



# Architectural Principles of Multi-Orbit Satellite Networks Using Cloud-Based Ground Infrastructure

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## Abstract

*The article examines architectural principles for multi-orbit satellite networks that rely on cloud-based ground infrastructure. Practical relevance is determined by the transition from single-orbit systems to layered constellations and by the operational need to scale gateways, processing chains, and service exposure through cloud platforms. Novelty lies in the joint consideration of multi-orbit networking mechanisms and cloud-ground disaggregation, with explicit attention to ground-station-as-a-service (GSaaS) and federated ground-station marketplaces. The study aims to systematize design decisions that improve service continuity, latency stability, and operational controllability for communication and Earth-observation missions. To achieve this aim, the work applies structured source analysis, comparative architectural decomposition, and synthesis of reference patterns. The study draws on recent peer-reviewed research on transparent NTN architectures, multi-layer resilience, SDN-based satellite control, dynamic routing, GSaaS optimization, federated scheduling, and security of satellite ecosystems. The conclusion formulates implementable principles for engineering teams responsible for customer-facing solutions and operations.*

**Keywords:** Multi-Orbit Satellite Networks, Non-Terrestrial Networks, Cloud Ground Segment, Ground Station as a Service, SDN/NFV, Inter-Satellite Links, Routing, Resilience, Cybersecurity, 5G/6G NTN.

## INTRODUCTION

Multi-orbit satellite systems (LEO-MEO-GEO) are increasingly used to combine low-latency access, wide-area coverage, and service continuity under heterogeneous traffic and visibility conditions. Parallel progress in cloud platforms has led to the re-architecture of ground segments: functions traditionally bound to fixed teleports are being decomposed into software-defined chains deployed near antennas, at edge points of presence, and in centralized clouds. For solution engineering and customer operations in a national space agency, the combined shift introduces a concrete engineering agenda: service design must align orbital-layer capabilities with cloud-ground elasticity, operational governance, and mission assurance.

The purpose of this article is to formulate a coherent set of architectural principles for designing multi-orbit satellite networks supported by cloud-based ground infrastructure, suitable for operational deployment. The objectives are to systematize multi-orbit network organization, with an

emphasis on inter-orbit interaction and gateway placement; to derive cloud-ground patterns that transform RF access into scalable digital services; and to synthesize a reference architecture that supports predictable performance, fault containment, and security governance across providers and missions. Scientific novelty is associated with an integrated treatment of:

- i) layered-orbit networking and routing dynamics,
- ii) cloud-native ground segmentation, including GSaaS and federated scheduling,
- iii) operations-driven design constraints typical for customer-facing engineering units.

## MATERIALS AND METHODS

The study's materials were selected to cover both sides of the target architecture: orbital networking and cloud-ground realization. O. Baselga [1] was used to interpret transparent NTN deployments and performance consequences of placing 5G components across satellite and terrestrial nodes; X.

