

## Integrated Ground Segment for a Greenhouse Gas Emissions Monitoring Constellation

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### Abstract

Six years ago, GHGSat Inc. and Kongsberg Satellite Services AS (KSAT) initiated conversations regarding a potential collaboration on ground segment services for the on-orbit GHGSat satellites for the purposes of augmenting existing capabilities and preparing for constellation growth. GHGSat, headquartered in Montreal, Canada, provides actionable greenhouse gas emissions data and insights using satellite and aircraft sensors. KSAT, a world leader in providing ground station services, has expanded its service offering to include satellite operations from the newly established Tromsø Spacecraft Operations Centre (TSOC) in Norway.

On 24 February 2023, Amund Nylund, Chief Operating Officer, sent KSAT’s first ever command to a GHGSat satellite. In-depth training on the satellite platform and ground software, integration with Application Programming Interfaces (APIs), and a cross-functional approach were key elements to the ongoing success of the joint mission. Today KSAT provides a seamless integrated ground service to GHGSat including both ground station network support and satellite operations for the constellation in orbit.

In this paper we discuss the evolution of the collaboration and hurdles encountered on the technical, contractual, and regulatory sides. We also review lessons learned from both the space and ground segment owners over the first two years of satellite operations. As KSAT grows its offering of integrated ground services and as GHGSat continues to expand its constellation, this paper will inspire and serve as a reference for new and traditional space on how full externalization of ground services is not only possible but can be an optimal solution both technically and business-wise.

**Keywords:** Satellite Operations as a Service, Ground Segment as a Service (GSaaS), constellation operations

### 1. Introduction

GHGSat provides accurate, verifiable, site-specific greenhouse gas (GHG) data to industrial and government customers, using satellite remote sensing technology. It collects this data in a large part from its own constellation of nine satellites based on the Space Flight Laboratory’s (SFL) NEMO microsatellite platform [1,2], launched between 2016 and 2023, and three hosted payloads on Spire’s LEMUR-2 16U microsatellite platform [3], all launched late 2023. More launches of both platforms are scheduled in the near future and will almost double the constellation by the end of 2026.. However, since the LEMUR satellites are owned and operated directly by Spire, their operations will not be discussed further in this paper, which will solely focus on the NEMO spacecrafts.

While payload operations have always been handled in-house by GHGSat, operation of the NEMO satellites was initially done by SFL. However, as the constellation expanded and the demand for GHGSat’s data increased, SFL came to the conclusion that their focus was on designing and manufacturing microsatellites, and only operating up until the satellites were fully commissioned on-orbit. As such, by 2022 the operations of six on-orbit satellites as well as three yet to be launched had to be transitioned to a new operator.

### 2. Establishment of Partnership

The initial exchanges between GHGSat and KSAT began in 2019 when GHGSat reached out to enquire about Ground Station as a Service. GHGSat already had functioning ground stations located in Canada and operated by Canadian companies, but wanted to increase its coverage by adding other geographical locations. The recently established KSATlite service was proposed. This service had been developed by KSAT for NewSpace customers seeking to optimize Operational Expenditure (OPEX) without sacrificing quality or service delivery. KSATlite was a

pioneer in usage of Application Programming Interfaces (APIs), standardized antennas, and software defined backends allowing for a wide variety of spacecraft radios and modulations to be supported with one single solution. The contractual relationship started with low volume support from Awarua, New Zealand, which served as an optimal complement to the existing Canadian support from Inuvik, Happy Valley-Goose Bay, and Toronto.

As KSAT was starting to open their new business line on Satellite Operations, and GHGSat was in search for a provider of such services, a dialogue started. Both companies acknowledged early on that this new service implied critical risks, and addressing them and ensuring success would require mutual trust and a dedicated effort. After extensive collaboration over a significant volume of email exchanges and regular video conferences, covering the technical, legal and regulatory aspects, GHGSat and KSAT reached a satisfactory agreement to externalize satellite operations.

During that time, GHGSat's ground station network was also expanded further to include coverage from Svalbard, Norway, an ideal location for satellites in Sun Synchronous Orbits (SSO). More satellites launched meant a higher need for support and, eventually, both companies agreed on a contract where GHGSat has 24/7 access to a dedicated antenna in Svalbard, whose exact location was handpicked by GHGSat for its optimal view atop the Platåfjellet. Over 100 passes are supported daily from that antenna, with a proficiency higher than 99.5%.

