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NEW FRONTIERS OF SPACE INNOVATION

Shaping the future of Space: Observation, Communication, Navigation, Exploration

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LEONARDO

contents

editorial

Space: humanity's new frontier

For centuries, Space has been capturing the shared dreamscape as a distant horizon, a promise of discovery, a symbol of progress. Today, Space is no longer the exclusive domain of science fiction. It has quietly become integral part of our day-lives, despite we are often not aware of that. From the navigation signals that guide our smartphones and cars, to the space-based imagery that monitors the health of our planet, to secure connections that protect our data and infrastructure, Space has become a vital layer of modern society. This transformation is proceeding at unprecedented pace and drives the growth of the global **Space Economy**. It is already worth hundreds of billions of euros annually, and it is scheduled to exceed **one trillion by 2030**. At the core of this revolution lies a powerful combination of forefront technologies: advanced robotics, cybersecurity, artificial intelligence, cloud computing, and new generations of satellites forming large constellations around Earth. This is not a distant vision, as it is a transformation that is reshaping entire industrial sectors and opens new opportunities for nations and companies willing to invest and innovate.

Space in our everyday lives

To grasp how deeply Space is woven into our daily life, consider a few simple actions of ours. Every time we check the weather forecast, call for a taxi through our favourite app, or navigate on a digital map, we rely on satellites orbiting hundreds or thousands of kilometers above us. Their signals deliver precise positioning and synchronization that enable services we take for granted.

Satellites also play a critical role in **global security and environmental sustainability**. They protect sensitive data, detect cyber threats, and monitor key infrastructure such as power grids and communication networks. They allow us to track deforestation, glacier melt, ocean conditions, and so on. In case of emergencies, satellite data provides rapid situational awareness and supports rescue operations. As digitalization accelerates, the value of this "view from above" grows exponentially. Data collected in orbit has become strategic knowledge for governments, businesses, and citizens alike. The ability to process, secure, and harness this information among the defining challenges of the 21st century.

A new Space race: public meets private

Unlike the space race of the last century — dominated by competition between superpowers — the new era features a large number of Countries with space capabilities, sees Europe now playing a leading role and private investors gaining increasing importance. Alongside NASA, ESA, and national agencies, private digital giants and startups are now shaping the future of Space.

In the years ahead, we will see **exponential growth in satellite constellations** consisting of hundreds or thousands of interconnected satellites delivering global broadband, resilient navigation, and unprecedented observation capabilities. At the same time, the **In-Orbit Servicing** - the ability to repair, refuel, or upgrade satellites directly in orbit - will reduce costs and help mitigate space debris. Private companies are also preparing to **commercialize orbit**. Projects for private space stations aim to host research, tourism, and industrial activities. Meanwhile, missions to the Moon are moving beyond exploration to serve as proving grounds for the technologies that will support the future Mars colonization.

Italy at the forefront of the Space Economy

In this global landscape, Italy plays a **leading role**, as it is one of the very few Countries worldwide able to cover the entire value chain of a Space mission. Thanks to its strong scientific and industrial ecosystem, our Country is recognized as a leader in several sectors of the Space Economy. Companies such as **Leonardo, Telespazio, and Thales Alenia Space Italia** are leading projects ranging from satellite services and secure telecommunications to robotic systems and habitation modules for deep-space exploration. This blend of tradition and innovation relies on deep roots: in 1964, Italy became the **third nation in the world** to launch a satellite in the frame of the San Marco project. Since then, it has contributed to landmark missions such as Rosetta, the first mission to land on a comet. Today, Leonardo and its group companies represent more than **75% of the Italian national space sector**, covering technologies such as high-tech sensors, atomic clocks, solar panels, drills, and robotic arms. Many of these innovations find also applications beyond Space, in fields such as energy, healthcare, and sustainable agriculture.
At the same time, a significant network of small and medium-size enterprises, along with a growing number of new companies and startups, provides the crucial foundation of skills and technologies that is mandatory for building up a complete value chain.

The Moon: a laboratory for the future

One of the most exciting prospects of the coming decades is the creation of the first **inhabited lunar bases**. These won't be simple scientific outposts, as they will be living laboratories where to learn how thriving in extreme environments. Astronauts and scientists will search for resources and test technologies designed to support future missions to Mars.
The challenge is how turning a hostile environment into a **self-sufficient settlement**. That means building controlled microclimates, producing food, recycling resources, and ensuring reliable communications. Benefits will extend far beyond the Moon. Technologies developed for lunar survival will have applications here on Earth: from sustainable agriculture to advanced recycling systems and new energy models.

Low Orbit: a new economic hub

While the Moon inspires our imagination, most economic activity will focus closer to home - **within Earth's orbit**. This is where we will see:

- **In-Orbit Servicing** for satellite maintenance, refuelling, and repositioning.
- **Private space stations** enabling research, tourism, and industrial production in microgravity.
- **Next-generation optical communication network**s providing secure, ultra-fast, and resilient links.

Managing this orbital ecosystem will demand extraordinary computing power. **Supercomputing, cloud infrastructure, artificial intelligence, and quantum computing** will be key assets in processing the massive data flows from satellites and constellations, while ensuring robust cybersecurity.

Space as a lens for understanding Earth

Beyond economics and geopolitics, Space is our best vantage point for **understanding the Earth**. Satellites monitor climate change, optimize resource use, and enhance fields like agriculture, defence, and remote sensing. The future will bring increasingly intelligent, autonomous satellites. Equipped with **onboard A**I and **distributed computing**, they will process data in real time, respond to unexpected events, and push the boundaries of exploration.

Polaris: a window on Space innovation

This issue of *Polaris Innovation Journal* offers a comprehensive look at a rapidly evolving sector. Articles cover topics ranging from compact hyperspectral payloads for Earth observation and in-orbit servicing systems to space lasers based on coherent beam combination. We delve into the industrial revolution transforming satellite production through the **Space Smart Factory**, and explore how optical networks are enabling secure, resilient, high-speed communications. We also examine the role of Low Earth Orbit constellations in positioning, navigation, and timing, and the use of sensor fusion techniques for safe lunar landings. Methodological insights include a trade-space analysis and concurrent design framework, along with an integrated feasibility study model for Earth observation. Together, these contributions reflect a sector in which miniaturization, digitalization, and collaboration are shaping the future.

To the Moon and beyond

Space is already reshaping our societies, economies, and cultures. From Earth's orbit to the lunar surface, from satellites overhead to supercomputers on the ground, the journey is well underway. Italy, Europe, and the world face an inspiring challenge: to turn Space into a frontier of progress, sustainability, and shared opportunities.

Enjoy this issue of the Polaris Innovation Journal. Let it guide you on a journey from Earth to the Moon, and far beyond.

Massimo Claudio Comparini
Managing Director Space Division

Compact Hyperspectral Payload for the PLATiNO-4 Mission: enabling High-Performance Earth Observation from Small Satellites

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Hyperspectral imaging enables a breakthrough in Earth Observation by capturing detailed spectral information across hundreds of narrow bands. The Compact Hyperspectral Payload (HYP P/L) developed by Leonardo for the PLATiNO-4 mission, within an Italian Space Agency (ASI) contract, offers high performance with reduced size, weight, and power (SWaP), making it suitable for equipping small satellites. This paper presents architecture, functionalities, imaging capabilities, and achieved performances of the instrument. With mass lower than 100 kg and GSD of 20–30 m, the HYP P/L covers the 400–2500 nm spectral range and supports both STRIPMAP and SPOTLIGHT imaging modes. Applications include agriculture, water quality, geology, urban planning, and disaster monitoring. The paper discusses the structural and thermal design of the payload, the in-flight calibration strategy, and the mission relevance, also highlighting how miniaturization supports high temporal resolution through constellation deployment.

INTRODUCTION

Hyperspectral imaging (HSI) has revolutionized Earth Observation (EO) by providing dense spectral decomposition of the surface-reflected radiation, across hundreds of narrow bands. Unlike multispectral instruments, which capture data over a limited number of broader bands, HSI allows precise identification of materials and phenomena through their spectral signatures. This capability enables diverse applications in environmental monitoring, resource management, and disaster response.

The technological evolution from traditional bulky hyperspectral payloads to compact architectures has opened new opportunities for deploying high-performance instruments onboard small platforms. The Italian Space Agency (ASI), through the PLATiNO program, fosters such transition by funding the development of innovative payloads. Leonardo, basing on its heritage from the PRISMA mission and contributions to the upcoming CHIME and PRISMA-SG missions, is leading the development of the HYP P/L instrument for PLATiNO-4 [1].

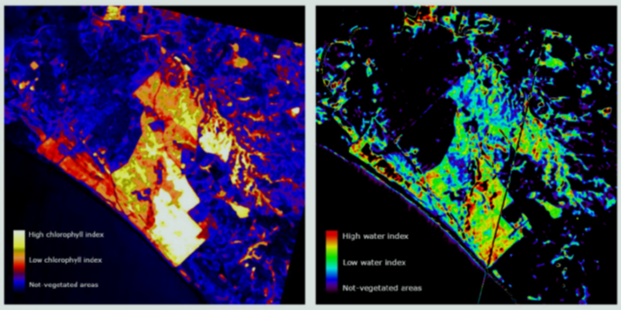
HYP P/L is a state-of-the-art imaging spectrometer designed to operate in low Earth orbit, delivering high spectral and spatial resolution, with minimized mass and power budgets. This paper details the design choices, performance achievements, and application relevance of the payload.

HYPERSPECTRAL EARTH OBSERVATION: CONTEXT AND APPLICATIONS

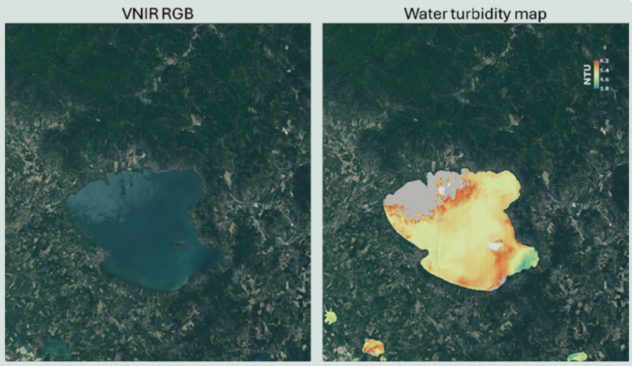
Hyperspectral imaging (HSI) enables the retrieval of rich and continuous spectral information from the Earth's surface, allowing for precise material identification and classification. This level of spectral detail supports a variety of Earth Observation (EO) applications across sectors and ecosystems [2]-[4].

Application Domains and Use Cases

Agriculture and Food Security: HSI provides biophysical and biochemical variable mapping, such as chlorophyll content, nitrogen uptake, and irrigation levels. It supports crop type classification [5], precision farming, and early stress detection (Figure 1).
Inland and Coastal Water Monitoring: by assessing absorption and scattering features, HSI enables the detection of chlorophyll, turbidity [6], bottom substrate characterization, and shallow water bathymetry. Applications also include the monitoring of wetlands and floating vegetation (Figure 2).
Soil and Geology: Hyperspectral imagery is effective in mapping soil texture (clay, sand, silt), organic carbon content, and carbonate presence. It also supports mineral exploration and degradation assessment.
Urban Environment and Infrastructure: HSI can distinguish construction materials, detect asbestos roofing, and support land use mapping. It enhances classification accuracy in complex urban scenes [9] (Figure 3).
Natural and Man-made Hazards: through spectral pattern recognition, HSI supports the identification of fire scars [8], active volcanic regions, and pollution events, including gas plumes [10] and industrial emissions (Figure 4).
Cultural Heritage and Archaeology: subtle spectral differences can help locate buried structures, map archaeological features, and monitor degradation of historic sites.
Forests and Biodiversity: spectral indices and red-edge features enable ecosystem mapping, species discrimination, and monitoring of vegetation stress.

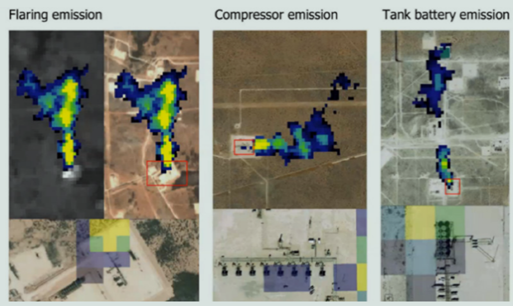


1-Crop health and irrigation mapping from hyperspectral data (courtesy of UniMIB)



2-Water quality monitoring over Trasimeno Lake (courtesy of CNR-IREA and ASI) [7]

3-Urban material classification in Tuscany (courtesy of Regione Toscana)



4-Detection of methane super-emitters from hyperspectral satellite data (courtesy of IIAMA)

Spectral Considerations

HSI sensors like HYP P/L span the VNIR and SWIR domains (400–2500 nm), covering key absorption features linked to pigments, water content, organic matter, and minerals. High spectral resolution (<10 nm) allows precise atmospheric correction, material unmixing, and advanced analytical techniques such as machine learning-based classification and target detection.
These capabilities, when combined with high spatial resolution (20–30 m GSD) and short revisit times enabled by small satellite constellations, provide a powerful tool for dynamic, multi-domain EO applications.

HERITAGE AND MISSION FRAMEWORK

Leonardo's journey in hyperspectral Earth Observation (EO) payloads dates back to longer than two decades, as it begun with planetary exploration instruments such as VIRTIS (Rosetta, Venus Express, Dawn), VIHI (BepiColombo), and JIRAM (Juno). That legacy transitioned into EO applications with significant achievements including the development of GOME-2 for METOP and, more recently, the hyperspectral instrument for the PRISMA mission.
Launched in 2019 under the coordination of the Italian Space Agency (ASI), PRISMA [11][12] was the first Italian spaceborne hyperspectral imaging mission. It demonstrated the ability to capture high-resolution spectral data (VNIR and SWIR) across 240 bands with GSD of 30 m and PAN of 5 m. The success of PRISMA laid the foundation for second-generation developments such as PRISMA-SG and contributions to the Copernicus CHIME mission.

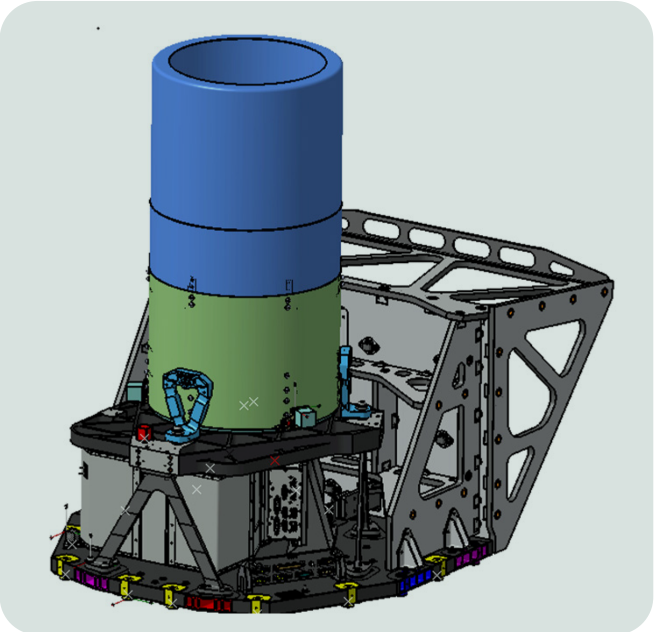
Within this series, the HYP P/L for PLATiNO-4 represents a key step toward payload miniaturization. It integrates lessons learned from PRISMA and PRISMA-SG while targeting the demanding constraints of small satellites. The instrument is part of the ASI-funded PLATiNO program, which promotes flexible, responsive missions based on a modular, agile platform. HYP P/L is also designed for interoperability with IRIDE, Italy's national Earth Observation constellation.
With its mass lower than 100 kg and highly integrated subsystems, HYP P/L offers performance comparable to large-platform hyperspectral instruments. Its development aligns with the broader trend towards constellation-based EO services, offering more frequent revisits and global coverage.

PAYLOAD ARCHITECTURE

The Compact Hyperspectral Payload (HYP P/L) consists of a tightly integrated assembly of optical and electronic subsystems, engineered to deliver high-resolution spectral imaging while maintaining strict constraints on mass, power, and volume.

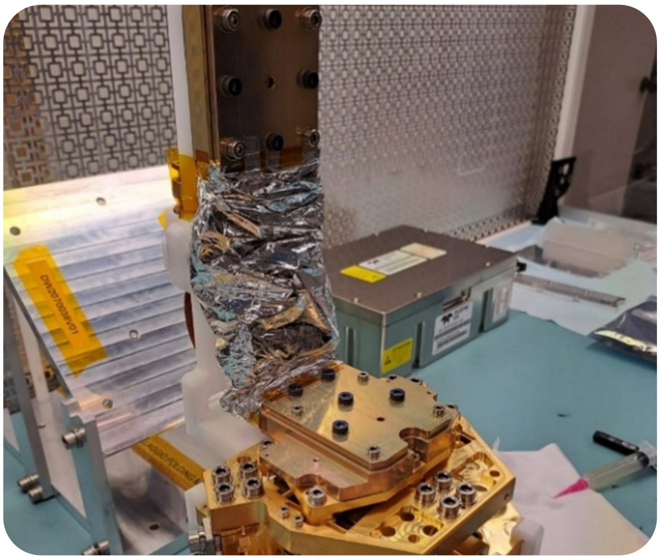
Instrument Optical Module (IOM)

The IOM (Figure 5) includes the Optical Head comprising the Telescope and Spectrometer Assemblies. The telescope uses a catadioptric design to collect and focus radiation onto the spectrometer slit. The spectrometer disperses the light in different wavelengths via a reflective diffraction grating and focalize them on a single detector that is located in the focal plane. The optical bench is mounted via titanium bipods to a CFRP baseplate for isostatic support, decoupling mechanical stresses and thermal expansion.
The optical bench and its protective cover create a closed light-tight cavity ensuring optical cleanliness and temperature stability. The cavity also houses the electro-optical units, including the Focal Plane Assembly (FPA), which is thermally controlled via heaters and radiators. The FPA (Figure 6) uses a custom detector that is sensitive across 400–2500 nm, with a cold shield and thermal strap connecting to an external radiator assembly.



5-HYP P/L Instrument Optical Module (IOM)

The thermal design guarantees optical alignment and detector performance. An active control system uses discrete heaters and thermistors to stabilize the spectrometer and the FPA. The radiator panel, supported by CFRP structures, dissipates heat via heat pipes, to maintain temperatures of the detector near 185 K.



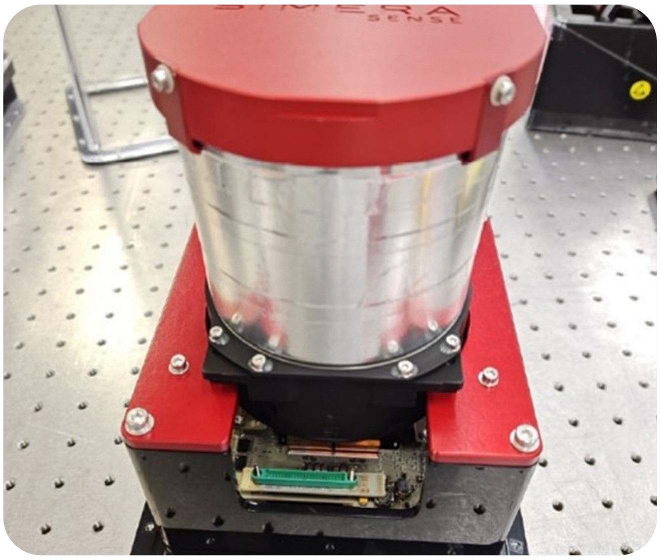
6-Focal Plane Assembly (FPA)

Video Acquisition Unit (VAU))

The VAU is responsible for detector readout, pixel correction, spectral binning, and real-time data handling. It integrates a radiation-hardened FPGA that interfaces with the detector through high-speed serial lines and performs CCSDS packetization before transferring data to the Payload Instrument Control Unit (P-ICU). The unit supports programmable calibration parameters, pixel gain/offset correction, and timestamping.

Panchromatic Camera (PAN)

Complementing the spectrometer, the MultiScape100 CIS PAN camera (Figure 7) offers 5 m resolution imaging across the full swath. Based on a monochrome CMOS sensor and digital TDI, it enables enhanced scene interpretation and spatial sharpening of hyperspectral data.



7-Panchromatic Camera (PAN)

OBSERVATION MODES AND IMAGING CAPABILITIES

The HYP P/L instrument is capable of operating in two observation modes that optimize imaging performance depending on the mission requirements:

- **STRIPMAP Mode**: in this configuration the instrument points the nadir and acquires continuous scenes along the ground track. The Ground Sampling Distance (GSD) is 30 meters, thus offering excellent balance between spatial resolution and swath width. This mode is ideal for wide-area monitoring and allows for acquisitions of up to 2800 km per orbit. The payload can conduct up to three acquisitions per orbit in this mode, considering the attitude constraints.
- **SPOTLIGHT Mode**: the satellite performs a pitch manoeuver to increase the dwell time over a target, enhancing the signal-to-noise ratio (SNR) and improving the spatial resolution to 20 meters GSD. This mode is optimal for targeted observations where finer detail is required, such as in rapid-response monitoring of disasters or high-value environmental assessments. However, the roll angle must be constrained within ±30° to avoid excessive geometric distortion and thermal penalties.

Both modes rely on the satellite's agility and onboard memory management, with data transmission prioritized during downlink windows. Up to three targeted scenes can be acquired per orbit in SPOTLIGHT mode, with the possibility of replacing an acquisition slot with a data downlink segment. Special care is taken to manage thermal loads on the cryogenic radiator, avoiding prolonged sun exposure during pitch manoeuvers near the Equator.

Operational Considerations:

- For multi-temporal analyses (e.g., vegetation monitoring), the STRIPMAP mode ensures consistent viewing geometry, due to its narrow roll range (±10°), which is critical for radiometric comparison across time;
- For urgent acquisition needs, such as natural hazards, the SPOTLIGHT mode offers responsiveness with improved image fidelity;
- Radiometric accuracy and SNR are preserved through onboard thermal controls and optimized spectral sampling.

The combination of these two imaging modes provides users with flexibility and responsiveness, fulfilling diverse Earth Observation requirements from wide coverage to precision targeting.

PERFORMANCE HIGHLIGHTS

The HYP P/L instrument delivers high level of performance across spatial, spectral, radiometric, and operational parameters, while maintaining compact and efficient design.

Key Performance Parameters

Orbit	Sun-synchronous @ 515 km
GSD (SPOTLIGHT)	20 m
GSD (STRIPMAP)	30 m
PAN GSD	5 m
Swath	20 km
Spectral Range	400–2500 nm (VNIR/SWIR)
Spectral Resolution	<10 nm
Radiometric Accuracy	<5%
Data Rate	1.1 Gbps
Power Consumption	110 W

Table 1 - HYP P/L Key Performance Parameters

Signal-to-Noise Ratio (SNR)

The SNR has been carefully optimized in both STRIPMAP and SPOTLIGHT modes. In STRIPMAP, the performance is aligned with CHIME and PRISMA benchmarks, while SPOTLIGHT mode leverages increased dwell time and reduced ground velocity to enhance the SNR significantly, particularly in the VNIR. The achieved SNR for reference radiance levels range from 400 in the visible up to 100 at longer wavelength in the SWIR.

Modulation Transfer Function (MTF)

The MTF exceeds 0.25 at Nyquist in STRIPMAP mode and remains above 0.2 in SPOTLIGHT mode, ensuring good spatial fidelity. PAN MTF performance exceeds 0.10, enabling effective sharpening and geolocation.

Spectral and Radiometric Performance

Spectral response functions are optimized to ensure co-registration across the VNIR and SWIR ranges. Spectral resolution remains stable and below 10nm across the full spectral range. Radiometric accuracy below 5% is achieved through precise optical and thermal design.
Overall, HYP P/L sets a benchmark in combining compactness with superior optical payload performance for small satellite missions.

IN-FLIGHT CALIBRATION STRATEGY

To ensure accuracy and consistency of the hyperspectral data throughout the mission, a rigorous Calibration and Validation (CAL/VAL) strategy [13] has been defined for the HYP P/L instrument. The approach is fully based on vicarious methods, which avoids the need for onboard calibration hardware and thereby reduces complexity and mass.

Calibration Approach

The calibration campaign includes multiple techniques:

- Dark Signal Calibration: acquired over deep Ocean during eclipse periods to measure and correct detector dark current;
- Flat-Field Calibration: Moon acquisitions are used to assess pixel-to-pixel relative responsivity across the detector array;
- Radiometric Calibration: absolute calibration is performed using radiometric reference sites, such as RadCalNet locations and pseudo-invariant calibration sites (PICS) like Railroad Valley (USA) and Dome-C (Antarctica);
- Spectral Calibration: based on atmospheric absorption features (e.g., oxygen, water vapor), the spectral calibration ensures the correct alignment of spectral bands to physical wavelengths.

