



EUROPEAN SPACE AGENCY

INTEROPERABILITY IN SATCOM GROUND SEGMENT

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EXECUTIVE SUMMARY

Satellite communication ground segments are moving from fixed, hardware-centric RF chains to packetised, software-defined and cloud-extensible architectures. This white paper assesses the interfaces, standards, service frameworks, orchestration mechanisms, performance measures, security controls and economic models needed to make that transition interoperable across vendors and operational domains.

Interoperability is a cornerstone of resilient ground segment architectures, enabling seamless integration across vendors, standards, and domains while supporting diversity, failover, and disruption-tolerant networking. DIFI and VITA-49 strengthen digital IF transport against disruption; OpenAMIP enables robust antenna-controller integration; DVB-S2X/DVB-RCS2 and 3GPP NTN enhance air-interface flexibility; and Mplify, TM Forum, SDN and NFV empower adaptive service and orchestration frameworks that underpin operational resilience.

The central finding is that open interfaces create value when paired with a coordinated control plane and explicit trust model. Otherwise, disaggregation can move integration risk rather than remove it.

An effective programme should combine standards-based procurement, conformance profiles, cross-vendor testing, end-to-end KPI measurement and secure orchestration. This creates a pathway from isolated ground systems to reusable, multi-orbit and service-oriented resilient infrastructure.

KEY TAKEAWAYS

- Address interoperability as a layered architecture spanning RF, waveform, transport, orchestration and operations.
- Leverage standard interfaces and portable software functions to reduce vendor lock-in and enable shared infrastructure.
- Validate multi-vendor interoperability through KPIs, PlugFests, security controls and lifecycle assurance.

Open RF transport is necessary, but end-to-end interoperability is achieved only when waveform portability, service APIs, orchestration and assurance work together



Table 1. Interoperability layer matrix

LAYER	PRIMARY INTERFACE OR FRAMEWORK	ROLE AND IMPLEMENTATION PRIORITY
Digital IF	DIFI / VITA-49	Multi-vendor RF/IF-to-modem transport; Standard evolution and industry engagement
Antenna control	OpenAMIP	Modem-to-antenna pointing and tracking; Controller messages and test antenna/modem pairings
Air interface	DVB-S2X/DVB-RCS2 / 3GPP NTN	Waveform efficiency and TN/NTN integration; Support Mobility and service-continuity behaviour
Waveform execution	WAVE / virtual modems	Portable software across compute environments; Specify execution, acceleration and lifecycle requirements
Service operations	Mplify LSO / TM Forum ODA	API-driven service and OSS/BSS integration; Adopt common service models, intent and assurance APIs
Control and assurance	SDN / NFV / KPI profiles	Cross-domain orchestration and measurable outcomes; Federate policy; validate latency, reliability and handovers



LIST OF ACRONYMS

Acronym	Definition	Acronym	Definition
3GPP	3rd Generation Partnership Project	ACM	Adaptive Coding and Modulation
AI	Artificial Intelligence	API	Application Programming Interface
APT	Advanced Persistent Threat	ASCII	American Standard Code for Information Interchange
COTS	Commercial Off The Shelf	D/A	Digital to Analogue
DIFI	Digital Intermediate Frequency Interoperability	DORA	Digital Operational Resilience Act
DVB-RCS2	Digital Video Broadcasting – Return Channel via Satellite, Second Generation	DVB-S2X	Digital Video Broadcasting Satellite Second Generation Extension
EDIM	Enterprise Digital Intermediate Frequency Multi-carrier	eCPRI	Enhanced Common Public Radio Interface
eRE	eCPRI Radio Equipment	eREC	eCPRI Radio Equipment Control
ESA	European Space Agency	ETSI	European Telecommunications Standards Institute
FAST	Future Advanced SATCOM Technology	FEC	Forward Error Correction
GbE	Gigabit Ethernet	GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System	GSaaS	Ground Segment as a Service
IFC	RF/IF Converter	IF	Intermediate Frequency
IFL	Inter-Facility Link	IP	Internet Protocol
IPv4	Internet Protocol Version 4	IPv6	Internet Protocol Version 6
IQ	In-phase and Quadrature	KPI	Key Performance Indicator
LEO	Low Earth Orbit	LSO	Lifecycle Service Orchestration
MANO	Management and Orchestration	MEF	Metro Ethernet Forum (now Mplify Alliance)
MEO	Medium Earth Orbit	NaaS	Network as a Service
NFV	Network Function Virtualisation	NGSO	Non-Geostationary Satellite Orbit
NTN	Non-Terrestrial Network	ODA	Open Digital Architecture
Open AMIP	Open Antenna Modem Interface Protocol	OSS	Operations Support System
PHY	Physical Layer	QoS	Quality of Service
RF	Radio Frequency	SATCOM	Satellite Communications
SASE	Secure Access Service Edge	SDN	Software-Defined Networking
SD-WAN	Software-Defined Wide Area Network	SFC	Service Function Chaining
SNS-JU	Smart Networks and Services Joint Undertaking	TN	Terrestrial Network
UDP	User Datagram Protocol	VITA-49	VITA Radio Transport Standard
vModem	Virtual Modem	VNF	Virtual Network Function
vRAN	Virtualised Radio Access Network	WAVE	Waveform Architecture for Virtualized Ecosystems