### **3. Technical Preparations**

#### *3.1 Training and Knowledge Transfer*

The Space Systems Operations team was formed at GHGSat in order to oversee satellite operations. Functioning within the larger Operations department, it is a small team responsible for ensuring the satellite platforms and ground station networks are achieving the service standards of GHGSat's downstream customers, in addition to securing and maintaining all regulatory licences required for operations. In relation to satellite operations, the team is responsible for providing engineering support to the KSAT operations team during anomaly debugging and performing flight dynamics tasks, such as collision avoidance and maintenance of the constellation orbital spacing.

To ensure a smooth transition and knowledge transfer from SFL to the newly formed GHGSat and KSAT operations teams, a comprehensive training session took place over three full days at SFL in November 2022, several months prior to the planned handover. During this period, the teams received in-depth information on the satellites, their subsystems, and the ground software. The training covered both routine and anomalous operations, including the relevant procedures. The GHGSat mission “flatsat” was also introduced, which consists of a complete set of satellite electronics and wiring harnesses assembled on a bench and running the same software as the satellites in orbit. The flatsat was subsequently used by the KSAT and GHGSat operations teams for familiarization with the satellite hardware and for testing of operational procedures before the handover of the on-orbit satellites.

A period of shadow operations was included, which allowed KSAT's team to observe and learn from the daily operations, ensuring familiarity with the software and workflows before taking on full operational responsibility. This period commenced after the training session, where the GHGSat and KSAT teams had remote access to SFL's satellite operations virtual machines (VMs) while the SFL engineers were still responsible for operations. For the GHGSat-C6 to C8 satellites, which launched on April 15, 2023 after the remainder of the constellation was handed over, the teams were also able to observe the commissioning process until those satellites were ready for the transition and nominal operations.

In order to assess preparedness prior to the handover of the satellites, an Operational Readiness Review (ORR) was held in Svalbard, Norway with the KSAT and GHGSat operations teams at the end of February 2023. Over the course of several days the teams worked together to ensure that all software and network interfaces were working correctly. KSAT's team also demonstrated their operational response to various routine and anomalous scenarios, and confirmed compliance to all requirements specified by GHGSat.

#### *3.2 Phased Handover*

The first satellite that was transferred under KSAT's operational control was GHGSat-D, or Claire, on February 24, 2023. Launched in June 2016, Claire was the GHGSat's first satellite and at the time of the handover to KSAT, was no longer in use for commercial observations. It could therefore be used by KSAT as a testbed, differing slightly from the rest of the constellation in terms of onboard architecture but similar enough to be a valuable training platform

for a team that was still becoming familiar with satellite operations. The handover marked an important milestone for KSAT as it was their first ever command sent to an on-orbit satellite, representing a significant step forward in KSAT’s expansion into satellite operations.

GHGSat-C1 and C2 were transferred to KSAT on March 7th and 13th 2023 respectively, once all of the outstanding follow-up actions from the ORR were completed. Since GHGSat-C3, C4 and C5 have slight differences in their payload electronics and uplink/downlink architecture compared to the two prior, and due to the launch of GHGSat C6, C7 and C8, a short pause was observed while KSAT became comfortable operating GHGSat-C1 and C2. GHGSat-C4 was handed over on April 24th, 2023 and GHGSat-C3 and C5 on May 8th. Finally, GHGSat-C6, C7 and C8 were handed over on June 6th, 7th and 8th once their commissioning was complete.

### 3.3 Ground Software Setup

The Mission Control System (MCS) software suite, developed by SFL, was deployed within KSAT’s Azure [4] cloud infrastructure. Hosting the system within the KSAT network facilitated a seamless integration with KSAT’s ground station network and ensured their engineers could efficiently support the mission. Hosting it in the cloud, using an Infrastructure as Code (IAC) paradigm, also facilitated the scalability, redundancy and security of the system. A copy of the MCS was also set up internally at GHGSat, acting as a backup Mission Control Centre (MCC) to ensure the resilience of critical satellite operations.

Ensuring service continuity was a top priority during the migration process. To achieve this, KSAT continued utilizing the MCS instead of rolling their own software solution, which allowed for uninterrupted operations and ensured access to third-level access and support from the bus manufacturer in the event of a spacecraft emergency. This approach mitigated risks not covered in standard mission training.

All prior spacecraft telemetry was also copied from SFL to KSAT, as well as operational databases and dashboards. This ensured that KSAT had full mission insight from day one, enabling seamless continuity.

To support mission operations, the KSAT Azure deployment was also integrated with key external interfaces, including:

- A data exchange interface for payload planning and observation sharing between KSAT and GHGSat
- The flatsat, at SFL’s premises, for procedure validation and training
- Space Situational Awareness (SSA) providers for orbital safety
- Remote access for GHGSat and SFL personnel to facilitate collaboration

Fig. 1 presents an abstract overview of the technical deployment for the Mission Operations service used to support the GHGSat constellation.

