Commercial Satellite Data Acquisition Program

GHGSat Principal Investigator Evaluation Summary

Goddard Space Flight Center
Greenbelt, MD

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Signature/Approval Page

Approval by:

Melissa Yang Martin Commercial Satellite Data Acquisition Program Manager Earth Science Division Headquarters/NASA	Date

Accepted by:

Dana Ostrenga Commercial Satellite Data Acquisition Project Manager Earth Science Division GSFC/NASA	Date

Preface

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Abstract

The evaluation summarized in this report was conducted by Principal Investigators (PIs) funded by NASA's Commercial Satellite Data Acquisition (CSDA) Program. The purpose of the evaluation is to determine the utility of the GHGSat data for the NASA Earth science research and applications community. The results of the evaluation help to inform NASA program management on the ability of the data to further augment NASA science.

Cover Art: Cover art is AI generated graphic using Microsoft Copilot Designer using term "commercial satellite constellation Earth observation across Atlantic AND Northern Hemisphere AND digital downlink"

Authored and prepared by

John R. Worden
GHGSat Evaluation Team Lead
Jet Propulsion Laboratory
National Aeronautics and Space Administration

Jaime Nickeson
CSDA Technical Science Coordinator
Science Systems and Applications Inc
National Aeronautics and Space Administration

Frederick Policelli
CSDA Project Scientist
National Aeronautics and Space Administration

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Executive Summary

NASA's Earth Science Division (ESD) Commercial Satellite Data Acquisition (CSDA) program selected six principal investigators (PIs), along with their teams, via a call for proposals under the NASA Research Opportunities in Space and Earth Science (ROSES) solicitation, to evaluate GHGSat as part of the third CSDA on-ramp. Instruments such as those launched by GHGSat quantify methane emissions at the facility scale (e.g. wellhead, pipeline, landfill) by projecting observed near-infrared radiances to methane plume concentrations and to emissions at roughly 30 m pixel resolution. Quantifying methane emissions using this technology is challenging because radiative interference can substantially affect identification of plumes associated with leaks. Nonetheless, this new class of measurements has the potential to directly quantify previously unobserved components (primarily emissions related to fossil fuels and waste) of the methane budget. For these reasons, NASA funded several investigations into the utility of these data for NASA Earth system science and applications. One of these investigations included a PI from the Environmental Protection Agency (EPA), and an additional investigator team from the National Oceanic and Atmospheric Administration (NOAA), was also added to the evaluation. These agency teams were selected because of the mutual benefit expected from their research.

The vendors participating in the CSDA Program are evaluated on the accessibility of vendor supplied data, accuracy and completeness of metadata, quality of user support services and documentation, usefulness of the data for advancing Earth system science research and applications, and the quality of vendor supplied data. Datasets purchased during the evaluations are archived by NASA, and after the evaluations have been completed, the evaluated data are made available to current and future government-funded researchers in accordance with the end user licensing agreement (EULA). The scientists evaluated the GHGSat data sets in the context of a variety of research topics (see Appendix).

The GHGSat evaluation kicked off with a first team meeting in January of 2023, and the team began formulating their data needs early in 2023. Delivery of initial imagery products requested by the researchers began in June 2023. This synthesis report distills and integrates the findings of research reports commissioned by NASA for the GHGSat evaluation. This report also includes recommendations that inform the way ahead for the program.

The report finds several strengths and weaknesses of these data for use in NASA Earth system science and applications. In summary, the investigators found that the GHGSat data are consistent with other independently measured data (satellite, aircraft, and ground). However, given the sampling characteristics, these data are best used in conjunction with other data sets, e.g. to support aircraft campaign (regional methane budget) objectives, or to corroborate other (e.g. satellite) measurements related to high methane emitters, or with a tip and cue strategy whereby a global mapper identifies a region with large emissions and GHGSat is used for source attribution.

1. Background

NASA's ESD formalized the CSDA program in 2020, following the successful Private-Sector Small Constellation Satellite Data Product Pilot that concluded that year. The objective of the CSDA program is to identify, evaluate, and acquire commercial remote sensing data that support NASA's Earth science research and application activities. When the Pilot transitioned into the sustained CSDA Program, on-ramping opportunities were released for new vendors with the idea of expanding and enlisting new commercial vendors as the industry expands with new candidates and capabilities. NASA's ESD recognizes the potential impact commercial satellite constellations may have in encouraging and enabling efficient approaches to advancing Earth system science and applications development for societal benefit.

In addition to the Pilot, NASA has conducted two evaluations since the Pilot, these included two vendors in On-Ramp 2 and four vendors in On-Ramp 3. GHGSat was part of On-ramp 3, and the three other vendors in this On-Ramp were wrapping up their evaluation activities in a similar timeframe following GHGSat.

NASA has moved into a sustainment phase for the vendors from the Pilot and On-Ramp 2 with data collected by these vendors made available to NASA and other government funded researchers, according to the EULAs. More information can be found on the CSDA web site, under Commercial Datasets. The table below shows the vendors that NASA has engaged with for commercial data evaluations thus far.

Table 1. CSDA Evaluation Activities.

Evaluation Effort	Vendor	Type	Report Delivery
Pilot	Maxar	Optical	Apr 2020
	Planet	Optical	
	Spire	Radio Occultation	
On-ramp 2	Airbus U.S.	SAR	Oct 2023
	BlackSky	Optical	Jun 2024
On-ramp 3	GHGSat	Optical	Aug 2024
	Capella	SAR	Dec 2024
	ICEYE U.S.	SAR	Dec 2024
	GeoOptics	Radio Occultation	Oct 2024
IDIQ On-ramp 1	Umbra	SAR	Aug 2025
	PlanetiQ	Radio Occultation	Aug 2025

The vendors were evaluated on the accessibility of data, accuracy and completeness of metadata and documentation, promptness and quality of user support services, and usefulness of the data for advancing Earth system science research and applications. NASA's CSDA Program license agreements were expanded following the Pilot to broaden the applicability of the commercial data for scientific applications across the U.S. Government. These license uplifts made the data more readily available across the government and improved both the value of these data and the opportunities for interagency collaboration. In addition, NASA has engaged in separate dedicated evaluation activities to assess the satellite data quality of each vendor.

Results from the Pilot and the On-Ramp 2 evaluations are available from the CSDA website. The final summary reports for all the On-Ramp 3 evaluations will also be published on the CSDA web site upon completion and review of the evaluation reports.

1.1 BPA On-Ramp 3

On-Ramp 3 evaluations were initiated in October 2022 with a request for information (RFI) seeking capability statements from the parties interested in providing data from spaceborne platforms for evaluation. To be responsive to the RFI, the commercial satellite vendors had to be U.S. companies with one or more spacecraft actively collecting data in low, medium, and geostationary Earth orbits with a minimum of near-continental-scale–coverage. Four vendors satisfied the RFI requirements and were asked to respond to a request for proposal. After review of the submitted proposals, NASA entered into a Blanket Purchase Agreement (BPA) with GHGSat, Inc. in September 2022. The vendors evaluated during On-ramp 3 are listed in Table 2.

Table 2. The vendors and sensor information for On-ramp 3 evaluations (constellation numbers shown reflect status during the evaluation).

