GLOBAL MONITORING OF GREENHOUSE GAS EMISSIONS

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ABSTRACT

Earlier this year, GHGSat launched the world's first satellite capable of measuring greenhouse gas emissions from targeted industrial facilities around the world. We will offer a single solution to measure emission rates of carbon dioxide and methane from selected targets with greater precision and lower cost than ground-based alternatives, across a wide range of industries. GHGSat will derive the emission rates of these sources from 12 x 12 km^2 maps of the atmospheric column densities of carbon dioxide and methane produced using its patented sensor at a spatial resolution better than 50 m. Satellite mass is less than 15 kg. Our solution will provide industrial site operators and government regulators with the information they need to understand and manage their greenhouse gas emissions better and ultimately to reduce them more economically. We will describe the system, including the sensor and satellite specifications. We will also describe our products and services and provide an early look at imagery from our first satellite.

BACKGROUND AND INTRODUCTION

Inspiration

In the summer of 2011, Quebec and California announced that they would implement a market-based "cap and trade" system to attribute a value to each ton of carbon emitted by industrial operators. Industrial operators would therefore be motivated to better measure their emissions, so that they could control and ultimately reduce them.

This announcement inspired GHGSat's founders. They understood that where there was a value to a ton of carbon, industrial operators and their government regulators would need precise measurements of emissions from industrial facilities, at attractive prices. GHGSat's parent company had already been working closely with a partner company through the 2000's for the Canadian Space Agency to develop key technologies to make such measurements from a satellite. They therefore began customer interviews, technical evaluations and financial analyses to determine whether they could profitably offer a solution.

They discovered an existing multi-billion-dollar market for carbon emissions, growing steadily as ever more jurisdictions imposed taxes or implemented carbon trading mechanisms, being served by a vast array of measurement products and services. They believed that their spectrometer technology could disrupt this large and growing market by offering a single solution with better precision and lower cost than alternatives, across a wide range of industries, anywhere in the world.

Within 3 months of the announcement, they secured two blue-chip customers, developed a preliminary technical solution, recruited a core set of vendors, and developed a business plan. GHGSat was incorporated in December 2011, secured initial financing through 2012, and began development in the spring of 2013.

R&D Progress

In just over two years from spring of 2013 to summer of 2015, GHGSat followed an accelerated development process to design, manufacture, integrate, assemble and test its first satellite system, designated “GHGSat-D” and later named “Claire”.

- The underlying science leveraged similar satellite measurements pioneered by NASA, the European Space Agency, and the Japanese Aerospace Exploration Agency over 30 years.
- The primary instrument was designed to provide similar precision, but with 100x better spatial resolution than the current state-of-the-art in order to measure emissions from targeted sites. Expert external reviewers were recruited to evaluate the design, and to support development.
- In order to meet a reasonable budget and to reduce risk, the primary instrument was designed to fit in a nanosatellite with proven space heritage. This resulted in a total satellite cost on order of 1% of that for other greenhouse gas measurement missions.
- The system was built and tested at component, sub-system, and integrated levels. External references were used where possible to verify performance.
- The system was awarded a US patent in January 2016, and a filing for the same was made under the Patent Cooperation Treaty in May 2015.

The satellite was successfully completed in Fall 2015. Sample images from acceptance testing are shown in Figure 1 and Figure 2 below.

The satellite was successfully launched in a sun-synchronous orbit by the Indian Space Research Organization in late June 2016.