The deployment leverages a combination of shared and mission-specific resources, balancing economies of scale while ensuring that the potential failure of one satellite’s ground systems does not impact the operations of others. As part of KSAT’s mission onboarding process, the system underwent rigorous testing, including validation of operational interfaces and dataflows under real-time simulation conditions.

To enhance operational scalability, KSAT developed (and is continuously improving) a custom monitoring system that collects and analyzes data from operational resources. The objective of this system is to automate monitoring of the ground segment and automate recovery and anomaly escalation. A further description of this system is provided in section 5.4.

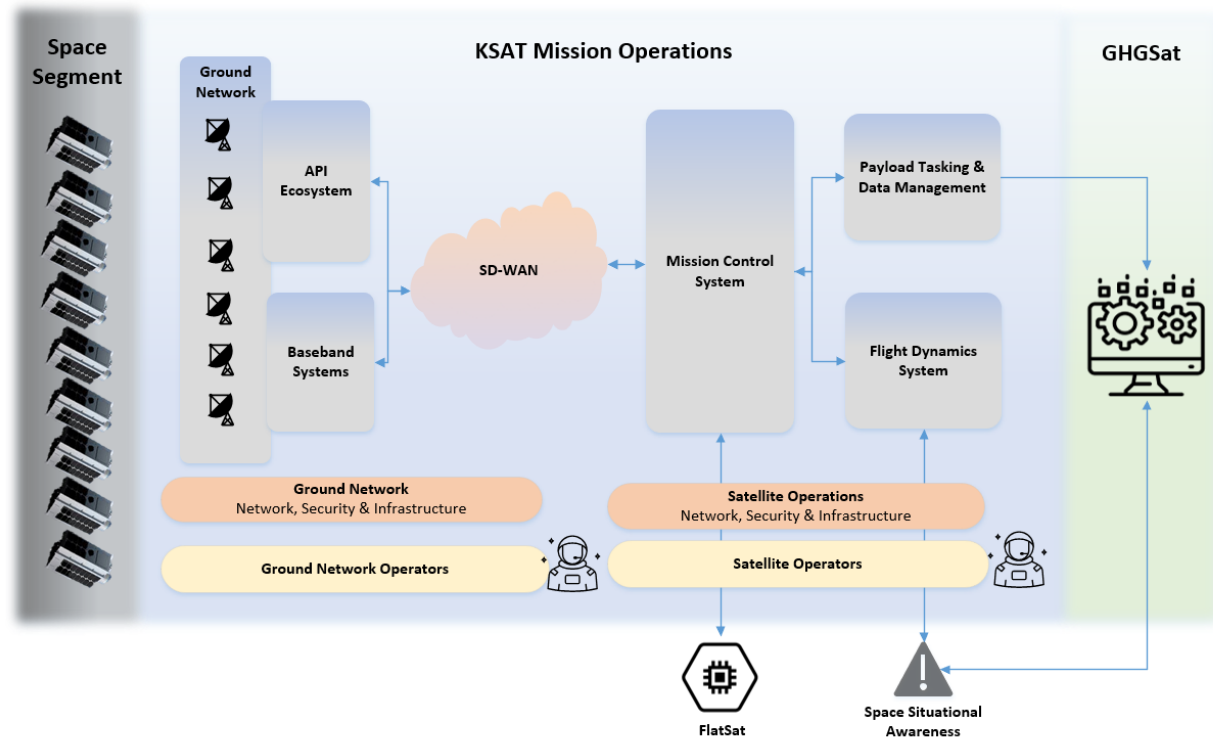


Fig. 1. Abstract overview of the technical deployment.

#### 4. Regulatory Considerations

In addition to the technical preparations, maintaining compliance with GHGSat’s regulatory licences played a critical role in bringing KSAT onboard for satellite operations. Transferring operations of a constellation of Canadian satellites to a foreign company represented pioneering territory in the Canadian regulatory landscape, which presented a distinct set of challenges. From the initial exploratory and contractual discussions until the transfer of satellites to KSAT’s operational control, GHGSat worked alongside Canadian regulatory bodies to maintain transparent communication and ensure compliance with all regulations.

##### 4.1 Radio Frequency Spectrum License

The GHGSat constellation satellites are licenced in Canada, and have space station spectrum licences issued by Innovation, Science and Economic Development Canada (ISED). These licences authorize the use of specific frequency bands for a defined orbital configuration. GHGSat holds spectrum licences in UHF, S-band and X-band. As a condition of licence, GHGSat must maintain compliance with Canada’s Radiocommunication Regulations, including maintaining Canadian direction and control [5]. For non-geostationary orbit (NGSO) satellites, the Network Operations Centre (NOC) must be located in Canada and must perform Telemetry, Telecommand and Control (TT&C) functions. There must also be staff located in Canada capable of initiating commands related to those functions. To ensure compliance, the NOC is hosted on Canadian servers and GHGSat’s Satellite Operations Team is able to perform all the same operations as KSAT’s team.