Vendor	Sensor Type	Temporal Coverage	Spatial Coverage	Satellites	Bands	Spatial Resolution
GHGSat	Optical	Jan 2021 - present	Global	10	1630 – 1675 nm	50 m
GeoOptics	GNSS-RO	Nov 2018 – Jan 2022	Global	0	N/A	12 km
Capella Space	SAR	Jan 2021 - present	Global*	4	X - Band	0.5 m
ICEYE US	SAR	Oct 2019 - present	Global	13-21	X - Band	0.5 m

**During the evaluation period, Capella lost its only polar orbiting satellite sensor, thus access to data over areas beyond 48.9 deg N/S were limited.*

1.2 GHGSat Imaging Capabilities and Products Evaluated

Each GHGSat satellite in their constellation contains a wide-angle Fabry-Perot imaging spectrometer. These GHGSat hyperspectral instruments use a narrow band of the short-wave infrared region of the spectrum, at high spectral resolution, to measure the vertical column of greenhouse gas abundance in the atmosphere. The sensors operate at high spatial resolution and are used to also quantify and delineate methane plumes from point sources.
GHGSat offers 3 datasets, described in the table below.

Table 3. GHGSat Products (adapted from GHGSat, Inc.)

Products	Data Levels	Description
Abundance Dataset	Level 2	Set of (a) Per-pixel abundances column average mixing ratio in ppb (parts per billion) or column density in mol/m^2 upon request) for CH_4, and (b) Per-pixel measurement error expressed as a standard deviation, for a single site, on single satellite pass, and (c) Quality flag layer.
Concentration Map	Level 2	High readability pseudocolor map in PNG format. Surface reflectance background image. Foreground image is CH_4 column-averaged concentration in excess of the local background level [ppb or mol/m^2].
Emission Rates	Level 4	Emission rate from targeted source estimated using abundance dataset(s) and applying dispersion modelling techniques.

The GHGSat abundance data product indicated above is referred to by the teams and in this document as methane enhancement or methane concentration enhancement. The associated concentration map is provided only if a plume is detected by GHGSat. The spatial resolution of the sensors is approximately 30 m, and the field of view of the sensor is about 12 x 12 km in size. The image in Figure 1 below shows an example of a GHGSat Concentration Map product.

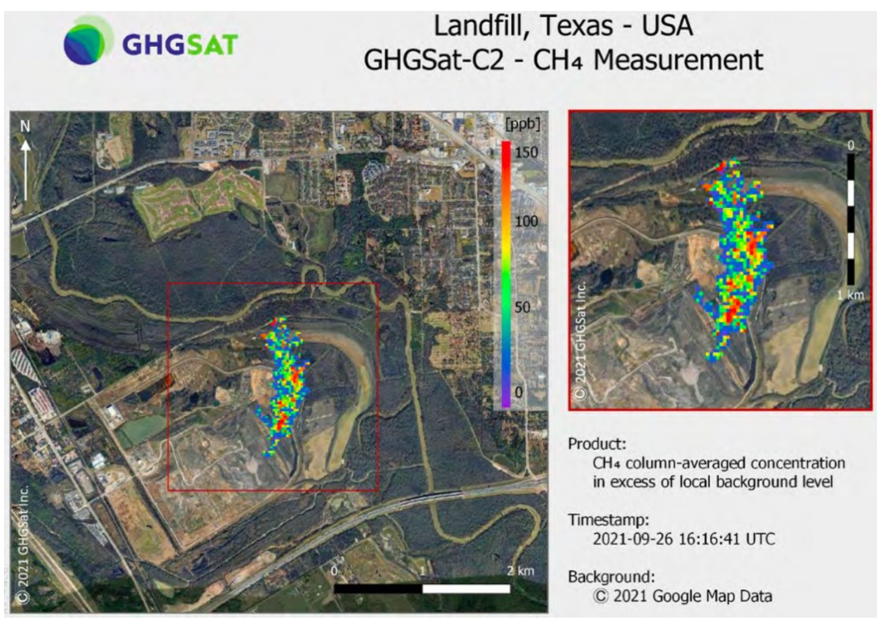

Figure 1. Example of a Methane Concentration Map product. (source: GHGSat, Inc.)

2. Evaluation Process and Criteria

NASA ESD selected six projects to perform the GHGSat evaluation. A seventh team from NOAA was added to the team shortly afterward, and CSDA then funded separate efforts to perform a quality assessment of the GHGSat data (all teams are listed in Appendix A).

Five of the investigations addressed the NASA carbon cycle and atmospheric composition focus areas by assessing the utility of GHGSat data to inform methane inventories, as well as wetland emissions that are adjacent to fossil methane emissions. Two investigations focused on assessing the GHGSat instrument characteristics, as well as the skill and accuracy of the GHGSat methane plume identification and emissions estimate. One investigation focused on assessing the capability of GHGSat for observing high methane emissions over ocean drilling sites.

The evaluation Principal Investigators (PIs) teams were required to provide interim, midterm, and final surveys and reporting, and to attend monthly discussions to ensure they had sufficient information and data access to complete their evaluations.

2.1 Evaluation Criteria

The CSDA program provided evaluators the following categories for reporting on their findings for both the quality and utility of the data.

A. *Access, Metadata and Support*
   I. Accessibility of vendor supplied data
      The ease and efficiency with which data can be searched, discovered, and downloaded from vendor systems.
   II. Accuracy and completeness of metadata
      The accuracy and completeness of metadata that accompanies the imagery and data provided by the vendor.
   III. Quality of support services, including documentation
      The availability, responsiveness, and technical expertise required to answer PI inquiries.

B. *Usefulness of the data for advancing Earth system science Research and Applications*
   The ability of vendor-supplied data to support Earth system science Research and Applications

C. *Quality of Vendor Supplied data*
   The quality of data attributes, such as radiometric calibration, geolocation accuracy, and platform intercalibration.

2.2 Program Activities

The evaluation was facilitated by conducting periodic reviews and surveys, PI all-hands, monthly technical interchange meetings. The evaluation timeline is depicted in Figure 2.

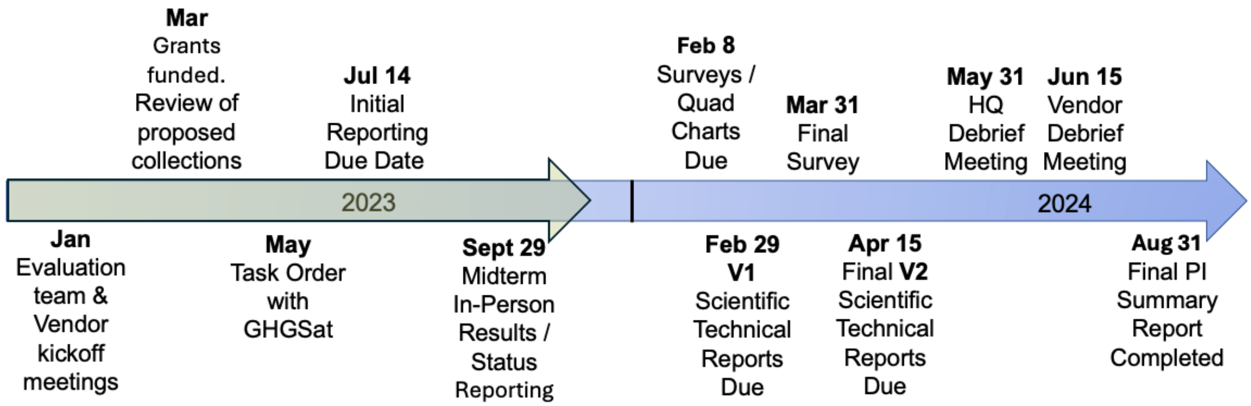

Figure 2. Timeline of Evaluation activities since awarding the purchase agreement.

