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Autonomous Ground Segment Control for Small Satellite Missions

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In recent years, the increasing deployment of satellites into non-geostationary orbit has sparked the emergence of new satellite missions and mega-constellations. Lower launch costs have enabled broader access to space, particularly for scientific and commercial missions. However, traditional ground segment operations now face significant challenges, including high operational costs, limited human resources, and the demand for real-time decision-making. Therefore, achieving autonomy in ground operations is essential to efficiently handle the growing number of simultaneous satellite links. This paper presents the operational concept of the user ground segment for the SeRANIS mission, a scientific satellite mission led by the University of the Bundeswehr Munich. The mission's core is the small satellite *Athene 1*, equipped with a software-defined payload hosting over 20 scientific experiments. Operating in a sun-synchronous orbit at approximately 550 km altitude, *Athene 1* supports multiple communication bands, including UHF, L-band, S-band, X-band, Ka-band, and optical communications. Accordingly, the ground segment features specialized tracking antennas, including dishes up to 4 meters in diameter, and an optical ground station to interface effectively with the satellite. This paper highlights the automation-centric concept developed to ensure minimal human interaction, cost efficiency, and scalability. The paper details the ground segment infrastructure, chosen methodologies, and supporting software tools, emphasizing their justification and effectiveness in autonomous operations.

Keywords: Ground Segment Operations, Small Satellite Missions, Autonomous Ground Control, Optical Ground Station, Tracking Antenna, Laser Communications

1. Introduction

Small satellite missions in low Earth orbit (LEO) have emerged as a pivotal approach in the realm of space exploration, particularly for scientific and research-focused objectives. These missions enable the rapid deployment of compact, yet capable, scientific platforms into orbit, allowing researchers to gather valuable data with reduced lead times. The relatively low cost of launching small satellites—primarily due to ride-share opportunities with larger missions—makes them an attractive solution for universities, research institutions, and emerging space nations. As a result, small satellites have become increasingly relevant for advancing scientific research, demonstrating new technologies, and performing in-orbit verification and validation of space systems.

However, the growing number of small satellite missions also brings operational challenges, particularly in the ground segment. Since these missions typically operate on limited budgets and are not driven by commercial business models, maintaining a cost-effective and efficient ground station setup is crucial. Employing 24/7 personnel to monitor and control satellite operations is often impractical, especially for academic or research institutions. This issue is further compounded in LEO missions, where satellite passes can occur at irregular hours, including nights and weekends, making manual operation infeasible. Therefore, the implementation of highly automated systems to control and manage ground station equipment is essential to ensure continuous satellite access, reliable data downlink, and overall mission success without incurring unsustainable labor costs. Autonomous systems significantly reduce operational costs and human error risks, enhancing reliability, responsiveness, and robustness. Such automation is not merely advantageous but essential for the sustainable operation and success of modern satellite missions.

The automation of ground segment operations has been a focal point in recent research, aiming to enhance efficiency and reduce human intervention in satellite communication systems [1, Chapter 11. Ground Data Systems and Mission Operations]. Various approaches have been explored to automate ground segment components, encompassing software, hardware, and organizational strategies. In software, the Multi-Agent Ground-operation Automation (MAGA) architecture utilizes autonomous agents to manage resource allocation and automate operation planning and execution [2]. Organizationally, initiatives like the European Space Agency's efforts in integrating test automation within the lifecycle of ground segment products highlight the move towards standardized, efficient deployment processes [3]. A notable contribution is the development of Yet Another Mission Control System (YAMCS), an open-source mission control framework designed for flexibility and scalability in spacecraft operations. Introduced by A. Sela in 2012, YAMCS offers real-time telemetry processing and automated command execution, facilitating streamlined ground segment management [4]. Further application of YAMCS is demonstrated in the ICE Cubes Control Centre, where it supports lean commercial operations through tailored configurations [5]. YAMCS will therefore be used to operate and control the user ground equipment of the small satellite mission Seamless Radio Access Network for Internet of Space (SeRANIS), a scientific mission at the University of the Bundeswehr Munich (UniBw M), Germany, [6].

The remainder of this paper is structured as follows: Section 2 introduces briefly the small satellite mission SeRANIS, and the design of the SeRANIS user ground segment is presented, highlighting its infrastructure, key components, and capabilities. Section 3 provides a short comparison of available ground operations and scheduling software solutions, emphasizing their suitability and effectiveness for autonomous satellite ground segment operations. Section 4 discusses the implementation of ground segment control and user data handling strategies using the YAMCS platform, including an assessment of automation features and operational advantages. Finally, Section 5 concludes the paper by summarizing key findings and offering an outlook on future developments and potential improvements for autonomous ground operations.