##### 4.2 Remote Sensing Space Systems License

In Canada, all remote sensing space systems are governed by the Remote Sensing Space Systems Act (RSSSA). Global Affairs Canada (GAC) is responsible for licensing their operation, ensuring that they maintain alignment with Canada’s national security interests and international obligations. Under the RSSSA, organizations involved in remote sensing activities are required to follow guidelines and submit necessary documentation to ensure compliance.

As part of the licence, individuals and organizations may be designated as System Participants, which authorizes that individual or organization to carry out Controlled Activities [6], including:

1. Formulating or giving a command to a remote sensing satellite of the system
2. Receiving raw data from a remote sensing satellite of the system
3. Storing, processing or distributing raw data from the system
4. Establishing or using
  - a. Cryptography in communications with a remote sensing satellite of the system, or
  - b. Information assurance measures for the system.

KSAT was added as a System Participant in the GHGSat Constellation Operating Licence during the process of onboarding their ground stations in order to perform certain Controlled Activities. Since their responsibilities were broadened as a satellite operator, the Controlled Activities they were authorized to perform required updating in their System Participant Agreement.

One of the key components of compliance under the RSSSA is the submission and maintenance of a Command and Data Protection Plan (C&DPP). This plan contains the applicant’s key security documents detailing physical, personnel, and information technology security for the entire remote sensing space system, which includes the space segment, ground segment, and the data. As KSAT had already been working with GHGSat to provide ground station services, certain aspects of the C&DPP had previously been submitted to detail the site security of the ground stations. The expansion to satellite operations required site security documentation for the Tromsø Spacecraft Operations Centre (TSOC) in Norway, as this is where KSAT’s team is located and where they would primarily be connecting to GHGSat’s NOC. Additional documentation was required on the IT security aspects of the NOC.

Throughout the preparations for KSAT to begin operating the GHGSat satellites, regular discussions were held with GAC to review and ensure all submission requirements were met. Key to the approval of the transfer were that GHGSat maintains remote access to the NOC and the ability to assume primary control of the satellites if needed. GHGSat also maintains visibility into KSAT’s operational procedures and documentation needed to perform the services agreed upon in the contract.

## **5. Lessons Learned, Potential Improvements & Recent Progresses**

The transition of operational responsibilities from one provider to another is inherently complex, involving technical, procedural, and organizational challenges. In any operational handover, there are risks that there will be more system downtime than typical, and this was especially a risk given the ground and satellite systems were being handed over from the organization in which they were developed to an operator who had no prior satellite operations experience. Despite these challenges, strong collaboration and communication between the GHGSat, SFL and KSAT operations teams, KSAT’s proactivity, as well as plenty of support from SFL’s engineers, ensured that the system downtime and resulting impact to GHGSat’s customers was relatively minor. Nevertheless, as is expected, valuable lessons emerged that not only can help inform future transitions, but also highlight potential system improvements.

### *5.1 Ramp-Up*

The intensive three-day training session delivered and recorded by SFL proved to be highly valuable, but naturally limited in its ability to cover the full depth and nuance of the large and complicated system of satellite operations. This session was provided during COVID-19 pandemic restrictions, adding an extra challenge since all health restrictions, including face masks and physical distancing, had to be respected.

Thorough documentation is essential for ensuring operational continuity, especially during a transitional period. While materials such as the training slides, recordings, and common procedures were provided, more comprehensive user manual-type documentation for all ground software components as well as the satellite would have greatly supported both the handover as well as ongoing operations. Such documentation would have helped aid with independent troubleshooting as well as experimentation on the flatsat, while serving an ongoing reference during operations.

### *5.2 Hand Over*

As discussed in section 3.2, the satellite operations were handed over to KSAT in a phased fashion. This strategy proved effective and would be the recommended approach for any operational transition. However, several opportunities for improvements were identified that could have potentially mitigated some of the challenges

experienced. One key recommendation is a more structured handover process, including daily scheduled calls between KSAT, SFL, and GHGSat.

In particular, the time zone difference between Norway and Eastern Canada could have been leveraged better to enhance continuity. For example, as KSAT performed their operations for the day, they could have collected their questions and notes in preparation for the start of business at GHGSat and SFL where a handover call could take place. This would provide a daily opportunity for clarifications, anomaly support, and discussion of the more nuanced aspects of operations, which may otherwise have been cumbersome and inefficient to do so over email or other communication platforms. Following the end of KSAT’s work day, SFL could then perform a high level assessment of the state of the satellites and all ground software prior to the few hours in which the system would not be monitored. This would not only provide a helpful last check by the experts, but also allow SFL the opportunity to note any specific feedback could be provided to KSAT for the next day’s call on how to assess and resolve any issues found.