2.3 Meetings, Periodic Reviews and Surveys

In addition to the team and vendor kick-off meetings, evaluation PIs were required to participate in periodic reviews and report on the usefulness of the data and current research progress. The PIs were asked to submit quad charts at three points during the evaluation, the first one shortly after gaining access to the data, the second at the evaluation midpoint, and lastly as part of their final submission. An in-person midterm meeting was held at the Goddard Space Flight Center which allowed the PIs to share their preliminary results and exchange information. All reports and surveys were synthesized in the creation of this final summary report.

2.4 Monthly Technical Interchange Meetings

Monthly conference calls were set up to facilitate technical interchange among the PIs and with CSDA staff to help identify and resolve issues related to data access, quality, completeness, and processing. The PIs were asked to identify issues and share information that might be relevant to other PIs. The conference calls were set up as a means by which to ensure timely identification and prompt resolution of issues that might arise. These meetings also allowed the CSDA staff an opportunity to gather and relay any concerns that the team may have to the vendor to accelerate resolution of any potential problems.

2.5 Community Engagement and Feedback

As the capabilities and numbers of commercial vendors grow, it is important to continuously monitor the development of new commercial technology, acquire relevant data to complement existing and future missions, and evaluate these data over time. The CSDA team continues to provide status updates, answer questions about data and data access, and provide information about future procurement opportunities for other constellation providers at various science conferences and workshops throughout the year. The community engagement serves as an open forum for dialogue between experts across the science data research community and helps to showcase NASA's progress and commitment to building stronger bonds with the commercial sector.

3. Key Findings

The evaluation was focused on assessing the utility of GHGSat data for advancing four of NASA's science focus areas and Earth Action Program. A summary of the research areas represented by the GHGSat evaluation PIs is presented in Figure 3.

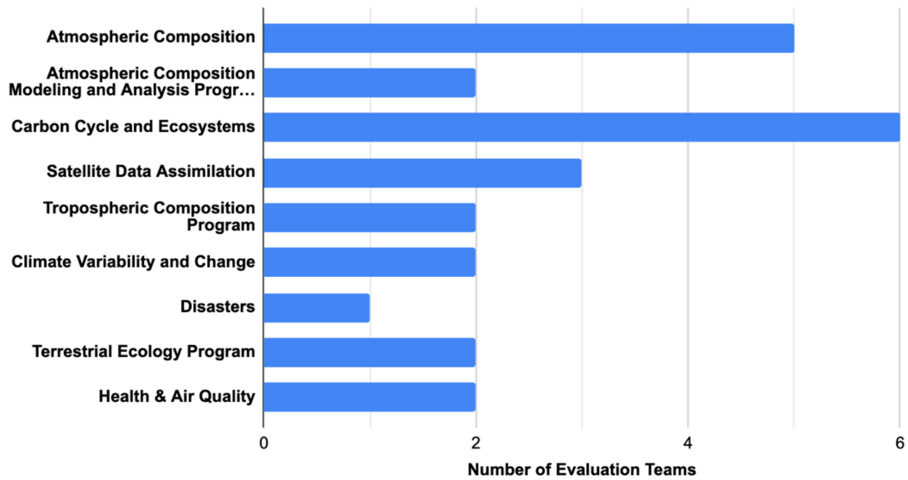

Figure 3. Evaluation research areas were varied, and some evaluations covered more than one research area.

The GHGSat data sets that were evaluated were acquired through the U.S. Government End User License Agreement (EULA) and were available only to the science team during the period of the evaluation. Following the evaluation period, the data are made available to U.S. Government-funded researchers through the CSDA Satellite Data Explorer (SDX). The GHGSat data and constellation are described in Tables 2 & 3, with evaluation criteria outlined in section 2.1. The key findings address the objectives of the evaluation and are described in the following sections.

3.1 Data Access, Customer Support, and Metadata

Data Access

CSDA investigations used a combination of GHGSat archive data and new data acquired through tasking of the GHGSat satellites. The teams first identified which of the historical archive data collected were useful for their investigations, through interaction with the GHGSat team and through perusal of the GHGSat data portal. The CSDA program management then negotiated with each team on the number of observations they could access for their investigation, and these data were subsequently made available to each team.

Data downloads were completed primarily through the GHGSat SPECTRA platform interface. This interface was found by most teams to be sufficient. However, one of the teams required bulk download of data and GHGSat accommodated this request through implementation of a file transfer protocol (FTP) interface.

GHGSat satellite data tasking to acquire new observations was performed via coordination between the evaluation team and GHGSat. The tasking was moderated by the CSDA program management to ensure that the necessary observations were delivered.

Customer Support

Overall, there was very high satisfaction with customer support for all evaluation teams. One of the team final reports provided a good summary of the level of satisfaction: "*The GHGSat team was responsive, generous with their time, and proactive with regards to weekly efforts to coordinate coincident observations with EMIT. Their team helped orchestrate the identification, prioritization, and tasking of specific targets that when successful provided the least time difference between observations from the separate platforms. Specifically, they introduced a data tracking system that streamlined the organization of GHGSat observation requests, tasks, deliveries, and missed targets. Without these efforts, this process would have taken considerably more time*."

Metadata

Based on a survey of the evaluation teams, they thought the metadata could be more complete; this issue was primarily related to including the wind field uncertainties. Furthermore, addition of wind fields for scenes that did not have a confirmed plume were desired and it is requested that if GHGSat data are acquired in the future that these are made available. As another example, one team sought more clarity on the methods used to estimate the source emissions rates and assumptions about factors such as wind speed and direction.

Documentation

The documentation provided by GHGSat was generally good, but there is not a specific user guide, instead there are instead a combination of documents and publications from the literature that together provide an understanding of the data. The emission estimation methods could have been made clearer in the documentation, as well as those used to determine the plume delineation.

3.2 Data Utility for NASA Science

The evaluation primarily focused on assessing the utility of data for advancing NASA Earth System science and applications. The evaluation team assessed the utility of GHGSat data for methane inventories, methane plume identification and emission estimates. Below, we discuss the benefits of using GHGSat data for science and applications through a summary of these investigations.