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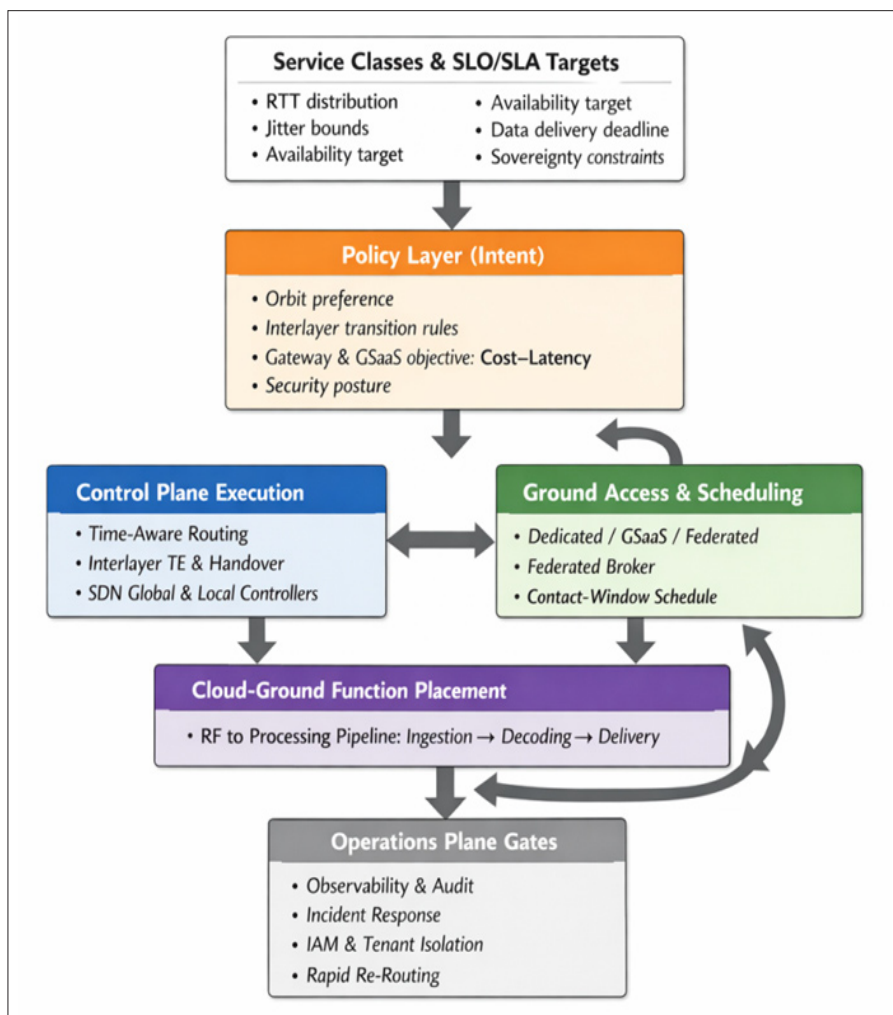
Cao [2] supported the synthesis of routing requirements under rapidly changing satellite topologies; M. Höyhtyä [3] provided multi-layer availability and resilience mechanisms with explicit interlayer routing considerations; W. Jiang [4] supplied SDN-oriented control and management views for satellite networking; Y. Jiang [5] contributed engineering insights into cloud-computing-based networked ground station systems; S. Mahboob [6] was applied to frame AI-supported NTN evolution and architectural control loops; R. Peled [7] supported the ground-segment security argumentation, including GSaaS exposure surfaces; A. Rago [8] was used to articulate multi-layer NTN architectural patterns toward 6G; G. Velusamy [9] supported the operational modeling of GSaaS as an optimization problem across cost and latency; H. Zhao [10] provided a federated GSaaS scheduling model and quantified benefits under simulation assumptions.

For writing the article, comparative analysis, structured literature review, architectural decomposition, conceptual modeling, and synthesis were applied, supplemented by consistency checking of design claims against the cited sources.

## RESULTS

Multi-orbit architecture engineering begins with the explicit separation of three interacting planes: the service plane (user-facing connectivity and mission data delivery), the control plane (resource allocation, routing policy, mobility, and handover management), and the operations plane (monitoring, incident response, configuration governance, and security). In multi-orbit systems, these planes interact across heterogeneous propagation and visibility regimes: LEO contributes to frequent topology changes and high handover pressure, MEO often provides regional continuity, and GEO offers stable, broad coverage with different delay characteristics. Multi-layer system studies emphasize that resilience gains stem from controlled interlayer connectivity and policies that shift flows between layers during congestion, outages, or visibility gaps, rather than from adding satellites without coordination [3].

To make the synthesis operationally actionable, the derived principles are consolidated into a policy-governed decision-to-execution chain that links service objectives to routing, ground access selection, and cloud-ground function placement (see Fig. 1).



**Figure 1.** Policy-governed coupling of multi-orbit routing and cloud-ground execution for operational deployment (author's synthesis)

The scheme clarifies that multi-orbit degrees of freedom yield stable service behavior only when orbit selection, interlayer transitions, GSaaS scheduling, and cloud function placement are enforced as policies with observability and auditable change control.

Routing and traffic engineering become the primary coupling mechanism between orbital layers and ground gateways. Surveyed routing work treats satellite networks as time-varying graphs where link availability and capacity evolve deterministically with orbital motion, forcing routing to balance responsiveness and stability [2]. In multi-layer settings, routing cannot be treated as a single, uniform problem. Intra-layer routing reacts to frequent ISL switching in LEO. In contrast, inter-layer routing must manage layer transitions as a strategic decision that affects latency variance, congestion risk, and gateway load. Multi-layer experiments and simulations reported in the literature support the claim that controlled use of additional layers can outperform purely single-layer strategies under load by providing alternative paths and reducing bottlenecks, assuming that interlayer links and policies are engineered coherently [3].