2. Overview of the Small Satellite Mission SeRANIS

2.1 Mission Overview

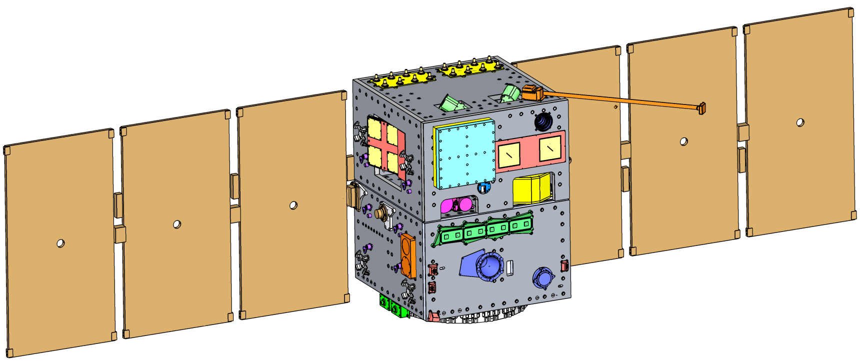


Fig. 1 Graphical illustration of the SeRANIS satellite *Athene 1*.

SeRANIS is a scientific mission at the UniBw M, Germany. The mission is funded by the Digitalization and Technology Research Center of the Bundeswehr (dtec.bw) and the European Union - NextGenerationEU. The core of SeRANIS is the small satellite *Athene 1*. The satellite provides a software-defined payload and carries more than 20 scientific experiments in a sun-synchronous orbit (SSO) at an altitude of around 550 km. The payload has a mass of approximately 90 kg and is equipped with various space-to-ground communications links in different frequency bands to interface the experiments, ranging from ultra-high frequency (UHF), L-band, S-band, X-band up to Ka-band and even optical communications. A more detailed overview in particular of the space segment, the mission objectives and the scientific payloads of the SeRANIS mission is provided in [6].

The ground segment of the SeRANIS mission consists of two main components: the User Ground Segment and the Satellite Control and S-band Network. A high-level functional overview of the SeRANIS ground segment is depicted in Fig. 2.

Mission operations is done in close cooperation with the German Space Operations Center (GSOC) of the German Aerospace Center (DLR). The Satellite Control and S-band Network is operated by the GSOC, which provides comprehensive satellite operations support throughout all mission phases. This includes mission preparation, launch and early orbit phase (LEOP), commissioning of both platform and payload, nominal (routine) operations, and the end-of-mission phase. During the mission preparation phase, detailed operational analyses and planning activities will be conducted, alongside the implementation, testing, and validation of the required ground systems.

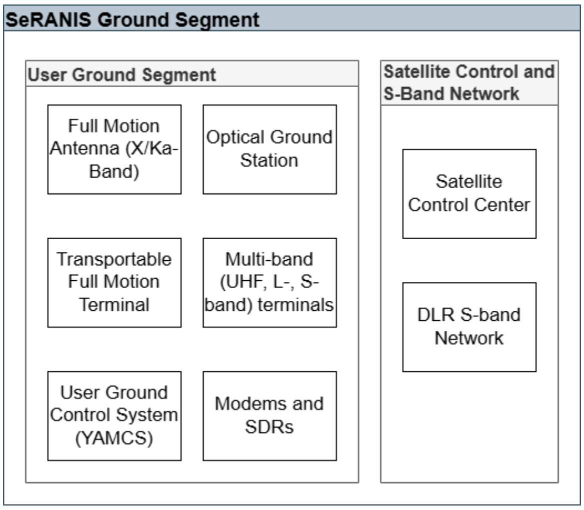


Fig. 2 Simplified functional view of the SeRANIS Ground Segment.

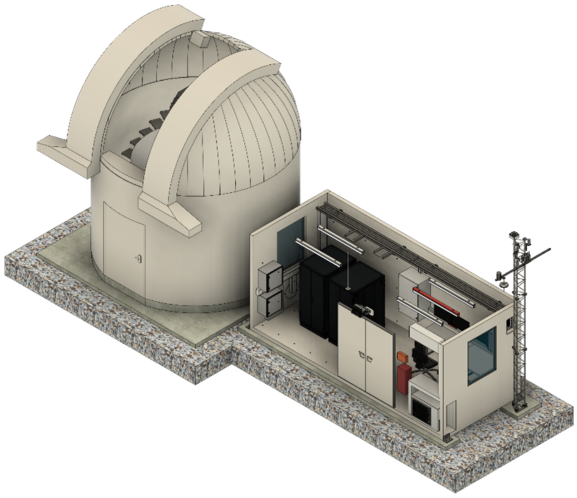


Fig. 3 Graphical illustration of the optical ground station in Neubiberg.

The GSOC provides the satellite control center as well as access to its existing S-band ground station network (see right part of Fig. 2), comprising ground stations in Weilheim (Germany) and Inuvik/O'Higgins (Canada/Antarctica). These stations will serve as the primary facilities for downlinking housekeeping telemetry. Any payload telemetry (TM) data received at these stations will be stored and subsequently made available to users. The telemetry equipment and associated systems at Weilheim and Inuvik/O'Higgins will be configured and adapted as necessary to meet mission-specific requirements. Additionally, if needed, the existing S-band network will be augmented by incorporating an extra S-band antenna provided by KSAT in Svalbard, Norway.

The focus in this paper is on the automated monitoring and control of the SeRANIS User Ground Segment. Its core elements are detailed in the following section.

