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A Shift Toward a Generic Software Development Approach for Satellite Mission Operations

Philippe Méhu*, Nathaniel Cziranka-Crooks, Jean-François Delisle, Patrick Irvin

Canadian Space Agency, Satellite Operations, Canada, philippe.mehu@asc-csa.gc.ca, nathaniel.cziranka-crooks@asc-csa.gc.ca, jean-francois.delisle@asc-csa.gc.ca, patrick.irvin@asc-csa.gc.ca

* Corresponding Author

Abstract

The Canadian Space Agency (CSA) has a long history of satellite missions that have significantly contributed to space exploration and the global understanding of Earth's resources. Since launching Alouette 1 in 1962, Canada has established itself as a leader in space innovation, particularly in Earth observation and international collaboration. CSA's satellite missions have had both scientific and practical impacts, benefiting Canadian society and the global community.

CSA's Satellite Operations Group has played a crucial role in managing operations for these missions throughout their lifecycle, relying on ground systems, hardware, and software solutions traditionally developed on a per-mission basis. However, in response to the growing need for agility and cost efficiency, CSA is shifting from custom-built mission software to a more standardized, generic software approach.

This transition is driven by the need for standardization, cost control, and scalability, aiming to reduce development time, lower maintenance costs, and improve interoperability across missions. However, this shift also presents challenges, including organizational resistance to change, potential limitations in meeting specific mission requirements, and complexities in integrating generic solutions into existing infrastructures.

This paper explores the strategic shift in CSA's satellite operations, focusing on the implementation of a Generic Mission Operations Center (GMOC) for satellite missions. Using a case study approach, it examines the challenges faced, such as stakeholder buy-in and technical integration, and the lessons learned in ensuring a smooth transition. Findings suggest that while generic software solutions provide significant benefits, their success depends on careful planning, stakeholder engagement, and a well-planned implementation strategy.

Keywords: Satellite Operations, Ground Segment, Mission Operations Center

Acronyms/Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
ARS	Antenna Reservation System
CI/CD	Continuous Integration / Continuous Deployment
CCMEO	Canada Centre for Mapping and Earth Observation
CPU	Central Processing Unit
CRAMS	Conjunction Risk Assessment and Mitigation System
CSA	Canadian Space Agency
COMMS	Communications Subsystem
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DM	Data Management
FD	Flight Dynamics Subsystem
GATN	Gatineau Satellite Station
GFE	Government Furnished Equipment
GMOC	Generic Mission Operations Center
GPU	Graphic Processing Unit
ICAN	Inuvik Satellite Station
ICD	Interface Control Document
IT	Information Technology
ITOS	Integrated Test and Operating System
ITS	Information Technology System
KPI	Key Performance Indicator
LLM	Large Language Models
ML	Machine Learning
MLOps	Machine Learning Operations
MM	Multi-Mission
MOC	Mission Operations Center
NGT	Northern Ground Terminal
PASS	Prince-Albert Satellite Station
PLAN	Planning Component
QEYSSat	Quantum EncrYption Science Satellite
RT3	Real Time Telemetry & Telecommand
SASK	Saskatoon Satellite Station
SCHM	Spacecraft Health and Monitoring
SCISat	Scientific Satellite Atmospheric Chemistry Experiment
SDLC	Software Development Life Cycle
SHUB	Saint-Hubert Satellite Station
SOC	Science Operations Center
STDP	Space Technology Development Program
STK	Systems Tool Kit
SXGT	S-Band/X-Band Ground Terminal
T3	Telemetry Tracking and Telecommand
TLE	Two Line Element

1. Introduction

1.1. Context

Historically, the Canadian Space Agency (CSA) has developed satellite ground segments in tandem with spacecraft development. From the initial funding through to planning and implementation, the ground segment was treated as an integral component of each space mission project. This approach enabled the CSA to successfully procure and operate multiple mission-specific ground segments, several of which remain in operation today.

A key advantage of this model was that each ground segment was purpose-built and fully tailored to the specific needs of its corresponding spacecraft. Development, integration, testing, and validation activities were closely coordinated with the spacecraft lifecycle. However, a significant drawback of this approach is the operational inefficiency associated with maintaining multiple, distinct ground segment solutions that often perform similar functions.

As the satellite industry moves into a new era—one that prioritizes efficiency, cost reduction, and standardization—the CSA has recognized the need to rethink its strategy for ground systems development and operations.

