# Evolution of Multi-Mission Nanosatellite Ground Segment Operations

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**The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) has been a pioneer in nanosatellite technologies since the first 1-kg "CubeSat" nanosatellites were conceived and designed. Since the launch of its first nanosatellite in 2003, SFL has launched three more nanosatellites, ranging in size from 3 to 7 kg and spanning different generations of technology. At least ten more nanosatellite missions will be launched by SFL over the next several years.**

**Each generation of nanosatellite platform technology has not only redefined the state of the art in terms of technological maturity and performance, but also in the aggressiveness, timeliness, and operational relevance of the missions that are undertaken. This advance in technologies is now opening up new applications that were previously not feasible or required substantially larger investments.**

**Along with these platform advances must come evolution in the approaches and technologies used to support them and achieve the mission. Early nanosatellites were frequently designed around single-string ground segments, namely a single mission control facility utilizing a single co-located Earth station to operate a single nanosatellite. While this approach is a good solution for very low cost technology development and demonstration missions it does not scale reliably or cost-effectively to operationally-relevant, mixed platform, multi-mission, and cross-support contexts.**

**To address these emerging needs, SFL has leveraged its flight operations experience to implement an evolved ground segment operational concept. This paper will present SFL's current state-of-the-art in nanosatellite ground segment implementation as demonstrated practically in current and upcoming missions, including specific mission case studies. A key aspect is the implementation of a framework to handle multi-satellite, multi-station operations in a reliable, extensible, and low cost fashion.**

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## I. Introduction

IN recent years, small satellite technology has matured to the point where it can now be used to enable aggressive, timely, and relevant missions for users whose only options previously were larger, more expensive satellites, or a non-satellite solution with much greater cost or lower coverage and flexibility. The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) has been a pioneer in micro- and nanosatellite technologies for over a decade.

SFL currently operates three satellites in orbit, and supports a fourth satellite built and launched by SFL but owned and operated by the government of Norway. Additionally, a large number of satellites are currently awaiting launch or under construction, based on SFL bus designs spanning several evolving generations of technology. A summary of the mission manifest is given in Table 1. Each mission has not only redefined the state of the art in terms of technological maturity and performance, but also in the aggressiveness and import of the mission. Early nanosatellites, both from SFL and other organizations around the world, were primarily technology demonstrations. The latest small satellite missions are increasingly tackling real-world problems including space science, Earth observation, and communications.

| Mission | Country | Inception | Launch | Objective |
|---|---|---|---|---|
| **MOST**[1] | Canada | 1998 | June 30, 2003 | Space astronomy, asteroseismology, extra-solar planets |
| **CanX-1** | Canada | 2001 | June 30, 2003 | Nanosatellite programmatic pathfinder |
| **CanX-2**[2] | Canada | 2003 | April 28, 2008 | Technology demonstration, greenhouse gas spectrometry, ionospheric measurements, materials degradation, |
| **CanX-6 (NTS)**[3] | Canada | 2007 | April 28, 2008 | Space-AIS demonstration |
| **AISSat-1**[4-5] | Norway | 2007 | July 12, 2010 | Space-AIS demonstration, operational AIS observation |
| **UniBRITE**[6] | Austria | 2004 | 2012 | Space astronomy, asteroseismology |
| **BRITE-Austria**[6] | Austria | 2004 | 2012 | Space astronomy, asteroseismology, technology transfer |
| **BRITE-Poland 1**[6] | Poland | 2010 | 2012 | Space astronomy, asteroseismology, technology transfer |
| **AISSat-2** | Norway | 2011 | 2013 | Operational AIS observation |
| **BRITE-Canada 1**[6] | Canada | 2011 | 2013 | Space astronomy, asteroseismology |
| **BRITE-Canada 2**[6] | Canada | 2011 | 2013 | Space astronomy, asteroseismology |
| **CanX-4**[7] | Canada | 2004 | 2013 | Precise, autonomous formation flying |
| **CanX-5**[7] | Canada | 2004 | 2013 | Precise, autonomous formation flying |
| **BRITE-Poland 2**[6] | Poland | 2010 | 2013 | Space astronomy, asteroseismology, technology transfer |
| **NEMO-AM**[8] | India | 2009 | 2013 | Earth observation, aerosol monitoring, multi-spectral |
| **CanX-7** | Canada | 2009 | 2014 | De-orbiting drag sail demonstration |
| **NEMO-HD** | Slovenia | 2012 | 2014 | Earth observation, high definition, multi-spectral |

**Table 1. SFL Small Satellite Mission Manifest.** *These missions are fully funded into operations.*

Along with the evolution of the satellite bus technologies, the requirements and philosophies of ground segment technologies has also evolved. A key driver for this evolution is the need to support a diverse network of Mission Control Centres and Earth station facilities in a reliable and flexible manner without a dramatic increase in operations costs. This paper summarizes SFL's current implementation of the ground segment approaches used to support these missions.