1. Introduction

Satellite communication ground segments are undergoing a fundamental transformation driven by digitalisation, virtualisation, and convergence with terrestrial telecommunications networks. Traditional hardware-centric architectures, built around fixed Radio Frequency (RF) chains and mission-specific infrastructure, are increasingly being replaced by software-defined, cloud-extensible systems capable of supporting multi-orbit and multi-vendor environments.

This transition is enabled by the adoption of packetised digital RF transport, virtualised modem functions, and standardised interfaces, which together decouple hardware from processing and allow greater flexibility in deployment, scaling, and service delivery. **As satellite systems evolve towards integrated satellite-terrestrial networks, interoperability becomes a critical enabler for achieving operational resilience, efficiency, and long-term sustainability.** By fostering adaptability and robust connectivity, interoperability ensures ground segments can withstand and recover from deliberate or inadvertent disruptions.

However, interoperability is not limited to individual technologies. It requires coordination across multiple layers, including RF digitisation, waveform execution, transport networks, service orchestration, and operational management. Established standards such as DVB-S2X/DVB-RCS2, eCPRI, and OpenAMIP, alongside emerging ones like DIFI, and frameworks from MEF (Mplify) and TM Forum collectively address different parts of this stack, but their integration into a coherent resilient system architecture remains a key challenge.

2. Ground segment reference architectures

Modern ground segment architectures are rapidly transforming from hardware-centric RF chains to fully packetised, software-defined and cloud-extensible systems. A key enabler of this evolution is the adoption of Digital Intermediate Frequency (Digital IF) transport, where wideband RF is digitised near the antenna and

carried as packetised In-phase and Quadrature (IQ) streams over Ethernet/Internet Protocol (IP) networks. Digital IF enables long-distance transport without analogue impairments, decouples modem locations from RF front-ends, and supports scalable, multi-vendor integration.

An early/precursor R&D programme such as the US Army's FAST (Future Advanced Satellite Communication Technology) introduced the Digital IF conceptual space. It explored digital and virtualised Satellite communication architectures and demonstrated the value of performing Analogue-to-Digital (A/D) and Digital-to-Analogue (D/A) conversion close to the antenna and replacing analogue Inter-Facility Links (IFLs) with Gigabit Ethernet (GbE) based transport using standard network switches. By decoupling signal processing from dedicated hardware, these concepts improved system flexibility, redundancy, and the ability to rapidly reconfigure communication paths, thereby enhancing resilience in contested or degraded environments. FAST effectively showed that, once Intermediate Frequency (IF) is digitised, it becomes a transport - networking problem, while implementations remain proprietary. Digital IF Interoperability (DIFI) emerged later to close the standardisation gap, providing a pathway toward interoperable IF transport interfaces and unlocking the full resilience, scalability, and flexibility benefits of digitalised Satcom architectures.

2.1 Lower-level transport & signal digitisation

The most effective way to avoid vendor lock-in and ensure interoperability between systems is through a standardised interface, widely adopted across the satellite communications industry.

Digital Intermediate Frequency Interoperability (DIFI) was developed to enable interoperability among digital IF systems. DIFI standard promotes:

Vendor neutrality

IP-based digital IF transport

Separation of waveform processing and RF hardware.

Two key components of the system are the RF/IF Converter (IFC) and the Enterprise Digital Intermediate Frequency Multi-carrier (EDIM), which can be a hardware modem or implemented as a virtual software modem. The IFC receives satellite signals and converts them from radio frequency to an intermediate frequency. It then digitises and packetises the signal into IQ data, which can be transmitted over a public or private network (can also work in the cloud). This IQ data stream is received by the EDIM modem, which demodulates and decodes it for delivery to end users.