1.2. Rationale

The pace of advancement in computing technologies significantly outstrips that of spacecraft systems. When ground and flight segments are developed concurrently using a traditional waterfall approach, there's a risk that ground system architectures will be outdated by the time the spacecraft is launched. Shifting away from this tightly coupled development model toward a decoupled, programmatic approach for ground systems allows for more flexibility and adaptability. Rather than being tied to the timeline of a specific mission, the development of generic ground segment solutions can continue as part of an ongoing program. This program-based model is more appropriate given the broader scope and extended duration of generic ground systems, which are designed to support multiple missions over time.

By establishing a common vision through the program, mission-specific ground segment developments can be integrated into the Generic Mission Operations Center (GMOC) core and used as references when instantiating ground segments for future missions. This modular approach also enables agile development, where continuous improvements to the core can be efficiently propagated across mission instances. It aims for the adoption of common approaches (core vs. specific missions) facilitating the development of new programs as suggested by the paper on ground segment services [1]. The adoption of a generic and flexible architecture allows for the efficient support of a wide range of space missions, while minimizing costs and maximizing the quality of support provided as discussed in J.C. Differding's paper [2]. As demonstrated by the German Aerospace Center (DLR) [3], multi-mission operations can reduce costs while maintaining a high level of reliability. By having a generic core, we aim to increase flexibility in the seamless integration of new missions, thanks to well-defined processes and modular infrastructure.

Through the development of a suite of reusable, generic ground segment components, CSA can reduce both the time and cost associated with mission-specific ground segment development. Additionally, this shared framework promotes consistency across operations and simplifies maintenance, as most systems are built upon a unified, standardized infrastructure.

2. GMOC Vision and Development Approach

2.1. GMOC Vision

The vision for GMOC is to establish a unified framework that integrates innovative, operationally efficient, and cost-effective solutions to streamline the development of mission operations control products. GMOC is intended to serve as the baseline Mission Operations Center (MOC) solution for upcoming Canadian government satellite programs.

To realize this vision, the satellite operations team has adopted a phased development approach for ground segment solutions. Each phase is designed to deliver a set of features and functionalities that are consolidated into a product release, forming successive versions of GMOC.

- The first phase served as an introductory foundation, focusing on the establishment of core GMOC infrastructure and automation capabilities. Key activities included the development of the generic MOC framework, implementation of automation features and virtualization of GMOC subsystems.
- The second phase concentrated on the flight dynamics (FD) subsystem, introducing generic maneuver planning tools, propulsion modeling capabilities, and enhancements to the graphical user interface.
- The third and current phase targets the real-time telemetry, tracking, and telecommand (RT3) subsystem. It includes the development of automation functionalities such as constraint checking, planning, and distribution. Additionally, it focuses on improving the deployment of GMOC instances and enhancing system architecture through the provision of multiple MOC environments.

2.2. Development approach

In the initial phases of GMOC development, the approach involved delivering software releases that addressed new Mission Operations Center (MOC) requirements not yet available. For instance, if a mission requires constellation management, this functionality gets prioritized and implemented within the generic MOC product line. At the beginning of the mission's operations development phase, the latest version of GMOC is retrieved from the GMOC main branch, and all mission-specific configurations are applied to create the mission MOC instance. This mission MOC instance is then finalized, integration-tested, and validated with the spacecraft.

New functionalities developed during mission instantiation and that qualify as generic features are integrated into the GMOC main branch. In contrast, functionalities that are strictly mission-specific and do not meet the criteria for generalization remain within the mission-specific instantiation of GMOC. In this revised development approach, the mission MOC timeline remains tightly synchronized across the ground and flight segments, even though they are managed by separate teams. Integration is facilitated through the concurrent design approach between the two segments as proposed by Hoffmann [4]. Continuous coordination between the two teams ensures that all interface control documents (ICDs) delivered by GMOC comprehensively address the spacecraft mission requirements.

3. System Description

The Generic MOC in development by the CSA is currently composed of the following generic components. Some of these components are developed internally, while others are procured commercially. The modular nature of the GMOC product allows for replacement of any of the components with an equivalent module that performs the same function.

- **Planning (PLAN)**: GMOC PLAN component facilitates the scheduling of any event related to the overall operations of the satellite throughout the entire mission life cycle. This includes the execution of science, payload activities, and the spacecraft maintenance activities based on the schedule established by the operations team. GMOC PLAN prepares all pre-pass products required for RT3 to execute the pass activities.