## II. Context of Need and Historical Approaches

For the first missions developed at SFL – namely the Microvariability and Oscillations of Stars (MOST), CanX-1, and CanX-2 missions – the development of ground segment paralleled the spacecraft development. The earth station was tailored to the requirements of the satellite, and the ground software was designed with a single satellite in mind. Figure 1 shows the salient details of this architecture: multiple client terminal programs interface through a single communication aggregator/moderator, the Communications MUX, which communicates with the satellite through dedicated ground station hardware.

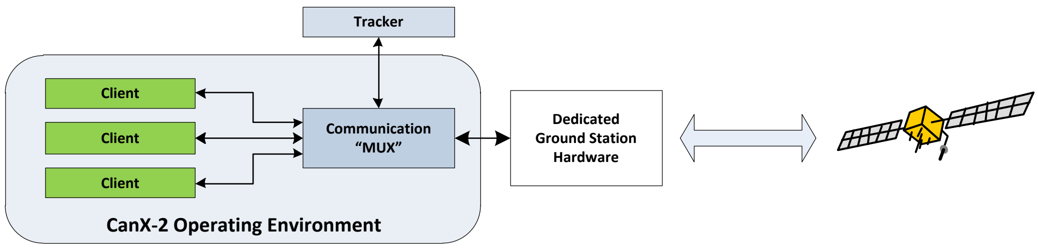


**Figure 1. Approached used in early SFL missions**

All the communication between client programs take place over a TCP/IP socket, encapsulating packets in the same protocol as used on the spacecraft. This makes it easy to accommodate new client programs for specialized data handling and data distribution. For current missions, the client programs perform automatic query and validation of real-time telemetry, downloading stored spacecraft telemetry, and command and control of the platform and its experiments. The Communications MUX is specific to the particular mission, having knowledge of the spacecraft protocols and acquisition sequence at the start of each contact. The acquisition sequence ensures that a link is established before client programs start interfacing with the satellite.

As the ground hardware is dedicated, scheduling is a matter of identifying all contacts above a minimum elevation threshold. The contact information is provided to the software by an orbit propagator and tracking program and is used to initiate automated operations.

The historical approach is sufficiently flexible that it continues to be the foundation for communicating with current SFL satellites during ground testing or when only a single station is used with the satellite on orbit. New client programs have been added to perform data handling for a mission-specific payload while the existing programs interface with the common spacecraft bus.

The gaps in this approach become apparent when it was necessary to share one ground station facility between multiple satellites. For example, in 2008, a station at SFL was shared between two nanosatellites, CanX-2 and CanX-6 (NTS). To accommodate both with minimal changes, the ground station modem became the device that switched between satellites, and the rest of the software architecture remained dedicated to a single satellite. Another software component was added to switch the tracking between the satellites.

The system required modification again in 2009, when additional ground stations were made available to download more data from CanX-6 during particular observation campaigns. These changes to incorporate extra links added complexity to the software and the workload on the operations team. Hence it became necessary to create a new architecture that would simplify adding/removing additional ground resources from the network, and simplify managing new satellites with the existing facilities. A new framework would also facilitate new and more efficient communication protocols to be employed on new missions that share the same ground stations.

## III. Ground Segment Framework

The ground segment framework, at its core, provides a method by which satellite operators interact with Earth station providers to establish a communication path between a Mission Control Centre and a satellite. Previous approaches had three core issues blocking an efficient path to scaling up single satellite-single Earth station configurations:

1. System details were generally hard-coded, for example details of control over Earth station equipment, or details of the satellite communication protocols. Changing these for different missions or bus technologies would require rewriting and retesting core software.
2. Complete control of an Earth station was assumed by a particular satellite project. Allowing other satellites to use portions of the same system would require complex software interactions and/or more hardware to be added to the station.
3. Scheduling and prioritization was either very simplistic (e.g. whichever satellite is in view first gets the pass support) or left up to manual action to resolve.

The evolved framework resolves these core deficiencies in the traditional approach along with a number of other smaller issues that get in the way of optimizing efficiency of Earth station utilization, satellite operations, and minimizing labour associated with nanosatellite mission execution.

### B. Driving Requirements

Based on extensive flight operations experience, a number of key driving requirements were established to drive the evolution of the nanosatellite ground segment operations framework development. These included:

- Utilize an extensible ground segment element linkage approach, allowing complex relationships between satellites and Earth stations, including single-single, single-multiple, multiple-single, or multiple-multiple.

- Follow a distributed design philosophy, ensuring that the failure of any single node would only result in the temporary loss of communication with a single satellite or Earth station. In particular, a central hub for managing authentication of satellites or Earth stations, or coordinating their interactions, is explicitly avoided.