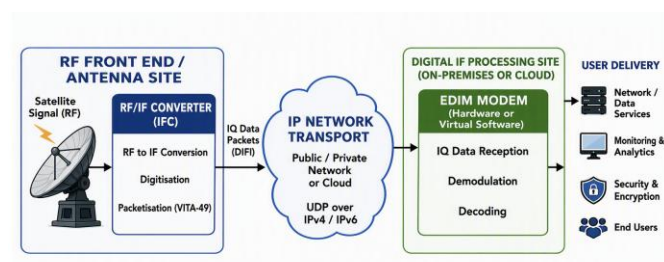


Figure 1. Simplified DIFI system architecture.

The DIFI standard is built upon VITA-49, an established RF packetization protocol. It consists of three primary components:

Context packets - These are mandatory 150-byte packets that define key signal parameters such as centre frequency, bandwidth and sample rate.

Signal data packets - These carry the IQ data within their payloads. Packet sizes can vary widely, from small 64-byte packets to jumbo frames up to 9000 bytes.

Command packets - Used for control and configuration purposes within the system.

The protocol operates over User Datagram Protocol (UDP), with support for both Internet Protocol version 4 (IPv4) and Internet Protocol version 6 (IPv6) headers. Signal data packets are aggregated to reconstruct the waveform, enabling flexible and efficient transport of RF signals over IP networks.

The DIFI packet flow supports cyclical payload structure, allowing RF waveform cycles to terminate and restart cleanly at the final packet of a given cycle. This allows users to define arbitrary packet sizes and export configurations to generate DIFI-compliant flows [1].

Interoperable Digital IF solutions enable seamless integration of antennas with virtualised ground segment infrastructures, allowing virtualised network functions (VNFs) and cloud native orchestration, further supporting the shift toward a modular, software-defined ground segment. Digital IF use cases include:

Virtualisation - Digital IF technology will be a key enabler for digital modems. It will provide operators with the flexibility to deploy new waveforms and, in conjunction with the implementation of virtual instruments, to monitor any signal from anywhere. By virtualising modem and signal-processing functions, operators can rapidly migrate services between compute platforms, recover from hardware failures, and dynamically allocate resources, significantly improving operational resilience and service continuity.

Diversity Antenna Sites - Digital IF fortifies ground segments against rain fade and atmospheric conditions and significantly enhances resilience and recovery in contested environments, including scenarios where assets may be deliberately or inadvertently degraded or physically damaged. This capability is central to maintaining continuity and robustness under adverse conditions. It also allows transmission over 100s of miles without degradation, regardless of the length of fibre or quality of RF cabling. Users will not need multiple fibre regeneration points to maintain signal quality.

Non-Geostationary Orbit Systems (NGSO) - The precise timestamping capabilities of the Digital IF enable accurate and deterministic handovers between antennas and gateways supporting NGSO constellations, reducing service interruptions and

ensuring seamless continuity during dynamic network operations. The same timestamping capability can also be leveraged for Geostationary Earth Orbit (GEO)-locating signals, via Time-of-Flight measurements supporting rapid fault localisation and interference identification. Together, these capabilities enhance Satcom resilience by improving service availability, accelerating fault recovery, and maintaining uninterrupted communications in both routine and degraded operating conditions.

Security Intelligence - The ability to geographically separate system elements with no impact on signal quality will enable 'behind the wire' encryption and reduce risk exposure. With a fully remote system monitoring/control, only the antenna would be in the line of fire if located in a hostile territory ^[2]. By reducing the attack surface, enabling secure remote operations, and supporting distributed architectures, Digital IF strengthens cyber and physical resilience, ensuring continuity of Satcom services even when individual sites or assets are compromised.

3. Software-defined gateways

The transition to digitised and packetised ground segment architectures fundamentally alters the role of terminals and gateways within satellite communication systems. Once RF is digitised, the terminals and gateways no longer need to be fixed close to the antenna or defined by hardware. Instead, they can evolve into software-defined and reconfigurable terminals that can be scaled and re-purposed across missions, and dynamic switching of waveforms and orbits, thereby enhancing system resilience through increased flexibility, redundancy, and rapid service recovery.

