downstream – AI/ML software used in EO apps, custom software incl. satellite data pipelines
Celestia Antwerp (https://www.celestia-antwerp.be)	Upstream – high-speed ground modems
Compolam (https://www.compolam.com)	Upstream – lightning-strike-protected composites
ConstellR (https://www.constellr.com)	Downstream – Thermal IR imagery for enhanced decision making
DELTATEC (https://www.deltatec.be)	Upstream – on-board electronics & video for ISS
DH Consultancy (https://dhconsultancy.com)	Enabler – radiation & space-environment modelling
EDGX (https://www.edgx.space)	Upstream – AI compute for in-orbit servicing
EHP (Euro Heat Pipes) (https://www.ehp.be)	Upstream – thermal hardware
ES Tooling (https://estooling.eu)	Enabler – fine-mechanical parts incl. aerospace

Company (official site)	Space link
Euro-Multitel (https://www.euromultitel.be)	Upstream – Securised Radio &Data Communication Cybersecurity & Quantum Key Distribution; AI/Multimodal Machine Learning (Data Fusion, Situation Awareness), Trusted AI For Critical Systems, Edge AI; Optical sensors and communications.
Eurosealings (https://www.eurosealings.be)	Upstream – high-performance metal seals
Finocas / Finindus (https://finocas.be)	Enabler – strategic VC backing materials for launchers
GDTech (https://www.gdtech.eu)	Enabler – FEM & CFD for launchers
GIM (https://www.gim.be)	Downstream – geo-data integration
Ingeniqs (https://ingeniqs.be)	Enabler – instrument prototyping
Lambda-X (https://lambda-x.com)	Upstream – optical payloads
M3 Systems (https://m3systems.eu)	Downstream – GNSS test & simulation
Materialise (https://www.materialise.com)	Enabler – 3-D printed flight parts
Melotte (https://www.melotte.be)	Enabler – precision + metal AM
NEXAT (https://www.nexat.be)	Downstream – Belgian OSS/BSS & service-platform operator for satcom networks; long-term ESA partner
OCAS (https://www.ocas.be)	Enabler – alloys for launcher tanks
OIP Sensor Systems (https://www.oip.be)	Upstream – space cameras
Open Engineering (https://www.open-engineering.com)	Enabler – multiphysics CAE for payloads
Redu Space Services (https://www.reduspaceservices.com)	Downstream – ESA ground-ops
Redwire Space (https://redwirespace.com)	Upstream – satellites & ISS equipment
SABCA (https://www.sabca.be)	Upstream – launcher structures
Safran (https://www.safran.com)	Upstream – propulsion & optics
Saint-Gobain (https://www.saint-gobain.com)	Upstream – mirrors/ceramics for telescopes
Septentrio (https://www.septentrio.com)	Downstream – high-accuracy GNSS
Siemens (https://www.siemens.com)	Enabler – digital twin & PLM for space
Skyline Communications (https://skyline.be)	Downstream – DataMiner sat-NMS
Sonaca (https://www.sonaca.com)	Upstream – aero- and launcher structures
Soudobeam (https://www.soudobeam.be)	Enabler - Assembly of metal structures by electron beam welding.
Space Applications Services (https://www.spaceapplications.com)	Upstream & Downstream – robotics & lunar rovers
SPACEBEL (https://www.spacebel.com)	Upstream & Downstream – flight SW & EO systems

Company (official site)	Space link
SPACE SSA (https://www.spacessa.be)	Downstream – space-domain-awareness platform
Starion Group (https://www.stariongroup.eu)	Enabler – system engineering for ESA
ST-Engineering-IDirect (https://www.idirect.net)	Downstream – satcom VSAT platforms
Strain2Data (https://www.strain2data.eu)	Enabler – structural strain sensors for launchers
Telespazio Belgium (https://www.telespazio.com/en/belgium)	Downstream – sat-ops & ground seg
Thales Group (https://www.thalesgroup.com)	Upstream & Downstream – payloads, secure satcom
Thales Alenia Space (https://www.thalesaleniaspace.com)	Upstream – prime satellite manufacturer
Toreon (https://www.toreon.com)	Enabler – space-ground cyber-risk
Tusk IC (https://tusk-ic.com)	Upstream – mmWave ASICs for sat-links
Umicore (https://www.umicore.com)	Upstream – battery & thruster materials
Veoware Space (https://veowarespace.com)	Upstream – reaction wheels
Verhaert (https://verhaert.com)	Enabler – space-tech incubator & product dev
Xenics (https://www.exosens.com/brands/xenics)	Upstream – SWIR & LWIR imagers