Although the Mission Control System is designed to be operated autonomously under normal circumstances, it was learnt quickly that there were a few minor issues that would appear and easily go unnoticed to the unfamiliar eye. While the issues were simple to recover, they required manual intervention and, if left undiagnosed for multiple contacts, could have significant impacts to downlink latency - as will be discussed in section 5.3 below.

Furthermore, the frequency of these ground segment incidents and the manual interventions required had not been discussed in detail during the training session, which was more focused on the critical but less frequent spacecraft anomaly resolution. A better approach could have been, prior to the handover, for SFL to share its operator logs with GHGSat and KSAT, so that the teams were better equipped to identify and recover from these occurrences. Preemptively setting up monitoring and alerting into the system to catch these potential problems from the beginning of the transition would also have been an improvement.

Indeed, the majority of built-in alerting mechanisms of the MCS focused on assessments of the satellite’s state of health. However, during the initial months it became evident that many of the disruptive issues originated on the ground, such as ground software crashes and antenna commanding anomalies. While KSAT responded quickly by developing monitoring, alerting, and eventually, recovery capabilities, the experience highlights the importance of the ground segment on satellite operations and should be critical not to be overlooked.

### *5.3 Operational Impact: Observation Count and Downlink Latency*

We can estimate the operation migration’s impact on system performance by comparing the daily number of observations taken by the GHGSat-C1 to C5 satellites, as well as the time necessary to downlink them, before and after the handover. Note that as GHGSat-C6 to C8 satellites launched just after this migration their numbers are not represented here.

Fig. 2 shows the evolution of the daily amount of observations successfully taken by the full constellation (in green), and GHGSat-C2 (in blue). With the exception of a few days where ground systems or spacecraft anomalies reduced this count, the migration’s impact on observation count was minimal or inexistent, thanks to some margin that existed at the time in the downlink bandwidth and storage space of GHGSat-C3 to C5.

The exception to this rule, GHGSat-C2, is shown more clearly in Fig. 3. Its daily observation count had to be reduced by approximately 25% for around six months as the KSAT and GHGSat teams adapted to some of its idiosyncrasies. Indeed, it is the constellation’s satellite that is operated closest to its limits: it is downlink-limited due to its lack of an X-band radio, uplink-limited by a UHF radio, its payload electronics only have sufficient onboard storage for around 48 hours of observations, and its observations are of a bigger size compared to the similarly-equipped GHGSat-C1. As such, any minor issue disturbing the nominal flow of its downlinking operations has impacts lasting a few days as there is little to no spare downlink capacity, whilst its onboard storage fills up. Additionally, and unrelated to the operational migration, August 2023 wildfires in Canada’s Northwest Territories damaged the optical fiber to the constellation’s Inuvik antenna, preventing the use of that station, just as the team was ready to ramp the observation count back up.

The average observation downlink latency did increase across the constellation during the migration, as is shown in Fig. 4. While the worst was again GHGSat-C2, all satellites were impacted by the effects of software crashes pending

better monitoring and mitigations eventually being put in place. The previously mentioned mid-August Inuvik wildfires also had an impact, until a backup Starlink terminal was put in place to mitigate them. However, this downlink latency increase was mitigated by margin in GHGSat's latency commitments and prioritization of more urgent observations and as such did not impact GHGSat's customers.

By September 2023, six months into the handover, there were no longer any long-lasting anomalies impacting observation count or latency. The constellation did not experience any other long-lasting operations-related anomaly since then, and is now taking much more observations at a lower average latency than before the handover.

