Development of the Structural and Thermal Control Subsystems for an Earth Observation Microsatellite and its Payload

by

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Graduate Department of Aerospace Science and Engineering
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Abstract

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Broad consensus has been reached in the scientific community that climate change is occurring and its cause is anthropogenic. Governments and other regulatory bodies are quickly implementing stricter and further reaching environmental regulations which require companies to regularly report emissions and penalize heavy polluters. To serve private and public end users in emissions monitoring GHGSat Inc. has contracted SFL to develop GHGSat-D, a remote sensing microsatellite with the mission objective of providing measurements of atmospheric carbon dioxide and methane at emission sources such as power plants and tailings ponds.

This thesis presents the author's contributions to the development of the satellite and payload structure as well as the thermal control subsystem from mission concept to system level testing. Each section begins with a discussion of the driving requirements followed by relevant background information. Analysis and design work is then presented followed by noteworthy results.

Acknowledgements

Dr. Robert E. Zee, thank you for providing me with the opportunity to complete my masters studies at SFL. Also, thank you for having the vision and drive to create what is today SFL. Without your efforts not only would I be poorer as an individual but the country would be poorer for lacking an institution on the cutting edge of its field, training its future leaders. Cordell, I doubt I could describe a better manager and consider myself lucky to have worked with you on the GHGSat-D mission. You helped me grow from an uncertain student to slightly more certain ex-student, which is no small feat.

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Nikki, because you asked repeatedly, here's your shout-out. I've intentionally misspelled your name though and put Ellie's acknowledgment before yours.

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Chapter 1

Introduction

The satellite Earth observation (EO) market is currently in an era of high growth, with the global market set to double within the next decade [1]. The data collected by these satellites is used for climate monitoring, city planning, resource utilization and military intelligence. Currently, the largest end user of Earth observation data is public authorities, followed by defense and intelligence agencies. However, private companies are a growing revenue stream, accounting for 43% of revenues in 2012 [2]. A growing trend in the EO market is the use of a constellation of small satellites with high spatial resolution and hyperspectral capabilities. This trend is partly attributable to the miniaturization of electronics and the implementation of a small space approach. The reduction in cost, from conceptualization to operations, due to these two factors has allowed for numerous private entrepreneurs to enter the market and quickly demonstrate the technologies and products required to prove their companies business case. One such company is GHGSat Inc., which has contracted Space Flight Laboratory (SFL) to develop a microsatellite bus along with the communications, computing and data handling, attitude determination and control, and thermal control subsystems. The mission, known as greenhouse gas satellite demonstration or GHGSat-D, is planned to have a one year lifetime in which it will provide as technology demonstration as well proof of concept for GHGSat Inc. Its mission objective is to monitor point and area source emissions of carbon dioxide and methane worldwide. If successful, a constellation of similarly capable satellites will be procured and launched, providing GHGSat Inc. with robust Earth monitoring capabilities and short revisit times. The development of the structure for the satellite and its payload, as well as the thermal control subsystem is presented in this thesis. All of the work completed for these subsystems, from mission conceptualization to flight system testing, is contained herein.

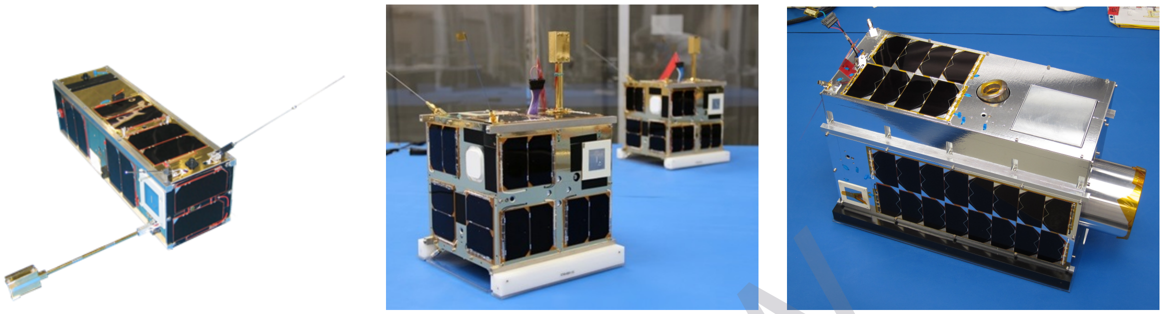
1.1 Greenhouse Gas Monitoring From Space

As broad consensus has been reached that climate change is anthropogenic in nature [3], governments and regulatory bodies are introducing stricter and further reaching environmental regulation regimes. Some of these regulations require companies to provide detailed greenhouse gas emission measurements and penalize them if they are exceeding allowable quotas. This affects companies top and bottom line as they must invest to measure their emissions and pay a tax if they are in excess. For example, in the Canadian oil sands companies must monitor fugitive emissions from tailings ponds. They currently do this by floating a flux chamber on a portion of the surface of the pond, and then extrapolating the point measurement to estimate the emissions for the entire pond. This process is not only costly and unsafe for the workers who must undertake it, but has measurement errors of 50% or greater [4]. GHGSat Inc. seeks to fulfill a need by reducing the cost companies must incur to monitor their GHG emissions. While a large amount of capital must be invested to design and launch satellites, they are capable of monitoring many locations worldwide with low operational costs. This allows companies to reduce their emissions monitoring costs by directing their funds to an outside contractor, such as GHGSat Inc. which specializes in greenhouse gas monitoring.

