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Multi-layer ground segment architectures for satellite constellations

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Abstract

During the last years the number of satellite constellations has significantly increased, with the consequent increase in the number of ground segments supporting them. While each constellation may serve a different purpose (e.g. navigation, communications, observation, etc.), their missions and roles of their associated ground segments usually offer many commonalities that can be leveraged to share information across their subsystems and make them more generic, aiming to support these missions in parallel towards a better sustainability; the final objective is the reduction of the ground infrastructure to optimize operational costs and resources, improving as well the coordination between missions and partners, and enabling the possibility of offering new services derived from a combined usage of the assets belonging to different missions.

Multi-mission ground segments are not a novel concept, as currently many operators worldwide monitor and control different satellite missions from single control centres; nevertheless, scaling this concept to a multi-layer approach for the concurrent management of several satellite constellations has not been an interesting topic until now, where the advantages of this strategy can be better exploited. A good example of the future opportunities in this area are the European Commission constellations such as Galileo or LEO-PNT, for which GMV is evolving their ground segments to enable this architecture in the future.

In a multi-layer architecture, mission services from different constellations share data to improve their efficiency (e.g. navigation, observability, safety), although sometimes it's required to keep an independent segregation of the critical information that cannot be directly exchanged. The challenges to be tackled are both technical and operational, as combining operations of several constellations -potentially flying at different altitudes with different purposes- requires elaborating a balanced operational concept, which considers the security constraints imposed by each one as well as their common technical aspects; the supporting set of ground assets should then exploit the fact that contemporary technologies enable the integration of specific functionalities of each mission in the same software architecture and in this unified operational concept.

At ground segment platforms level, most of the computational services associated with a single constellation (e.g. flight dynamics, task planning, task orchestration and automation, product generation, etc.) can be expanded to provide additional functions to deal with several missions in parallel with just software changes. These components are then supported by flexible service-oriented virtualization architectures that can be scaled up to the required performance, and a set of common platform services (such as networks, storage, authentication, security) with the right granularity to be aligned with the segregation requirements and the operational concept. With this approach, even if the core satellite/mission control services need to be specific for each mission, the aggregation of the remaining supporting services will allow a dramatic reduction of the required resources and operational efforts to manage them.

This paper expands the concepts introduced above by examining the architectural design, operational challenges, and enabling technologies required to implement a multi-layer ground segment effectively. By analyzing both technical and operational considerations, it aims to demonstrate the benefits of such approach, which may include enhanced resource efficiency and improved mission coordination.

Keywords: Ground Segment, Satellite constellation, Multi-layer, Multi-mission, Sustainability, Service-oriented architectures, Performance

Acronyms/Abbreviations

Low-earth orbit (LEO), Medium-Earth orbit (MEO), Geostationary orbit (GEO), Inclined Geosynchronous Orbit (IGSO), Software (SW), Hardware (HW), Application Programming Interface (API), Role-based Access Control (RBAC), Attribute-based access control (ABAC), Zero-trust architecture (ZTA), Fault detection isolation and recovery (FDIR), Position Navigation and Timing (PNT), Satellite-Based Augmentation System (SBAS), Global Navigation Satellite System (GNSS).

1. Introduction

The rapidly expanding number of satellite constellations—including diverse applications in navigation, communications, and Earth observation—has increased the complexity of ground operations. While most of the ground segments associated to each mission share many commonalities and could benefit from sharing most of their resources, multi-mission architectures are not a usual approach; even if some of these multi-mission ground segments have demonstrated efficiencies by consolidating resources for smaller-scale missions, they have yet to fully address the demands of managing multiple orbital layers (LEO, MEO, GEO) under one unified infrastructure.

To advance beyond current multi-mission models, this paper explores the concept of a **multi-layer ground segment** that integrates modern technologies (e.g., service-oriented and data-centric architectures, virtualization, automation, homomorphic encryption) to manage multiple constellations from a single platform. This approach aims to reduce the hardware footprint and operational overhead typically incurred by mission-specific ground segments, while simultaneously maintaining strict security partitions and need-to-know boundaries.

The primary objectives of this paper are to examine the technical and operational challenges associated to this approach, illustrate how a consolidated, service-oriented architecture can mitigate these challenges, and demonstrate the resulting benefits in terms of cost reduction, resource efficiency, and improved coordination.