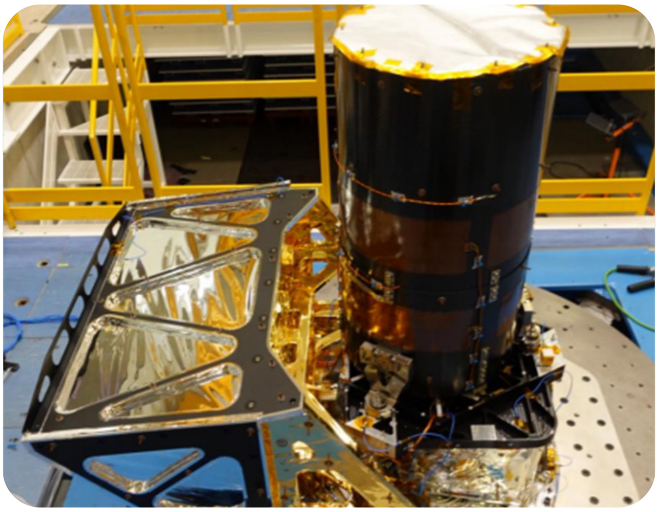
The ground processing chain includes calibration parameter updates, trending analyses, and radiometric validation. The use of standardized targets and harmonized procedures ensures interoperability with PRISMA, CHIME, and other hyperspectral missions.

Performance Monitoring Routine acquisitions of reference targets are scheduled to track temporal drift, while inter-comparison with concurrent satellite data provides additional assurance. The combination of lunar and terrestrial targets offers a robust reference base for both spectral and radiometric assessments.

This calibration strategy ensures that the HYP P/L maintains its high-accuracy performance across its full spectral range over the full lifetime of the mission.

DEVELOPMENT STATUS

HYP P/L passed the Critical Design Review. Structural and thermal models, and the spectrometer proof-of-concept have been validated. Proto-flight models are undergoing environmental testing (Figure 8), with full delivery expected in 2025.



8-Instrument Optical Module under qualification vibration testing

DISCUSSION and CONCLUSIONS

The successful miniaturization of a high-performance hyperspectral instrument opens new mission concepts in which revisit time, spatial coverage, and cost are optimized through satellite constellations. HYP P/L's compact design does not compromise data quality, enabling mission planners to achieve scientific and commercial objectives with reduced infrastructure. The Compact Hyperspectral Payload developed by Leonardo for PLATiNO-4 achieves state-of-the-art spectral and spatial performance in a form factor suitable for small satellites. Its successful deployment paves the way for responsive, high-frequency hyperspectral EO missions, serving a wide array of end-user needs across agriculture, environment, geology, and hazard monitoring.

AKNOWLEDGEMENTS

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Developing Critical Technologies for In-Orbit Servicing

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Space Experts agree upon the fact that In-Orbit Servicing (IOS) robotics will introduce a fundamental change in the Space exploration and exploitation. Capabilities like in-orbit assembly, repairing, and refuelling will enable life extension, performance upgrade and reliability improvement of future or even already flying Space assets, with the aim of possibly increasing the benefit-cost ratio and make possible the construction of large structures, such as telescopes, stations, scientific outposts. Moreover, the possibility of de-orbiting of decommissioned satellites, or re-orbiting/relocation of active satellites will improve the sustainability of the Space, given the high amount of "space junk" now present in low earth orbit. For all these reasons, the Italian Space Agency (ASI) recently awarded a contract for an In-Orbit Servicing demo mission to an Italian consortium led by Thales Alenia Space Italy, including Leonardo, Telespazio, Avio, D-Orbit, and other Space companies. Two key subsystems of the IOS mission are the capture and refuelling subsystems.

INTRODUCTION

In-Orbit Servicing (IOS) activities, like active debris removal, refuelling, maintenance, assembly, inspection, can make a real difference in use of the Space. Indeed, they introduce new capabilities such as extending the life of flying Space assets, constructing very large structure in orbit, re-using/reconfiguring already flying systems, with the fundamental aim of reaching a more sustainable exploitation of the Space and savings in term of cost.

In addition, as the number of satellites and the complexity of space missions increase, the need for standardized mechanical interfaces results as a crucial aspect for facilitate interoperability, reduce costs and enhance mission flexibility.

For all these reasons, in the last decades, agencies, companies, and academia have been investing considerable efforts in developing IOS technologies, with the earliest conceptual studies performed already in the early 1980s [1]. The first demonstration mission was carried out in 1997 by JAXA with the Experimental Test Satellite VII (ETS-VII) that verified autonomous rendezvous and docking, teleoperation and servicing tasks [2]. Afterwards, in 2007, the Defence Advanced Research Project Agency (DARPA) launched the Orbital Express mission with the aim of testing autonomous servicing tasks (docking, refuelling, ORU replacement) [3]. Other two demo missions that tested IOS technologies were the China's Aolong-1 in 2016 and ELSA-d by Astroscale in 2021 [4]. Northrop Grumman launched in 2019 the Mission Extension Vehicle 1 (MEV-1), which was the first mission to extend the life of an already flying satellite in GEO: Intelsat 901. The MEV-1 reached the target satellite and performed the servicing tasks in 2020. Afterwards, another extension vehicle, the MEV-2, was launched by the same company in 2020 and successfully docked to the target satellite Intelsat 10-02 [5].

Currently, a number of IOS missions are planned to be launched in the next years, among which: ESA-funded Clearspace-1 [6], Robotic Servicing of Geosynchronous Satellites by DARPA [7], Mission Robotic Vehicle by Northrop Grumman [5].

Along with them, an Italian consortium led by Thales Alenia Space Italy, including Leonardo, Avio, D-Orbit

and other companies, has been recently awarded a contract by the Italian Space Agency (ASI) for an In-Orbit Servicing demo mission. This initiative is funded by the In-Orbit Economy line of investments of the National Recovery and Resilience Plan (PNRR) presented by the Italian Government in the frame of the Next Generation EU programme [8]. The IOS demo mission will be performed with two main Space assets: the servicer is the satellite capable of carrying the technologies to perform IOS services, while the target is in charge to support the in-orbit validation of the technologies and functions enabling different IOS tasks. These latter are: de-orbiting of a decommissioned satellite, re-orbiting/relocation and take-over of an active satellite (including repetition capability of the mating and detachment), refuelling of an active satellite, repairing/refurbishment on-orbit of a satellite. This article presents the main requirements and challenges in designing the robotic system (a subsystem of the capture system), and the refuelling system mechanical interface (a subsystem of the refuelling system), which are in charge of Leonardo.
The article is organized as follows: in section “DEMO MISSION OVERVIEW” an overview of the Italian IOS demo mission is given; in sections “ROBOTIC SYSTEM” and “REFUELING MECHANICAL INTERFACE” the robotic system and the refuelling mechanical interface are presented, including their requirements and main challenges; in section “ROBOT CONTROL UNIT”, the electronics architecture is presented. Finally, in section “CONCLUSIONS”, the content of the article is summarized and future developments are discussed.

DEMO MISSION OVERVIEW

The functions the Italian IOS demo mission system has to demonstrate can be subdivided in two subsets: near-future and mid-term-future functions. The former ones are deemed necessary in the near future, in order to enable capturing and providing services to non-collaborative satellites (i.e., unprepared for servicing) which can be non-cooperative or cooperative satellites, (i.e., showing a tumbling motion or not). These functions are:

- Orbit transfer of the servicer to reach the orbit of the target;
- Target tracking and inspection in both cooperative and non-cooperative scenarios;
- Safe rendezvous and approach with the target in both cooperative and non-cooperative scenarios;
- Target capture and rigidization of the servicer-target stack in both cooperative and non-cooperative scenarios;
- In orbit services:
    - Attitude and Orbit Control System (AOCS) takeover: attitude and orbit control of the target satellite
    - Relocation of the target to another orbit
    - Disposal of the target at the end of life.

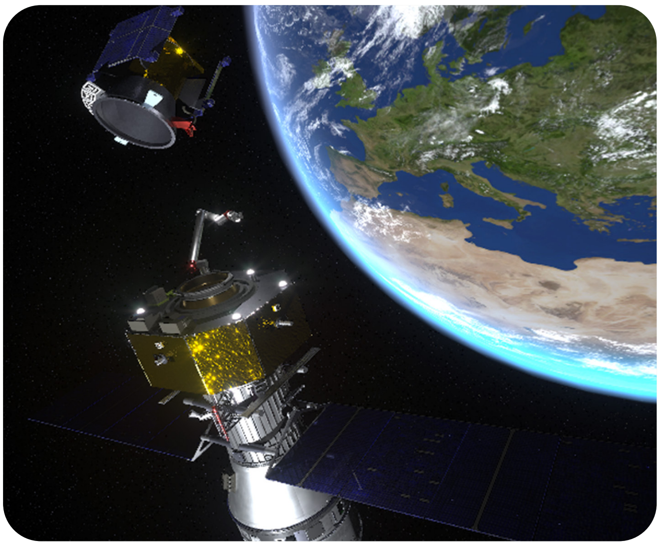
Note that capturing a non-collaborative satellite requires the exploitation of features that are common to different customer spacecraft. For this reason, the Launch Adapter Ring (LAR) is selected as grasping feature in the mission, since it is present in most of potential client spacecraft. This is a reasonable choice already proposed and investigated in literature. In particular, the IOS demo mission system is required to be compatible with the common European LAR size.
The second subset of functions requires the target satellite to be collaborative, i.e., prepared for receiving services.

It is indeed reasonable to imagine the use of a standard or dedicated interface on future satellites in order to enable and facilitate the IOS activities. Therefore, in the demo mission, the target satellite shall be equipped with specific interfaces, in order to validate the following capabilities:

- Refuelling of the target satellite tank(s);
- Refurbishment of the target satellite, i.e., Orbit Replaceable Units (ORUs) transfer.

To demonstrate such functions, the Italian IOS demo mission includes two Space assets, to be launched together on a Low Earth Orbit (LEO):

- the Servicer: a vehicle carrying the IOS technologies to be validated;
- the Target: a satellite to support the in-orbit validation of the IOS operations and technologies.



1-In Orbit Servicing demo mission (credit Thales Alenia Space)

The target will be launched with the servicer and, will belong to the small satellite class. However, the system design solution is required to be scalable and guarantee its applicability to targets of higher class of satellites, e.g. Cosmo Skymed and Sentinel satellites.
To accomplish those functions, the IOS system shall comprise a capture and refuelling subsystems. The former one is made up of a robotic system and a vision system, while the latter one is composed of a fluidic system and a mechanical interface. A suitable design of these subsystems is essential to accomplish the required IOS activities. In the following, the main requirements and design challenges of the robotic system and refuelling mechanical interface, which are under the responsibility of Leonardo, will be discussed.

ROBOTIC SYSTEM

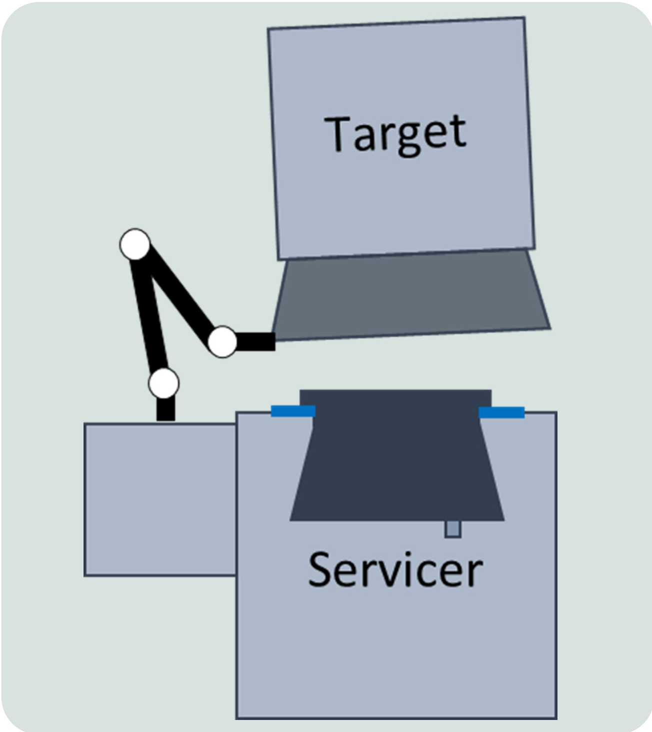
The robotic system is required to fulfil the following main functions:

- Perform a soft capture of the target by using the LAR as the grasping feature;
- Dissipate the residual velocity between the target and the servicer (due to error in their synchronization);
- Drag the target towards the servicer;
- Compensate the residual misalignment between the servicer and the target;
- Perform the hard berthing to establish a rigid connection between the satellites by using the LAR of the target;
- Perform the manipulation and transfer of an Orbital Replaceable Unit (ORU).

To accomplish those functions, the robotic system includes different active mechanisms:

- Robotic arm;
- End effector (mounted on the arm);
- Berthing mechanism (mounted on the servicer).

In addition, the entire system shall be able to operate in the thermal and radiation environment of the LEO.
In the following paragraph, the main features of the robotic subsystems are discussed.



2-Schematic representation of Target spacecraft grasped by Robotic arm

Robotic arm

The robotic arm is a central element of the mission, since it is in charge of the most critical tasks of the capturing manoeuver, along with the ORU manipulation. In particular, the arm shall fulfil the following functions:

- Place the end effector within a workspace compatible with the GNC (Guide Navigation and Control) limits and grasping performance of the end effector itself;
- Dissipate possible residual motion between the target and the servicer (due to non-ideal servicer-target motion synchronization);
- Drag the captured target towards the hard berthing mechanism on the Servicer;
- Perform ORU manipulation.

To achieve these capabilities, the robotic arm is required to provide:

- good positional accuracy for the capture phase and the ORU manipulation;
- compliant behaviour during contact situations in order to limit the interaction forces;
- high dexterity;
- good velocity performance to accurately track the moving grasping point.

An important trade-off to be made is the testability of the main operations of the robotic arm on Earth in 1-g environment. Testability in the full workspace can be very challenging, taking into account the size of the arm,

defined by the servicer performance which requires to catch the target at a certain distance; in addition, a certain stiffness is also needed for structural and control performance. Indeed, on-ground testability in the whole workspace would lead to remarkably oversizing the actuators, because of the joint torques generated by the arm own weight, which can be significantly higher than those needed for on orbit operations. Such oversizing could generate considerable impacts on mass and volume. Off-loading systems can be designed, but they are usually quite complex, could introduce limitations in the testing and could introduce additional disturbance that should not be present during the real application. On the other hand, limitation of the testable workspace on ground can be a good compromise. This solution avoids excessive oversizing but requires careful design of the ground arm operations, in order to avoid exceeding the allowable workspace limits, and suitable analyses with accurate models.
The need of relatively high joint torques for 1-g testability and high velocity for grasping point tracking can lead the design of the joints towards a single-stage solution, rather than to a two-stage one that is typical to planetary robotics, driven by a brushless motor. In this regard, the DEXARM [9], a robotic arm developed by Leonardo, is one of the past projects the Leonardo heritage for IOS demo missions is rooted in.
Moreover, each joint is equipped with an electronic board driving the motor, acquiring the sensors and performing low level control. In the DEXARM, local electronics has been selected, rather than central electronics. This choice requires less harness along the arm and enables more accurate measurement of the torque. On the other hand, it results in a hollow-shaft design of the joint and, for a Space application, in a more complex thermal design.

End Effector

The end effector is mounted at the tip of the robotic arm and its main function is the grasping of the target LAR. Since the actual section shape of the LAR is not exactly the same for all the satellites of interest, the End Effector design shall accommodate those differences, to ensure sufficient contact points and, consequently, a stable grasp. This is considered a challenging requirement.
Other important features of the end effector are the maximum opening width of the fingers and the grasping capability. Indeed, its design is required to be compatible with the overall positioning errors coming from the robotic arm, vision system, and GNC performance. Moreover, it is important that the closure motion of the end effector is sufficiently fast to avoid the target escapes from the grasping workspace, especially in a non-cooperative scenario.
Finally, the end effector shall withstand the loads arising during the operations. Three different situations can be identified: the capture phase, the dragging towards the servicer, and the interaction with the other mechanisms (hard berthing, and, especially, the ORU). In the first case, the forces should be limited thanks to the free-floating dynamics of the target and the compliant behaviour of the arm. However, it is a quite critical situation in which fault cases may result in uncontrolled collisions that shall be handled properly and require a robust design of the end effector. In the second situation, the sizing scenario is the non-cooperative one, in which servicer and target have a tumbling motion generating centrifugal forces that would separate the two satellites. Finally, during the interaction with the other mechanisms, and especially with the ORU, the end effector shall withstand the loads due to peg-in-hole and engagement operations. All these load requirements result in a certain robustness of the end effector and in a sufficient preload provided by its actuator/s. A trade-off is necessary between competing needs of relatively high velocity and preload, in order to avoid too heavy mechanism, which would affect both the arm performance and the overall system mass (always critical in Space applications).

Hard Berthing system

The hard berthing mechanism is on board the servicer and is in charge of rigidizing the servicer-target stack and of withstanding the loads arising from de-tumbling, de-orbiting, and orbit transfer manoeuvers.
As well as the End Effector, the requirement of compatibility with unprepared satellites naturally leads to the use of the target LAR as the mechanical interface. Similarly, the system is required to work with different class of spacecraft, and thus its grasping system shall be able to adapt to LARs which may be different not only in diameter, but also in shape of the cross section.
In order to guarantee the correct mating between the servicer and the target, the residual positioning error between the LAR and its interface, due to inaccuracy of the arm, of the end effector (non-ideal grasp), and of the vision system, is an important aspect the design of the hard berthing mechanism has to take into account.

If not properly considered, this may result in impossibility of grasping the satellite or in wrong distribution of the loads, which would lead to failure of the mission. Therefore, it is essential to foresee a system that compensates these relative positioning errors.
Finally, the actuator/s and the structure of the hard berthing shall be sized according to the loads arising from the tumbling motion of the two satellites (in the non-cooperative scenario), the de-tumbling operation, the de-orbiting manoeuvre, the repetition of the berthing, and the orbit transfer manoeuvre for target relocation.

REFUELING MECHANICAL INTERFACE

The refuelling mechanical interface is part of the refuelling system whose purpose is to demonstrate the feasibility of transferring a fluid between two spacecraft mated together. Along with the mechanical interface, the system includes the fluidic subsystem that is not treated in this article, as it is the responsibility of D-Orbit. The refuelling mechanical interface includes two parts, one mounted on the servicer and the other one mounted on the target. The refuelling process will start only after the confirmation of the correct mating, provided by a dedicated sensor suite, with the servicer-target stack rigidized. The mechanical interface shall fulfil the following main functions:

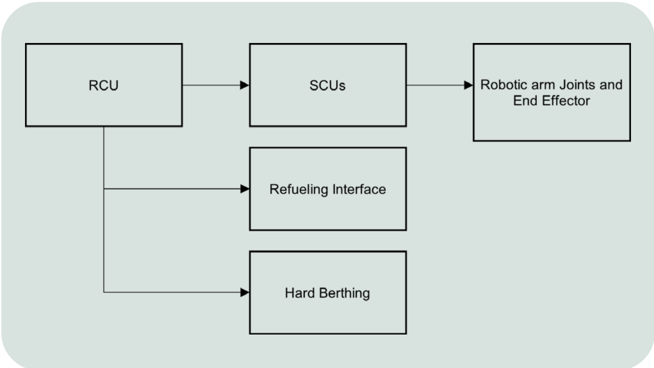
- Maintain a sealed fluidic connection between the servicer and the target, ensuring a fluidic transfer between them;
- Provide the sensors that allow to establish when the interface is ready to perform the fluidic transfer.

In order to guarantee a reliable connection while minimizing any leakage, it is important to compensate possible misalignments between the two parts and provide an efficient sealing system. This latter component, along with the structure, shall be designed compatible with the operative pressure range of the fluid and the maximum allowable flow rate. Another important aspect to take into account in designing the sealing system is the resistance to multiple mating/de-mating cycles, which can deteriorate the system and jeopardize the performance.
Finally, the mechanical interface shall guarantee that no phase transition occurs during the fluid passage, and thus a thermal control is required.

ROBOT CONTROL UNIT

The design of a control unit for such a complex robotic system presents architectural challenges, since it involves several actuators and sensors with multiple electrical and EMC characteristics. Typically, robotic mechanisms include analogue sensors and brushless motors, which require a considerable number of wires. For control units of robotic systems, two approaches are commonly adopted [10]:

- the Centralized electronic unit approach, where a single unit located inside the satellite or rover runs the high level SW and the Servo-Control of the mechanisms;
- the Distributed electronics approach, where a central unit performs the high level tasks, while the Servo-Control of the mechanisms is performed by localized units, orchestrated by the central unit via a serial link.



3-Electronics unit architecture

In a Space mission, the centralized approach features the advantage that all the electronics is located in a thermally regulated environment inside the satellite, where it is also shielded against Total Ionizing Dose (TID).

On the other hand, a more complex harness is required, because all the sensors and actuators are connected to the central unit, while in the distributed approach the harness connecting the central unit to the localized units is often much simpler (i.e. power and serial link).
In the case of the IOS Italian demo mission, the subsystem to control are:

- the Robotic arm;
- the Hard Berthing mechanism;
- the Refuelling mechanical interface.

The electronics system under development has a modular approach that includes a central unit, called Robot Control Unit (RCU), and several Servo Control Units (SCU), which are in charge of the low-level control of the Robotic arm joints and End Effector. The Hard Berthing mechanism and the Refuelling mechanical interface are controlled directly by one of the boards of the RCU (called Actuator Module), which has a similar internal architecture of the SCU.
This approach allows to limit harness on the robotic arm and to reduce the possible electro-magnetic noise on the measurements from the sensors, which could be picked up by the wires, for the case of low-voltage signals (e.g. strain gauges).

CONCLUSIONS

In this article, an overview of the Italian In-Orbit Servicing demo mission has been presented. In particular, the requirements, high level input, and main challenges for the design of the robotic system and the refuelling mechanical interface has been dealt with. The design of these key subsystems has been identified as critical for the success of the demo mission.

ACKNOWLEDGEMENTS

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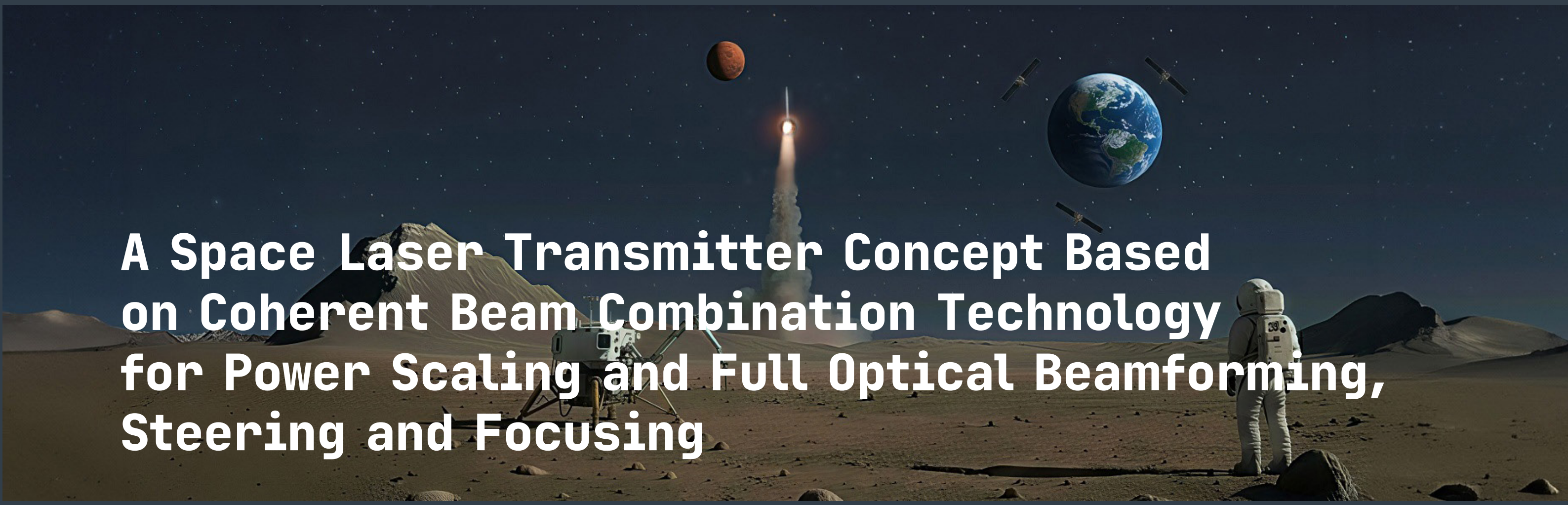


A Space Laser Transmitter Concept Based on Coherent Beam Combination Technology for Power Scaling and Full Optical Beamforming, Steering and Focusing

Fabrizio Giuseppe Bisesto, Alessandro Perna

Leonardo - Space Division

The Coherent Beam Combination (CBC) technology allows to scale up the optical power of a laser source, overcoming any limitations due to non-linearity, which appears when the intensity becomes too high. Moreover, a CBC system in tiled-aperture configuration acts as an optical antenna, provided that a proper algorithm is available that locks the optical phases in the correct way. Here, we propose a solution consisting of sampling the wavefront of the overall pupil by means of the 0th order phase of the single beams, enabling the possibility to perform beamforming, in detail the steering and focusing features, together with the laser power scalability. This kind of technology can lead to more compact LiDAR generation, without additional opto-mechanical devices for angular scanning and focusing, thus contributing to reduce the SWaP of the whole system.

