Orchestrated Ground Platform

Software-defined, Virtual, Cloud-Native

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***Abstract*— Innovation in space has led to tremendous new capabilities in orbit, paving the way for satellite operators to serve customers and markets as never before. Constellations of high-bandwidth satellites and software-defined payloads with thousands of spot beams promise to deliver more data and services anytime and anywhere. 3GPP 5G New Radio for Non-Terrestrial Networks (NR-NTN) and 5G Narrowband Internet of Things (NB-IoT) have already been incorporated into ground systems and on-orbit satellites. Further, sensor technology and companies deploying satellites for Earth Observation have exploded. This dawn of new possibilities brings the question: How is the ground segment advancing and evolving to keep pace? This paper will explore how ground systems are moving into the digital world through digitizing RF, virtualizing baseband, and orchestrating the CONOPS to exploit key enabling technologies. Specifically, we will discuss how standards, service orchestration and automation, Software Defined Networks (SDN), the transition to software virtualization for hardware/firmware functions, and cloud-enabled transport will deliver increased agility, resiliency, scalability, security, and lower costs to the ground segment.**

Keywords—orchestration, virtualization, satellite, network, ground system, signal processing, cloud-native functions, software-defined, SDN, GSaaS, smallsats, GEP, resiliency, flexibility, extensibility. LEO, GEO, MEO, earth observation, satcom, standards, 5G, IoT, multi-orbit, multi-mission, commercial, defense, cloud, 3GPP

I. Trends in the Space Market

Space is changing in how it is used and how spacefaring participants view it. Access to space and commoditization of space-industry components (i.e., spacecraft and their payloads, launch systems, and ground infrastructure) has opened the door for anyone to develop and deploy space-based systems. Terrestrial networks have also seen rapid innovation. As a result, the lines between these networks and ground systems continue to blur. However, despite rapid innovation in space-based platforms and terrestrial networks, satellite ground systems have remained firmly rooted in decades-old technologies and architectures. Given the ability to design systems for flexibility and extensibility, the technical paradigm is now shifting from the approach of proprietary boxes to something completely different. This software-based approach enables users to seamlessly access the combination of multi-constellations and multi-orbit approaches through countless applications.

The combination of different elements introduces several market disruptive factors, such as:

- Proliferation of Earth Observation (EO) Satellites demanding flexible, cloud-integrated ground systems.
- A massive increase in available satellite bandwidth.
- Software-defined satellites with reconfigurable payloads driving requirements for flexible ground infrastructure.
- The reduction in the cost of manufacturing satellites and launching them into service has made small constellations of small satellites feasible.
- Small constellations of EO, NB-IoT, and other mission-specific MEO and LEO satellites have driven the need for a shared, dynamic ground infrastructure.
- Adopting technologies and methods from the Telco ecosystem and 3GPP is moving ground stations from proprietary to standards-based systems and software.
- Increase in congestion in space requiring multi-domain integration for automated service reconfiguration.
- Sharing frequency bands and tighter integration with the rest of the telecoms world, including 5G and future technologies.

These factors set trends in the space market and push satellite ground architectures to evolve.

A. New Satellite Architecture

Developing and deploying new space systems, constellations, and components have rapidly increased commercial space services and offerings in a domain previously dominated by government agencies. New commercial space companies, services, and offerings tend to be more willing to adopt risk, use unproven technologies, or utilize new architectures—all to gain an advantage over commercial competition. Examples include hybrid-space environments (combinations of HEO/LEO/MEO/GEO) as well as software-defined or programmable payloads, both of which provide mission flexibility over the life of the satellite and develop a launch cadence where mission failure is tolerable to a degree (the *fail fast, fail often* mentality).

Since single satellites are significant targets, defense organizations worldwide are deploying new space technologies to provide resiliency unavailable in legacy systems. Both defense and commercial organizations share a common interest in deploying these technologies at scale and in an extensible manner.