2. Background

Historically, the approach of managing multiple space missions through a unified ground segment architecture has been employed on several occasions. These multi-mission ground segments typically provide an effective solution for supporting multiple small-scale missions through a shared ground infrastructure and operational teams; this concept does not impose homogeneity requirements for the missions to be controlled, as different spacecrafts with different payloads and objectives can be supported.

In the last years, the evolution of system topologies towards the integration of spacecrafts flying at different orbits (LEO, MEO, GEO, IGSO) has led to the definition of multi-layer missions, where different layers refer to these multiple orbiting altitudes of the associated constellations; this concept assumes that these architectures have been conceived and designed as a multi-layer system, rather than a loose aggregation of different layers. Therefore, a multi-layer ground segment would be characterized by having an integrated and scalable architecture designed to support the management and operations of multiple satellite constellations operating across various orbital layers.

Multi-mission ground segments are evolving to meet key objectives for multi-layer mission operations, such as increasing operational efficiency, reduce costs and improve resource utilization. Notable examples of multi-mission systems include NASA's Multi-mission Operations Center (MMOC), which provide a reconfigurable environment to support diverse missions such as Kepler/K2, SOFIA and LADEE [2.1]. MMOC illustrates the role of automation in managing multiple satellites, a capability for multi-layer architectures. Similarly, the European Space Agency (ESA) has also advanced in the concept through the European Ground Segment Common Core (EGS-CC), applied in projects like the German Aerospace Center's (DLR) LUNA initiative [2.2]. Studies in this topic include the IEEE proposal for a modular ground station design for educational and research purposes, capable of supporting satellites across VHF, UHF and S-band frequency [2.3], or the 2024 study conducted by MDPI Electronics examines the architecture of multi- layered satellite communication systems, focusing on the integration of satellites in LEO, MEO and GEO to increase availability and resilience [2.4]; this design is adaptable, enabling the integration of multiple orbital layers within a shared infrastructure. These examples highlight the growing demands for adaptive, integrated ground segments with the ability to support multi-layer missions and their different operative nature.

Nevertheless, this approach for Multi-layer ground segment has not been commonly applied in the past; cases such as EGNOS [2.5], an SBAS system that makes use of three GEO satellites (as secondary payload) and a network of ground stations, and Galileo [2.6], with its MEO constellation and a complete ground segment, exemplify systems that leverage multiple orbital layers but are operated independently from ground. EGNOS was not conceived originally as part of the Galileo system and was incorporated later to the European GNSS strategy. While EGNOS makes use of the Galileo signal to provide improved accuracy in the navigation services, both systems are not exploiting the -currently complex- possibility of a combined management of their ground assets.

3. Challenges in Multi-layer Ground Segment Design

Managing different constellations from a single ground segment imposes some challenges to be tackled for the at both technical and operational level; these challenges, mainly driven by the specific sizing, environmental constraints and governance approaches for each constellation, will impose different routine contact times, special operations and contingency procedures to be supported by the multi-layer ground segment. Considering a worst-case scenario where different constellations are managed by independent operators with specific need-to-know restrictions (see Fig.1), the ground assets must support strict data segregation and sharing schemas and operations may have to deal with complex planning, additional security protocols and potential governance issues.

