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DEVELOPING A COMPONENT BASED GROUND SEGMENT FOR END-TO-END AUTOMATION OF OPERATIONS FOR CONSTELLATIONS AND SMALLSATS

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Abstract

The increasing number of commercial small missions and constellations has led to a focus on reducing ground segment operations cost and technical barriers for new space operators. In response, Starion has developed Astral, a ground segment solution tailored to meet the evolving needs of both commercial and institutional markets, providing an integrated environment for the different systems and components of a satellite ground segment.

Starion's objective is to ensure that end-to-end support from preparation to operations can be achieved with the same toolset. Astral has been designed from Starion's experience in supporting our customers in operations and uses a combination of both established and state-of-the-art technologies. ASTRAL's design objectives are:

- Operations focused including heritage and experience in preparation activities and tools
- Modular design, with interfaces to other tools/systems
- Designed for SmallSats to constellations
- Rapid to configure and deploy.
- Low-cost to operate and maintain.
- Cloud-ready with web-based Interfaces
- Inclusion of optional support for analytics and AI.
- Standards-based:
  - CCSDS TM/TC.
  - SCOS-MIB, EGS-CC CDM TM/TC database
  - Extensible to support other standards/ customer specific needs.
- Support for ground stations as a service.

The development of such complex system implies facing a series of challenges and requirements resulting from the agile aspect of the supported missions, the high need for automation, support for new standards and operational concepts (e.g. File-Based Operations) and the specific requirements resulting from each spacecraft's on-board software design. However, the complexity increases even further when the same solution has to also be able to cope with the needs for fleets and constellations. This means addressing also scalability of the design, secure distributed deployment and a change of paradigm in the way the spacecraft are operated and the operational information is processed and displayed to the users.

All these topics will be explained in the paper including use case examples for customers such as Astroscale and Argotec . This paper will provide and a description of the capabilities, development challenges and tailoring needs of a state-of-the-art Ground Segment Software Solution, specifically focusing on current topics including :

- Modularity and flexibility to support heterogenous needs (including legacy software) and mission sizes.
- Integration and tailoring of a component-based system
- Complete end-to-end configuration and operation of the mission via a single system.
- Security by design aspects for a cloud enabled system
- Possible AI usage/integration across mission phases and domains of expertise.
- Constellation Dashboarding of the information

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Keywords: Ground Segment, Operations Automation, Constellations, Mission Planning, Automation

1. Introduction

The objective behind the development of Astral was to establish a component-based satellite ground segment solution, allowing satellite operators to have a high degree of flexibility to integrate their own or third-party components and to interface to other systems. Astral is also developed to be deployed on servers, private cloud and public cloud infrastructures.

The system has been built based on Starion's longstanding operational heritage in the development of ground segment, mission automation and operations preparation tools, integrating operationally proven components and offering a high degree of automation supporting multiple spacecraft.

2. Operations concept

Constellations and fleets of spacecraft once limited to GNSS and large telecommunications satellite operators are now being used for a very wide set of low-cost applications including high resolution optical and radar Earth Observation, LEO & MEO telecoms, RF signal monitoring, and maritime & aircraft tracking.

While current spacecraft control systems like EGS-CC have been designed to be scalable to meet these challenges, they don't provide the situation awareness necessary for operators of constellations/fleets and complex networks of ground stations. Ways also need to be found to ensure the configuration and deployment meet the simplicity and low costs needed for cubesat and smallsat operators. A new approach is therefore required to meet the specific needs of operations of cubesat, smallsats, and constellations. As well as low-cost, high levels of automation, and speed and ease of deployment, for constellations, it will specifically need to address:

- Management of the constellation/fleet to provide continuity of service (e.g. in-orbit spares, over provision of operational in-orbit satellites).
- The Concept of Operations (CON-OPS) to operate the constellation/fleet as a system delivering a service rather than a set of individual spacecrafts.
- New CON-OPS for individual spacecraft e.g. Fail-Safe where the spacecraft goes into a "safe mode" until operators can investigate a problem vs. Fail-Operational, where the spacecraft remains operational after a failure e.g. switches to a redundant chain or operates in a degraded mode.
- Layered automation – e.g. constellation planning & re-planning, constellation orchestration (i.e. scheduling at constellation level), spacecraft automation (from ground and onboard), ground station and ground facility automation.
- Efficient use of ground segment resources (e.g. people, ground stations, compute and wide area network resources) through automation, effective use of cloud resources, use of ground stations as a service etc.