B. Cloud-Based Infrastructure

Although not a disruptive capability, cloud techniques and technologies have bred disruptive innovation in satellite networks.

Cloud services companies have seen the potential to expand their business through specialized services for space-based solutions. Commercial space companies use cloud infrastructure from hyperscalers to store and process large downlinked datasets and distribute information products to end customers. Five years ago, what was new and innovative is now a standard operating procedure as companies look to reduce costs while increasing their services and customer base through web technologies. Cloud infrastructure is a cost-effective way for these companies to bring their information to market more quickly than before.

Different cloud deployment models are implemented depending on latency, control, cost, and compliance requirements. Some companies have the scale to build their own on-premises private cloud, while others might opt for a hybrid model, allowing their on-premises services to expand into a full cloud during surge times. Companies can quickly take on new customers and scale their systems with this approach. Finally, others find implementing control systems or combining the control and data path in the cloud the best option.

Whatever variation in deployment method is chosen, standard servers utilize cloud-native software to build scalable services quickly and securely. A trend that started in terrestrial networks has now moved into satellite ground infrastructure networks, seeing the transition from purpose-built hardware solutions to cloud-native functions (CNFs) running on generic compute.

Whether provided by a third party or managed internally, cloud infrastructure presents an environment for CNFs to be hosted, managed, and rapidly deployed. This allows satellite networks to adapt to customers' unique requirements without necessitating widespread hardware installation or replacement.

C. Software-Defined Networking (SDN)

SDN is the new foundational paradigm for building and operating complex space networks. SDN is already well-established in the terrestrial network world, especially among telecommunications and cloud service providers. These providers seek to realize every bit of economic and operational value from their infrastructure, and their successful implementation runs the gamut from traditional L2/3 VPNs to SD-WAN to the 3GPP/5G network. SDN enables centralized and programmable network control by separating the control and data planes, supporting the dynamic management of network resources, and working alongside virtualization to improve service delivery, orchestration, and scalability.

An SDN platform can bring economic benefits beyond simply virtualizing individual network components. These include centralized management of hybrid and multi-orbit satellite-terrestrial networks, dynamic resource allocation based on demand or service level agreements, simplified integration with 5G core networks, and automation for service provisioning, failover, and network optimization.

D. 5G Non-Terrestrial Networking (NTN)

The 5G NTN standards extend the capabilities of 5G beyond terrestrial coverage by leveraging Low-Earth Orbit (LEO), Medium-Earth Orbit (MEO), and Geostationary Orbit (GEO) satellites to provide direct-to-device (D2D), IoT, and broadband services. By aligning with the broader 3GPP 5G architecture, 5G NTN supports standardized 5G core network functions, interoperable and open interfaces, network slicing, and service orchestration across space and ground segments.

This standardization allows for tighter integration with terrestrial mobile networks, reduces vendor lock-in, and accelerates time-to-market for new services. As satellite networks become more software-defined and cloud-native, 5G NTN provides the necessary framework to ensure scalability, interoperability, and service continuity across multi-orbit constellations and hybrid network environments.

These standards aren't just for telecommunications. They can reduce cost, increase time to market, and provide interoperability with various systems, from billing systems to service provisioning for any satellite-based mission from EO to D2D. GSaaS providers and ground station owners who embrace a platform that provides multi-mission and multi-domain support based on ETSI and 3GPP standards will be able to grow their customer base and services at exponential rates. New markets can be onboarded in weeks to months at a low cost.

E. Space as a Contested Domain

The commercialization of space and space components is making the space environment increasingly complex. Access to space has expanded due to reduced costs brought about by smaller spacecraft and reduced development costs, added by the decrease in launch costs through reusable launch vehicles and rideshare technology, allowing just about any organization or private citizen to deploy assets in space.

When space was the domain of large corporations and governments, a relatively small group controlled spectrum management and its usage. Now that access to space is becoming more readily available, interference – intentional or not - is a genuine concern. Even though agreements exist to mitigate interference between LEO constellations and between LEO and GEO orbits, it still happens. As more LEO constellations are launched, interference in space and on the ground will increase.