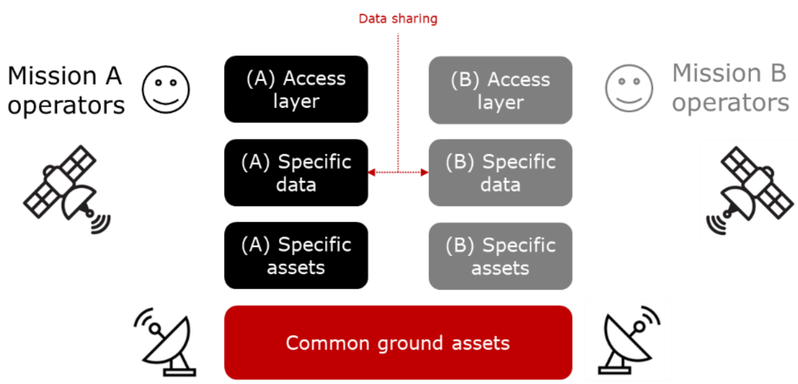

Fig. 1. Multi-layer ground segment with independent operations

Assuming that a significant number of ground assets will be shared between missions will require the definition of isolated zones on top, in order to store mission-specific data, as well as secure mechanisms to exchange the subset required to improve operations on the other side. The bottom layer of common ground assets must then support the scalability of the system and the integration of heterogeneous systems, and therefore flexibility requirements will become very relevant. This worst case assumes as well that access layers are not shared between missions, meaning that dedicated operational positions for each team are available and they do not share the same operational rooms.

On the operational side, challenges start with resource scheduling: a common operational concept should stablish the regulation of the ground stations supporting the constellations if they need to be shared, especially for the management of special operations; constellations in different orbits for different purposes have rather different communication requirements and contact times. In case a centralized planning approach is not feasible, it would be required to design robust negotiation and conflict resolution mechanisms, potentially without sharing the complete planning details from each side during this process. A high flexibility of the scheduling schema is therefore required to modify operational priorities on short notice, with a high degree of automation.

Even if all this process is automated and monitored by independent teams on different operational rooms, it is expected that some high-level coordination between operators is required, imposing additional security protocols to reduce data leakages. This coordination will also require a clear governance model to avoid issues related to different operational priorities, chains of command or disagreements.

4. Core Components of Multi-layer Ground Segment Architectures

Leaving aside the operational challenges related to security protocols and governance model, the key for the success of the multi-layer ground segment approach is the definition and implementation of the ground assets management platform which fulfils the requirements identified previously; this platform is defined the combination of hardware and software services that supports the ground segment functions, implemented as virtualized software components.

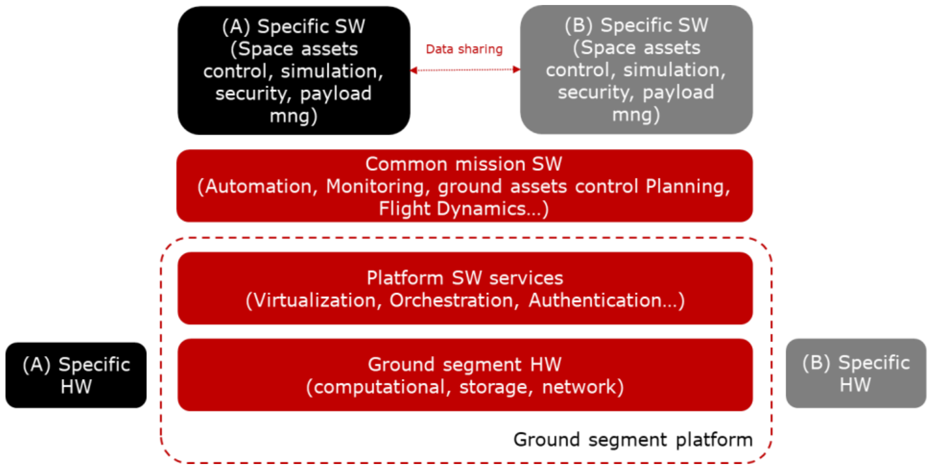

Fig. 2. Ground Segment platform logical architecture

As depicted in Fig.2, the ground segment platform supports the deployment of both common and specific SW components on top and provides the mechanisms as well to manage mission specific HW if required. The bottom layer includes the hardware associated to the provision of computational, storage and network resources required by the upper layers to run, as well as the antenna network supporting ground to space communications; this layer is expected to be fully shared between missions, and its optimization will be the one of the greats contributor to reduce the footprint and the cost of the system associated to ground assets procurement, management, maintenance and obsolescence resolution (including vulnerability management).

If required by the mission context, this HW layer must provide the physical segregation between different security domains to allow the definition of isolated security zones and the mechanisms to exchange data between them, such as cross-domain devices (e.g. diodes or secure gateways). With this strategy, the upper SW layers will manage the requirements associated to flexibility to support the integration of heterogeneous systems, the services scalability and the need-to-know segregation within the same security domain.