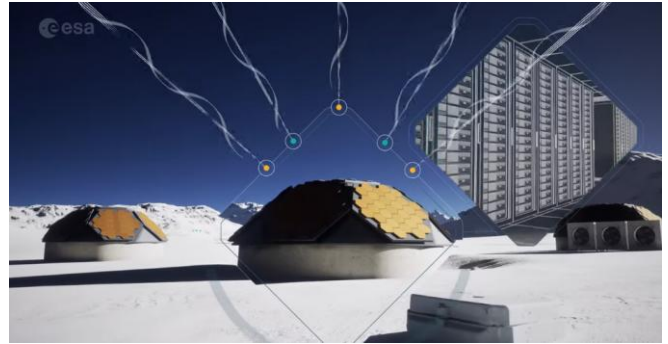


Figure 2. Innovative ground segment concepts.

From an interoperability perspective, software-defined gateways act as convergence points between digitised RF transport, waveform execution environments and higher-layer orchestration systems. When combined with DIFI, software-defined gateways enable RF signals from antennas and front ends to be processed by shared pools of virtualised modem functions running on Commercial Off-the-Shelf (COTS) hardware, cloud platforms or edge compute nodes.

The Waveform Architecture for Virtualized Ecosystems (WAVE) Consortium, which operates under IEEE Industry Standards and Technology Organization (IEEE-ISTO) governance focuses on enabling waveform software to run across virtualised and distributed computing environments. In this context, DIFI and WAVE address complementary layers of the architecture: DIFI standardises the transport of digitised IF data, while WAVE seeks to standardise how waveform applications are deployed and executed in virtualised environments ^[3].

Industry participation in both initiatives has increased in recent years, reflecting growing interest in open and interoperable satellite ground systems. DIFI has already released multiple versions of its standard and regularly conducts interoperability testing through industry PlugFest events. The vision is similar to the disaggregation and open-interface approach adopted by Open Radio Access Network (O-RAN) in terrestrial 5G networks, although satellite virtualisation standards remain less mature and continue to evolve. Their long-term success will depend on widespread adoption,

robust conformance testing, and interoperability across different hardware acceleration and software platforms.

4. Interoperability layers & service frameworks

Software-defined terminals and gateways create the foundation for virtualised signal processing. The ability to use modem functions in software and process digitised RF flows across hardware environments is part of the interoperability problem. To fully achieve it, it requires that different components can interact coherently across multiple functional layers: RF control, transport, network and service orchestration. Digital IF transport enables the decoupling of RF front ends and waveform processing. Software-defined gateways extend this into digital signal processing. However, without antenna control, radio transport, waveform adaptation and service lifecycle management, these capabilities remain isolated rather than integrated.

Interoperability layers can be understood as a stack of functional layers, each responsible for enabling coordination between otherwise independent system components. This layered view reflects how satellite communication can converge with broader telecommunications architectures, where well-defined interfaces enable scalability and multi-vendor ecosystems. Interoperability is a key enabler of resilience at system level, allowing seamless integration across vendors, standards and domains.

4.1 Antenna-modem integration

OpenAMIP is a text-based protocol that uses American Standard Code for Information Interchange (ASCII) messages to enable communication between a satellite modem and an antenna controller. It allows the modem to instruct the controller to locate and track a specific satellite, while also supporting the exchange of information needed to establish and sustain the link. This protocol is designed to enable coordinated automatic beam switching between the modem and the controller, along with providing status reporting. OpenAMIP does not provide a way for security or authentication, so any protection or validation must be

implemented through lower-layer protocols, chosen by the modem and controller ^[4].

4.2 Radio transport

Enhanced Common Public Radio Interface (eCPRI) has potential relevance for software-defined satellite communication gateways as a telecommunications-mature model for transporting digitised radio signals over packet networks. The scope of the eCPRI specification is to enable efficient and flexible radio data transmission via a packet based fronthaul transport network, like IP or Ethernet.

Radio base stations offer deployment flexibility to mobile network operators, i.e., in addition to an all-in-one radio base station, a more flexible radio base station system architecture involving remote radio equipment can be supported. This is achieved by functional disaggregation and decomposition of the radio base station into two basic building blocks, the eCPRI Radio Equipment Control (eREC) and the eCPRI Radio Equipment (eRE). Both parts may be physically separated (the eRE may be close to the antenna, whereas the eREC is generally located in a conveniently accessible site) and connected via a transport network.