2. Universities and Research or Technology Organisations

Universities and Research or Technology Organisations	Space link
BIRA-IASB / Royal Belgian Institute for Space Aeronomy (https://www.aeronomie.be)	Up/Downstream – PI of the PICASSO CubeSat and provider of atmospheric data & models for ESA
Cenaero (https://www.cenaero.be)	Enabler – HPC simulation for aero & space
Centre Spatial de Liège (CSL) (https://www.csl.uliege.be)	Upstream – designs/calibrates optical payloads & operates one of ESA's main environmental test centres
CRM Group (https://www.crmgroup.be)	Enabler – developed ESA-funded phase-change-material thermal units for Ariane 6 launcher electronics
imec (https://www.imec-int.com)	Upstream – "DARE" radiation-hardened-by-design ASIC platform for spacecraft electronics
ISSEP (www.issep.be)	Downstream – EO data services
KU Leuven (https://www.kuleuven.be)	Upstream – leads ESA's CubeSpec 6U small-sat mission and hosts multiple space-instrumentation labs.

Universities and Research or Technology Organisations	Space link
Multitel (https://www.multitel.be)	Enabler – Securised Radio &Data Communication Cybersecurity & Quantum Key Distribution AI/Multimodal Machine Learning (Data Fusion, Situation Awareness), Trusted AI For Critical Systems, Edge AI Optical sensors and communications.
Royal Observatory of Belgium (ROB) (https://www.astro.oma.be)	Upstream – Solar-physics division supplies real-time ESA space-weather forecasts & sunspot indices
SCK CEN (https://www.sckcen.be)	Enabler – radiation testing for spacecraft
Sirris (https://www.sirris.be)	Enabler – Belgian industry-led tech-innovation centre; ESA Space Solutions ambassador & advanced prototyping labs.
UAntwerpen (University of Antwerp) (https://www.uantwerpen.be)	Downstream – IDLab develops ultra-low-power GNSS / PNT tech for satellite-IoT & ESA projects.
UCLouvain (https://www.uclouvain.be/fr/louvain4space)	Enabler – Upstream – Downstream - (Louvain4Space), Energy Particle Telescope, antennas, EO (data processing), radiation tolerance, space telecommunications, cybersecurity and AI
ULB (Université Libre de Bruxelles) (https://www.ulb.be)	Enabler – CREST hub drives space-science & engineering R &D across life-support, materials, thermal control, etc.
ULiège (https://www.uliege.be)	Enabler – (S3L) Hybrid vibration damping Upstream – runs student CubeSats (OUFTI series) and interferometric nano-sat concepts with CSL support
UMons (www.umons.ac.be)	Downstream – (SECO) Space-situational-awareness data
UNamur (www.unamur.be)	Downstream – (Naxys) Space-situational-awareness data
VITO (https://www.vito.be)	Downstream – operates the PROBA-V Terrascope ground segment and Copernicus EO data services
von Kármán Institute (VKI) (https://www.vki.ac.be)	Upstream – built QARMAN CubeSat to test atmospheric re-entry and leads launcher aerothermodynamics R &D
Vrije Universiteit Brussel (VUB) (https://www.vub.be)	Upstream – researchers designed a free-form CubeSat imaging spectrometer for climate monitoring.

3. Government, clusters and industry representation

Government, clusters and industry representation	Space link
Agoria (https://www.agoria.be)	Cluster – Belgian technology federation; hosts Belgospace, the forum that unites most Belgian space-industry companies.
BELSPO – Belgian Science Policy Office (https://www.belspo.be)	Policy – coordinates Belgium's federal space policy and manages the national financial & programmatic contribution to ESA
JRI4Space (www.space4relaunch.be/jri4space)	Cluster – non-profit association grouping Walloon space companies, research centres and universities to foster collaboration and global outreach
Skywin (https://www.skywin.be)	Wallonia's competitiveness cluster in the aerospace and aviation sector
VRI – Vlaamse Ruimtevaartindustrie (https://vri.vlaanderen)	Cluster – non-profit association grouping Flemish space companies, research centres and universities to foster collaboration and global outreach.

Composition Ad Hoc Technical Committee Space Defence Applications

The technical committee, composed of experts from industry, research institutions, and defence, plays a key advisory role in the technology roadmapping process roadmaps, ensuring alignment with DIRS objectives, and defining subdomain scopes and priorities.

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This

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