2.2 SeRANIS User Ground Segment

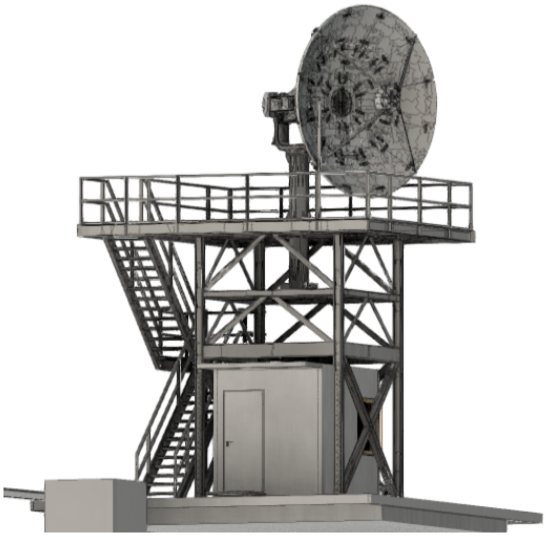
The User Ground Segment must be equipped with antennas and terminals capable of supporting the required frequency bands for establishing communication links with the payload of *Athene 1* and downlinking experimental data. Specifically, the User Ground Segment of the SeRANIS mission includes three tracking antennas with diameters of up to 4 m, an optical ground station (OGS), and the corresponding hardware and software infrastructure necessary for monitoring, control, and payload data handling.

2.2.1 Optical Ground Station

One key element is the OGS in Neubiberg (see Fig. 3). The facility comprises a Ritchey-Chrétien Nasmyth telescope with an aperture of 70 cm and protected aluminum-coated mirrors optimized for wavelengths between 1000 nm and 1700 nm. The telescope assembly, positioned at a height of 3.85 m to mitigate ground turbulence, is enclosed by a dome with a diameter of 4.6 m and a height of nearly 6 m, enabling full 360° rotation at speeds of up to $10\,^\circ\,s^{-1}$. It includes three exit pupils supporting various optical instruments and remotely switchable laser beams. Tracking accuracy is better than 3″ in closed-loop mode, facilitated by a fine-tracking system. The OGS integrates advanced safety features, including Aircraft Detection (ADS-B), a laser interlock controller, and weather sensors that automatically close the dome in less than 20 s during adverse conditions. Communication with the *Athene 1* satellite employs CCSDS standard optical on-off keying (O3K), targeting data rates of up to $1\,\mathrm{Tbit\,s^{-1}}$ in the downlink and $100\,\mathrm{Mbit\,s^{-1}}$ in the uplink. Additionally, the station will support channel characterization, atmospheric research, and future experiments involving coherent optical communication at 1064 nm as well as quantum key distribution (QKD). A more detailed description of the OGS can be found in [7].

2.2.2 Full Motion Tracking Antenna

The 4.0 m full motion tracking antenna used in the User Ground Segment is designed for versatile satellite communication applications. The system features a 4.0 m diameter, 19-piece carbon fiber reflector with Gregorian optics, mounted on an X-Y pedestal configuration. To ensure an unobstructed 360° field of view and to support elevation angles down to a minimum of 5°, the antenna is installed on an elevated platform (see Fig. 4(a)). A key



(a) Full motion tracking antenna for user traffic.

(b) Transportable 1.6 m full motion tracking terminal.

Fig. 4 User ground segment equipment: Full Motion Antenna (left) and Transportable Full Motion Tracking Terminal (right).

element of the system is its 12-port feed assembly, which provides high operational flexibility. It includes four X-band ports for Fixed Satellite Services (FSS), two X-band ports for Earth Exploration-Satellite Service (EESS) to downlink experimental data from *Athene 1*, and four Ka-band ports for both uplink and downlink communication, supporting not only the SeRANIS mission but also FSS and military Ka-band applications. Additionally, two Ka-band ports are allocated for monopulse tracking.

2.2.3 Transportable Full Motion Tracking Terminal

The Transportable Full Motion Tracking Terminal is a dual-band system supporting both X-band and Ka-band operations through interchangeable feed systems, amplifiers, and low-noise block-downconverters (LNBs). Designed for rapid deployment and high performance, the antenna features a 1.6 m segmented carbon fiber composite reflector, consisting of nine sections, and a high-speed X-Y pedestal capable of tracking rates up to $15\,^{\circ}\,\mathrm{s}^{-1}$. The antenna can be fully assembled in less than 30 min, making it highly suitable for mobile ground segment applications (see Fig. 4(b)). It meets international standards for tracking in LEO, MEO, and GEO missions and supports continuous full-motion operation through an integrated servo system and antenna control unit (ACU).

In the context of the SeRANIS mission, the antenna serves as both a backup to the fixed 4.0 m full motion antenna and as a dedicated platform for supporting advanced Ka-band multi-beam experiments onboard *Athene 1*. These experiments will evaluate novel algorithms for satellite beam-steering and the performance of a next-generation phased array antenna. The system offers robust radio frequency (RF) performance. The antenna supports the same frequency bands as the 4.0 m system. If needed, the system can be further upgraded with other feeds for additional frequency bands, such as Ku-band, to extend its operational versatility.