Tools to capture the interference of NGSO on NGSO and NGSO on GEO are currently coming to market. The value of these tools will expand when they are integrated into the same standards-based platforms as modems and baseband infrastructure.

II. Implications to GSaaS and SmallSat Operators

The rapid adoption of new space systems, technologies, and architectures—along with additional access to space through new launch options—is forcing ground systems towards a higher level of standardization. Furthermore, ground systems are shifting to a software-defined, ground-based infrastructure without sacrificing security, reliability, and agility. The ground systems supporting these new trends in the space market must standardize mission interfaces and leverage standard commercial technology to the greatest extent possible.

A. New Competition

The capability of new satellite architectures to create markets has driven an increased demand for ground systems combined with cloud-based architectures. Customers who have elected to build private, company-owned infrastructures in the past now use Ground Station as a Service (GSaaS) providers.

There are well-established GSaaS companies that, in the past, used hardware-based modems to deliver services to their customers, a highly manual process that took weeks or months to deploy new services. Some of these companies have already fully migrated off of hardware solutions except for unique requirements where software is not yet available. Others are in the process of migrating to a virtualized, orchestrated platform to deliver GSaaS. Most new entrants are deploying cloud-native modems on orchestrated platforms, providing them with a faster, lower cost to market.

Some of these GSaaS providers see the value in utilizing others' assets, and we see more inter-company collaboration. Adopting a standards-based platform will facilitate this interoperability, providing seamless service to the end customer.

B. Rising Costs Met with Pricing Pressure

New GSaaS competition tends to run leaner and faster and is more willing to take on risk—resulting in price pressure throughout the service market. Additionally, new business models, hybrid architectures (antenna sharing), and large amounts of initial investor funds vastly reduce the business requirements of market entrants and allow them to develop a worldwide offering at an accelerated pace. It is worth noting that while new competition is more agile in some ways, they tend to lack the experience of market incumbents. Consequently, new space customers see the experience level of providers as less of an issue until the market matures.

Market incumbents tend to have legacy infrastructure that requires engineering resources and technology refreshes to maintain and support existing customers and respond to the competition's pressure. These requirements result in CAPEX and OPEX expenditures that are separate from supporting new space customers, necessitating service providers to manage two networks essentially.

Hybrid architectures and new LEO constellations reduce the aperture requirements on the ground. Oftentimes, this causes legacy infrastructure to be incompatible or too costly to support the customer. A provider must now be able to simultaneously support a customer with a legacy infrastructure and constantly changing customer requests. This includes automatically changing the services rendered from one mission to the next, which is usually driven by satellites.

C. Change in Customer Base

One of the most significant implications for existing GSaaS providers is the shift in the end customer base. Typically, this is a move from the legacy domain-dominated government agencies to new commercial customers (many of which are startups). With this, GSaaS providers are feeling pressure to scale rapidly, demonstrate their network's extensibility, and provide additional services on an ever-increasing cadence. This is especially true of services intended to address problems or issues once on-orbit.

Many of these new customers desire to be part of a development ecosystem in which they can implement third-party systems. Much of this desire is to integrate GSaaS into the customer's product/service offering as a value-add, thus giving the eventual end customer a seamless experience. Customers are looking for service providers who can offer ease of integration within the ground and space layers, facilitate extensive automation, and streamline interconnections with a customer's private network(s).

Interactions with and by these new space customers—as well as with many legacy government customers—are becoming increasingly complex. Many customers are facing new regulations, additional security constraints (especially from a cybersecurity standpoint), and data trust models. Ensuring that information products generated by new space customers is accurate and uncorrupted can often drive new requirements into the GSaaS provider's network.

D. Evolve to Flourish

The new space economy allows GSaaS providers to virtualize their legacy infrastructure by leveraging their heritage (multi-mission, multi-tenancy) environments. These technologies can be deployed to legacy programs and larger government customers when used as a proving ground.

