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Transitioning from LEO to Lunar Missions: Applying Human Spaceflight Innovations

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Abstract

In our ongoing journey to enhance the operational capabilities of Europe's laboratory in space aboard the International Space Station (ISS) and to advance lunar mission preparedness, we have made significant strides in both the Columbus Monitoring and Control System (MCS) modernization project[1] and the innovative integration of EGS-CC[2], DTN[3], HCC[4] and Zigbee technologies within the LUNA Analogue Facility. These efforts are pivotal in transforming current operations and laying a robust foundation for future European space exploration missions to the moon.

The Columbus MCS modernization project, focused on transitioning to the new MCS-R system, will undergo comprehensive testing by on-console personnel in 2025, ensuring readiness for broader integration and ultimately operational transition. Central to this transition is the evolution of the EGS-CC framework, which underpins the MCS-R system and supports its development and operational goals.

Simultaneously, the EGS-CC framework plays a crucial role in the LUNA facility project, a pioneering infrastructure at the Cologne site aimed at preparing for future human and robotic missions to the Moon. The facility provides a unique environment for simulating lunar surface activities and establishes a globally recognized center of competence for lunar exploration. The planned integration of Delay-tolerant networking (DTN) for efficient space link communications will provide a realistic background for Lunar mission simulations, and Zigbee for low-cost, low-power IoT sensor interaction is being developed to enhance environmental monitoring and safety within space facilities.

MCS-R, and to a lesser extent MCS-L, have prioritized the integration of automated testing protocols, and are leveraging DevOps methodologies, such as continuous integration/continuous deployment (CI/CD) pipelines. This approach enables early identification and resolution of potential issues, thus maintaining system integrity and performance. The implementation of CI/CD pipelines facilitates faster and more reliable deployment within the operational infrastructure, ensuring that new EGS-CC releases are seamlessly integrated and tested.

The collaboration between ESA, DLR, and other key partners has been instrumental in overcoming technical and operational challenges, ensuring seamless transitions and integration. This collective effort has solidified the foundation for the full deployment and operationalization of these systems.

Looking ahead, the synergy between the MCS modernization project and the LUNA facility will be fully realized once both systems are operated from the same control room, evolving the Columbus Control Centre into the Human Exploration Control Center[5]. This integration will optimize resource utilization, including operators and infrastructure, thereby enhancing overall mission efficiency and effectiveness.

In summary, the combined efforts in the MCS modernization and LUNA facility projects represent a pivotal moment in the advancement of human spaceflight operations. The accomplishments achieved to date highlight our dedication to supporting future lunar missions and other endeavours beyond low Earth orbit, setting the stage for a new era in European space exploration.

Keywords: Columbus, LUNA, MCS, EGS-CC, HECC

1. Introduction

Human space exploration is entering an exciting new phase marked by significant technological advancements and renewed ambitions for missions beyond low Earth orbit. As the European Space Agency (ESA) extends its human spaceflight focus towards the Moon—in support of NASA's Artemis lunar missions—it is leveraging decades of operational expertise from the International Space Station (ISS) and the proven legacy of the Columbus laboratory module. Europe's contributions to Artemis, such as the Orion European Service Module (ESM), the Lunar I-HAB habitation module as well as the Lunar View module for the planned Lunar Gateway, underscore its commitment to this transition.

To support this ambitious goal, a strategic evolution of the ground segment is necessary—from the management of individual, mission-specific control systems to a versatile multi-mission control infrastructure. Historically, European human spaceflight operations have relied on dedicated ground segments uniquely tailored to specific missions, limiting flexibility and scalability for future exploration initiatives. Now, leveraging advanced technologies and common operational frameworks, ESA is transitioning towards a multi-mission approach, ensuring resource optimization, enhanced interoperability, and streamlined operational processes.

Central to this strategy are two pioneering projects: the modernization of the Columbus Monitoring and Control System (MCS-R) and the development of the Monitoring and Control System for the LUNA Analogue Facility (MCS-L). For over 18 years, the Columbus MCS has reliably supported ISS operations from the Columbus` Control Centre (Col-CC) at the German Space Operations Center (GSOC) in Oberpfaffenhofen. The legacy system operates continuously (24/7), with successful spacecraft operations critically dependent on operational products such as scripts, monitoring checks, displays, and command stacks. These products, developed and refined over nearly two decades, must now be migrated to a modern platform without requiring a complete re-validation of the extensive functionality provided by the legacy system.

However, new operational requirements and comprehensive obsolescence management—necessitating multiple hardware migrations, operating system upgrades, and a clear focus on advanced security measures—have driven the decision to modernize the legacy system. MCS-R addresses these challenges by migrating several legacy operational products into a new format based on the European Ground Systems Common Core (EGS-CC), with a comprehensive on-console testing phase scheduled for 2025 to re-validate the system during live operations.

In parallel, the German Aerospace Center (DLR) is developing MCS-L to monitor and control the cutting-edge LUNA Analogue Facility at the DLR Cologne site. Designed to prepare for both human and robotic lunar missions, LUNA focuses on innovative communication technologies - such as Delay Tolerant Networking (DTN) and the Zigbee protocol for low power Internet of Things (IoT) applications - to enhance the realism, safety, and efficiency of mission simulations. The facility benefits directly from the extensive operational experience, methodologies, and lessons learned during 18 years of Columbus operations and the ongoing modernization efforts with MCS-R.