2.2.4 Customized Multi-Band Tracking Antenna

The Customized Multi-Band Tracking Antenna is a compact and modular system designed for satellite command and telemetry operations in LEO. It supports autonomous tracking of multiple satellites based on a priority scheme and integrates key components—including transceiver, rotor control, and processing unit—into a single 19″ instrumentation rack. The station employs software-defined radio (SDR) technology, offering flexible, real-time reconfiguration of modulation, coding, and data rates to adapt to various mission needs. The antenna system consists of an outdoor assembly, featuring circularly polarized VHF and UHF Yagi–Uda antennas and a 2 m meshed reflector for L- and S-band, mounted on a rooftop cross-boom with heavy-duty azimuth and elevation rotators capable of all-weather operation. The structure is equipped with lightning protection and supports remote operation capabilities.

For the SeRANIS mission, this antenna has been extensively customized to support a wide range of communication links with *Athene 1*. Specifically, the antenna front ends and feeds are optimized for operation in UHF, L-band, and S-band. These links are managed by SDRs integrated into the system, enabling experimental waveform support for

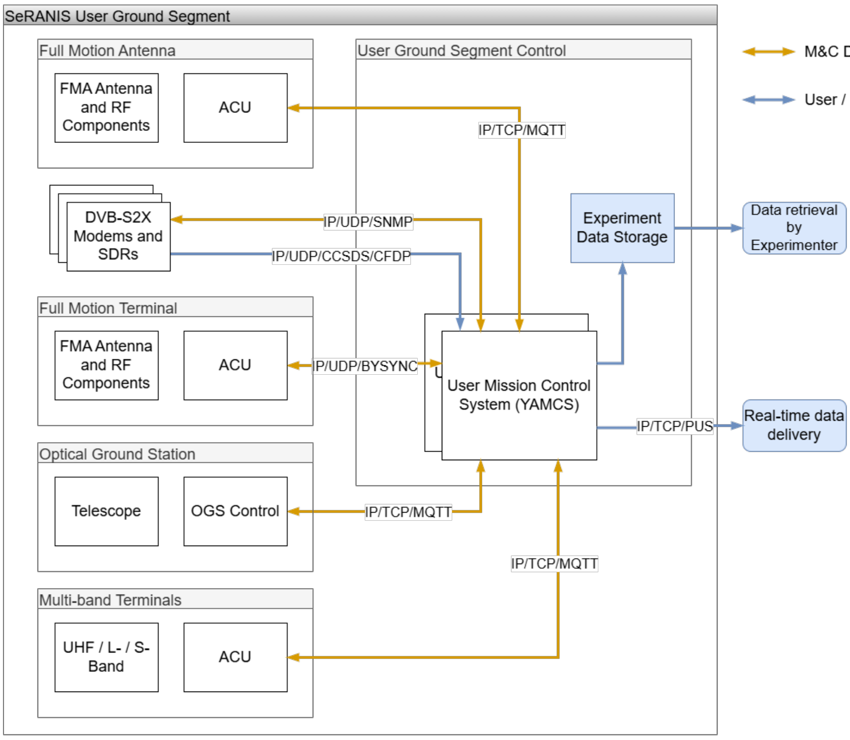


Fig. 5 Key elements for autonomous ground segment control.

flexible mission experimentation and performance validation.

2.2.5 Modems and Software Defined Radios

To support the high-throughput data requirements of the SeRANIS mission, a combination of advanced satellite modems and SDR platforms is employed. A central component is a high-performance DVB-S2(X) satellite modem, which is based on a flexible FPGA- and software-defined architecture, allowing for seamless integration into complex communication systems. The modem supports the DVB-S2X and DVB-S2 standards according to ETSI EN 302 307-2 and EN 302 307-1, respectively. It provides a wide range of modulation formats, from QPSK up to 256APSK, with symbol rates of up to 500 MSym/s and data rates reaching up to 3 Gbit s^{-1} per direction. Configurable roll-off factors include 35 %, 25 %, 20 %, 15 %, 10 %, and 5 %. Additional features typically include high linearity and spectral purity, built-in predistortion compensation, and the capability to function as a Layer 3 bridge or router with traffic shaping and quality-of-service (QoS) support.

In the SeRANIS mission, the demodulators are specifically configured to downlink experiment data over X-band using CCSDS over ETSI DVB-S2 (ETSI EN 302 307-1) and DVB-S2X (ETSI EN 302 307-2). Symbol rates of up to 200 MSym/s and peak throughputs of 600 Mbit s^{-1} per polarization must be handled, forwarded, processed, and stored by the ground segment systems. These requirements directly impact the design of data handling pipelines, as discussed in Section 4. Moreover, the modem enables direct extraction of IQ samples, which can be used for post-processing and waveform analysis in environments such as MATLAB.

For uplinking experiment data and reconfiguration files—including new images for onboard FPGAs and SDRs—Ka-band DVB-S2(X) links are used in conjunction with the modulator functionalities of the same class of modems. To complement the satellite modem infrastructure, the SeRANIS mission also employs several SDR platforms for flexible waveform generation and reception.