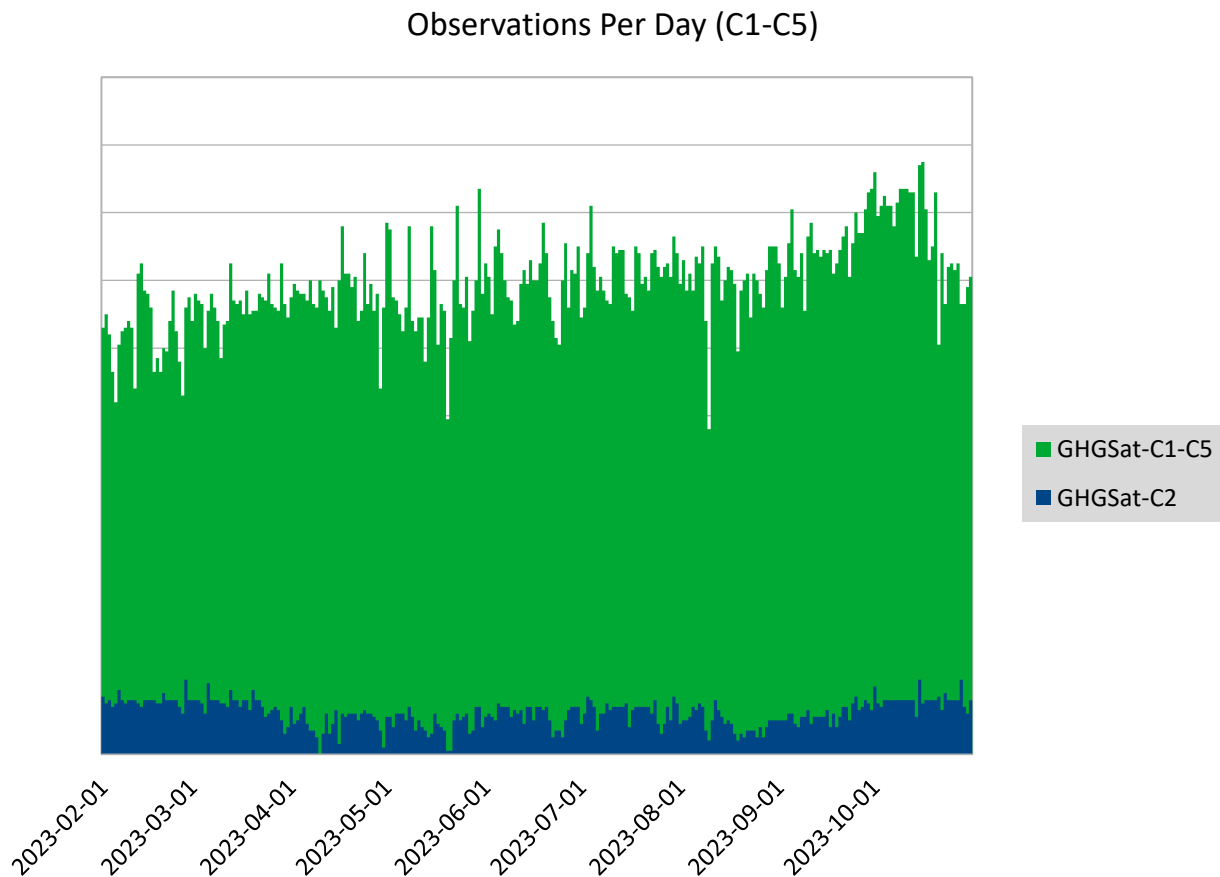


Fig. 2. Daily constellation observation count (GHGSat-C1 to C5 and C2 only).

### Observations Per Day (C2)

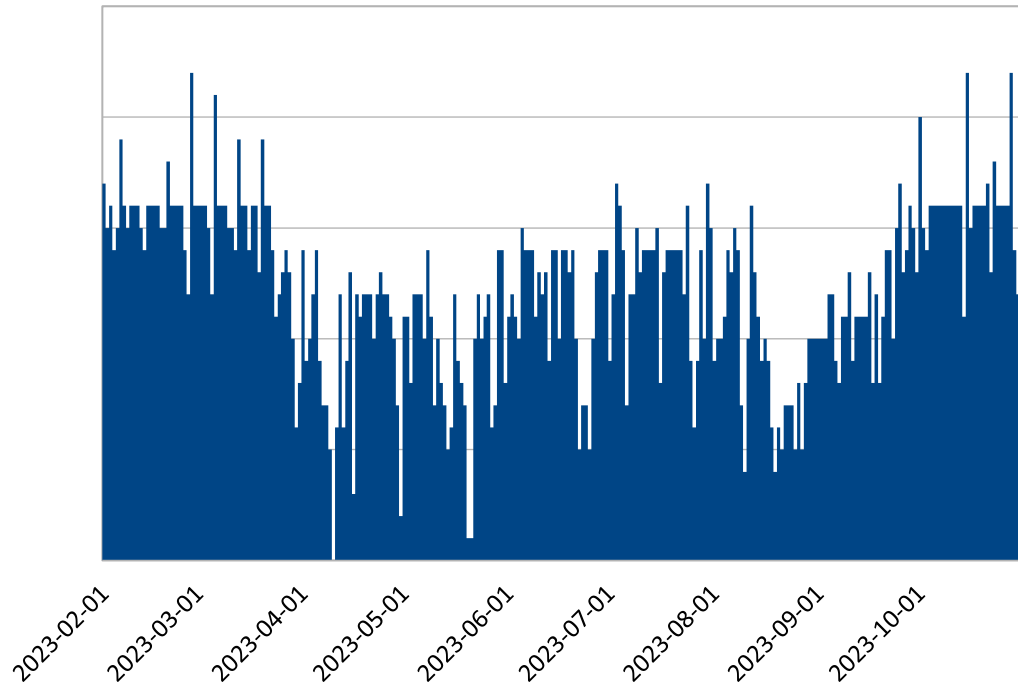


Fig. 3. Daily constellation observation count (GHGSat-C2).