Both projects embrace automation and modern DevOps methodologies, particularly Continuous Integration/Continuous Deployment (CI/CD) pipelines coupled with automated testing frameworks. This approach not only eases the revalidation process but also addresses challenges related to future hardware migrations and operating system updates. By leveraging the common EGS-CC infrastructure, MCS-R and MCS-L are converging within a unified ground segment that will transform the Columbus Control Centre into a comprehensive Human Exploration Control Centre (HECC). This evolution promises significant operational synergies, improved resource utilization, and a robust foundation for managing future lunar - and eventually interplanetary - missions.

This paper explores the technological advancements, operational innovations, methodological approaches, and collaborative dynamics underlying these initiatives. It underscores Europe's strategic foresight in transitioning from ISS operations to ambitious lunar exploration, effectively paving the way for future interplanetary missions.

2. MCS-R: Columbus Control System Modernization

The Columbus Monitoring & Control System (MCS), deployed for ISS operations, was built in the early 2000s as a proprietary application and has served reliably for over 18 years. However, as technological paradigms shifted, the legacy system - based on outdated middleware and custom-built components - began showing limitations. Its aging design increasingly struggled with modern security requirements, comprehensive obsolescence management, and the need for frequent hardware and operating system migrations as part of enhanced security measures. ESA's MCS-R initiative was launched to replace this monolithic system with a modular, more flexible architecture using the European Ground Systems Common Core (EGS-CC) framework - an ESA community-licensed project allowing for open collaboration and flexible modifications [2].

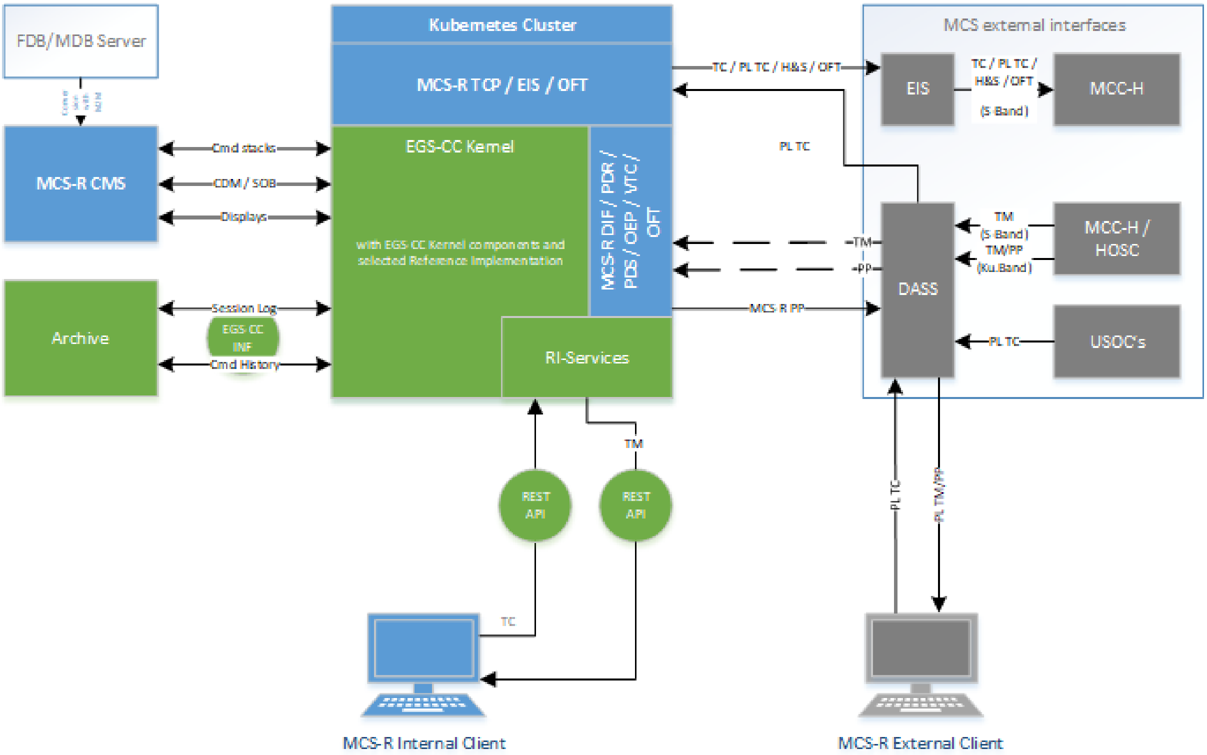


Figure 1 High-level architecture of MCS-R. In blue the components that have been developed on top of the components provided by EGS-CC in green. All components in grey remain as is and have not been altered as part of the MCS-R project.

2.1 Technological evolution

The evolution from a 25-year-old tech stack to MCS-R represents a significant modernization, transitioning from legacy Ada/C++/Java/CORBA components to a modular, service-oriented architecture built on EGS-CC and OSGi containers. By leveraging containerized deployments with Kubernetes and embracing modern DevOps practices, the system now supports dynamic scaling, improved resilience, and streamlined operations—all while maintaining vital legacy interfaces with ISS and Columbus ground systems.

Key aspects of this evolution are:

- **Adoption of EGS-CC:**
  MCS-R builds upon the modular, service-oriented architecture of EGS-CC. The transformation involves replacing the legacy Ada/C++/Java/CORBA based runtime components with modern Java services running in OSGi (Apache Karaf) containers. This new structure not only improves maintenance and scalability but also ensures the seamless reuse of standardized telemetry, telecommand, and archiving services provided by the EGS-CC Kernel and used across space missions.