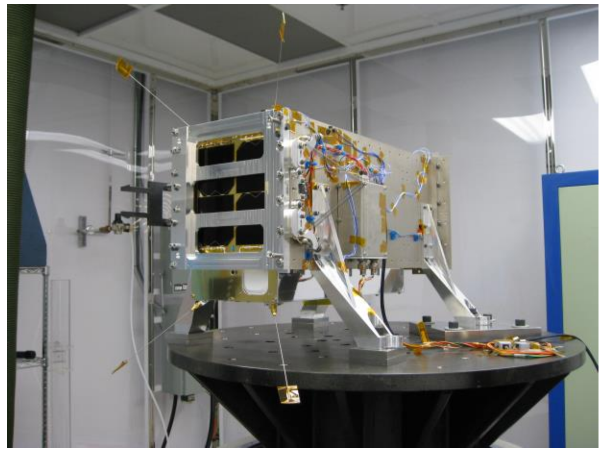

Figure 1: GHGSat-D in its XPod deployment mechanism, during vibration testing

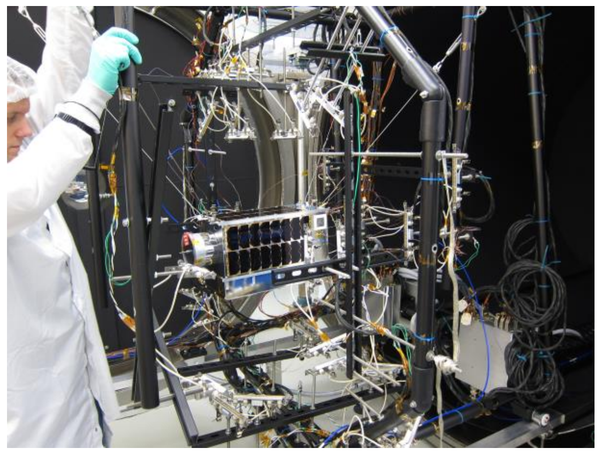

Figure 2: GHGSat-D in a harness prior to thermal vacuum testing

GHGSat-D Team

GHGSat recruited a core set of vendors for its first satellite:

- Xiphos Systems Corporation provided the complete processing infrastructure for GHGSat algorithms, include both the payload processor (using Xiphos’ Q7 hybrid processor) and the post-processing chain on the ground.
- MPB Communications Inc. provided the payload, including both the primary (short-wave infrared, or SWIR) and secondary (visible-near infrared, or VNIR) payload.
- The University of Toronto Institute for Aerospace Studies – Space Flight Laboratory (UTIAS-SFL) provided the satellite bus, based

on its NEMO-class bus, as well as launch and operations services for GHGSat-D.

- James Sloan, Professor Emeritus from the University of Waterloo, provided expert support to GHGSat as GHGSat-D's mission scientist.

This core group of vendors was supported by a number of additional partners and subcontractors.

MISSION OVERVIEW

GHGSat-D will monitor greenhouse gas emissions for several industries including oil and gas, power generation, mining, pulp and paper, pipelines (natural gas), landfills, chemicals, metals and aluminum, cement, agriculture and transportation. In each of these industries, GHGSat-D will measure emissions from target sites anywhere in the world. Sites can include:

- Industrial facilities with fixed, concentrated sources of emissions (e.g. stacks)
- Area sources with emission hotspots (e.g. landfill methane, pipeline leaks)
- Fugitive sources over wide areas (e.g. tailings ponds, mine faces)

GHGSat-D's mission objectives are to:

- Validate the business case for GHGSat Inc.;
- Verify and validate the technology to measure emissions of carbon dioxide and methane from targeted, land-based sources with emissions greater than 50 kt CO_2 eq per year;
- Engage at least one regulatory authority for the recognition of GHGSat technology as a valid tool for monitoring and reporting greenhouse gas (GHG) emissions;
- Market the information products, using sample data from at least ten different facilities, of different types, in different geographic locations, with different amounts of background emissions.

MISSION REQUIREMENTS

GHGSat-D is designed to meet the following key requirements:

Technical

- Target any site in the world between 60° South and 80° North;
- Quantify the carbon dioxide total atmospheric columns above target sites;
- Quantify the methane total atmospheric columns above target sites;
- Generate images of target sites, for geolocation purposes;
- Quantify greenhouse gas columns at a ground sample distance of 50 m or less;
- Quantify GHG columns in a field of view of at least 12 km x 12 km at altitude of 500 km.

Operational

- Operate for minimum of one year on orbit;
- Be capable of observing at least 1,000 target sites or more per year with GHGSat-D alone;
- Verify GHGSat data products by comparison with other available ground- and space-based measurements;
- Support various satellite tasking priorities.

Quality

- Produce a data product containing spatially resolved mixing ratio of carbon dioxide within the field of view. The target precision will be 1% of the atmospheric background level;
- Produce a data product containing spatially resolved mixing ratio of methane within the field of view. The target precision will be 1% of the atmospheric background level;
- Produce emission rate estimates where single-site GHG emission rates as low as 50 kt CO_2eq/yr are quantified. The detection threshold and emissions rate precision for specific sites will depend on gas species, local meteorological conditions, season, terrain and other variables;
- Determine the presence of clouds and aerosols in the full field of view of the payload.

