→ THE EUROPEAN SPACE AGENCY

CONVERGING EARTH AND SPACE: 6G NON-TERRESTRIAL NETWORKS

By ESA CSC (Connectivity and Secure Communications)
Space for 5G/6G and Sustainable Connectivity

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Acronym	Definition
3GPP	Third Generation Partnership Project
4S	Space Systems for Safety and Security
5G	5th Generation
5G EOSiS	5G Earth Observation Server in Space
5GAA	5G Automotive Association
6G	6th Generation
6G-LINO	6G Laboratory In-Orbit
AI	Artificial Intelligence
AICOMS	AI for Satellite 5G Communications
ARM	Advanced RISC Machine
ARQ	Automatic Repeat Request
ARTES	Advanced Research in Telecommunications Systems
AT	Advanced Technology
CCSDS	Consultative Committee for Space Data Systems
CEPT	European Conference of Postal and Telecommunications Administrations
C&G	Competitiveness & Growth
CSC	(ESA) Directorate of Connectivity and Secure Communications

Acronym	Definition
D2D	Direct-to-Device
DFT	Discrete Fourier Transform
DIFI	Digital Intermediate Frequency Interoperability
DSP	Digital Signal Processing
DVP	Digital Video Broadcasting
ECC	Electronic Communications Committee
ECSAT	European Centre for Space Applications and Telecommunications
EDRS	European Data Relay Satellite System
EOSiS	5G Earth Observation Server in Space
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
ESTOL	ESA Specification for Terabit/sec Optical Links
ETRI	Electronics and Telecommunications Research Institute, South Korea
ETSI	European Telecommunications Standards Institute
EU	European Union
FBMC	Filter Bank Multicarrier

Acronym	Definition
FCC	Federal Communications Commission
FM22	Working Group Frequency Management Project Team (CEPT)
FPGA	Field Programmable Gate Array
GEO	Geostationary Earth Orbit
GFDM	Generalised Frequency Division Multiplexing
gNB	Next Generation NodeB
GNSS	Global Navigation Satellite System
GSMA	The GSM Association
GSOA	Global Satellite Operators Association
HAPS	High Altitude Platform Station
HELENA	Highly Skilled Satellite community Members to drive 3GPP NTN standardization
HydRON	High Throughput Optical Network
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IoT	Internet of Things
IRIS²	Infrastructure for Resilience, Interconnectivity and Security by Satellite
ISAC	Integrated Sensing and Communication

Acronym	Definition
ISL	Inter-Satellite Link
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
LEO	Low Earth Orbit
MEC	Multi-access Edge Computing
MEO	Medium Earth Orbit
MIXELS	Demonstration of an experimental 5G g-NodeB in space
MNO	Mobile Network Operator
MSS	Mobile Satellite Services
MSSA	Mobile Satellite Services Association
NB	Narrowband
NDA	Nondisclosure Agreement
NR	New Radio
NTN	Non-Terrestrial Network
OCT	Optical Communication Terminal
OFDM	Orthogonal Frequency Division Multiplexing
O-RAN	Open Radio Access Network
OTFS	Orthogonal Time Frequency Space

Acronym	Definition
PAPR	Peak to Average Power Ratio
PAT	Pointing, Acquisition and Tracking
PIC	Photonic Integrated Circuit
PNT	Positioning, Navigation, and Timing
PPP	Public Private Partnership
QKD	Quantum Key Distribution
QoS	Quality of Service
R&D	Research and Development
RAN	Radio Access Network
REMI	Direct Access 5G Satcom Reference Mission
RF	Radio Frequency
RIC	Radio Intelligent Controller
RIS	Reconfigurable Intelligent Surface
SA	System Architecture
SAA	Seamless Air Alliance
SATCOM	Satellite Communications

Acronym	Definition
SCS	Supplemental Coverage from Space
SDA	Space Development Agency
SDN	Software Defined Networking
SMO	Service Management and Orchestration
SNO	Satellite Network Operator
SNS-JU	Smart Networks and Services Joint Undertaking
SPL	Strategic Programme Line
Tbps	Terabit-per-second
TEC	(ESA) Directorate of Technology, Engineering and Quality
TN	Terrestrial Network
UAV	Unmanned Aerial Vehicle
V2X	Vehicle-to-Everything
WG	Working Group
WRC	World Radiocommunication Conference
XR	Extended Reality

EXECUTIVE SUMMARY

As digital infrastructure becomes more integral to societal well-being and economic growth, it is essential to overcome the geographic and environmental limitations of terrestrial networks. 6G Non-Terrestrial Networks (NTNs) represent a revolutionary extension of digital connectivity, integrating space and airborne platforms into the mobile ecosystem to provide secure, resilient, and ubiquitous coverage across the globe.

This whitepaper outlines the European Space Agency's (ESA) bold vision to position Europe at the forefront of 6G NTN innovation. Through coordinated action across research, standardization, infrastructure development, and industrial collaboration, Europe can lead the deployment of a sovereign, open, and inclusive global communications fabric. ESA's roadmap features flagship missions, such as Sunrise, 5G EMERGE and HydRON, next-generation research and development (R&D) platforms like the ECSAT and ESTEC 5G/6G NTN laboratory, and strategic partnerships to align spectrum, technology, and policy for long-term impact.

NTNs will:

- Unlock seamless mobile broadband for billions, including in remote, maritime, and underserved areas.
- Power intelligent networks with onboard artificial intelligence (AI) and edge computing.
- Enable secure quantum-encrypted and optical communications.
- Drive societal transformation through new applications in health, security, sustainability, and mobility.

The paper addresses the core technological and system-level challenges and opportunities facing 6G NTN, including the need for direct-to-device development with intelligent network automation, scalable onboard processing, and robust multi-orbit system design. A central focus is placed on the future role of optical communications within NTN, not only to enhance capacity and inter-satellite networking, but also as a foundational component for secure, high throughput links in emerging NTN architectures.

The convergence of terrestrial and non-terrestrial networks is no longer optional, it is inevitable. Europe must act now to ensure that this transformation reflects our values and serves the common good.

"6G Non-Terrestrial Networks (NTNs) represent a revolutionary extension of digital connectivity, integrating space and airborne platforms into the mobile ecosystem to provide secure, resilient, and ubiquitous coverage across the globe."

1. NTN EVOLUTION:

Reimagining the Global Connectivity Fabric

Non-Terrestrial Networks (NTNs) are evolving from traditional satellite communication into fully integrated components of the terrestrial-mobile infrastructure. They form a hybrid ecosystem combining satellites in low Earth orbit (LEO), medium Earth orbit (MEO), and geostationary Earth orbit (GEO) with high altitude platform stations (HAPS) and unmanned aerial vehicles (UAVs), delivering dynamic, low latency services at scale.

This section explores the foundational structure of NTN, the current market and policy landscape, and the breadth of applications enabled by 6th Generation (6G).

1.1 OVERVIEW OF NTN

Modern NTNs provide broadband, Internet of things (IoT), and mission-critical services across challenging environments. They are no longer siloed from terrestrial networks but instead designed to function as native extensions of mobile systems, with direct-to-device (D2D) capabilities, regenerative payloads, and hybrid radio frequency (RF)-optical links.

Key enablers include:

- Third Generation Partnership Project (3GPP)-compliant protocol stacks onboard satellites.
- Optical inter-satellite links (ISL) and Quantum Key Distribution (QKD) for secure data transfer.
- Unified network management across terrestrial network (TN) and NTN domains.

This shift ensures NTNs are agile, interoperable, and capable of supporting emerging verticals. It is important to highlight that while legacy satellite communications can be regarded as a component of an expanded NTN ecosystem, the term NTN in its current form, differs in terms of scope, standardisation, and integration with TNs. Table 1 outlines the key distinctions between NTN and traditional satellite communication systems.

In our view, NTN can also expand to include advanced optical communication technologies, such as ISL, ground-to-space optical communications, quantum communications, and QKD. More importantly, ESA envisions hybrid RF/optical communication solutions as a fundamental component of the future satellite communication (SATCOM) landscape. A comprehensive discussion on hybrid technologies is provided in Section 3.

Table 1: Key differences between NTN and legacy Satellite Communication systems.

	NTNs	Legacy SATCOM
System Architecture	Encompass satellites, HAPS, UAVs	Limited to satellite-based communication
Standardisation	Integrated into 3GPP (5G/6G) standards	Uses proprietary or International Telecommunication Union (ITU) / European Telecommunications Standards Institute (ETSI) defined standards (i.e., Digital Video Broadcasting [DVB] based)
Integration with TN	Works seamlessly with TNs	Operates independently or with limited integration
Use Cases/ Technology	Includes D2D, NTN-based IoT, backhaul, hybrid RF-Optical	Primarily used for broadband, TV, military

1.2 CURRENT LANDSCAPE

NTNs are undergoing a historic transformation—shifting from niche satellite systems to integral pillars of the global digital infrastructure. This evolution is driven by the convergence of disruptive technologies, new standardisation pathways, and bold industrial strategies. NTNs are no longer complementary—they are becoming essential.

COMMERCIAL MOMENTUM AND MARKET MATURITY

The global NTN market is accelerating, fuelled by the rise of LEO mega-constellations, reducing launch costs, and the advent of D2D capabilities. Pioneering players are deploying multi-orbit networks that support both broadband and narrowband IoT services. From maritime coverage to low-power tracking, NTN use cases are now commercially viable across multiple verticals.

The D2D segment is particularly dynamic, targeting a vast addressable market of over 5 billion smartphone users. Among D2D service flavours—direct-to-phone, direct-to-terminal, and NTN-IoT—the direct-to-phone model promises the fastest growth, with forecasts exceeding 50% compound annual growth by 2033[1]. These solutions are now being embedded into mainstream handsets, supported by both satellite and terrestrial mobile network operators. A comprehensive analysis of the various D2D partnership frameworks and go-to-market models are provided in two reports[1] [2].

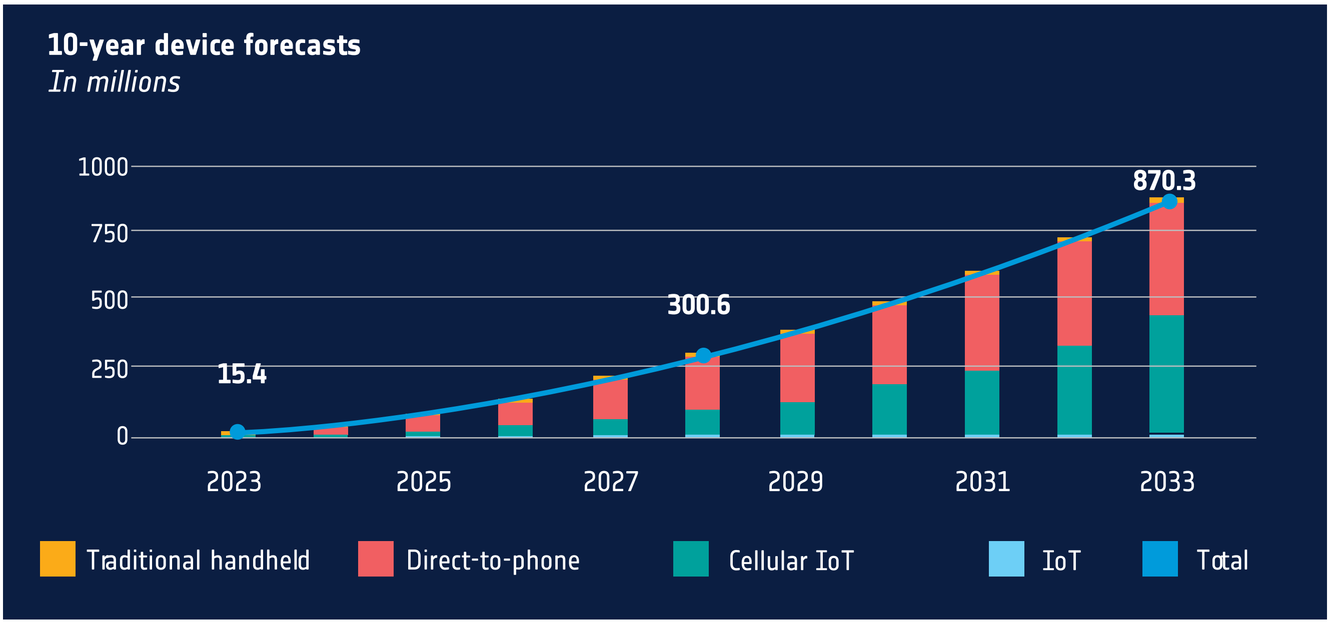


Figure 1: Device forecast demonstrating the growth potential of different D2D flavours[1].