There are several other satellites on orbit with the capability of monitoring atmospheric carbon dioxide and methane levels. However, the mission objectives for these satellites are typically focused more on scientific research, such as measuring atmospheric greenhouse gas concentrations on a regional and global scale. For this reason, their instruments have spatial resolutions on the order of kilometers. GHGSat-D has been designed with a spatial resolution of less than 50 meters, allowing for measurements of specific emission sources such as tailings ponds and power plants.

1.2 Space Flight Laboratory

Space Flight Laboratory (SFL), located at University of Toronto Institute for Aerospace Studies, is a research laboratory dedicated to pushing Canada's capabilities in the development of small satellites. SFL provides end-to-end services from mission conceptualization to satellite design, analysis, integration, testing, launch services and operations. To date, SFL has developed and launched 12 small satellites with ten more under-development. By utilizing a small team approach and microspace philosophy, SFL has been able to successfully compress the development time from mission conceptualization to launch drastically. The combination of smaller satellites and reduced development time has led to the realization of large cost reductions. By building highly capable satellites, from the nano (1-10kg) to micro (10-100kg) satellite classes, SFL is fulfilling its objective of providing responsive missions at an affordable cost. SFL has developed four standardized buses in-house with multi-mission use in mind. These are known as the CanX-2 bus, generic nanosatellite bus (GNB), next-generation Earth monitoring and observation (NEMO) bus, and NEMO-150 bus. The CanX-2 bus is SFL's oldest design and has a 3U form factor derived from the cubesat standard maintained by Cal Poly [5]. GNB is the most common bus used for SFL nanosatellite missions and has a form factor of 20 cm x 20 cm x 20 cm. It is an evolution from SFL's work on CanX-2 and was driven by the need for a larger payload volume to fulfill more ambitious mission objectives. The GNB has proven ideal for technology demonstration, communication, and astronomy missions, however it is too small to accommodate high resolution Earth observation payloads. Following the growing trend of utilizing small satellites for Earth observation, SFL has developed a larger NEMO bus which has an internal volume twice that of the GNB (42 cm x 26 cm x 20 cm). The increased mass, volume and power consumption limits on the payload, as well as its rectangular profile, make the NEMO bus ideal for EO missions.



(a) CanX-7 (CanX-2 Bus) (b) CanX-4/5 (GNB) (c) GHGSat-D (NEMO Bus)

Figure 1: Various SFL Spacecraft

1.3 GHGSat-D Mission Overview

GHGSat-D is a technology demonstration mission with the objective of monitoring greenhouse gas (GHG) emissions at targets of interest across the globe. The capability of measuring GHG emissions is not unique to GHGSat-D, several launched or planned satellites have similar capabilities. Where GHGSat-D differs from these missions is its microsatellite form factor and high spatial resolution. By imaging with a high level of spatial resolution, GHGSat-D will be able to accurately attribute greenhouse gas emissions to their source allowing for localized monitoring and focused regulatory actions. In utilizing a microsatellite sized bus for the mission, a cost reduction on an order of magnitude has been realized, creating an attractive business case with a product both useful and affordable for interested parties. This is evident in the broad support for the mission across the business and government communities in Canada. Boeing, Sustainable Development Technology Canada, Canadian Space Agency and Canada's Oil Sands Innovation Alliance, among others, have committed to provide either financial or operational support.

The mission utilizes a variant of the NEMO bus and carries a single payload with two instruments. The primary instrument is a spectrometer which images in the short-wave infrared spectrum. It is tuned to measure absorption bands for both carbon dioxide and methane. The secondary instrument is a hyperspectral sensor which detects the presence of clouds and aerosols in the primary instrument's field of view. Due to their high albedo, if a cloud is detected the primary instrument's measurement for that location is discarded. Also, as aerosols can present themselves as greenhouse gases, if they are detected a correction must be applied to the primary instrument's measurements to ensure accuracy. As a demonstration mission, GHGSat-D has a planned operational lifetime of one year with the potential for operations to be extended several years longer if performance requirements are met. Currently scheduled for launch in the first quarter of 2016 on the Indian polar satellite launch vehicle (PSLV), the satellite will be inserted into a 500 km sun-synchronous orbit with a 9:30 local time descending node (LTDN). If successful, GHGSat-D will serve as a proof of concept for GHGSat Inc. who has the intention of launching a constellation of similarly capable satellites. This will allow for the company to increase the number locations that can be monitored, while reducing the revisit time between measurements.

1.4 Thesis Scope

This thesis covers the design and analysis of the structural and thermal control subsystems for the bus and payload of the Earth monitoring microsatellite GHGSat-D as well as the work completed for system level testing. The contributions of this author are both significant and integral to the success of the mission as every component comprising the satellite is reliant on structural integrity being maintained and temperature limits being respected. During the period over which the research for this thesis was conducted the GHGSat-D mission progressed from the system design review to partially through system level testing. This provides the rare ability, for a masters thesis, to present material over nearly the entire development cycle for a satellite. An overview of the material contained in this thesis is presented below.