SYSTEM DESIGN

GHGSat-D's system architecture is summarized in Figure 3 below.

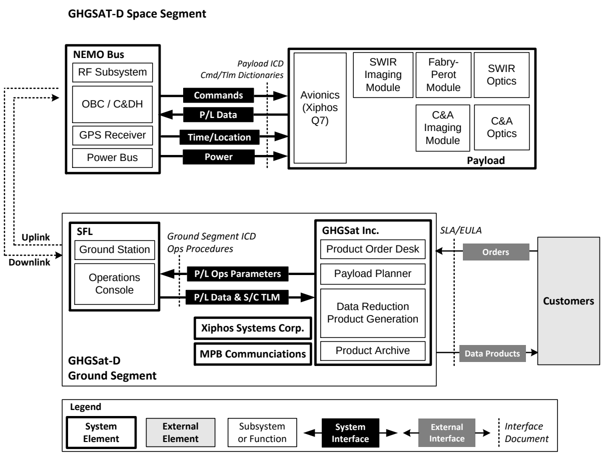

Figure 3: GHGSat-D System Architecture

The space segment includes the bus and payload. The ground segment includes the Earth station and post-processing infrastructure. Each of these is described in the following sections.

GHGSat-D's observation sequence is planned on a daily basis based on customer orders and operational considerations (e.g. periodic calibration and system maintenance).

Space Segment - Bus

GHGSat-D spacecraft bus was provided by the Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS). The form factor of GHGSat-D was derived from NEMO-AM and has a primary body measuring 20x20x42cm with an additional 7x18x42cm mezzanine on one side (-X). The mass of GHGSat-D, payload included, is less than 15 kg.

The entire attitude and orbital determination and control subsystem on GHGSat-D draws heritage from that found on SFL's BRITE satellites, which in turn draw partial heritage from several other SFL missions.

Attitude determination on GHGSat-D is achieved with a suite of onboard sensors. For coarse attitude determination, a set of five sun sensors plus a magnetometer provide a full three axis solution with flight heritage from four SFL spacecraft. For fine attitude determination, a star-tracker is mounted directly to the payload itself for optimum alignment stability over temperature.

Fine and coarse attitude control on GHGSat-D is achieved using a set of three orthogonal reaction wheels. Detumbling and momentum dumping capabilities are provided by a set of three orthogonal vacuum core magnetorquers.

The reaction wheels used on GHGSat-D are provided by Sinclair Interplanetary and are a high-torque variant of the wheels on NEMO-AM. The additional torque provided by this variant of the wheel is expected to improve slew rates without having a significant impact on pointing performance.

Orbit determination on GHGSat-D is accomplished via a Novatel OEMV-1G GPS Receiver. This particular receiver and its associated antenna have over twelve years of flight heritage from SFL missions. To simplify operations, both the payload and the spacecraft will be connected to and can request position, velocity and time information from the GPS receiver.

The anticipated level of pointing accuracy is approximately 0.4 degrees, corresponding to less than 30% of the instrument's field of view. This will ensure that target sites will be located in the central portion of the images.

Space Segment - Payload

GHGSat-D's payload includes two spectroscopic instruments used for remote sensing of greenhouse gases. The primary instrument is a spectrometer operating in the short-wave infrared (SWIR) based on a Fabry-Pérot interferometer. This instrument provides imagery of the ground target and spectroscopic information on target gas abundances (greenhouse gas for this mission). GHGSat-D also contains a secondary instrument for cloud and aerosol detection.

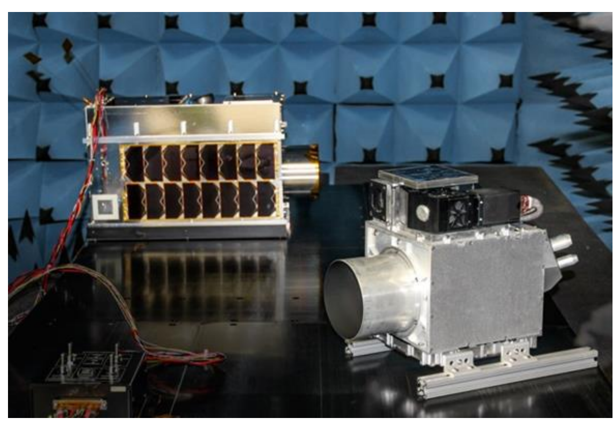

Figure 4: Flight payload (right) and satellite (left). At the time this image was taken, the satellite contained an engineering model of the payload.