STANDARDISATION ADVANCEMENTS

NTNs have progressed from experimental concepts to standardised components of the global mobile ecosystem. Since 3GPP Release 17, satellite support has been integrated into official specifications. The upcoming Release 20 and 21, will embed NTN support into native 6G architectures, including regenerative payloads, mesh networking, and NTN-aware radio access protocols.

This alignment ensures NTNs can leverage existing device ecosystems, operate under unified mobility management frameworks, and support multi-access edge computing (MEC) in space. ESA has played a critical role in these developments through ongoing contributions to 3GPP Radio Access Network (RAN) and System Architecture (SA) groups.

ECOSYSTEM COLLABORATION

The current NTN ecosystem is characterised by novel multi-stakeholder business models that blend traditional satellite expertise with mobile-native approaches. Satellite Network Operators (SNOs), Mobile Network Operators (MNOs), hyperscalers, and chipset vendors are forming cross-sector alliances to jointly address:

- Spectrum coordination and licensing
- RAN virtualisation and O-RAN compliance
- Billing and service integration
- Global roaming and seamless handovers

These partnerships accelerate time-to-market, unlock economies of scale, and ensure service continuity across domains.

REGULATORY PROGRESS

Globally, regulators are increasingly recognising the strategic role of NTN in delivering universal service and ensuring resilience. Notable milestones include:

- The Federal Communications Commission (FCC)'s Supplemental Coverage from Space (SCS) framework, which allows SNOs to partner with terrestrial MNOs and share spectrum dynamically.
- The World Radiocommunication Conference (WRC)-27 agenda, which includes dedicated studies on satellite-based International Mobile Telecommunications (IMT) use, particularly in sub-3 GHz bands.

These frameworks pave the way for flexible licensing models, interoperability, and interference protection across NTN and TN systems.

STRATEGIC RELEVANCE

As geopolitical tensions and climate risks challenge traditional infrastructure, NTNs offer a resilient, sovereign, and globally available alternative. From emergency communications and disaster recovery to defence-grade security and redundancy, NTNs are now considered strategic assets in national infrastructure planning.

1.3 USE CASES AND APPLICATIONS OF 6G NTN

The integration of NTNs into the 6G ecosystem unlocks a new era of intelligent, pervasive, and resilient digital services—serving humanity beyond the limitations of terrestrial infrastructure. 6G NTN supports a broad spectrum of use cases across sectors, environments, and mission types. Its ability to combine global reach, low latency, high throughput, and enhanced security makes it a unique enabler for both commercial and societal transformation.

The fundamental NTN use cases are defined in "Study on using satellite access in 5G"[3] and further expanded in "Study on satellite access – Phase 3"[4], along with various technical reports[5]-[8], refining them to align with the evolving requirements of 6G. In our view, the following use cases will have the most significant impact in the 6G era.

D2D Broadband Access

Building on existing and upcoming 3GPP NTN releases, 6G NTN will significantly enhance seamless mobile broadband by connecting billions of users in remote, maritime, and sparsely populated areas. D2D communication will play a key role in ensuring service continuity during terrestrial network outages and natural disasters. This capability is essential for bridging the digital divide and advancing global digital inclusion.

Device-to-Device Connectivity

Beyond network coverage, 6G NTN enables direct communication between devices, even when ground networks are unavailable. This supports ultra-resilient mesh networks for critical operations, such as emergency response, tactical defence, and autonomous fleet coordination, where immediate peer-to-peer communication is vital.

Remote Healthcare and Emergency Services

NTNs deliver ultra-reliable, low-latency links to power telemedicine, remote diagnostics, and connected ambulances in rural and isolated regions. During natural disasters or pandemics, NTNs can ensure real-time situational awareness, live medical consultations, and rapid deployment of emergency networks where terrestrial systems are disrupted or overwhelmed.

Smart Agriculture and Remote Industry

6G NTN provides precision connectivity for agriculture, mining, and energy operations in remote areas. Real-time data from IoT sensors enables efficient water use, pest control, and yield monitoring, while ensuring safety and productivity in hazardous environments like oil rigs, wind farms, and deep mines.

Autonomous Transport and UAV Networks

Autonomous vehicles, drones, and next-generation aviation systems will require uninterrupted, high-precision communications. NTNs support vehicle-to-everything (V2X) connectivity, in-flight control, drone traffic management, and maritime navigation across global corridors. NTN's global footprint ensures continuous service across cross-border and off-grid routes.

Environmental Monitoring and Climate Intelligence

NTNs enable persistent observation of environmental indicators—from wildfire tracking and flood detection to air quality monitoring and deforestation alerts. Coupled with edge AI, NTN satellites can process and relay actionable data in real time, enhancing disaster prediction, response, and climate mitigation strategies.

Global Asset Tracking and Supply Chain Visibility

From shipping containers and aircraft to livestock and humanitarian aid, NTNs offer end-to-end asset visibility, even in the most remote supply chains. Through low-power satellite IoT devices, enterprises gain predictive insights on asset location, condition, and security—boosting efficiency, transparency, and resilience.

High-Precision Positioning, Navigation, and Timing (PNT)

6G NTN augments the traditional global navigation satellite system (GNSS) with centimetre-level accuracy, high integrity, and timing synchronisation. This supports critical infrastructure, precision agriculture, automated ports, and defence systems, offering redundancy and robustness against jamming, spoofing, or terrestrial disruptions.

Extended Reality (XR) Applications and the Industrial Metaverse

The improved latency, timing and Artificial Intelligence (AI) orchestration of Software Defined Networks (SDNs) for 6G NTN will provide high throughput traffic required of future XR devices and software. Thanks to optimised 6G networks, high polygon counts will be easy to stream alongside audio and live video Holographics to users anywhere on earth. These refinements will encourage the adoption of Industrial Metaverse applications where IoT sensors and high-fidelity CAD renders combine to create digital copies of critical infrastructure and equipment for active monitoring and support.

2. ADVANCED FEATURES OF 6G NTN:

Intelligence, Interoperability, and Innovation

2.1 KEY TECHNOLOGY DRIVERS

Although 6G and by extension 6G Non-Terrestrial Networks (NTNs) have not yet been fully defined, several emerging technological advancements are expected to play a pivotal role in enabling the seamless integration of NTN within the 6G ecosystem. The European Space Agency (ESA) envisions the following key technologies as instrumental in shaping this evolution.

Artificial Intelligence (AI) and Edge Computing in Space

The combination of AI and edge computing in space is emerging as a key enabler for intelligent, autonomous network operations. Satellites are expected to perform real-time data processing onboard, which significantly reduces latency and dependence on ground infrastructure. By deploying lightweight AI models and distributed learning at the edge, these platforms can dynamically manage network resources, optimize routing decisions, make efficient use of spectrum resources, mitigate interference, and generally adapt to changing conditions. The ability to process, interpret, and act on data directly in orbit moves NTN much closer to meeting the requirements of real-time, mission-critical services in 6G, particularly those aligned with the use cases outlined in the previous section. ESA has recently released a whitepaper discussing state-of-the-art AI technologies for Terrestrial Network (TN) and NTN connectivity[9].

Advanced Radio Interfaces and 6G Regenerative Payloads

Regenerative payloads and advanced radio interfaces are central to how 6G non-terrestrial networks are being designed to operate with more autonomy and intelligence. By handling protocol processing directly onboard, regenerative payloads reduce round-trip delays and ease reliance on ground infrastructure, making them key to enabling real-time services in orbit[10]. When these systems adopt Open Radio Access Network (O-RAN) principles, they support disaggregated and virtualised RAN functions, bringing flexibility and interoperability across different vendor ecosystems. In addition, placing specific O-RAN components directly onboard, as proposed in Space O-RAN concepts[11], creates the foundation for embedding AI control within the RAN. This enables more efficient spectrum use, dynamic beam steering, and real-time responsiveness, all of which are critical for NTN to operate at scale and adapt to varying conditions.

Beam Forming and Antenna Technologies

Beamforming and advanced antenna technologies are fundamental to the performance and flexibility of 6G NTN. Electronically steerable arrays allow satellites to dynamically direct beams toward specific users or regions, improving link quality and reducing interference. Multi-beam capability, combined with frequency reuse, enables better spectral efficiency, essential for scaling coverage in dense or high-demand areas. In Low Earth Orbit (LEO) systems, fast beam tracking ensures service continuity as satellites move rapidly across the sky. These technologies also support dynamic cell shaping, making it possible to allocate capacity on demand.

Advanced Waveforms

Advanced waveforms are currently under investigation to tackle key 6G NTN challenges, including severe Doppler shifts, large propagation delays, synchronisation complexity, and strict power constraints. Prominent candidates such as Orthogonal Time Frequency Space (OTFS), Generalised Frequency Division Multiplexing (GFDM), Filter Bank Multicarrier (FBMC), and Discrete Fourier Transform spread Orthogonal Frequency Division Multiplexing (DFT-s-OFDM) offer improved Peak to Average Power Ratio (PAPR), spectral efficiency, and robustness compared to OFDM, with OTFS notably strong against Doppler effects. While Third Generation Partnership Project (3GPP) NTN standardisation still relies primarily on OFDM-based waveforms, the introduction of advanced waveforms may be explored in future releases, depending on research progress and evolving 6G use cases.

Integrated Sensing and Communication (ISAC)

ISAC is envisioned as a foundational component of the 6G vision, enabling dual-purpose waveforms to support both connectivity and remote sensing from spaceborne or airborne platforms. A key use case involves detecting unauthorised UAVs in restricted airspace using NTN payloads, enhancing security in no-fly zones. Another NTN scenario applies ISAC for maritime monitoring, where LEO satellites provide broadband access alongside ocean surface sensing to aid shipping and navigation. These applications leverage NTN's wide-area coverage and persistence to extend ISAC capabilities beyond terrestrial limitations. Additional NTN-related ISAC use cases such as disaster response, environmental monitoring, and border surveillance are documented in a study report[12], which outlines several use cases across terrestrial and non-terrestrial domains.

TN/NTN Orchestration and Management

TN/NTN orchestration and management frameworks must coordinate end-to-end lifecycle management, mobility anchoring, and dynamic spectrum sharing and service placement across both domains. O-RAN concepts such as the Non-Real-Time Radio Intelligent Controller (RIC) and Service Management and Orchestration (SMO) can be extended to support NTN elements by enabling cross-domain resource optimisation. Similarly, 3GPP defines the management architecture for network slicing and performance assurance, which can be expanded to include NTN nodes through interface alignment and unified data models. Orchestrators must handle challenges such as high-latency links, variable beam coverage, and intermittent connectivity, making AI-driven, intent-based orchestration essential. This convergence enables critical use cases including uninterrupted communications, inflight connectivity, and remote IoT service delivery, amongst all, managed under a common automation framework.