Structural Subsystem

The structural subsystem is responsible for interfacing with all of the satellite's components as well ensuring their survival during vibration testing and launch. This chapter covers the design and analysis of the satellite structure. First, the driving subsystem requirements and their impact on the structural envelope and layout are discussed. An overview of the final structural design is then presented, including a list and description of the components which constitute the spacecraft. The development of the wiring harness for all of the power and data connections between the avionics is also covered. Lastly, the methodology used when analyzing the satellite's structure is presented along with the results of the static and modal finite element analyses.

GHGSat-D Payload

The payload for GHGSat-D contains two instruments which are required to fulfill the mission objective of measuring the concentration of carbon dioxide and methane in the atmosphere over specific emission sources. The optical designs and performance specifications for the two instruments, an infrared spectrometer and visible to near infrared hyperspectral sensor, are covered. The requirements driving the design of the payload are then presented followed by a more detailed discussion of the optical and stray light requirements. Background on different optomechanical techniques is provided with regards to mounting the optics and allowing for the required adjustments. The detailed design of the payload structure is then covered in depth. Finally, the results of the finite element analysis for the payload are presented.

Thermal Control Subsystem

Required to maintain all of the components within their temperature limits for the duration of the mission, the thermal control subsystem for GHGSat-D has been designed with reliability in mind. This chapter provides background information for both the space thermal environment as well as the control methods implemented in GHGSat-D. Also presented are the requirements for the thermal control subsystem and the rationale behind them. The design of the subsystem flows from these requirements and consists primarily of the passive thermal control methods such modifying external thermo-optical properties and thermally coupling and isolating components. Though less reliable and more complex than passive methods, active control methods were implemented where required. The rationale for including these methods is covered. The finite difference method model for the spacecraft is presented alongside the applicable boundary conditions. The thermal analysis was completed using worst case methodology in which two sets of boundary conditions are selected which envelope all other possible cases. The results of this analysis are presented with a brief discussion of the components which have had their requirements eased.

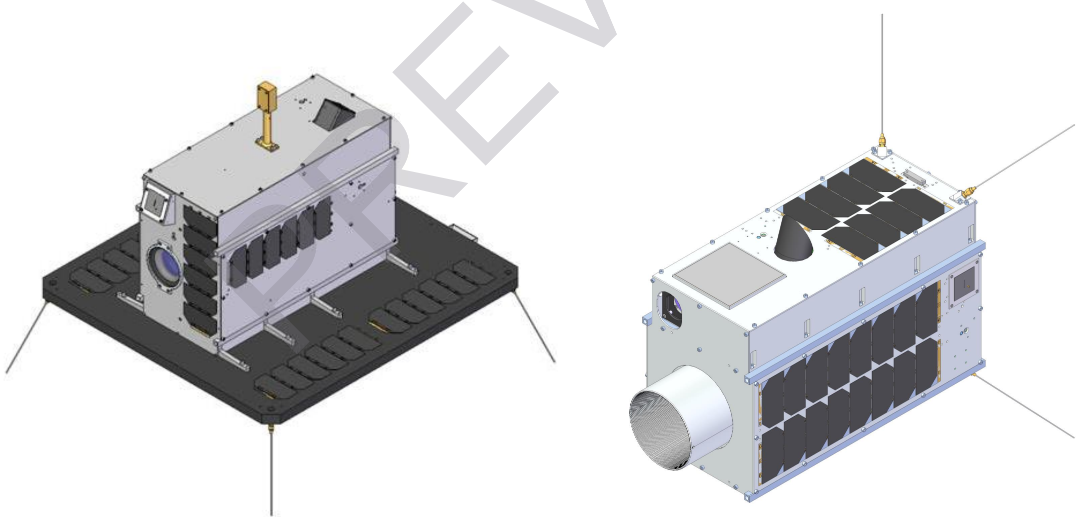
System Level Testing

There are several system level tests completed for every satellite at SFL, three of them are detailed in this section. These are the electromagnetic compatibility (EMC) test, vibration test, and thermal vacuum (TVAC) test. This chapter discusses the rationale and methodology for each test. Preliminary work for the vibration and TVAC test is included along with the results of a preliminary EMC test. Design changes implemented to resolve issues discovered during this test are also presented.

Chapter 2

Structural Subsystem

The structural subsystem of the satellite is responsible for providing mounting interfaces for all of the components required in order to meet mission objectives. It also must provide structural support for said components during testing, launch, and operations, ensuring their survival. As the structure interfaces with every other subsystem within the satellite, it is necessary to have a broad understanding of the other subsystems requirements and to trade-off between them. GHGSat-D was originally conceived to make use of the NEMO-AM bus, shown in Figure 2a, which is another SFL bus that had already completed its design and analysis phase [6]. However,



(a) GHGSat-D Bus at Proposal (b) Finalized GHGSat-D Bus

Figure 2: GHGSat-D Bus Development

when development finally began for GHGSat-D, SFL had completed a full redesign of its power subsystem, and thus a new structure was necessary. The design of the GHGSat-D bus began in earnest based on the system requirements and using the lessons learned during the development of the GNB and NEMO bus. Presented in this chapter are the requirements which drove the design of the GHGSat-D bus along with its final detailed design. Structural analysis work completed to verify the subsystem level requirements is also presented.