Virtual solutions offer several advantages to service providers looking to capture a larger market share. Instead of just building a better network, software-defined solutions allow service providers to build a better network, deploy systems faster (shorter infrastructure lead times), and respond to customer demand in near real-time.

Niche markets exist where hardware-based solutions continue to provide superior solutions. However, these tend only to support specialized customers and are ill-suited to the general customer base. Service providers must balance supporting niche markets (low volume/high margin) and capturing mainstream markets (high volume/lower margin).

E. Virtualization and the Asymmetric Advantage

To address changes in the service provider's customer base and the customer's mentality to *fail fast, fail often*, service providers need to develop, deploy, trial, and evolve at a cadence that rivals the end customer. When competed against legacy systems, virtualization, cloud infrastructure, and SDN provide an asymmetric advantage to the service provider—the ability to provide an extensible, adaptable, and scalable network to react to customer demands.

In legacy systems, updates to physical appliances (hardware modems) either require an on-site update or a wholesale replacement of the unit. Under this model, high-volume, multi-tenancy support is difficult—if not impossible—to scale. Engineering resources are spread thin and redundancy comes in the form of additional hardware, all of which drive CAPEX and OPEX costs.

Virtualized networks not only provide the flexibility to address these demands but also gives providers an advantage over legacy systems by allowing these networks to deploy additional environments (sandbox, development, and production) at the cost of host infrastructure. This is an inexpensive resource in a cloud environment where network operators can develop and evolve the system.

A single technology stack baseline equipped with a virtual environment supporting multiple tenants comes standard to customers. Compatibility with stack versions can be maintained through customer testing or version-controlled implementations. Furthermore, hosting customer software can be accommodated without network reconfiguration.

The importance of a single technology stack cannot be understated. The effort to accommodate multiple subsystems, vendors, or network architectures dramatically increases the costs to support customers. Requiring engineering resources to understand and serve as experts in multiple systems and technologies reduces efficiencies; lowers the return on labor; and, ultimately, drives down customer satisfaction.

A virtualized network technology stack allows service providers to optimize their network while also:

- Reducing the risks of vendor lock-in.
- Increasing their capability to support a range of customer demands.
- Creating a secure environment to support multi-tenancy.

A single technology stack also provides accurate customer onboarding while reducing overall cost.

Virtual deployments can be supplied to end customers as only generic compute is required for hosting. This includes compatibility testing and configuration development. This approach places much of the engineering effort on the end customer.

Treating the customer first, rather than the network, is a reality with virtualization. Virtual solutions give service providers the advantage of addressing customer demands without requiring a complete network rework. This allows the organization to move closer to consistently maintaining a customer-centric focus. Qualifying customer requests shifts from questions around costs, resources, and timelines to further discussion about the number of services, a provider's ability to offer discounts or bundles, and additional services to improve the customer experience.

III. A New Age for Space Ground Transformation

Kratos developed a standards-based, multi-mission, multi-domain ground platform (OpenSpace® Platform) built on three key pillars: digitization, virtualization, and orchestration. This platform addresses these market trends and solves the issues they create for smallsat operators and GSaaS providers.. While some customers tend to implement one or more of these, all pillars must be implemented to truly address market changes and become the dominant GSaaS provider. For NGSO and Smallsat Operators, a platform-based approach built on standards such as ETSI MANO, 3GPP, and Open APIs, provides an end-to-end system that breaks the vendor lock-in, allowing for multiple vendors to bring their assets to a single platform.

A. Digitize RF at the Antenna

The RF must enter the digital domain close to the antenna to support an agile, scalable, and extensible software-defined architecture. Once in the digital domain, the digitized spectrum (RF/IF) is transported over standard Information Technology (IT) networks using open standards, such as the IEEE-ISTO Std 4900-2021: Digital IF Interoperability Standard (DIFI) for VITA 49.