Astral is designed to offer these capabilities using an "as a service" approach, the aim being to make constellation operations more easily accessible, reliable and affordable, supported by a 'systems of systems'.

3. System Overview

Astral consists of various components, each supporting different ground segment elements. Each element can also be replaced by customer-provided or third-party components, depending on the specific needs and constraints of the mission

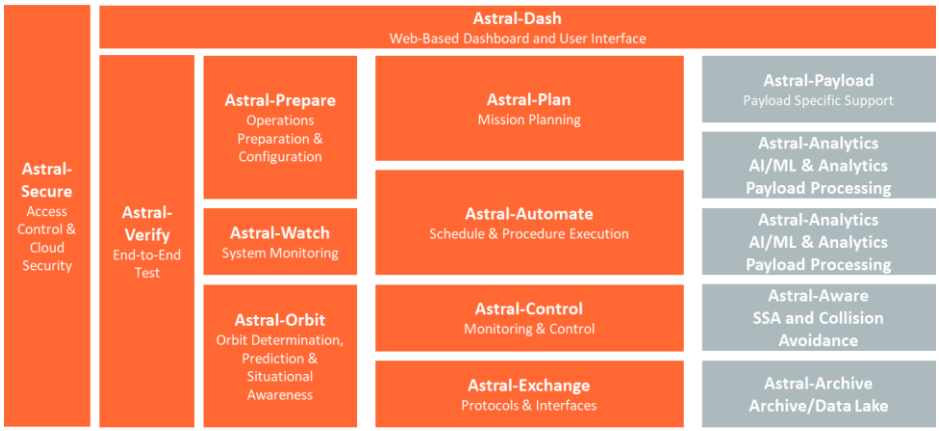

Fig. 1. Overview of Astral components. Core components are shown in orange. Grey components tend to be mission specific and are not included as standard.

The Astral architecture is built with a series of key design objectives to ensure an open, secure and scalable solution:

- Open Architecture – The system is designed to easily transition from operating existing satellites to supporting future missions and heterogeneous spacecraft. This is achieved by allowing the individual adaptation of each component to the needs of the mission.
- Multi-Mission support built in from the ground up; each mission can be supported by single or multiple instances of Astral-Control and other components. Open-APIs to connect to the underlying MCS, architecture fully supports a completely spacecraft agnostic approach.
- Security by design – Constellation and mission instance isolation results in clear separation of data and services, increasing overall resilience and availability. This approach ensures resilience required for the current constellations.
- Orchestration and Automation – Ensures consistency of data across the mission instances through efficient database management, while supporting true lights-out operations driven from Astral-Plan and Astral-Automate reducing the need for an operator in the loop.
- Common Interfaces and Open APIs – Modern interfaces that support Open APIs, allowing new missions and best in class products to be augmented into the operations interfaces, this results in a familiar toolset for the operators, maximizing efficiencies for operating hundreds of satellites.
- Ground Station Interface – Flexibility to cope with different ground station providers.

One of the key design decisions was to use existing components as far as possible. This allowed the development team to focus efforts on the integration and improvement of the individual subsystems. It also brough in a large level of background, experience and flight heritage to expand on.

3.1. System Components

The modules within the Astral suite include:

Astral-Dash – provides a high-level, browser-based view of the overall spacecraft and ground segment status and can be closely linked to each operator's concept of operations. Typical dashboard displays can include:

- fleet constellation status;
- individual spacecraft and ground station status (e.g. red/green);
- next spacecraft pass over a ground station;

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- status of ground segment elements;
- current executing timelines
- it can also include 3D views of the spacecraft orbit/attitude.

At the heart of the system is a customizable dashboard that serves as the primary interface for monitoring a fleet or constellation level. It compiles data from multiple MCSs / MPSs and additional ground segment elements. The dashboard displays metrics or indicators derived from collected data based on user-defined parameters. These metrics are then accessible directly from the dashboard interface. The Astral-Dash component powers the dashboard's web user interface, presenting an overarching view of a system of systems (e.g. a fleet) status and allowing users to create tailored displays for their payloads. The dashboard's capabilities may be expanded to include automation, planning, scheduling, and flight dynamics data. The front-end architecture is built on modular components that seamlessly connect to REST-based services.