The integration of TN/NTN networks with data network management is also a key focus of ESA's High Throughput Optical Network (HydRON) mission, further detailed in Section 5. HydRON aims to de-risk the deployment of end-to-end optical satellite communication (SATCOM) networks, and in doing so, will develop, mature, and demonstrate advanced network management concepts. These will mirror the orchestration and automation capabilities anticipated in future 6G systems, providing a realistic testbed for validating next-generation TN/NTN integration strategies.

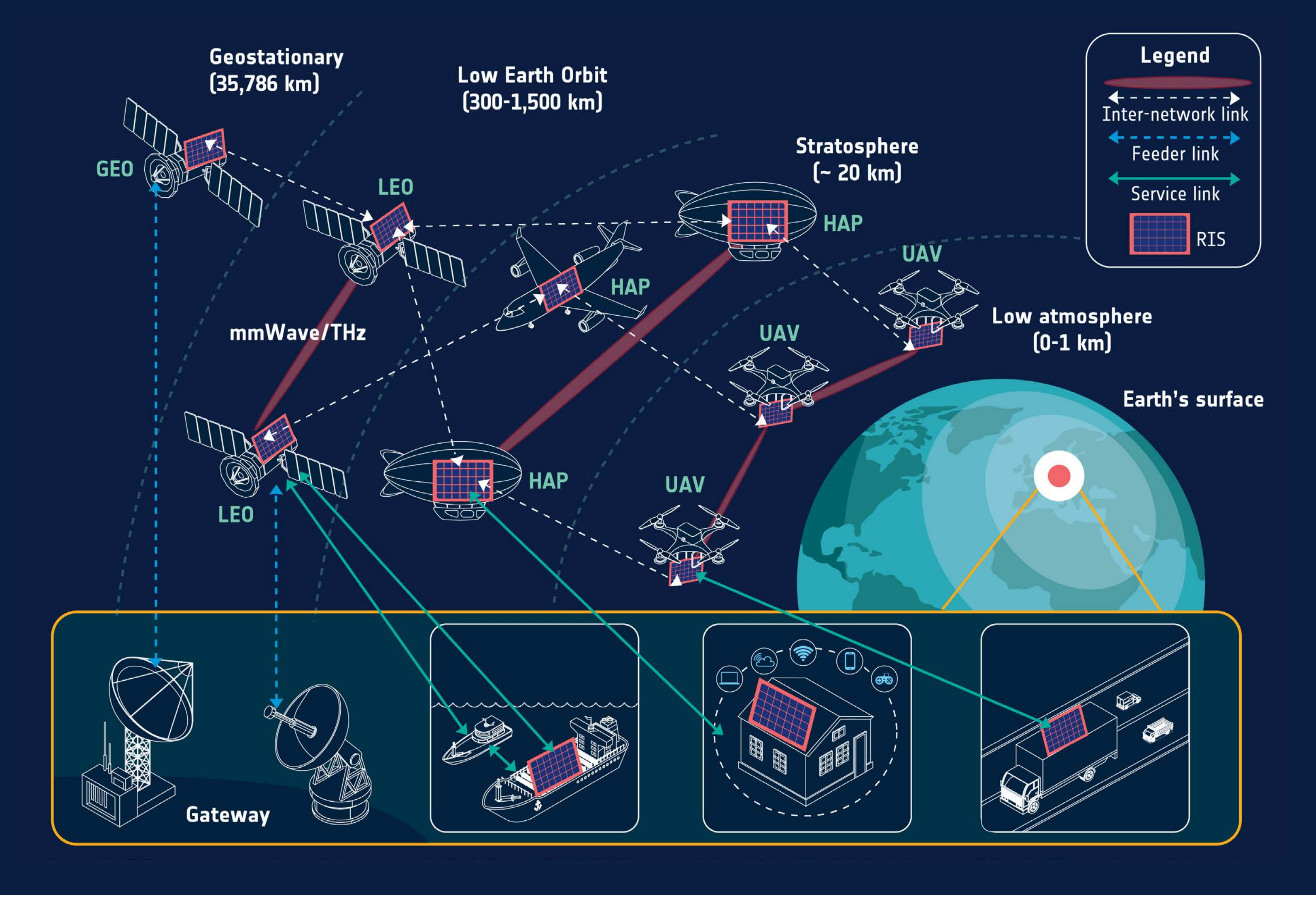


Figure 2: RIS integrated in 3D NTN[13].

Reconfigurable Intelligent Surfaces (RIS)

RIS can be a key enabler for boosting the flexibility and performance of NTN in 6G. By intelligently controlling how radio waves are reflected, or transmitted, RIS can improve link quality where traditional satellite signals face challenges like blockages or signal fading[13]. They can be deployed on aerial platforms to extend coverage in dense urban areas or during emergency situations where ground infrastructure is compromised. For moving platforms like planes and ships, RIS supports real-time beam steering, keeping links stable and efficient. In space, RIS can also support inter-satellite links by managing interference and enhancing signal directionality. On top of that, RIS helps with secure and energy-efficient backhaul and enables smarter use of spectrum through reflective control. Altogether, RIS adds an extra layer of adaptability to NTN deployments, helping push toward more resilient, efficient, and globally available networks.

Energy-Efficient Developments

Energy-efficient technologies are becoming a critical design pillar for NTN. Energy optimisation spans across multiple layers of the NTN architecture, from payload design and adaptive waveform strategies to intelligent link management and traffic scheduling. In relation to RIS deployments discussed previously, they can reduce active power consumption by passively manipulating signal propagation, while energy-aware beamforming and sleep-mode strategies allow satellites and user terminals to dynamically adapt to real-time demand. Power-efficient hardware and low-resolution signal processing are being studied to minimise consumption at the physical layer. Additionally, the AI-based resource orchestration enables predictive traffic steering and load balancing, optimising energy use across both ground and space segments. These approaches align with 6G's ambition to achieve sustainable, energy efficient infrastructure, without compromising global connectivity.

2.2 STANDARDISATION AND REGULATORY LANDSCAPE

At the time of writing, 3GPP standardisation efforts are centred on the development and finalisation of Release 19, scheduled for completion in December 2025. The March 2025 3GPP 6G Workshop in Incheon, South Korea, played a pivotal role in aligning the industry's vision and setting key priorities for the evolution of next-generation radio technologies, system architectures, and protocol frameworks.

A fundamental objective of 6G is the pursuit of ubiquitous coverage. In this context, NTN is expected to be integrated as a native and foundational component of 6G from the early stages of the standardisation process. International Mobile Telecommunications (IMT)-2030 timelines for terrestrial and satellite systems align with the start of the 6G normative phase under Release 21.

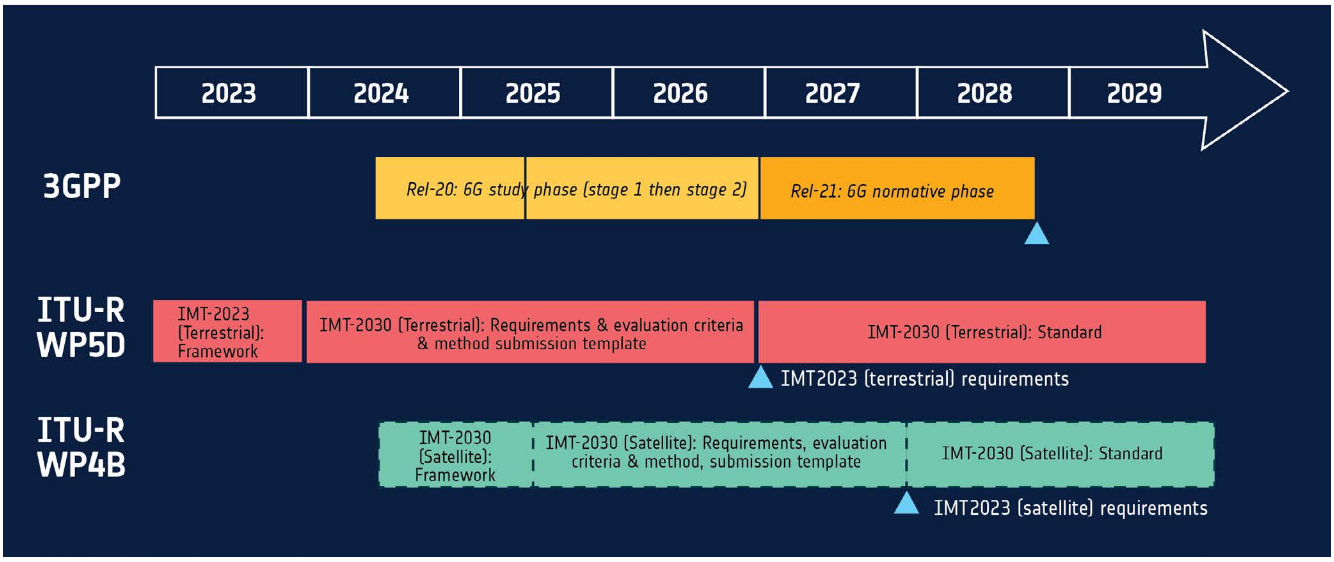


Figure 3: Indicative timelines for IMT-2030 and 3GPP 6G standardisation activities.

In parallel, regulatory efforts are advancing to secure spectrum for Mobile Satellite Services (MSS). WRC-27 Agenda Item 1.13 is evaluating potential new allocations for MSS in the 694–2700 MHz range to enable direct satellite-to-device services. These studies address spectrum needs and compatibility with terrestrial systems. The main objective is to ensure that MSS stations do not cause harmful interference to, or claim protection from, stations operating in the mobile service[14].

The FCC's SCS framework[15]—formalised in 2024—allows Satellite Network Operator (SNO)- Mobile Network Operator (MNO) collaborations for shared use of terrestrial bands, enabling hybrid satellite-cellular services. The T-Mobile and Starlink authorisation under this framework represent a milestone in eliminating coverage gaps.

In contrast, Europe lacks an equivalent framework due to fragmented spectrum ownership across member states. Nevertheless, momentum is building through IRIS² and European Union (EU) regulatory dialogues that seek to harmonise access.

3. ESA DRIVING VISION:

Strategic Autonomy through Innovation

The European Space Agency (ESA) is uniquely positioned to lead Europe's efforts in shaping the future of 6G non-terrestrial networks (NTNs). As a trusted, neutral convener with deep technical expertise and a proven innovation track record, ESA drives forward industrial alignment, cross-sector integration, and global leadership in space-enabled connectivity. ESA's strategic approach supports Europe's ambitions for digital sovereignty, resilience, and sustainable growth.

3.1 INDUSTRY COLLABORATION FRAMEWORK

ESA plays a pivotal role in catalysing the integration of space-based systems into the terrestrial-dominated 6G ecosystem. This is primarily enabled through its flagship programme— **Advanced Research in Telecommunications Systems (ARTES)**—which provides financial and technical support across multiple Strategic Programme Lines (SPLs) and cross-cutting initiatives[16].

Key ARTES domains include:

- Space for 5G/6G and Sustainable Connectivity.
- Space Systems for Safety and Security (4S).
- ScyLight for Optical and Quantum Communications.
- Generic Programme Lines supporting Partnership Projects, Advanced Technology (AT), and Competitiveness & Growth (C&G).

Through ARTES, ESA empowers industry to develop and validate critical building blocks for 6G NTN, such as:

- Direct-to-device (D2D) access and protocol stacks.
- Multi-orbit system architectures.
- Optical and quantum payloads.
- Secure and resilient satellite-terrestrial integration.

These efforts are fully aligned with Europe's standardisation roadmap and market strategy, ensuring that innovation translates into scalable infrastructure and competitive commercial services.

3.2 STANDARDS AND PARTNERSHIPS

ESA plays a central role in shaping and supporting global standardisation efforts and fostering strategic partnerships that ensure the successful integration of satellite systems into next-generation networks.