These open standards encapsulate more than just spectrum samples. They also capture information that includes gains, attenuation, center frequency, bandwidths, and much more. All this information can be used in a software modem (operating in an SDN) or transported to another digitizer for faithful reconstruction. Higher-level systems can also use the associated spectrum information to generate Key Performance Indicators (KPIs) that could be related to Service Level Agreements (SLAs).

Digitizing at the edge (or digitizing at the antenna) offers the following additional benefits to ground systems:

- Antenna systems are managed as nodes on the IT network. This allows for maximum redundancy, increased resilience, lower management cost, and increased flexibility in customer supportability.
- Antenna system data plane interfaces become standardized (i.e., a network baseline). Every antenna produces a digital waveform that can be processed in a virtual environment or faithfully recreated for hardware platforms.
- The entire gateway and network terminals can now be managed as IT infrastructure. Software functions replace legacy L-band analog infrastructure of matrix switches, combiners, and splitters.
- The digital waveform can contain one or more signals or carriers. This allows for optimization and multiple contact support (e.g., constellations, formations, etc.). Each carrier can be addressed via an IP address, just like any other service on the network.
- Using digital waveforms, standard customer support is available with software-based modems. However, mission-unique software can accommodate customers with custom waveforms, use cases, or space architectures.

Digitization at the antenna has many benefits for ground systems. It allows operators to move spectrum anywhere worldwide (e.g., processing centers, cloud providers, customer endpoints, etc.). This is useful for many applications, most notably sovereign networks, where the RF signals are transmitted in one country, and decryption and signal processing happen in different countries.

B. Assured Data Transport and Delivery

Digitizing the RF spectrum at the antenna using DIFI is a fundamental keystone. However, it is only half of the digitizing strategy. Deterministic, high-quality, assured transport of digitized spectrum over standard IT networks must be achieved to comply with satellite communications' real-time stream requirements.

Network quality is usually not an issue when operating in a direct connection or Local Area Network (LAN) environment. As the network's complexity increases, the need for assuring spectrum transport also increases. The introduction of firewalls, Virtual Private Networks (VPNs), and Wide Area Networks (WANs) add variability to the overall system latency but are also sources of potential transport errors.

Protocols, such as Transmission Control Protocol (TCP), might be implemented to address transport errors, out-of-order packets, and other issues. However, TCP emphasizes congestion avoidance algorithms, which are adversely affected by long transmission times. Additionally, they cannot supply high throughput on long networks, no matter how fat the pipe is. Likewise, protocols such as User Datagram Protocol (UDP) may be implemented to provide better throughput and latency sensitivity. However, UDP is not reliable.

Standard forms of error correction, such as Reed-Solomon, could be applied to a UDP stream of packets to reduce overall latency. That being said, the transmission cannot be guaranteed to be error-free. Variants of packet re-transmission (coupled with UDP) address the desire to be error-free but also increase latency in the overall link. A balance between latency and error-tolerant transmission must be evaluated and depends on a customer's end-use case.

C. *Network Function Virtualization (NFV)*

Higher orders of magnitude in bandwidth management and reconfiguration requirements have become more challenging. Given this, a traditional ground network architecture based on a legacy framework will never scale sufficiently from an economic or technical standpoint.

With the entire spectrum digitized at the antenna and assured transportation in place, NFV (the process of decoupling the network functions from proprietary hardware) provides a new way to create, distribute, and operate network services.

These functions (e.g., modems, channelizers, switches, etc.) become Virtual Network Functions (VNFs). Each VNF is fully functional within an x86-based software container. To achieve desired rates, state-of-the-art digital signal processing techniques are used in addition to leveraging advances in computing, such as:

- High-performance packet processing is available through high-speed, multi-core central processing units (CPUs) with high Input/Output (I/O) bandwidth.
- Smart Ethernet Network Interface Card (NIC) is used for load sharing, TCP offloading, and routing packets directly to Virtual Machine (VM) memory.
- Poll-mode Ethernet drivers rather than interrupt-driven drivers (e.g., Linux NAPI and Intel's DPDK).