In operational scenarios, real-time data from various sources, including Control, Automate, Orbit, Plan and inputs from operators or ground stations, will be collated. This data, encompassing logs, telemetry, and health metrics, will be processed and presented to users in their preferred format.

The primary use cases addressed by Astral-Dash are:

- Fleet Operations involve the support, monitoring, and control of two or more spacecraft operated as a fleet, yet functioning largely independently.
- Constellation Operations entail the support, monitoring, and control of two or more spacecraft that share a common mission and are operated as a unified system to provide a service.

Fig. 2 Astral-Dash

Astral-Prepare – provides an environment to prepare spacecraft operations procedures and to validate them against the spacecraft database. Validated operations procedures, whether manual, semi-automated or automated, are essential for safe, reliable operations of both space and ground segments.

Procedures are authored in flowchart and script editors. The flowchart is synchronised with the scripting editors, so changes made in one are immediately reflected in the other.

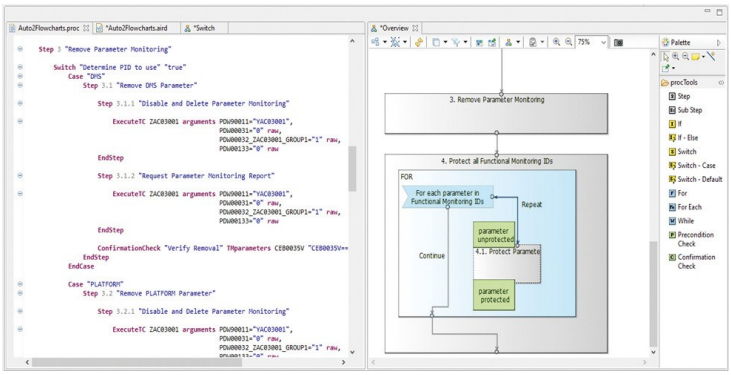

Fig. 3. Astral-Prepare

Astral-Prepare supports authoring of manual and automated spacecraft and ground procedures and consistency checking of telemetry (TM) and telecommands (TC) with the spacecraft database. It also supports the validation and publishing of procedures to a flight operations manual and the spacecraft database management functions.

The script editor is based on a formalised data model which also drives the flowchart. Each presentation is therefore a view of the same procedure data. The script editor dynamically checks the script against the spacecraft database and provides lookups and prompts, as well as standard language syntax checks. The flowchart editor is good for overall procedure structural design and visualisation, while the script editor is good for implementing the details of procedure steps.

Astral-Prepare supports multiple users and uses a shared central data repository providing version control and ensuring a procedure is only edited by one person at a time. It supports multiple spacecraft within a mission (constellation missions) and multiple missions on the same server (installation).

Astral-Orbit – is an integration of GMAT, a third-party flight dynamics package supporting the automation process. GMAT provides a low-cost capability suitable for many missions supporting Orbit determination, prediction, and visualisation. It can be used to propagate the orbits and produce event files which are then used by Astral Plan e.g. to consider eclipse events and pass information for specific Ground Stations. Third-party packages can be used instead, according to the client's preferences and needs.

Fig. 4. Astral-Orbit

Astral-Plan – is a mission planning system enabling constraint-based planning for platform and payload operations. It supports planning of multiple spacecraft operations and multiple domains, allowing each spacecraft to have different payload and resource constraints. Because Astral-Plan is integrated with other Astral components, it will be aware of available spacecraft operations procedures and spacecraft commands.

The Mission Planning System supports constraint-based planning for platform and payload operations. This includes the following:

- The import of orbital events, ground station passes and instrument operations requests (from a file)
- Import of the spacecraft database and operations procedure definitions (form Astral-Prepare)
- Spacecraft resource modelling (e.g. electrical power generation & storage, fuel, onboard data storage, thermal) that can be consumed and replenished (where applicable)
- Adding and editing activities in the schedule (as procedures or commands). These can be planned according to an event, another procedure completing or at a specific time.
- The generation of a constraint-free schedule of activities for ground-based execution and/or uplink to the spacecraft.