### GHGSat C1-C5 Average Observation Downlink Latency

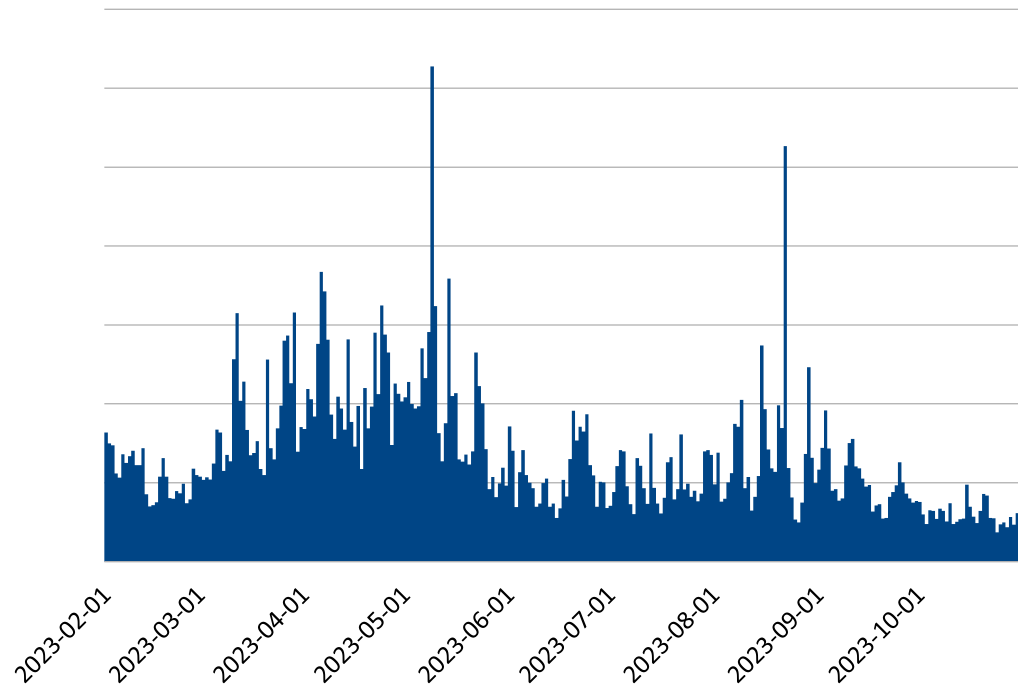


Fig. 4. Observation downlink latency.

#### 5.4 Improvements

Since the handover, operational procedures, training material, processes and both spacecraft and ground system monitoring and recovery have been continuously improved.

The Mission Control System is still used to provide real-time alerts and monitoring functions of ongoing anomalies on the spacecraft through its graphical interface, log files and e-mail notifications. However, to improve the scalability and event driven approach to the operations of the GHGSat constellation, KSAT also developed an internal Multi-Mission Monitoring System (MMS), built on top of the MCS, to support both the constellation and other commercial missions.

The MMS was developed in parallel with GHGSat operations and is designed to collect, analyze, and act on mission-relevant data. The system continuously monitors key performance indicators, including:

1. Satellite health and performance
  - a. Telemetry threshold violations
  - b. Bus performance trends that could impact operations
  - c. Failure detection in mission-specific sequences
2. Orbital safety and collision avoidance
  - a. Conjunction Detection Message (CDM) processing
3. Ground and infrastructure monitoring
  - a. Ground network performance
  - b. Infrastructure availability and performance
  - c. Ground system functionality
4. Mission-specific data handling
  - a. Payload data reception and transfers

When the system identifies an anomaly, it first tries to initiate an automated recovery process for the given problem. If this solves the issue, a ticket is generated in KSAT’s anomaly management system and checked out by an operator before being closed. If the automated recovery fails, or if it doesn’t exist for the specific problem, the MMS escalates the anomaly to the on-duty operator, who recovers the issue and closes it in the anomaly management system.

The MMS is continuously improved, and its current performance can be measured by looking at the Mean Time to Acknowledge (MTTA) and Average Resolve Time (ART) of anomalies. MTTA is used as a measurement of how quickly the operators on duty acknowledge that an anomaly is ongoing, measured from identification on ground, whereas ART is a measurement of time between identification on ground and resolution of the anomaly. Time until resolution is highly dependent on ground station availability, anomaly severity and mission CONOPS.