3rd Generation Partnership Project (3GPP)

ESA has actively supported 3GPP's NTN-related activities since Release 15 and continues to contribute to system architecture and radio access network (RAN) working groups through the Highly skillEd sateLlite community mEmbers to drive 3GPP Non-Terrestrial Network standardisation (HELENA) initiative.

ESA's engagement ensures that satellite-native features—such as D2D support, regenerative payloads, and mobility anchoring—are progressively embedded into 5G Advanced and 6G. ESA maintains regular participation in plenary and technical sessions, providing continuity and direction on behalf of its Member States.

International Telecommunication Union (ITU) and European Conference of Postal and Telecommunications Administrations (CEPT)

Although not a formal ITU member, ESA collaborates closely with the ITU Radiocommunication Sector (ITU-R) and CEPT through technical study groups and policy consultations. Recent collaboration with ITU focuses on harmful interference mitigation for satellite systems. ESA also provides expert input to national regulators and European coordination platforms (e.g., CEPT Electronic Communications Committee Working Group Frequency Management 22 [ECC FM22]), particularly in areas related to D2D spectrum policy, enforcement, and monitoring.

O-RAN Alliance

ESA recently joined the O-RAN Alliance, advocating for the inclusion of NTN in future open RAN architectures. ESA is contributing to the establishment of a dedicated NTN working group, supporting the development of open, interoperable RAN specifications tailored for multi-orbit systems. The goal is to ensure NTN support in virtualised, modular, and AI-driven 6G RAN environments.

NTN Forum

To enable broader industry engagement, ESA founded and leads the NTN Forum -the largest global community focused exclusively on NTN development. With hundreds of registered companies, the Forum organises its activities around four working groups (WGs):

- Pre-standardisation and regulatory alignment (WG1).
- Consolidation of vertical requirements (WG2).
- TN/NTN experiments and technology validation (WG3).
- Devices and chipsets (WG4).

The Forum facilitates information exchange, industry alignment, and collaboration on pre-competitive research and prototyping for 5G Advanced and 6G NTN.

International Collaboration and Fora

ESA has forged influential partnerships with key international organisations to ensure the seamless integration of NTN technologies into mainstream telecom ecosystems. These include:

- GSM Association (GSMA): Joint GSMA Foundry and ESA campaigns to expose industry to ESA ARTES funding through the GSMA Foundry Challenge model, and collaboration within the already established GSMA NTN Community, launched in 2024.
- Mobile Satellite Services Association (MSSA).
- Seamless Air Alliance (SAA).
- Global Satellite Operators Association (GSOA).
- Electronics and Telecommunications Research Institute, South Korea (ETRI).
- 5G Automotive Association (5GAA).

These collaborations allow ESA to amplify Europe's influence, accelerate cross-sector adoption of NTN capabilities, and maintain strong transcontinental cooperation on technical, policy, and market development fronts.

4. ESA AS AN INNOVATION CATALYST FOR 6G NTN

The European Space Agency (ESA) is not only a strategic enabler of 6G non-terrestrial network (NTN) – its innovation portfolio actively drives the development, integration, and validation of cutting-edge technologies. Through its physical laboratories, in-orbit demonstrations, and flagship projects, ESA provides the infrastructure, tools, and partnerships needed to turn 6G NTN concepts into scalable, operational capabilities.

4.1 THE ECSAT 5G/6G HUB

Located at the European Centre for Space Applications and Telecommunications (ECSAT) in Harwell (UK), the ESA 5G/6G Hub has been operational since 2022. Developed with the support of the UK Space Agency and implemented by CGI, the Hub serves as a focal point for advancing seamless TN/NTN integration.

The Hub supports a diverse array of associated development activities in collaboration with industrial and academic stakeholders, enabling the testing and validation of critical technologies such as edge computing, advanced network orchestration, optical satellite backhauls, neutral hosting models, and hybrid terminal innovations.

These activities provide both industry and academic partners with a flexible and dynamic environment to explore and refine interoperable solutions under real-world conditions. Looking ahead, the Hub will expand its capabilities to include dedicated NTN and direct-to-device (D2D) testbeds, Artificial Intelligence (AI)-driven automation, dual-steer terminals for seamless satellite and terrestrial integration, and advanced constellation simulators for multi-orbit environment emulation. This phase will also incorporate mmWave infrastructure and Open Radio Access Network (O-RAN)-based components, allowing for comprehensive validation of open, intelligent, and scalable 6G NTN architectures that are set to shape the future of global connectivity.

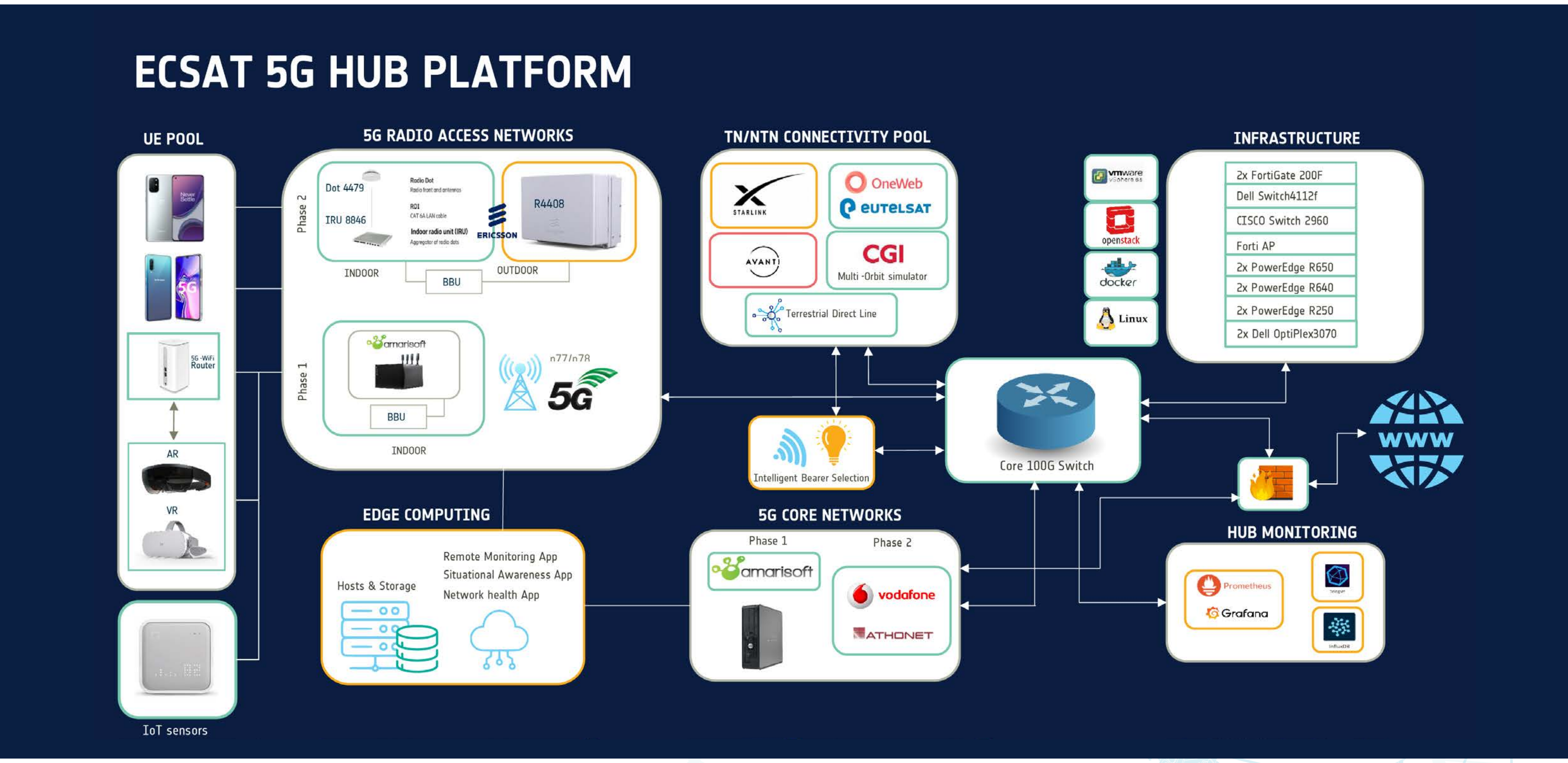


Figure 4: High-Level ECSAT 5G/6G Hub infrastructure.

4.2 THE 5G/6G TELECOM LAB AT ESTEC

The 5G/6G Telecom Lab at ESA's European Space Research and Technology Centre (ESTEC) in The Netherlands, serves as a key innovation and validation environment for NTNs. The lab supports advanced system prototyping, integration testing, and performance evaluation across multi-orbit satellite platforms, and it enables the emulation and experimentation of NTN scenarios aligned with 3GPP specifications. The lab plays a central role in supporting industry partners, validating technologies developed under the Advanced Research in Telecommunications Systems (ARTES) programme and internal initiatives, and contributing to standardization through close collaboration with 3GPP and other global fora.

A significant milestone was achieved with the successful demonstration of the world's first 3GPP-compliant NTN link over Low Earth Orbit (LEO). The connection was established with the Telesat LEO 3 satellite using an Amarisoft 5G protocol stack, marking a major step forward in validating the operational feasibility of 5G NTN in space-based environments. The team, comprised of engineers from ESA's Technology, Engineering and Quality (TEC) directorate, who led the technical system design and integration, alongside experts from the Connectivity and Secure Communications (CSC) team under the Space for 5G/6G Strategic Program, as well as engineers from Telesat and Amarisoft, maintained continuous connectivity from 10º to 80º elevation during the satellite pass, concluding at 30º to avoid potential interference with the Geostationary Earth Orbit (GEO) arc.

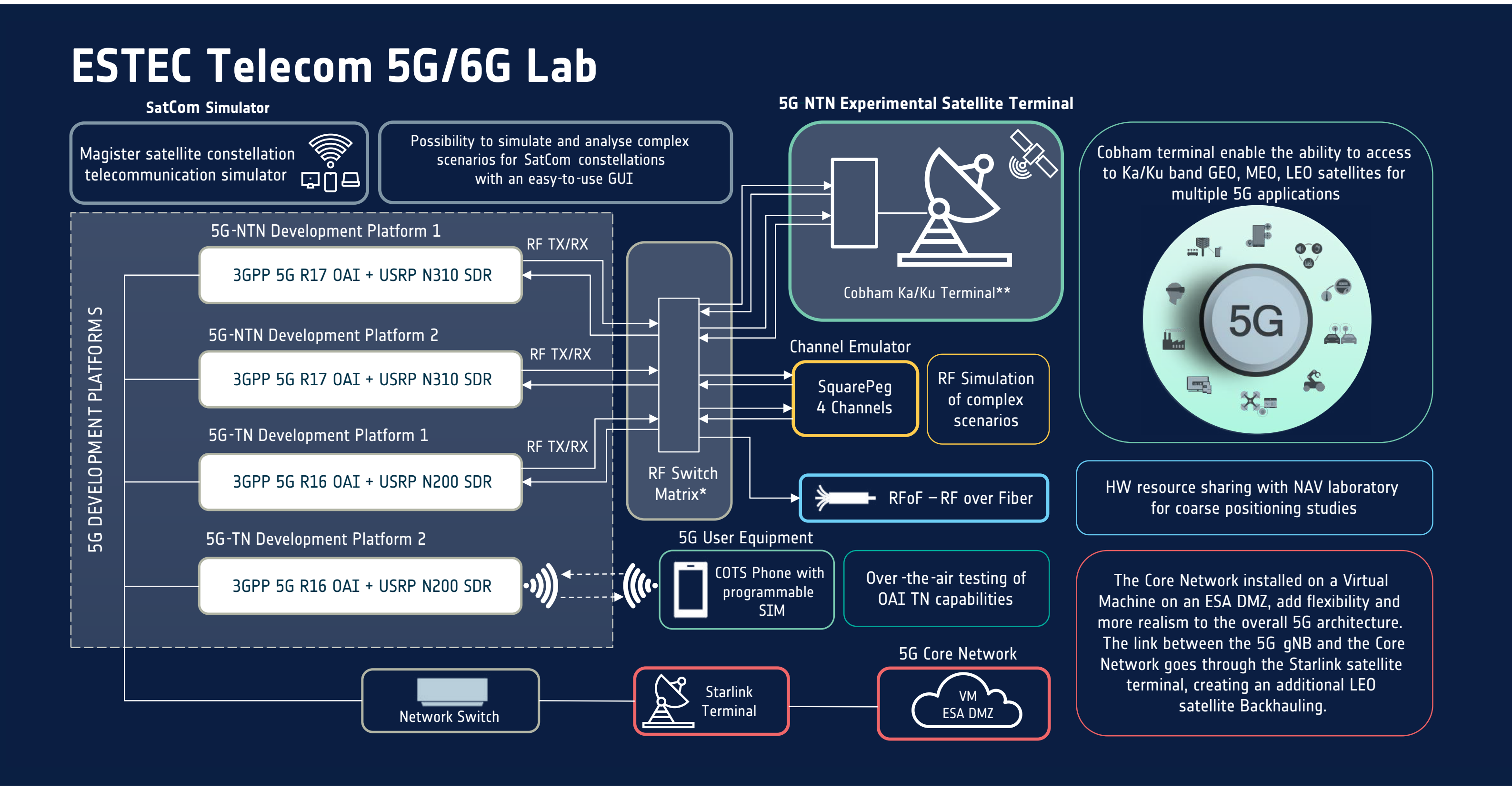


Figure 5: High level diagram of the 5G/6G Telecom Lab infrastructure at ESTEC.