Evaluation of Methane GHGSat Plume and Emissions Data Using EMIT

Instruments such as GHGSat typically quantify methane emissions by first projecting observed radiances in the near infrared to a methane concentration, or alternatively, a methane signal that is "enhanced" relative to the background atmospheric methane concentration. This is performed using an inversion algorithm that accounts for the transfer of radiation through the atmosphere and reflected off the surface, convolved with the instrument characteristics (Jervis et al. 2021). Pixel clusters of the methane enhancement (atmospheric methane that is larger than background levels) are then combined with visible imagery to identify a "plume" and its likely source (e.g. gas well head, livestock pen). The plume structure is then related to an emission strength via a second inversion that involves knowledge of the wind field strength (e.g. Jacob et al. 2022).

One of the investigations compared NASA's Earth Surface Mineral Dust Source Investigation (EMIT) mission observations of methane concentration enhancements and corresponding emissions to equivalent observations from GHGSat. The EMIT team and GHGSat first coordinated to task the GHGSat instrument to collect data over a set of methane emitting facilities that the GHGSat sensor could observe within one hour of the EMIT observations. Of the 128 GHGSat observation requests, 70 cloud-free scenes were delivered, and 36 of those scenes were found by GHGSat to have enhanced methane concentrations indicative of methane emission sources. The EMIT sensor observed enhanced methane concentrations in 31 of those 36 scenes. In one case of coordinated, cloud-free observations, EMIT observed a plume and GHGSat did not. In general, the EMIT team found that the plume shapes observed by GHGSat and EMIT were consistent (Figure 4), with similar shapes and orientation. This consistency between the GHGSat and EMIT observations is an excellent indirect validation of both instruments, as the plume shape and direction can often be a result of radiative artifacts from surface albedo variations. Radiative artifacts typically depend on surface albedo variations, viewing angle, and solar zenith angle. The EMIT and GHGSat sensors are in different orbits with different viewing and solar zenith geometry; consequently, agreement on the plume shapes supports the conclusion that neither observation is strongly affected by radiative artifacts for the observed plumes.

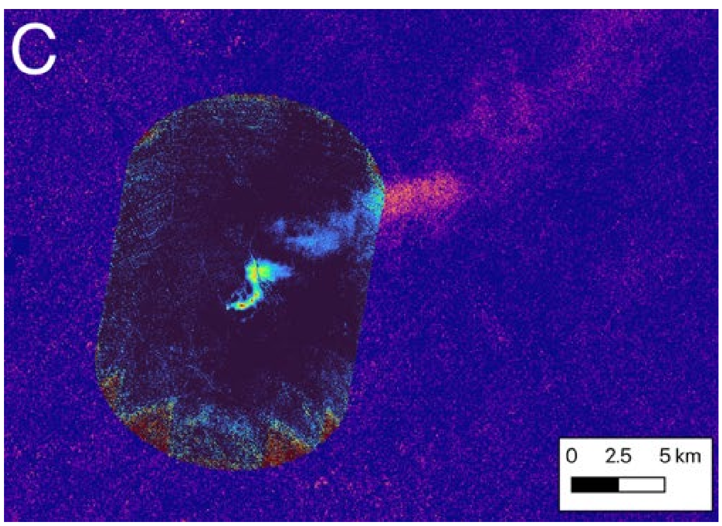

Figure 4. An overlay of GHGSat methane concentration enhancement data (oval) within a corresponding EMIT image (bounding rectangle), demonstrating that EMIT and GHGSat observed similar methane plumes over a facility.

Methane emissions were also quantified from the enhanced methane concentrations observed by EMIT (e.g. Figure 5). These are calculated by relating the enhanced concentrations to emission via wind fields (e.g. Varon et al. 2018 Jacob et al. 2022, Thorpe et al. 2023). The team found that the best agreement with GHGSat emissions was for those (EMIT based) emissions generated using the Thorpe et al (2023) methodology and with EMIT observations that were within 20 minutes of the GHGSat observations (upper right panel, Figure 5). However, it is unknown why the other approaches in Figure 5 show worse agreement, specifically when an effort was made to closely replicate the GHGSat emission estimation approach using EMIT enhancement data (lower panels in Figure 5). Identifying the "best practices" for relating observed methane enhancements to emissions, coupled with a robust validation network, are both needed to validate the emissions estimate approach and instrument sensitivity as discussed next.

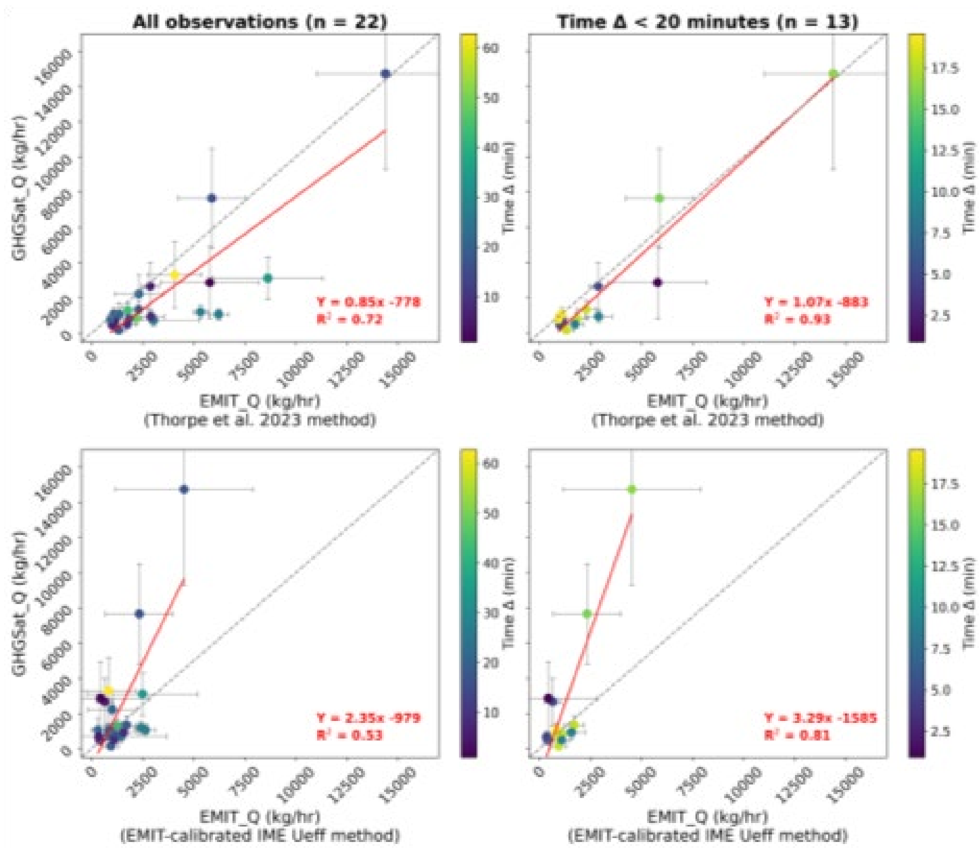

Figure 5. Comparisons between GHGSat emissions and EMIT emissions. The best agreement (upper right panel) are observations that are less than 20 minutes apart and using the EMIT plume to emission processing algorithm published in Thorpe et al. (2023).