The NFV model adds scalability and flexibility. Service providers can launch, improve, and incrementally optimize services using software updates rather than wholesale hardware replacement. Without compromising capability, this strategy:

- Reduces CAPEX expenditures by reducing the need to purchase purpose-built hardware.
- Reduces OPEX by reducing space, power, and cooling requirements and simplifying the rollout and management of services.
- Accelerates time-to-market by reducing the time required to deploy new services. GSaaS providers can develop, deploy, trial, and evolve at a cadence that rivals the end customer.
- Provides agility to quickly scale services up or down to address changing demands, all done via software on commodity hardware.
- Allows for new and creative pricing models to lower the cost to the provider and, in turn, the end customer, increasing competitiveness in the market.

D. *Virtual Network Functions (VNFs)/Cloud-Native Functions (CNFs)*

First it is essential to understand the difference between VNFs and CNFs, then the advantage of CNFs over VNFs.

VNFs are software implementations of network functions that traditionally run on dedicated, purpose-built hardware. This was the first wave of virtualization of HW into virtual machines. To create a gateway satellite downlink/uplink service, assuming the RF front-end of the modem is already digitized into DIFI, several VNFs will be required. First, the L-Band infrastructure of splitters and combiners must be turned into software VNFs. Next, the modulators/demodulators must be moved into software (the other part of a modem), processing, and, in some cases, recording functions that used to exist in HW must also be moved into software VNFs.

Let's pause for a moment to mention that the success and lack of vendor lock-in come through standardization. The DIFI Consortium (https://dificonsortium.org/) has over 65 members ranging from ground station suppliers to satellite operators to government organizations. It is through this ecosystem the customers benefit in the ability to buy DIFI Digitizers from the supplier that matches their requirements for RF digitization the best while knowing that part of a traditional HW modem will work with any of the software modem suppliers that are confirmed DIFI compliant. Easing the integration of these various vendors VNFs/CNFs is a standards-based open platform described in this section.

An important consideration when creating VNFs is creating them for cloud environments, that is, creating them as CNFs. Telcos, satellite operations, and GSaaS companies are all looking at one or more on-prem or cloud-based architectures for their service architectures. Containerization and microservices architectures improve agility, resilience, and orchestration.

Combining or re-combining CNFs to generate services can rapidly develop and deploy offerings. These CNF-based services offer extensibility, interoperability, and scalability while maintaining or improving responsiveness and resilience in an architecture built to be future-proof from the ground up.

- **Extensibility:** Digitizing RF signals from the antenna allows virtualization of the ground infrastructure. In contrast, the digital spectrum enables extensibility in a completely new fashion that allows for greater discrimination of capabilities. As digital signals are processed, the spectrum can be proactively analyzed to detect RF interference or degrading performance and reconfigured to avoid those problematic issues.
- **Responsiveness:** Services can reconfigure themselves dynamically to support LEO/MEO/GEO multi-missions driven by network supply, demand, and threat changes.
- **Interoperability:** Open industry standards allow the overall architecture to accommodate any vendor or third-party CNFs. The interoperability inherent in the architecture prevents vendor lock-in and allows (or rather drives) solutions with continuously evolving best-of-breed capabilities.
- **Resiliency:** The approach shifts from an architecture based on redundancy at the subsystem level to one based on resiliency at the overall network level. Every antenna can provide digital-IF to any network function, allowing any Ground Entry Point (GEP), gateway, or terminal to take the place of a non-functioning GEP, gateway, or terminal. Should one network function fail, the ability to remap operations to a separate function is inherent to the architecture. This creates a self-healing system enabling perpetually resilient operations.
- **Scalability:** Network systems scale vertically and horizontally. This is facilitated using well-defined and standardized demarcation points connecting all ground assets in an end-to-end service approach.
- **Future Proof:** Software-driven reconfigurations eliminate the need to change core network hardware, which future-proofs network investments. With spectrum digitized, software-defined ground systems can be orchestrated as an integrated, synchronized system in a virtualized or cloud environment. The CNFs adjust as satellite payloads reconfigure, performing digital signal processing, scaling, and optimizing performance on the ground. The potential to support In-Service Software Upgrades (ISSUs) allows the network to support modern capability without a re-architecture of the network. Custom or future capabilities can be supported with an as-needed model.
- Network functions (i.e., processing chains) can be used flexibly with capacity allocated, reallocated, and overbooked to ensure it is available where and when needed.