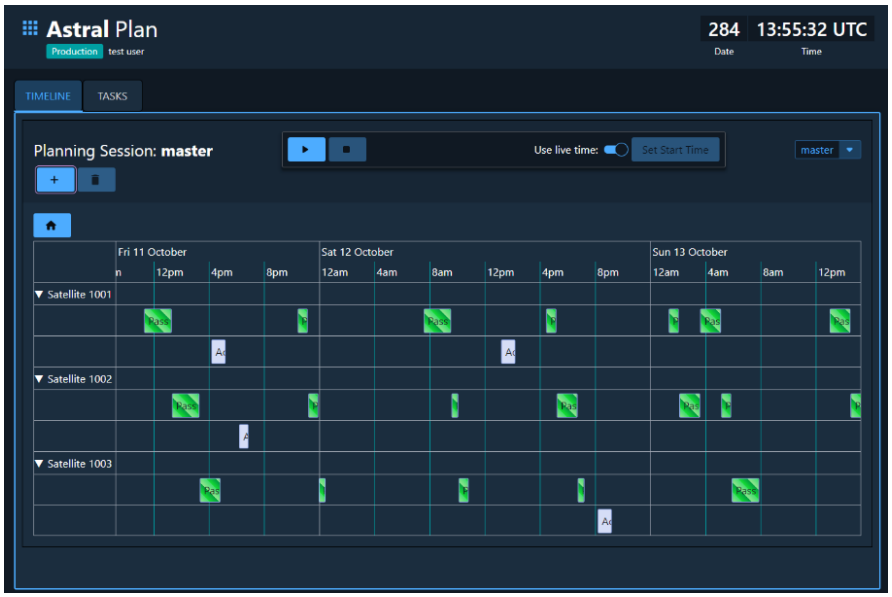

Fig. 5. Astral-Plan

Astral-Automate – supports the execution of the schedule generated from Astral-Plan or another planning tool. It is typically used by operators as the primary view to monitor progress, only using the mission control system to look at parameter values or send manual commands. It additionally supports the automated execution and debugging of procedures developed by Astral-Prepare. It interfaces to the systems being automated (such as the mission control software) and allows you to step through a procedure to understand what is happening, and debugs accordingly. This interface has been implemented to support different MCS components with the following systems being currently supported:

- REST API (used for EGS-CC)
- EXIF (used for SCOS)
- MQTT (other external systems like CCS5)

Once validated, procedures are typically initiated from a schedule, but individual or multiple procedures can also be executed and controlled from the user interface.

As well as sending TCs and monitoring the spacecraft TM, procedures can be used to automate ground segment activities, such as ground station passes.

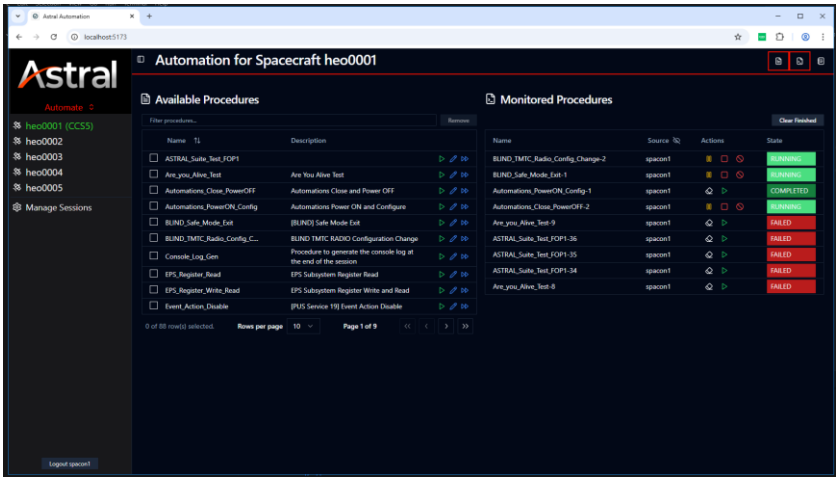

Fig. 6. Astral Automate

Astral-Control – is designed to be agnostic with respect to the mission control system kernel. Current deployments support both the European Ground System – Common Core (EGSCC) and the Satellite Control and Operation System 2000 (SCOS-2000) because Starion has expertise in configuring, adapting and deploying these mission control systems.