A key architectural feature of the ground segment is the flexible interconnection of modems and SDRs with various RF front ends and tracking antennas, including the full motion tracking antenna, the ISIS ground station, and the transportable full motion terminal. This is achieved through the use of RF switch matrices, which allow dynamic routing of transmit and receive paths according to mission demands.

2.2.6 User Ground Control System

The User Ground Segment Control System of the SeRANIS mission (see Fig. 5) is composed of two main components: the hardware infrastructure and the software platform based on YAMCS. The hardware architecture is designed to meet the demanding data handling requirements associated with high-throughput satellite downlinks and is implemented in a cold-redundant configuration using two identical servers for operational reliability.

The hardware specification is derived from the expected data rates and volumes generated by *Athene 1*. The system must support a peak over-the-air data rate of 700 Mbit s^{-1}. Accounting for protocol overheads (UDP, IP, Ethernet), each modem is estimated to generate a data stream of approximately 850 Mbit s^{-1}. With two parallel data streams (one per polarization), the total peak data rate may reach up to 1700 Mbit s^{-1}. A typical communication window of 8 min yields a total data volume of roughly 55 GB per pass. Considering up to four passes per day [6], this results in a daily data volume of approximately 220 GB. For long-term storage, the system employs a rolling data retention scheme with a capacity of 15 TB, sufficient for 60 days of operation. After this period, the oldest data is overwritten under the assumption that it has been successfully fetched by the respective experimenters.

To meet these requirements, each server is configured with a high-performance network interface controller featuring four 10 Gbit SFP+ ports. For data storage, an NVMe RAID system is utilized, comprising 8 PCIe 4.0 lanes with dual M.2 SSDs, achieving writing speeds of more than 5000 MB s^{-1}, sufficiently high to be not the bottleneck in the data handling system.

The software infrastructure is based on a Linux operating system and the open-source mission control system YAMCS. Further configuration details of the software stack and its integration with the ground segment are discussed in Section 4.

3. Comparison of Ground Operations and Scheduling Software

Efficient mission operations and scheduling software are essential for the autonomous control and operation of ground segments, particularly in small satellite missions. According to the NASA State-of-the-Art Small Spacecraft Technology Report (2024), several software solutions currently meet the highest technological readiness level (TRL 9), meaning they have been fully validated through successful mission operations and are widely available for implementation [1].

Table 1 Comparison of Ground Operations and Scheduling Software

Software Name and Vendor	Pros	Cons
COSMOS (OpenC3)	• Open-source • Adaptable and customizable • Community-supported improvements	• Requires specialized in-house expertise • Challenging for resource-limited missions
Galaxy (The Hammers Company)	• Robust command & telemetry management • Proven reliability since 2000 • Mature, stable performance	• Proprietary licensing • High operational costs • Limited flexibility
Orbit Logic Family of Products (Orbit Logic)	• Comprehensive mission planning • Optimized for complex scheduling scenarios • Suitable for precise mission requirements	• Proprietary solution • High costs • Reduced flexibility for autonomous missions
YAMCS (Space Applications Services)	• Open-source with high flexibility • Proven real-world deployment (e.g., ICE Cubes) • Modular and adaptable architecture • Cost-effective, community-driven	• Requires initial setup and customization

COSMOS (OpenC3) is a prominent open-source command and control platform designed for use throughout all phases of testing and operations [8]. Its open-source nature enables users to adapt and expand capabilities freely, fostering collaborative improvement and customization. However, the necessity for specialized in-house expertise to maintain and modify the system can pose challenges for resource-limited missions.

Galaxy, developed by The Hammers Company, is a longstanding proprietary solution available since 2000 [9]. Galaxy provides robust command and telemetry management and has a proven track record of reliability.

While mature and dependable, its proprietary licensing structure limits flexibility and increases operational costs, potentially disadvantaging research and academic missions with constrained budgets.

Orbit Logic provides a comprehensive family of mission planning and scheduling products applicable to aerial and satellite imaging applications [10]. Orbit Logic's products excel in complex mission planning scenarios, particularly beneficial for missions requiring precise scheduling and optimization. Nevertheless, the proprietary nature of Orbit Logic's software similarly imposes cost and flexibility constraints, making it less favorable for autonomous, cost-sensitive small satellite ground operations.

YAMCS, developed by Space Applications Services, is an open-source mission control system (mission control system (MCS)) originally designed in 2007 to extend the European Space Agency's standard MCS for supporting the operations of the Columbus module on the International Space Station (ISS) [4]. It has since evolved into a versatile software suite suitable for a wide range of aerospace applications. YAMCS supports real-time telemetry processing, commanding, and archiving, and is particularly well-suited for payload operations. It also provides message-based middleware, archiving, and flexible display functionality.

The software has continuously evolved, incorporating new features such as the The Yamcs Notification Add-on (TYNA) notification service [11], which significantly reduces on-console service hours and supports the objective of autonomous operations. YAMCS enables parallel execution of multiple operations, and its built-in archiving and display tools enhance situational awareness and mission control capabilities.