E. Leverage Cloud Infrastructure

Cloud infrastructure can be provided in two main ways: the standard array of cloud services such as AWS/Azure/Google/Oracle cloud or on-premise infrastructure.

On-premise infrastructure typically consists of a pool of generic compute aggregated under a Virtual Infrastructure Manager (VIM). The VIM could be VMWare or OpenStack to manage VMs. The second virtual abstraction layer comes when leveraging technologies like containers on the VIM. Kubernetes is typically used at this layer to provide the infrastructure to run containers that can be individual CNFs or a platform such as OpenSpace that manages the CNFs and data pipelines (also known as service chains – several CNFs that work in serial to provide a customer's service.)

While cloud-based architectures tend to be expensive, planning for network peaks incurs additional costs. The cloud provides a means for customers to pay as needed for peaks and excess capacity (e.g., Launch and Early Orbit Phase [LEOPs]), anomalies, etc.). Some cloud suppliers, such as AWS, have extended their systems to provide VNFs and/or CNFs to provide the specific satellite function the customer requires, similar to a GSaaS provider.

Many space customers leverage cloud providers for data storage, data product generation, and customer interface. Ground systems must extend this process and seamlessly integrate with a customer's environment. The level of integration can materialize in many forms, including, but not limited to, the following examples:

- Simply passing baseband data to a cloud endpoint (Internet Protocol [IP] address)
- Integration of security measures (e.g., firewalls, VPNs, etc.)
- Deployment of Edge Cloud or instantiations of the cloud providers' technology stacks at the ground station

On-premise cloud infrastructure is the only cost effective way to address and scale these different levels of integration. Hosting customer-supplied devices, such as modems, VPNs and firewalls, consumes floor space and resources (e.g., power, cooling, etc.). On top of that, these devices require engineering resources to manage, maintain, and secure. Further, hosting customer-furnished equipment leads to non-standard deployments, which drives single customer usage or additional maintenance costs. Virtual implementations of VPNs and firewalls can be hosted in a secure environment next to the digital signal processing or analog infrastructure by using on-premise cloud deployments.

Many different on-premise cloud deployments can be supported for ground stations. A centralized, virtual infrastructure provides control and status of the entire network. It also manages customer requests and scheduling and provides an environment for development, product, and support teams to test, trial, fail, and troubleshoot while leaving operational systems inviolable. Due to backhaul requirements, Edge Cloud or virtual infrastructure is typically deployed at the GEP to minimize network backhaul. These deployments are managed from the central infrastructure but also provide deployments of local processing, which reduces latency to the customer by providing the end customer direct connectivity to the GEP.

F. *Service Orchestration*

This platform goes beyond the virtualization of individual network functions by employing the true power of SDN—service orchestration, resource orchestration, and service chaining to design, deploy, and manage networks. With spectrum digitized, software-defined ground systems can be orchestrated as an integrated, synchronized system in a cloud environment. As satellite payloads reconfigure, the ground platform adjusts to perform digital signal processing, scaling, and performance optimization on the ground.

To enable ground system functions to work autonomously and seamlessly without manual stitching or configuration of subcomponent products, sequences of CNFs (referred to as service chains) adapt to pseudo-real-time changes in network supply and demand. Orchestration frameworks automate the instantiation of service chains and the required resources at scale through industry-standard interfaces.