- **Flight Dynamics (FD)**: GMOC FD component provides GMOC with the past and future position of the satellite based on satellite GPS telemetry (if available) and tracking data from telemetry tracking and telecommand (T3) component. FD also generates and distributes all products required within or external to the MOC that are based on orbital position and environment. To achieve this, the FD component uses wrapper scripts to interact with the Systems Tool Kit (STK) application programming interface (API).

- **Real Time Telemetry and Telecommand (RT3)**: RT3's main purpose is to ingest and display telemetry from the Spacecraft and send commands to the Spacecraft based on the provided schedules from PLAN. For the GMOC product, the RT3 is currently composed primarily of the Galaxy software (formerly known as Integrated Test and Operating System (ITOS)) for the return of spacecraft telemetry frames from the ground stations and forwarding payload and spacecraft commands to the ground stations. Uplink encryption is also available in this component.
- **Data Management (DM)**: GMOC DM component provides GMOC with a central data transfer facility, archiving (short and long-term) and general configuration control of spacecraft data. GMOC DM is also responsible for processing all science data received from the mission spacecraft in preparation for forwarding to the Science Operations Center (SOC) node.

- **Spacecraft Health and Monitoring (SCHM)**: GMOC SCHM component provides GMOC with the ability to generate analysis reports based on the received spacecraft telemetry. It performs the de-commutation of the telemetry data and provides trending of long-term telemetry for analysis purposes.

These components are used daily in operations to enable communication to and from the spacecraft via the communications (COMMS) component. Operators at the Saint-Hubert mission control center carry out the necessary procedures based on the tasking and schedules provided by the science team (or the order desk) and the operations team. Each GMOC component relies on internal and external data flows to ensure that all pre-pass, pass, and post-pass products are properly processed and delivered to the appropriate component. The overall MOC architecture is designed to be generic and is provided as a complete system to client missions. Mission-specific features or enhancements are implemented as required to ensure that the MOC components meet all mission requirements. Furthermore, GMOC is residing in a virtual environment and can be deployed and configured at multiple locations. This provides ground systems redundancy and enhances the operational availability of the ground system. The figure below illustrates the MOC within the context of the broader ground segment architecture.