- Use industry-standard communication protocols (e.g. TCP/IP) and operating systems within each element of the framework, with inter-element security provided as necessary. In particular, complex, costly, and single-source technologies are avoided at all costs, and the system is designed such that open networks may be used to minimize costs and maximize flexibility.

- Implement simplicity of configuration, such that only local knowledge of a particular satellite or Earth station is necessary to join a ground segment network. In particular, the need for an Earth station operator to understand the operations or protocols of a satellite is kept to an absolute minimum. A heterogeneous environment is desired.

- Implement modularity of components, such that adding a new communication protocol, Earth station design, or hardware does not involve modifying any of the core software.

- Support a high degree of operational autonomy, such that personnel are not explicitly required to support either satellite or Earth station operations due to characteristics of the ground segment framework. A goal is to allow zero operator interaction for routine operations of the entire network.

- Allow downlink-only, uplink-only or non-collocated/diverse downlink-uplink station operations.

### C. Key Functionality

At its core, the ground segment framework provides several key but limited-in-scope areas of functionality. The framework:

- Provides an automated negotiation mechanism to schedule contact supports for each satellite and Earth station in a given support network. The framework determines upcoming pass information for each satellite and Earth station combination, and then determines an optimal scheduling based on user-specified priorities and constraints.

- Supports offline scheduling support at the Earth station level, to allow coordination of Earth stations not part of the main network or to allow operating entities to use their own scheduling mechanisms.

- Acts as a network to relay packets to (and from) the modular satellite control programs, via an active Earth station, from (and to) an active satellite.

- Allows the satellite operator to control and monitor many aspects of the Earth station configuration in real time (e.g. transmission/reception frequencies for Doppler correction or anomaly operations, link data rates, transmission power levels, etc.) to allow maximum flexibility without requiring Earth station operators to be present.

- Tracks an active satellite at the corresponding active Earth station and orients its antennas.

- Logs packet and telemetry information at both the Earth station and satellite level for bookkeeping and fault recovery.

- Provides status and pass support information to the satellite operating environment, such that the latter is informed when the ground-space communication path is open. The specific details of how and where this path is achieved is not required by the satellite operating environment.

- Generates email-based summary reports such that operators are able to follow and monitor ongoing space mission operations without needing to access the main operating environments.

### D. Framework Components

The core software consists of three components described below and summarized in Figure 2.

Tracker[9] is used to provide both a visual and programmatic interface for the propagation of a satellite's orbit and pass information using the Simplified General Perturbations 4 (SGP4)[10] algorithm and interfaces with an Earth station's antenna tracking system. Available contact information for a given satellite is provided to other elements in the framework via TCP/IP connections.

Master is the interface point between a satellite's operating environment and the rest of the ground segment. It represents a single satellite within the framework.

Station is the core control component for a single Earth station within the ground segment. It is responsible for providing an interface to the Master components to configure, establish, and execute a satellite support contact in the context of a multi-mission, cross-support environment.

Within each component, areas where changes may need to be made to low-level functionality are extended as separate modules. This allows the ground segment to be expanded and extended without requiring changes to the core framework and the associated costs associated with this development and deployment. The most important modules are those related to specific Earth station hardware and satellite-level communication protocols.