4.3 FLAGSHIP ACTIVITIES DRIVING 6G NTN

IRIS^2

The IRIS^2 Satellite Constellation is the European Union's flagship initiative, focused on enhancing security, safety, and resilience by providing secure, high-speed connectivity to governmental users. This multi-orbit constellation of 290 MEO and LEO satellites will deliver reliable broadband across the European Union, bridging connectivity gaps for both public institutions and private sectors. In later phases, IRIS^2 will also enable commercial developments, broadening its impact.

As the Commission's trusted partner, ESA will act as the Qualification and Validation Authority, overseeing the project's development. ESA will also contribute through ESA optional programmes[17] (e.g., ARTES framework) towards the integration of cutting-edge technologies through partnerships with both established space industry leaders and emerging innovators, fostering a diverse ecosystem. This approach, coupled with the multi-orbit architecture, will ensure scalability to meet future demands and enable seamless interoperability towards the progression to 6G NTN technologies.

NTN Partnership Projects

As part of the 5G/6G Strategic Programme, part of ARTES, ESA's Public Private Partnerships (PPP) combines public funding with private sector expertise to accelerate the commercialisation of space-based technologies. Amongst all, two flagship initiatives, Sunrise and 5G-EMERGE, are advancing satellite-terrestrial integration toward 5G Advanced and 6G NTN.

- Sunrise (an ESA partnership with Eutelsat Oneweb). Following the successful launch of JoeySat in 2023, which demonstrated beam hopping and beam tracking for 5G, Sunrise has entered its third phase to develop regenerative 5G processors, multibeam antennas, and innovative applications.
- 5G-EMERGE (an ESA partnership with over 30 European companies in 8 ESA member states). It aims to create an open, multi-tenant ecosystem connecting near-edge infrastructure at satellite teleports with far-edge nodes via virtualised satellite links to 5G NTN and future 6G base stations. In its second phase, which commenced in November 2024, the project is focusing on mobile broadcast services, D2D communications, and micro edge-casting technologies.

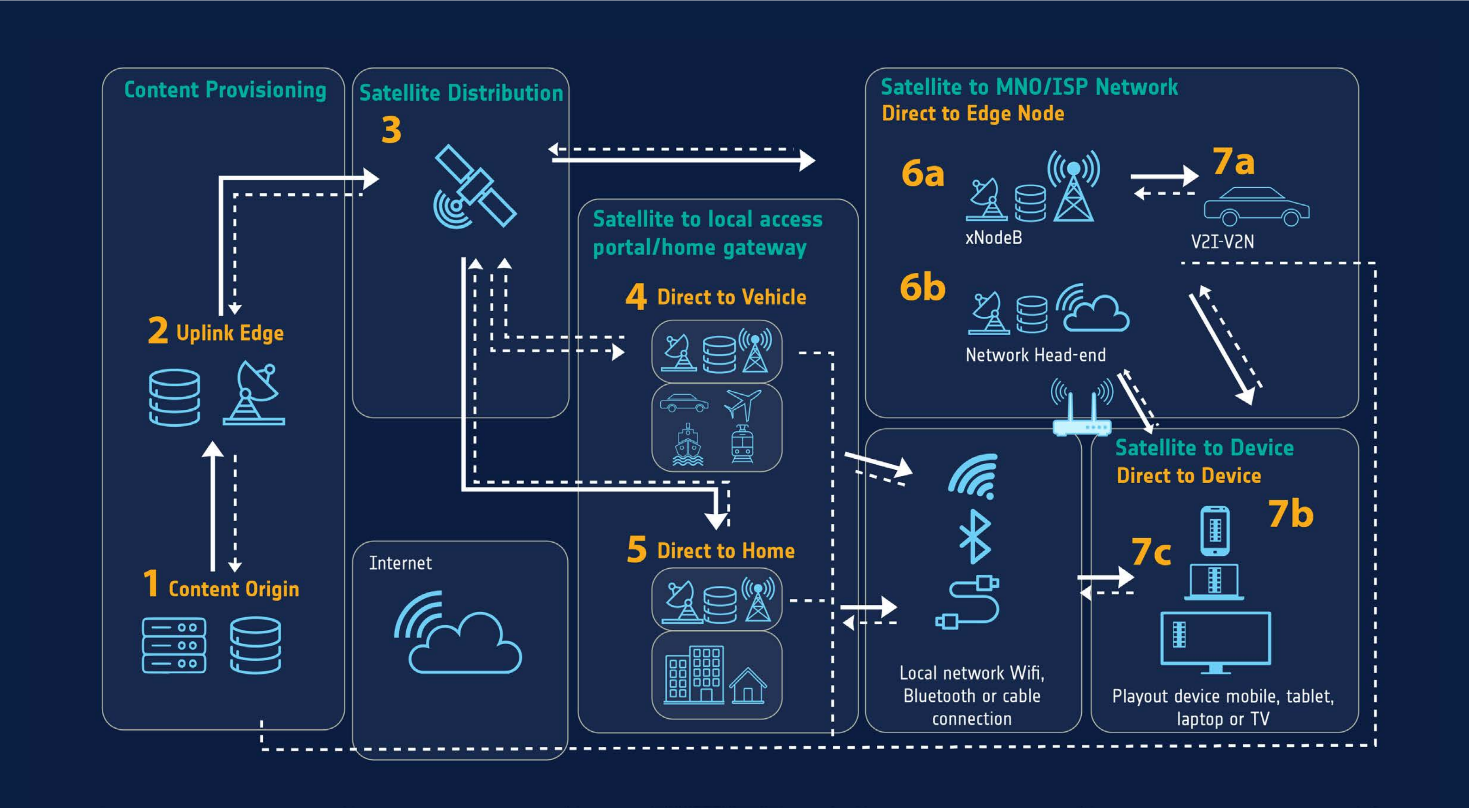


Figure 6: A Conceptual overview of the 5G EMERGE architecture.

6G LINO and the 6G OpenLab: Pioneering In-Orbit 6G Experimentation

At the heart of ESA's vision for experimental 6G NTN infrastructure is the 6G Laboratory In-Orbit (6G LINO), a purpose-built CubeSat satellite that serves as the cornerstone of the broader 6G OpenLab concept. Scheduled for launch in early 2026, 6G LINO marks one of the world's first in-orbit platforms dedicated to full-scale 6G NTN experimentation.

The satellite is a 16U CubeSat equipped with a sophisticated digital and RF payload, featuring:

- A software-defined gNodeB onboard
- S-band user links and Ka-band feeder links
- Onboard AI capabilities via Advanced RISC Machines (ARM) and field programmable gate arrays (FPGAs)
- Full support for in-orbit software updates, enabling reconfiguration during flight

Its modular digital architecture allows for experimentation with novel waveforms, regenerative payload functions, spectrum sharing strategies, and real-time handover mechanisms between TN and NTN layers.

Complementing the satellite, ESA's ground infrastructure includes:

- Multiple protocol stacks—new radio (NR) and narrowband (NB)-IoT
- Channel emulators for TN/NTN conditions
- NTN enhancements for O-RAN enabled Next Generation NodeB (gNBs)
- High-speed backhaul and spectrum test licenses
- Advanced testing equipment and mobile drive-test terminals

The 6G OpenLab is not limited to 6G LINO. It federates a growing ecosystem of assets:

- REMI (ESA experimental 5G LEO satellite, launching 2025)
- MIXELS (onboard Kepler satellites, live Q3 2025)
- External platforms such as Telesat LEO 3, i2cat's 6G StarLab, and planned High Altitude Platform Station (HAPS) campaigns (e.g., Skydweller, Sceye)

This federated infrastructure will evolve in parallel with 3GPP's 6G standardisation process, especially during the study phase of Releases 20 and 21 (2025–2027), where early experimentation can most meaningfully shape architectural decisions – particularly for RAN optimisation in spaceborne scenarios.

Critically, the 6G OpenLab embodies a multi-layered open innovation model:

- Open to global collaborators exploring TN/NTN convergence
- Open to additional satellite and terrestrial assets for federation and scalability
- Open to vertical sector integration, enabling full use-case validation across domains

ESA is also exploring partnerships with the European Commission's SNS JU to make 6G OpenLab accessible to 6G-funded research consortia. A scheduler-based system will regulate experimentation slots, and confidential access will be facilitated via trusted gatekeeper entities under ESA-managed nondisclosure agreements (NDAs).

By enabling realistic, collaborative, and standardisation-aligned experimentation, 6G LINO and the 6G OpenLab position Europe at the forefront of global NTN research and development (R&D)—bridging ambition with action, and vision with validation.

D2D and Regenerative NTN payloads

ESA has recently signed an agreement with Viasat to advance D2D technologies, enhancing European competitiveness in this field. Additionally, discussions with multiple stakeholders are underway to develop D2D solutions and systems with new projects in the pipeline focused on regenerative payloads and end-to-end system development. A recent example is the project signed off with MDA UK to develop a regenerative payload compliant with the 3GPP NTN standards.

