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Advanced Ground Segment Systems for Modern Space Missions

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Abstract

Ground segment products (mission centre, control centre including the flight dynamics system) are highly interdependent from a space mission point of view. In addition, satellite operations, especially when dealing with a multi-satellite or even a multi-orbits context) are becoming more and more complex with increasing quantities of data coming from the payload to be processed.

In order to achieve effective operational engineering, it is necessary, from the definition of the ground system to the satellites operations, to combine the operating requirements of such complex systems with the new capabilities for all "space ground segment" assets, including latest IT skills and components.

Nowadays, a performing and full-operating ground segment system must therefore be designed including recent technologies (Kubernetes, for example), based on precise layers that make the system independent of the chosen IT solutions (servers, cloud) and integrate cross-functional aspects (e.g. security) into the overall design of the system.

System development must be an effective mix of customised software elements and mission-specific developments.

Technological solutions must also take into account future needs, such as the evolution of the space market, with more launches, more satellites constellations, more interaction and more intelligence between the different parts (platform, payload, ground stations, type of orbit, duration of mission), etc.

These systems must therefore incorporate:

- A high level of scalability. For example, it must be possible to easily add or remove one or several satellites to the system monitoring,
- A high level of resilience: auto-correction, fault tolerance, data loss prevention are necessary to allow operators to concentrate on the most important operational needs,
- More intuitive views and UI, to help operators (that are not all experts anymore) for a better monitoring and understanding of the operations. For example, 3D views can be proposed for constellation monitoring, with the possibility to focus on a specific satellite with a button click,
- An easy re-useability of the system for multi-mission purpose.

Finally, cost is becoming an increasingly important factor.

The high level of resilience already mentioned, self-repair, combined with automatic monitoring systems and increasing use of AI, should reduce the number of operators, and significantly reduce software maintenance costs.

Other improvements such as auto-scaling and intelligent analysis of data flows, payload data processors orchestration… allow to process in near-real time, and bringing very significant cost reductions.

As a ground system supplier, mastering these issues in a homogeneous system should enable to offer end-customers 'As a service' systems, where the customer chooses from a catalogue the services that interest him, enabling him to calculate and then quickly control the costs that he will have to take into account, as well as the performance that he will obtain.

Based on 40 years' experience in Ground Segment Engineering, CS has been developing a new generation of Ground Segment (GOSMIC) for the past five years in line with the above objectives.

1. Introduction

The evolution of space missions has led to increased complexity in satellite operations, particularly in multi-satellite and multi-orbit contexts. This complexity is driven by the growing volume of data from payloads that need to be processed, the growing size of constellations to ensure full coverage of the earth and/or low revisit times, the heterogeneity of platforms and payloads, and the new communication technologies allowing full visibility and accessibility of each satellite in the constellation such as ISL or 5G. To meet these challenges, ground segment systems shall now be designed to combine the operating requirements of complex systems with new capabilities and assets, especially the latest IT architecture and components.

The landscape of software architecture has been subject to major transformation over the past decade. The shift from monolithic architectures to microservices, the rise of containerization and orchestration platforms, and the integration of cloud-native technologies have all played an important role in the definition of modern software development. These major changes are now coming in ground segment implementation bringing significant improvements in various domains such as flexibility, modularity, scalability, resiliency, maintainability and thus creating new efficient software systems.

2. Technological Advancements in Ground Segment Systems

1.1. IT Platform & Architecture

By the mid-2010s, the microservices architecture emerged as a response to the constraints of former monolithic architectures. Microservices decompose complex applications into a collection of smaller, independent services that communicate through lightweight interfaces such as HTTP resource APIs. They are characterized by their autonomy, loose coupling, and domain-oriented design. Each microservice is designed, developed, and deployed independently, allowing teams to work on different parts of the application simultaneously. This independence also enables continuous integration and continuous deployment (CI/CD) practices, leading to faster and more reliable software releases.

Several prominent enterprises (including GAFAM) led the way in the early adopting of microservices architecture. These companies transitioned from monolithic architectures to microservices to enhance their service quality and benefit from an accelerate application delivery and reliability.