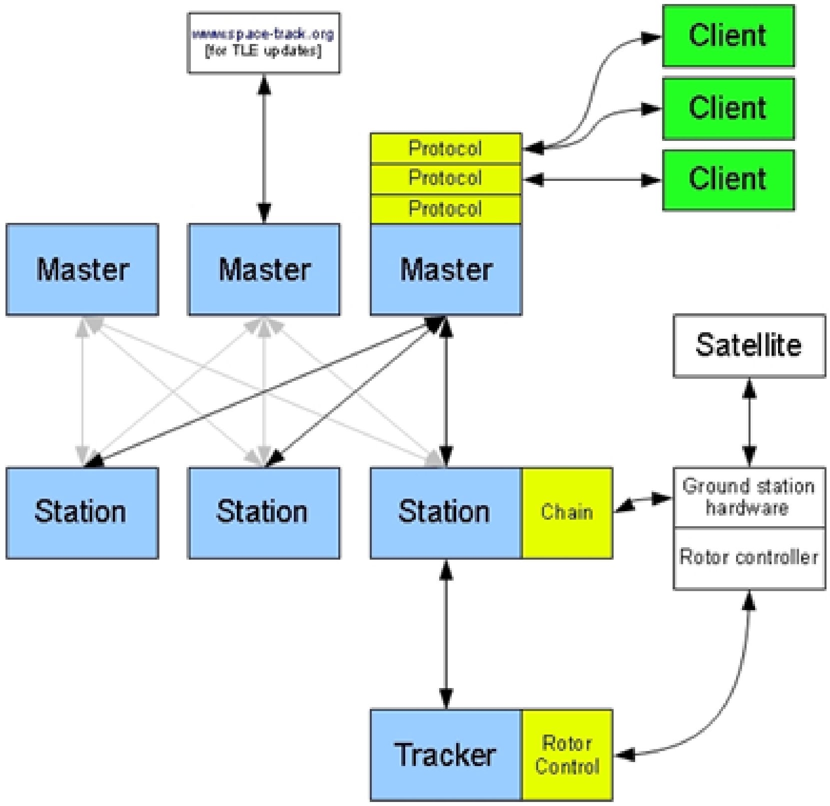


**Figure 2. Overview of the ground framework architecture.** *Light blue indicates a core component, yellow a module that extends the functionality of a core component, and green which is a custom standalone component.*

### E. Framework Description and Design

Pass allocation is an important role of the framework, and becomes non-trivial when a station has multiple satellites in view at the same time and/or a satellite is in view of multiple stations at the same time. In this situation decisions must be made as to which station will track which satellite. Given the distributed nature of the framework this process is handled by a series of negotiations between each Station/Master combination. The negotiation process is summarized in Figure 3.

In simplified form, the negotiation begins with the Station sending the Master the upcoming pass information for a particular satellite. The Master, upon receiving this information, decides if it wants the same Station to be active during that pass – based on whether any other

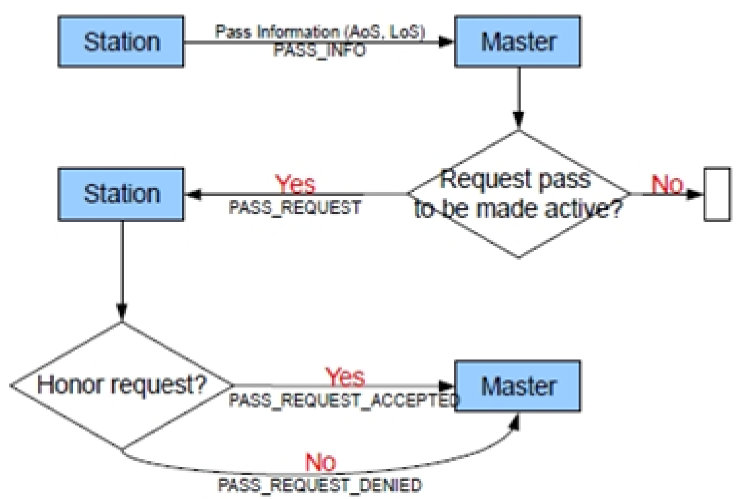


**Figure 3**. **Simplified overview of the pass request negotiation.**

Stations are better suited to be active at the same time. The Master can, if so desired, send the Station a pass request packet. The Station will then decide whether to accept or reject this pass request – based on whether any other satellites would be better monitored at the same time.

At the core of the negotiation mechanism is a concept of priority maintained by the Earth stations. It is broadly assumed that Earth station facility services are multi-mission by nature, and the Earth station provider must have a mechanism by which to set allocation priorities and support levels to honour cross-support agreements between entities. Thus, the negotiation mechanism factors in Earth station constraints in the event that multiple satellites are in view at the same time. These negotiations are dynamic in nature as adding/removing another Station/Master can result in the renegotiation of all the currently allocated passes.

Another important role of the framework is to route information from a satellite's ground control programs, the Clients, through the Master, to the active Station, then through the ground station hardware, to the satellite itself – and the same process in reverse. The custom Protocol component is used to provide a human-readable form of a packet, if applicable, any necessary packet buffer manipulation, and tracking of source/destination addresses necessary for the routing of response packets. Each Client identifies its associated Protocol when it first connects to the Master. The Master routes the packet to the active Station, which then routes the packet through the Chain component to the ground station hardware. The Chain encodes the knowledge necessary to connect to and control the ground station hardware. Chain modules are also present for wired links, used in spacecraft testing on the ground.

## IV. Implementations

The following sections discuss several real-world SFL-led implementations of the ground segment concept. A subset of missions is discussed to show a number of different combinations of satellites and Earth stations, and their unique characteristics.

### F. Satellite Case Study 1: CanX-2 (Single Satellite, Single Earth Station)

CanX-2 is a 3.5 kg triple-Cubesat launched from India on April 28, 2008 and continues to operate today. Its mission is twofold:

- Demonstrate technologies necessary for next generation nanosatellites, including telemetry and commanding systems, command and data handling, and three-axis attitude stabilization with single axis control
- Provide a platform for several scientific experiments, including a spectrometer and a GPS-based ionospheric measurement experiment

CanX-2 is operated from SFL's Mission Control Centre (MCC) facility in Toronto, Canada. Although it can be provided with support from other stations, it is primarily operated via the collocated SFL Earth station facilities. This case represents the simplest configuration of the ground segment framework, and is typical of most existing and planned nanosatellite missions. The ground segment configuration of CanX-2 is shown in Figure 4.