Metro Ethernet Forum (MEF) standards are the core of the orchestration framework. These standards allow vendor-supplied CNFs to be interoperable through well-defined, standardized APIs. They also will enable the system to interface with operational and business systems and share data across the enterprise.

Using standards, ground systems coordinate and communicate with satellites in multiple orbits across frequency bands, supporting multiple protocol languages at different times. They move traffic between them on the fly and avoid intra- and inter-network interference.

Selection of standards, such as MEF:

- Provide a body of standards already extensively used by terrestrial networks to solve several similar issues.
- Enable end-to-end services to flow dynamically between SDN-based terrestrial networks, software-defined satellites, and *white-box* customer equipment.

An orchestration framework automates what was previously siloed, manual, point-and-click configuration tasks. Shifting configuration and management from people and processes to technology and automation enables the network to scale, whether it is supporting a single software-defined satellite or a multi-orbit constellation.

Through an embedded zero-trust architecture, the ability to regularly change attack vectors and support just-in-time deployments enhances existing security functions and policies. An orchestrated framework:

- It empowers providers to enable a responsive ground system that reacts to changes in supply and demand and also embraces cloud-native architectures.
- Optimizes configurations to support multiple GEPs, domains, satellites, orbits, and missions.
- Lowers operating costs by automating hundreds of hours of manual tasks and maintenance.
- It is oriented around developing, deploying, and automating service chains versus single-point software applications.
- It allows for scaling functions horizontally and vertically by separating the automation domains (e.g., service orchestration versus resource orchestration).

When coupled with CNFs, service orchestration allows a GSaaS provider to provision services on the fly hundreds of times a day based on customer demand.

G. *Common Operating Platform (COP)*

Orchestration manages flexible scaling and load balancing, which supports and simplifies software upgrades and resource utilization in a virtual environment. Additionally, orchestration provides uniform management of mixed configurations across the cloud infrastructure. Because of orchestration's flexibility and scalability, the network's complexity rapidly increases.

Management of a network today is more than response times to incidents. Customers are looking for service providers who can offer ease of integration within the ground and space layers, facilitate extensive automation, and streamline interconnections with a customer’s private network(s).

Monitor and control systems that provide status on network devices are a step above logging on to each device directly. However, they cannot offer cross-organization automation, multiple domain monitoring (network, GEP, RF link), or truly provide KPIs for the network when supporting hundreds of customers and thousands of passes.

Implementing a comprehensive platform approach instead of managing individual functions, applications, or appliances enables service providers to bring existing equipment and next-generation networks under one management system. This provides a COP across the enterprise. Unifying disparate systems into one view delivers the advantage of gaining deeper insights through enhanced visibility into network performance, which leads to improved Quality of Service (QoS), customer satisfaction, and revenue.

IV. CONCLUSION

The digital transformation of ground systems supports the innovations of small and large constellations and software-defined satellites. These innovations drive the shift from purpose-built hardware systems intended for more static environments to software-defined virtual systems designed for highly resilient, dynamic systems.

Key advancements—such as virtualizing the ground system for IP compatibility, transitioning from legacy hardware to software, and utilizing orchestrated and automated operations—are essential.

Using digitization, virtualization, and orchestration in a software-defined ground architecture is crucial to the future of connecting satellite systems, communication service providers, terrestrial networks, and the global sharing of data and analytics.

High-value services (overall network availability) are the initial targets of orchestration. However, mission operators aim to incorporate every aspect of service management into an orchestrated architecture. Improving the mission experience to create an environment that anticipates and reacts faster to any user need or threat related to services is critical.

Orchestration allows ground system and satellite operators to be the engine of continuous change and adaptation to user needs. A scalable, extensible, multi-domain management platform is capable of reporting across multiple dimensions and leveraging enhanced analytics engines, real-time dashboards, and historical reporting to gain insight into the network. All of this offers maximum uptime and improved SLAs for a provider's customer base.