While DIFI standardises digital IF transport specific to satellite communication, eCPRI defines functional splits between radio units and baseband processing in virtualised Radio Access Network (vRAN). The potential relevance of DIFI and eCPRI merits investigation, as it could enable satellite communication gateways to adopt fronthaul like architectures, supporting cloud-based processing, tighter 5G/6G integration, and harmonised transport and control across terrestrial and satellite networks ^[5].

4.3 Satellite communication air interfaces

Digital Video Broadcasting - Satellite Second Generation Extended (DVB-S2X) is an extension of the DVB-S2 standard designed to significantly improve the efficiency and robustness of satellite communications. It introduces a range of Physical-layer upgrades from

DVB-S2, that allows satellite links to operate closer to the Shannon limit while supporting both broadcast and broadband satellite communication applications. These upgrades include higher order modulation (up to 256-APSK - Amplitude and Phase-Shift Keying), smaller roll-off factors, improved filtering, etc. New operational modes target very low signal-to-noise ratios.

Beyond efficiency gains, DVB-S2X supports emerging techniques such as beam hopping, where satellite beams time-share coverage dynamically based on demand. Amendments to the standard enable this capability, improving flexibility and resource allocation in modern GEO and NGSO systems. This makes DVB-S2X a key enabler for next-generation satellite communication air-interfaces built around software-defined payloads and demand-driven capacity planning.

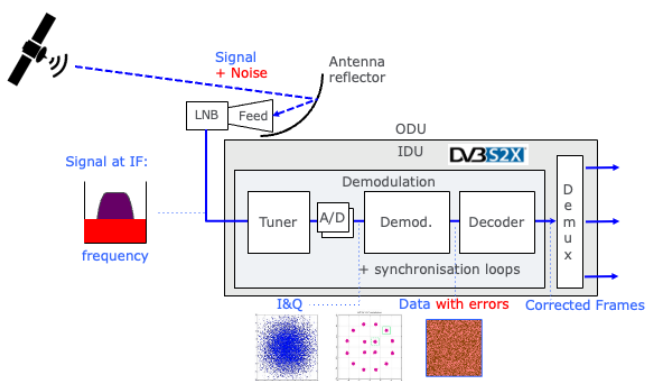


Figure 3. Conventional DVB-S2X receive data-path.

Following the layered interoperability approach, DVB-S2X is best seen as a foundational enabler of interoperability at the air interface, which must be complemented by emerging standards (e.g. DIFI, service APIs) to support full interoperability across virtualised and multi-vendor satellite communication architectures [6],[7].

For a two-way satellite communication, DVB-S2X should be considered alongside the Second Generation DVB Return Channel Satellite (DVB-RCS2). In a typical satellite broadband network, DVB-S2X carries data from the hub to user terminals. DVB-RCS2 provides return link transmission methods and controls that allow terminals to send data back towards the hub. Together,

they provide a basis for services like satellite internet access [8].

From an interoperability perspective, DVB-RCS2 provides terminal profiles that identify the capabilities required for different applications. Terminals and hubs must support compatible profiles, signaling and transition options to operate together. Recent revisions also introduce additional positioning and handover signaling for NGSO systems. Interoperability should therefore be verified for the selected equipment and operating configuration, supported by DVB's published reference signals and test procedures [9].

In parallel, the 3rd Generation Partnership Project (3GPP) Non-Terrestrial Networks (NTN) standards introduce a complementary air-interface framework aligned with the 5G ecosystem, extending cellular technologies (New Radio (NR) and Narrowband Internet of Things (NB-IoT)) to satellite systems. NTN defines adaptations to waveform design, timing advance, mobility management, and link budgeting to address the large propagation delays and Doppler effects inherent to satellite links. This enables native integration of satellite connectivity into terrestrial 5G/6G networks, supporting use cases such as direct-to-device communications, IoT backhaul, and hybrid terrestrial satellite services. **Within a layered interoperability context, 3GPP NTN plays a key role in bridging satellite and mobile networks, enabling seamless service continuity and strengthening network resilience through multi-domain connectivity, terrestrial-satellite failover, and alternative communication paths when terrestrial networks are degraded, congested, or unavailable.**

4.4 Broader networking operations

MEF Forum is now called Mplify Alliance, since June 2025. Mplify is a global alliance of enterprises, service providers, cloud and technology providers, data centres and systems integrators, collaborating to accelerate the AI-powered digital economy. Through standardisation, automation, certification, and community-led innovation, Mplify is empowering secure, scalable and

trusted services that drive Network-as-a-Service (NaaS) adaptation across a global network ^[10].