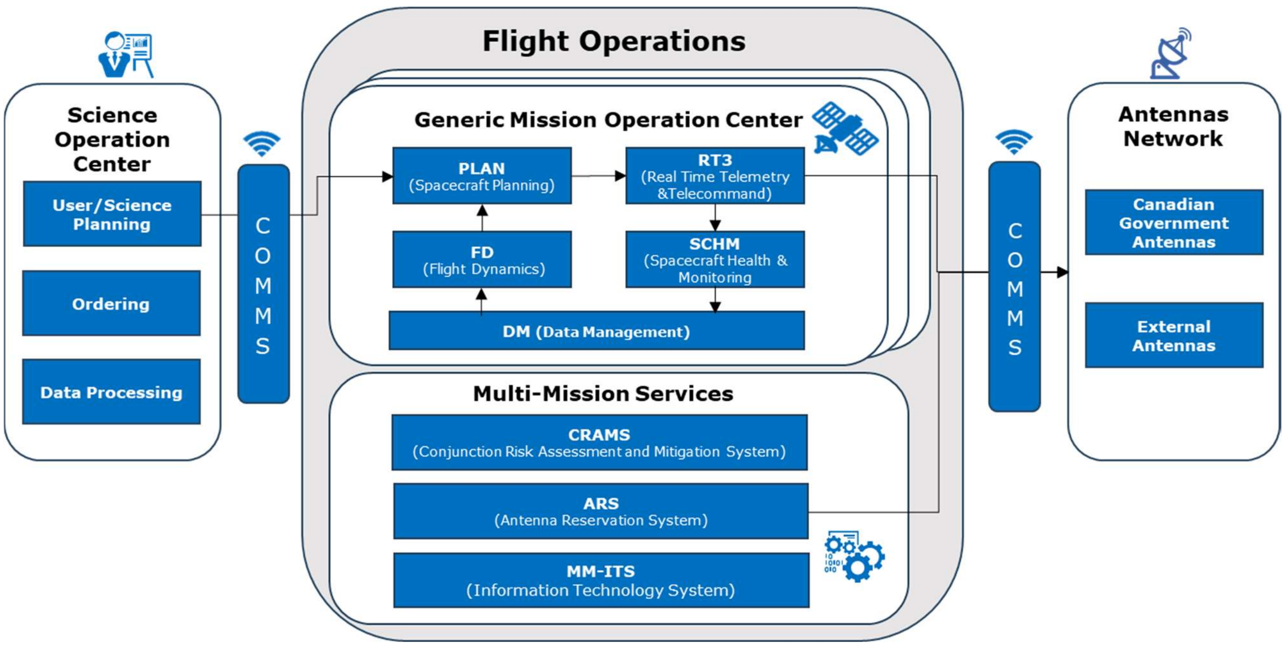

Fig. 1: Ground Segment Architecture (credit CSA)

The interface between the Science Operations Center (SOC) and the MOC is developed on a mission per mission basis and this work is usually undertaken during the operations development phase of the mission. The development work during this phase will ensure that all the required interfaces and message flows between these two blocs are adequately configured, developed and tested to meet the mission requirements. The diagram below provides a summary of some of the common products flowing to and from the MOC. The exact messaging type, format and frequency of these messages are determined by the mission and implemented during the operations development phase of the mission. Development of the GMOC provides flexible interfaces for the science team and the external stations to reduce the amount of work required to make the interfaces compatible.

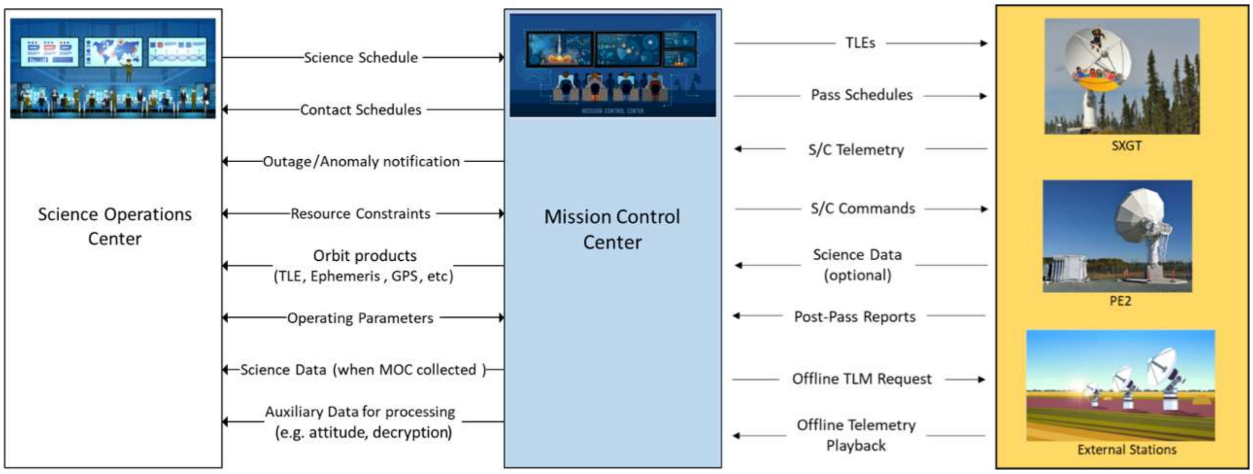

Fig. 2: Science-MOC-Ground Data Flows (credit CSA)

The interface between the MOC and the ground stations is well-established, having been used successfully across multiple past missions. The Canadian Space Agency has access to several S and X-Band ground station facilities through our partners at Canada Centre for Mapping and Earth Observation (CCMEO). Currently, four antennas are operational. One at the Inuvik Satellite Station (ICAN), two at the Prince-Albert Satellite Station (PASS) and one at the Gatineau Satellite Station (GATN). Two additional antennas are in validation phase and will soon be available to the operations team.

4. Lessons Learned

The development of the GMOC product has been underway for over three years, during which the team has faced a range of challenges and gained valuable experience now documented as lessons learned.

4.1. Stakeholder Engagement

One of the key factors behind the early success of this initiative was the behind-the-scenes effort to promote and gain buy-in for this new approach to ground systems development. Traditionally, the mission project team held responsibility for both the space and ground segments. To shift this model, the operations team had to effectively advocate for the new vision to upper management. Through persistent engagement and strategic communication, the team secured the necessary support from leadership and other critical stakeholders, ultimately gaining approval for the first three phases of GMOC development.