The primary instrument restricts the incident spectral passband to a narrow wavelength region between 1600-1700 nm selected for the presence of spectral features for methane and carbon dioxide, as well as relatively little interference from other atmospheric species, H_2O in particular.

The optical design of the primary instrument includes three lens groups (in addition to the Fabry-Pérot interferometer), as well as beam-folding mirrors required to fit the telescope into the NEMO bus. The first lens assembly is a large telescope doublet at the input, and the second is a collimating assembly which together provide the magnification required by the system. The third lens group is an imaging assembly which forms an image of the target scene on the focal plane array.

The focal plane array selected for GHGSat-D is a high sensitivity InGaAs SWIR camera with advanced dynamic range enhancements. The focal plane array is in a 640 x 512 array format, of which GHGSat-D masks the area outside the central 512 x 512 array. The selected InGaAs array has heritage on a NASA mission.

Ground Segment – Earth Station

GHGSat-D has begun operation with a single Earth station in Toronto at SFL. In the event that demand exceeds the capacity of this single station, GHGSat will deploy additional ground stations at appropriate locations.

Ground Segment – Post-Processing

Each GHGSat target observation produces approximately 200,000 measurements of the atmospheric radiance in the SWIR, one for each ground pixel.

Each measurement provides a representation of the top-of-the-atmosphere spectral radiance emerging from a given ground pixel. However, the execution of atmospheric radiative transfer models is too computationally expensive to be performed for each ground pixel. As GHGSat's field of view is small compared to previous or existing GHG-measuring missions, we assume that the atmospheric state in the field of view, as relevant to GHGSat, can be represented in the instrument's field of view as an average state plus small, near-surface enhancements due to localized emitters. The column density retrievals are then performed in two distinct steps.

- In the first step, the full forward model, including the instrument model and a radiative transfer model is used to perform an iterative retrieval over a portion of the whole scene. Heuristics will be used to select upwind portions of the field of view that are not likely to be affected by known local emitters. This yields average values of the background columns, as well as per-observation instrument correction parameters similar to spectral shifting or squeezing parameters in classical grating instruments. The full forward model is then linearized around this point, yielding a scene-wide linear model.
- The second step derives a linear model and error parameters for each ground pixel from the scene-wide linear model. This derivation takes into account the sampling path specific to each ground pixel. The model is then inverted, giving per-ground pixel excess column density estimates for CO_2, CH_4 and H_2O and fit residuals. Large excess column densities or residuals would affect a smaller number of ground pixels where further iterations of the forward model can then be afforded. Finally, iterative retrievals using the full forward model are performed on a small random selection of the overall column density map to validate the results.

The extraction of the emissions rate of CO_2 and/or CH_4 from a target measurement is referred to as emissions retrievals. Emissions retrievals take as input the abundance maps produced by the column density retrievals described above. These maps are then iteratively compared with a dispersion model that takes in meteorological conditions, terrain data and knowledge of source positions and simulates the dispersion and propagation of the plume for a given emissions rate. The dispersion model output is then converted to column densities for comparison with the satellite data. The estimated emissions rate and its uncertainty given the satellite observations and auxiliary data are obtained via convergence.

PRODUCTS AND SERVICES

Column density retrievals and emission retrievals are offered to customers as (i) commercial satellite imagery products, and (ii) value-added services based on GHGSat’s own imagery products.

Commercial Satellite Imagery

GHGSat imagery is a measurement of greenhouse gas (specifically carbon dioxide and methane) concentrations in the atmosphere immediately above targeted industrial facilities. A simulated example is shown in Figure 5 below.