CanX-2 uses two frequency bands, and actually makes use of up to two Earth stations at the SFL facility simultaneously. Control of these stations would traditionally be performed by a single set of software driving both stations. However, in this instance the framework's flexibility to allow separated stations to be used for uplink and downlink operations is used. This eliminates the scenario where another type of satellite, which only requires one of the two stations, to not tie up both thereby increasing scheduling flexibility and efficiency for the overall facility. Additionally, CanX-2 can benefit from the framework's ability to allow redundant failover stations. Thus, even simple traditional-style missions can benefit from the evolved approaches.

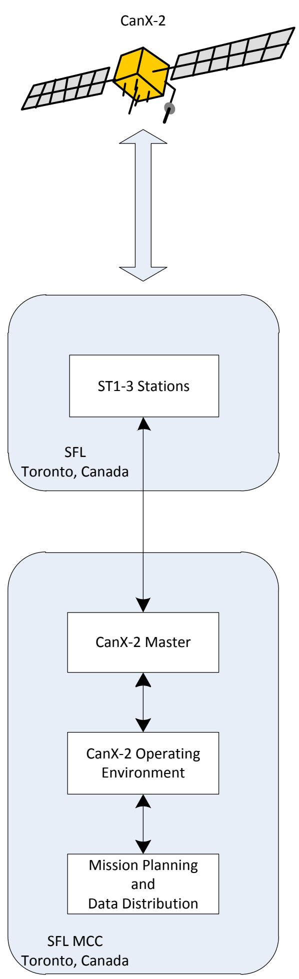


**Figure 4. CanX-2 ground segment configuration.**

## G. Satellite Case Study 2: MOST (Single Satellite, Multiple Earth Stations)

MOST is a 53 kg microsatellite launched from Plesetsk, Russia on June 30, 2003. It is a space astronomy mission funded by the Canadian Space Agency, and it carries a 15cm aperture optical telescope.

Its primary science mission is to perform asteroseismology. Due to the extreme sensitivity of the instrument it is also performs extrasolar planet observations. It is a world-class space astronomy mission that often performs joint observations and science with much larger observatories such as Hubble and Spitzer. Its scientific insights have been groundbreaking and it continues to rewrite astronomy textbooks today.

MOST is operated from SFL's MCC facility in Toronto, Canada. Earth stations are located at SFL, as well as at the University of British Columbia (UBC) in Vancouver, Canada, and the Institute for Astronomy (IFA) in Vienna, Austria. The ground segment configuration for MOST is shown in Figure 5.

The ground segment framework handles all coordination between the various stations at the satellite's control centre. An additional complication, namely the overlap of coverage between the Vancouver and Toronto stations, is handled automatically by the framework such that only one of the two stations is used during the overlap time.