Cloud-based ground infrastructure redefines the classic notion of a “gateway” as a distributed chain of functions that begins at RF front ends and culminates in a cloud-native delivery pipeline. A networked ground station architecture based on cloud computing treats antenna sites as access points, with baseband processing, protocol termination, and data handling orchestrated through cloud resources [5]. This restructuring changes capacity planning from “per-teleport hardware sizing” to “elastic compute and storage planning” under deterministic contact windows and variable downlink volumes. The architectural consequence is a shift toward microservice-style decomposition of telemetry, tracking, and control (TT&C), mission data ingestion, decoding, processing, cataloging, and customer delivery, with the cloud acting as the integration substrate for multi-mission operations.

Ground Station as a Service introduces an additional abstraction layer, exposing ground access as an on-demand service with scheduling, pricing, and resource selection integrated into the operational architecture. GSaaS research frames the problem as a joint optimization of latency and cost, combining ground-station selection with cloud-processing placement [9]. Another line of work advances GSaaS further into federated ecosystems where multiple GSaaS providers can be combined, and where scheduling chooses providers and compute placement as a unified decision. A federated GSaaS model reports measurable improvements, under its simulation setup, relative to non-federated strategies, including significant reductions in download latency and cost under certain assumptions [10]. These works imply a

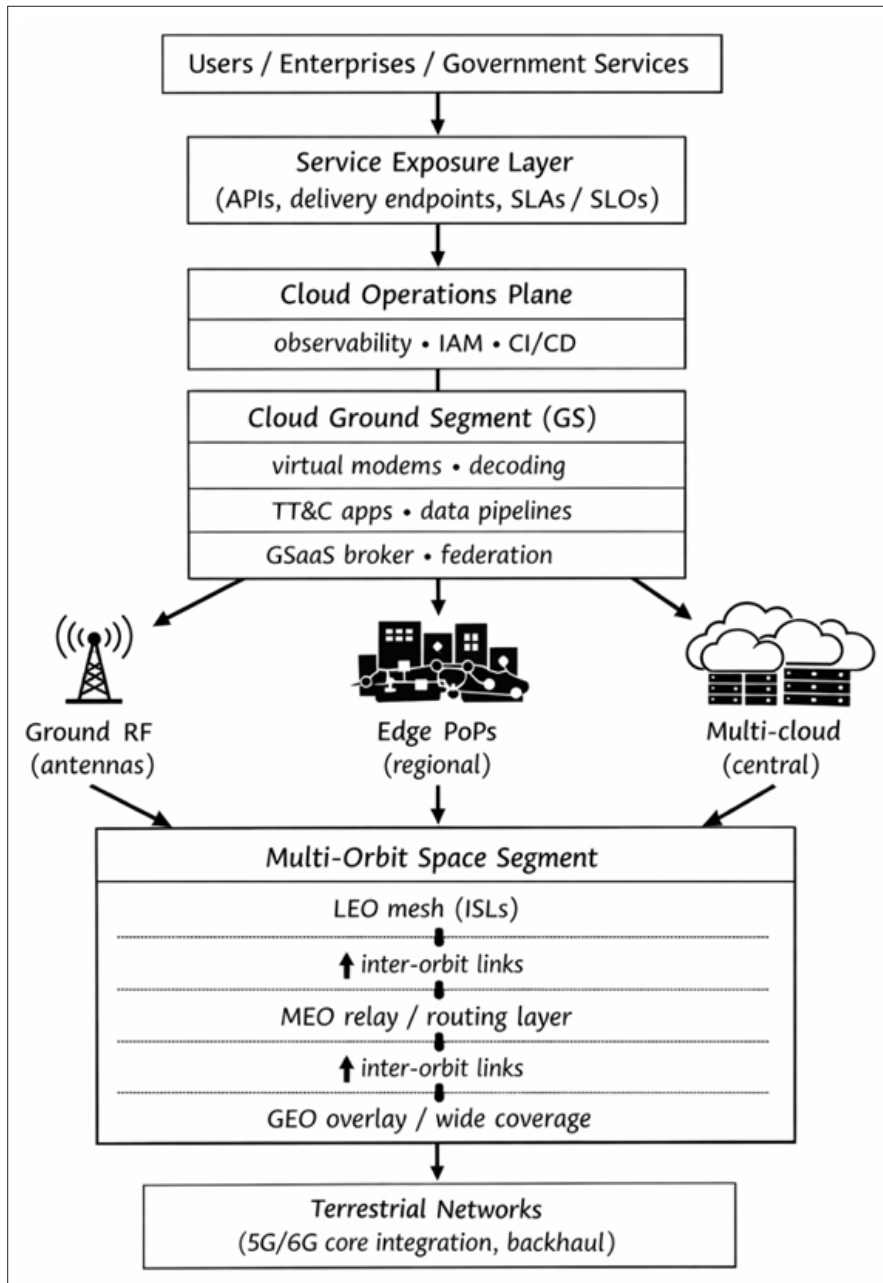
concrete architectural principle: in multi-orbit networks, the “ground segment” is not a fixed asset set; it is a controllable market-like resource whose selection logic must be designed and governed as part of the network architecture.