INTRODUCTION

The power/energy scaling of single-fibre laser systems has faced several fundamental limitations. The main ones are related to NLE (Non Linear Effect), such as SBS (stimulated Brillouin scattering), SRS (stimulated Raman scattering and TMI (transverse mode instability) [1]–[3]. Hence, the beam combining of multiple lasers has always been the first measure to increase the power of laser systems beyond the achievable output power from a single laser.

The Laser beam combining provides an impactful platform for the realization of a single high-power beam from multiple low-power lasers. A combination of individual lasers can be achieved both coherently and incoherently.

In 2011, the first kW-level Coherent Beam Combination (CBC) of fibre lasers was demonstrated by Ma et al., using the single-frequency dithering technique [4]. In the same year, a 4 kW output power fibre laser was achieved through the CBC of eight laser amplifiers, with combining efficiency of 78% [5]. In 2020, a 16 kW single mode fibre laser with the dynamic beam for advanced material processing was reported. Recently, a 7.1 kW CBC of seven narrow-linewidth, linear-polarized all-fibre amplifiers has been achieved by Ma et al. [6].

In that work, they implemented the Stochastic Parallel Gradient Descent (SPGD) algorithm for the phase-locking system, and by applying the 95% filling factor, they achieved 86% of PIB in the far-field intensity pattern.

One of the main advantages in using CBC in tiled aperture configuration, i.e. in a symmetric array of collimated beams, relies in the possibility to control the wavefront of the combined laser beam, which enables some features, such as beam steering and focusing, usually demanded to an optomechanical device. The use of such technology for Space applications would definitely allow to reduce the SWaP of a laser transmitter, providing a motionless steering and focusing system.

COHERENT BEAM COMBINATION BASIC CONCEPTS

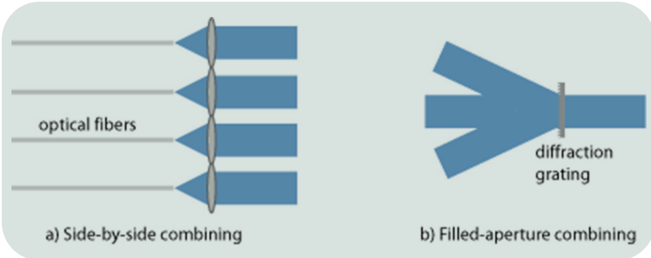
The CBC technology relies on the spatial overlapping of multiple laser sources, while keeping as low as possible the phase noise, i.e. the phase differences between all the sources are zero.

This condition establishes a constructive interference, leading to peak intensity that scales as the square of the source number, i.e. N2, together with linearly summing all the single beams' power.
Two different approaches can be identified, based on the chosen geometry (Figure 1):

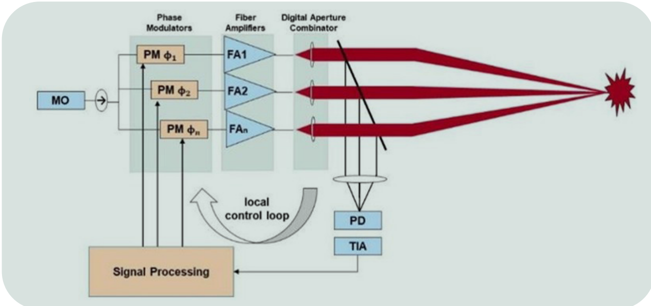
a. the tiled aperture configuration, where the beams define a 2D array (typically hexagonal) of collimated, side-by-side lasers, resulting in the far field in a beam with some surrounding lobes, whose intensity depends upon the filling factor of the array;
b. the filled aperture configuration, where the beams are stacked and spatially overlapped in the near field, allows for a pure gaussian combined beam in the far field.

Comparing the two approaches, the first one offers much higher scalability, with reduced volume and size, and the possibility to spatially sample and control the wavefront of the combined laser beam. Therefore, it would enable to perform beam steering and focusing. Moreover, the possibility to correct the effects due to the atmospheric propagation would also be feasible, as well as the high precision pointing (sub-microradians) by means of proper phase modulators.
Figure 2 shows a typical example of a CBC system architecture. A Master Oscillator (MO) is multiplexed in N linearly polarized channels, passing through each own phase modulator (PM) and then feeding a Fibre Amplifier (FA).

All the amp outputs are collected by a device called beam combiner. In the tiled aperture configuration, it produces an array of collimated beams. In the filled aperture configuration, it produces a single beam. In both cases, a control loop is needed to generate the correction signals for the PM and achieve constructive interference, keeping the phase differences close to 0.



1-CBC configurations: a) tiled aperture, b) filled aperture

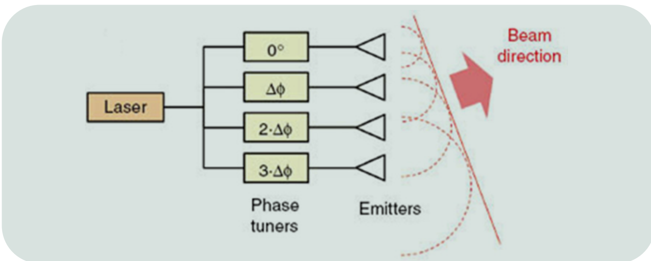


2-Typical CBC system architecture

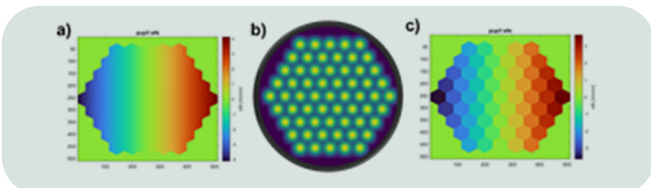
WAVEFRONT MANIPULATION WITH CBC

Here, for sake of simplicity, only the beam steering functionality is analysed, but the same principle applies to the beam focusing.
In Figure 3, a 1D array of laser source is reported. Assuming that the initial phase differences are 0, here the phase modulators are configured to provide a tilted wavefront of an angle equal to ΔΦ. The condition to be fulfilled is that the phase difference between each consecutive sources must be an offset equal to ΔΦ.
In Figure 4, the same concept described above is extended to a 2D hexagonal array composed by 61 sources. The needed wavefront to steer a continuous beam (i.e. not an array made by discrete sources) of angle Φ along the horizontal axis results in a tilted wavefront as shown in Figure 4a. Considering the array geometry (Figure 4b), the resulting reconstructed wavefront, using the optical phase of the single sources, is shown in Figure 4c. The performance of the beam steering performed in such a way, strictly depends upon the goodness of the wavefront fitting, made by the piston term of the single sources optical phases, in the hypothesis the system only employs phase shifters.

On the other hand, using also the first order term of the phase would improve the beam quality at the end. However, the array could be designed in order to tailor the steering performance in a certain angular range.



3-Beam steering with optical phases

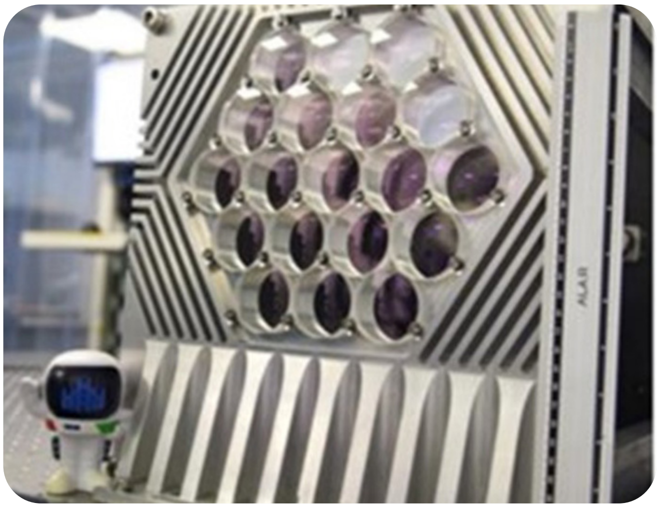


4-Wavefront sampling with tiled aperture CBC

LEONARDO ACHIEVEMENTS IN CBC

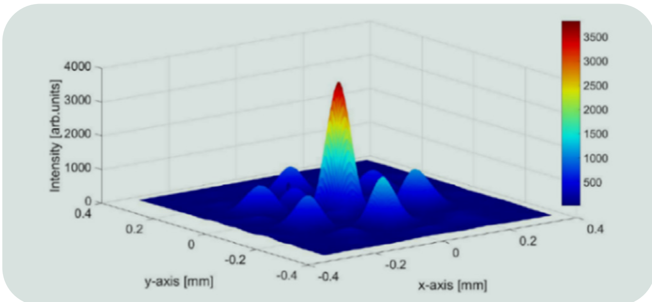
Leonardo has been working in CBC technology for 5 years, achieving remarkable results in system design and optical phase locking algorithms.
Figure 5 shows the beam combiner developed at the Leonardo site in Pomezia, currently hosting 7 CW high power fibre laser sources. The device has been designed aiming to a trade-off between maximizing the PIB, while avoiding any high-power damage to the optics and the structure. However, this device is quite heavy and features volume around 80l, but we are currently investigating new technologies and fibre components to definitely shrink it.
Due to the high optical power, requiring high level of cleanness and safety, our CBC system is installed in a proper ISO-6 clean area in the Leonardo HELIOS laser facility sited in Pomezia, as shown in Figure 6.
The use of the laser in this area is allowed only to qualified personnel and only with low optical power for alignment. When switching to high power, the system control and monitoring is made from a dedicated facility room. The resulting combined beam is shown in Figure 7 [7].

The residual phase noise is lower than $\lambda/27$, leading to 40% PIB, achieved by a proprietary locking system with 1ms convergence time.



5–Leonardo beam combiner for high power laser sources

6-Clean area in the Leonardo laser facility in Pomezia



7-Combined beam of the Leonardo CBC system

CONCLUSIONS

In this paper we have presented a brief overview of CBC technology and its feature to control the wavefront of the resulting beam in the tiled aperture configuration, able to perform motionless optical beam steering and focusing. An example of reconstruction of a tilted wavefront for beam steering has also been presented.
An overview of the results achieved by Leonardo in the field of CBC with high-power laser sources is shown. Our know-how in this field is still growing and we are acquiring new competencies in fibre processing also.

This will help to develop very compact systems, able to be used also for application in Space, where the employment of a motionless scanning device would lead to reduction in SWaP and to higher level of performance. The next studies will also concern the combination of pulsed laser sources, typically playing the role of transmitter in Doppler LIDAR instruments.

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Space Smart Factory and Space Joint Lab: Thales Alenia Space Innovation in Satellites Manufacturing

Giovanni Campolo, Valeria Turrini, Giovanni Morabito, Gianluca Graglia, Laura Tosoratto

Thales Alenia Space Italia

In recent years, the Space sector has been experiencing a real industrial revolution. New digital technologies, combined with the large availability of capital that the web big players have forcefully injected into the sector, are modifying products and production processes. This paper describes how Thales Alenia Space Italia (TASI) is facing such challenge, also by realizing a new industrial plant, whose new concept was presented a few years ago at the Leonardo Innovation Award. Such new concept aims to put the innovation at the core of the production cycle by means of the introduction of Digital Technologies, a Joint Lab for a continuous innovation and a new business model, the so-called Factory-as-a-Service. At the realization of the Space Smart Factory (SSF) and its associated Space Joint lab has contributed the “Piano Nazionale di Ripresa e Resilienza” (PNRR) investment throughout the “Space Factory 4.0“ project carried out by the Italian Space Agency (ASI) [1]. This paper had been written shortly before the opening of the new plant it describes, which was officially commissioned with the attendance of the President of the Italian Republic, Hon. Sergio Mattarella on October 7th, 2025 just a few days before this new issue of the Polaris Journal was published.

INTRODUCTION

The new digital technologies and the large availability of funds that big internet players have forcefully injected into the Space sector are modifying products and production processes. The ambition, no longer hidden, is to change the way Space has been thought of, up to now. We are moving from the concept of a Space that offers services defined by few commercial players-if not institutional-to that one of a Space creating commercial services itself that are made available to many types of users. In this perspective, Space is destined to change the future,as well as cyberspace transformed the world at the beginning of the third millennium, the capability to innovate is unquestionably the founding element of this revolution. Today we are already inside the “Space 4.0”, where new Space applications and the potential services provided are starting to reveal previously unknown opportunities. These latter are significantly impacting the economy and our everyday life (just think of satellite navigation), also stimulating global growth. This is mainly due to the increasingly widespread use of digital technologies that is being made, which enable and generate new applications and therefore services. On the other hand, digital technologies overturn, in a positive sense, the current production systems, as they enable higher level of product quality, at lower costs and in shorter times. All of this happens in a sector of excellence that for decades has followed its somewhat rigid dynamics which have been mostly influenced by the spending capacity of the Institutions.

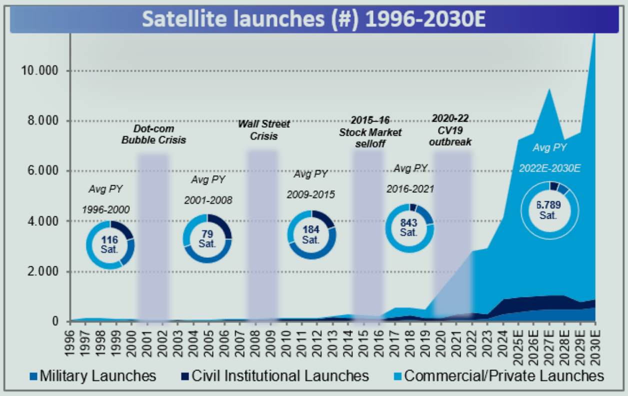
SATELLITE MARKET IN NEW SPACE ECONOMY

The Space market of New Space Economy will grow ~7% by 2030, with not yet explored opportunities, due to use of advanced digital analytics, new business models and satellite-services. Such a growth is driven by constellations, in particular by Low Earth Orbit (LEO) constellations.

Unlike traditional satellite models with large, high end satellites, constellations deploy numerous smaller units with shorter life spans, benefiting from economies of scale in production and from reduced launch costs. The advance in satellite and ground technologies are especially remarkable in broadband connectivity via High Throughput Satellites (HTS) and Non-Geo Satellite Orbit (NGSO) systems. These are reshaping the industry, as they enable satellite services to compete with terrestrial networks in providing high-speed, low-latency connectivity. Advancements like optical inter-satellite links and electric propulsion offer cost-effective, scalable solutions, but such a rapid growth also brings challenges, including increased competition and environmental concerns related to satellite debris, which push the adoption of more sustainable practices. By 2029, four key constellations - OneWeb, Starlink, Amazon Kuiper, and Telesat - are expected to account for over 70% of the market demand. The shift to constellations has resulted in a more vertically integrated commercial satellite sector, with operators that go increasingly building and operating their own systems.

As satellite systems become more specialized, EO, Satcom and emerging applications such as autonomous vehicle navigation and cislunar services are gaining momentum.

Beyond the projects mentioned before, several constellations and multi-satellite initiatives are rapidly emerging across various sectors, too. In Europe the ESA and the European Commission are pushing the realization of constellations to react to the redefinition of the LEO applications landscape which has taken place over the past five years, and has relegated the European integrators to the back row. European Resilience from Space (ERS), LEO PNT (+ 200 satellites) and IRIS2 with its 290 LEO and MEO satellites are the main programmes that are appearing on the horizon, to build an EU “system of system”. Let’s not forget also the small constellation of the Moonlight project with its 5 satellites in orbit around the Moon. Alongside these institutional pushes, there are also those ones coming from numerous private investors. In this sense, this trend is confirmed by the announced commitment of LEONARDO for the creation of a constellation of 38 satellites [2], 18 for defence and 20 for civil use.



1-Elaboration on Novaspace, Satellites to be built and launched, Dec. 2024

All these constellations feature very ambitious plans, as the first launch windows span between 2026 and 2028. These challenging schedules can be targeted only by an industrial chain able to provide high volumes and lower production cost and lead-time. Concerning volumes, the pace of 1 satellite per month can be achieved with current processes and methods. If we are aiming to produce in the order of 100s units or more per year, then we do need to change our paradigm in terms of industrial processes and product design.

With the Space Smart Factory initiative, TASI has changed the paradigm, by working on three different aspects:

- huge **investment** for the new Assembly, Integration, and Testing (AIT) plant whose processes are now fully digital, automated and virtualized as much as possible (e.g. use of robot/cobot);
- **new design** of the product platform “NIMBUS” that adapts it to the mass series production and new technologies (e.g robotic);
- the **continuous Innovation**, through a dedicated laboratory created inside the factory, but kept independent from it, to join researchers and innovators from both institutions and private: a research hub for promoting continuous innovation of the TASI products.

SSF - INNOVATION AND OPPORTUNITIES IN SPACE MANUFACTURING

The next paragraphs provide an overview and some details of how Thales Alenia Space has implemented its new strategic approach focused on Innovation. Finally, a look to the new business model targeted by the SSF is also provided.

Covid-19 and PNRR

Soon after the Covid-19 pandemic, at the beginning of the country's Recovery phase, TASI had to decide whether to ride the wave of innovation by investing, or to be overwhelmed by new transitions. Pushed also by the PNRR (Next Generation EU initiative), TASI has proudly designed and launched its Space Smart Factory, one of the largest digital and reconfigurable production facilities of its kind in Europe. The facility is part of a system of interconnected Space factories based in Italy [3], which use advanced technologies to build satellites of different sizes, suitable to various fields and applications. Over €100 million have been invested in the TASI Space Smart Factory, funds from the Italian Space Agency (ASI) included, through the PNRR project "Space Factory 4.0". This new cutting-edge facility is located at a technology hub, the Tecnopolo Tiburtino in Rome. The project for building the plant and realizing a complete industrial AIT centre kicked-off on 2023 and had been completed by Summer 2025. The plant was officially inaugurated on October 7th, 2025.

2-An image of the Space Smart Factory plant

The Space Smart Factory plant

Thales Alenia Space Smart Space factory is conceived as one of the largest Space manufacturing site in Europe. It covers an area of 21000 m^2 with 5000m^2 of clean room ISO 8 and 1900m^2 for offices and other collaborative activities.

By the beginning of 2026, the SSF production capacity will exceed 100 satellites per year: a capacity that fully satisfies the plan of ESA and EU next constellations, and is unique in Europe. The ambitious target is to reach the capacity of one satellite per day in a couple of year (2028), also by means of the full re-design of the NIMBUS platform that aims to become the favourite platform for the EU constellations. This capacity of the SSF has been already reached by pushing on different features, such as for example:

- the production flexibility that is achieved thanks to modular clean rooms and to the integration of automation and digitalization, which allow the SSF to be reconfigured basing on the demands of institutional and commercial market;
- the technologies utilized, which include numerical modelling and Digital Twin, VR/AR techniques, integrated simulators connected with the supply chain, and high levels of automation with robots and cobots throughout all phases of the activities carried out at the plant.

Reference [9] provides a video on theSpace Smart Factory.

Assembly Integration and Test

Most of the volume of the new building is dedicated to ISO8 clean rooms configured as a huge open space that can accommodate satellites of various sizes. The layout of this area respects all the LEAN manufacturing principles and is compliant with "classified" Space programs.
Five permanent test facilities are hosted in the SSF building and clean room area, to address environmental, mechanical and RF tests. More specifically:

- Thermal Chambers: the thermal cycling facility is designed to perform thermal cycling tests on Satellites and subsystems. It essentially consists of a parallelepiped-shaped chamber with front opening, an air treatment system that uses a refrigeration machine and a series of resistors, an inerting system using GN2, control and data acquisition system. The SSF hosts two thermal chambers, with different capacity.
- Thermal Vacuum Chamber (TVAC): the thermal vacuum chamber (Space Simulator) is a complex facility designed to perform thermal balance and thermal vacuum tests on satellites or subsystems, simulating the extreme temperature and pressure conditions they will encounter during their operational life in orbit. The TVAC model HVT240K-170130 GN2 will allow qualification and acceptance tests in vacuum, of satellites up to the 8-ton class.
- Vibration Test Facility (Shaker): this facility is designed to test and qualify Space systems against the vibration loads encountered during the launch phase. It enables comprehensive testing of components from

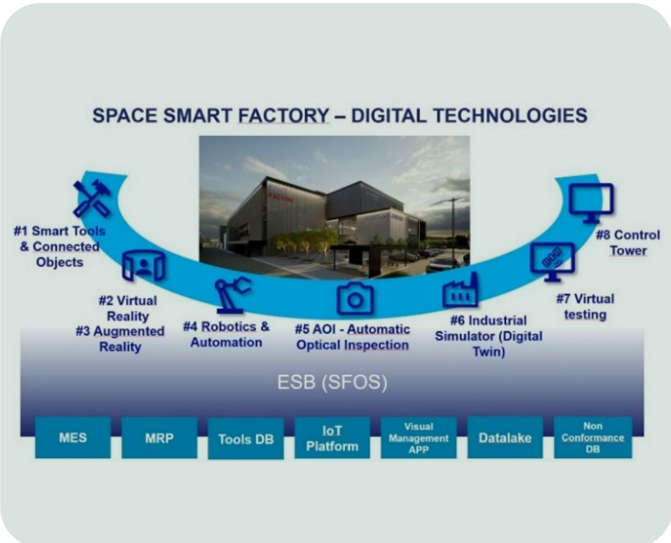
from individual Space subsystems to fully integrated satellites. The Shaker ensures the generation, control and precise measurement of vibrations. It is reconfigurable and allows the execution of two types of tests: in plane test (horizontal vibrations) and out of plane test (vertical vibrations), even relating to large loads, thanks to its sliding table.

- Anechoic Chamber: it is utilized for electromagnetic compatibility testing on a satellite and its subsystems. The area for its placement features usable height of 14 meters. It is designed to attenuate radio frequency electromagnetic waves within the chamber, while also shielding against any signals originating from outside.

The Clean Room areas can host other test facilities like the Direct Field Acoustic Noise (DFAN), which is set up in case of need during program execution in the reconfigurable areas.

3-The TVAC facility during its installation at the SSF

DIGITAL CONTINUITY AND INDUSTRY 4.0 IN SSF



4-High Level functional architecture for Digital Technologies at the SSF

The concept of Digital Continuity is delivered by implementing the connection of the shopfloor and enabling a data flow between engineering, production and AIT through enterprise applications and IoT. It is one of the key pillars needed to reach the production rates requested by the market, while maintaining control on the quality targets.
With the introduction of Internet of Things (IoT), Data Lake platform, Enterprise Service Bus, data go flowing from the Factory to company applications for monitoring, reporting and information extraction, also based on Artificial Intelligence.
The execution of activities by AIT operators is supported and facilitated by digital tools, such as the Manufacturing Execution System (MES) and the Manufacturing Resource Planning (MRP), integrated with Robotics and supported by virtualization and simulation technologies such as Virtual Reality, Augmented Reality, Virtual Testing and industrial process simulation.

Robotics and automation

Autonomous Mobile Robots are introduced in the clean room to automatize logistics of material, subsystems and even small satellites. The objective is to increase the efficiency by introducing robots to set AIT operators free from low value added tasks.
The robotic arm and integrated systems are used as well for spacecraft and subsystems alignment procedures and for automatic inspection. The robot accuracy allows to rapidly perform a scanning of the as-built, through a laser scanner highlighting defects and reducing the need for reworks.

Industrial Internet of Things

Industrial IoT allows the connection of shopfloor machines and devices to be able to control and monitor them. The capability of IoT to connect tools to the MES application enables the introduction of guided execution and automated activity tracking: *smart* tools can be programmed by the MES and results/measurements are automatically retrieved for reporting. Test facilities as well can be connected and monitored through dedicated dashboards that summarize the status of the test centre. All real time data is stored for further analysis and exploitation or for the introduction of advanced anomaly detection algorithms.

Augmented and Virtual Reality

Augmented Reality (AR) and Virtual Reality (VR) are well known in consumer videogame market, but at the same time in the last years they have had interesting applications in the aerospace domain, to support manufacturing with both augmentation and immersivity provided by digital and wearable devices.
At the SSF, the target use cases for AR are:

- to assist assembly and integration activities by showing information overlayed and positioned onto the real scene, to illustrate a procedure step or a full task and to guide the execution while connected to the MES:
- to assist quality inspection by showing CAD models in the device overlayed and positioned onto the scene, to show the as-designed and to allow comparison with the as-built, to identify defects.

VR is used both at engineering and at production level. The objective is to provide a virtual environment of the product based on CAD that enables:

- to explore them collaboratively in VR, enabling accessibility studies, de-risking, integration area simulation and design to AIT;
- to author integration procedures, comprising animations, textual instructions, images, documents and links to the 3D model features, in a format that is useful both for visualization in VR and for import into the MES;
- to provide an environment suitable for training sessions for AIT operators.