Evaluation of GHGSat emissions using NASA AVIRIS-NG and GAO data

Another study looked to determine if GHGSat data (and by extension, other satellite-based methane plume measurements) can be used to evaluate methane inventories, and any changes to these inventories that may occur, for example, by remediation efforts. As part of this study, the team estimated the probability of detection (POD) for the GHGSat instrument by comparison of emissions from GHGSat and NASA's Airborne Visible-Infrared Imaging Spectrometer – Next Generation (AVIRIS-NG) and the Global Atmospheric Observatory (GAO) aircraft data taken over the Permian Basin (e.g. Cusworth et al. 2021). The aircraft data, with its higher signal to noise ratio (SNR) and smaller footprint can be used to bound the POD. This POD estimate also used a simulated emissions distribution, convolved with different probability of detection curves, to find a best fit for the GHGSat POD (Figure 6), by matching the GHGSat and AVIRIS/GAO distributions for emissions greater than 1000 kg/hr, convolved with different simulated emission distributions. They found that for observations in the Permian Basin, the GHGSat POD threshold of 50% occurs at around 250 kg/hr to 300 kg/hr, in contrast to the GHGSat stated value of 100 kg/hr. Furthermore, the 90% POD occurs at approximately 500 kg/hr; this higher value is consistent with other studies presented in this report, as almost all of the GHGSat observations shown are larger than 500 kg/hr, supporting the higher POD estimate, otherwise lower emissions would have been reported in these studies. Two hypotheses could explain the optimistic POD reported by GHGSat: 1) the methane point-release validation experiments are location in regions that are not representative of conditions (e.g. albedo and clouds) normally observed by GHGSat, and 2) the validation experiments do not test the plume mapping and quality assessment steps that are needed to relate concentrations to emissions. For example, a human-based quality control step is used in all emission estimates, and this may bias the results for single-blind validation experiments where the human knows that a plume at a specific location likely exists. Alternatively, validation experiments need to occur in regions with albedo variability that is consistent with what is observed globally. This characterization of GHGSat sensitivity being too optimistic would also apply to all other facility scale measurements. Therefore, the conclusion here should be that "point release" validation experiments should ensure that they are capturing all the uncertainties in the radiative transfer, plume identification, quality assessment, and emission estimate steps.

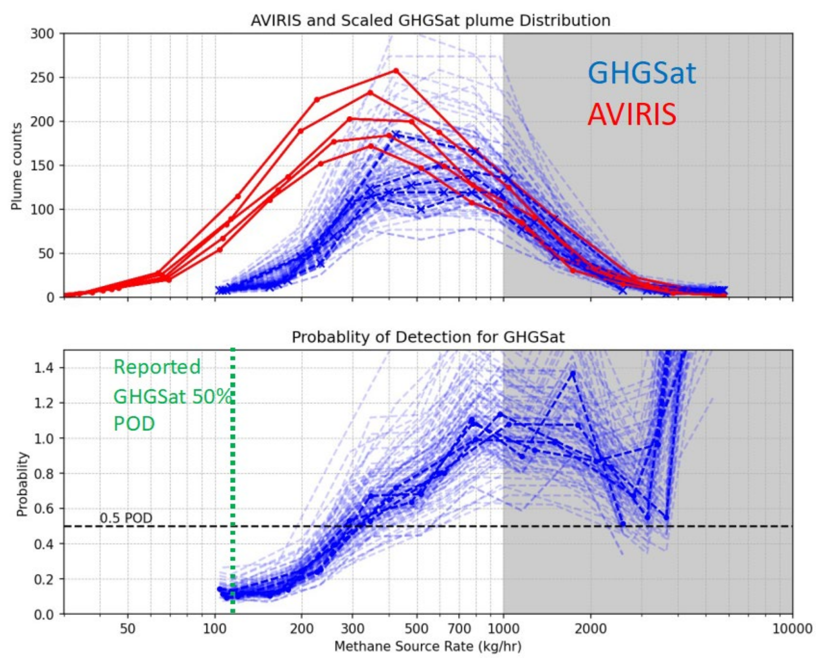

Figure 6. Estimate of GHGSat POD based on comparison of AVIRIS-NG / GAO and GHGSat data in the Permian Basin.

Improving Wetland Emission Estimates

Another study evaluated the utility of combining GHGSat facility scale measurements with total column methane (XCH_4) data from the European Space Agency (ESA) TROPOspheric Monitoring Instrument (TROPOMI) sensor. There are many wetland areas globally, such as those in Siberia, Canada, the USA, and Nigeria that are near regions with fossil extraction or delivery infrastructure, and these facilities could be sources of significant co-located methane emissions. Estimating wetland emissions using concentration data, such as those from satellite or aircraft observations, must therefore account for both wetland and fossil fuel emissions. The goal of this study was to test if both facility scale GHGSat data and TROPOMI total column data could jointly constrain fossil and wetland fluxes when these emissions are sufficiently close in proximity that the TROPOMI data alone cannot resolve them.

Unfortunately, the GHGSat data could only quantify fossil emissions in one of the five requested regions because of clouds and albedo variability confounding the observation, or because the fossil emissions were not always observed. The investigators found that the observed fossil emissions for the examined site were much larger than assumed. Consequently, an estimate just using TROPOMI data alone would likely place this discrepancy in the wetland estimate, biasing its result. The authors concluded that while GHGSat data alone could not address their science objective, they were successful in their goal of demonstrating the utility of facility scale methane observations for improving wetland flux estimates in regions where both fossil and wetland emissions are large.

Evaluation of Urban/Landfill Methane Emission Inventories

Three of the studies examined if GHGSat data can be used for evaluating methane emission inventories for cities and/or landfills. In particular, the goals for these studies included the determination of whether GHGSat data could be used to 1) detect "leaks", 2) supplement modeled estimates with actual measurements, and/or 3) test models of landfill emissions.

One of the studies compared GHG emission estimates from landfill sites across the USA to different methane emission inventory models. Methane inventory models depend on the particular site and its reported activity, combined with a set of parameters that relate the site information to emissions, all of which have significant uncertainty. For example, Figure 7 shows the inventory models and GHGSat data for eight of the observed landfills. The difference between models can be quite large (e.g., almost an order of magnitude difference for the Nevada Landfill models). Figure 7 demonstrates that the GHGSat data can distinguish between two models for about half of the landfills examined. The biggest challenge with using GHGSat data for this purpose was the sparseness of the data. The uncertainties shown in Figure 7 are only from the uncertainties in the wind fields, whereas there is likely additional uncertainty from how the plume shape is defined that is more challenging to calculate but can still be significant (e.g. Figures 4 and 5). This team noted that, "Despite some of the concerns addressed above, GHGSat provides a unique and extremely valuable data product. The resolution of methane emissions and time of product delivery would allow for mitigation of mechanical system failures that is not available from any other satellite or aerial platform currently. The evaluation finds GHGSat products to be of high value and would encourage NASA to consider their utility until a time when similar data products from a government source could be generated for all U.S. locations on a daily or weekly basis."