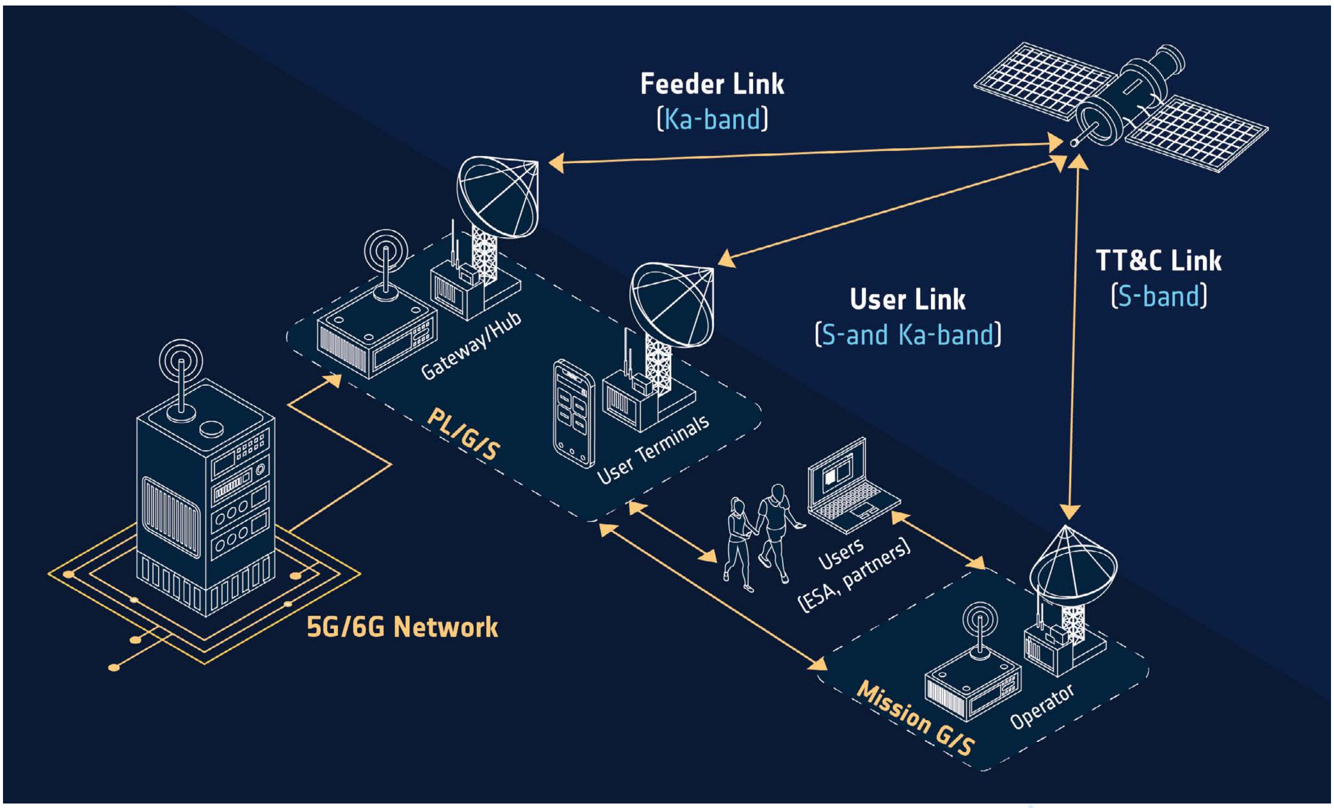


Figure 7: Conceptual system diagram of 6G-LINO.

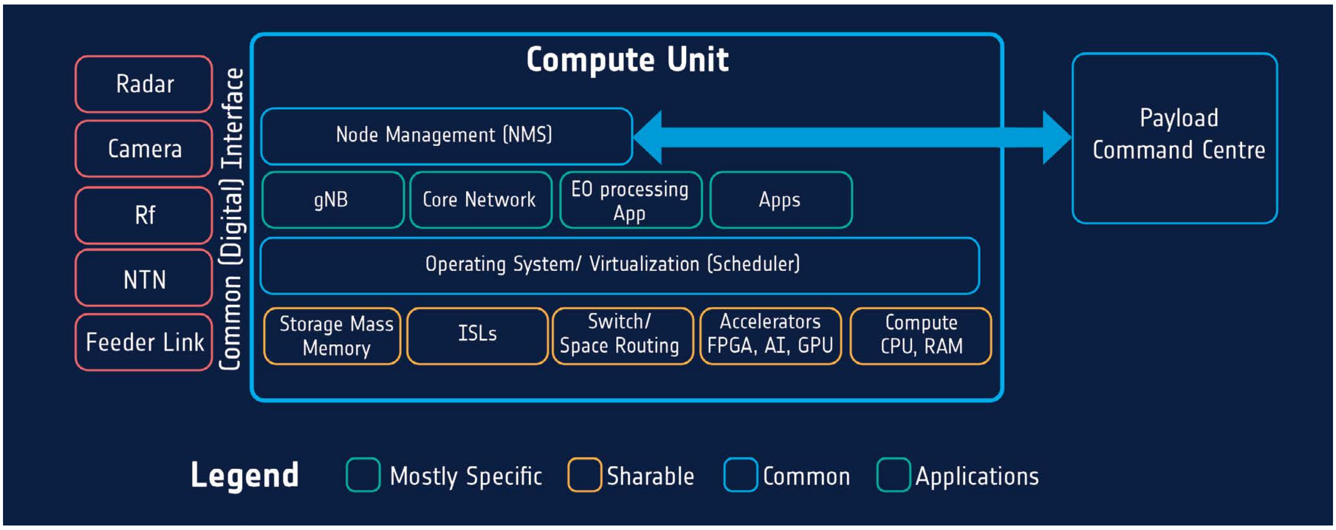


Figure 8: 5GEOSiS system architecture.

Integrated Communications and Sensing (ISAC)

A critical activity closely aligned with 6G use cases and technologies is the 5G Earth Observation Server in Space (EOSiS). 5G EOSiS provides a versatile hardware platform and testbed for experimentation and validation of ISAC concepts and methodologies. This initiative represents a novel and rapidly emerging field, particularly regarding satellite payloads and their application in space environments. The project's primary goal is the development of a regenerative NTN payload capable of dynamically processing Earth observation and communication data simultaneously.

NTN User Terminal and RAN developments

As part of the 5G/6G SPL project portfolio, several ongoing and planned activities focus on NTN RAN developments across the S, Ku, and Ka frequency bands. Additionally, there are co-funded and fully funded projects dedicated to developing multi-orbit, multi-beam terminals and flat-panel antennas. Furthermore, developments are underway to integrate Open RAN and Digital Intermediate Frequency Interoperability (DIFI) interfaces into NTN terminals and radio access nodes. A notable example is the critical development by All.Space, which is currently developing a Ka-band flat-panel antenna featuring multi-beam and multi-orbit capabilities, alongside an integrated 5G NTN protocol stack and RF sensing functionalities.

AI-DRIVEN NTN SYSTEMS

ESA is actively advancing AI-enabled NTN technologies, in full alignment with the recently published 3GPP 6G use cases and service requirements[18]. Current and upcoming activities are primarily focused on data-driven network management and service orchestration, with particular emphasis on intelligent routing, network slicing, and security optimisation. A key initiative in this domain is the AI for Satellite 5G Communications (AICOMS) project, which is driving the development of machine learning-based enhancements for the 5G NR physical layer, predictive algorithms for interference mitigation, and data-driven methods for packet routing, fault detection, identification, and autonomous recovery.

Please refer to the ARTES project space[19] for more information on ESA 5G SPL NTN activities.

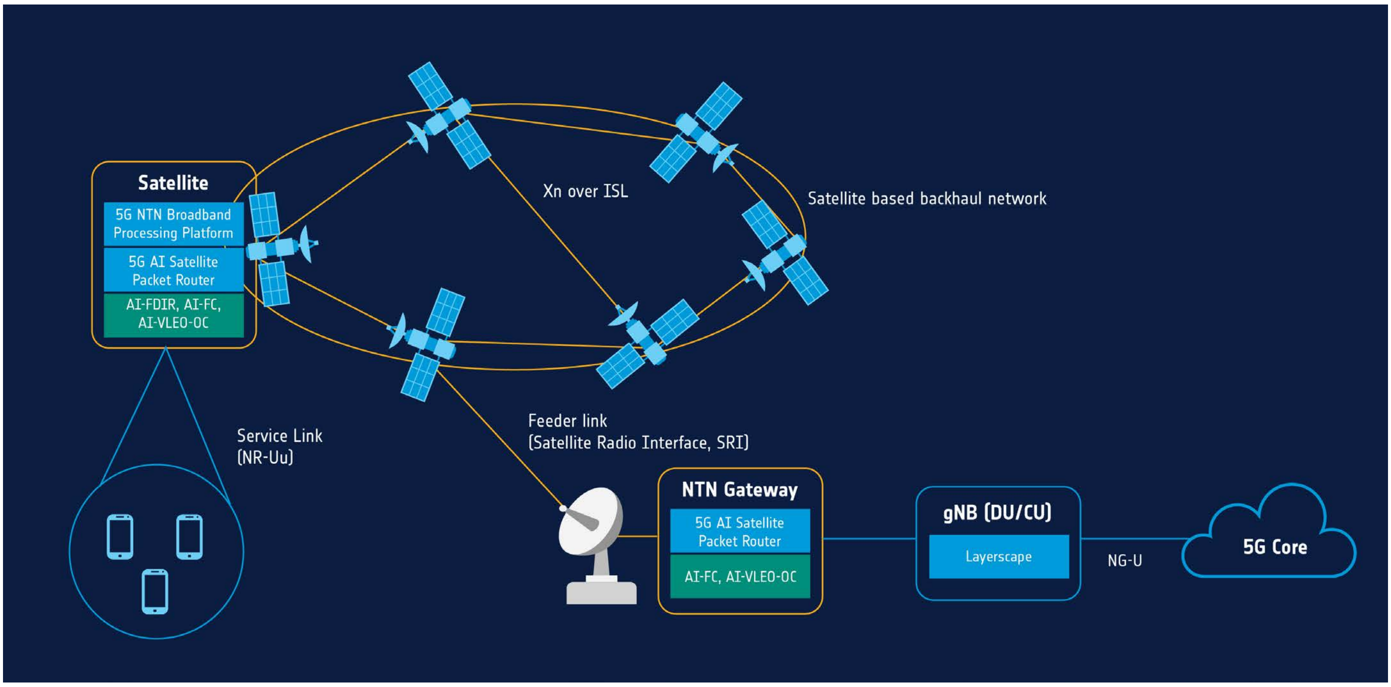
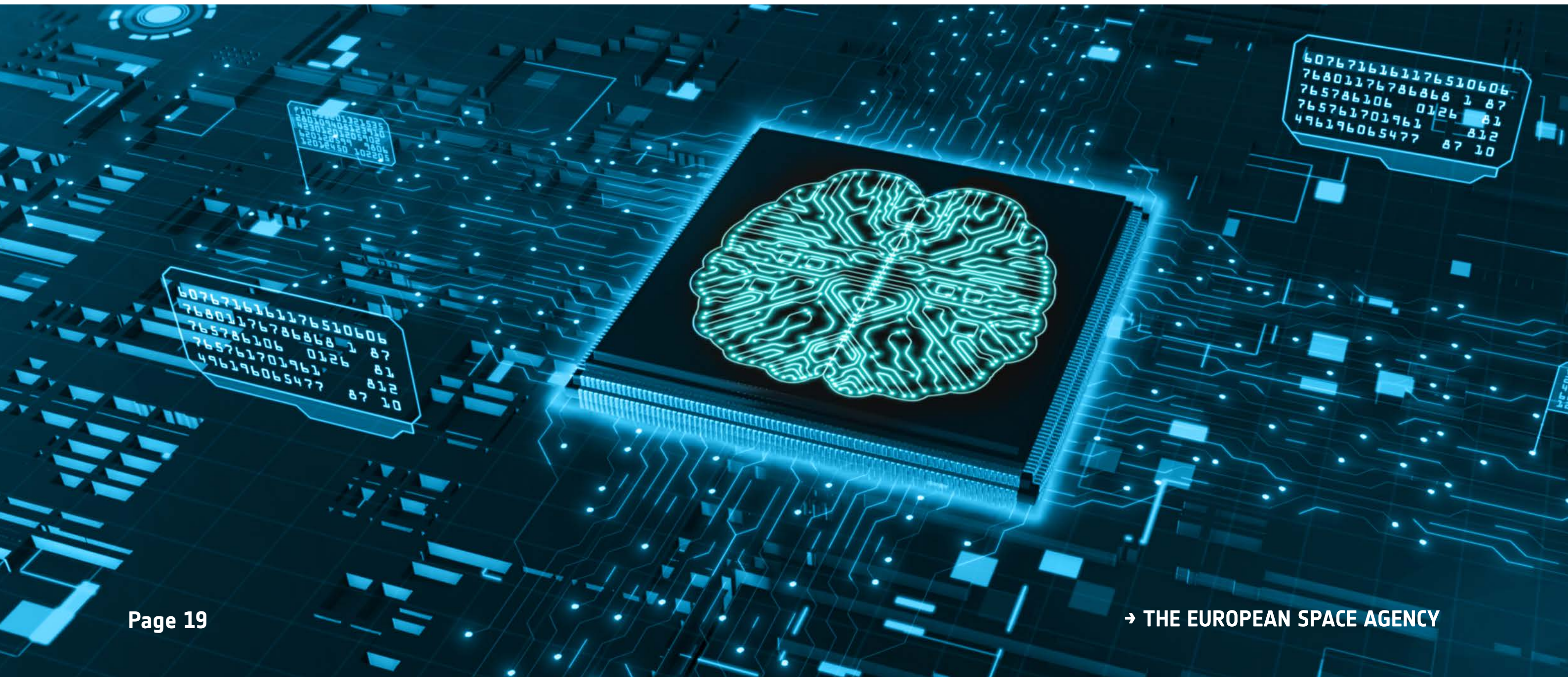


Figure 9: AICOMS system design concept.