2.1 Driving Requirements

Compiled in Table 1 is a non-exhaustive list of the requirements which drove the material selection and the structural design of the satellite [7]. These requirements also defined the envelope of the satellite as well as the placement of the components that constitute it.

A number of the structural requirements are driven by the higher level system requirement of maintaining compatibility with the XPOD Duo separation system. Figure 3 shows the XPOD Duo loaded with GHGSat-D on the left and by itself on the right. The XPOD Duo interfaces with the satellite in the eight locations that have been highlighted with red circles. To fix the spacecraft in place, each of these locations on the XPOD Duo has a tooling ball which mates with a cup machined into the spacecraft structure. Another driver of the structural

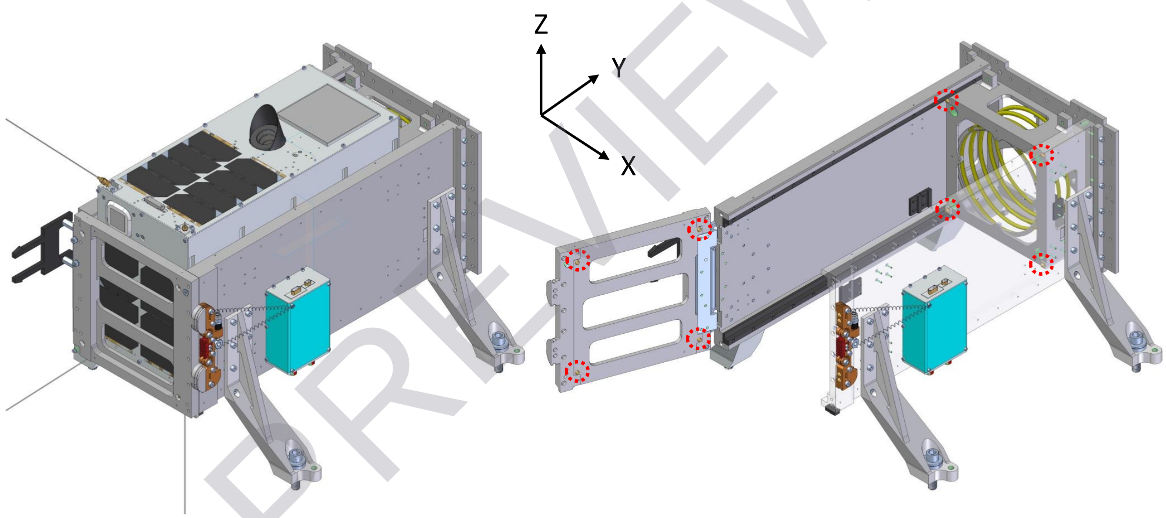


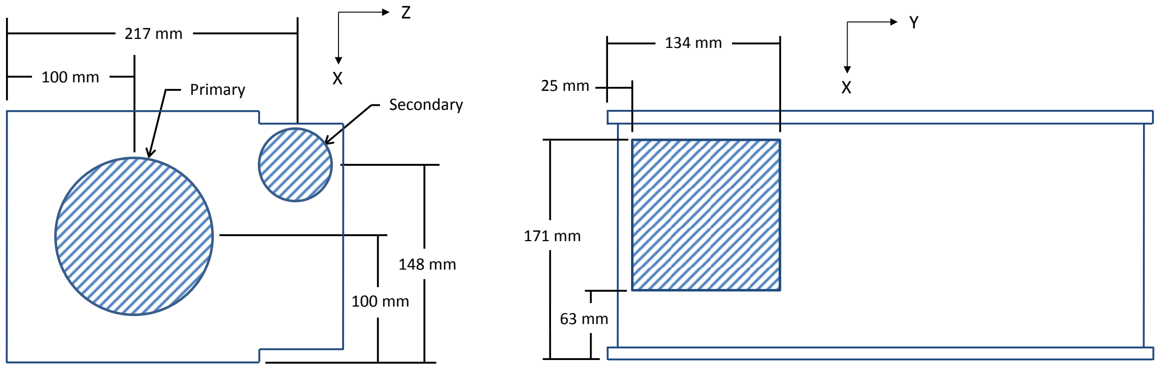
Figure 3: XPOD Duo with GHGSat-D (left), XPOD Duo Interfaces (right)

design for GHGSat-D, and the placement of the components within the bus, is the payload interface control document (ICD) [11]. After a period of discussion and iteration with the payload provider, structural considerations such as apertures, and volume and mounting point allotments, were finalized for the payload. The apertures provided, shown in Figure 4, are for a primary and secondary instrument (–Y Panel) as well as a radiator (+Z Panel).

The volume allotted to the payload occupies half of the interior of the spacecraft. An external volume was also provided, constrained by the XPOD Duo, for a baffle. The envelope of the allotted volume is shown in Figure 5a. The payload is required to interface with mounting points located on the –Z and +Z trays as shown in Figure 5b. There are twenty mounting points total, eight in both the X/Y and Y/Z planes, and four in the X/Z plane. By requiring the payload to be mounted in all three planes, the use of pins for alignment was avoided.