- **Containerized Deployment with Kubernetes:**
  Rather than relying on traditional virtualization platforms such as VMware, MCS-R leverages a Kubernetes-based deployment. By containerizing each major component of the system, Kubernetes orchestrates the deployment across a dynamic cluster of nodes. This approach decouples the system from specific hardware and offers benefits such as autoscaling, rolling updates, improved fault tolerance, and better resource utilization of existing hardware. Moreover, the fine-grained decoupling of the architecture into separate pods enables robust monitoring and observability. Dedicated monitoring tools - such as Prometheus for metric collection and Grafana for visualization - can be integrated to capture real-time performance data and logs at the pod level. This setup not only facilitates proactive alerting and rapid issue isolation but also supports continuous performance tuning, ensuring that MCS-R remains highly resilient and adaptable in a dynamic production environment. Seamless migrations

and continuous delivery pipelines are further bolstered by Kubernetes' orchestration capabilities.

- **Streamlined Operational Deployment:**
  The legacy MCS relied on deploying five redundant servers and thirteen dedicated MCS clients per instance, resulting in a total of seventy persistently active virtual machines that required continuous management by the Ground Control Team (GCT) and sustained engineering teams. In contrast, the revised MCS-R architecture supports on-demand instantiation of instances and dynamic scaling of MCS-R clients based on actual operational requirements and activities, enabled by transitioning from VMware virtual machines to Kubernetes pods. Additionally, the migration from a traditional client-server model - where dedicated clients required individual configuration - to a centralized processing kernel that uniformly delivers information to all clients has further streamlined system setup and improved operational consistency.

- **Operational Continuity:**
  A paramount requirement was maintaining existing interfaces with legacy ISS and Columbus ground systems as well as international and European partners. MCS-R achieves this by employing custom "interface service" adapters developed as OSGi bundles that integrate well into the EGS-CC service-oriented architecture. These adapters implement legacy protocols and interfaces, guaranteeing operational safety and connectivity remain uncompromised even as underlying technologies are modernized.

- **Modern DevOps Practices:**
  The MCS-R project embraces continuous integration/continuous deployment (CI/CD) pipelines and automated testing frameworks, which have been instrumental in delivering frequent, regression-tested updates. These practices dramatically reduce time-to-console and minimize risks associated with deploying mission critical software, thereby ensuring a smooth transition from legacy operations to the modernized system.

2.2 Distributed Operations

MCS-R pioneered distributed operations within the EGS-CC framework by serving as a centralized router for all User Support and Operations Center (USOC) commands, streamlining command exchange across the system. This advancement not only introduced multi-source commanding but also extends EGS-CC functionalities by introducing command classification and authorization - features that, while not essential for satellite operations, are critical for the safety and integrity of human spaceflight missions.

AOS / LOS: Mismatch
Forward Link: NOK
ESA GS Inhibit: Mismatch
Checkpoint: Mismatch
Uplink Path: Mismatch
Command Safing: Mismatch
Connection Status: Connected
TCs Received: 0

Priority (Priority) # Commands Queued: 0
Standard (Standard) # Commands Queued: 0
DataLoad (DataLoad) # Commands Queued: 0

USOC_1 (CADMOS) # Commands Queued: 0
USOC_2 (ERASMUS) # Commands Queued: 0
USOC_3 (BUSOC) # Commands Queued: 0
USOC_4 (MARS) # Commands Queued: 0
USOC_5 (MUSC) # Commands Queued: 0
USOC_6 (ACESAUTO) # Commands Queued: 0
USOC_7 (ACES) # Commands Queued: 0
USOC_8 (EDR2) # Commands Queued: 0

Figure 2 MCS-R provides the concept of command queues and command authorization that can be supervised and controlled by the Columbus GCT according to operational needs

Importantly, the generic implementation of command queues and classification mechanisms in EGS-CC is designed with future human spaceflight missions in mind, ensuring that the rigorous safety and security requirements of crewed operations can be consistently met.

3. Iterative Feedback and Tailoring of Columbus Operations

A pivotal factor in the success of MCS-R is the continuous feedback loop with experienced Columbus flight and ground control teams. Their nearly two decades of operational expertise drove significant refinements during the development phase. Key lessons from 18 years of Columbus operations directly influenced several innovative features in MCS-R:

3.1 Automated AOS/LOS Calculations

In the legacy system, operators had to manually combine different data sources to determine Acquisition of Signal (AOS) and Loss of Signal (LOS) periods. MCS-R automates these calculations, ensuring precise, real-time determination and indication of the availability of TM/TC communication paths, without the need for manual intervention.

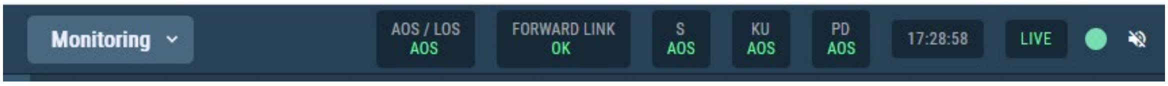


Figure 3 AOS/LOS indicators as well as TM reception indicators have been added to increase operational awareness of the current connection status between the ground and space segment

This was achieved by developing a sliding window algorithm that continuously monitors all incoming packets and, in real time, calculates metrics based on the telemetry source - whether S-band, Ku-band, or Processed Data - and the system's connection status to the MCC-H ground segment. Previously, determining connection status required additional dedicated tools alongside the MCS, relying partly on predictive estimates.