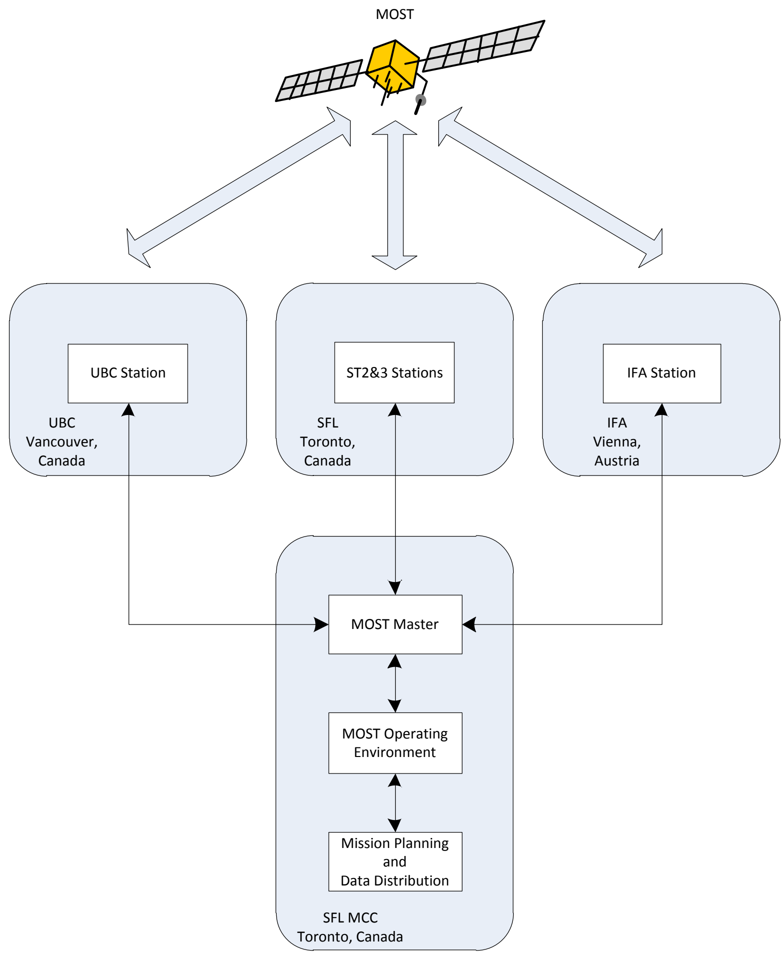


**Figure 5. MOST ground segment configuration.**

The implementation and utilization of the original ground segment implementation for MOST over many years of operation provided key insight and experience. The evolved system is in many ways a more refined system used to control MOST for most of the last decade.

### H. Satellite Case Study 3: AISSat-1&2 (Multiple Satellites, Single Earth Station)

The Automatic Identification System Satellite (AISSat) No. 1&2 are identical 6.5 kg nanosatellites based on SFL's current Generic Nanosatellite Bus (GNB) platform. The GNB platform is one of the most advanced nanosatellite bus platforms that are currently deployed in orbit.

AISSat-1 was launched from India on July 12, 2010 and was the first GNB mission to be deployed. AISSat-2 is scheduled for launch in the spring of 2013. Their primary mission is to provide a capability to monitor maritime traffic in Norwegian territorial waters in real time utilizing the Automatic Identification System. Data from this system is used operationally by the Norwegian Coastal Authority as well as numerous other invested users in Norway. It is one of the first examples of a true high-availability, operationally-relevant satellite system based entirely on nanosatellite technologies.

The satellites are operated from the Norwegian Defence Research Establishment (FFI) campus in Kjeller, Norway, just outside of Oslo. The Earth station facilities are located at the Kongsberg Satellite Services (KSAT) SvalSat facility located outside of Longyearbyen in Svalbard, Norway. The ground segment configuration for AISSat-1&2 is shown in Figure 6.

The satellites use two physical Earth stations for UHF and S-band frequencies. The S-band station, SG40, is shared with other missions such as Proba-2. SG40 is scheduled by KSAT scheduling mechanisms outside of the framework's control, and this information is used to schedule the other Earth station (SG14). The framework's ability to handle external scheduling mechanisms is utilized here to coordinate operations of the two Earth stations.

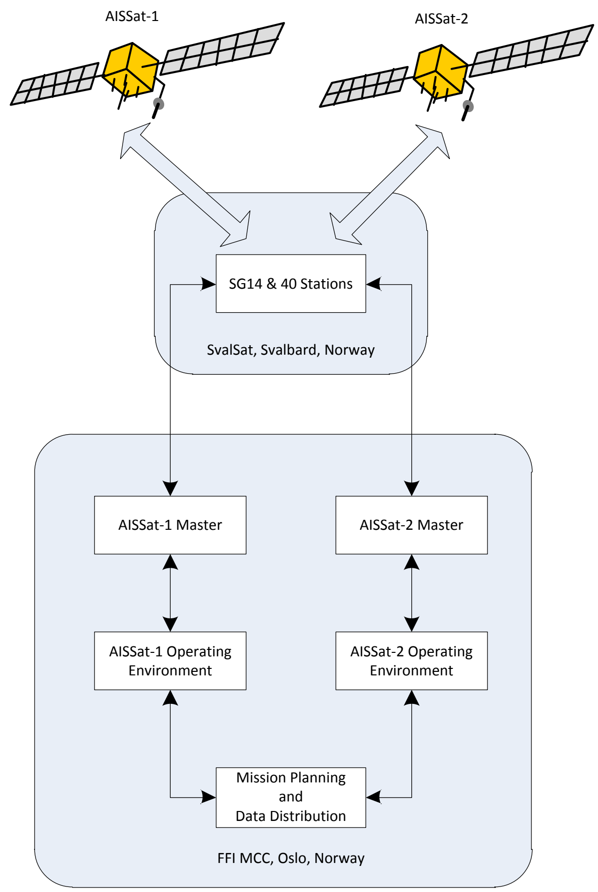


**Figure 6. AISSat-1&2 ground segment configuration.**

### I. Satellite Case Study 4: BRITE Constellation (Multiple Satellites, Multiple Earth Stations)

The Bright Target Explorer (BRITE) Constellation is a series of six 6.5 kg nanosatellites based on SFL's GNB platform. Carrying precision star trackers, they are expected to be the most precisely controlled nanosatellites ever deployed in orbit. The constellation is scheduled to be deployed over the next 1-2 years, with the first three satellite being deployed in the fall of 2012.