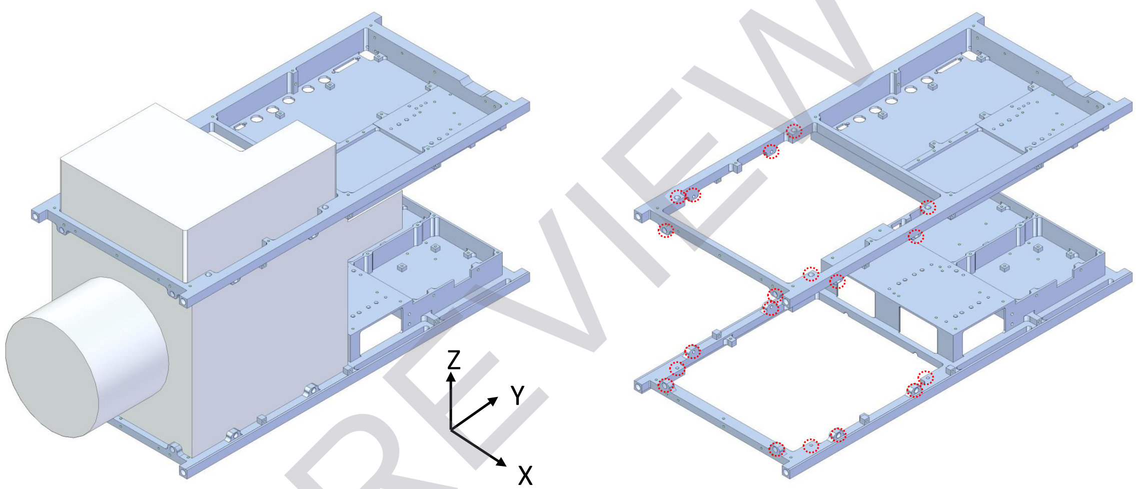
Table 1: Structural Subsystem Driving Requirements

No.	Description	Rationale
	General Requirements	
STR1	All structural components shall be at a common ground with the resistance between any two points being 1Ω or less.	To reduce the potential for arcing between surfaces
STR2	All volumes shall be vented using an aperture with an enclosed volume to aperture area ratio of less than 143 m.	To avoid damage or deformation caused by pressure differentials and remove virtual leaks during testing. Value is conservative based on analysis [8] and compared to rule of thumb [9]
STR3	All components within the satellite shall be mated with a preload greater than the 5σ acceleration value of the composite random vibration spectrum	Using the 5σ value is a conservative approach to ensure components do not shift due to vibration during testing and launch, removing the need to complete a dynamic analysis
STR4	The structure shall be composed of materials that exhibit a total mass loss of no more than 1% of the component's initial mass and that contain no more than 0.1% collected volatile condensible material	Reduce potential for outgassed material to short electronics or degrade optics
	Launch Vehicle and Separation System Requirements	
STR5	The satellite rails shall be 440 mm in length with the feet forming a square with an edge length of 195 mm center to center. There shall be no protrusions from the +X, –X and +Y panels with a height greater than 5 mm	To maintain compatibility with the XPOD Duo Separation System
STR6	The satellite shall have a mass of less than 15 kg	To maintain compatibility with the XPOD Duo Separation System
STR7	The satellite shall have a first natural frequency greater than 90 Hz	To ensure compatibility with all candidate launch vehicles (Dnepr, PSLV, Vega, Soyuz)
STR8	The satellite shall be designed to not yield, with a margin of safety greater than 50%, under launch-like quasi-static loading which is defined as the 5σ acceleration value of the composite random vibration spectrum	To ensure no yielding of the structure will occur during launch on any of the candidate launch vehicles. The 5σ value is overly conservative to remove the need for a dynamic analysis. The margin of safety is to account for uncertainties (modeling, material)
	Component Requirements	
STR9	The satellite shall provide the mounting points, volume and apertures for the payload specified in the payload ICD	Ensure compatibility with the payload
STR10	The satellite shall provide mounting interfaces, volume, surface area and apertures for the ADCS, Power, C&DH, and Communications subsystem components	Required for other subsystems to meet their requirements. A list of these components is shown in Table 3
STR11	The star tracker shall be mounted directly to the main structural component of the payload with its aperture on the same face as the radiator. It should be oriented at an angle 108° with respect to the payload aperture as recommended by [10]	To reduce errors introduced by integration misalignment and thermal gradients. Ensure star tracker functionality is not degraded by stray light during payload operations



(a) -Y Panel (b) +Z Panel

Figure 4: Payload Apertures



(a) Volume (b) Mounting Points

Figure 5: Payload Allotments

2.2 GHGSat-D Structure

The solid model for the structural subsystem was developed using the Solid Edge CAD package. The structure for GHGSat-D is comprised of two trays, two risers and six exterior panels. The trays are the main structural components of the satellite with the payload creating a rigid connection between them. Using the trays and payload to form a rigid frame for the satellite has been employed successfully in past SFL missions. The panels and risers form an enclosure around these components, shielding the internal avionics and actuators. They also provide surface area for mounting components and solar cells, and applying thermal tapes. There are two rails on each of the trays with a foot at both ends of each rail. As mentioned in the previous section, a cup is machined into each of these feet to interface with a corresponding ball in the XPOD Duo separation system, securing the satellite in all axes. An exploded view of the structural components can be seen in Figure 6. The outer dimensions of the satellite are 440 mm x 200 mm x 267 mm. The length of the rails as well as the spacing between their feet is driven by STR5.