The adoption of microservices was closely followed by the rise of containerization technologies. Containers provide a lightweight, portable, and consistent runtime environment for applications, ensuring that they run reliably across different computing environments. Docker, introduced in 2013, became the standard for containerization and played an important role in popularizing the use of containers in software development.

As the use of containers grew, the need for effective management and orchestration of containerized applications became evident. Kubernetes, an open-source container orchestration platform, emerged as the most widely adopted solution in both academia and industry (Docker Swarm is also extensively used). These platforms offer features like automated scaling, load balancing, and self-healing capabilities, making it easier to manage complex, distributed applications.

Major Cloud providers are now leveraging Kubernetes for scalable flight dynamics and mission planning operations in satellite mission control centers. By proposing cloud-based managed services, Cloud providers enable advancements like AI, automation, and digital twins in mission operation centers (MOCs). This approach helps manage the complexity of growing satellite constellations and provides opportunities for modernization.

Nevertheless, this may also come with some drawbacks, the first one being the coupling with infrastructure. Most cloud providers propose libraries and utilities to simplify development and operations. These resources help streamline processes, enhance efficiency, and reduce the complexity of managing satellite operations. By utilizing these components, developers can quickly deploy and manage applications, leveraging automation tools to ensure smooth operations. This reliance on cloud services will also introduce major dependency on the provider assets, leaving no possibility – or at an heavy cost – to migrate to any other cloud provider. To solve this vendor lock-in problem, the concept of Cloud agnosticity was introduced and is now an essential feature of a cloud native Ground Segment design, allowing a total independence from specific cloud platforms.

The second important concern is cloud sovereignty: this refers to the control and governance of data that is stored and processed in a cloud, ensuring compliance with local laws and regulations, security policies and avoiding interference with any foreign authority (e.g. Cloud Act). The nationality of the cloud provider is becoming a significant concern for satellite ground segments due to international context.

Countries may impose restrictions or mandates on data storage and processing, requiring that it be handled within national borders or by companies headquartered in friendly nations. This has led to a growing preference for cloud providers that can guarantee compliance with these regulations and offer assurances regarding data privacy and security.

As the global landscape becomes increasingly complex, satellite operators must carefully consider the geopolitical implications of their cloud provider choices. Ensuring that the provider aligns with the regulatory requirements and national interests of the countries in which operations are conducted is now a critical point.

These considerations have led to prefer an on-premise deployment on a dedicated hardware platform for a majority of space companies. On-premise deployments can offer enhanced control, security, and compliance with specific regulations, making them a comforting choice in the face of the disadvantages and possible dangers of external cloud providers.

Despite these considerations, it is undeniable that cloud-native technologies, and the practices associated with them, have revolutionized the way applications are developed, deployed, and operated. Some of the major advances brought by these technologies are described below.

1.2. Scalability

Scalability is a critical attribute for modern ground segment systems, especially in the context of dynamic, massively multi-satellite and extensible constellation. The integration of these features ensures that the system can adapt to changing mission requirements and technological advancements. Scalability shall be considered in several ways:

- Scalability in terms of satellites' number: The number of satellites for a project will vary along time. From the first demonstration satellite or batch sent in orbit up to the decommissioning, a mission goes through several phases during which the number of satellites will increase or decrease in turn. The ground segment architecture should not limit the size of your constellation in terms of satellites. It should benefit of all advantages procured by the new IT infrastructures: dynamic instantiation of components, dynamic hardware resources allocation…
- Scalability in terms of users' number: also depending on phases during the project, the number of users having simultaneous access to the interface will vary. From the LEOP where all the different operational teams will be in number (Engineers from ground, on-board, FDS, platform and payload experts, management…) to the routine phase managed by a minimal team, the system should be scalable and capable of handling all these situations.