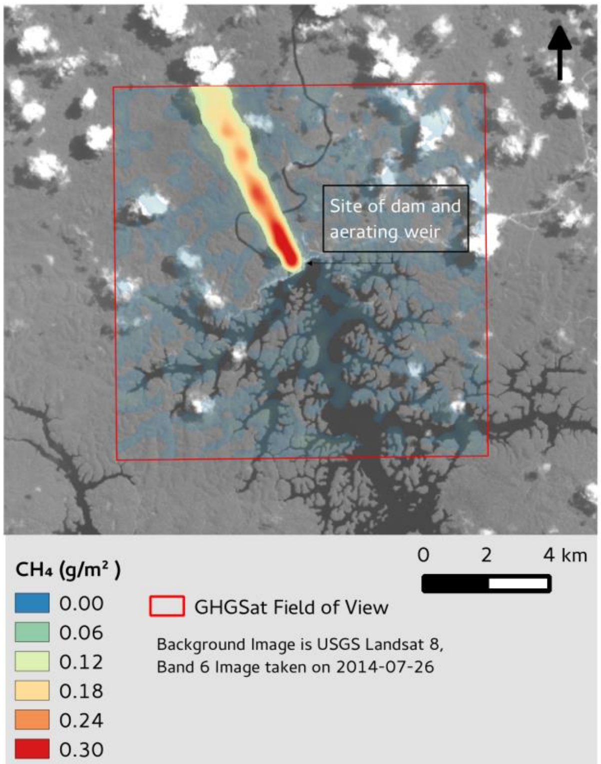

Figure 5: Simulated concentration map of methane emissions from Petit Saut hydroelectric reservoir in French Guyana

Value-Added Services

In addition to commercial satellite imagery, GHGSat offers technical services based on its own satellite imagery products, including but not limited to:

- Estimates of site-specific emissions rates from targeted industrial facilities, using microscale inverse dispersion modelling techniques
- Source identification, using image processing techniques
- Leak detection, by using change detection techniques
- Regulatory enforcement, by monitoring emissions from targeted sites over sustained periods

Detailed product and service information is available separately form GHGSat.

VALIDATION

A ground test campaign was performed prior to launch.

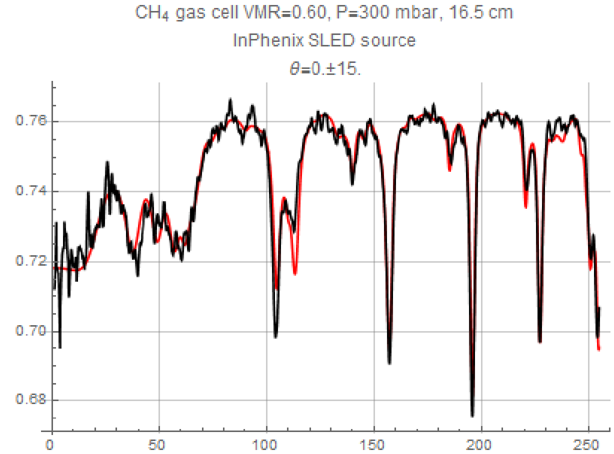

Figure 6: Measured (black) vs predicted (red) intensity (vertical) by pixel (horizontal)

For example, a series of measurements were conducted to test the forward model that includes the instrument and the radiative transfer through the atmosphere. For the laboratory measurements, gas cells with fixed total pressure P and mixing ratio X of each GHG (in a buffer of dry nitrogen) were used as a surrogate for the atmosphere. The values of P and X were chosen by comparison with the predicted contrast and feature width seen in top of atmosphere solar radiance spectra (which can be calculated using radiative transfer software).

The setup for this test involves shining a light source whose spectrum covers our spectral bandpass through a gas cell, and illuminating the instrument with the transmitted light. In order to remove the effects of variations in the spectrum and angular distribution of the source, the image was divided by another one taken with the gas cell removed. In Figure 6, the image has been integrated over an angular range of 30 degrees and the recorded signal is plotted vs pixel position. The very good agreement in shows the fidelity of the model for the instrument and for the transmission through the gas cell.

On-Orbit Testing

On-orbit commissioning of the GHGSat-D satellite and payload has recently completed.

GHGSat's focus is now turning to a series of on-orbit validation efforts involving a variety of different scenarios, including:

- Controlled releases of methane from known sources, such as a gas plant

- Emissions from known sources with well-characterized emission rates, such as a thermal generation facility.

- Emissions from areas with complex sources, such as (a) tailings ponds in Canada's oil sands region, and (b) a hydraulic fracturing basin with dozens of wells, and where the field of view also contains a vent for coal mine methane and an animal feedlot.

GHGSat expects to publish results from initial measurement and validation efforts in the coming months.

ACKNOWLEDGEMENTS

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