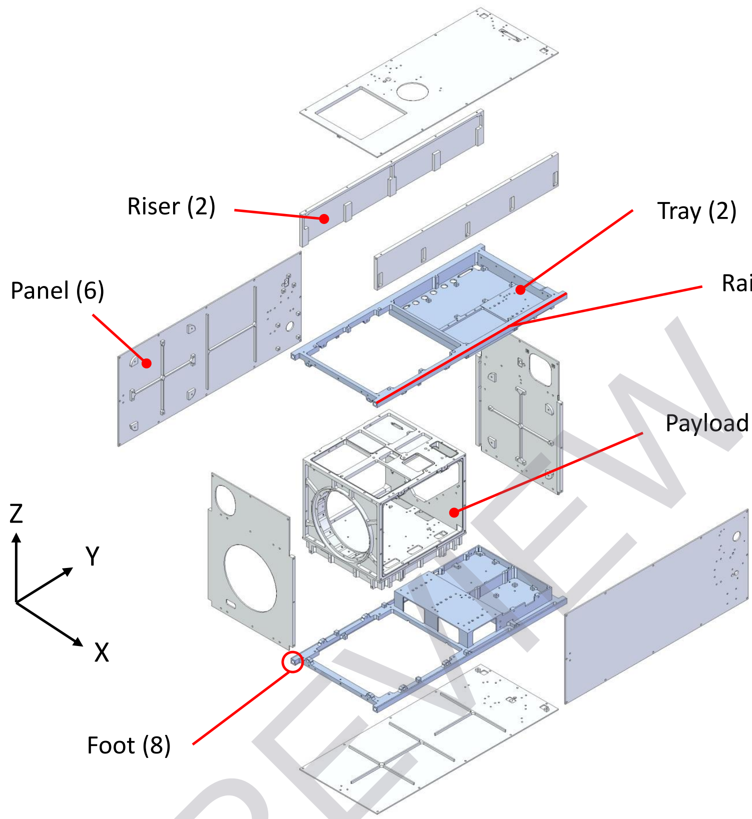


Figure 6: GHGSat-D Structure Exploded View

The entirety of the structure for GHGSat-D is machined from aluminum 6061 alloy. Shown below in Table 2 is a comparison of the candidate materials investigated for the structure. The properties used to compare the materials have been chosen for their importance in meeting overall system and mission requirements. Density is a key property as many missions are mass constrained. The easiest way to reduce the mass of a spacecraft is to switch to a lower density material for the structural components. Strength to density ratio was given a low weighting during material selection as machining panels thin enough to take advantage of this property creates other issues, such as mounting components for example. High thermal conductivity is of high importance as the overarching goal of the thermal control subsystem is to meet requirements while being as simple as possible. This is much easier to accomplish when the structure of the satellite serves to thermally couple all of the components. Magnetism is another important property as a high parasitic magnetic dipole will affect the magnetometer readings and degrade attitude control performance. Lastly, as a result of the low cost targets and short development periods for small space, the cost of procuring and machining materials is an important factor. Materials which are costly, have long lead times, special machining requirements or necessitate complicated surface treatments are to be avoided. This is referred to as stock to flight cost and composites were not evaluated for exactly this reason.

Table 2: Candidate Material Comparison

Material	Density	Strength to Density	Thermal Conductivity	Magnetic	Stock to Flight Cost
Aluminum 6061 T6	2.73	102	167	No	Low
Titanium 6Al 4V	4.43	199	6.7	No	High
Stainless Steel 316	8.00	26	16.3	Yes	Low
Magnesium ZK60A T5	1.83	167	120	No	Medium

Values taken from http://matweb.com/

After examining the different materials it is clear that aluminum and magnesium are the best candidates. Comparing the two, they vary primarily in density and stock to flight cost. The mass for GHGSat-D remained under the 15 kg limit with margin, as required by STR6, even with an aluminum structure. As exceeding the 15 kg mass limit was not a concern, aluminum was selected over magnesium. This was because of aluminum's higher thermal conductivity and lower cost. The structure for the satellite also serves as the electrical ground for all of the avionics; as such it is necessary to ensure that all of the structural components are electrically coupled. The oxide layer that forms on the surface of aluminum is electrically non-conductive. Therefore, a chromate conversion coating was applied to all of the aluminum components to maintain their conductivity. This conversion coating is also applied to protect the parts against corrosion. Iridite NCP was selected as the conversion coating over the more popular Alodine 1200S. This is due to the fact that Alodine 1200S contains hexavalent chromium which is a known carcinogen. Some parts may require filing after the treatment is applied releasing particulate into the air. For this reason, it was decided that Alodine 1200S presents an unnecessary risk to personnel. However, Iridite NCP is not an ideal solution as it performs worse than Alodine [12] and cannot be visually inspected. Future missions should investigate further for treatments which can, at the least, be visually inspected.

Structural Design Guidelines

There are number of guidelines and practices followed for all structural designs completed at SFL. The basis for these comes from previous missions and graduate students' work. A good reference for the rationale behind some of these practices is Grant's thesis [13]. Several of the recommendations made by Grant, along with the other guidelines, were used throughout the design phase of GHGSat-D. Several of the guidelines worth noting are listed below.