Both of these features can be handled with an horizontal scaling which can be automatic in most advanced systems, adjusting the number of applications replicas based on observed metrics (such as CPU utilization or custom metrics). When demand increases, the system scales out the application by adding more pods; when demand decreases, it scales in by reducing the number of pods. This dynamic scaling ensures that the application can handle traffic spikes gracefully without overprovisioning resources.

1.3. Resilience & high availability

Resiliency offers several advantages that contribute to the robustness and reliability of cloud-native applications. It refers to the system's ability to detect/recover from failures and continue to provide services without interruption. This fault tolerance reduces manual intervention and ensures that the system can handle unexpected issues gracefully. This is achieved through a combination of several features and best practices such as pod replication (grants a continuous availability ensuring that there are always multiple instances of an application running), health check (using liveness and readiness probes to monitor the health of applications), auto corrective actions (application restart or service instance disabling).

These resiliency mechanisms are one of the bases that ensures the high availability and fault tolerance of applications. The other pillar of high availability is the dynamic distribution of applications among the physical or virtual machines that runs the applications (nodes in Kubernetes). This distribution ensures that applications remain available even if some pods or nodes fail. These mechanisms provide high availability which is critical for maintaining service continuity and meeting new user expectations.

With modern High Availability provided now by container orchestrators such as Kubernetes, this question is raised: Is the Backup instances of control and mission centers still useful?!...

In former architectures, the Backup consisted in an instance of the system deployed on the Nominal and a second instance deployed on the Backup. The Backup instance is in passive mode and a continuous (or not) replication of the data is performed. On a switch operation, the Backup is “un-passivate” and operators connect to the Backup instance.

Experience has shown that this architecture is cumbersome, complex to implement and very often specific to each application with possible side effects on performances. Furthermore, it is challenging to test all the situations where a switch is performed.

Modern native cloud applications now rely on the robust and flawless High Availability provided by container orchestrators. As such applications are designed to be stateless, the pod replication and/or the auto-restart implemented by Kubernetes is enough to make applications High Available. If an application needs a persistent state, the latter is stored into a “volume” that is replicated by the infrastructure or into stores (databases, buckets, NFS,…) that offer their own replication mechanisms.

With modern High Availability, just a single instance of the system is deployed. In this case, we can say that the High Availability is supported by the infrastructure without complexifying the applications.

This has a major impact on the way Nominal and Backup sites are designed and implemented today: a single Kubernetes cluster can be deployed with nodes on both the Nominal and the Backup sites. Affinities are finely tuned so that the replicas are always on the Backup. In particular, the Control Plane and ETCD that manages the cluster, and the volumes are continuously replicated so that the whole state of the cluster is never lost.

With such a topology, the switch to Backup occurs when an administrator *drains* (i.e., deactivates) nodes on the Nominal site or when the whole Nominal crashes; partial switches are also automatically performed when a node or a pod crashes.

While this new paradigm of High Availability works efficiently for co-located or near-range physical sites where communication latencies are low, it can bring some challenges when sites are separated by long distances with high latency. The inherent latency can affect the synchronization of data and the responsiveness of applications, leading to potential issues in service continuity and performance.

Studies are currently being conducted to verify the feasibility of such configurations over long distances. These studies focus on understanding the impact of latency on replication mechanisms, the performance of the control plane, and the overall user experience. Solutions such as optimized data transfer protocols, advanced caching strategies, and latency-aware resource management are being explored to mitigate the effects of high latency.

The results of these studies will soon determine the best practices for deploying Kubernetes clusters across geographically dispersed sites without compromising on the reliability and efficiency of High Availability mechanisms.

3. Modern User Interfaces

The complexity of satellite operations necessitates intuitive user interfaces to aid operators who may not be experts in the field. In recent years, there has been a significant shift towards web interfaces in managing modern ground segment systems. This transition is driven by the advantages of web interfaces, such as their accessibility from any device with a web browser (without requiring any specific hardware or software installation on client side), This flexibility allows operators to monitor and manage systems from various locations (with standard and shared workstations), enhancing operational agility. This also ease updates through central deployment (no need of individual updates on client side).