BRITE Constellation is a space astronomy mission. Each satellite carries a small optical telescope, with different spectral responses in several of the satellites. This allows greater science with a full constellation performing simultaneous observations, while still allowing groundbreaking science from each satellite individually. Its primary science is asteroseismology, similar to MOST, but the constellation's target star catalog is different and complementary.

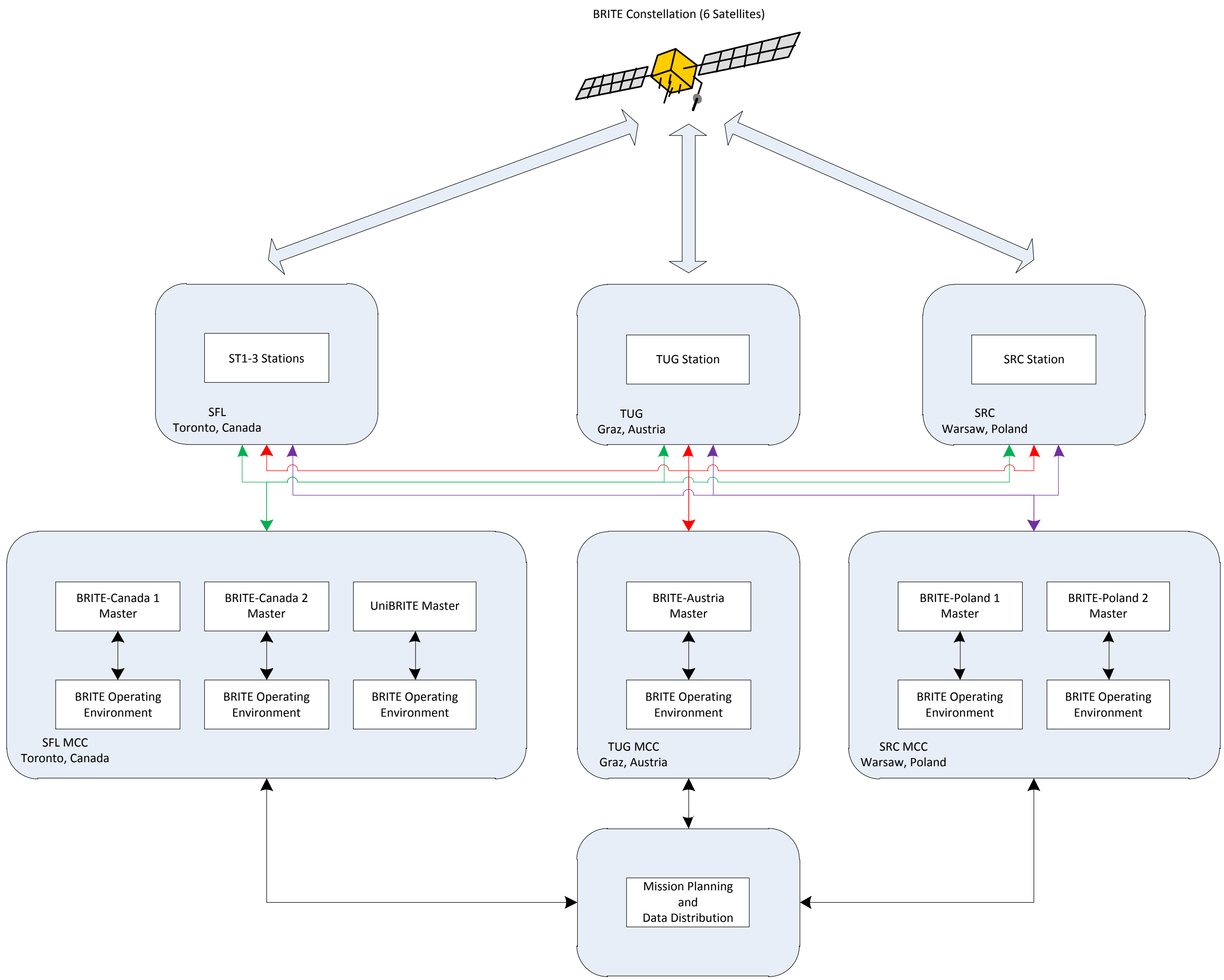


**Figure 7. BRITE Constellation ground segment configuration.**

The BRITE constellation is an international collaboration comprising a multi-national science team coordinating the observations of the entire constellation, and satellite operators from Canada, Austria, and Poland. Each country is providing and operating two satellites in the constellation, with any of the six satellites able to be operated from any of the three countries. The BRITE constellation will include stations at SFL in Canada, at the Technical University of Graz (TUG) in Austria, and the Space Research Centre (SRC) in Poland. Nominally, each country will tend to operate its satellites from its own Earth stations, but other stations can be used either to speed commissioning of a newly-launched satellite, increase the overall scientific data output of the constellation, or during anomaly operations for a satellite in trouble when more time coverage is desired by the operations team. The BRITE constellation ground segment configuration is shown in Figure 7.