Control-plane design increasingly relies on software-defined networking concepts. SDN-based satellite networking surveys describe how logically centralized control can provide consistent policy enforcement across distributed satellite and ground resources, while decoupling control decisions from forwarding elements [4]. In multi-orbit settings, SDN concepts naturally map onto a hierarchical controller organization: a global controller maintains cross-layer policies and service objectives, while local controllers execute rapid reactions to link events, handovers, and congestion signals. This organization becomes particularly relevant when the ground segment is cloud-based, as orchestration systems already provide primitives for configuration rollout, observability, and service health management. SDN policies can be tied to these primitives to ensure that network behavior aligns with operational intent, rather than relying on ad hoc, per-site configurations.

A further architectural dimension is the interaction with 5G/6G NTN integration patterns. Transparent NTN architectures studied along operational mega-constellation paths demonstrate that distributing 5G components across nodes (e.g., shifting functions between terrestrial and satellite-adjacent elements) alters round-trip time statistics and jitter characteristics, thereby impacting service-level design [1]. The operational interpretation for a customer operations unit is that “multi-orbit + cloud ground” must be engineered with explicit service classes: some services tolerate higher jitter and longer RTT, others require controlled variance; therefore, layer selection, gateway selection, and function placement must be expressed as policy constraints rather than treated as an implementation detail.

Security and assurance constraints tighten when ground functions are cloud-hosted and when GSaaS introduces shared infrastructure. A security evaluation of satellite systems emphasizes that the ground segment is frequently targeted and that cloud-based ground stations expand exposure surfaces through shared platforms, remote management, and complex supply chains [7]. For architecture, the implication is structural: security cannot be limited to encryption on links; it requires isolation boundaries between tenants, auditable control actions, hardened identity and access management for orchestration layers, and incident playbooks that include revocation and rapid reconfiguration of ground access.

Figure 2 summarizes a reference architecture that consolidates the above findings into an engineering-ready model.



**Figure 2.** Reference architecture for a multi-orbit satellite network with cloud-native ground infrastructure (adapted from [1; 8–10])

The structure aligns multi-orbit data paths with SDN-enabled control, placing cloud-ground functions as a scalable substrate for both TT&C and mission data delivery. It incorporates GSaaS and federated scheduling as first-class components.

## DISCUSSION

The synthesized results indicate that multi-orbit design and cloud-ground design form a single coupled problem for operational engineering. Multi-orbit topology provides degrees of freedom only when routing, gateway placement, and function placement are treated as policy-controlled variables. Cloud-ground infrastructure provides elasticity only when the system is decomposed into isolatable functions with measurable interfaces and when scheduling

decisions unify antenna access and compute placement, rather than optimizing them independently. The literature suggests that resilience and continuity in multi-layer satellite communications depend on inter-layer routing policies and controlled handovers, rather than layer multiplicity alone [3]. In contrast, GSaaS work supports treating ground access as a schedulable resource under explicit cost–latency objectives [9; 10].