The core technologies selected to implement the platform SW services layer should include SW virtualization, that will support the deployment of service-oriented components and their orchestration mechanism (e.g. Kubernetes). Other candidate common services to be included in this layer are:

- Centralized authentication service, including a common user database for all missions with the required information to ensure need-to-know segregation.
- Centralized addressing service, to simplify network deployments and management.
- Centralized monitoring service, with a common metrics database for all ground segment assets that provides the relevant aggregated information to the operators of each mission.
- Centralized data exchange and storage services, allowing the implementation of a data-centric architecture which provides storage and communication services to the business services.
- Security services, including cybersecurity monitoring, can be included as well in this layer to be provided as a service.

This set of services will then provide a solid and complete base for the business services layer to run, ensuring a seamless and transparent approach for the platform maintenance and potential extensions, minimizing downtimes. It should be noted that these business services must be enforced by design to make use of the platform services, so they are implemented with access control attributes (RBAC or ABAC) managed by the authentication service, observability API to be used by the monitoring service, generic APIs and integration with service mesh to make use of the centralized data exchange and security services, etc. Then, the physical instantiation of this platform can be supported by private or hybrid cloud deployments (for specific scenarios), to provide as well additional resilience capabilities.

The common mission SW layer encompasses the components providing the core business functions expected to be shared. Adopting an ambitious approach, most of the ground segment capabilities can be incorporated within this set:

- Mission planning; the common mission planning function should manage all the planning needs for the mission, including both space and ground assets activities, and eventually operators resources as well to enable the creation of a complete, optimized and consolidated schedule. Even if some mission specific input data cannot be provided as input for this function (e.g. sensitive space or ground assets activities), some obfuscation techniques could be used to allow these dataflows, as explained later. Centralization of this function is the key to enable a proper conflict-free resource management to simplify the governance of the ground segment.
- Flight dynamics; apart from some specific space assets platform computations, most of the flight dynamics functions can be shared between missions. Computational results, commands or reports can then be segregated by need to know and be used by the specific mission control layers.
- Automation; the orchestration and automatic task execution triggering can be centralized for all services.
- Operations preparation; whenever the specific space assets control software allows it, a common approach for the definition of the operational procedures of all missions supported would simplify a lot their management in a multi-layer ground segment.
- Archiving; making use of the data centric approach, a common archiving function could be provided including the required segregation per need-to-know for specific products if required.
- Analysis functions; oriented to provide the operator with the capability to analyze telemetry data received from the supported missions, this function can make use as well of the data centric approach to have access to the required data from a single point to perform the required processing.
- Ground assets control; the execution of administration, maintenance and operational tasks on the ground assets can be performed as well from this common layer, assuming all these assets are properly managed by the planning and orchestration functions to resolve conflicts and priorities.
- FDIR function, which makes use of the metrics retrieved by the monitoring service to enable early detection of ground segment anomalies and drive required isolation and recovery actions.

Finally, the top layer would encompass the independent SW components to be managed for each mission; these functions are normally quite segregated, although in some cases they may include cross-layer applications that facilitate missions' coordination. They make use of the common layer to receive the inputs required to perform their tasks:

- specific space assets commanding and control; closely coupled to each spacecraft platform, in a worst-case scenario each orbital layer could require a completely different approach for its commanding and control.
- simulations; similarly, simulation functions are expected to be independent for each space asset platform, although in some cases common components could also be shared between layers (depending on the platforms similarities).
- payload management; this category comprises the functions associated to the specific payload in each orbital layer, that cannot be shared between missions due to need-to-know requirements or other incompatibilities (e.g. navigation data processing).

One of the key capabilities of the multi-layer ground segment is the possibility of exchanging data between these mission-specific functions to improve their operations without revealing sensitive information and preserving the need-to-know boundaries. Some potential applications of this data exchange would include:

- collision avoidance scenarios, where different constellations could provide encrypted orbit parameters into a single collision-detection algorithm without disclosing exact orbit parameters
- common resource scheduling, where operators could submit encrypted requests (e.g., time windows for ground station access) to the common scheduling service without revealing the content to the other side.
- shared telemetry information, to allow a central engine to perform pattern detection or forecasting, enabling a common advanced situational awareness.