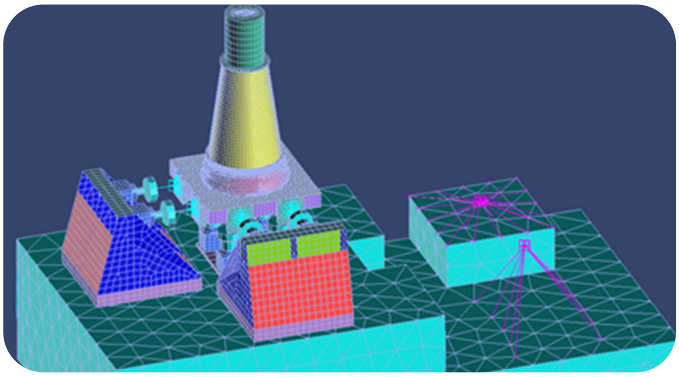
The Integration of these tools with the PLM, the MES and in general enterprise applications (Digital Backbone) is of great importance to obtain data continuity.

Industrial Simulator

The Industrial Simulator application provides the “what-if analysis” capability and the Discrete Event Simulation (DES) of the Industrial Processes. It allows creating a parametric model for AIT lines, able to provide elements to evaluate the impact of a change in schedule, resource availability and logistics. This model enables simulating the industrial response to customer demand, including supply chain, as well as it is able to tune or react to changes during execution.
At the SSF the industrial simulator is connected to the Digital Backbone to get input used to initialize and feed the model, for example by retrieving facility availability from IoT.

Virtual Testing

Virtual Testing aims to realize representative models of the test facilities to perform the foreseen spacecraft test processes, nominally executed by means of specific test facility e.g. the shaker for vibration test, in a virtual manner.
While real, non-virtual, testing is still a mandatory step in the AIT process, the objective of virtual testing is to assess feasibility of the real test, by predicting the behaviour of facility and satellite, in order to de-risk the real test, optimize the test configuration or in general to anticipate issues.



5-Representation of the FEM model for the Shaker facility + dummy model at the TASI plant in Rome Tiburtina suitable for Virtual Testing. A similar extended approach will be used to model the Shaker facility at the SSF.

The final goal is to build a "digital twin" of the system made of "equipment + Mechanical Ground Support Equipment (MGSE) + Test Facility".
Virtual testing is currently already performed in the TASI AIT [4][5] context as Vibration Virtual test targeting: assessment of the feasibility of the test and assessment of the test criticalities before test execution. The model update (refinement of the facility model) is done through past tests and test on dummy model.
Within the SSF, an update of the model for the new Shaker will be done, as well as the introduction of a Virtual DFAN simulation in collaboration with the academic domain [6].

Control Tower and data exploitation

The Control Tower is the central hub for data and the visualization of the Key Performance Indicator (KPI) which is useful to provide a global vision about activities ongoing inside the clean room and about the status of the plant. Real time data gathering is enabled by IoT and by connectors to enterprise applications, while data preparation and transformation is performed on the Data Lake platform, implementing also a proper Data Governance.

Enterprise Service Bus (ESB)

The ESB is the foundational building block to implement the data flow across the factory. To be able to connect different tools through a variety of communication protocols, the SSF digital architecture introduces this element that ensures data exchange between digital applications – IoT in primis – and the Digital Backbone i.e. enterprise applications ensuring decoupling and abstraction, scalability, easier management of connectors and control of data flows.

Sustainability

The Space Smart Factory 4.0 is also an industrial plant with very low environmental impact, since all the materials used for its construction are recyclable, all the technologies and systems are highly efficient, renewable energy sources are used and its environmental integration is high. The Factory is silver rated according to the Leadership in Energy and Environmental Design (LEED) certification [7].

THE SSF BUSINESS MODEL

Considering the dynamics of the Space market, it is possible to envisage that the demand for testing services will also grow up, and an adequate response will be needed. In Italy and even in Europe, there are currently very few outsourced AIT (Assembly, Integration, and Testing) services. Outsourced AIT services (Factory-as-a-Service, or FaaS logic) are whereas present in the US market, but they remain inaccessible to Italian and European actors, primarily for logistical reasons. It is therefore believed that the TASI Space Smart Factory can also address a potential demand for testing services from the national and European industry and from research entities to be offered in a FaaS logic.

The resulting benefits are:

- increase in available testing capacity for the entire supply chain in the face of a rapidly growing market;
- greater ROI (Return on Investment) of national infrastructure investments and containment of investments required for Italian SMEs to access the New Space market;
- better positioning of the entire national ecosystem towards institutional clients. The availability of testing services offered according to the FaaS logic can be a competitive advantage at international level;
- promotion of collaborative and open innovation practices in the national ecosystem.

SPACE JOINT LAB

The Space Joint Lab is an integral part of the Space Factory plant but at the same time it is kept completely autonomous. This is a completely dynamic collaborative environment designed to host a plurality of functions aimed at training new professional figures in the field of Space disciplines and for developing innovative ideas and products.

It is a collaborative ecosystem that aims to be a point of connection between Research and Development Institutions, Universities, Start-Ups, Suppliers, SMEs and other Industrial partners, even those outside the current Space supply chain. The laboratory, at the first floor of the SSF plant, covers an area of approximately 500m^2 which currently includes 5 thematic research areas.

Research Areas

- The AR/VR area includes various visors and tactile devices to increase interaction with virtual objects. Its goal is to provide researchers with tools for creation and use of digital environments, whose functionality supports business opportunities. This area can be used for training operators towards AIT procedures, thus facilitating the introduction of new resources into clean room daily activity.
- The area dedicated to the Digital Twin of the industrial process provides the tools necessary for the development of simulation models needed for the optimization of production and in particular of satellites.
- The area dedicated to write and train Artificial Intelligence (AI) algorithms is equipped with 6 stations for SW coding that are directly connected to a system for High Performance Computing which allows training complex Deep Learning and Large Language Model architectures. The area is completed by a Datalake for storage of the data processed in the laboratory.
- The Robotic area is designed to study automation for industrial processes and in particular for Space products. The area includes a robotic cell composed of two robotic arms and an AMR (Autonomous Mobile Robot) that can be used to simulate the supply of materials from the warehouse to the production area and the movement of satellites. The robotic area is equipped with an AMR, a KUKA KR20 and a KUKA KR120.
- The Advanced Materials area is dedicated to research on new materials and also includes the use of 3D printers.

Finally, an Auditorium is available inside the laboratory, as a common space suitable to promote, discuss and disseminate research activities, to host meetings and lessons for schools and universities. It is a common space conceived to share ideas, and to host talks, round tables and events that address basic research and industrial development topics.
The laboratory has already hosted some researches, and one of them in particular has involved the robotic cell. In fact, within the framework of a PNRR project called “Rome Technopole” [8], a semi-automatic assembly and inspection of a modular small satellite platform has been realized with the contribution of University Of Rome “La Sapienza” and EGICON S.r.l.. Using AI, the cell is guided by an Object and Pose Detection algorithm, to automatically recognize flight units and their positioning within the scene. Then, the system performs the automatic integration of subsystems and modules and the final quality check, by means of Anomaly Detection algorithms. Reference [10] provides a video of a demonstration of robotic satellite subsystem assembly conducted within the Joint Lab research.

CONCLUSIONS

The Space Smart Factory and the Space Joint Lab originate from the idea of putting Innovation at the core of the Production cycle, to realize an ecosystem based on the perfect synergy among people, digital technologies and data, where the satellite constellations of the next future will be born. Thanks also to the foresight of the Italian Space Agency, we are taking an important step in the evolution of the Space industry, combining technological innovation and sustainability in a highly automated and intelligent environment.

The launch of its operations by end of 2025 strengthens the strategic response of TASI and of the Italian Space sector to the challenges and opportunities of today’s Space market, creating a strong bond that links the supply chain, small and medium-sized enterprises and research centres.

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Satellite Optical Communication Networks: new Solutions and Technologies for High Performance, Secure and Resilient Systems

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Thales Alenia Space Italia

Satellite communication constellations are increasingly attracting the interest of commercial, institutional and military stakeholders needing high-speed, low-latency and globally available cyber-secure connectivity. Optical communications for secure and resilient, high-speed links between satellites and with ground stations, along with network solutions based on dynamic data routing capabilities onboard the satellite, are key elements that enable the evolution of new satellite communication constellations. This paper focuses on system solutions and technologies for satellite optical communication networks, shows their role in addressing emerging user needs, analyzes the state-of-the-art and the evolution of constellations and technology and reports the vision and the ongoing developments in Thales Alenia Space Italia.

INTRODUCTION

In the past decades, the demand for secure satellite communications has significantly increased in commercial, institutional and military sectors, driven by the need for high-speed, low-latency and globally available cyber-secure connectivity. This trend is expected to be confirmed in the coming years.

Institutional and military operational scenarios require the availability of a multiplicity of information that are produced by different systems and have to be distributed by means of communications networks in the areas of intervention, including those not served by terrestrial infrastructures. There is an increasing need for establishing resilient, flexible and always-available connections in areas that are not covered or are poorly served by terrestrial networks, as well as in post-crisis scenarios in which the terrestrial networks could have suffered critical damages.

It is recognized that these requirements cannot be met by terrestrial communication networks alone, as they are unable to guarantee reliable and ubiquitous connectivity and to serve remote and critical areas, due to their irregular and/or insufficient coverage. Therefore, satellite communication infrastructures have to be integrated with existing terrestrial infrastructures to ensure resilient access to telecommunication services at all times.

Thales Alenia Space Italia (TAS-I) is defining new concepts, solutions and technologies for multi-mission and multi-orbit satellite communication systems for institutional, military and commercial use, based on satellite constellations. The proposed solutions are multi-orbit, since they include a combination of satellites orbiting at different altitudes, namely at Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO). These constellations use optical communication technologies to provide secure and resilient high-speed optical links between satellites and with ground stations and user terminals. The system is configured as a satellite network where all the satellites are interconnected in a fully meshed topology via on-board packet routers and optical inter-satellite links (ISL), and can communicate with ground stations and user terminals via optical links (potentially complemented by the radio frequency link). This paper focuses on system solutions and technologies for satellite optical communication networks, by showing their role in addressing emerging user needs, analyzing the state-of-the-art and the evolution of constellations and technology, and reporting the vision and the ongoing development in Thales Alenia Space Italia.

WHY SATELLITE OPTICAL COMMUNICATIONS NETWORS?

The exponential growth of the demand for the exchange of data across the globe, along with an increased ground user request for high performance data transfer (i.e. high speed and low latency), results in the need for high data rate connectivity both in-space and on-ground. The dynamic change of this demand, together with its fast growth in new areas, is often not met by the terrestrial network capabilities due to the required infrastructure development time. Furthermore, the in-Space request may be satisfied with some operational difficulties using classical radiofrequency links due to the crowding of the spectrum typically used for high date rate connectivity. Satellite optical communications networks, integrated with the existing terrestrial networks, enable to flexibly serve both in-Space and on-ground users and are the key solution to fulfil these needs.
Satellite optical communications networks can leverage on:

- Space-to-Space and Space-to-ground high-data rate connections;
- Multiple orbits to support low latency, high availability scenarios and to adapt to the different user requests;
- Advanced routing protocols and switching capabilities to enable traffic engineering of user data, adapting to multiple user requests (in terms of type of connectivity and data rate) and network topology dynamicity;
- Optimized satellite ground segment network, to maximize availability of Space-ground links and to minimize infrastructural costs.

Optical Space networks provide significant advantages with respect to purely terrestrial fibre optic networks:

- The free Space speed of light is about 1.5 times the speed of light in optical fibres, therefore latencies in architectures with LEO satellites will typically be lower than for fibre links between distant points on the globe.
- The global reach of satellite constellations can provide a vastly superior coverage and enable more trunking opportunities in areas where terrestrial infrastructure deployment is difficult to achieve or is already highly congested as wells as services in the mobile environment. This includes also operational scenarios requiring a quick deployment.
- Attenuation in free Space over distance is significantly less than for fibre links requiring fewer amplifiers/repeaters to maintain performance.
- Connecting locations on the ground through a Space network allow for the exchanged data to not cross any intermediate national border being delivered directly to the user headquarter. Furthermore, the inherent low probability of intercept of optical links increases the connection security.

In general, several categories of users (and relative use cases) can benefit from satellite optical communications networks:

- Terrestrial Network Operators (TNO), which are deemed primarily interested in expanding their network towards two directions:
  - long distance interconnections to different regions, also overcoming national sovereignties;
  - extension of services in underserved areas.

  The key requirements for terrestrial operators are: high service availability, low cost per bit and low latency, all of them comparable with those of terrestrial networks.
- Telecommunication Satellite Operators (TSO), which are interested in satisfying the increasing capacity demand by evolving towards GEO high throughput satellites interconnected to each other by inter satellite links and being connected to ground through high-speed optical feeder links or towards multi-orbit constellations involving different orbital layers (LEO, MEO, GEO), with intra-orbit and inter-orbit connectivity. Similarly, to terrestrial operators, the key requirements for Telecommunication Satellite Operators are high service availability and low cost per bit. Existing and planned constellations are still relying on radiofrequency links between Space and ground to achieve high service availability. The availability of high-speed optical links between satellite and user terminals/ground stations are interesting features that increase the overall system capacity.
- Governmental entities, which is a user category emerging in the recent years. Their primary interest is in the availability of a secure communication infrastructure to use for institutional purposes. Governmental entities may be at national or international (e.g. European) level. In this case, the use of full optical communications would inherently enhance the level of security.
- Other user categories, e.g. Private Network Users (PNU) or Space\Airborne Users (SAU), can also rely on services provided by the above-mentioned stakeholders, and represents specific use cases.

STATE-OF-THE ART SOLUTIONS AND TECHNOLOGY

Several satellite systems implement optical communications for high data rate and secure connections by means of optical links. Among these, for example, there are:

- European Data Relay System (EDRS) that utilizes laser communication technologies to relay data from LEO satellites to ground stations in near real-time.
- NASA's Laser Communications Relay Demonstration (LCRD) that seeks to validate robust and efficient optical communication systems which can offer data rates significantly higher than RF systems.
- TeraByte InfraRed Delivery (TBIRD): experimental project by NASA to achieve more than 100 Gbps data transfer rates from Space to Earth using optical communication technology.
- SpaceX Starlink has been developing and deploying the Starlink satellite constellation for global broadband coverage. Recent launches include satellites equipped with optical inters-satellite links technology to enhance network communication efficiency.

However, in general, except for technology demonstrator and scientific systems, optical communications in operational systems mainly rely on purely optical inter-satellite link between close satellites, to reduce latency and increase efficiency. These solutions thus are mainly characterized by the following limitations:

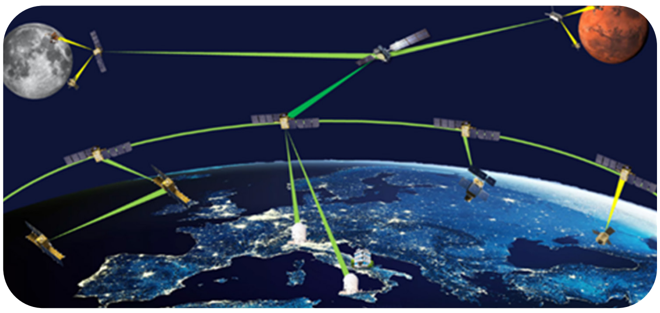
- Small size aperture optical antennas;
- Low number of available simultaneous optical links;
- Low range connections;
- Lower data rates (in the order of a few Gbps);
- No optical feeder links between satellite and ground stations.

The use of inter-satellite link enables the concept of networking in satellite constellation. Currently, the state-of-the-art includes some examples mostly adopted for LEO satellite constellations. The main satellite constellation networking solutions focus on several key aspects, such as data transmission efficiency, network resilience, low latency and global coverage.
Several actors in the Space arena are developing and deploying their own constellations, in most cases based on full proprietary solutions as far as the networking aspects are concerned. SpaceX's Starlink is currently considered one of the most advanced LEO satellite constellation. Starlink aims to provide high-speed, low-latency Internet around the world, through a network that uses inter-satellite links to improve data transmission performance.
OneWeb is also developing a large constellation of LEO satellites. OneWeb is focused on bridging the digital divide by providing connectivity to remote and rural areas. It uses a mesh network enabled by optical inter-satellite link to ensure efficient and resilient communication between satellites.
Amazon's project Kuiper aims to create a LEO satellite constellation to offer high-speed, low-latency Internet connections. Kuiper will leverage advanced phased array antenna technologies to improve accuracy and capacity of the satellite communications toward users and optical inter-satellite link to interconnect satellites.
Telesat is developing the Lightspeed constellation, a network of LEO satellites designed to provide high-speed broadband connectivity services. It uses advanced routing and interconnection technologies to maximize coverage and efficiency.
SES O3b mPOWER is developing a MEO network called O3b mPOWER, which aims to offer high-performance connectivity services, including full bandwidth flexibility and low latency for commercial and government users. No inter-satellite link solutions is envisaged in this case.
Despite significant advances in non-geostationary (LEO, MEO) satellite constellations, which are witnessed by the examples reported above, there are several limitations and challenges that operators have to face from a performance and routing capacity perspective.
The latency performance in end-to-end data transfer is a key parameter for satellite constellations. Although the latency of LEO constellations is significantly lower than of GEO satellites, it can still vary depending on the geographic location of the users and the satellites. The need to pass data among multiple satellites in orbit to reach different destinations can cause fluctuations in latency, which requires efficient routing and forwarding protocols and algorithms to select the optimal paths. Routing data via LEO satellites must be very dynamic, as satellite orbits cause frequent changes in available paths. Routing management and optimization is complex and requires advanced network algorithms. The need for well-distributed ground stations and advanced antenna systems to maintain the connection with LEO satellites is a key factor, especially to execute control functionality over the communications to be set-up and handled throughout the constellation. These stations must be able to track and follow moving satellites, and handle the data forwarding. Standardization of communication protocols between satellites and ground stations must be improved to ensure efficiency and interoperability, especially in view of the widespread use of 5G (and 6G) communication protocols. Variation in protocols between different providers can cause inefficiencies and technical difficulties. Managing a network with thousands of satellites requires extremely powerful and scalable control and management systems. Scaling the network to accommodate growing user and data demands is an ongoing challenge.

EVOLUTION OF SATELLITE OPTICAL COMMUNICATIONS CONSTELLATIONS

New Satellite Constellations

Thales Alenia Space Italia is developing new concepts for satellite constellations, where optical communications networks play a key role. The solutions are based on a multi-orbit concept (see Figure 1) in which satellites are deployed on different layered LEO/MEO/GEO orbits and are integrated in a single network system. The multi-orbit approach allows to minimize the number of satellites, ensuring at the same time the requested coverage and revisit time on ground, as well as connectivity among the different satellites. This new concept allows for high flexibility of the network configuration but requires advanced routing and control & management schemes to allow the network to select the optimal paths to forward the data towards the final destination and to quickly react or reconfigure itself during operations. The final outcome is to maintain end-to-end links with the agreed quality of service (QoS) level, taking into account the dynamic topology of the satellite network so as to guarantee high quality level of the communication experienced by the user.
New satellite networks will be fully interoperable and integrated with the terrestrial network so that data can be exchanged transparently from Space to ground and vice versa, basing on the best path selected to reach the destination.
Satellites are not only placed on different orbits but may also be architecturally different. In order to optimize resources, some functionalities can be distributed across the constellation and other ones can be present only in certain satellite nodes.
For example, data storage can be distributed so that each satellite has to carry only a portion of the data or they can be concentrated in a few satellites easily reachable from any other satellite (e.g. in MEO or GEO). Data processing can be distributed by providing cloud-processing capabilities, or it can be dedicated in each satellite as in edge-processing.
All these functions are possible thanks to the ability of the network to move large chunks of data across the constellation, reliably and in a short time. So, optical high data rate links together with high speed routing are key to enable these services.



1 – Concept of multi-orbit satellite optical communication network

Advances of Satellite Optical Communications

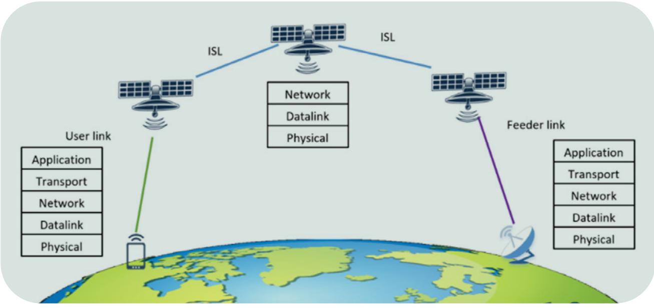
Optical communications in the new satellite constellations play a key role. Optical links offer the possibility to support very high transmission speed (up to Tbps or higher) with limited power, with intrinsically high security level. These benefits can be exploited widely, not only by using short range optical inter-satellite links between satellites on the same orbital plane, but also leveraging on multiple optical inter-satellite links between satellites on different orbital planes at the same altitude and even inter-orbit optical links connecting satellites at different altitudes. Moreover, optical communications can be used for very high speed connection between satellites and optical ground stations.
The fast evolution of optical Space technologies is also allowed by the spacialization of terrestrial items. The current target for free-space optical links is to provide 100Gbps per single wavelength but the evolution of terrestrial technologies suggests that this value could raise to 400Gbps or more in a few years. In addition, with the increase of efficiency and output power of optical amplifiers, it will be possible to host multiple wavelengths on a single link, allowing to multiplex and demultiplex data streams both at digital and optical level.
Satellites will be able to embark smaller and more efficient terminals that will enable connection with satellites on the same orbit or on different orbits. Furthermore, optimizations are ongoing in the techniques to mitigate the channel fading induced by the atmospheric turbulence effects on ground-to-Space links, incrementing their availability also in adverse atmospheric conditions.

Thanks to adaptive network functions and fast acquisition procedures, the recovery time due to a failure will be minimized. Furthermore, optical links are becoming increasingly suitable for long range communications, thanks to the development of highly efficient coherent modulation schemes.
On the basis of the above considerations, it is possible to forecast that free-Space optical links will be more and more a baseline for satellite communications networks, by complementing and in some cases by replacing radiofrequency links in several applications. Future satellite communication systems will rely on a reliable, resilient and secure optical backbone network on which different types of services and applications can be built, to provide connectivity as well as data storage and processing services globally on and around Earth and in the inter-planetary Space. This new evolution is made possible by the increasing effort on the advancement of higher performance technologies and system concepts, such as:

- **Optical space terminals**, are smaller and lighter than radiofrequency communication components and include optical transceivers supporting very high data rate optical connections with other network nodes (satellites or ground stations) and with heterogeneous user typologies. Wavelength-division multiplexing (WDM) solutions allow for increased throughput for optical communication systems providing connections at more than 100 Gbps. In addition, larger size optical Space terminals are under development with telescope size up to 25 cm, enabling reliable optical links from/to GEO satellites.
- Standardization process for **modulation techniques** and, in general, **optical waveforms,** enable interoperability among different satellite optical communication networks and improve the efficiency and reliability of high-speed data transmission in Space. Thales Alenia Space Italia is currently involved, with other stakeholders, in the activity of the European Space Agency (ESA) for definition and assessment of the standard interface specifications for the next generation optical inter-satellite links and optical Space-to-ground links, i.e. the ESA Specifications for Terabit/sec Optical Links (ESTOL).
- **Turbulence mitigation processing (TMP)** techniques, are designed to mitigate the atmospheric effect on optical communications that causes fading events. The temporal profile of these events cause data packet errors rather than errors on individual bits within the transmitted data. For this reason, the correction must take place at data block (packet) level, rather than at single bit level. Due to large propagation delays or to the lack of a return link, it is not possible to use Automatic Repeat Queuing (ARQ). In these cases, the Forward Error Correction (FEC) technique can be used, which involves transmitting redundancy packets (based on error-correcting codes) that allow the receiver to reconstruct the lost packets from the received ones without further communication with the source. In the field of optical satellite communications, various coding techniques are proving their effectiveness. Thales Alenia Space Italia is developing TMP solutions up to 100 Gbps, in order to ensure more reliable and resilient data transmission, for integrated satellite and ground optical communication networks.
- **Pointing, acquisition and tracking (PAT)** advanced technologies and strategies, driven by the need for high precision, reliability, and efficiency in establishing and maintaining optical links between fast moving LEO satellites and other network nodes (i.e. ground station, users or other satellites).
- Optical Ground Terminals (OGT) enhanced with **Adaptive Optics (AO)** solutions, enable counteracting the optical wavefronts deformation effects due to the atmospheric turbulence. The AO solutions measure the phase of the incoming radiation received from the satellite and correct it by using the combination of a deformable mirror and a fast steering mirror. Advanced OGTs allow for robust and high data rate optical links from satellite, including GEO nodes.

Networking Solutions and On-board Routing for Improved Performance and Security

The satellite communication system solution proposed by Thales Alenia Space Italia is based on a concept of satellite constellation in which each satellite becomes a node of a telecommunications network, connected in fully meshed topology configuration with its neighbour nodes by means of inter-satellite link and being capable of making autonomous decisions on traffic routing (see Figure 2).