It has been successfully deployed in commercial environments such as the ICE Cubes Control Centre, where it demonstrates lean operations and adaptability through tailored configurations [5]. Today, YAMCS is widely used as a mission control software solution across scientific and commercial applications. As an open-source platform, YAMCS offers substantial flexibility, allowing users to autonomously manage ground segment equipment, customize mission functionalities, and integrate with diverse hardware configurations. Its modular architecture, as described in the official server documentation [12], enables scalable deployment to meet varying mission requirements.

Considering the aforementioned software solutions, the selection of an open-source product is highly advantageous for small satellite missions due to cost-effectiveness, adaptability, and community-driven support. Among the reviewed options, YAMCS stands out, offering the optimal balance of maturity, adaptability, and proven real-world application. Consequently, we employ YAMCS as the primary software solution for operating the user ground segment in the SeRANIS mission.

4. Ground Segment Control and User Data Handling

4.1 System Overview

4.1.1 Data Handling

YAMCS employs a packet preprocessor to detect errors in received packets and to extract essential information for subsequent processing steps. It supports a variety of widely used telemetry frame processing protocols established by major space agencies, including the Packet Utilization Standard (Packet Utilization Standard (PUS)) from European Space Agency (ESA), core Flight System (cFS) from National Aeronautics and Space Administration (NASA), and CubeSat Space Protocol (CSP). This aligns with the objectives of the SeRANIS mission, which aims to foster collaboration with other research institutions and serve as an open research platform within the space community.

Additionally, YAMCS leverages a modular framework based on streams and processors to decouple and manage the data flow. Streams carry tuples of data, enabling users to manipulate and transform information as it moves between components. This architecture provides high flexibility, facilitating dynamic changes in data formats and enabling the routing of commands to various processors as needed [12].

4.1.2 User Interface and Integration

YAMCS features a web-based graphical user interface (GUI) that enables operators to interactively visualize telemetry data and issue control commands. The software is compatible with a variety of development and visualization tools, including Open Mission Control Technologies (OpenMCT) and Grafana, allowing users to design mission-specific displays and dashboards. For the SeRANIS mission, custom telemetry displays are developed using the built-in YAMCS Studio and subsequently uploaded to the display section of the YAMCS server. This enhances data visualization capabilities beyond raw telemetry, enabling enriched representation and manipulation of mission data.

Moreover, the system is extended for SeRANIS with a custom YAMCS plugin that defines an additional server route. This feature supports the visualization of satellite position and projected orbital trajectory over the coming hours via an interactive map interface. This integration further improves situational awareness and operator efficiency during mission operations.

4.2 Integration of SNMP and ACU for Monitoring and Control

A key strength of YAMCS lies in its high degree of customizability, allowing users to define mission-specific functionality through user-defined services. These services enable the integration of unique telemetry and command processing routines tailored to heterogeneous systems. In the SeRANIS ground segment, multiple antennas and related subsystems employ different protocols for monitoring and control. However, not all of these protocols are natively supported by YAMCS. Therefore, custom telemetry and command processors must be implemented for each device, as illustrated in Fig. 6.