This cooperative data processing can be supported by the platform by making use of Homomorphic encryption, allowing computations to be performed on encrypted data without ever decrypting it and where only the data originator can decrypt the result to obtain the plaintext output. While this approach may impose additional computational overhead and some algorithmic complexity, it can be implemented only on those high-value use cases and enable the desired resource sharing in a secure way.

5. Results: expected advantages and benefits

The proposed multi-layer ground segment approach could provide benefits to satellite constellation operators and stakeholders, going beyond mere technological integration. By optimizing the use of shared resources, reducing duplication of infrastructure, and facilitating seamless data exchange among diverse missions, this architecture can unlock significant cost savings and strengthen cooperation across different orbital layer, and enable the provision of ground segment, operations and mission as a service.

A primary driver for adopting a multi-layer ground segment is the potential for cost savings through the consolidation of physical and virtual infrastructure. The unification of ground assets for several missions (including ground stations, control centers, and supporting software platforms, etc.) reduces significantly the hardware procurement and lowers operating costs related to running operations, maintenance and personnel; obsolescence resolution and vulnerability management at both hardware and software levels are also notably improved, as this harmonization benefits both the definition and application of security policies. Moreover, centralized scheduling of ground station passes enables efficient time-slot utilization and reduces idle periods. Operators can benefit from simpler logistical arrangements for deploying, upgrading, or replacing common hardware components, with reduced downtime and no duplicated infrastructure investments.

Beyond cost savings, the shared architecture improves overall sustainability and environmental footprint by reducing the volume of hardware and energy resources required to support multiple orbital layers. Fewer physical sites, antennas, and data centers lead to lower power consumption and reduced carbon emissions. This approach also mitigates the need for continuous hardware upgrades across multiple mission-specific ground segments, as system evolution can be managed in a single, coherent technology roadmap for all operators involved.

The multi-layer concept forces collaboration among diverse missions, even when strict security partitions are maintained. By unifying non-sensitive functions described previously, operators can align on best practices, share partial insights, and enable the definition of unified operational procedures for these functions. The common platform services layer should provide interoperability benefits, including simplified data exchange, standardized interfaces for monitoring and control, and consistent authentication and security policies. This interoperability can speed up response times to anomalies or changing mission demands, since different teams can coordinate more effectively on a shared baseline of tools and workflows. Consequently, the multi-layer ground segment architecture is expected to contribute to an improved coordination and interoperability across missions.

A ground segment infrastructure designed from the beginning to scale in resources and functionality, and supported by a cloud infrastructure, facilitates the implementation of concepts like ground segment as a service, operations as a service, or mission as a service. In fact, this approach shall enable the implementation of innovative services that exceed the capabilities of any single mission. The management of combined navigation, earth observation, communications or security data with diverse timing, coverage and resilience capabilities from a unified ground infrastructure enables sophisticated cross-layer operations with potential applications in emergency response, environmental management, autonomous systems, and global logistics, among others. Although this data might already be available and could be gathered and integrated from various independent missions or providers, the ability to utilize it at an earlier stage and maintain direct control over the sources can serve as a distinct advantage with significant strategic or commercial implications.

6. Case study: LEO-PNT and Galileo

The growing demand for high-accuracy and resilient PNT services has motivated the exploration of multi-layer solutions that expand beyond existing MEO-based constellations, such as Galileo, by incorporating LEO segments. In current Galileo operations, the “PNT Backhaul” comprises ground and onboard equipment (such as uplink stations, onboard mission receivers, sensor stations, transponders, etc.), forming a robust but highly complex network. While this diversity the desired redundancy, it also increases the system complexity, operational overhead, and maintenance costs. Introducing a unified multi-layer ground segment that integrates both LEO-PNT and Galileo infrastructures can reduce these inefficiencies by consolidating equipment, reusing hardware across mission functions, and leveraging more sophisticated redundancy strategies (e.g., inter-satellite links or integrated payloads).

A centralized ground segment platform would enable this unified approach, allowing the simplification of several aspects, from mission-data exchanges to orbit determination and timing. For instance, onboard measurements from LEO-PNT satellites can be rapidly downlinked and fused with Galileo data, improving real-time orbit and clock corrections. In turn, terrestrial would receive and distribute critical mission and telemetry information through a shared infrastructure rather than multiple independent networks. As a result, both LEO and MEO constellations can benefit from enhanced accuracy and agility while reducing the hardware footprint in ground operations.