3.2 Streamlined On-Board Downlink / Uplink Process

Historically, managing downlink and uplink operations to the Columbus module required manually calculating transfer times, coordinating data flows, and converting data files from binary to ASCII. With MCS-R, these processes have been integrated into a unified, automated workflow that minimizes operator involvement and significantly reduces the risk of human error. For routine transfers, the system now prompts for only the most essential options, while still allowing for detailed configuration when necessary. Since operational file transfers are a regular part of ongoing operations, this streamlined process drastically cuts down the time required to complete these tasks - saving an estimated one hour per week that can be redirected to more valuable activities.

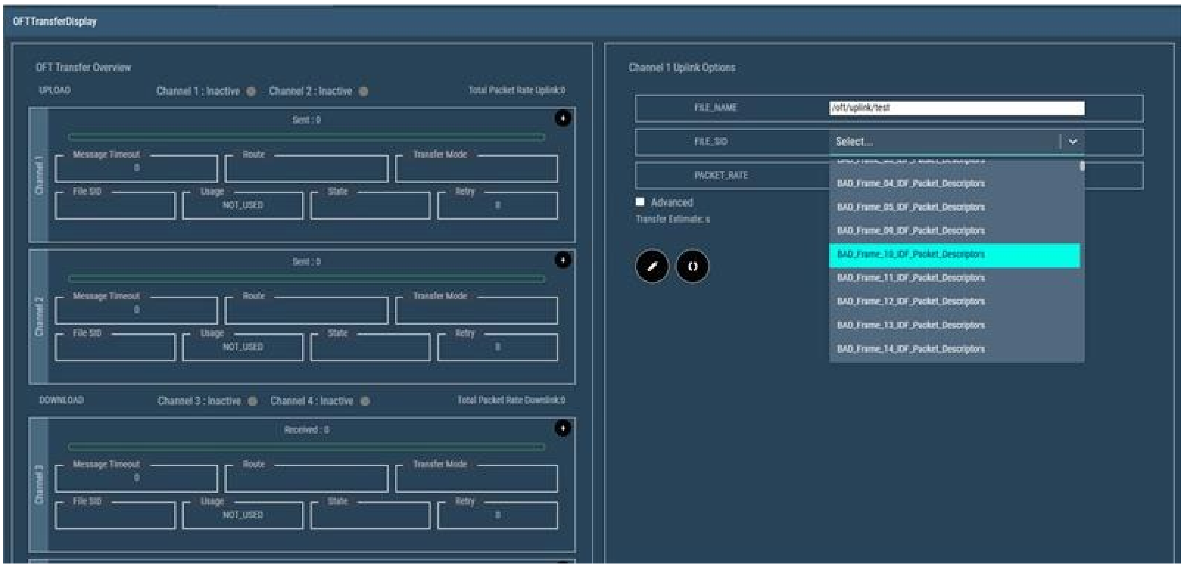
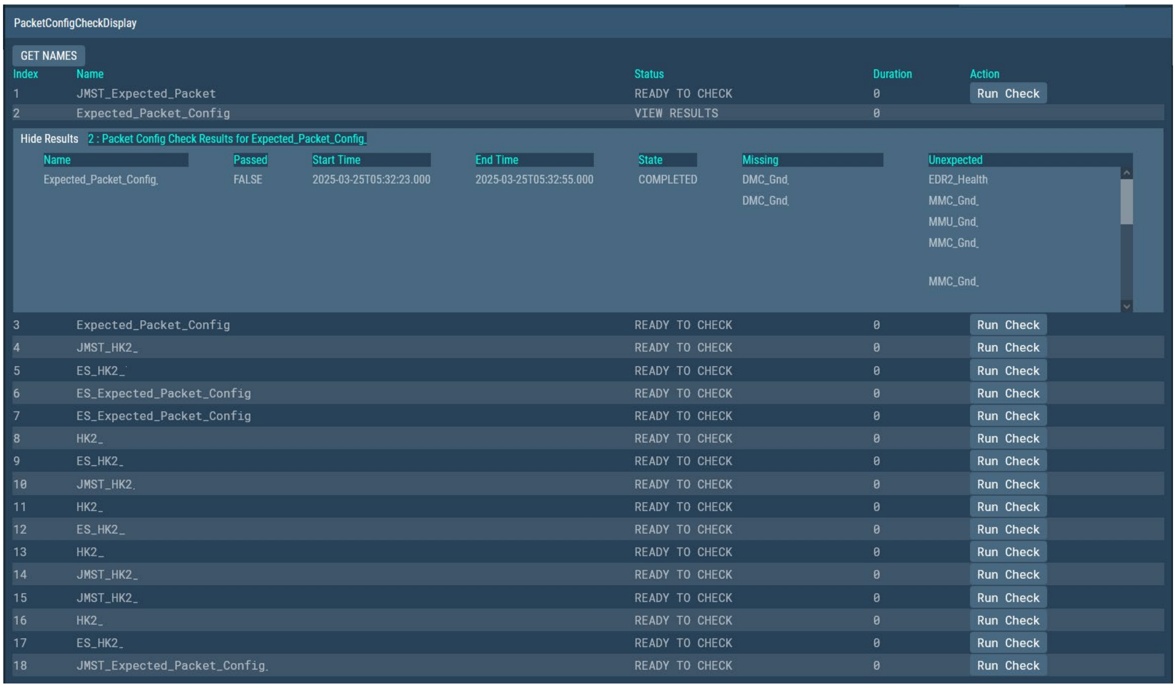


Figure 4 The new Operational File Transfer (OFT) widget streamlines the file transfer process between ground and space segment by requiring only minimum user input

3.3 Enhanced Monitoring Capabilities

Feedback from operational teams underscored the need for advanced telemetry monitoring. The new system now incorporates automated evaluation of incoming packets, batch enablement of monitoring limits, and sophisticated monitoring checks that leverage EGS-CC's capabilities. These improvements ensure that anomalies are detected promptly, and that on-board system performance is continuously validated.