5. EMBRACING EMERGING TECHNOLOGIES:

Optical and Quantum

The European Space Agency (ESA) views Non-Terrestrial Networks not as isolated satellite systems, but as adaptable frameworks for integrating next-generation technologies—including optical communications, quantum encryption, and hybrid Radio Frequency (RF)-optical architectures. These capabilities are critical to realising the vision of a global, intelligent, and resilient 6G network that seamlessly extends beyond Earth's surface.

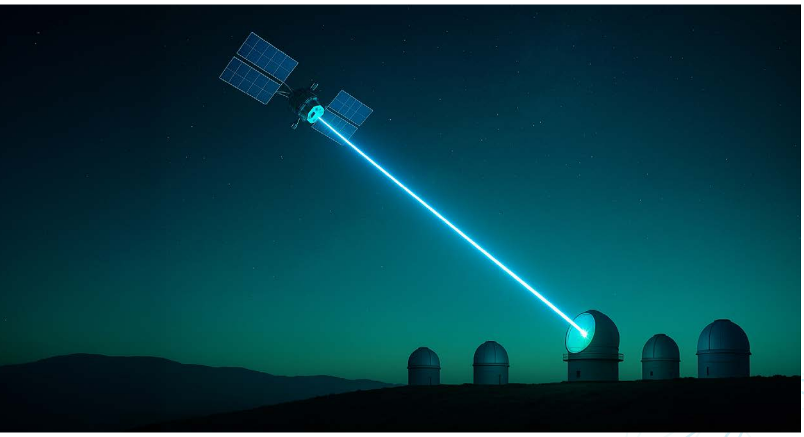
5.1 OPTICAL COMMUNICATIONS AND QUANTUM KEY DISTRIBUTION (QKD)

Optical Communications

Satellite systems are undergoing a paradigm shift. Where once limited to RF bands and large geostationary platforms, next-generation satellites are evolving into dynamic, networked nodes—leveraging optical communications for ultra-high throughput and global interoperability.

ESA has pioneered this domain through missions like the European Data Relay Satellite System (EDRS) [20], [21], and today, optical inter-satellite links (ISLs) [22]-[29] have reached significant maturity. Commercial and military constellations across the globe—such as Starlink, Kuiper, and the U.S. Space Development Agency (SDA)[30] constellation—have adopted these technologies at scale.

The next frontier lies in optical downlinks and feeder links, which connect satellite networks to terrestrial systems. These links promise terabit-per-second (Tbps) throughput, secure narrow beams, and reduced RF spectrum congestion. However, challenges such as atmospheric turbulence, precise pointing, and terminal integration must be addressed for full commercialisation.



Some key enabling technologies for future optical communications are the following:

- **Advanced flexible modulation formats**, supporting data rates ranging from hundreds of Mbps to several Tbps, depending on the use case. The integration of current specifications, such as the Space Data Association's Optical Communication Terminal (OCT) and ESA Specification for Tbps Optical Links (ESTOL), into a unified standard within the 6G framework would significantly advance the convergence of optical networks and 6G NTNs.
- **Time diversity techniques** to ensure reliable cross-atmospheric links. Including adaptive optics, long channel interleaving, erasure coding, and automatic repeat request (ARQ), these techniques provide a wide range of benefits and drawbacks in terms of complexity and latency and operate at different layers (from the physical layer up to the network layer), providing powerful design options to address different use cases with different solutions.
- **High power amplifiers** for dense wavelength division multiplexing. When amplification is necessary, managing potential nonlinear effects, such as four-wave mixing, is crucial for maintaining a power-efficient system.
- **Artificial Intelligence (AI) for resource allocation, routing, and handover**. As optical ISLs are planned in several constellations (single or multi-shell), having AI-based algorithms capable of adapting to the dynamic conditions of the network (driven by the atmosphere's dynamics) is of paramount importance.

Quantum Communications and QKD

Optical channels are also foundational for emerging quantum communication systems, particularly QKD. By exploiting the principles of quantum entanglement, QKD enables inherently secure key exchanges immune to conventional and quantum computing attacks.

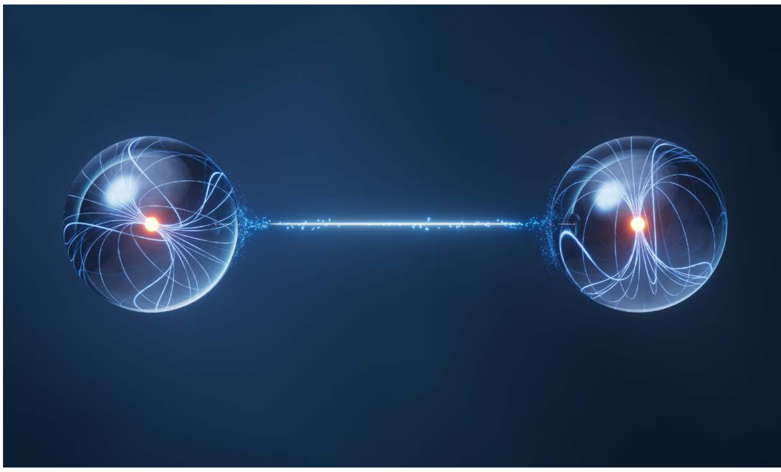
Satellites play a crucial role here: while terrestrial QKD is limited by fibre loss over long distances, free-space optical links from low Earth orbit (LEO) satellites can deliver keys to distributed national nodes with lower attenuation.

ESA supports these developments through the EuroQCI initiative and its own Quantum Cross-Cutting Initiative, laying the groundwork for future Quantum Information Networks – global infrastructures that connect quantum sensors, computers, and users via space-enabled entanglement distribution.

For this, some enabling technologies are the following:

- **Quantum memories and repeaters**. Quantum memories enable the storage and retrieval of quantum states, which is essential for managing quantum information across different parts of the network. Quantum repeaters extend the range of quantum communications by dividing long distances into shorter segments. By mitigating the effects of loss and noise over long distances, quantum repeaters facilitate the creation of large-scale, secure quantum networks.

- **Efficient photon counting detectors**. By enhancing the sensitivity and durability of these detectors, more secure and efficient quantum key distribution may be achieved. These detectors are also used for deep-space communications, enabling optical communications from the Moon, Mars, and even further.



5.2 UNIFYING TECHNOLOGIES: TOWARDS RF-OPTICAL CONVERGENCE

The integration of RF and optical technologies within 6G NTN opens up powerful new possibilities for hybrid architectures that dynamically adapt to environmental conditions and operational demands. These systems intelligently leverage the strengths of each medium: RF for its robustness to atmospheric impairments (e.g., fog and clouds) and wide-area coverage, and optical for its ultra-high bandwidth and enhanced security in clear-sky conditions, especially for inter-satellite and high-capacity feeder links. This dynamic adaptability supports use cases such as:

- high-throughput backhaul via optical inter-satellite and satellite-to-high altitude platform station (HAPS) links combined with flexible RF access for mobile users

- seamless handover between RF and optical links based on real-time weather conditions

- intelligent routing of data to bypass congested or degraded paths

- demand-driven provision of high-capacity optical backhaul only when required by data-intensive applications

- rapid deployment of secure communication platforms in disaster zones using unmanned aerial vehicles (UAVs) and HAPS
- seamless integration of quantum-secured optical channels with traditional RF networks

Key technologies enabling this convergence include:

- advanced photonic integrated circuits for compact hybrid terminals.
- AI-driven software-defined networking (SDN) for unified control and dynamic resource allocation.
- adaptive waveforms supporting flexible switching between RF and optical channels.

Key convergence areas are included in Table 2.

Although the integration of RF and optical links offers significant advantages, it also introduces a set of unique challenges that must be considered. In particular, for the design of a combined RF–optical terminals the main technical issues relate to the coexistence of RF and optical apertures, the potential impact of optical components on the performance of high-precision RF systems, and the separation of RF and optical signal paths[31].

Table 2: Optical-RF Convergence: use cases, .challenges, and solutions.

Use Case	Description	Challenges	Potential Solutions
Feeder Link Capacity Enhancements	High-throughput optical links replace congested RF gateways	High power, weather sensitivity	Adaptive optics, time diversity techniques, weather-aware routing
Optical-enabled HAPS/UAV	HAPS/UAV as temporary relay or hotspot booster	Compact optical terminal, stable pointing, acquisition, and tracking (PAT), weather sensitivity	Photonic integrated circuits (PICs), high-speed digital signal processing (DSP), AI-based link management
Hybrid RF-Optical Terminals	Devices that switch or blend optical and RF links	Complex integration, aperture coexistence	AI-driven link management, hybrid modems, shared components, cross-technology waveforms
In-Space Optical Networking	Point-to-point/ multipoint ISLs for satellite coordination	Link stability under motion	Mesh protocols, fine steering optics
Joint Network Control Management	Unified control planes and quality of service (QoS) management	Different protocol stacks, dynamic topologies and channels	AI-driven orchestration, edge computing, network softwarisation
QKD Integration	Secure quantum key exchange via optical links	Atmospheric loss, precision timing, quantum memories and repeaters	Integrated key management and timing control
Deep-Space Communications	Optical Earth–Moon or interplanetary relays	Beam pointing, narrow margins	Deep-space tracking terminals

These use cases illustrate the **complementarity of RF and optical domains** in building robust, high-capacity, and secure 6G NTN networks. However, implementation requires careful consideration of physical design, interface management, and cross-standard compatibility (e.g., 3GPP vs. consultative committee for space data systems (CCSDS) / Institute of Electrical and Electronics Engineers (IEEE)).

ESA continues to explore this convergence by evaluating whether 3GPP standardisation should evolve to accommodate hybrid optical-NTN user equipment, particularly at the interface and protocol stack level. This would mark a strategic shift toward truly unified, software-defined global networks.

5.3 HYDRON: ESA'S HIGH THROUGHPUT OPTICAL NETWORK

The **HydRON mission** is ESA's flagship effort to validate end-to-end optical network integration with TN/NTN infrastructure. It will demonstrate the world's first fully optical, multi-orbit transport network, extending fibre-grade performance into space.