- All fasteners should be secured using threaded holes rather than nuts. As there is limited space within the spacecraft during integration it can be very difficult if not impossible to hold a nut in place when fastening a screw. Also, there are a number of sensitive components that could be damaged by dropping nuts onto or into them.

- Aluminum has been used for all of the structural components, for reasons stated previously, however it is soft compared to the stainless steel screws. There is the potential for the threaded holes in the aluminum parts to be ruined when a stainless steel fastener is inserted. These threaded holes will also be used repeatedly causing wear and fatigue of the threads. Nitronic Helicoil inserts should be used to protect the threaded holes in the aluminum parts and increase the number of cycles they can undergo.

- Ribbing should be designed into any thin plates, such as the panels, to facilitate manufacturing. It was found in past missions that machine shops had difficulty milling large thin plates without causing them to warp.

- There should be no blind holes; however, if required, vented screws should be used. It is best practice to avoid blind holes for a couple of reasons. They are unvented and as such the air trapped between the bottom of the hole and screw tip can cause a virtual leak when vacuum testing the spacecraft. They are also difficult to remove Helicoils from if necessary. An allowance is made for the holes beneath solar cells as they will be sealed regardless once the solar cells are laid down. If through holes are used in these locations it is possible for a pocket of trapped air to cause the cell to crack when going from ambient pressure to vacuum.

- The placement of the different components in the spacecraft should be completed with the wiring harness in mind. Wire routes and tie down locations should be specified during the design phase of the structure. Components which share numerous connections between one another should be placed in close proximity to each other. An example of this would be the on-board computers and radios or battery pack module and modular power system.

- The placement of different components should also consider the assembly procedure. Integration constraints should be reduced to allow for a flexible assembly procedure. It is very inefficient if multiple components must be de-integrated whenever a single component is removed. The best approach is to design such that the handling required for the components throughout the entire assembly, integration and testing phase is minimized. Where possible, components should be combined into sub-assemblies so that they can be integrated with the structure as a single unit. Adequate clearance for any assembly tools required must be included.

- Thermal conduction paths for all components should be definite. This means that the thermal path from a component to a heat sink, such as the structure, should not be able to change due to vibration or temperature. The accuracy of the hand calculated conductances that are input into the thermal model benefit greatly from having thermal paths that are well defined and unchanging.

Subsystem Components and Placement Constraints

Each of the subsystems within the satellite require a number of components to meet the mission objectives. To facilitate integration, the satellite was designed as a number of separate sub-assemblies. The complete GHGSat-D bus consists of five panel, two tray, and the payload sub-assemblies. As per previous SFL missions, all of the sub-assemblies within the spacecraft, excluding the payload, are named corresponding to their location in the spacecraft with respect to its reference frame. Compiled below in Table 3 is a list of all of the components which comprise each of the respective sub-assemblies. The payload sub-assembly is not listed because at the spacecraft level it is treated as a single unit. A detailed description the payload is presented in Chapter 3. Also not contained in this list is the star tracker. As required by STR11 the star tracker is mounted directly to the payload and is therefore not a part of any of the satellite sub-assemblies. The star tracker is used to allow for GHGSat-D to meet its fine pointing requirements. For it to perform as specified, the star tracker must maintain an exclusion angle of 30° between it and limb of the Earth and an angle of 60° between it and the Sun. A placement analysis was completed by Shen [10] to find the orientation at which the availability of the star tracker would be optimized. An angled bracket was then designed to create an interface for the star tracker with the payload that orients it as required.

Table 3: GHGSat-D Sub-assembly Components

+X Panel	–X Panel	+Y Panel	+Z Panel	–Z Panel	+Z Tray	–Z Tray
Solar Cells (16)	Solar Cells (16)	Solar Cells (8)	Solar Cells (8)	Solar Cells (16)	Modular Power System	S-Band Transmitter
Separation Switch (2)	Magnetorquer	Magnetorquer	Magnetorquer	UHF Antenna (2)	GPS Enclosure Module	Reaction Wheel Module
Sun Sensor	Sun Sensor		Sun Sensor		DC to DC Converter	Sun Sensor
S-Band Antenna	S-Band Antenna		UHF Antenna (2)		Battery Pack Module	UHF Receiver
			Test port			On-board Computer (2)
						Rate Sensor Module

There were numerous placement constraints which came from either other subsystem requirements or the structural design guidelines. These have been compiled in Table 4. All of the components were kept towards the +Y end of the spacecraft as the internal volume at the –Y end has been allotted to the payload. It was also for this reason that the –Y panel was kept clear of any components, negating the need to run harness along the length of the spacecraft and simplifying the assembly process. Both of the radios were placed such that their coaxial connectors were at the +Y end of the interior. By placing the UHF and S-band antennas near the +Y end of the structure as well, it was possible to keep the routing of the coaxial cables localized to the end of the structure.