Index	Name	Status	Duration	Action
1	JMST_Expected_Packet	READY TO CHECK	0	Run Check
2	Expected_Packet_Config	VIEW RESULTS	0	

2 : Packet Config Check Results for Expected_Packet_Config_

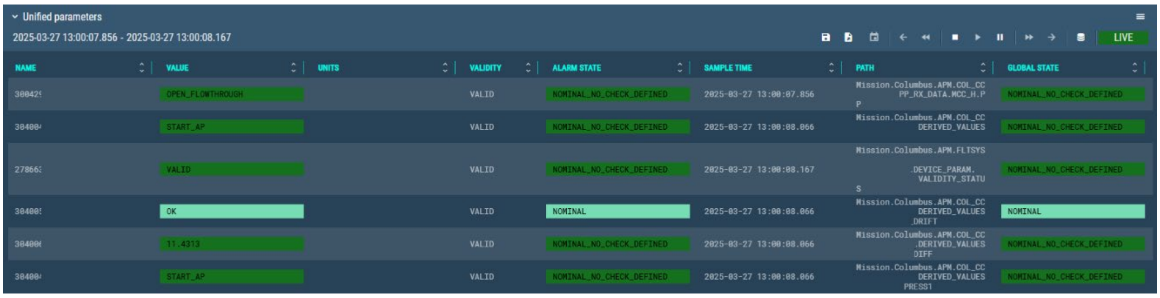
Name	Passed	Start Time	End Time	State	Missing	Unexpected
Expected_Packet_Config_	FALSE	2025-03-25T05:32:23.000	2025-03-25T05:32:55.000	COMPLETED	DMC_Gnd_ DMC_Gnd_	EDR2_Health MMC_Gnd_ MMU_Gnd_ MMC_Gnd_ MMC_Gnd_

Index	Name	Status	Duration	Action
3	Expected_Packet_Config	READY TO CHECK	0	Run Check
4	JMST_HK2_	READY TO CHECK	0	Run Check
5	ES_HK2_	READY TO CHECK	0	Run Check
6	ES_Expected_Packet_Config	READY TO CHECK	0	Run Check
7	ES_Expected_Packet_Config	READY TO CHECK	0	Run Check
8	HK2_	READY TO CHECK	0	Run Check
9	ES_HK2_	READY TO CHECK	0	Run Check
10	JMST_HK2_	READY TO CHECK	0	Run Check
11	HK2_	READY TO CHECK	0	Run Check
12	ES_HK2_	READY TO CHECK	0	Run Check
13	HK2_	READY TO CHECK	0	Run Check
14	JMST_HK2_	READY TO CHECK	0	Run Check
15	JMST_HK2_	READY TO CHECK	0	Run Check
16	HK2_	READY TO CHECK	0	Run Check
17	ES_HK2_	READY TO CHECK	0	Run Check
18	JMST_Expected_Packet_Config_	READY TO CHECK	0	Run Check

Figure 5 A new packet check mechanism was implemented to help the operator to determine if all expected telemetry packets are being received or if certain packets are missing or unexpected.

3.4 Unified Telemetry Streams

Operators traditionally had to reconcile multiple telemetry sources - such as PathTM and Processed Data - each with its own processing routine. By unifying these sources within the EGS-CC Tailoring Data Model (TDM), MCS-R presents a single, cohesive monitoring interface regardless of data origin. This consolidation enhances situational awareness and diagnostic accuracy.



2025-03-27 13:00:07.856 - 2025-03-27 13:00:08.167

NAME	VALUE	UNITS	VALIDITY	ALARM STATE	SAMPLE TIME	PATH	GLOBAL STATE
30042	OPEN_FLOWTHROUGH		VALID	NOMINAL_NO_CHECK_DEFINED	2025-03-27 13:00:07.856	Mission.Columbus.APM.COL_CCPP_RX_DATA.MCC_H.PP	NOMINAL_NO_CHECK_DEFINED
30400	START_AP		VALID	NOMINAL_NO_CHECK_DEFINED	2025-03-27 13:00:08.066	Mission.Columbus.APM.COL_CCDERIVED_VALUES	NOMINAL_NO_CHECK_DEFINED
27866	VALID		VALID	NOMINAL_NO_CHECK_DEFINED	2025-03-27 13:00:08.167	Mission.Columbus.APM.FLTSYS.DEVICE_PARAM.VALIDITY_STATUS	NOMINAL_NO_CHECK_DEFINED
30400	OK		VALID	NOMINAL	2025-03-27 13:00:08.066	Mission.Columbus.APM.COL_CCDERIVED_VALUES.DRIFT	NOMINAL
30400	11.4313		VALID	NOMINAL_NO_CHECK_DEFINED	2025-03-27 13:00:08.066	Mission.Columbus.APM.COL_CC.DERIVED_VALUESDIFF	NOMINAL_NO_CHECK_DEFINED
30400	START_AP		VALID	NOMINAL_NO_CHECK_DEFINED	2025-03-27 13:00:08.066	Mission.Columbus.APM.COL_CCDERIVED_VALUESPRESS1	NOMINAL_NO_CHECK_DEFINED

Figure 6 Independent of the source or type of the telemetry (Processed Data, Synthetic Parameter, Path TM Parameter) all parameters hold the same meta-data and can be used equally in MCS-R

Overall, the iterative feedback process during the agile software development lifecycle ensured that the modernization of the Columbus MCS was not merely a technological refresh but a user-centric overhaul that directly addressed long-standing operational challenges. It laid the groundwork for a system that is both forward-looking and deeply rooted in operational reality.