Mplify defines many service standards, including those for underlay connectivity, as well as overlay services, such as Secure Access Service Edge (SASE) and Software-Defined Wide Area Network (SD-WAN). The combination of the service standards (underlay connectivity and overlay services), together with Lifecycle Service Orchestration (LSO) APIs, enables enterprises to adopt network-based, software-defined services and accelerate digital transformation. By using LSO standards to automate both within and between providers at the underlay connectivity layer, which is synched with the SASE and SD-WAN overlay layer, service providers can deliver modern digital services to their customers ^[11].

Frameworks such as Mplify illustrate a shift toward API-driven service abstraction, decoupling underlay connectivity from overlay services via standardised interfaces (e.g. LSO). In satellite communication, this addresses interoperability limitations of vendor-specific ground systems by enabling disaggregated, software-defined architectures. This approach supports dynamic service provisioning, orchestration across domains, and integration with SD-WAN/SASE and broader telecom architectures. This evolution is key to positioning satellite communication within end-to-end, cloud-native NaaS environments alongside terrestrial infrastructures.

The **TM Forum (TMF)**, launched in 1988, aims to standardise operations and promote interoperability. It currently comprises three missions (growth, innovation, and customer experience), five strategic themes, and multiple collaborative projects, and has strong relevance for satellite communication modernisation. Themes such as autonomous networks, cloud-native IT and networks, and AI-driven operations directly support satellite communication's transition from proprietary, hardware-centric systems toward software-defined, interoperable architectures.

The topic of autonomous networks is being discussed with other standardisation organisations such as 3GPP

and ETSI. The intent model and API, which are the purpose of achieving the overall architecture and automation, have been standardised.

There are active discussions on automation scenarios using Generative AI, creation of a common telecom large language model and clarification of the relationship between architecture and use cases.

TM Forum initiatives, particularly Open Digital Architecture (ODA) and Open APIs, provide a structured approach to transforming Operation Support System (OSS)/Business Support Systems (BSS) into modular, interoperable systems. For the satellite communication sector, this is highly relevant as current operations are often constrained by fragmented, vendor-specific management environments. ODA enables the separation of functions such as Engagement Management (customer interaction) and Intelligence Management (AI-driven operations), linked through standardised APIs. This supports automation, intent-based control, and integration with telecom ecosystems. As a result, satellite communication can evolve toward software-defined, AI-enabled operations, improving interoperability at the service, orchestration, and operational layers within multi-domain networks ^[12].

5. Generic orchestrator & control plane

The orchestration and control plane is a fundamental enabler of interoperability within modern satellite communications systems. As satellite networks evolve towards multi-orbit architectures, software-defined payloads, virtualised ground segments, and tighter integration with terrestrial telecommunications infrastructure, interoperability can no longer be achieved solely through standardised interfaces at the physical or network layers. Instead, a higher-level intelligence layer is required to coordinate resources, manage network behaviour, and maintain service continuity across heterogeneous domains. This role is fulfilled by the orchestration and control plane.

Control plane - Rather than representing a single network component, the control plane can be viewed as a distributed decision-making framework responsible for translating operational objectives into network actions. It maintains awareness of network topology, gateway availability, satellite visibility, traffic demand, service-level requirements, and infrastructure health. Based on this information, it dynamically selects gateways, orchestrates traffic routing, manages handovers between satellites and beams, and coordinates the deployment of network functions. In effect, the control plane provides the logic necessary to transform a collection of independently operated assets into a coherent and interoperable system.

Orchestration - The importance of orchestration becomes particularly evident in integrated satellite-terrestrial environments. Future satellite communication systems are increasingly expected to operate as extensions of wider telecommunications and cloud ecosystems rather than as isolated networks. Satellite communication services may traverse satellites in multiple orbits, terrestrial transport networks, cloud-hosted processing environments, and edge computing resources before reaching end users. Maintaining interoperability across these domains requires a consistent mechanism for policy enforcement, resource allocation, traffic steering, and service assurance. **Consequently, orchestration must operate across multiple administrative boundaries and technology stacks while preserving end-to-end service objectives. In this context, interoperability and operational assurance become key enablers of resilience, ensuring service continuity and coordinated recovery across diverse infrastructures and operational domains.**

Three key factors are driving the increasing importance of orchestration and control-plane functionality:

Decoupling network functions from dedicated hardware through virtualisation.