Table 4: Component Placement Constraints

Component	Description	Rationale
Batteries	The battery pack must have a capacity of greater than 70 Wh and a voltage of 12 V. Should be placed in close proximity to modular power system	To ensure depth of discharge never exceeds 20% and voltage requirements for the payload are met
Solar cells	Must be wired into strings of eight cells. Both X and –Z panels must have two strings, +Y and +Z must have one	The string voltage must exceed the battery voltage for the power avionics to function properly. Power generation requirements are met with eight strings
Reaction wheels, Magnetorquers and rate sensors	Must have three of each component mounted orthogonal to one another with a known rotation with respect to the principal body axes	Required for the attitude determination and control subsystem to meet requirements
Sun sensors	Must be placed on each face, except for the –Y	Allow for attitude determination regardless of attitude
Magnetometer	Must be placed away from large current sources such as the reaction wheels. Nearby fasteners and components must be nonmagnetic	Reduce the affect of magnetic fields generated within the spacecraft on measurements
Star tracker	Must be mounted directly to the structure of the payload and have an aperture on the same face as the payload radiator. Must be oriented such that Earth and Sun exclusion angles are respected	Minimize misalignments due to thermal expansion and mechanical interfaces. Ensure performance requirements are met, bright light saturates the detector
On-board computers	Must be stacked. Should be placed centrally within the satellite interior.	Minimize volume consumed and reduce wire harness complexity.
GPS receiver	Should be mounted in same assembly as GPS antenna	Reduce length of cable connecting the two components, allow for integration as a single unit
GPS antenna	Must be oriented, with a clear view, towards the GPS constellation during payload operations	Ensure GPS solutions are successful during payload operations
UHF receiver and S-band transmitter	Must be mounted in an enclosure with an interior as similar as possible to the one utilized in previous GNB structures	Mitigate the potential of introducing new electromagnetic compatibility issues
S-band antennas	Two patch antennas must be mounted facing opposite directions. Should be mounted near the S-band transmitter	To create an omnidirectional radiation pattern. To reduce co-ax cable length
UHF antennas	Four monopole antennas must be mounted such that they create a square profile. Should be mounted near the UHF receiver	Same as S-band

2.2.1 +Z Tray Sub-assembly

The +Z tray contains several small assemblies which are integrated as separate units and can be dropped into the +Z tray sub-assembly when desired, these are referred to going forward as modules. The rationale behind this approach is twofold. It allows for the integration process to be compartmentalized, which reduces assembly constraints at the sub-assembly and system level. This reduces the need to remove several components in the case of a part failure. Another benefit is the potential for multi-mission use. NORSAT-1, another satellite which is currently undergoing integration at SFL, utilizes variants of some of the modules found in GHGSat-D. The +Z tray contains the GPS module, battery pack module, and modular power system (MPS). A DC to DC converter is also mounted to the +Z tray to regulate the line voltage from 5 V to 3.3 V for the GPS receiver. The bulkhead connectors have been implemented to allow for the MPS and wiring harness to be integrated independently into the spacecraft. This wouldn't be possible without the bulkhead connectors as most of the wires coming off of the MPS are soldered directly to the cards.

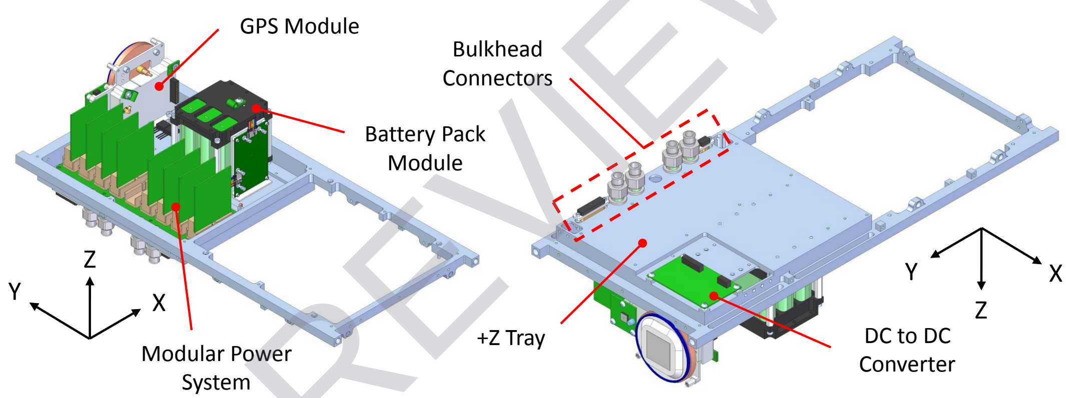


Figure 7: +Z Tray Sub-assembly

The GPS module, shown in Figure 8, contains both the GPS receiver and GPS antenna. These components allow the satellite to localize its position in space in real-time by receiving signals from the GPS constellation. The error on the satellites real-time position knowledge is dependent on several factors but is typically accurate to within ±10 m. To reduce the potential for electromagnetic compatibility issues with the other avionics, an enclosure was designed to shield the GPS receiver. The GPS antenna was also shielded from the interior of the spacecraft through the use of a conductive gasket installed around the edge of its face. This gasket is compressed between the antenna and the +Y panel. The +Y sun sensor is also mounted to the GPS module. Sun sensors are used to identify the attitude of the spacecraft with respect to the solar vector. As the +Y panel is the last to be integrated with the spacecraft during assembly there is little room to make connections between the wiring harness and components on the panel. By placing the sun sensor on the GPS module, only the panel connector, which is wired to the magnetorquer and solar cells mounted to the +Y panel, must be mated.