2–Satellites are nodes of a telecommunication network thanks to payloads implementing on-board routing capabilities

These inter-satellite links enable the creation of a mesh network where data can be routed through multiple satellites before reaching their final destination.

On-board routing involves satellites equipped with advanced processing capabilities to handle data traffic and performing real-time decision-making processes regarding the routing of data packets, similar to what occurs in terrestrial routers and switches. On-board routing reduces the dependence on ground stations, decreases the latency in end-to-end data transmission and optimizes the network performance.

The on-board packet router enables the concept of a multi-mission constellation, allowing the satellite constellation to become a real telecommunications network. In fact, the development of the router makes the satellite a telecommunications node capable of working at higher levels of the communication protocol stack, including a network layer, a data link layer and a "processed" physical layer, on top of the "analogue" physical layer capability (i.e. filtering, amplification, frequency conversions etc.), which have characterized the traditional transparent satellites for decades.

The on-board packet router will be the heart of the satellite payload of the future constellations and will allow the traffic of different users to be routed by using optical inter-satellite links to reach the final destination in the fastest and optimal way. The satellite can receive data from a traffic source but the destination of the communication may not be reachable from the same satellite because it could not be under its coverage. Thanks to the presence of optical inter-satellite links between the satellites and to the on-board router capabilities, the data traffic can be forwarded hop-by-hop to other satellites until it reaches the satellite that is providing the communication service to the destination user. To meet these features, the solution needs a reprogrammable on-board router that performs high-speed switching and forwarding, up to 100Gbps per port, and in-band control and management functionality. Concerning the network management, a centralized routing architecture approach is selected for user data traffic, since the system will handle large end-to-end flows that require the holistic perspective of the entire network.

Within the system, it will be possible to have a centralized control entity that acts as the primary control point for all space and ground nodes. This entity also determines all physical connection paths and their associated physical characteristics, as well as its associated management and operational structure, based on the expected satellite constellation orbits. Such satellite constellation orbits are mostly geometric and deterministic models, based on mission characteristics. Therefore, the network topology is an input to the network management system and the routing function (regardless of how it is implemented).

A Software Defined Network (SDN) based approach is adopted for network management, routing configuration and traffic forwarding. In a SDN, the control plane (network plane) and the data plane (forwarding plane) are decoupled, thus enabling a direct programming of the network plane via a (or more) SDN controller(s). Implementation of SDN architectures where the network management is decoupled from the physical hardware, enables flexible, programmable routing and improved network responsiveness.

The advances in the networking solutions for satellite communication constellation mainly concern the design and development of the above defined on-board upper layers processing capabilities. These include not only routing and forwarding capabilities, but also network management solution to deploy the configuration in a continuously changing network topology, due to the satellites movement.

The main benefits of onboard routing are:

- Reduced latency: direct routing of data packets within the satellite network shortens the path and reduces latency, compared to ground station based routing.
- Increased reliability and redundancy: the ability to reroute traffic dynamically in case of satellite failures or link disruptions enhances the overall network resilience.
- Cost efficiency: minimizes the need for extensive ground infrastructure and reduces operational costs. Optimizes bandwidth utilization by rerouting the traffic, basing on real time network conditions.
- Scalability: supports the scaling up of satellite constellations by simplifying the management and routing of growing data volumes across a larger number of satellites.

As it is necessary in each network, cyber-security plays a key role also in the context of satellite optical communication networks that must provide cyber-secure communications. High level of protection may be obtained with a combination of solutions. These solutions include encryption mechanisms implementing protection of data in transit and at rest and can include also cyber-secure routing with location obfuscation guaranteeing that the network addresses of the source and of the destination nodes are not revealed. This allows to protect the information about the position of the users.

These solutions could be further expanded by exploiting the multi-mission concepts where the encryption key is distributed by means of Quantum Key Distribution (QKD) solutions.
Security is also obtained by exploiting the properties of the optical communications which are characterized by very narrow beam ensuring inherent low probability of intercept.

Ongoing Development

Thales Alenia Space, Italia is carrying out several initiatives, programs and development in the area of satellite optical communication networks.
Thales Alenia Space Italy is leading the High thRoughput Optical Network Demonstration System (HydRON-DS) Element #2 “LEO Multi-Orbit Extension Layer” program funded by the European Space Agency (ESA). The program aims to develop a high data rate (up to 100 Gbps per link) optical communications network for the demonstration of end-to-end data transport between users on the ground and users in Space, across multiple ground and Space nodes, and among multiple orbits. The HydRON-DS Element #2 system will be composed by:

- a LEO satellite, capable of multiple optical communication connections;
- a GEO node represented by a payload embarked on a GEO satellite;
- two Optical Ground Stations (OGS);
- a HydRON Control Centre (HCC), that orchestrates the whole network.

The aim of each OGS is to provide an advanced optical communication system, capable of effectively managing data routing and switching. The system performs conversion between optical and electrical signals, optimizing communications and mitigating the effects of the atmospheric turbulence. In addition, the OGS ensures smooth coordination of command and monitoring data between the control centre and operating units, thus ensuring efficient network management and optimal communications performance.
In the dynamic interface between the HydRON-DS Space node and ground nodes, the performance of optical links is significantly challenged by atmospheric turbulence. This turbulence can lead to severe deep-fading events. Such prolonged disruptions can result in substantial data loss when operating at target data rates of 10 Gbps and 100 Gbps per wavelength, severely degrading the overall link throughput.
To address these critical challenges, the system incorporates additional turbulence mitigation coding techniques. These techniques are strategically applied to the Space-to-ground optical communication link, in order to effectively counter the adverse effects of atmospheric turbulence.
In this context, Thales Alenia Space Italia is also actively contributing to the evaluation phase of the ESTOL standard aimed at identifying the most reliable coding technique.

The commitment of Thales Alenia Space Italia in these analyses not only aims to ensure the adoption of cutting-edge solutions in optical communications, but also contributes to strengthening the effectiveness and sustainability of standards in the long term, This will facilitate the development of increasingly robust and reliable communication systems.
In the context of the HydRON-DS project, Thales Alenia Space Italia is developing the satellite onboard routing module. The router implements Multiprotocol Label Switching (MPLS) technology with both edge and core provider functions, to support 10Gbps packet switching and traffic aggregation at the edge. This allows the user to access the transport network directly in Space. The local controller is able to select the MPLS edge provider routing function or the core routing function based on the network configuration. The most important role of MPLS edge routers in the network is to perform the following edge functionalities:

- Internet Protocol (IP) data forwarding: is based on IP data routing instructions, to forward IP user data in the network;
- MPLS access de/encapsulation: with popping or pushing label, to create or terminate connections (label switched path).

The onboard router also implements 100Gbps port switching capabilities to forward traffic to different core routers and to different users.
The MPLS has been chosen also because it is a technique to provide controlled traffic engineering for flow of packets for different service/user classes in core networks. This is done by assigning end-to-end “virtual paths” (called tunnels) of predefined capacity to different demand streams corresponding to different service classes associated with certain user groups that require differentiated quality of service (QoS). In this way, a much more flexible packet routing can be achieved as compared to the link-metric dependent shortest-path type of routing. The MPLS achieves control over packet flows and thus can perform traffic engineering in a flexible way, through a concept called label switching, enabling routers within a network domain, to forward packets only according to a prepended label. The MPLS mechanism directs data traffic along predetermined networking path described on the labels, named Label-Switched Path (LSP), by exchanging label information. It provides compatibility and interoperability with existing MPLS networks and can be considered more reliable due

to large historical deployments. The tunnels in the network can have a certain capacity (i.e. transmission rate) assigned to them. A tunnel for a traffic class may be established by assigning a given capacity so as to guarantee a certain quality of service (QoS).
The solution enables the constellation to easily interact and interoperate with terrestrial systems.
For the development of these new technologies, the fundamental building blocks for the production are often characterized by high complexity, difficulty in sourcing or dependence on a few suppliers. Their availability is critical for the functioning of entire production chains. Developing robust and resilient supply chains requires a holistic approach that involves all actors in the chain, from design to production, from logistics to distribution. It is important to create networks of reliable suppliers, to invest in supporting infrastructure and technologies, and to adopt risk management strategies. It is also important to reduce dependence on a single supplier or geographic region for the supply of key components. This goal can be achieved through diversification of sources, exploration of new markets and development of alternative technologies. In summary, the integration of advanced technologies and the development of resilient supply chains are key aspects in addressing the challenges related to non-dependence and to ensure continuity of the production in strategic sectors.
Thales Alenia Space Italia facilities will allow to execute test validation campaigns aimed at verifying the functionalities and the performance of the on-board router in a satellite optical communication scenario. Thales Alenia Space Italia is currently conducting tests in its space research laboratory, the Space Photonic and Quantum Research Laboratory (SPQR). This facility, devoted to research and demonstration activities in the area of optical and quantum communications is currently used to develop a high-speed end-to-end optical communication system. Through the experiments carried out at the SPQR laboratory, an optical link across the atmosphere is emulated and tested by using the real HW equipment, including routing functionalities. This will enable significant advances in the field of optical telecommunications networks.
The test and validation campaign is complemented by the test activity on the HydRON Simulator Testbed (HySIMULED) reproducing the HydRON system features and behaviours in highly representative HW/SW environment, in order to validate its main concepts, verify the protocols and algorithms (including the routing) and assess the overall performance. Satellite optical communication networks are currently under design and development not only for Earth-based missions but also for several interplanetary missions taking the optical communications as key feature. The increased number of exploration infrastructure studies and future programs (like for example, those targeting Moon or Mars missions) will indeed hugely benefit from the availability of optical communications network providing high data rates, lower power requirements, and routing capabilities. For this reason, Thales Alenia Space Italy is currently involved in different studies and activities.

CONCLUSIONS

The evolution of user needs, as well as the advances in satellite constellations and technologies, are radically transforming the landscape of global communications that are characterized by a growing demand for high data rate, ubiquitous and cyber-secure connectivity.
Thales Alenia Space Italia is defining new concepts, solutions and technologies for multi-mission and multi-orbit satellite communication systems for institutional, military and commercial use based on satellite optical communication network constellations.
Optical communications for secure and resilient high-speed links among satellites and between satellites and ground stations, along with network solutions based on dynamic data routing capabilities on board the satellite, are key elements enabling the evolution of the new satellite communication constellations. The system is configured as a satellite network where all the satellites are interconnected in a fully meshed topology via packet routers and optical inter-satellite links and can communicate with ground stations and user terminals via optical links (potentially complemented by the radio frequency link). This paper has presented system solutions and technologies for satellite optical communication networks, showing their role in addressing emerging user needs, analyzing the state-of-the-art and the evolution of constellations and technology and reporting the view and the ongoing development in Thales Alenia Space Italia.

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Towards Low Earth Orbit Navigation Systems: Contributions from the European LEO-PNT Program and Thales Alenia Space

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Thales Alenia Space Italia

The evolution of Space-based Positioning, Navigation, and Timing (PNT) infrastructure is undergoing a paradigm shift, driven by the growing demand for precision, resilience, and continuity across a wide array of sectors ranging from autonomous systems and telecommunications to critical infrastructure and financial networks, etc. While legacy Global Navigation Satellite Systems (GNSS) remain foundational, their fundamental limitations are challenging to these sectors, including weak signal strength, susceptibility to jamming and spoofing, multipath interference, and degraded performance in dense or obstructed environments. Concurrently, the rise of the New Space Economy (NSE) and the rapid deployment of Low Earth Orbit (LEO) mega-constellations have opened new possibilities for Space-based navigation. LEO satellites offer inherently stronger signal reception, reduced latency and higher angular velocity, making them particularly suitable for robust positioning in urban, indoor, and contested environments. These benefits have positioned the LEO-PNT systems as a strategic complement to the GNSS, contributing to a hybrid, multi-layered navigation architecture for the future. This article provides a comprehensive overview of the emerging global LEO-PNT landscape and State-of-the-Art LEO-PNT approaches, with a dedicated focus on contribution from the European LEO-PNT Program and Thales Alenia Space (TAS), which is at the forefront of designing reconfigurable, secure, reliable and high-performance navigation solutions. The article explores hints long-term vision guiding Europe's transition toward a sovereign, flexible, and resilient Space-based PNT capability.

INTRODUCTION

Legacy Global Navigation Satellite Systems (GNSS) form the cornerstone of modern Positioning, Navigation, and Timing (PNT) infrastructure, supporting a vast array of applications. Their precision, reliability, and global coverage have made them indispensable. However, the GNSS systems face mounting challenges such as limited signal strength, vulnerability to jamming, spoofing, interference, multipath propagation, and poor performance in obstructed or urban environments, emerging cybersecurity threats etc. [1]-[4]. Additionally, the emergence of ambitious Space exploration goals such as establishing sustained human presence on the Moon has further emphasized the need to diversify and extend PNT capabilities beyond Earth [5]. This expanding scope of applications highlights the urgency of developing more robust, flexible, and resilient navigation systems that can operate across different domains and environments.

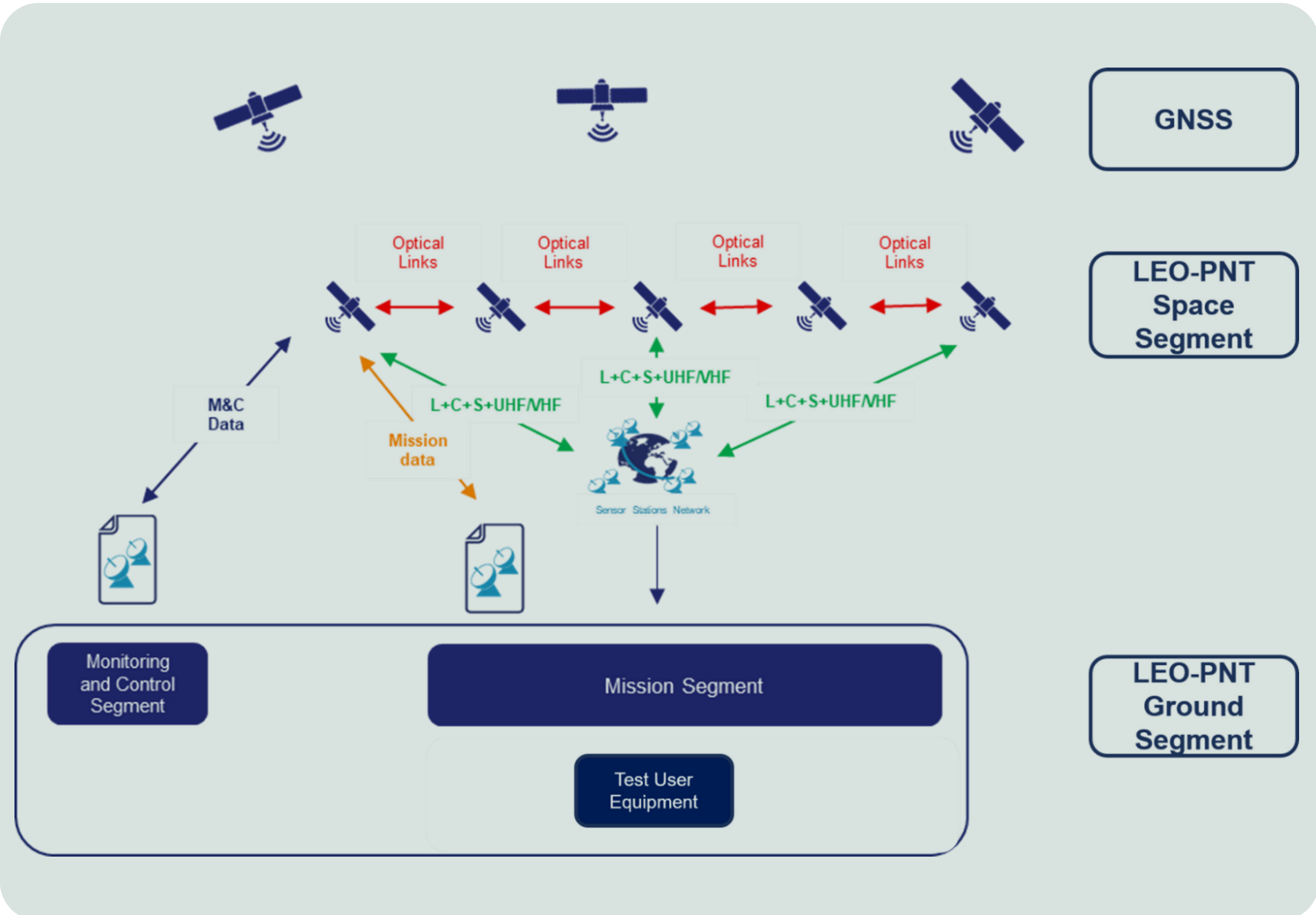
On other hand New Space Economy (NSE) and race to launch mega-constellation in Low earth orbit (LEO) is gaining traction for various applications such as telephone, internet, telecomm, global connectivity, IoTs etc. In line with these current trends, the LEO-PNT systems are increasingly being recognized as a complementary solution that enhances resilience, robustness, and continuity of the Space-based navigation. The LEO-PNT architectures are addressing critical gaps and ensure more secure, flexible, and responsive PNT services across diverse application domains [6]. Unlike GNSS, the LEO satellites orbit at altitudes of 340 - 2000 km, which enables faster movement across the sky, stronger signal reception, reduced latency, and improved coverage in urban and indoor environments. These characteristics make LEO satellites relevant for PNT applications [4]-[7].

At the intersection of this technological shift stands Europe's response to a concerted effort to develop sovereign LEO-PNT capabilities through the hybrid, multi-layered navigation architecture shown in Figure 1. It features three main layers:

- the Outer Medium Earth Orbit (MEO) based GNSS layer;
- the LEO-PNT constellation of 5 satellite with Optical inter-satellite links (OISLs) capabilities;
- the LEO-PNT Ground segment consisting of Monitoring and Control Segment, Mission Segment and test User.

This approach is being spearheaded by the European Space Agency (ESA), supported by CNES, ASI, DLR and other institutional actors, with Thales Alenia Space (TAS) leading the industrial front. Their efforts are shaping the future of European navigation in flexible, secure, and sustainable way. Therefore, this article provides an overview of the global LEO-PNT landscape, with a dedicated focus on European efforts, particularly the European LEO-PNT Program, and on the pioneering role of TAS. We explore the state-of-the-art in LEO-PNT, various architectural approaches, and the strategic vision that TAS brings to this next-generation navigation infrastructure. The reminder of this article is organized into five sections. Section-II underscores the necessity for alternatives like LEO-PNT by examining the challenges faced by legacy GNSS systems.

Section III provides an overview of the current state of the LEO-PNT technology. Section IV discusses Europe's role and vision for the development of LEO-PNT, along with TAS's contributions to this emerging field. Finally, Section V presents the conclusions.



1-Preliminary LEO-PNT multi-tier Architecture

CHALLENGES OF LEGACY GNSS AND MOTIVATION FOR LEO-PNT

GNSS include several constellations; GPS, GLONASS, Galileo, and BeiDou along with regional systems like QZSS, NavIC or BeiDou Regional Service, and the planned KPS [8]-[11]. Despite their global utility, GNSS systems face technical, environmental, and geopolitical challenges that affect reliability, resilience, and security, particularly in critical applications [1]-[4]. Key limitations include signal obstruction and multipath propagation in urban, forested, or indoor environments, where the line-of-sight to satellites is blocked or distorted. Reflected signals can cause significant positioning errors, especially in dense urban canyons. Atmospheric and Space weather effects further impact performances. Signal delays in the ionosphere and troposphere especially affecting single-frequency receivers, can degrade accuracy. Events like solar flares and geomagnetic storms intensify these effects, leading to service interruptions, particularly at high latitudes.

While systems like Galileo include features such as the Public Regulated Service (PRS) to improve robustness, all the GNSS users remain exposed to space weather-related disruptions [2].

Cybersecurity threats including interference, jamming, and spoofing are growing concerns. GNSS signals are weak at the

Earth's surface, making them easy targets for disruption. Spoofing attacks, in particular, can mislead receivers, posing serious risks to sectors like aviation, autonomous transport, and critical infrastructure. Anti-jamming and anti-spoofing measures are being deployed, but those vulnerabilities persist [1][2].

Standard civilian GNSS services also have accuracy limitations, often offering meter-level precision only under ideal conditions. Performance degrades in remote areas or under poor satellite geometry [12]. These challenges are driving interest in LEO-PNT.

STATE-OF-THE-ART IN LEO-PNT

LEO-PNT represents a transformative evolution in satellite-based navigation. Several studies have proved that operating at lower altitudes, the LEO satellites enable stronger signal reception, faster Doppler dynamics for alternative positioning methods, and improved coverage in urban and obstructed environments. These benefits are particularly compelling for emerging applications in autonomous mobility, indoor localization, and GNSS-challenged scenarios. Some of the key features of LEO-PNT are as follows:

Cost-Effectiveness and Scalability

LEO satellites are significantly cheaper to manufacture and deploy. Their shorter orbital lifetimes (typically 5 - 10 years) also allow for quicker technology refresh cycles and for use of COTS that enable faster adoption of newer payload capabilities and security features. The ongoing deployment of mega-constellations like Starlink, OneWeb, and Amazon Kuiper demonstrates how commercial LEO systems benefit from economies of scale, reusability in launch vehicles, and modular satellite manufacturing [6] [13]-[15].

This cost-efficiency translates into more rapid constellation build-up, making the LEO-PNT services more readily available than a new MEO-based GNSS system.

Increased Satellite Visibility and Robust Geometry and Resilience in GNSS-Denied Environments

LEO mega-constellations consist of hundreds to thousands of satellites in orbit, offering significantly higher satellite visibility at any given time and location on Earth [15]. This high density of visible satellites improves Geometric Dilution of Precision (GDOP), a key metric in determining the accuracy and precision of position solutions[1][2][15][16]. High satellite density also ensures that navigation signals are less dependent on any single satellite or orbital plane, thereby enhancing system robustness in the event of local signal interference, jamming, spoofing, GNSS denied areas, urban canyons, indoor facilities, and conflict zones or space weather disturbances [13].

Approach	Description	Advantages	Challenges
Hosted Payload	Additional PNT payload is hosted on satellites whose primary function is not navigation (e.g., Earth observation, telecom). Used in early-stage demonstrations (e.g., Luojia-1A, EGNOS payload on Eutelsat 5 West B) [18]-[20]	• Cost-effective compared to dedicated constellations • Good for early testing and experimentation • Leverages existing missions	• PNT is secondary, so accuracy and service continuity may be limited. • Limited power/resources on host satellite • Complex subsystem integration • Potential security vulnerabilities.
Signal of Opportunity (SoO)	Utilizes signals from existing LEO communication constellations (e.g., Starlink, OneWeb, Orbcomm) not originally intended for PNT. Navigation extracted from downlink signals and public TLEs [21]-[23]	• No need for new satellite infrastructure • High satellite availability • Cost-effective for navigation purposes • Attractive for commercial satellite operators	• Difficult receiver design for TOA extraction • No direct access to satellite ephemerides • Ephemeris errors due to TLE usage • Lack of on-board atomic clocks prevents tight synchronization.
Fused LEO-PNT	Embeds navigation data into existing communication/remote sensing signals without changing hardware. Focus on protocol-level integration (e.g., DVB-S2X, 5G PRS). GNSS used as backhaul [24]-[28]	• Dual-use of LEO satellites for communication and navigation • Efficient use of orbital resources • Supports sustainable space utilization	• Requires cooperation with satellite operators • Complicated beam scheduling • Navigation needs multiple visible satellites • Trade-off with communication bandwidth • Requires advanced synchronization and message tailoring for LEO dynamics
Dedicated LEO-PNT	Purpose to build a LEO constellations designed solely for PNT services. E.g. TAS-ESA demonstrator and proposed Xona constellation [16][29]-[31].	• Configurations are optimized for availability, GDOP, and global coverage. • High accuracy and service reliability • Tailored design for navigation • Useful in GNSS-denied environments • Potential backup to MEO GNSS	• Requires a large constellation for coverage • Synchronization is complex • Risk of space debris and traffic management • Expensive infrastructure and satellite clocks

Table 1-Overview of LEO-PNT approaches, advantages and disadvantage

Enhanced Signal Strength and Lower Latency

Due to their proximity to Earth, LEO satellites offer stronger received signal compared to GNSS satellites. Such increased signal strength improves the signal acquisition and tracking, especially in challenging or obstructed environments such as urban canyons, forests, and indoor spaces. Additionally, LEO satellites enable lower latency in time transfer and data communication, which is beneficial for time-critical applications. Their higher power, shorter signal travel time, and different frequency bands can bypass many jamming techniques designed for GNSS bands. Moreover, the diversity in signal origin and waveform structure (especially in opportunistic PNT using 5G or satellite communications) provides a multi-layered defence against spoofing or signal degradation, thus reinforcing the resilience of Positioning, Navigation, and Timing infrastructure.

Improved Positioning Accuracy via Doppler Diversityn

LEO satellites move much faster across the sky (~7.5 km/s) compared to their counterparts. This rapid motion results in a high rate of change in the Doppler shift, which can be exploited for Doppler-based positioning algorithms to enhance positioning accuracy. This additional diversity complements legacy GNSS and strengthens the resilience and precision of hybrid navigation solutions.