Table 1 structures the operationally relevant distinctions between orbit layers and the architectural consequences for a cloud-ground implementation. The entries reflect how multi-layer NTN designs are positioned in recent research, including resilience motivations and architectural decomposition toward future NTN evolution [1; 3; 8].

**Table 1.** Orbit-layer characteristics and architectural implications for cloud-ground integration [1; 3; 8]

Orbit layer	Dominant engineering drivers	Implications for network architecture	Implications for cloud-ground architecture
LEO	frequent topology change; dense handovers; high ISL dynamics	routing must be time-aware and stable under switching; policy-driven handover control	contact-window automation; elastic decoding and buffering; rapid configuration rollout
MEO	regional continuity; relay opportunities between layers	interlayer path selection to reduce congestion and improve continuity under load	regional edge processing placement; orchestration aligned with relay scheduling
GEO	stable wide coverage; overlay behavior with different delay regimes	overlay routing and service-class differentiation; integration patterns depend on the function split	predictable gateway provisioning; long-lived pipelines; strict jitter-aware SLA handling

The cloud-ground dimension raises governance and sovereignty questions that are central to a national space agency. GSaaS and federation increase flexibility but introduce dependency on shared infrastructure, provider policies, and cross-border data flows. Security research emphasizes that the ground segment is a primary target for adversarial attention and that cloud-based ground services expand the attack surface through remote control and shared platforms [7]. From an operational viewpoint, mitigation is architectural: implement segmentation between TT&C and

mission payload data processing, enforce least-privilege orchestration, adopt auditable change management, and maintain the capability to reroute ground access across providers during incidents.

Table 2 compares ground deployment models relevant to customer operations: dedicated ground, cloud-assisted dedicated ground, GSaaS, and federated GSaaS. The synthesis is anchored in engineering approaches for cloud-based ground stations [5], GSaaS optimization [9], federation [10], and security considerations [7].

**Table 2.** Ground infrastructure deployment models and design consequences [5; 7; 9; 10]

Model	Resource abstraction	Operational benefits	Primary architectural risks
Dedicated ground segment	fixed teleport assets; mission-owned scheduling	full governance over TT&C and data paths	limited elasticity; slow scaling under demand spikes
Cloud-assisted dedicated ground	antennas fixed; processing and delivery cloud-hosted	faster pipeline scaling; improved integration with customer delivery	orchestration misconfiguration risk; cloud dependency for processing
GSaaS	ground access exposed as an on-demand service	cost-latency optimization via scheduling; faster market access	vendor policy constraints; multi-tenant isolation requirements
Federated GSaaS	Multiple GSaaS providers combined under a broker	improved flexibility; alternative paths during congestion/outage; quantified gains under simulation assumptions	governance complexity; heterogeneous trust boundaries

The results support a practical engineering stance for customer-facing solution design: multi-orbit systems should be offered as policy-governed services where the operator controls service classes, routing preferences, and ground access strategies through an operations plane. In this model, SDN-style control unifies cross-layer intent [4], routing logic aligns with time-varying topology constraints [2], and cloud-ground orchestration translates intent into executable configurations. For integration with NTN evolution, performance measurements for transparent architectures demonstrate that function placement directly affects RTT and jitter, necessitating the explicit alignment of architectural choices with customer expectations and contractual metrics.

## CONCLUSION

The article's purpose was achieved by formulating

architectural principles that treat multi-orbit networking and cloud-ground infrastructure as a single, engineered system. The first objective was addressed through a layered plane model where routing and interlayer policies regulate how LEO, MEO, and GEO resources contribute to service delivery, enabling continuity and congestion avoidance without uncontrolled oscillations. The second objective was addressed by defining cloud-ground as a decomposed function chain, in which antenna access, baseband processing, TT&C applications, and mission data pipelines are orchestrated as scalable services. GSaaS and federation are treated as schedulable resources rather than external add-ons. The third objective was fulfilled by a reference architecture that combines SDN-guided control, time-aware routing assumptions, and cloud-native operations primitives, while embedding security governance into segmentation, identity control, auditability, and incident-driven reconfiguration.

The resulting principles align with solution engineering practice in customer operations by translating orbital and ground complexity into policy-controlled service behavior with measurable performance and controllable operational risk.

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