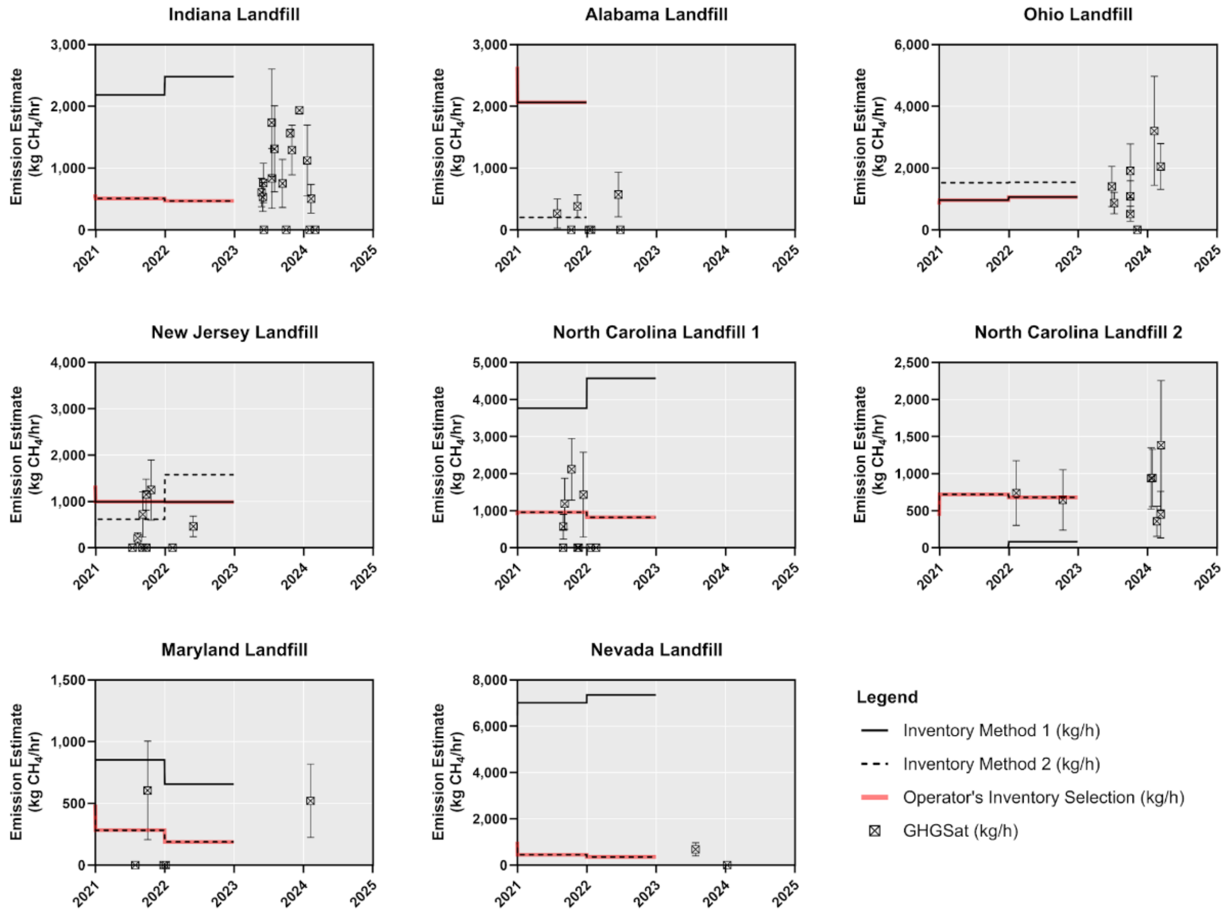

Figure 7. GHGSat data can be used to choose between inventory models in about 50% of the observed landfills.

Another study examined the use of GHGSat observations for quantifying methane emissions in Indianapolis, Indiana. They compared GHGSat emissions over an Indianapolis landfill to those derived from aircraft and tower data. The team derived their own emissions from the GHGSat Level 2 (L2) plume data, using publicly available algorithms (e.g. Varon et al. 2018; Jacob et al. 2022), and compared them to the emission data delivered by GHGSat. They found that when averaged over a year, the comparisons between the emissions from GHGSat, tower, aircraft, and their own emission values (derived from GHGSat data) were consistent (within the uncertainties), as shown in Figure 8. However, it was unclear, because of data sparsity, if GHGSat data could resolve emission variability at monthly to seasonal timescales.

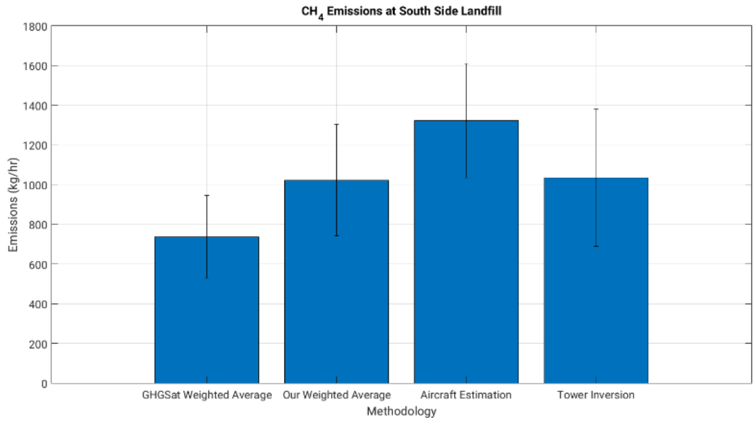

Figure 8. Comparison of GHGSat yearly averaged emissions (left two columns) to those from aircraft and tower data.

Yet another investigation over Rio de Janeiro, Brazil, examined the utility of GHGSat data for supplementing inventory estimates of landfill methane emissions. The landfill facility estimated source emission rates based on a model proposed under the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (see https://ghgprotocol.org/ghg-protocol-cities). The team received GHGSat archival data from 2022 and 2023 as well as four tasking opportunities in 2024; all the observations covered a high-priority landfill called Seropedica. GHGSat and the study team confirmed three collections over Seropedica with one plume each, and four collections with two plumes each, for a total of 11 plumes identified (two examples are shown in Figure 9). Initial analysis by the study team found general agreement between the order of magnitude of the source emission rates for the plumes using the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories modeling method and the GHGSat-estimated source emissions rate. The team did note variability in the source emissions rate estimate based on factors such as wind speed, land surface temperature and wind direction. Further work and ground-based observations will be helpful to clarify these variations. The team also had a learning experience with GHGSat in understanding how to request the right dataset from the GHGSat team in order to receive a full analysis of identified plumes and estimated source emission rates.

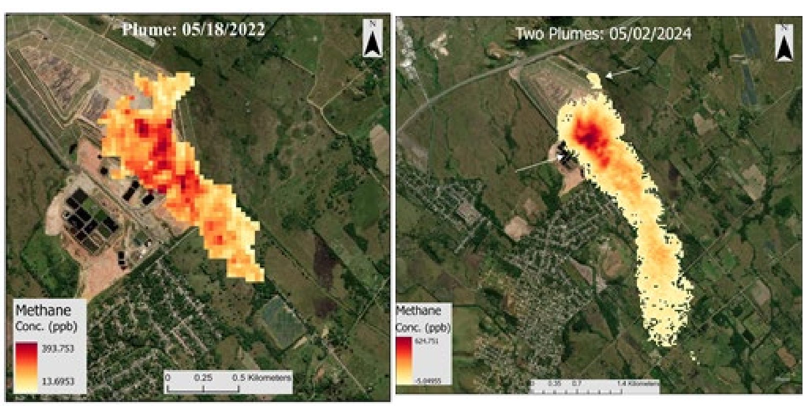

Figure 9. One team used GHGSat to estimate source emissions rates for landfills in Rio de Janeiro and found general agreement with modeled, inventory-based emission estimates. The image shows two observations of the Seropedica landfill in Rio de Janeiro. The left image shows one plume, and the right image shows a large plume and a small plume, identified by GHGSat.