Mitigation of Multipath Effects

In dense urban areas, the high speed and close proximity of LEO satellites help mitigating the multipath effects, as reflections are not static over the time, making it easier to detect and eliminate by using signal processing techniques. Additionally, the steeper signal incidence angles from LEO reduce the likelihood of strong ground-based reflections, thereby enhancing accuracy in urban navigation [6][17].

LEO-PNT IMPLEMENTATION APPROACHES

LEO-PNT implementations is broadly classified into 4 major types shown in Table 1 that provides a comparative overview of the four major implementation approaches for delivering PNT services via LEO satellites viz, Hosted Payload, Signal of Opportunity (SoO), Dedicated LEO-PNT, and Fused LEO-PNT, and offers a unique strategy, balancing performance, cost, complexity, and sustainability.
Table 1 highlights the advantages and disadvantages of each approach, which will be helpful for trade for implementation of the LEO-PNT architecture.

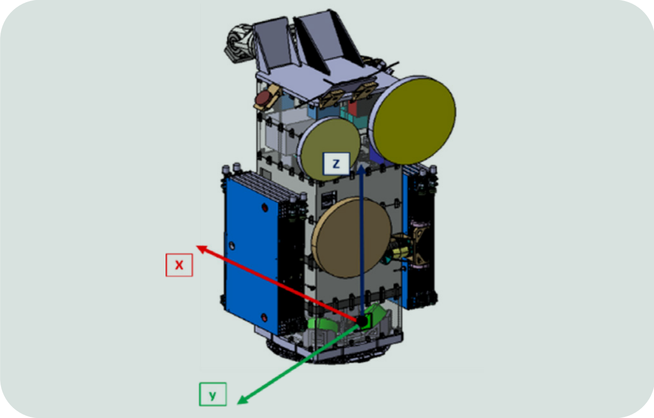
EUROPE'S VISION AND INDUSTRIAL CONTRIBUTIONS TO LEO-PNT

The European Union (EU) has recognized that the future of secure, accurate, and autonomous navigation must go beyond the traditional Galileo and EGNOS. This recognition is rooted in the growing vulnerability of the MEO-based PNT systems to cyber threats, signal interference, and geopolitical dependencies. EU has adopted a multi-layered approach to PNT, whose LEO constellations serve as a complementary and reinforcing layer to its existing navigation infrastructure (Figure 1). A crucial driver behind this initiative is the EU's strategic program Infrastructure for Resilience, Interconnectivity and Security by Satellites (IRIS^2). Although being primarily envisioned as a secure European satellite communication constellation, IRIS^2 also supports "non-communication missions of strategic interest," with LEO-PNT being identified as a high-priority capability. IRIS^2 highlights the importance of autonomy in critical infrastructure and positions Europe to compete in the evolving domain of Space-based navigation and security services [32].

Alongside IRIS^2, the ESA has launched a dedicated LEO-PNT Demonstrator Program, aimed at de-risking critical technologies and validating new PNT architectures in LEO. This includes not only the Space segment comprising multiple LEO satellites but also the Ground segment, user terminals. The purpose is not merely to test technologies but to shape the European policy and programmatic decisions for future operational PNT infrastructures [30].
This institutional effort is a direct acknowledgment that the LEO-PNT can enhance the navigation performance. More importantly, it ensures that Europe is not reliant on external actors especially non-European mega-constellations for the continuity of its critical navigation services. Thus, EU institutions are not only funding the technological building blocks but are also shaping regulatory and governance frameworks that will support the future LEO-PNT deployment on sovereign terms.

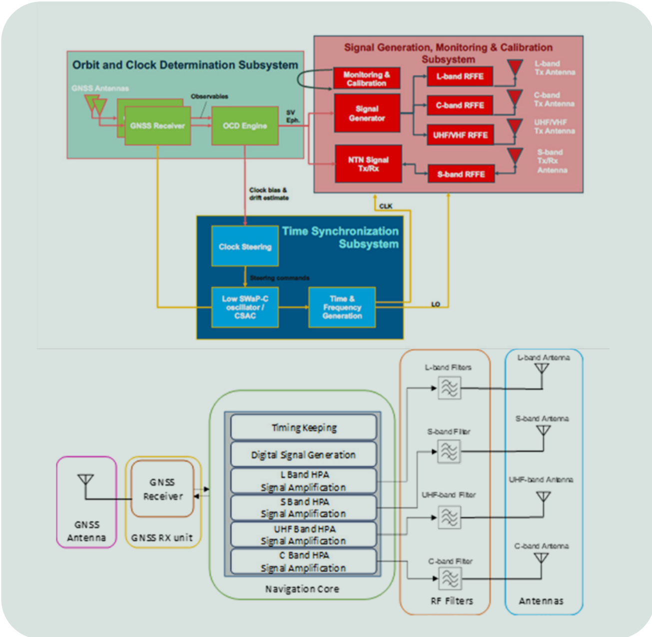
THALES ALENIA SPACE: INDUSTRIAL LEADERSHIP IN THE LEO-PNT REVOLUTION

TAS is playing a central role in transforming Europe's vision for LEO-PNT into a technical and operational reality. With decades of experience in European navigation programs such as EGNOS and Galileo, TAS brings deep expertise in Space systems engineering, from payload and signal design to Ground segment integration and service delivery. At the heart of its LEO-PNT efforts is the New Italian Micro Bus (NIMBUS) platform (Figure 2), a modular, agile, and cost-efficient satellite bus tailored for small LEO constellations. Designed for rapid production and in-orbit configurability, NIMBUS is ideally suited to the evolving needs of the LEO-PNT, supporting frequent technology refreshes and adaptable signal formats.



2-New Italian Micro Bus (NIMBUS)

Crucially, the platform is compatible with OISLs, enabling constellation-level clock synchronization and advanced time-transfer capabilities.
The navigation payload design follows a modular architecture (Figure 3), allowing flexible configurations that go ranging from reduced-capability versions (e.g., fewer frequencies) to fully featured payloads supporting multiple signals and waveforms. The prototype modulation schemes demonstrate such adaptability, enabling dynamic selection based on mission requirements or interference environments.
Beyond the hardware, TAS is actively shaping the strategic direction of the European PNT. In collaboration with ESA, the European Union, and national Space Agencies, TAS contributes to defining the long-term roadmap for LEO navigation services. The current demonstrator is not merely a technical experiment, as it is a foundational step towards an operational European LEO-PNT constellation that will be scalable, interoperable with Galileo, and aligned with both institutional and commercial needs.



3-LEO-PNT general Navigation Payload modular concept

The TAS approach consolidates the LEO-PNT concept through a robust and adaptable payload capable of meeting the demanding needs of future applications. Key benefits include:

- High Accuracy: enables precise positioning, critical for autonomous systems and advanced user technologies;
- Fast Convergence: reduces the time-to-fix for real-time and mobile applications;
- Spectrum and Geometrical Diversity: complements the MEO-based GNSS with new techniques for enhanced reliability and robustness.

Through this integrated technology and strategy roadmap, TAS is not just building a LEO-PNT payload, as it is actually laying the foundation for Europe's next-generation Space-based navigation infrastructure.

CONCLUSION AND FUTURE TRENDS

LEO-PNT is becoming a foundational pillar for the future of resilient space-based navigation. Its ability to augment the traditional GNSS with enhanced signal strength, low latency, and global coverage, positions it as a critical enabler for meeting the rising demands of emerging PNT applications. Through initiatives such as the LEO-PNT Demonstrator and the NIMBUS platform, TAS is laying the groundwork for operational constellations that tightly integrate with Galileo, IRIS², and future European satellite infrastructures. Looking ahead, the development of LEO-PNT systems signals a shift towards multi-tiered and interoperable navigation architectures. These architectures will feature dynamic interplay between GNSS, LEO-based signals, and other Space assets. Key enablers of this evolution include digital payloads, flexible waveform generation, and OISLs, which will allow for real-time coordination, system-wide synchronization, and distributed time transfer. Ultimately, the LEO-PNT is more than a supplement to the GNSS, as it is a stepping stone towards a resilient, reconfigurable, and autonomous global navigation system. The integration of tightly-coupled multi-layered space segments and intelligent on-board processing will redefine how navigation services are delivered and secured in the coming decades. Furthermore, the capabilities developed for LEO-PNT hold significant promises for supporting future lunar missions. As ambitions for sustained human presence on the Moon gain momentum, there is a growing need for PNT systems that can extend beyond terrestrial orbits. In this context, LEO-PNT can serve as a technological and architectural precursor to cis-lunar navigation infrastructures. Features such as autonomous timekeeping, OISLs, and modular navigation layers will form the critical building blocks for interoperable Earth - Moon PNT systems. Incorporating these developments into a broader roadmap not only strengthens Europe's strategic autonomy in Space but also paves the way for deep Space exploration enabled by robust and scalable navigation solutions.

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Multi-Sensor Fusion and Resilient PVT Techniques for Safe Lunar Landing Missions

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Moon exploration has become a relevant new domain for a new age of space commercialization, where a wide range of public and private enterprises are increasing in the last years their interest and investments in lunar missions, leading NASA, ESA and JAXA to start their exploration initiatives. Recently, many studies have been conducted to demonstrate the improvements in terms of Position, Velocity and Timing (PVT) estimation for users, enabled by a Navigation Constellation around the Moon. The objective of this study is to describe an approach that utilizes sensor-fusion techniques based on a tightly-coupled Extended Kalman Filter (EKF) to integrate lunar GNSS-like one-way ranging signals with a wide range of on-board observables, such as Inertial Measurement Units (IMU), altimeters, Two-Way Ranging (TWR) and Vision-Based Navigation (VBN) techniques for the estimation of both the spacecraft state and the receiver clock bias and drift. The selected lunar landing mission use case requires demanding navigation accuracy performance to reach the target landing. area, in this case the Shackleton Rim. The VBN algorithms applied for this study, implement Deep Learning techniques and are based on seleno-referenced lunar images generated through an innovative tool developed in the Telespazio Concurrent and Collaborative Design Facility (C2DF), for supporting the Interactive Mission Modelling, Visualization/Validation (IMMV^2) functionality.

INTRODUCTION

Objective of this paper is to present an approach that utilizes sensor-fusion techniques based on a tightly-coupled Extended Kalman Filter (EKF) to integrate the One-Way Ranging (OWR) signals provided by a NAV Constellation around the Moon with other sensors available on-board a lander. In this work, several observables have been taken into account: an Inertial Measurement Units (IMU), an altimeter, the Two-Way Ranging (TWR) provided by an additional lunar satellite, and the Vision-Based Navigation (VBN) technology have been considered for estimation of both the spacecraft state and the receiver clock bias and drift. This paper report in synthesis an extensive work presented at ION 2024 [1]. In this respect, the paper provides a brief overview of the new lunar era and the scenario considered. Then it is described the detail of the simulated scenarios within the Interactive Mission Modeling, Visualization/Validation (IMMV^2), while the central part presents the multi-sensor fusion functional architecture and the description of the principal modules and sensors implemented. A dedicated section is present to describe the results in five different use cases. The final section is dedicated to conclusions.

THE NEW ERA OF LUNAR EXPLORATION: LANDING MISSIONS

The lunar exploration has become a key area of focus in the rapidly growing field of Space commercialization. In recent years, both public and private organizations have demonstrated increasing interest and investment in missions to the Moon.

The increment of cis-lunar activities has led to notable initiatives from NASA, ESA, and other Space Agencies, all working collaboratively to deepen our understanding of the lunar environment and explore its potential resources. A primary goal of these efforts is to establish a Lunar Communication (COM) and Navigation (NAV) Constellation around the Moon, which will support future human and robotic missions, such as Artemis [2] and Argonaut [3]. In the long term, those services will also facilitate the emergence of a "Lunar Economy", encompassing Space tourism and on-site utilization of lunar resources, making future solar system exploration more cost-effective and accessible.

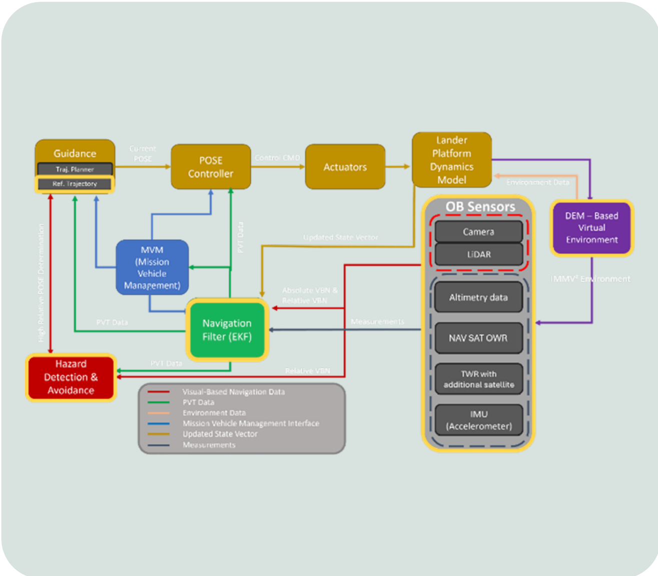
Ensuring accurate positioning capabilities is a pillar of these initiatives. Historically, lunar missions have relied on deep-Space Earth-based ground infrastructure to track spacecraft trajectories. The current challenge is to leverage a dedicated Navigation Constellation to enhance navigation accuracy for lunar mission users. Given that only a limited number of navigation satellites will initially operate in the cis-lunar environment, it is essential to demonstrate the integration of their data with measurements from other sensors, such as IMUs, altimeters, TWR with additional satellite and VBN or Visual Odometry and so on, depending on the type of the involved asset.

In this work, a landing mission is considered.

The NAV Constellation consists of four spacecraft in four Elliptical Lunar Frozen Orbit (ELFO). The simulation includes a DEM-based virtual environment that generates synthetic data like images and LiDAR point clouds. Looking at the architecture in Figure 1, only the highlighted components are used in this study, being the development of the remaining components planned for future work.

The architecture also includes a HD module that activates during the terminal descent phase, typically at altitudes between 2500 and 1500 meters. This module is crucial for ensuring safe and precise landing, by identifying and avoiding hazards at the landing site. The detailed implementation of the HD module and its performance are not objective of this work.

In conclusion, this paper builds on an earlier study that has explored multi-sensor fusion techniques without integrating any VBN into the system [4]. In this work, the VBN component (absolute and relative) is integrated, depending on the altitude of the lander along its trajectory towards its landing site.



1-GNC simulation architecture. The yellow outline indicates the blocks implemented in this study

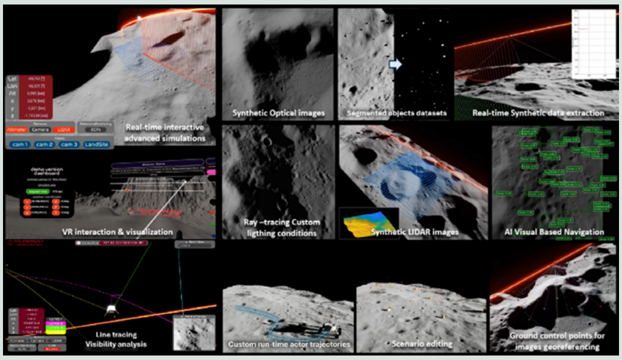
MISSION SCENARIO: LANDING ON THE SHACKLETON RIM ABOVE THE LUNAR SOUTH POLE

The conducted study exploits a landing trajectory that starts from approximately -75° latitude, spanning a total angle of around 30° and lasting for about 22 minutes. The trajectory profile has been developed basing on the guidelines of the reference trajectory of the ESA's Argonaut lander [1]. It starts from a Low Lunar Orbit, reaches an High Gate Arrival (HGA), and then proceeds with an almost vertical descent towards the Low Gate Arrival (LGA) over the Shackleton Rim, its landing site.

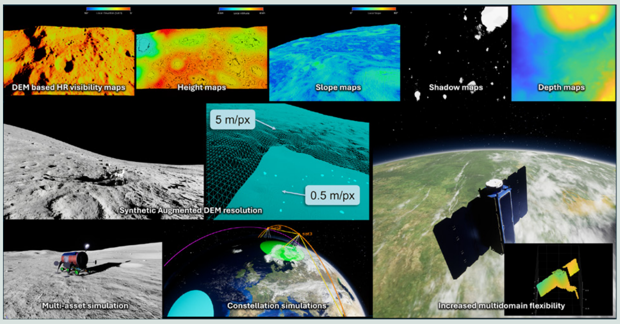
Since the Shackleton Rim has been selected as one of the key potential landing sites identified by NASA for the future Artemis missions [1], it is considered as the landing site (Shackleton Rim). It is also characterized by a sufficient average annual exposure to solar illumination.

THE INTERACTIVE MISSION MODELING, VISUALIZATION & VALIDATION TOOL FOR SYNTHETIC DATA GENERATION

The IMMV² tool has been developed during the last year within the Telespazio Research and Innovation Laboratories (R&I Labs) [7] [8]. This tool provides both Mission Designers and Users with a co-simulation realistic virtual environment for Mission Digitalization, 3D Modelling and End-to-End (E2E) Testing and Validation forming what is



2-Main functionalities of the IMMV²



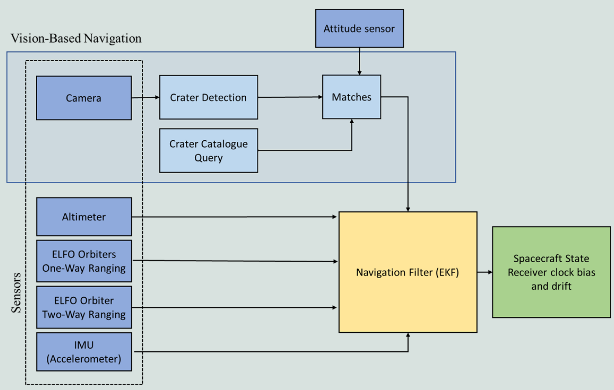
3-Additional functionalities of the IMMV²

is known as the Mission Digital Twin (MDT). Leveraging cutting-edge technologies, it uses the Unreal Engine (UE) platform for realistic rendering, synthetic data generation, and Virtual Reality (VR) interactivity. Moreover, this tool enables comprehensive fault analysis, detection, and exclusion mechanisms for system robustness, employing advanced sensor fusion across multiple synthetic datasets. In an era where complex Space missions demand for high safety standards and minimized risks, the MDT is essential for anticipating potential system behaviours that could jeopardize the mission success.

In this study, one of the principal modules of the tool, called Visual Scenario Generator (VSG), has been utilized to set up the scenario environment and produce fully synthetic images and altimetry data for the VBN. Through the VSG, it is possible to generate georeferenced Optical/LiDAR images and other synthetic observables under various conditions by placing custom sensors on user asset models in the scenario. This is also critical for creating large, fully synthetic datasets to train AI technologies (e.g., VBN) or develop high-fidelity mission digital twins. The lunar DEM reconstructed with the VSG, has been generated starting from topographic data collected by the Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA). Using integrated maps at different resolutions (30m/px to 5m/px), the abovementioned process has allowed to generate high fidelity meshes of the lunar region of interest, as described in [4]. Fractal noise has been used to overcome, in certain regions, the 5m/px resolution limit of LRO LOLA maps. The main functionalities are summarized in Figure 2 and Figure 3.

MULTI-SENSOR FUSION: FUNCTIONAL ARCHITECTURE

The implemented multi-sensor fusion navigation architecture is shown in Figure 4. The part of the scheme that is reported in the upper part and is highlighted with a blue rectangle represents a simplified view of the VBN block. The lower part highlights the other sensors and observables that feed the Navigation Filter (yellow block). The green block includes both the spacecraft state and the receiver clock bias and drift To obtain accurate estimate of the lander position along all the different phases of its trajectory, the VBN is integrated in the existing navigation architecture, together with the Navigation Constellation observables and additional sensors measurements. In this work, the limited number of Navigation satellites forces the implementation of a tightly coupled approach to incorporate satellite measurements with the remaining sensors needed to provide Position, Velocity and Timing (PVT) estimate. The full description of the main building blocks is described in [4].



4-Multi-Sensor Fusion Functional Architecture

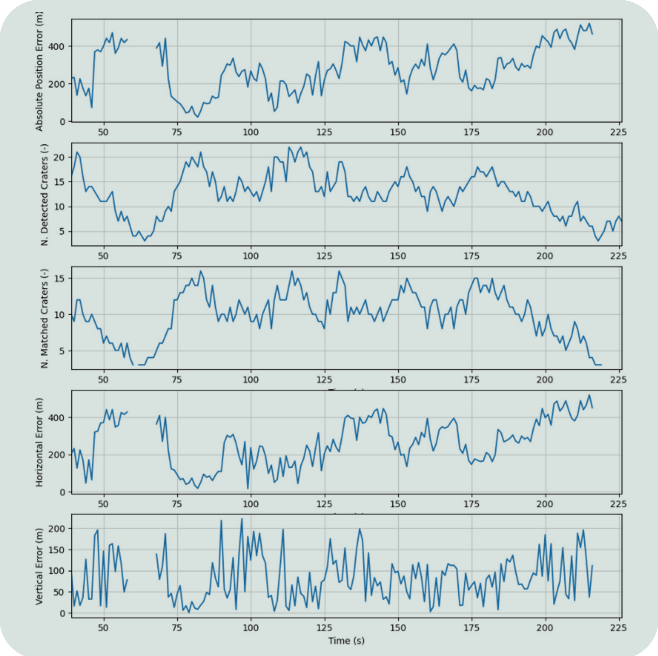
RESULTS

This section presents the results of the Absolute & Relative VBN algorithms for the portion of the trajectory in which the two solutions work, and Sensor Fusion algorithm for the entire trajectory when the other observables are available:

1. Absolute VBN Algorithm performance;
2. Relative VBN Algorithm performance;
3. VBN, IMU, Altimeter + 1 NAV Satellite;
4. VBN, IMU, Altimeter + 4 NAV Satellites;
5. VBN, IMU, Altimeter + 1 NAV Satellite + TWR.

Case 1: Absolute VBN Algorithm Performance

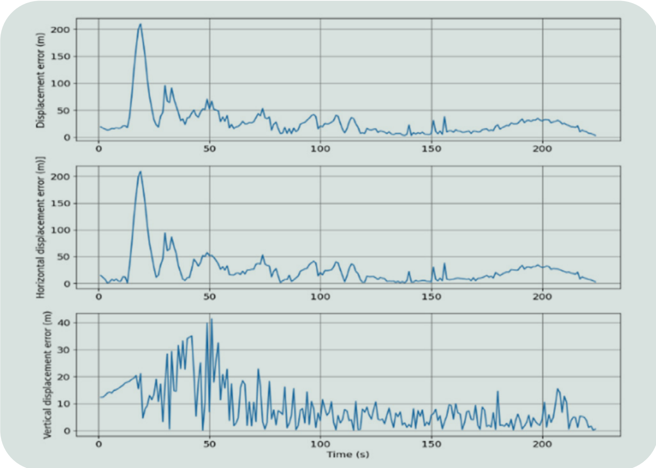
In this section, the performance evaluation of the absolute pose estimation algorithm is showed. Following the stage described above on the Absolute VBN, this methodology has been adopted: a series of uniformly spaced images have been captured along the initial segment of the landing trajectory, from 17 to about 14 km of altitude. Each image has been processed by the absolute pose estimation algorithm, which has involved detecting craters, matching them with the onboard catalogue, and retrieving the pose by solving the corresponding PnP problem. The camera's boresight axis has been assumed to be pointing to the nadir direction for the entire descent phase. Figure 5 shows the trend of the total error and its components, both horizontal and vertical, alongside the number of detected and matched craters. The selected lunar region serves as an excellent test case for the algorithm, featuring a diverse array of craters in terms of size, density and distribution.
Firstly, the lander overflies an area with scarce distribution of craters, resulting in increased error. For approximately 10 seconds, the number of matched craters is insufficient to solve the associated EPnP problem [5]. An increment in number of the detected and matched craters corresponds to a general decrease in the error level. Note that an equal number of matched craters does not always yield the same error level. This discrepancy is due to the presence of mismatched craters and varying crater arrangements within the images. In the final segment of the trajectory, the reduced altitude no longer allows for a sufficient number of craters to be detected or matched with the onboard database, so it becomes necessary the implementation of a relative VBN algorithm. The absolute VBN pipeline has yielded an average position error of 270.14 m, with a horizontal component of 216.11 m and a vertical component of 54.028 m.