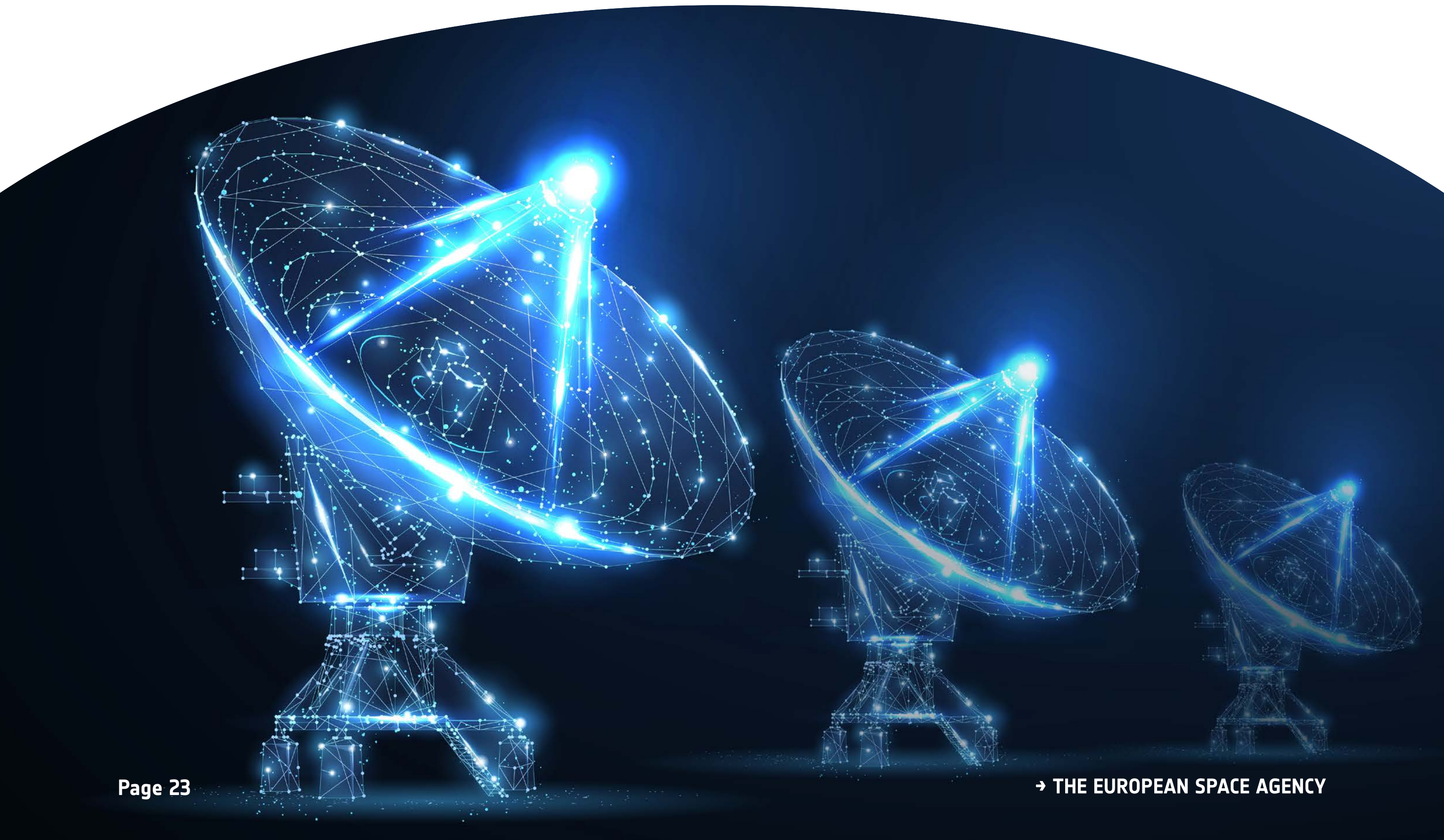
As shown in Figure 10, the demonstration system includes:

- Element 1: A constellation of 10 LEO satellites with inter-satellite and ground-facing optical links, developed by Kepler Communications (Canada).
- Element 2: An 11th LEO satellite equipped for cross-plane and cross-orbit connectivity to medium Earth orbit (MEO)/ geostationary Earth orbit (GEO) nodes.
- Element 3 *(in definition)*: User segment development focused on optical ground terminals and hybrid access devices.

Together, these elements will validate:

- Optical mesh networking
- Multi-orbit service delivery
- Interfacing with terrestrial fibre and mobile systems

HydRON showcases how ESA transforms theory into infrastructure—ensuring that Europe is ready to lead the integration of optical transport into the global 6G NTN ecosystem.



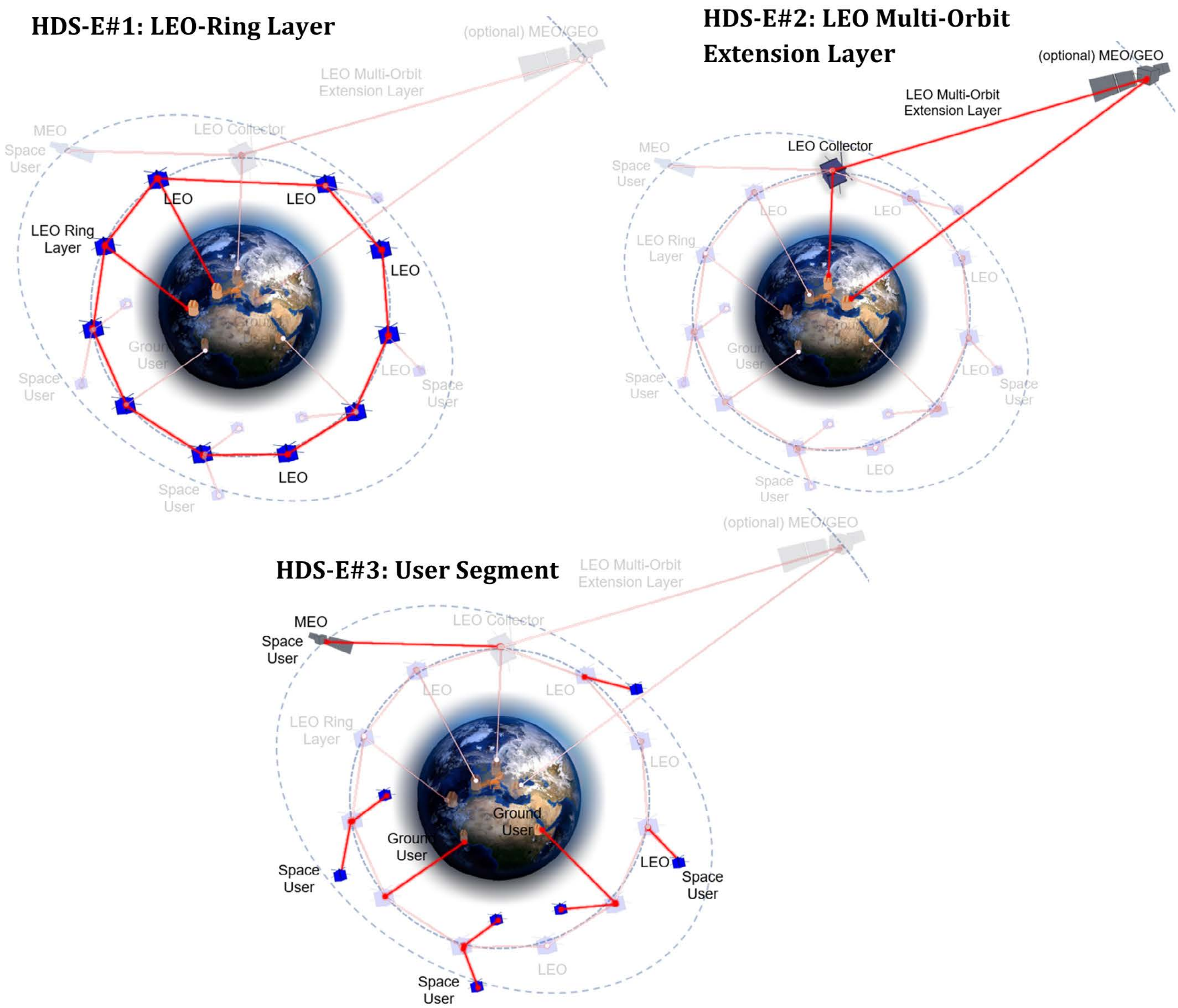


Figure 10: HydRON Demonstrator's architecture.

HydRON is poised to be a foundational contributor to the development of 6G NTN by demonstrating the "fiber in the sky" concept. Its main contributions will be the following:

- **Establishing Ultra-High Capacity Optical Backbone:** HydRON aims to demonstrate the world's first all-optical, multi-orbit transport network with terabit-per-second capacities. For 6G NTN, which envisions pervasive connectivity and data-intensive applications (e.g., holographic telepresence, digital twins, real-time Earth observation), such a high-capacity backbone is essential.
- **Seamless Integration with Terrestrial Networks:** A key goal of HydRON is to demonstrate the integration of its ground segment in terrestrial networks. This aligns perfectly with the 6G NTN vision of a unified, three-dimensional network architecture.
- **Multi-Orbit Connectivity:** HydRON Element 2 will demonstrate LEO-MEO or LEO-GEO connectivity, paving the way to the multi-layered architecture envisaged in 6G NTN.

- **Advancing Key Technologies:** HydRON will validate critical technologies for optical communications, such as optical terminals, onboard packet routers, PAT systems, time diversity techniques, and network control and orchestration. These advancements will directly feed into the development of hybrid RF-optical architectures for 6G NTN. While HydRON focuses on optical, the lessons learned in managing such high-throughput, dynamic space network will be valuable for the network management and AI-driven resource allocation required for seamless switching between RF and optical links based on environmental conditions and traffic demands.

- **Paving the Way for Future Commercial and Institutional Missions:** By demonstrating the feasibility and benefits of terabit-per-second optical satellite communications, HydRON will de-risk and accelerate the adoption of similar technologies for future commercial and institutional satellite missions.

In essence, HydRON is not just about faster satellite links – It's about establishing the fundamental technological building blocks and operational paradigms for the high-capacity, low-latency, and resilient optical backbone that will be indispensable for realising the ambitious goals of 6G NTN.

6. CONCLUSION AND CALL TO ACTION:

Europe's Moment to Lead

The 6G era will redefine not only how we connect—but how we govern, secure, and scale our digital infrastructure across borders, orbits, and generations. In this new landscape, Non-Terrestrial Networks (NTN) are not optional add-ons. They are foundational pillars for achieving universal access, technological resilience, and strategic sovereignty.

This whitepaper has charted a path for the integration of 6G NTN across architecture, spectrum, and systems. It has showcased the European Space Agency (ESA)'s efforts in:

- Advancing **multi-orbit orchestration** and regenerative satellite systems.
- Building testbeds, terminals, and virtualised RANs for seamless terrestrial network (TN) / NTN integration.
- Championing open standardisation and spectrum access in Third Generation Partnership Project (3GPP), International Telecommunication Union (ITU), and Open Radio Access Network (O-RAN).
- Unlocking next-generation capabilities through optical, quantum, and Artificial Intelligence (AI)-driven technologies.

From optical satellite constellations to AI-based orchestration and quantum key distribution, ESA is ensuring that European solutions are not just present in the 6G landscape—they are defining it.

But now, the call is greater.

FROM VISION TO VELOCITY

The shift from roadmap to reality must accelerate. Europe must now focus on:

- Translating strategy into execution through funding, test infrastructure, and cross-border alignment
- Deploying sovereign, interoperable platforms that reflect Europe's values of openness, trust, and sustainability
- Driving commercial scale-up by enabling global partnerships that embed European technologies in world markets

ESA stands ready to lead this charge—providing the coordination, validation, and foresight necessary to unite the space and telecom sectors under a common goal: a future-proof digital backbone that spans from the Earth to the Moon, and beyond.

WHY 6G NTN, WHY NOW

Without NTN, there is no global 6G.
Without sovereignty, there is no secure digital future.
Without ambition, there is no leadership.

Let us make Europe the first region to realise a truly global, intelligent, and autonomous 6G network, powered by the sky, and shaped by our shared values.

The next chapter begins now.

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