Web interfaces are designed to be easy to use and comprehensive for users, making complex tasks more manageable even for those with limited technical expertise. Operators are often more familiar with web-based environments, which can reduce training time and increase adoption rates. Web interfaces provide a user-friendly environment where operators can efficiently navigate through various operations, enhance the operator's ability to monitor and understand operations effectively, and access critical information quickly.

Web interfaces can be easily secured through centralized authentication and access control mechanisms. This ensures that only authorized operators can access sensitive system functions, enhancing overall security.

To achieve the best results in interface usability and functionality, it is critical to integrate operators into the design process. Operators can provide valuable insights into the practical aspects of interface interaction, ensuring that the final product meets the actual needs and preferences of those who will be using it daily. Collaborative workshops, feedback sessions, and iterative design reviews can be employed to gather operator input and refine the interface accordingly.

One effective method for creating and testing user interface designs is the use of mock-up tools such as FIGMA. FIGMA allows designers to create interactive prototypes that can be shared and tested with operators, facilitating real-time feedback and rapid adjustments. This approach ensures that the interface is not only aesthetically pleasing but also functional and intuitive, greatly enhancing the operator experience.

4. Cost-Effectiveness

Cost-effectiveness is another significant advantage brought by scalability, resiliency, and modern web user interfaces. The adoption of standard web technologies for interfaces eliminates the need for specialized hardware or software installations on the client side, allows rapid mock-up and shorter developments time, which reduces upfront costs and ongoing maintenance expenses. This approach leverages existing infrastructure and resources, optimizing their use and ensuring that operators can access and manage systems efficiently without incurring additional costs.

Furthermore, the scalability of these systems allowing a dynamic allocation of resources based on demand, ensures that hardware costs are kept in check. Resilient systems minimize downtime and maintenance needs, thus reducing the overall operational expenses and in particular the number of required human intervention. By integrating cost-effective strategies into the development of ground segment systems, organizations can achieve a balance between high performance and economic efficiency, ensuring that they are well-equipped to meet future needs and technological evolution.

These advancements not only enhance operational efficiency but also contribute to the long-term sustainability and affordability of ground segment systems. As the industry continues to evolve, the focus on cost-effectiveness will remain a key priority, driving innovations that support both performance and budgetary constraints.

5. Operational Efficiency and Technological Evolution

The advent of advanced technologies and methodologies has empowered organizations to streamline their processes, reduce costs, and enhance productivity. Automation, machine learning, and AI-driven analytics have revolutionized the way operations are managed, enabling near-real-time decision-making and proactive issue resolution. This relentless pursuit of efficiency ensures that businesses remain competitive and agile in a constantly evolving landscape.

Automation is a key feature of operational efficiency. By deploying advanced automation technologies, operators can optimize routine tasks, reduce manual errors, and minimize operations time. Automated ground segments can handle operations of wide constellations, complex concepts of operations, and limit human resources required to operate the whole system.

AI is also a new important feature allowing enhancement of operational efficiency in satellite control centers and mission centers. By utilizing machine learning algorithms, these centers can predict potential issues before they arise, enabling proactive maintenance and reducing downtime. AI can analyze vast amounts of data in real-time, offering insights that would be impossible to glean through manual methods. This capability allows operators to retrieve necessary information in time, to make informed decisions quickly, and optimize the performance of satellite constellations.

As AI technology continues to evolve, its applications in satellite control and mission centers will expand, driving further innovations and efficiencies.

Conclusion

The development of a new generation of advanced ground segment systems is essential for the effective management of modern space missions. The integration of recent technologies has totally transformed the landscape of these systems. By incorporating recent technologies, ensuring scalability and resilience, providing intuitive user interfaces, and focusing on cost-effectiveness, these systems can meet the complex requirements of multi-satellite and multi-orbit operations.

Advanced automation and AI-driven technologies have further propelled the satellite ground segment industry towards a future where real-time decision-making and proactive maintenance becomes standard practices rather than the exception.

The experience and expertise of CS in Ground Segment Engineering have led to the development of the GOSMIC system, which responds these challenges and sets a new standard for ground segment systems.