Dynamic coordination of resources across multiple gateways, satellites, beams, and orbital layers.

Integration of Satcom infrastructure into cloud-native and telecommunications environments.

Software-Defined Networking (SDN) and Network Function Virtualisation (NFV) provide the primary architectural mechanisms used to implement these capabilities. SDN introduces centralised network control through programmable controllers that maintain a global view of network resources and traffic flows. NFV complements this by virtualising traditional hardware-based network functions, allowing modem processing, routing, security, and other capabilities to be deployed as software instances on shared computing infrastructure. **Together, the SDN and NFV technologies enable orchestration of resilient systems to respond dynamically to changing operational conditions while reducing dependence on specialised hardware^[13] and avoiding correlated vulnerabilities.**

For interoperability, the significance of orchestration extends beyond simple network management. Effective interoperability requires that information and decisions can be exchanged consistently between different systems, operators, and technology domains.

While SDN and NFV provide the programmable infrastructure needed to automate network behaviour, additional interoperability mechanisms such as DIFI, standardised telemetry interfaces, common operational abstractions and KPI-driven assurance frameworks are required to ensure that orchestration decisions can be executed consistently across heterogeneous network platforms.

The effectiveness of any orchestration architecture is also strongly influenced by the placement of controllers, orchestration components, and gateway resources. Excessive latency between control elements and operational assets can delay responses to handovers, routing changes, or fault recovery events. Both academic research and industry developments increasingly favour distributed and cloud-native orchestration architectures capable of maintaining local responsiveness while preserving global network visibility^{[13], [14]}.

Interoperability within next-generation satellite communication systems depends not only on common interfaces and protocols but also on the existence of a coordinated orchestration and control plane capable of managing resources across multiple domains. By providing unified decision-making, policy enforcement, and service coordination, the orchestration layer acts as the operational glue that enables satellite, terrestrial, cloud, and edge infrastructures to function as a resilient integrated communications ecosystem.

6. Interoperability KPI framework

A coherent KPI framework is essential for evaluating interoperability across multi-orbit and multi-domain satellite communication networks. The 3GPP/ETSI TS 28.554 KPI catalogue provides the foundational rules for end-to-end performance metrics (latency, throughput, reliability, session setup, session retainability), serving as reference metrics for satellite communication. Complementary guidance from the 5G-PPP TMV group strengthens this baseline by detailing methods, tools, and best practices for KPI acquisition, including open-source test harnesses and commercial analysers, which are vital for satellite communication - TN hybrid evaluations ^[15].

For satellite-specific interoperability, the SNS-JU work on service continuity KPIs fills a long-standing gap, proposing explicit definitions for TN/NTN access switching. These metrics are directly related to orchestration platforms and are essential for validating multi orbit routing and gateway handover policies ^[16].

DIFI's growing adoption across the industry makes digital-IF interoperability testing a central pillar of satellite communication ground segment validation. The v1.2.1 and v1.3.0 updates include class definitions, sampling-rate conventions, timestamping, and resolve flow control issues, that directly influence multi-vendor compatibility. These developments are reinforced through regular DIFI PlugFests, which provide collaborative environments for multi-vendor interoperability testing, validation of implementations, and alignment of data formats and timing behaviour.

Complemented by emerging certification efforts, they aim to establish conformance benchmarks, ensuring consistent implementation and accelerating industry-wide adoption of interoperable digital IF solutions.

7. Security, trust & compliance

The transition toward interoperable, software-defined, and cloud-hosted satellite communication ground segments has fundamentally reshaped system resilience, while significantly altered the security posture of satellite systems. Multiple recent studies converge on the same conclusion: the ground segment is now the primary attack surface, surpassing the space segment in accessibility, exposure, and potential systemic impact ^[17].

Historical cyber incidents were often contained within a single operator or mission. Recent events demonstrate a shift toward strategic, cross-border disruption, particularly against interoperable and commercial infrastructures. The KA-SAT attack (2022) ^[18] remains a defining case, but some follow up analyses in 2023-2025 show a sustained increase in Advanced Persistent Threat (APT)-level targeting of ground systems, including mission control networks, cloud-hosted services, and supplier IT environments ^[19].