The main functions of ASTRAL control are:

- Core monitoring and control independent of specific interfaces and protocols
- Processing of monitoring information once decoded from transfer containers and defined in terms of standard data types
- Processing of control actions independent of specific interfaces and protocols
- Management of monitoring and control data definitions
- Archiving of monitoring and control information
- Automation (procedures and scripts)
- Data access, distribution, and archiving services for source and processed M&C data
- General infrastructure, application support and runtime management
- Support for external systems via a service integration platform.
- Web UIs to operate the spacecraft.

Astral-Watch – This component provides system monitoring and control, including local security monitoring. It monitors the entire Astral deployment, collects logs and supports alerting and post-event analysis.

Astral-Verify – Often an operations simulator or flatsat is not available until rather late in the timeline of a ground segment development. Astral-Verify, configured using the spacecraft database, solves this problem, enabling early testing and end-to-end testing of the monitoring and control chain by simulating the reception of telecommands and generation of simple telemetry.

Astral-Secure – Astral employs role-based access control (RBAC) and reverse proxy technology to protect its components from unauthorised access when deployed in a cloud.

Depending on the level of security required by the mission and the infrastructure already in place, a number of security options can be implemented and are supported external to the core Astral components.

- SSH has been used to provide Public Key Authentication for the different ground terminals preventing the repetitive use of a password but also enabling a secure connection.
- Network configuration has been used between different ground stations allowing only machines of known name and IP Address to communicate between terminals.
- VPN Tunnels have been used to ensure the direct connection between Ground Station and Ground Terminal or Ground Station and external data providers is secure. Different VPN configuration can be used to define the encryption level and the end point restrictions between the devices.
- Data Diodes or Unidirectional Gateways can be considered to create a demilitarised zone or distinct separation within the physical or virtual environment. The use of Hardware Enforced Security devices will depend on the security requirements of the project, the defined boundaries and the classification within the different networks.

Astral-Aware - Drawing on its extensive mission operations experience with SPICE, Starion has created a solution for Space Situation Awareness that can handle hundreds of thousands of bodies concurrently and perform geometry computations, strengthening the system's capability to manage complex spatial data and operations. The solution provides a robust and accurate orbit prediction model, crucial for collision risk assessment. The integration of AI/ML algorithm also reduces uncertainty in predicting satellite trajectories and improves decision-making processes for collision avoidance manoeuvres. It also incorporates flexible optimization of collision avoidance strategies and risk mitigation techniques, based on manoeuvring for collision, which are vital for satellite operators to ensure the safety and longevity of space assets. Further information can be found in [1].

4. High Level architecture

The high-level architecture of the system when fully deployed is shown in the following diagram. Astral has been deployed in private cloud environments (VMWare) and public clouds (AWS). It is not tied to a specific cloud infrastructure. Containerization allows for the use of Kubernetes (or similar container orchestration systems) to deliver scalability in the cloud environments. This facilitates a multi-mission, multi-tenant deployments.

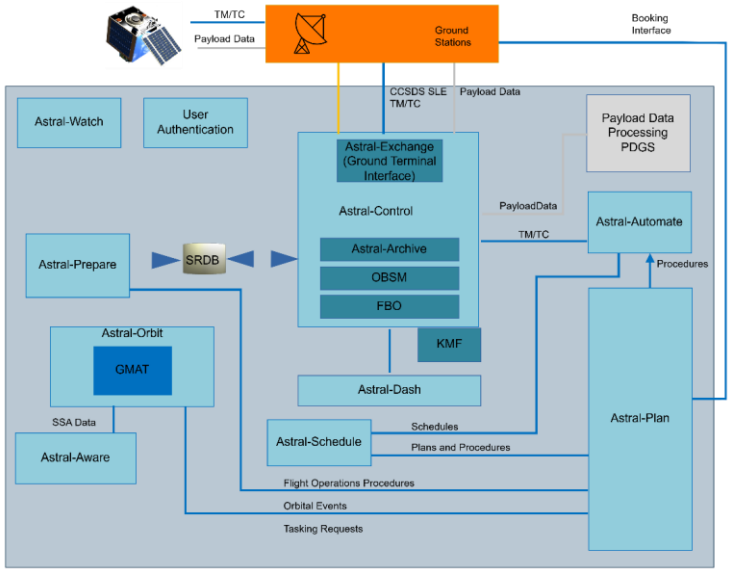

Fig. 7. Astral high level architecture

5. Concept of Operations

Astral's concept of operations is intended to support the satellite monitoring and control of a heterogeneous constellation of satellites using different TM/TC exchange formats by using multi-mission elements as far as possible and spacecraft-specific elements limited to the direct interactions with the spacecraft.