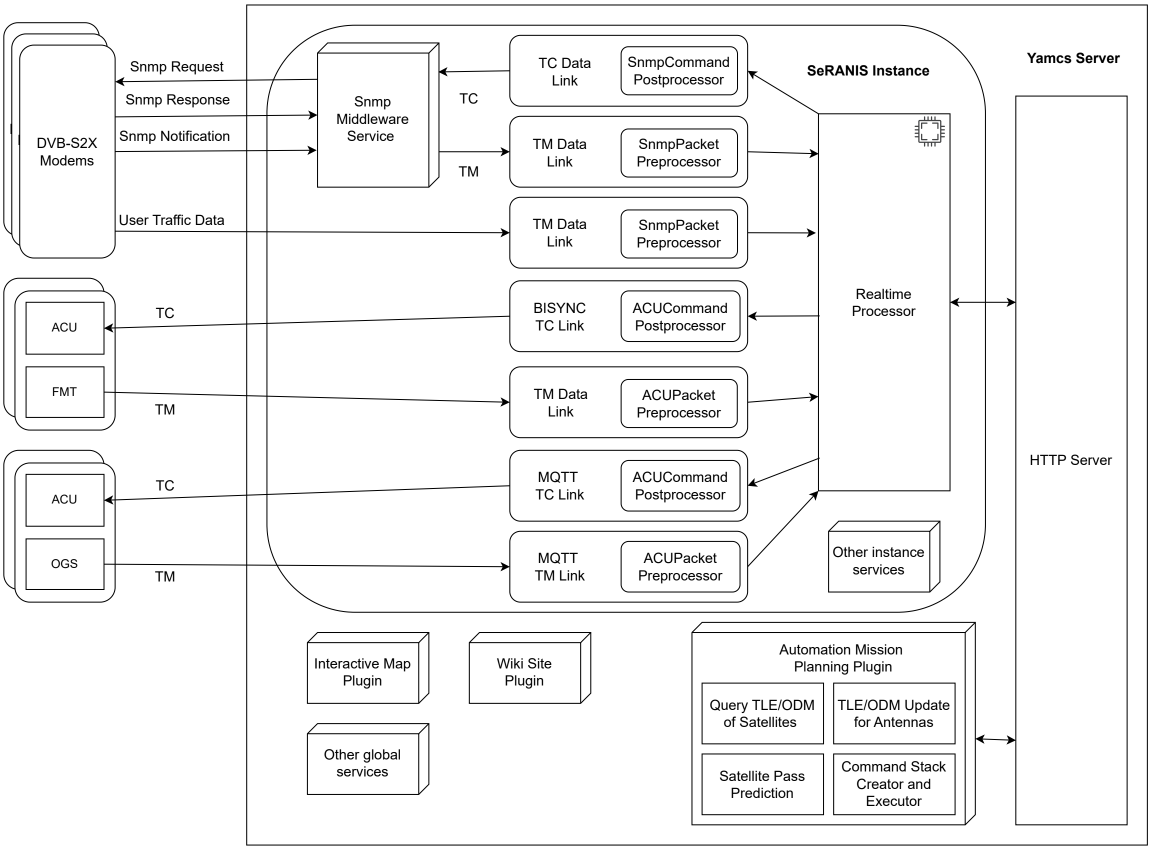


Fig. 6 Customized YAMCS architecture for SeRANIS mission.

For example, Simple Network Management Protocol (SNMP) is used in SeRANIS to communicate with the Digital Video Broadcasting (DVB)-S2X modems. To support this, a custom SNMP middleware service has been developed and integrated into the YAMCS instance. This middleware converts YAMCS telecommands into SNMP requests and processes SNMP agent responses into YAMCS-compatible telemetry. Commands are issued via the web-based interface and passed through the HTTP server to the real-time processor. Defined using XML Telemetric and Command Exchange (XTCE) format, each command includes the SNMP object identifier (OID), variable type, and associated value. The command is then routed to the SNMP middleware service through an internal server port.

Depending on the request type, the appropriate handler within the middleware processes the command, converting it into an SNMP request directed to the relevant SNMP agent on the target modem. If a valid response is received, the middleware immediately acknowledges the telecommand and formats the returned parameter values into XTCE-compliant telemetry. In case of errors (e.g., invalid parameters or connectivity loss), no telemetry is returned; instead, an error event with detailed diagnostics is raised for easier troubleshooting.

Beyond setting and querying RF parameters, the modem state is monitored using regular SNMP `GETBULK` operations. Monitoring parameters are, for example, the temperatures of the CPU, modulator, and demodulator boards that can be sampled every second with an accuracy of 1 °C. Continuous temperature monitoring ensures that thermal thresholds are not exceeded during prolonged operation. In addition, SNMP-based alerts and traps can be visualized as events within the YAMCS server.

On another front, the ACU used for the Transportable Full Motion Terminal employs a protocol derived from IBM's binary synchronous communications protocol (BISYNC). In this setup, the ACU acts as a slave device managed by a master station, with individual units identified via unique addresses. To enable remote control over Ethernet, the YAMCS telecommand data link was modified to support User Datagram Protocol (UDP)-based communication. For the OGS, command and control are achieved via the MQ Telemetry Transport (MQTT) protocol. Notably, YAMCS provides a dedicated plugin for MQTT, facilitating seamless integration of MQTT-compliant devices into the mission control infrastructure.

4.3 User Traffic Data Handling

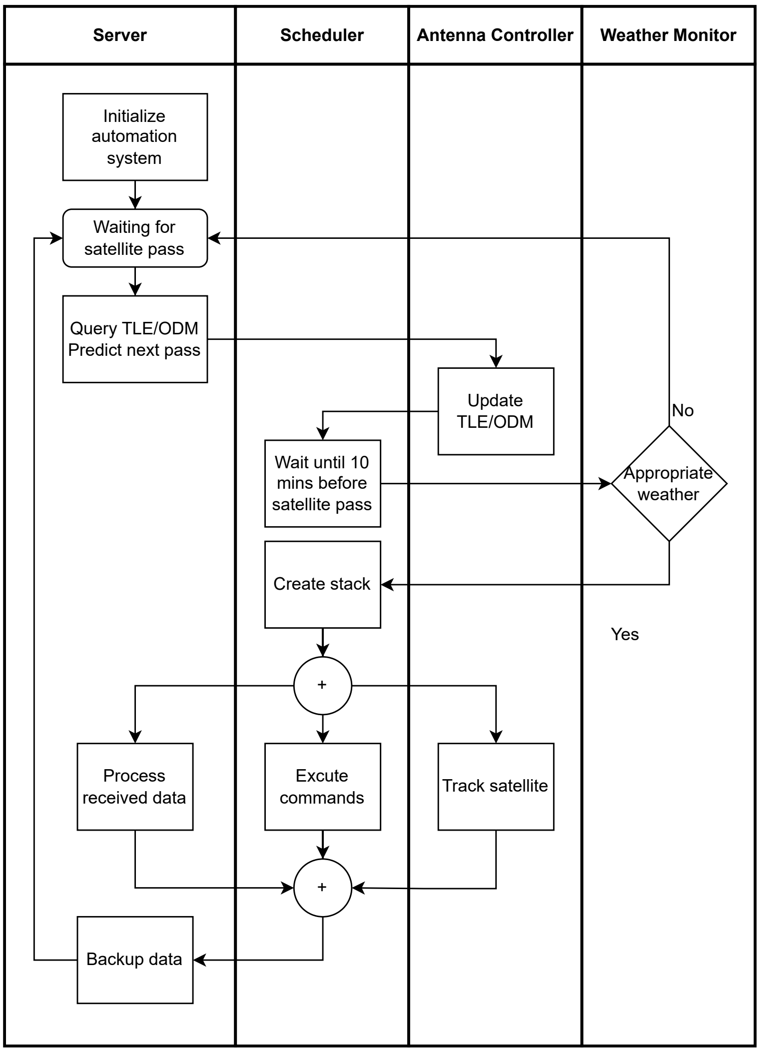


Fig. 7 Mission automation in each satellite pass.