At the same time, Global Navigation Satellite System (GNSS) interference campaigns across Europe (jamming and spoofing) underline the coupling between cyber and RF domains, illustrating how attacks on ground networks can rapidly propagate into critical services such as aviation, maritime navigation, and energy distribution.

Recent research work confirms that the proliferation of LEO satellites increases these risks, as larger numbers of ground sites, automation layers, and third-party integrations make systems more fragile and trust is not consistently enforced ^[20].

Interoperability standards are foundational resilience enablers, providing the flexibility and adaptability needed to withstand evolving threats. However,

resilience is only fully realized when interoperability is paired with explicit security architectures that proactively address vulnerabilities. Digitised signal streams transported over IP must be protected against interception, replay, timing manipulation, and injection attacks, particularly where waveform processing is remote from antennas. Industry case studies show that digital IF can reduce the number of attacks if cryptographic boundaries are relocated “behind the wire” and managed centrally. However, this requires harmonised encryption, key management, and identity binding across vendors, which is currently unevenly implemented in the ecosystem ^[1].

Between 2024 and 2026, Europe has become a leading regulatory actor in space cybersecurity. The proposed EU Space Act (2025) introduces binding obligations for both space and ground infrastructure, explicitly covering cyber-risk management, encryption, testing, incident reporting, and supply chain assurance, mirroring and extending the Digital Operational Resilience Act (DORA) (Regulation (EU) 2022/2554) from the financial ICT sector into the space domain. In parallel, Germany's BSI IT-Grundschutz Profile for Space Systems-Ground Segment represents the first comprehensive lifecycle security baseline specifically tailored to satellite ground infrastructures, explicitly acknowledging virtualisation, cloud hosting, and multi-operator environments ^{[21], [22]}.

8. Economic and business models

The traditional economic model of satellite communications rested on a small number of space assets paired with dedicated, orbit and mission specific ground infrastructure. These systems were designed around predictable demand, and relatively static service portfolios. Such assumptions no longer hold. Market analyses show that constellations and hybrid GEO-MEO-LEO strategies have fragmented demands. At the same time, the shift towards digitalisation has shortened the lifecycle of the ground segment compared to space segment, creating a gap between fast developing ground and long - lasting space segments ^[23].

In this context, interoperability becomes an economic solution to rigid traditional ground segment systems. Ground infrastructures that cannot be reused, shared, or dynamically orchestrated become too costly, particularly when traffic migrates across orbits, operators, or the type of service that is provided. Economic literature and comments from operators consistently highlight that key cost factor is not how powerful the system is, but how flexible and efficiently it can be used. **Interoperability allows the infrastructure to be treated as a pool of shared resources, rather than a collection of mission-specific assets.** This is like what happened in telecoms and cloud computing, where open interfaces allowed more flexible and scalable business models ^[24].

Market evidence indicates that interoperable Ground Station as a Service (GSaaS) platforms derive their advantage from utilisation density. Contact windows, spectrum resources, and compute elements can be scheduled across missions, customers, and institutional or commercial users, significantly reducing marginal cost per service hour. In contrast, non-interoperable ground systems struggle to achieve sufficient utilisation, particularly as constellation sizes grow and per-satellite contact times shrink. Regulators and industry players increasingly recognise that duplicating separate ground systems is inefficient at a large scale ^[25].

Multi-orbit connectivity further amplifies the economic importance of interoperability. While multi-orbit architectures improve resilience and coverage, defence and government users have repeatedly stressed that resilience has an explicit cost. Each additional orbit introduces new terminals, service contracts, and operational complexity, and without interoperable orchestration these costs scale linearly or worse. Interoperable ground and control planes allow resilience to be invoked selectively, shifting optimisation from cost per bit to cost per assured service outcome, a transition widely discussed in defence and government forums ^[26].

Interoperability affects competition across the industry. Closed systems can maximise short-term profits but limit adaptability and increase systemic risk. Open, interoperable systems encourage competition at higher levels, such as service management, optimisation, and long-term support. For Europe, this is especially important in terms of strategic autonomy, supply-chain resilience and reducing dependence on external providers ^[26].

Taken together, the available evidence indicates that interoperability in the ground and user segments is not just an efficiency and resiliency gain but a key economic strategy. It enables flexible cost structures, supports service-based business models, mitigates the cost of resilience in multi-orbit systems, and strengthens long-term competitiveness. **For ESA, the economic question is no longer whether interoperability is desirable, but how it can be governed and sustained to maximise long-term value while controlling systemic risk.**

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