4. MCS-L: LUNA Analog Monitoring & Control System

In parallel to upgrading ISS operations, DLR is developing MCS-L to support LUNA, a state-of-the-art lunar analogue facility in Cologne. LUNA is essentially a "Moon on Earth" - a large indoor regolith sandpit designed to simulate lunar surface conditions. It will serve as a platform for astronaut training, robotics demonstrations, and integrated mission simulations for future Moon missions.

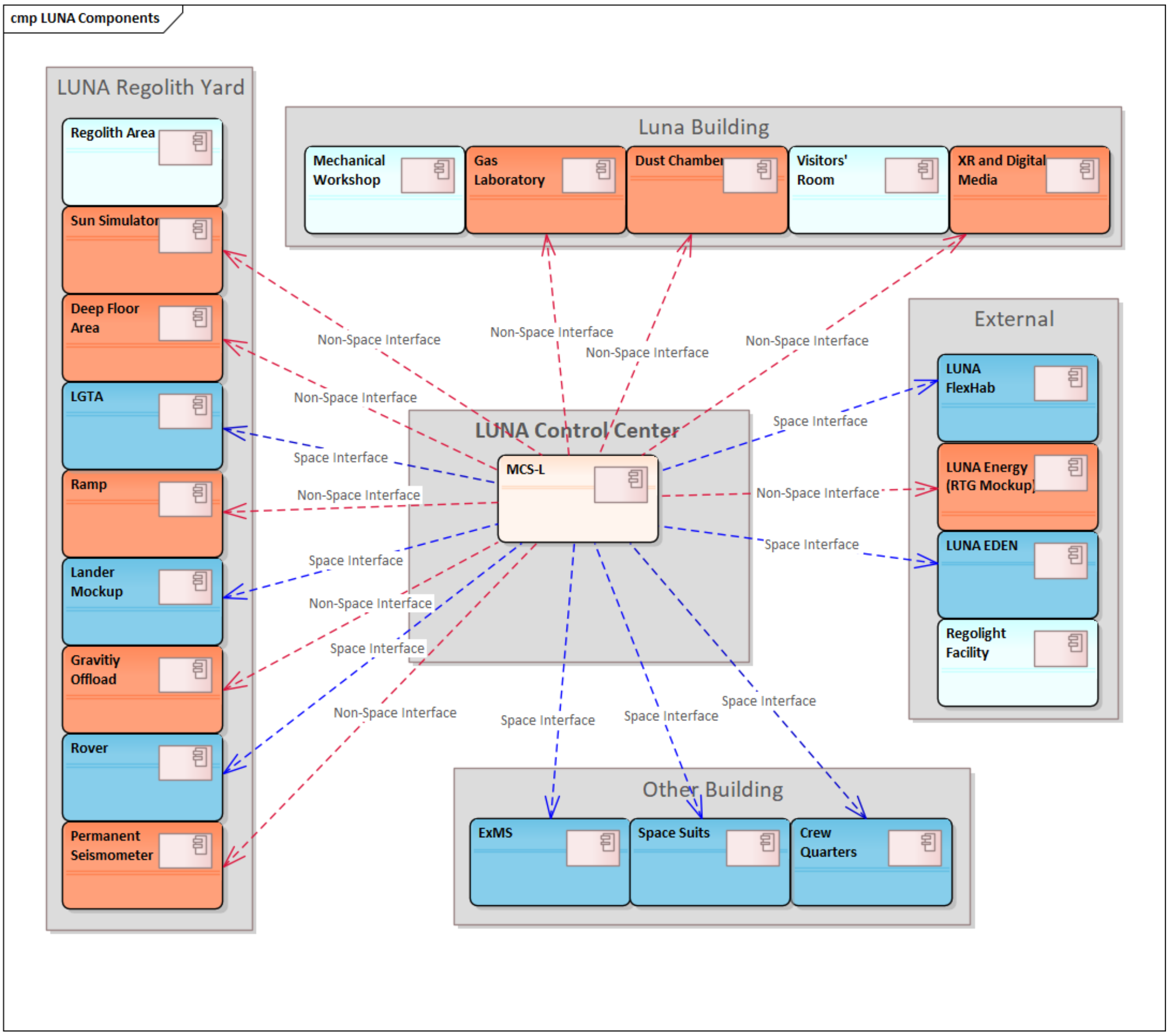


Figure 7 MCS-L is at the core of the LUNA Ground Segment and will integrate with various space and non-space elements. Elements marked in red are considered non-space elements, whereas blue elements are considered space elements. The elements depicted in light blue will not be integrated into MCS-L.

Key features of MCS-L include:

- **Support for Advanced Communication Protocols:**
  LUNA requires simulation of long delay space communications. MCS-L will integrate Delay/Disruption Tolerant Networking (DTN) using modern protocols like the CCSDS Bundle Protocol (BP) to emulate the real-world delay conditions of lunar communications.

- **Integration of Terrestrial Wireless Sensors:**
  The facility leverages commercial IoT solutions, such as Zigbee humidity, temperature and proximity sensors, to gather environmental and operational data. An interface gateway (Zigbee to MQTT) will convert and package these sensor readings into a simplified customized telemetry format (JSON) for processing within the EGS-CC framework.