Detection of Emissions from Ocean Drilling Sites

One of the investigations aimed to examine how well GHGSat data could quantify methane emissions from ocean drilling sites. Water absorbs the shortwave infrared energy used to detect methane so to enable over-water detections, this investigation took advantage of the GHGSat sun glint mode. They noted that GHGSat in this mode is very well characterized, effective, and easily tasked, and that among the commercial satellites capable of GHG detection, GHGSat's sunglint mode was unique. While only 11 out of 125 scenes over the ocean showed methane plumes, the team characterized this as valuable information for detecting leaks. Consequently, the team suggested that the GHGSat data could be used in a tip and cue configuration, whereby one instrument (such as the Sentinel-5P, TROPOMI, Sentinel-2, and in the future, GOSAT-GW) finds evidence for large emissions, and then uses that information to direct GHGSat to the likely source for attribution and quantification purposes (e.g., Varon et al. 2019).

3.3 Data Quality

A quality assessment was performed using a set of guidelines, similar to those used for past CSDA investigations, but adapted for greenhouse gas (GHG) sensor data. GHGSat data includes both "column enhancement" and "emission" products and the two products are characterized and validated using different methodologies. Consequently, we provided a data quality assessment for both the atmospheric column and the emission data products in order to provide as accurate an assessment of the GHGSat products as possible. The matrices in figure 10 show our initial quality assessment of these products. Section 3.3.1 summarizes assessments on geolocation accuracy and sensor spatial resolution.

The criteria used to evaluate each box are described in a document referenced in the quality assessment report (CSDA, 2024). The rationale used to grade each box were generated, as best as possible, using input from the CSDA investigations. We expect the initial set of data quality guidelines and assessments will undergo review and it is likely that changes in rationale, based on further discussion, will lead to changes in the criteria as well as the grading. However, we do not expect the change in grading to affect the overall assessment of the GHGSat data for NASA Earth System science and applications.

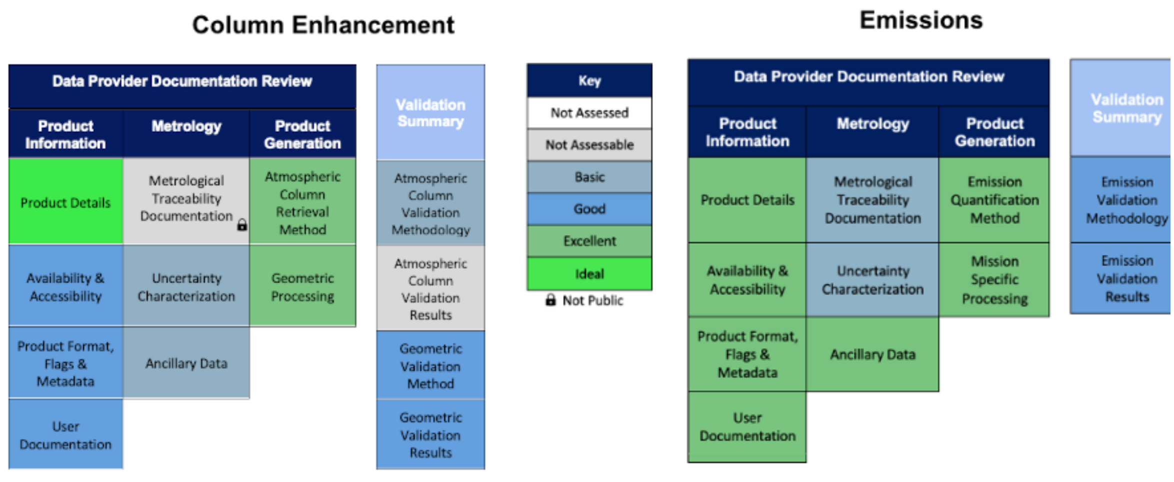

Figure 10. Summary quality assessment matrix for GHGSat data products.

3.3.1 Assessment of Geolocation and Resolution

Accuracy of the geolocation of GHGSat data was the focus of an additional evaluation effort. GHGSat images were compared to those from Landsat 8/9 SWIR bands with a "registration" algorithm that attempts to find common features in both images. This approach was used to find that the geolocation of the GHGSat data were highly stable and accurate to approximately a half a pixel (~15 meters, Figure 11) for most images. However, this accuracy degraded beyond latitudes of 70 degrees N/S to approximately two to three pixels.

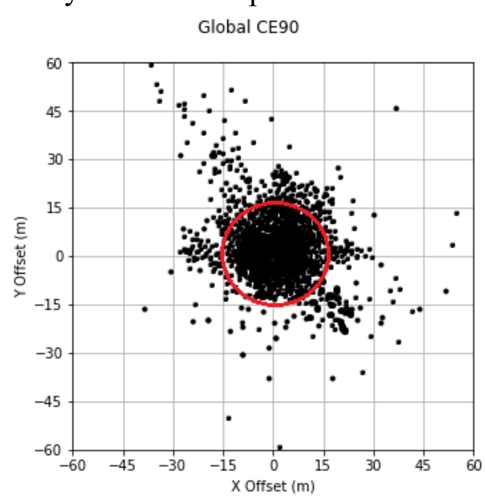

Figure 11. X and Y offsets for GHGSat data relative to Landsat. The red circle represents the 90th percentile of circular error.

Validation of the image spatial resolution specified by GHGSat was another focus of this evaluation. The geolocation subject matter expert team evaluated four images from three GHGSat sensors. They found the sensor spatial resolution varied from 60 – 70 m for the different sensors analyzed. This is similar to the GHGSat specification for sensor spatial resolution of 50 m; however, it is twice the pixel size of 30 m.

Based on this analysis, the Geometric Validation Methods and Results (under Validation Summary in Figure 10) received a "Good" score. For additional details, see the GHGSat Quality Assessment Report.

4. Summary and Recommendations

The evaluation found several benefits as well as limitations in the use of GHGSat data for science and applications. These are summarized below.

4.1 Benefits of GHGSat Measurements

Robust Plume Identification

Comparisons between GHGSat plume detections with other remote sensing measurements such as EMIT showed good agreement; this is actually a very useful cross-validation of GHGSat and EMIT data because the observing conditions are very different for these two instruments as they are in different orbits. Radiative effects, such as variable surface albedo and "spectral confusers" (e.g. carbonate materials), are the primary source of plume artifacts. Therefore, consistent identification of plumes between the two instruments indicates that both instruments can robustly identify plumes associated with "large emissions".