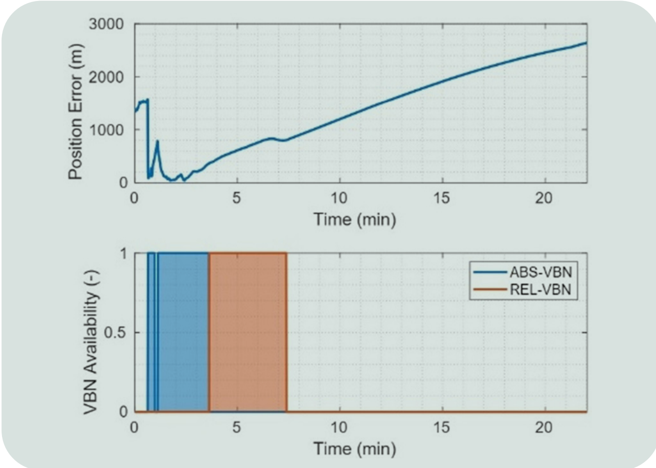
5-Position estimation error of the Absolute VBN along the first trajectory segment, from 17km to about 14km of altitude. The no. of detected and matched craters is also showcased, along with the horizontal and vertical position error components

Case 2: Relative VBN Algorithm Performance

Figure 6 shows the time evolution of the error in the estimation of relative displacement, with its horizontal and vertical components, along the trajectory segment of interest. The mean error is approximately 25 m, with horizontal and vertical components of 22.39 m and 5.83 m, respectively.



6 - Time evolution of the error in the estimation of relative displacement, with its horizontal and vertical components



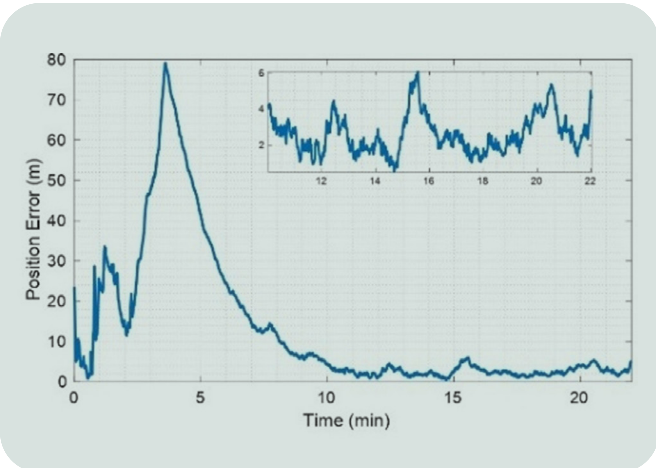
7 - EKF navigation error with IMU, altimeter and VBN and availability of the Absolute and Relative VBN measurements. The thrusting phase begins at minute 3.

Case 3: VBN / IMU / Altimeter + 1 Navigation Satellite

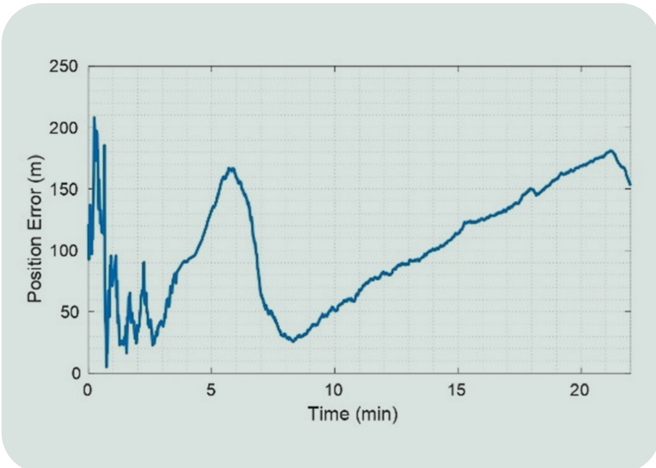
Figure 7 shows the navigation performance when the VBN measurements are integrated within a navigation filter that further leverages the IMU and altimeter readings. Simulations have shown that the usage of the relative VBN measurement can reduce the final navigation error up to 1 km, with respect to the scenario in which only the absolute measurements are leveraged. Finally, once all the VBN measurements become unavailable, the position error keeps increasing because, similarly to the initial few minutes, the filter does not have enough observables to properly determine the lander state.

Case 4: VBN / IMU / Altimeter + 4 Navigation Satellites

Figure 8 reports the position error when the previous architecture is further enhanced with the usage of one-way measurements from a NAV constellation. In this way, it is possible to improve the position estimation. A total of four navigation satellites are visible throughout the whole landing trajectory. It stands clear that, thanks to the optimal constellation geometry, once the filter has reached convergence, the navigation error is extremely small. The only exception happens at about 4 minutes, when a peak error of about 80m is reached. However, such sudden drop in performance is caused by the large thrust manoeuvers performed to target the desired landing site.



8 - EKF navigation error with IMU, altimeter, VBN and 4 NAV satellites



9 - VBN / IMU / Altimeter + 1 Navigation Satellite + TWR

Case 5: VBN / IMU / Altimeter + 1 Navigation Satellite + TWR

The last case investigated, whose results are reported in Figure 9, shows the situation in which only a single one-way navigation signal is captured by the on-board receiver. However, at the same time, an additional and more accurate observable with respect to the OWR signals is obtained by performing TWR with a satellite along a 12h period ELFO. With this configuration, the overall position error never exceeds 200m. It is important to stress that the actual error strongly depends on the relative geometry of the satellites with which OWR and TWR are performed [6]. If they are closely aligned, the information provided by the two will not allow an accurate reconstruction of the trajectory, due to the much higher dilution of precision. Additionally, after 9 minutes, i.e., when the VBN measurements cease to be available, the position error gradually increases because a single OWR satellite, also together with the TWR and altimeter readings, is not enough to provide complete observability of the state. Considering this point, the benefits of having a VBN solution are clearly evident during the earliest minutes of the landing, where the position error is consistently kept below 100m.

CONCLUSIONS

This section provides a summary of the work presented and highlights the next steps. The IMMV^2 tool, developed in the Telespazio R&I Labs, has been presented. Exploiting the capabilities of its VSG module, it is possible to generate highly precise, geolocated and realistic lunar orbital/surface scenarios and, consequently, high-resolution images, fundamental for the VBN process.
Then, an advanced navigation architecture based on multi-sensor fusion, with the integration of different measurements and VBN module, has been presented.
The simulations have highlighted that a proper integration of OWR signals provided by a Lunar NAV Constellation, inertial sensors and VBN can guarantee good navigation performance for a landing user. Five use cases have been presented. They show how a combination of VBN, IMU, Altimeter and four Navigation Satellites can guarantee a position error in the order of tens of meters. If only one satellites is present, a combination of OWR, VBN, IMU and altimeter can guarantee good navigation performance below 100m, until the absolute VBN provides measurements.
As soon as the relative navigation is introduced, the position error increases, remaining below 1 km.
Furthermore, it is worthwhile to note that the position error can be mitigated and lowered below 200 m, if this latest configuration is integrated with a TWR observable provided by an ELFO orbiter in an optimal relative geometrical configuration with respect to the navigation satellite.
The VBN complete pipeline for both absolute and relative mode has also been presented. In the case of absolute VBN, it demonstrates an average position error of 270.14 m, with horizontal component of 216.11m and vertical component of 54.028 m.. In the case of relative VBN, the average position error is of 25 m, with horizontal and vertical components of 22.39 m and 5.83 m, respectively.

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A User-Driven Trade-Space Analysis Framework for the Concurrent Design of Optimal Space Mission and System Architectures

Alessia De Matteis

Telespazio S.p.A

This work presents a holistic, user-driven approach to the preliminary design of Space missions and system architecture. It integrates Set-Based Concurrent Engineering (SBCE) and Model-Based Systems Engineering (MBSE) to align technical configurations with diverse user needs. The method unfolds in five phases: formulation, enumeration, simulation, evaluation, and down-selection using Pareto optimality. It enables the optimization of mission architectures by balancing technical performance (e.g., revisit time, latency, coverage) with user satisfaction, offering a flexible, iterative framework for decision-making and trade-off analysis across multiple domains.

INTRODUCTION

The complexity of modern engineering systems such as those of the Space sector, necessitates of advanced methodologies to manage and optimize the design, implementation, and operations. System Engineering (SE) plays a crucial role in this process, providing an environment to the development and management of complex projects. One of their definitions from [1], asserts that “systems are integrated set of elements created and used to provide products or services for the benefit of users and other stakeholders”, remembering SE fundamental aspect of the focus on end users. Understanding and prioritizing user needs ensures that the systems developed are not only technically optimal, but also deliver satisfaction to their users, granting their success especially in contexts such as those of satellite constellations [8]. Current Space scenario is undergoing a rapid transformation with the influx of private companies [2], increasingly assuming roles formerly held by government Space Agencies, or collaborating with them. This trend fosters close collaboration between public and private Space Agencies, promoting the development of mega-constellations of small satellites for different purposes via Medium Earth Orbit (MEO) or Low Earth Orbit (LEO), and providing more affordable services at lower costs [3][4].

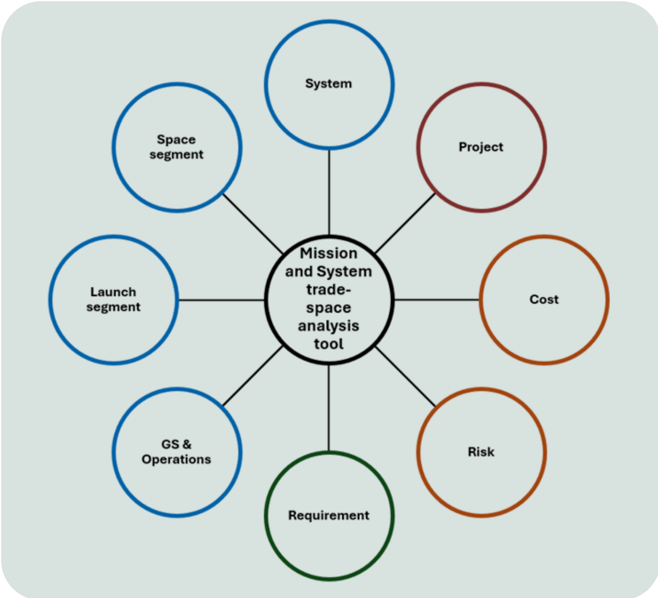
To effectively incorporate user needs into the preliminary design process of such complex systems, the Model-Based System Engineering (MBSE) and Set-Based Concurrent Engineering (SBCE) are invaluable. The MBSE uses comprehensive models to manage system complexity, It ensures that all the requirements are traceable and that the system design is coherent and robust, thus facilitating the translation of requirements into technical specifications [5][6]. This capability is perfectly aligned with the current trend of Industry 4.0 [7][8], in particular with the consideration of a digital model as the central hub where designers can work together, enhancing the efficiency of the system. SBCE complements this by enabling the exploration of multiple “compatible” (feasible industrial products) design configurations simultaneously, helping to identify optimal solutions early in the design process, fostering innovation and reducing risks associated with the conventional sequential design methods [9]. The integration of the MBSE and SBCE within a user-focused framework supports systematic and iterative design adjustments, ensuring that technical performance is aligned with user expectations.

The combination of these methodologies not only streamlines the decision-making but also ensures that the final system architecture maximizes both technical efficiency and user satisfaction. The purpose of this paper is therefore to present an integrated user-driven trade-space analysis framework for the preliminary design of Space constellations.

THE HOLISTIC USER-DRIVEN FRAMEWORK

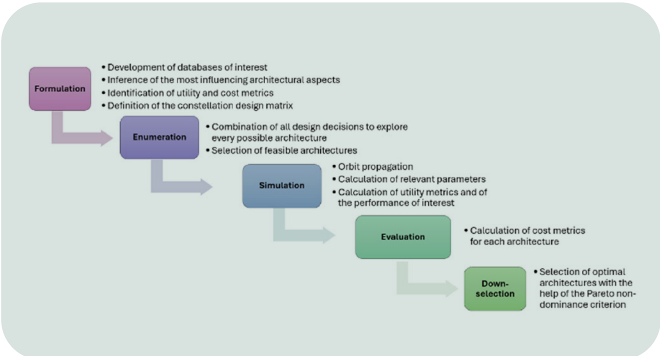
The necessity for an integrated framework capable of optimize the preliminary design process of a constellation in order to obtain more efficiency and less waste of resources, leads the research to a framework based on the following systematic holistic user-based approach [10][11]. The conceptualization of an advanced mission and system trade-space analysis framework demands for a holistic and integrated approach capable of traversing diverse engineering dimensions, including crucial aspects such as system, project, costs, risks, requirements, ground segment, launch segment, Space segment, and operations.
This complexity necessitates a sophisticated assessment system capable of addressing dynamic interactions among these varied categories [12].
The primary objective of this analytical framework is to provide a means for the simultaneous analysis of the involved variables, considering the extensive range of inputs provided through databases playing a central role in informing the decision-making process. Variables may encompass system design parameters, operational requirements, associated costs, potential risks, and various other pertinent factors.
Integrating different engineering perspectives into a unified platform enables the visualization and analysis of relationships between categories, thus facilitating to understand critical trade-offs and interactions among different aspects of the system.

This multidimensional approach paves the way for a more comprehensive and accurate assessment, allowing engineers to effectively explore the extensive trade-space and make informed decisions at every stage of the system development.



1-Capabilities of the trade-space analysis tool environment

A MODEL-BASED APPROACH FOR THE PRELIMINARY DESIGN OF CONSTELLATIONS



2-The trade-space approach for the preliminary design of constellations

The **formulation phase** is preceded by the identification and study of users' needs and by the definition of technical constraints. It is articulated in the following steps:

1. Development of a customer/users database of locations and requirements;
2. Inference of the most influencing architectural aspects, Constraints and Assumptions;
3. Identification of relevant utility and revenue/cost metrics for users;
4. Definition of the constellation design matrix. It aims at identifying some key features of the constellation.

The first step is to create: A **user requirements database** extrapolated by the user needs analysis. This database serves as a critical instrument to ensure that the preliminary design meets specific requirements coming from the user needs. it is a database of the locations of interest, derived from the user needs, with an assigned priority score so to ensure that essential needs are met first. Then the **definition of constraints** (e.g., a defined range of orbit altitudes to consider for obtaining a minimum requested resolution from users) **and assumptions** (e.g., circular orbits or radar frequency for SAR sensors) is followed by the definition of the most influencing architectural aspects for the preliminary design. These are, for example, the number of satellites composing the constellation, as well as the orbital planes and the total mass of each satellite. As inference, it follows the definition of **utility metrics and revenue metrics**. Utility metrics are measures that allow to evaluate how much a system satisfies the technical requirements e.g., the data-rate or the amount of the downlinked data from the constellation, the resolution of the images taken by the constellation, the coverage of the interested zones taken by the constellation. Revenue metrics, instead, are measures that allow to evaluate how much the system generates in terms of both financial or user revenue, e.g., the financial profits and the return on investment of the constellation, the reduction of its operative costs and the satisfaction of the user needs. Both utility and revenue metrics constitute the fundamental performance measures. These considerations are crucial for the passage from the business case of users and customers to the technical case of the utility and revenue metrics.

Finally, a "**constellation design matrix**" is defined. In a constellation design matrix each row represents an individual architectural parameter of the constellation, together with its quantitative values. Therefore, it is a matrix in which all the variable parameters chosen by the designer are listed inside the first column, while all the variable values belonging to the parameter are listed inside the subsequent columns. The constellation design matrix is a core concept of the formulation phase because it is the output of the phase that represent this first technical-user-focused analysis. The number of satellites, the number of orbital planes, the orbital altitude, the on-board memory, the aperture diameter of the optical instrument and the antenna bit rate are the parameters that go varying for the analyses of different constellation architectures. The constellation design matrix and technical assumptions and constraints in output from the formulation phase are the inputs for the **enumeration phase**. It is divided into the following phases:

1. Combination of all design decisions to explore every possible architecture;
2. Selection of orbital and architectural parameters.

Inside this phase all the architectural configurations of the constellation design matrix are explored by combining the variable parameters of each line of the constellation design matrix with those of the other lines. For example, the constellation design matrix in Table 1 generates 144 configurations (2 #sat · 3 #orbital planes · 3 orbital altitudes · 2 o.b.memories · 2 SAR payloads · 2 downlink antenna bitrates).

# sat	24	48	
# orbital planes	3	4	6
Orbital altitude	600 Km	800 Km	1000 km
o.b. memory	256 GB	512 GB	
SAR payload	SAR Payload A	SAR Payload B	
Antenna bitrate	300 Mbitps	500 Mbitps	

Table 1 - Example of constellation design matrix

The enumeration allows the combination of all the design decisions to explore all the possible architectures and to select them, discarding the unfeasible ones according to designers' decisions. The selected architectural combinations are the outputs of this step. The utility metrics and the database of the locations of interest, with their priority values defined in the formulation phase as well as the architectures given in output from the enumeration, are the inputs for the **simulation phase**. This step consists in:

1. Orbits Propagation;
2. Relevant parameters (Access times to consequently handle other specific aspects of the constellation);
3. Calculation of the utility metrics and of the parameters of interest.

It simulates the propagation of the orbits of the satellites belonging to each architecture, computing a relevant performance, such as accesses to ground stations, or maybe visibility parameters, to finally calculate the utility metrics. Architectures for the constellation are evaluated in the fourth step of the method based on the user requirements database, the revenue metrics and the simulation's output. It consists in evaluating each architecture with the revenue metrics. The calculation is done basing on the previous results of the simulation.

With the help of the importance scores defined according to the user needs, utility, and revenue metrics, two cost functions are created as follows.

$$\text{Revenue Cost} = \sum_{j=1}^{n} \left(\sum_{i=1}^{k_j} \text{Weight}_i \cdot \text{Sign}_i \cdot \text{RevenueMetric}_i \right)$$

$$\text{Utility Cost} = \sum_{j=1}^{n} \left(\sum_{i=1}^{k_j} \text{Weight}_i \cdot \text{Sign}_i \cdot \text{UtilityMetric}_i \right)$$

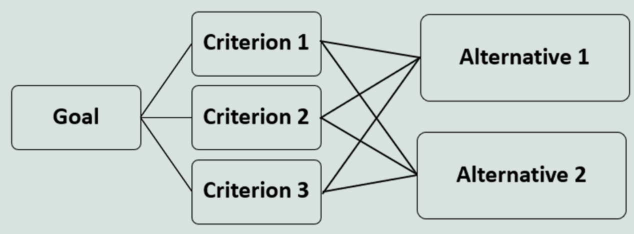
Revenue metrics could differ depending on the case study considered (e.g., the term "revenue" could indicate financial metrics of revenue or user metrics of revenue as it serves to evaluate architectures from different points of view). It defines the financial profit generated by the sale of services, or by the reduction of operating costs due to services provided by the constellation, but it also gives a quantitative measure of the satisfaction of user needs in terms of services provided by a constellation. The **down-selection phase** performs a down-selection of solutions by applying the Pareto non-dominance criterion.

Inputs of this phase are revenue/cost and utility metrics, and it makes use of the Pareto non-dominance criterion to find a Pareto frontier of optimal solutions in terms of utility and revenue in a trade-space of solutions containing all architectures considered inside the simulation (represented by a point inside the trade-space). The Pareto non-dominance criterion is based on the concept of dominance: the set of non-dominated solutions (Pareto front) is the set of points (of the trade-space) for which no solution exists that outperforms them. The criterion allows designers to identify the architectures with the most efficient trade-offs across utility and cost metrics, in fact, the trade-space could be bi-dimensional, but also multi-dimensional, depending on different typologies of metrics considered.

THE FRAMEWORK

Based on the approach already introduced, the user-focused framework presented takes as input information from the industrial world and from the service context in which the constellation has to be inserted. In particular, the input information specifies industrial constraints in a SBCE database trough compatible configurations, Payload and Platform specifications, and user needs constraints in a user needs database through services, their importance values, and market analysis. The integration of the SBCE and MBSE provides substantial benefits in industrial and service environments. The SBCE is an approach that encourages the parallel exploration of multiple design solutions, allowing for the evaluation of various options and gradual convergence on the optimal solution. The MBSE, on the other hand, uses digital models to define, analyse, and verify the requirements and functionalities of a complex system. Their combination enhances the management of design complexity and accelerates the development cycle. In industrial settings, this translates into reduced development times and costs, increased product quality, and greater flexibility in responding to changing market requirements [5][9]. In services context, this integration optimizes operational processes, improve resource efficiency, and ensure faster implementation of innovations [6]. Overall, the combined adoption of the two approaches represents a winning strategy for tackling the complex challenges of the modern world, promoting a more robust and adaptive approach to the development of complex systems [13]. The information is elaborated within two parallel paths, as described in the following:

1. A formulation of a constellation design matrix of possible alternatives for the considered Area or Volume of Interest satisfaction of services is done. In this way the following steps of simulation are assessed. Then, all the possible architectures are filtered according to the enumeration step constraints of the presented approach and then, they are all simulated with the tool used by the designer. Utility and Revenue metrics are found, weighted through an Analytical Hierarchy Process (AHP) [14] (Figure 3), and compared within a final trade-space exploration of solutions. Figure 4 shows the framework for each step.
2. A digital model of the complex system and its requirements through the MBSE is done (Figure 5).

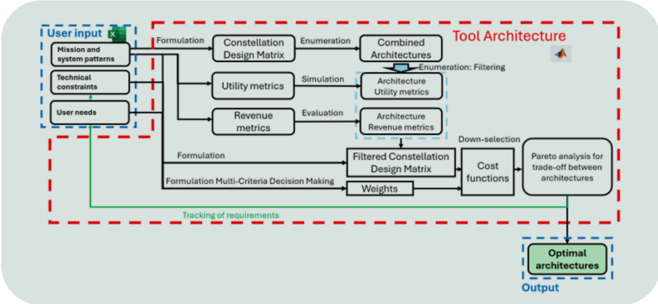


3-Diagram representing AHP principles

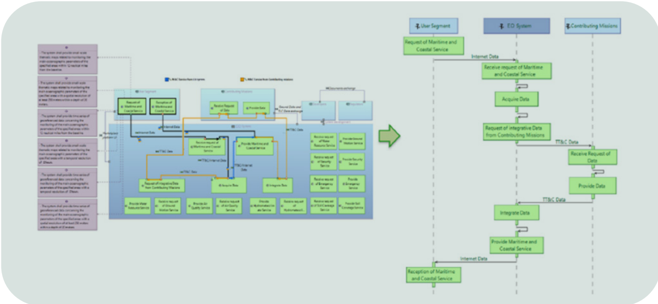
The outputs from the analysis, specifically the digital model with assigned requirements and Pareto frontier optimal solutions, are crucial for guiding further design studies.

The digital model with assigned requirements serves as a comprehensive and dynamic representation of the system, capturing all the necessary specifications and constraints in an accessible and modifiable format. This facilitates better communication and collaboration among stakeholders, ensuring that all the design considerations align with the project's goals [5] and, therefore, aligning with current trend of Industry 4.0.

The Pareto frontier represents the set of optimal solutions that balance multiple competing objectives, such as cost, performance, and risk. By providing a visual and analytical means to assess trade-offs, the Pareto frontier helps designers to identify the most efficient and feasible solutions, streamlining the decision-making process [15]. Availability of these outputs enables a more informed and efficient design process, reduces the risk of costly iterations and enhances the overall quality and robustness of the final product.



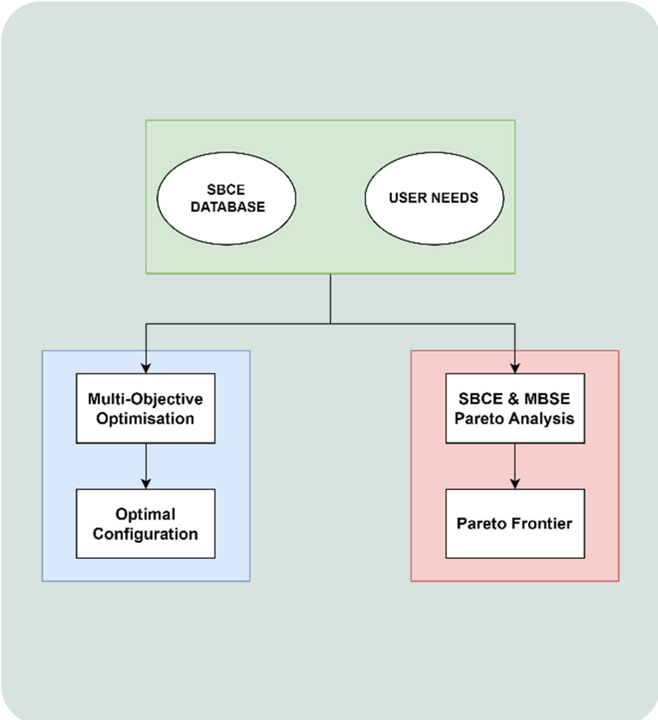
4-Framework used for the preliminary trade-space analysis of Space mission systems



5-Example of Digital Model, in particular of System architecture with functional chains and assigned user needs on the left and the respective temporal scenario on the right

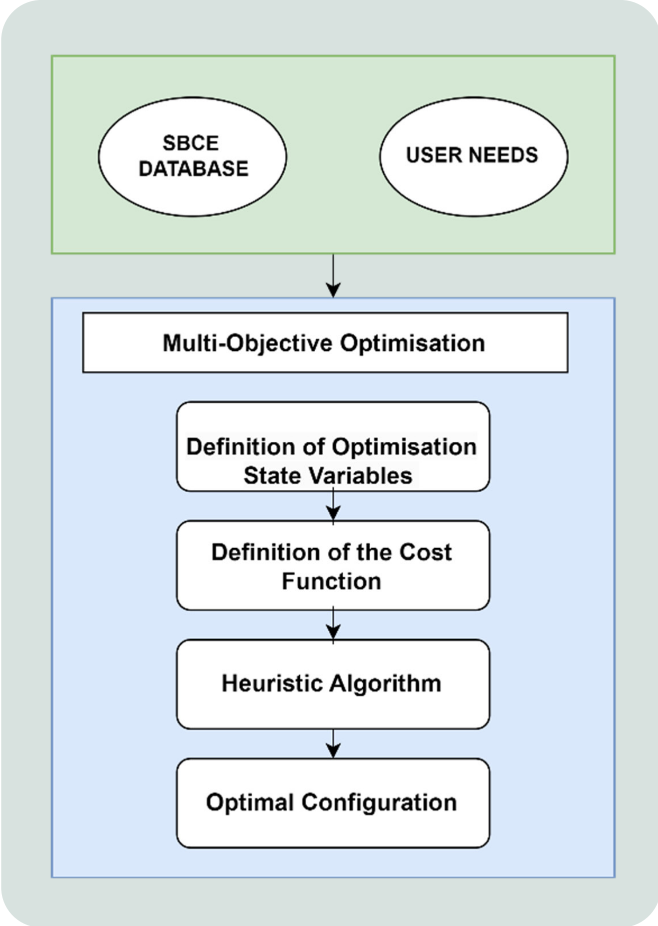
ALTERNATIVE DOWN-SELECTION APPROACH

Down-selection is the last stage of the framework for designing the optimal solution. It can follow a different approach than the Pareto analysis, which evaluates multiple compatible constellation configurations and performs trade-space analysis. This approach is useful when the number of compatible configurations is very large and utility and revenue matrices have a large number of parameters to consider.
Alternatively, when, for example, the constraints and inputs allow us to search for the optimal solution over a small set of possible configurations, in that range of variability it is possible to search for the optimum by applying the Multi-Objective Optimization that uses heuristic algorithms to identify which optimal configuration can be adopted to select the optimal solution. Both of the workflows share the same inputs: the SBCE database and the user needs database, as shown in Figure 6. Multi-Objective Optimization uses heuristic algorithms to identify the optimal configuration that meets the user needs while respecting the system constraints. These algorithms are widely applied in Space mission design, particularly for Earth Observation and global coverage missions, where balancing multiple objectives is essential [16] [17].