The BRITE constellation represents the most complex configuration where not only are the operations of multiple satellites coordinated at a high level, and operated by diverse entities, but also due to the cross-support and rapid ground segment network reconfiguration requirements. This mission is one of the main drivers for the evolution of nanosatellite ground segment implementations.

### J. Earth Station Facility Case Study: SFL

The case studies shown previously have looked at the ground segment framework's ability to space mission activities primarily from the satellite operator's perspective. However, an Earth station provider also benefits greatly from some of the characteristics of the framework. In particular, it allows a diverse set of satellites based on different technologies (physical layer formats, protocols, etc.) to be operated from a given facility with minimal interaction during real-time operations, and assists in optimally scheduling a variety of supported satellites with ease. This is particularly important for reliability, as the Earth station operator will want to minimize effort and time required to re-task Earth stations and shuffle satellite supports in the case of a failure condition.

An example Earth station facility configuration is shown in Figure 8, with four missions with different Earth station needs being supported by four Earth stations. Each satellite is tasked to both primary and secondary stations. Even with such a relatively simple configuration, the relationships and scheduling complexity is already quite large and this problem grows exponentially with number of Earth stations used and satellites supported. The ground segment framework facilitates management of the Earth station facilities with a minimum of up-front labour, and allows rapid reconfiguration.

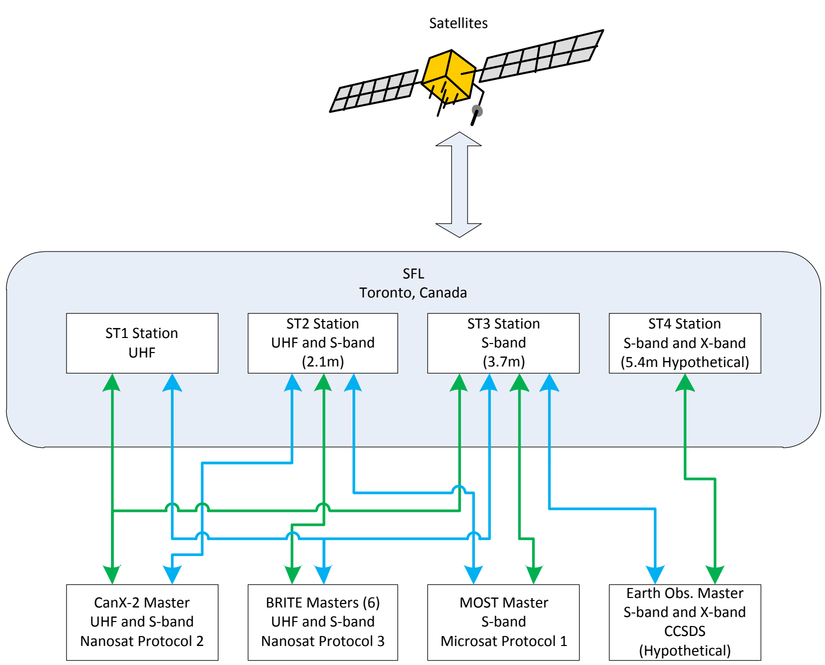


**Figure 8. SFL Earth station facility support configuration.** *Green indicates primary support allocation, and blue indicates secondary.*

## V. Conclusion

Nanosatellites are now a viable tool for ambitious missions in a variety of real-world applications, including Earth observation, space science, and communications. Historically, the mission scope has not required complex interactions between Earth stations and the satellite operators. However, the historical approaches do not at all scale to even moderately complex configurations, certainly without significant increase in costs. SFL has evolved a next-generation ground segment operations framework that addresses the needs of nanosatellite missions going forward to allow flexible, cost effective, and reliable space mission operations to be undertaken by both Earth station providers and satellite operators.

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## Appendix A
## Acronym List

| | |
|---|---|
| **AISSat** | Automatic Identification System Satellite |
| **BRITE** | Bright Target Explorer |
| **FFI** | Forsvarets Forskningsinstitutt (Norwegian Defence Research Establishment) |
| **GNB** | Generic Nanosatellite Bus |
| **UHF** | Ultra-high Frequencies |
| **IFA** | Institute for Astronomy |
| **KSAT** | Kongsberg Satellite Services |
| **MCC** | Mission Control Centre |
| **MOST** | Microvariability and Oscillations of Stars |
| **SFL** | Space Flight Laboratory |
| **SGP4** | Simplified General Perturbations 4 |
| **SRC** | Space Research Centre |
| **TCP/IP** | Transmission Control Protocol/Internet Protocol |
| **TLE** | Two-Line Element |
| **TUG** | Technical University of Graz |
| **UBC** | University of British Columbia |
| **UTIAS** | University of Toronto Institute for Aerospace Studies |