- **Integration of additional Terrestrial Elements:**
  Zigbee was selected primarily due to its low power consumption and robust mesh networking capabilities. As highlighted in [7], technologies based on IEEE 802.15.4 - of which Zigbee is a leading implementation - are well-suited for applications requiring minimal energy use while ensuring reliable communication in interference-prone environments. Its inherent ability to form self-healing, scalable networks make it ideal for distributed sensor deployments, ensuring continuous data collection even if individual nodes fail. Additionally, Zigbee's widespread adoption and mature ecosystem promote interoperability and ease of integration, which are crucial for sustaining long-term operational reliability

in both terrestrial and mission-critical settings.

- **Adaptation of EGS-CC Core Components:**
  Just like MCS-R, MCS-L is built on the EGS-CC framework. This common base enables the partial reuse of generic telemetry processing, commanding workflows, and archiving mechanisms. Additionally, insights from MCS-R and Columbus can be shared between the teams, including processes and knowledge related to deployment strategies, component development, and configuration, thereby reducing development time and risk.

- **Dual Mode Operations:**
  MCS-L will monitor and control both simulation equipment (such as the sun simulator) in real-time as well as test equipment like rovers via the DTN network with possible communication delays. This duality will allow the system to support both immediate, onsite interventions and realistic simulation of lunar mission scenarios.

An early release of MCS-L is scheduled for deployment in 2025, paving the way for integrating the initial non-space components - namely, hall sensors and seismic sensors installed in the facility's deep floor area. Additional functionality, including the communication with experiments over DTN, is currently on track for 2026.

5. Unified Operations in the Human Exploration Control Center (HECC)

By leveraging the same EGS-CC technology base, MCS-R and MCS-L have provided the foundation to work in concert within the integrated Human Exploration Control Centre [5]. The new HECC will combine the operational strengths of Columbus with the innovation of LUNA, providing a unified platform that supports a broad spectrum of space missions.

Table 1 compares the two systems:

Aspect	MCS-R (Columbus ISS)	MCS-L (LUNA Analog)
Operational Focus	Real spacecraft operations – Columbus ISS module	Simulated lunar surface missions – LUNA analogue facility
Development Motivation	Replace aging legacy system; extend ISS ground support	Develop a new system for lunar mission training and testing
Communication Interfaces	Legacy ISS protocols (CCSDS, Processed Data, EIS) – maintained via adapter layers	Lunar protocols (CCSDS/DTN) and terrestrial IoT (Zigbee) – unified via different adapters
Implementation Platform	EGS-CC based OSGI bundles; Java/OSGi; deployed as Kubernetes services	EGS-CC based mission core; extended for DTN and IoT sensor integration
Key Challenges	Seamless migration without downtime; operational continuity and the migration of almost 20 years of operational products	Emulating lunar delays; integrating heterogeneous sensor data; access control and security;
Role in HECC	Primary system for ISS operations; provides proven processes and operational workflows for a crewed spacecraft	Training and simulation platform; enables testing of new concepts

Table 1: Comparative Overview of MCS-R and MCS-L projects

Unified under the HECC, both systems will share infrastructure services such as computing resources, storage, databases, network components, and user interfaces. This shared environment will reduce training time, improve interoperability, and maximize resource utilization. As the HECC evolves, it is envisioned to be capable of managing multiple mission profiles - from ISS operations to live lunar missions - using the same underlying technology and operational procedures.

Figure 8 A view of the STRATOS console in one of HECC's control rooms with the new MCS-R clients running on the lower screens

6. Model Based Systems Engineering and Enterprise Architect

The complexity inherent in developing modern ground systems justified a rigorous, model driven approach to streamline the design process in these projects. Both MCS-R and MCS-L adopted Model Based Systems Engineering (MBSE) practices from start, a strategy facilitated by the use of Sparx Systems Enterprise Architect (EA).