Robust Emission Estimates

Two of the studies compared the GHGSat estimated emissions with independent estimates such as from tower, aircraft, and satellite (EMIT). In all cases they found that the GHGSat based emissions were essentially consistent (within uncertainties) with the independent results. This suggests GHGSat data could be useful for scientific studies if there were enough data available to generate statistically meaningful estimates. For example, one study suggested that yearly mean methane emissions from GHGSat could be used to evaluate inventories for waste facilities.

Ocean Glint Capability

One of the investigations aimed to examine how well GHGSat data could quantify methane emissions from ocean drilling sites. This investigation took advantage of the GHGSat ocean glint capability, which they noted as being unique to GHGSat.

Low Latency / Transient Emission Detection

Another feature of the GHGSat measurements is the low latency; GHGSat data can be obtained within 2-3 days. Only the Carbon Mapper mission has the potential for a similar latency, however there is an additional charge for this capability. The lower latency capability is critical for reporting transient emissions, such as mechanical failures in oil/gas or waste facilities.

4.2 Limitations of GHGSat Measurements

The evaluation found a number of limitations with respect to using GHGSat data for science investigations and applications. Many of these limitations were common across the investigations and were related to concerns about how transparency and intellectual property impact GHGSat data reproducibility and availability, data sparseness and uncertainties, and characterization of the detection threshold / probability of detection for low emissions.

Transparency / Intellectual Property

The original satellite observations (a convolution of observed radiances with the instrument spectral response function) were not available to evaluators in part because they are considered intellectual property; this means that investigations cannot trace the L2 (concentration enhancements) and L4 (emissions) estimates to original measurement. This may impede use of these data for science investigation if a journal requires all parts of the data stream to be publicly available. A related but separate concern is that the data can be purchased with a "hold" on it (up to one year) such that it is unavailable for use by others. While this only affected a small fraction of the available data (less than 0.1%), it does raise the concern that use of GHGSat data could result in biased statistics when evaluating emissions over a region. These limitations are inconsistent with NASA's open science and open data policies. Despite these concerns, all comparisons between GHGSat with other independent data sets were found to be consistent, at least for larger emission rates (> 500 kg/hr) used with the investigations, suggesting that the quality of the GHGSat column and emission products are not affected by the lack of transparency of the original satellite data.

Transparency / Reproducibility

Based on the documentation available, which included publications on the concentration enhancement and emission estimates (Jervis et al. 2021; Varon et al. 2018), the team could not systematically replicate the plume mask or the emission estimates. However, all teams were able to generate their own emission estimates from the provided L2 data using publicly available algorithms. In general, there is good agreement between these independent emission estimates and the GHGSat data such that this lack of reproducibility did not impede the investigations.

Data Sparsity and Uncertainties

Several of the CSDA evaluations were challenged to address their science objectives because of data sparsity. For example, the wetland, ocean, and Rio de Janeiro studies were only able to obtain a few (one to six) observations of methane plumes from archival data, however additional observations of plumes occurred once new tasking was enabled. Uncertainties in the emissions, typically calculated from uncertainties in the wind fields, amplified these poor statistics and corresponding comparisons between GHGSat data and other data sources used in the evaluation.

Validation of Emissions Sensitivity

Another study showed that the probability of detection (POD) needed to be better characterized in order to use the lower emission measurements (e.g. < 500 kg/hr) for science investigations. For example, GHGSat's reported POD threshold of 100 kg/hr, based on point-release experiments, is likely too low; the actual threshold is more likely to be around 250 kg/hr. This difference between the stated and actual POD is probably not particular to GHGSat but likely includes all facility-scale measurements from satellite and aircraft, because they baseline their POD against similar point-release experiments for validation. Consequently, point-release experiments, that are used to validate the probability of detection of an instrument, likely need to be revisited; we suggest that there is a need to conduct point-release experiments with a larger range of observing conditions and emissions. These experiments also should follow a protocol to account for the exact methodology (including human delineation) used to project the raw satellite measurements to the plume map, and thus to the emission estimates, to better assess how they are affected by each of the steps.

5. Conclusions

The final team survey of the CSDA evaluation team included the following question: “Do you recommend NASA continue to provide access to these data? 1 – No, 3 – Buy in conjunction with other data sets to support science / applications, 5 – data are a critical observable for Earth System science and applications”. The question was discussed further during our final meeting, and six of the PI’s voted “3” and the remaining two voted “5”. This result is consistent with the outcomes of the investigations. While the GHGSat data were found to be consistent with other independent data sets, most investigations were challenged to utilize the data for science purposes because of sparse sampling and large uncertainties. On the other hand, a couple of the investigations thought that observation of a plume (which typically occurred for emissions larger than 500 kg/hr) could be “actionable”, that is, this information could lead to follow-on measurements.

Based on the CSDA evaluation, we believe that currently available GHGSat measurements are best used in combination with other measurements (e.g. to support an aircraft campaign or with satellite observations) to support science investigations as source attribution or to corroborate an independent plume observation. GHGSat data could also be used as a tip and cue resource, whereby a different instrument finds evidence of large methane emissions, and GHGSat data is used to identify the source(s) and quantify the corresponding emissions. This type of approach has already been described in the literature (Varon et al. 2019).

The team also recommends that NASA support measurements that can be used to evaluate the GHGSat plume measurement sensitivity (e.g. probability of detection) and emissions. While we found that the GHGSat POD thresholds are likely not well characterized for low emissions (e.g. less than 500 kg/hr), we note that this problem is likely endemic to all current facility-scale measurements. Well-crafted validation campaigns that account for the aerosol and albedo variability found in different scenes and that includes the complete set of steps; from the original instrument measurement to plume identification, quality assessment, and the final emission estimate, could greatly improve the characterization of this class of measurements and the utility of their data.

While we recognize that intellectual property concerns may inhibit reporting of the original (Level 1) GHGSat data, we recommend that GHGSat make available, to the extent possible, all the GHGSat data and ancillary data needed for a user to replicate the steps between L2 (columns) through L4 (emissions).

There was an Algorithm Theoretical Basis Document (ATBD) provided by GHGSat, but the document was not made available to investigators until after the analysis period, due to miscommunication. It does not appear that this issue inhibited the investigations, as emissions were independently calculated using the L2 data and then compared to the GHGSat emission estimates. However, we recommend that steps should be taken so that similar occurrences are not repeated in future evaluations.

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Appendix A. Listing of Evaluation Research Projects

Evaluators	Investigation Title
Nikolay Balashov UMD/ESSIC and NASA GSFC	Evaluation of GHGSat Point Source Quantification in an Urban Environment
Clayton Elder JPL / Caltech	Evaluation of GHGSat methane datasets with respect to EMIT methane plume data
Max Krause U.S. EPA Office of R & D	Landfills as a variable methane source
Ben Poulter NASA GSFC	Evaluating GHGSat for monitoring natural ecosystem methane fluxes
Davida Streett NOAA/NESDIS	GHGSat Evaluation of offshore emissions in the Gulf of Mexico
Danielle Wood MIT	Assessing Accuracy of Greenhouse Gas Emission Inventories in a Multi-Municipality Metropolitan Area
John Worden JPL / Caltech	Evaluating GHGSat plume data for updating CH4 emission inventories and trends
Gary Lin Co-Is: **Alana Semple, Bin Tan** **NASA GSFC**	GHGSat Geometric Assessment