The solution is based on multi-domain functions supporting automated, semi-automated and manual operations (please see **Error! Reference source not found.**, below).

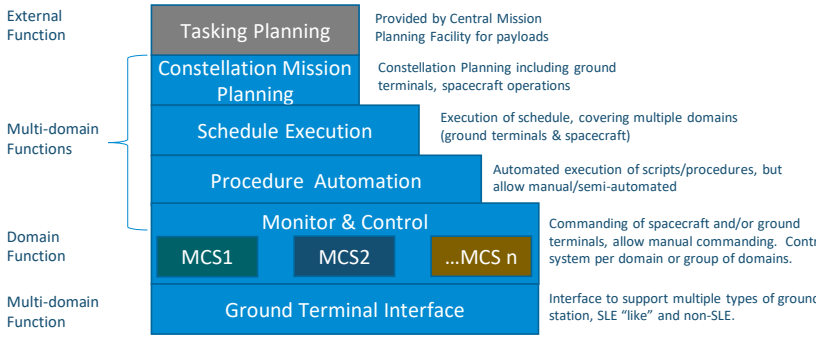

Fig. 8. Layered Constellation Automation

Astral-Dash provides a constellation wide dashboard showing the overall status of each domain based on pre-defined KPIs, with the ability for the operator to drill down or filter to view only the domain(s) they wish to see. Astral-Schedule provides the overall view of the constellation scheduled activities being executed (these can be automated or semi-automated/manual for critical or contingency operations). The schedule can be viewed as a whole, by domain or groups of domains. Astral-Automate supports the automated or semi-automated (operator-in-the-loop) execution of operations procedures or scripts. Finally, Astral-Control provides detailed displays for spacecraft commanding and telemetry. This provides a consistent operations interface across all the domains, while supporting concurrent operations across multiple domains. A single operator can get an overview of the whole constellation or multiple operators can each view the domains that concern them, allowing operators to work concurrently.

If a third-party mission control system (other than Astral-Control) needs to be integrated (e.g. from an existing spacecraft), the Astral-Dash, Schedule and Automate Layers can remain, with only the operator interface being different at the lowest level, provided the third-party system supports a suitable automation interface (e.g. REST, or a messaging protocol). Since the Astral-Control user interface (UI) supports a REST API, it may be possible to supplement the user interface of the third-party control system with displays based on Astral-Control user interface. However, this would need further investigation on a case-by-case basis.

6. Integration of AI/ML applications

Astral-Analytics is provided as a tailored component that can be adapted to the specific needs of the missions. It consists in the integration of the AInabler Machine Learning Platform developed by Starion for ESA [2]. This provides a data platform, which enables its users to build, train, and deploy machine learning models accessing the information form the various Astral components. I can also be used for other types of data science and engineering developments, outside of the scope of artificial intelligence. Applications can run on top of it to support the operators including a chat-like assistant, tools for anomaly investigations or incident analysis.

7. Astral Use Case examples

Astral is used operationally in various missions showing its capability to be adapted to different use cases and operational scenarios.

Argotec's HEO constellation mission is using the Astral-Prepare, - Plan and – Automate components to support its upcoming smallsat EO constellations of up to 40 satellites. Starion has integrated Astral with the existing MCS to provide adaptations for constellation and to support fully automated operations. Additionally, Starion's team provides cybersecurity engineering for the mission.

Starion has also provided the full Ground segment for the Astroscale missions, Elsa-d, Adras-j and the upcoming Elsa-m, with the first 2 missions having flown successfully. In this case the ASTRAL-control component was based on SCOS2000,m extended to support File Based Operations through a Starion-developed extension. Thes mission have also flown with automated operations through Astral-Prepare, -Plan and -Control and using -Exchange to connect to the Ground stations

8. Summary

Astral provides a component-based solution allowing the use of the default Astral-provided components, or the integration of third-party products and systems. This provides greater flexibility, allowing the use of the best components to meet the operator's needs to operate single spacecraft or multiple spacecraft.

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