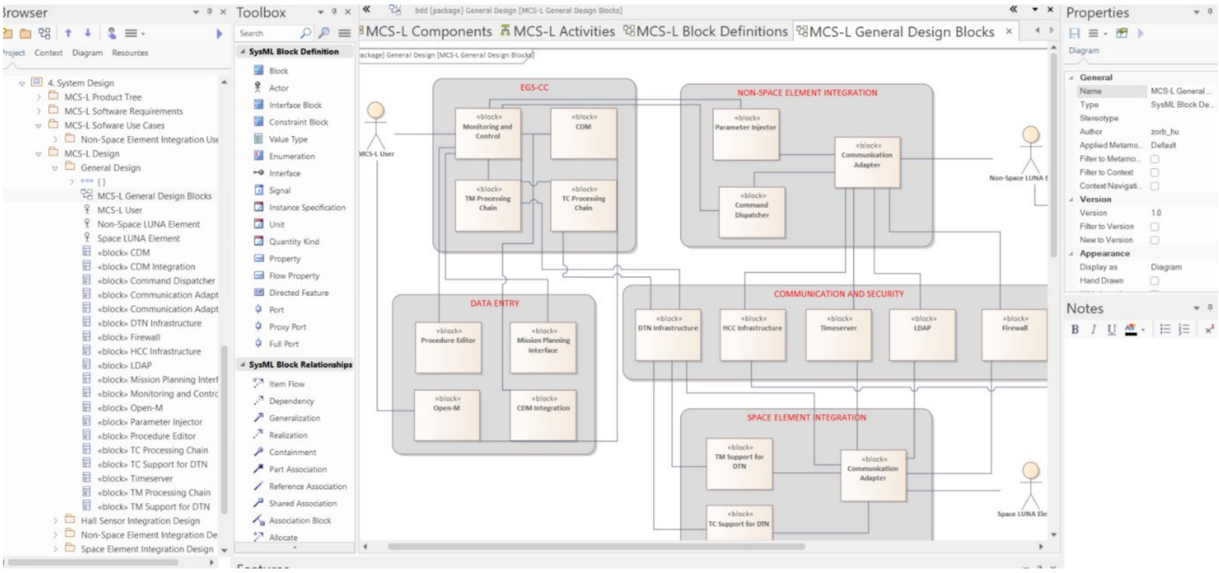


Figure 9 The MCS-L system architecture has been modelled entirely in Enterprise Architect. Artefacts and outputs have also been re-used for documentation purposes and to facilitate the design process in various boards and meetings

Key MBSE contributions include:

- **Architecture Modelling and Code Synchronization:**
  The projects began by modelling system components, architecture and interfaces using UML/SysML modelling language within EA. As development of MCS-R progressed, the actual source code of the project was regularly imported to update these models, ensuring that design and implementation remained consistent. This iterative approach is well-regarded in digital engineering - endorsed by at least 27.4% of engineers in a recent survey [7] - and is expected to enhance long-term system maintainability, a benefit also recognized by most survey respondents [7].

- **Centralized Requirements and Test Management:**
  For MCS-R, all functional, performance, and security requirements were entered into Enterprise Architect and linked directly to corresponding design elements (components) as well as test cases and scenarios. This approach creates a complete traceability chain that enabled continuous verification throughout the development lifecycle.

- **Automated Documentation and Traceability:**
  EA's robust reporting capabilities allow for the automated on-demand generation of design documents and traceability matrices. This ensures that every requirement will be addressed and that each test case is appropriately linked to a requirement, reinforcing the overall quality assurance process.

- **Round Trip Engineering:**
  By enabling the generation of UML diagrams directly from source code and reconciling these with the design model, the MBSE approach minimizes discrepancies and supports ongoing system validation. This continuous loop of verification and documentation is critical in achieving operational readiness.

This MBSE approach, centered on Enterprise Architect, provided the backbone for rigorous system validation within MCS-R. With every component traceable from requirements to tests, the MCS-R project ensured that operational and safety criteria were met - an essential aspect given the high stakes of human spaceflight missions. MCS-L draws from the development concepts of MCS-R to provide a customized modelling workflow, given the more dynamic evolution and experimental nature of the project and differences in stakeholder and safety requirements.

7. Future Perspectives and Lessons Learned

The MCS-R and MCS-L projects exemplify how decades of operational experience at GSOC can be harnessed to drive next generation system development. Looking ahead, several key lessons and future directions emerge:

- **Operational Agility:**
  The integration of advanced DevOps methodologies and new deployment strategies not only streamlines future operations but also paves the way for rapid responses to emerging mission requirements. Future work will likely explore further automation and integration of artificial intelligence for anomaly detection to assist operators in their decision making.

- **Interoperability Across Missions:**
  As the HECC evolves, there is strong potential to extend its capabilities to other missions, including further Lunar and Martian operations. A unified control centre that can support a variety of mission profiles will be a cornerstone of Europe's long-term strategy for interplanetary human and robotic exploration.

- **Enhanced Simulation Environments:**
  The success of MCS-L within the LUNA project, which creates a realistic lunar analogue, might pave the way for more advanced simulations. Future enhancements may incorporate virtual reality (VR) or augmented reality (AR) technologies [8], providing immersive training environments for both astronauts and mission controllers.

- **Collaboration and Informed Decision Making:**
  By embracing a modern DevOps approach that emphasizes agile development and early stakeholder integration, we ensured that the MCS-R project evolved in line with end user needs and operational realities. This approach enabled us to build the right tool in the right way - with end users actively

engaged from the outset to facilitate early familiarization and timely adaptations. Moreover, our diverse team, supported by decades of operational expertise, guided key design decisions and proactively identified operational constraints that might have otherwise been overlooked. A transparent development process characterized by four-week sprint cycles and regular reviews with ESA and DLR management, as well as the broader operations community, fostered informed decision-making and effective collaboration throughout the project.

- **Cross-Project Synergies:**
  Continuous exchanges between the MCS-R and MCS-L teams facilitate the sharing of best practices and lessons learned. This synergy not only enhances the individual outcomes of each project but also drives collective innovation, reinforcing a culture of shared expertise and continuous improvement.

8. Conclusion

With the imminent operational deployment of MCS-R and the ongoing development of MCS-L, Europe is dramatically upgrading its ground segment capabilities in preparation for lunar exploration. These projects merge decades of operational experience with modern technologies to support both current ISS operations and future lunar missions. Leveraging a unified EGS-CC framework, advanced automation, and rigorous MBSE practices, the new systems ensure that the HECC will be fully equipped to manage diverse mission profiles.

The continuous feedback loop from Columbus flight and ground control teams played a crucial role in shaping MCS-R, demonstrating that real-world operational insights can drive significant improvements in mission control technology. As a result, Europe will get a robust, adaptable, and scalable platform ready to support human exploration not only on the ISS but also on the Moon - and eventually beyond.

Europe will be firmly positioned for the Artemis era, with a control centre that integrates advanced technology, streamlined processes, and deep operational insights. The groundwork laid by MCS-R and MCS-L will serve as the blueprint for future interplanetary mission control systems, ensuring sustained excellence in mission operations for years to come.

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