In the SeRANIS mission, user traffic data from the spacecraft is transmitted using the CCSDS File Delivery Protocol (CFDP) protocol, encapsulated within Consultative Committee for Space Data Systems (CCSDS) TM frames. Notably, the CCSDS packet layer is omitted in this context, as it does not offer additional utility for payload data transfer. This decision aligns with the SeRANIS mission design, where payload applications do not utilize standard CCSDS packetization for scientific data. Instead, the payloads on *Athene 1* employ the Trivial File Transfer Protocol (TFTP) protocol to transfer data files to the onboard storage system. Each CFDP packet includes a source entity ID that uniquely identifies the originating experiment. This identifier is structured from a combination of the onboard storage device ID, Ethernet link ID, and the experiment ID.

On the ground, YAMCS is configured with a UDP data stream—specifically, the `UdpTmDataLink`—to ingest incoming CCSDS TM frames. YAMCS extracts the embedded CFDP packets from these frames and forwards them to a real-time processor. These packets are then handled by the CFDP service in YAMCS, which organizes them into logical storage units referred to as "buckets". Each bucket corresponds to a remote directory on an File Transfer Protocol (FTP) server and is uniquely assigned to a specific experiment, enabling efficient and modular data management.

An exception to this standard CFDP-based file transfer mechanism is the Onboard Close Range Rendezvous Simulation (ORenS) experiment, which requires real-time streaming of its scientific data. This experiment, conducted by GSOC, aims to evaluate operational concepts for close-range rendezvous in on-orbit servicing missions. The experiment is conducted by recreating a real-time operational environment in GSOC, where images are generated on board and received via TM during a contact with the satellite. The operational team then executes simulated maneuvers in real-time via a real communication link, allowing a more comprehensive evaluation of risks and limitations than a pure simulation. To accommodate this, the user data payload within CFDP packets is extracted and forwarded over a Transmission Control Protocol (TCP) connection. This is realized through a parallel input stream that mirrors the primary CCSDS TM frame stream but utilizes a custom preprocessor. The preprocessor inspects each incoming packet's source entity ID, and if it matches the ORenS experiment ID, the payload is routed directly to a TCP server for real-time analysis.

This hybrid approach of combining file-based and real-time data handling ensures the ground segment can meet the diverse operational requirements of both bulk scientific data collection and low-latency experimental data streams.

4.4 Automation Mission Planning Plugin

Mission automation is a core design objective of the SeRANIS ground segment, as the ground system is tasked with maintaining consistent connectivity to the *Athene 1* satellite, which completes multiple orbital passes per day. To streamline operational workflows and reduce manual intervention, an automated mission planning plugin has been developed and integrated into the system.

This automation plugin provides a suite of functionalities essential for mission execution:

- Retrieval of two-line element set (TLE) and orbital data message (ODM) data from the GSOC, or other publicly available internet platforms, like, e.g., Space-Track.org,
- Prediction of upcoming satellite passes based on orbital elements using Simplified General Perturbations (SGP) models,
- Automated updating of TLE and ODM information for antenna systems,
- Monitoring of local weather conditions to assess tracking feasibility,
- Generation and execution of command stacks for user ground segment components associated with satellite passes.

These functionalities work in coordination to facilitate the autonomous planning and execution of satellite contacts. The entire automation process is illustrated in the swim-lane diagram shown in Fig. 7, which details the decision-making flow during each satellite pass.

The automation plugin supports the broader goals of the SeRANIS project by enabling lean operations, minimizing the need for human-in-the-loop decision making, and improving responsiveness to dynamic mission conditions. Similar mission planning and automation frameworks have been shown to enhance ground station efficiency and scalability in other small satellite missions [13].

5. Conclusion

This paper presented the design and implementation of an autonomous ground segment for the small satellite mission Seamless Radio Access Network for Internet of Space (SeRANIS). By integrating advanced tracking antennas, a flexible software-defined radio infrastructure, and the open-source Yet Another Mission Control System (YAMCS) mission control system, the user ground segment achieves a high level of automation with minimal human intervention. The developed architecture supports a wide range of communication links and enables robust data handling capabilities, including real-time and file-based user traffic processing. The custom integration of heterogeneous subsystems and the implementation of a mission automation plugin further enhance the system's responsiveness, scalability, and operational efficiency. Future work will focus on expanding autonomous features, improving fault detection and recovery mechanisms, and integrating additional communication standards to support evolving mission requirements.

Acknowledgements

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