4.2. Funding Strategy

The funding strategy had to be revised to operate independently of individual project budgets. Traditionally, ground segment development was financed through allocations from specific mission projects, funnelled to the operations team. However, to ensure the continuity of GMOC development during periods when no new space missions were underway, the operations team leveraged readily available resources from the operational budget to initiate the early phases of GMOC.

With significant progress now achieved in these initial phases, the organization is actively working to secure long-term funding for a dedicated program aligned with the GMOC vision. This sustained funding will support the development of generic ground segment solutions over the next decade, enabling the next generation of Canadian satellite missions.

4.3. Project Planning

Initially, the team faced significant schedule pressure, as the Quantum EncrYption Science Satellite (QEYSSat) mission was set to launch shortly after the GMOC project began. This urgency led to decisions that favored legacy solutions over taking a step back to re-evaluate broader workflows and foundational software architecture choices. As mentioned earlier, closely coupling ground segment development with a spacecraft mission can result in short-term decisions that compromise the long-term usability and robustness of the ground segment. In hindsight, dedicating additional time to properly establish the GMOC software architecture and development approach would have been beneficial. This would not only have accelerated progress over time but also ensured a stronger foundation for the entire program.

4.4. System Validation

As previously mentioned, the original plan was for the QEYSSat mission to be the first to utilize the updated GMOC. However, following multiple delays, the decision was made to validate the initial version of GMOC using the Scientific Satellite Atmospheric Chemistry Experiment (SCISAT)—a legacy mission still in operation. Leveraging an active satellite provided a valuable opportunity to identify bottlenecks in the ground segment instantiation process and to optimize workflows for future mission deployments. This validation also served as a proof of concept, demonstrating to stakeholders that GMOC is both generic and adaptable enough to support a wide range of missions—past, present, and future. As an added benefit, SCISAT received a retrofitted mission operations center, enhancing its capabilities with new features and functionality.

4.5. Hiring, Training and Knowledge Strategy

The strategic shift toward a developer-oriented mindset requires an evolution in the skillset of the operations team. To sustain ground segment development capabilities within the government, it is essential that the team includes members with strong expertise in IT architecture, software development, and artificial intelligence. This approach enables the CSA to reduce its reliance on external contractors while maintaining the internal proficiency needed to realize the GMOC vision.

As noted by [5], this strategy must include effective training for the operations team and the implementation of robust knowledge management tools to support 24/7 multi-mission satellite operations. Furthermore, as demonstrated by [6], it is critical to integrate flight operations teams early in the development of multi-mission systems. Historically, limited involvement of operations engineers during initial phases has resulted in operational gaps that later demand increased human and technical resources.

5. Future GMOC Development

The future development of GMOC aims to integrate artificial intelligence and business intelligence into a modular, generic, and adaptable reference software architecture tailored for CSA's future missions. The solution features a generic user interface portal designed to deliver an optimal and standardized user experience. Development is currently underway to provide advanced analytics capabilities that support decision-making through key performance indicators (KPIs) related to ground operations.

Key developments of the next phases of GMOC include:

- Enhanced artificial intelligence & automation processes
- Performance dashboard and satellite operation business intelligence
- Generic reference architecture

5.1. Enhanced Artificial Intelligence & Automation processes

Future GMOC development will integrate enhanced artificial intelligence technology and automation to support decision making and system capabilities while preserving safety in critical systems. GMOC components will rely more on AI-driven automation for satellite anomaly detection, fault recovery, and optimized scheduling. Current topics being investigated are:

- **Agile Mission Planning and Optimization**: The objective is to optimize resource scheduling to better coordinate the use of ground stations and satellites as detailed by J. Yang [7] and to automatically schedule maintenance during free station slots without interfering with satellite missions as explained by B. Mametsa [8]. Currently, work is being carried out under CSA's Space Technology Development Program (STDP) to investigate how to implement such a system for a multi-mission environment.
- **Intelligent Satellite Anomaly Diagnostic & Recovery System**: This type of system focuses on capturing time-dependent trends in telemetry datasets, to detect anomalies at an early stage and recommend a course-of-action for the recovery, as discussed by Z. Li [9]. Recent work has also been carried out under two STDP investments relating to machine learning and anomaly detection. This type of system will enable the detection of anomalies by leveraging algorithms that identify patterns in the data indicative of potential failures. As noted by [10], this capability can assist operators by allowing ground control systems to take corrective actions before issues become critical.
- **Intelligent Satellite Tasking & Control System**: By developing an integrated algorithm to maximize data collection while respecting satellite memory limits, the tasking chain can be optimized as discussed by C-H Kim [11]. This can be achieved through the application of on-board autonomy to manage nominal situations and anomalies, guaranteeing mission continuity with limited human intervention as seen in Warhaut [12].
- **Spacecraft Engineering AI Copilot Aids:** To assist operations, another advancement is the establishment of a machine learning operations (MLOps) platform and data engineering solutions to ensure the production and deployment of additional artificial intelligence capabilities, including Generative AI, large language models (LLM), deep machine learning, and operational data analytics.

All of the above will be carried out using responsible AI practices while considering environmental impacts and ensuring AI safety conformity for critical systems. To achieve this, AI learning assurance processes will be core to the development process.

5.2. Operation Performance Monitoring

Enhancing flight and ground operations efficiency through data-centric performance measurement is essential for ensuring the long-term sustainability of our operations as new missions are integrated into our portfolio. By leveraging performance-driven insights, satellite operations can remain cost-effective. The integration of generic business intelligence tools enables comprehensive data analysis, supporting strategic decision-making and fostering continuous improvement across mission operations. Based on the insights gained from these tools the overall direction of the GMOC program can be better steered to remain in line with the program objectives. The primary output of the above tools will be operations performance dashboards. These will feature clear visualizations of key performance indicators (KPIs) and operational metrics. Example KPIs include:

- order to delivery durations and data/ product delivery metrics
- ground station performance and operational workload
- satellite health statistics and satellite outage durations
- system resource utilization and network performance
- volume of data received and end-to-end Latency metrics
- planning session duration and successful/missed manual passes

As presented by K. Marston in his paper regarding the business sense of multi-mission elements [13], we aim to achieve reduced operational costs through reuse of common elements across multiple programs and improved standardization. This will be done while balancing the increased complexity required to meet varying mission needs. Operation performance monitoring dashboards will provide us with the necessary decision-making information to manage the trade-off between cost and complexity.

5.3. Generic Reference Architecture

The system will implement software development lifecycle practices (SDLC) including analysis, design, implement, test, and deployment a of generic software architecture. This architecture will include a centralized web user interface framework and common framework capabilities that will support adaptation of the generic blueprint for mission specific needs. With the adoption of a modular architecture, it offers increased flexibility and adaptability, allowing for the harmonious integration of subsystems into an interoperable system that can support mission specific configuration. This architecture aims to optimize and improve the efficiency of future program operations to manage the complexities associated with satellite constellations in a cost-effective and safe manner as referred to in J. Howard [14], M.K. Ben-Larbi [15] and R.A. Richards [16]. It also provides a robust test environment ensuring coordination between systems and increased automation that reduces the need for manual tests. This in turn increases operational reliability by ensuring representative testing before and during critical phases of the mission as detailed by Z. Wei [17]. We aim to establish a technology stack that implements a generic yet flexible architecture to improve interoperability and automation.

6. Conclusions

The shift from mission-specific ground solutions to a more generalized GMOC implementation at the CSA has paved the way for integrating emerging technologies into satellite operations. The program's focus has evolved from approach supporting individual missions to developing a generic solution capable of serving multiple current and future missions.

As the Satellite Operations group broadens its role from traditional spacecraft operations to include development responsibilities, it becomes increasingly important to maintain a high level of awareness of emerging ground system technologies that can enhance operational effectiveness. To support this evolution, the team actively monitors advancements not only within space agencies and aerospace companies, but also in industries outside the space sector whose expertise can be leveraged for satellite operations. Key technological domains under close observation include artificial intelligence, quantum computing, cloud computing, and business intelligence.

The early success of GMOC has laid the foundation that will help accelerate ground segment development timelines for upcoming missions but also modernize legacy missions by providing them with a more capable and efficient Mission Operations Center. This early GMOC success has generated strong interest within the organization, leading to a commitment of additional funding to further expand and realize the GMOC vision. The generic solution is already enhancing development efficiency while enabling the integration of artificial intelligence into satellite mission operations.

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