6-Framework Block Diagram

Figure 7 illustrates the block diagram of the Multi-Objective Optimization tool. While the inputs to this optimization are the same as those used in the Pareto analysis, the methods differ significantly in approach.
The optimization process starts by defining the state variables, typically the classical orbital elements (e.g., inclination, semi-major axis, eccentricity, and argument of perigee) derived from the user needs and the SBCE database. These variables are bounded and constrained basing on the mission-specific requirements, including launch constraints and operational limitations.
Next, a cost function is defined, incorporating key performance indicators (KPIs) such as the revisit time, coverage, and access duration. This function guides the algorithm towards the configurations that best align with mission objectives. To ensure accuracy, the cost function must be designed to avoid conflicting objectives and reflect the user's priorities.
After defining the parameters, the heuristic algorithm is executed. Unlike the Pareto analysis, which explores a broad set of potential solutions, the Multi-Objective Optimization focuses on finding out the specific configuration that best satisfies the user's needs. The algorithm iteratively explores the solution space, adjusting the configuration until the optimal solution is identified.
For successful convergence, the search space must be carefully defined, and the cost function must align the objectives to avoid conflicts. The proper definition of these elements ensures that the optimization algorithm can explore the solution space efficiently and converge on a feasible, optimal configuration.



7-Multi Objective Optimisation Cost Function

CONCLUSIONS

The proposed methodology integrates the Model-Based Systems Engineering (MBSE) and the Set-Based Concurrent Engineering (SBCE) to enhance the preliminary design process of complex Space systems. This approach supports the parallel exploration of multiple design alternatives and the development of a comprehensive digital model that aligns the user needs with technical requirements. By maintaining a broad design Space, the integration of the MBSE and the SBCE fosters a flexible and adaptive process, capable of responding to evolving user demands and industrial constraints, while ensuring efficient traceability of requirements from both perspectives.

A robust and flexible design environment is essential to improve clarity and efficiency in the early design stages. A key outcome is the creation of a unified digital MBSE model that serves as a single source of truth across all subsystems, reducing ambiguity, improving communication, and minimizing costly iterations. Overall, the SBCE integration offers significant advantages: aligns with industrial constraints, explores compatible configurations, evaluates performance comprehensively, and optimizes solutions. The framework is scalable and adaptable, offering broad applicability across various mission types and system architectures.

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An Integrated Space Mission and System Modelling Analysis for Complex Space Design: the Earth Observation Case Study

Alessia De Matteis
Telespazio S.p.A.

The article introduces a trade-space analysis tool designed to support complex Space mission planning, with strong emphasis on its application to a real-world case study. Specifically, the tool is applied to feasibility studies for Earth Observation missions, including hybrid configuration. It enables automated exploration of mission architectures by evaluating multiple variables, constraints, and performance metrics by using Pareto non-dominance in a multi-dimensional Space. This allows decision-makers to assess how changes in design preferences do affect trade-offs across domains like cost, risk, and service quality. Within the Telespazio Concurrent & Collaborative Design Facilities (C2DF), where expert judgment traditionally guides trade-offs, the tool represents a significant shift, as it allows automating these processes. The case study demonstrates the tool's adaptability and effectiveness in identifying optimal solutions and revealing unexpected trade-offs. Ultimately, the application highlights the tool's value in enhancing the earliest mission design phases through a systematic, model-based approach that supports informed and flexible decision-making.

INTRODUCTION

In response to growing complexity of the modern Space missions, particularly in the domain of Earth Observation (EO), this work highlights the application of an advanced design support tool that optimizes the EO constellation planning. The EO missions, such as those involving large satellite constellations, present unique challenges due to the need to coordinate multiple subsystems and meet diverse service requirements. Traditional engineering approaches often fall short in managing such complexity, especially during early design phases. To address this, the study applies a model-based methodology within the Telespazio C2DF environment, demonstrating how automated trade-space analysis can improve the decision-making. The tool's effectiveness is showcased through a dedicated EO case study, where it supports the exploration of architectural alternatives and helps identifying optimal configurations. This application underlines the tool's value in improving the efficiency, flexibility, and robustness of the EO mission design, particularly in scenarios with hybrid constellation in terms of platform and payload.

TRADE-SPACE ANALYSIS TOOL OVERVIEW

The trade-space analysis tool (described in detail in [18]), applied in this case study, is able to integrate various components related to Space mission design including space, and launch segment, ground segment and operations, system, project, risk, and cost analysis. The tool is articulated in five phases (Figure 1):

Formulation Phase:
- Build a database of user needs and locations of interest, including priority levels;
- Define utility metrics (e.g., data rate, resolution) and revenue metrics (e.g., ROI, profitability).
- Enumeration Phase:
- Create a constellation design matrix listing architectural parameters (e.g., number of satellites, orbits);
- Generate and simulate all possible configurations to compute Key Performance Indicators (KPIs) and utility metrics.

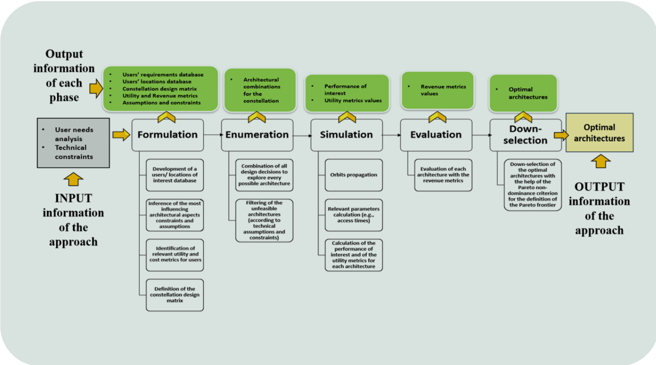
Enumeration Phase:
- Create a constellation design matrix listing architectural parameters (e.g., number of satellites, orbits);
- Generate and simulate all possible configurations to compute Key Performance Indicators (KPIs) and utility metrics.

Evaluation Phase:
- Evaluate each architecture by using revenue metrics;
- Apply cost functions for utility and revenue, weighted by importance scores derived from user needs:

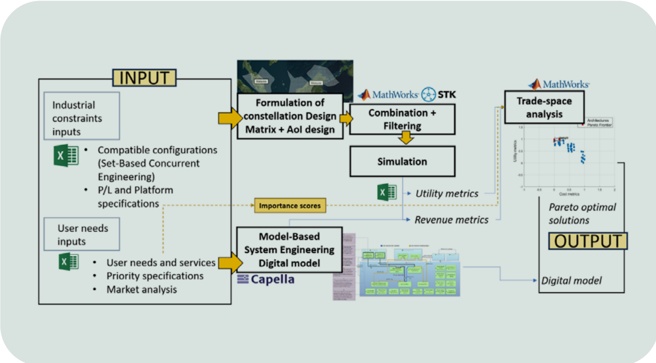
Down-selection Phase:
- Use the Analytic Hierarchy Process (AHP) [3] to determine metric weights via pairwise comparisons;
- Perform the Pareto-based trade-space exploration to identify optimal configurations [4].

All phases foresee the **MBSE Integration:**
- Build a digital model using ARCADIA methodology in Capella© [5];
- Link requirements to system functions and entities, enabling real-time visualization and validation of user needs.

The primary objective is to facilitate the exploration and optimization of different system architectures by analysing a wide range of input variables provided through an Excel©-format database.



1-Trade-space analysis tool concept overview



2-Architecture of the trade-space analysis tool based on the SBCE, MBSE approach principles

These variables encompass industrial constraints such as compatible configurations, payload and platform specifications, and the user needs input through services to provide, priority specifications, market analyses. The tool consists of a parallel between the Model-Based Systems Engineering (MBSE), built with the Capella© software, and the Set-Based Concurrent Engineering (SBCE), built with Matlab© and STK©, having continuous interactions thanks to the integration within the design process of the user needs specifications and requirements (Figure 2).

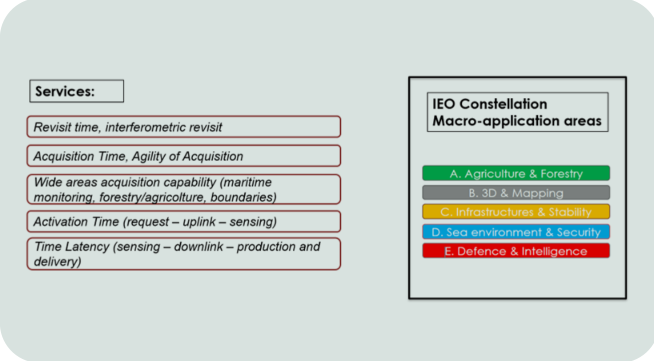
EO CONSTELLATION CASE STUDY

EO small satellite constellations are playing a pivotal role within the new Space economy, as they offer near-real time capabilities for remote sensing [6], [7]. By providing high-resolution imagery and data across multiple spectral bands, they are revolutionizing industries such as agriculture, disaster management, urban planning, and climate science [9]-[14]. Between this wide range of services, the maritime and coastal ones, such as vessel tracking, maritime traffic management, and environmental monitoring, gain significant advantages through enhanced real-time data accuracy and comprehensive coverage 0 [2][15][16]. One of the key challenges in the deployment of EO constellations for such diverse applications is ensuring that the constellation design meets the specific needs of each use case, while remaining cost-effective and sustainable. Therefore, a SAR constellation for maritime services has been studied as the case study for the early application of the tool [15].

User needs and industrial inputs analysis

The design of this SAR constellation begins with the identification of the technical constraints of the satellites and the specific needs of maritime and coastal users.

The formulation phase, for capturing the evolving user inputs, includes discrepancy and gap analysis, development of a user needs matrix (traceability matrix), prioritization, territorial segmentation, integration with preliminary design simulations, and final impact analysis.
The process begins by identifying discrepancies between user needs from previous European EO missions and insights from current market analyses. This ensures a comprehensive understanding of emerging service demands.
A tabular framework is created where rows represent the user needs and columns capture the key data categories, such as macro-areas (e.g., agriculture, 3D mapping), area of interest, acquisition time, and technical requirements. This structure clarifies the relationships between services and technical specifications, serving as a foundation for traceability.
The macro-area organization, shown in Figure 3, supports the definition of priority levels and enables automatic requirement prioritization based on the specific user or customer.
The EO mission's area of interest is then divided into distinct geographic segments, with user needs assigned accordingly. This segmentation supports location-based prioritization and is fundamental to link the user needs with the technical aspects of the preliminary design. In fact, the simulations for the trade-space analysis of the preliminary design of an EO constellation will be done with the segmentation introduced inside this phase. Figure 6 shows an example of segmentation of this case of study regarding a scenario of the Mediterranean Area of interest and EEZ.
The inputs from the industrial environment can be put inside different Excel sheets, in order to maintain coherence with a SBCE environment. An example of this is showed in Figure 4. The SAR payload and platform specifications are set and are the industrial inputs and constraints for future simulations and future studies.
These parameters are used to create detailed databases that guide the selection of the key metrics for the constellation's performance (Figure 5): revisit time, latency, coverage, and cost.
Considering all the information from the input databases, in the enumeration phase, the constellation design matrix is defined. Variable architectural parameters are selected: number of satellites, number of planes, inclination, phase between satellites in the same plane, right ascension of the ascending node, network of ground stations.
All the admissible configurations are provided by combining all the constellation design matrix parameters, so before moving to the simulation phase, one must have properly filtered out all the unfeasible and meaningless configurations.



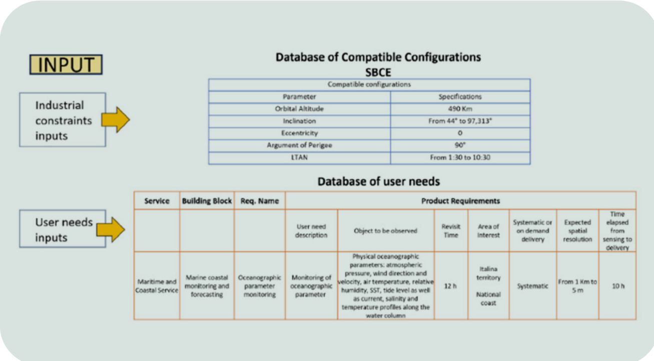
3-Macro-areas and services potentially given from the new constellation under study

Platform	
Parameter	**Specification**
Lifetime	6 years
Launchers Compatibility	Vega-C
Propulsion Type	Electrical

AOCS	
Parameter	**Specification**
Flight attitudes	Nadir Point (+Z Nadir, +X Vel) Sun Point (+Y Sun, +X Vel) Firing (Pitch 90°) Roll (+-50°)
Max roll rate (deg/s)	1.3
Max pitch rate (deg/s)	0.65
Max yaw rate (deg/s)	0.40

Sensor Payload	
Parameter	**Specification**
Radar Frequency	X-band (9300-10300MHz).
Performance Range (FOR)	15-50 deg
Data Access Range	15-50 deg
SM Swath	25 km
SM GR Resolution	2.3 m
SM Az Resolution	2.3 m

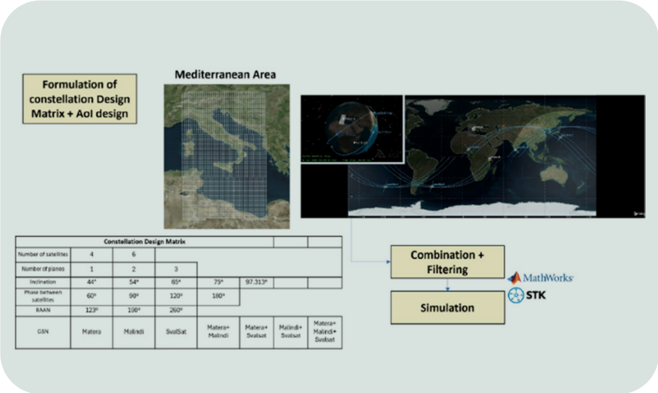
4-Excel SBCE industrial inputs and constraints for the SAR preliminary analyses



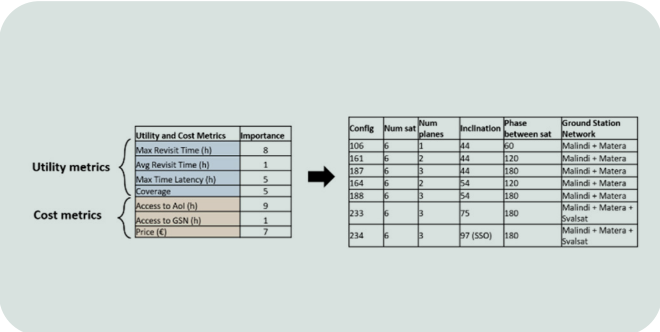
Compatible configurations	
Parameter	Specifications
Orbital Altitude	490 Km
Inclination	From 44° to 97,313°
Eccentricity	0
Argument of Perigee	90°
LTAN	From 1:30 to 10:30

Service	Building Block	Req. Name	Product Requirements						
			User need description	Object to be observed	Revisit Time	Area of interest	Systematic or on demand delivery	Expected spatial resolution	Time elapsed from sensing to delivery
Maritime and Coastal Service	Marine coastal monitoring and forecasting	Oceanographic parameter monitoring	Monitoring of oceanographic parameter	Physical oceanographic parameters: atmospheric pressure, wind direction and velocity, air temperature, relative humidity, SST, tide level as well as current, salinity and temperature profiles along the water column	12 h	Italina territory National coast	Systematic	From 1 Km to 5 m	10 h

5-Inputs from user needs and technical constraints put inside databases



6-Constellation design matrix and high-level diagram of the different phases of the tool structured in Matlab© and STK©



Utility metrics / Cost metrics

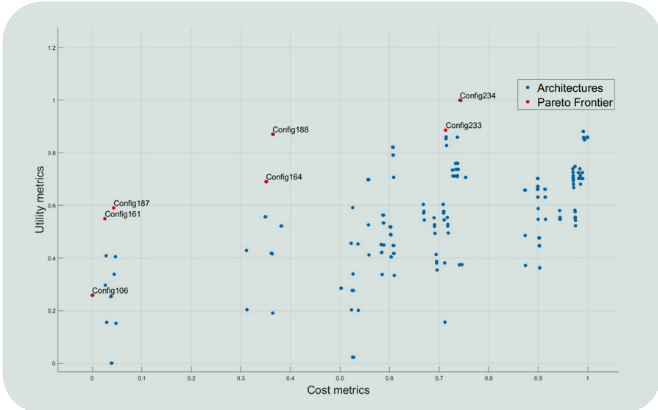
Utility and Cost Metrics	Importance
Max Revisit Time (h)	8
Avg Revisit Time (h)	1
Max Time Latency (h)	5
Coverage	5
Access to AoI (h)	9
Access to GSN (h)	1
Price (€)	7

Config	Num sat	Num planes	Inclination	Phase between sat	Ground Station Network
106	6	1	44	60	Malindi + Matera
161	6	2	44	120	Malindi + Matera
187	6	3	44	180	Malindi + Matera
164	6	2	54	120	Malindi + Matera
188	6	3	54	180	Malindi + Matera
233	6	3	75	180	Malindi + Matera + Svalsat
234	6	3	97 (SSO)	180	Malindi + Matera + Svalsat

7-Utility and cost / revenue metrics with respective importance values used for the trade-space analysis

Trade-space and Pareto Analysis

The input of the last phase, the Down-selection phase are the utility and revenue metrics values evaluated in the Simulation phase, while the output of this phase is the best configuration.
After the creation of utility and cost / revenue weight functions, their values for each architecture are compared within the trade-space, and the Pareto frontier of optimal solutions in cost and utility metrics is found (Figure 7, Figure 8).



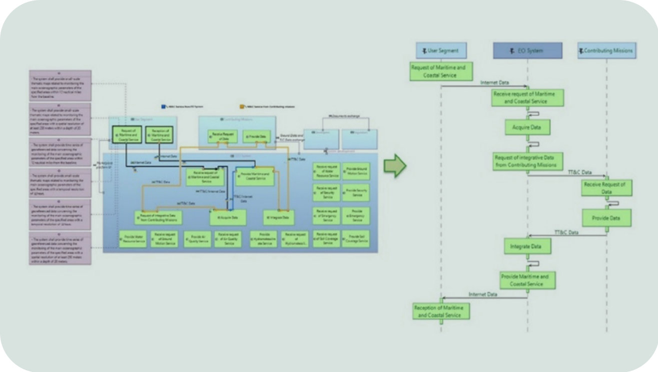
8-Trade-space analysis according to utility and revenue/ cost metrics weight functions of the different configurations for the space architecture, with respective Pareto frontier

RESULTS AND DISCUSSION

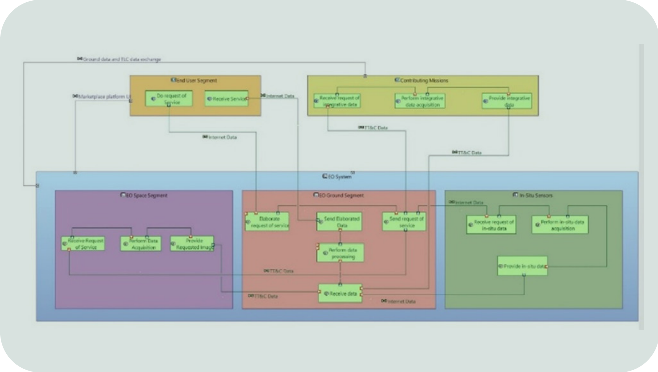
Results of this comprehensive design process reveal that the optimal SAR constellation consists of six satellites. Depending on the specific performance and cost requirements, different configurations may be selected according to the requirements specified within the other output of the tool: the digital model of the system (Figure 9, Figure 10, Figure 11). A high-performance, high-cost configuration includes satellites with high orbital inclinations and multiple ground stations to ensure global coverage and low latency. In contrast, a medium-performance, medium-cost configuration reduces the number of ground stations or selects a lower inclination to balance cost and performance. Finally, a low-performance, low-cost configuration is suitable for missions with less stringent requirements, where cost savings are prioritized over coverage and revisit time (Table 1). By leveraging advanced modelling tools and methodologies, such as MBSE and SBCE, it is possible to develop constellations that meet the diverse needs of users across multiple sectors, while remaining sustainable and within the budget.

Configuration	Importance	Config 106	Config 161	Config 187	Config 164	Config 188	Config 233	Config 234
Max Revisit Time (h)	8	19,5	10,8	11,6	8,9	8,4	4,7	5,1
Avg Revisit Time (h)	1	16,7	8,2	8,4	7,9	6,8	4,5	4,7
Max Time Latency (h)	5	0,10	0,12	0,13	0,05	0,05	5,7	1,3
Tot Coverage of AoI	5	1	1	1	1	1	1	1
Access to AoI (h)	9	34,2	33,8	33,5	26,6	26,4	18,8	18,1
Access to GSN (h)	1	79,5	79,2	78,6	79,3	77,3	118,0	148,8
Price (M€)	7	26,3	32,3	34,3	32,3	34,3	40,2	40,2

Table 1-Pareto frontier values of utility and cost / revenue metrics



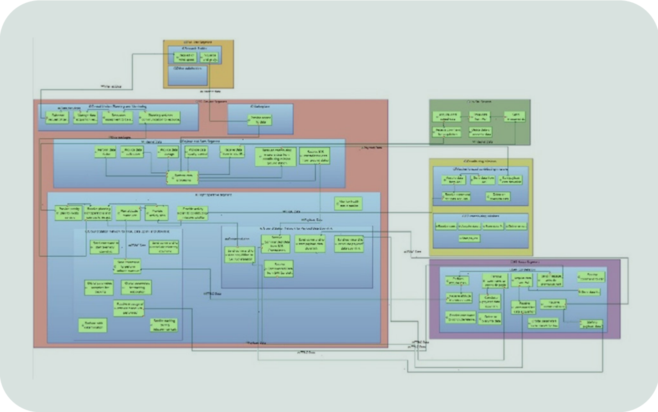
9-EO System analysis with Capella©



10-High level EO System logical analysis with Capella©

CONCLUSIONS

The paper illustrates in a realistic application the power of applying an integrated, holistic, trade-space analysis tool that implements SBCE and MBSE for the integration of the user needs within the preliminary design process of a small satellite constellation. Its efficiency has been proved thanks to its application on a preliminary design of a SAR constellation. Seven optimal configurations in revisit time, time latency, coverage, access to Area Of Interest, Access to Ground Station Network, and Price, are found. One of the significant innovations of this tool is addressing towards the automation of the Telespazio Concurrent & Collaborative Design Facilities (C2DF) trade-off process.



11-Second level EO System logical analysis with Capella©

By integrating MATLAB©-driven automation, the tool enhances efficiency and accuracy of the system development, enabling engineers to rapidly evaluate a broad range of architectural possibilities. Future developments are the enhancements of the automation of the tool, with advanced connections between Capella Software©, Matlab©, STK©, and Excel©, as well as with the application to bigger constellations, different services, and, therefore, multi-payload constellations.

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