Operationally, a common mission-planning system prevents conflicts by pooling station and antenna resources in real time, allocating contact windows based on priority and orbital constraints. LEO-PNT satellites, with their shorter orbital periods, need more frequent ground station passes than MEO constellations like Galileo, which typically have fewer but longer contact windows. By unifying these schedules, operators can ensure optimal use of ground assets, avoiding bottlenecks or idle periods. This approach also facilitates tighter integration with external services such as the International GNSS Service (IGS), which provides precise orbit and clock corrections, and the Space Surveillance and Tracking (EUSST) network, which helps monitor space debris risks. A single mission-planning tool can thus negotiate contact opportunities for both constellations, factoring in debris avoidance manoeuvres, collision risk assessments, and real-time operational priorities.

Beyond scheduling, a unified monitoring and control platform can centralize anomaly detection and situational awareness. For example, telemetry from LEO-PNT satellites—often updated more rapidly—may uncover performance drifts or reveal unanticipated environmental effects that could also impact MEO operations. This data is then fed back into Galileo's monitoring loops, enhancing the reliability of higher-altitude services. Integrated archiving and data analysis functions amplifies this synergy further: logs, event records, and telemetry data from both layers are stored in a shared repository, simplifying end-to-end diagnostics and cross-layer trend analysis. In addition, leveraging unified automation and operations preparation capabilities enables faster rollout of common procedures—such as uploading software patches or implementing flight operation directives—across multiple orbits, standardizing workflows and reducing operator workload.

Combining LEO-PNT and Galileo in a multi-layer ground segment would therefore enable the simultaneous management of the different orbital layers. Taking advantage of the functionalities provided as a service, operations would be simplified and the overall complexity of backhaul links would be reduced, with lower operating expenses, and an enhanced timeliness of PNT services. Ultimately, this unification paves the way for greater reliability, faster response to anomalies, and a more integrated approach to satisfy the increasing demand on the satellite navigation services domain.

8. Conclusion

The multi-layer ground segment approach presented throughout this paper addresses an innovative approach to manage increasingly diverse constellations while controlling costs, reducing infrastructure complexity, and streamlining operations. By unifying hardware and software resources under a shared service-oriented framework, operators can eliminate much of the duplication inherent in single-mission ground segments by taking advantage of latest improvements in virtualization, centralized monitoring, and automated planning. This consolidation has the potential to reduce the ground segment footprint, optimize operations and maintenance, and leverage the design of new services, while simultaneously preserving strict security segregation via mechanisms like homomorphic encryption and access-control frameworks that protect the need-to-know boundaries.

The possibility of developing new services based on the combination of different constellations' capabilities is one of the most interesting possibilities unlocked with this approach; frequent updates from LEO platforms can enhance real-time analytics for MEO or GEO satellites, improving scheduling accuracy and anomaly detection. Common platform services also enable better situational awareness, whether for collision avoidance or advanced data fusion that integrates navigation, Earth observation, and communications. These gains in flexibility and responsiveness may ultimately create opportunities for innovative applications in fields such as emergency response, global logistics, and autonomous system support, reflecting the growing demand for high-performance and resilient space-based service; the synergies that arise from the proposed scalable design enable and boost existing -but not so successful- concepts for the provision of ground segment and operations as a service.

Despite these benefits, further work is required to refine governance models, address varying regulatory constraints (e.g. accreditation challenges), and ensure harmonized data formats and communication protocols across different layers and organizations. Advances in artificial intelligence and machine learning—particularly for real-time scheduling and resource allocation—can push automation to higher levels of efficiency, while developments in inter-satellite links, optical communications, and edge computing may allow even more robust and fault-tolerant designs. The willingness of companies or agencies to address the challenges identified to implement this multi-layer concept now depends more on bureaucratic, commercial, or strategic growth in the space sector than on technology readiness, which has been demonstrated is no longer an obstacle.

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10. Contributions

Carla Conesa, Galileo GCS Systems Engineer at GMV; background investigation, reference checks, use case development.