Fig. 5 and Fig. 6 present the average MTTA and ART of the GHGSat constellation between December 2024 and March 2025, respectively. For these four months, the MTTA was 6 minutes on average, and the ART 98 minutes. As most GHGSat ground stations are near the North Pole and the satellites have an orbital period of approximately 95 minutes, the latter value corresponds roughly to the typical time between two contacts.

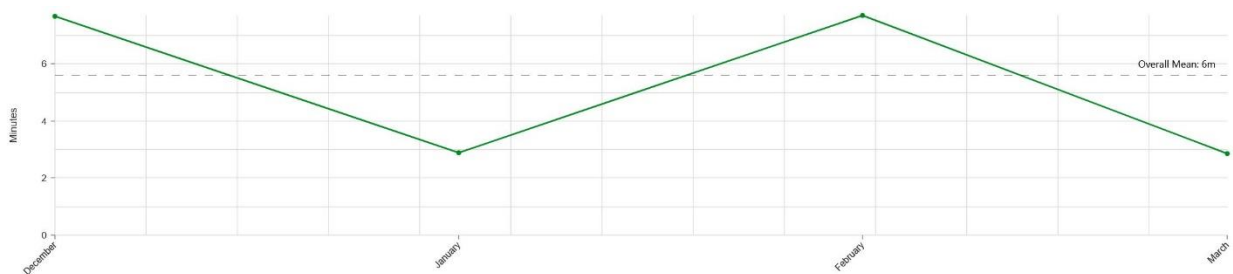


Fig. 5. Performance of mean time to acknowledge (MTTA) between December 2024 and March 2025.

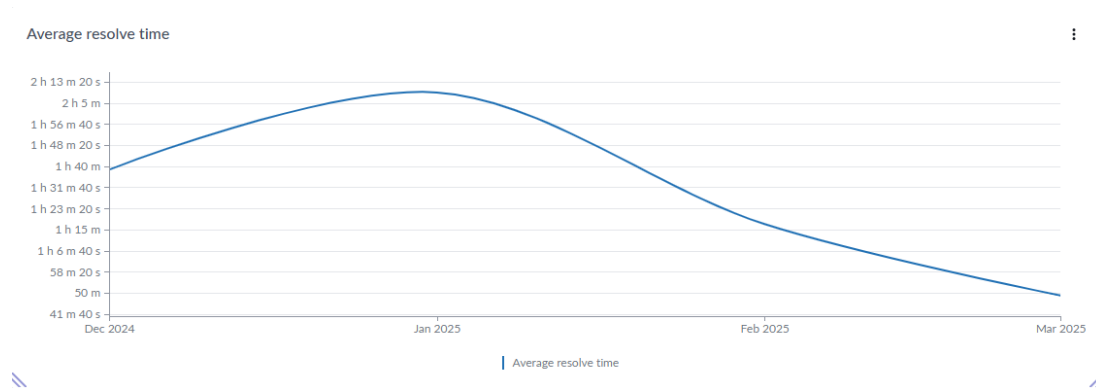


Fig. 6. Performance of average resolve time between December 2024 and March 2025.

Near-term improvements of the system will focus on improving long-term trending analytics by utilizing machine learning and AI with the objective of enabling proactive monitoring that can identify anomalies before they impact operations.

## 6. Conclusion

The collaboration between GHGSat and KSAT demonstrates that a model of outsourcing integrated ground services, including both ground station support and satellite operations, to an external partner is not only possible but advantageous to streamline mission operations. While the handover presented various challenges and areas for improvement, it was overall a hugely successful transition and service to GHGSat's customers was unimpacted.

Two years have now passed since the handover, with additional satellite launches planned for the near future. The partnership between GHGSat and KSAT surpassed initial expectations of both organizations, and has matured into a highly effective collaboration characterized by excellent communication and shared objectives.

## Acknowledgements

We would like to thank the whole staff, past and present, at the Space Flight Laboratory for their support over the years, and in particular to Daniel Kekez for his seemingly infinite knowledge and his work to ensure smooth operations of these satellites. We are glad to be amongst the (likely hundreds of, at this point) people who can rely on you when we ourselves cannot resolve a problem or answer a question.

We would also like to thank the teams at ISED and GAC for their ongoing support and transparent communication, particularly their availability to participate in regular meetings which provided opportunities to share our progress and have any questions answered.

Lastly, we greatly appreciate the opportunity to present our work at SpaceOps 2025 and thank both the Canadian Space Agency and the Canadian Aeronautics and Space Institute for hosting this conference in Montreal, Canada.

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