DATA.AIR Gen 1

Formal Alternative Test Method

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CHANGE HISTORY

Version	Release Date	Notes
a	30 May 2024	Initial submission
b	6 September 2024	Revision
c	24 January 2025	Revision

CONTENTS

1 Scope and Application

1.1 Scope

This document describes the procedure associated with the GHGSat DATA.AIR Gen 1 product, which aims to detect, localize, and quantify methane emissions. This method is applicable for demonstrating compliance with the procedures in 40 CFR §60.5398b for fugitive emissions components affected facilities and compliance with periodic inspection and monitoring requirements for covers and closed vent systems, specifically demonstrating compliance through periodic screening in 40 CFR 60.5398b(b), as approved, per 40 CFR §60.5398b(d). Affected facilities could include but are not limited to, single wellhead only sites, small well sites, multi-wellhead sites, well sites with major production and processing equipment, centralized production facilities, and compressor stations.

1.2 Application

The application of this technology is per the Environmental Protection Agency's 40 CFR part 60 New Source Performance Standards (NSPS): Subparts OOOO, OOOOa, and OOOOb, and Emissions Guidelines (EG): OOOOc, for the Oil and Natural Gas Source Category.

The test method is applicable to methane (CH4, CAS No. 74-82-8) emissions from oil and gas facilities. This method can be used, as approved by the Administrator, in lieu of the applicable fugitive monitoring requirements in either §60.5397a or §60.5397b and inspection and monitoring of covers and closed vent systems in either §60.5416a or §60.5416b. This test method may be used for fugitive monitoring requirements in §60.5397c and monitoring of covers and closed vent systems under §60.5416c when a state, local, or tribal authority incorporates the model rule (i.e. OOOOc) for the emission guidelines as part of their State Implementation Plan (SIP) or elsewhere approved as applicable.

The test method is a performance-based method to determine whether individual component emissions remain below prescribed thresholds.

1.3 Method Sensitivity

Application of GHGSat DATA.AIR Gen 1 under this protocol provides a methane detection threshold of 13.4 kg/hr with a probability of detection of 90%. This sensitivity was determined through single-blind controlled releases performed by independent third-party. The methodology and analysis are described in section 13 of this document.

1.4 Data Quality Objectives

Adherence to the requirements of this method will ensure the data supporting the technology's objective will be accurate and of quality. The technology's objective is to screen for fugitive emissions from oil and methane-emitting components and provide an alert to an operator that triggers a leak detection and survey response.

Requirements to achieve the target performance are described in sections 4 and 9 of this document. Factors that can limit the detection performance include:

- Time of day (solar illumination)
- High wind speed
- Light path obscuration by clouds, fog, smoke, or tree cover.
- Low albedo (ground reflectance)
- Offshore targets

2 Summary of Method

The detection is based on hyperspectral imaging spectrometers that operate in a narrow band of the short-wave infrared (SWIR) region of the electromagnetic spectrum. The instruments have high spatial and spectral resolution, to enable high-precision measurements of the vertical column densities of methane in several hundred thousand pixels within the instrument field of view (FOV).

The sensors can be mounted in any appropriate third-party aircraft and deployed with an operator as required for aerial survey campaigns. GHGSat typically deploys on twin engine aircraft, able to maintain consistent surveying speed and be large enough to accommodate our camera port. Surveys are performed during daytime in clear weather conditions as the measurement is based on the analysis of backscattered sunlight.

The key steps of the measurement procedure are listed below.

1. **Data acquisition**: The airborne imaging spectrometer is flown above sites of interest (potential methane emitters), measuring the solar illumination backscattered from the ground.
2. **Retrieval**: Methane concentration is computed by analyzing the wavelength-dependence of light intensity in the shortwave infrared (SWIR) part of the electromagnetic spectrum. A physical model of the atmosphere, optical instrumentation, and ground reflectance is fitted to the measured data using nonlinear regression. This step outputs a map of methane concentration at ~1.5m resolution.
3. **Inspection and emission identification**: The concentration maps are inspected to identify areas containing elevated methane concentrations, which indicate the presence of emissions sources. The origin of the emission is also localized based on wind direction, plume morphology and visual imagery of the terrain (both our own and publicly available).
4. **Source rate quantification**: If one or more emissions are found, the emission rate is calculated for each of them.
5. **Alerts and delivery**: Results of the survey are delivered to customers, which include the methane concentration map, emission rate of each methane plume, and the geographic coordinates of their origin. The customer is informed of every detected emission for which we determine that it originates from one of their facilities.

As a note, GHGSat provides measurement as a service. All steps from acquisition to delivery are performed by qualified GHGSat personnel.

3 Definitions of Method

Table 1. Definitions and acronyms

Term	Definition
Albedo	Fraction of the sun radiation reflected by the ground surface
Attitude	The orientation (3D angles) of an aircraft, spacecraft or imaging platform.
Column density	Concentration of a gas species (e.g. methane) per surface area of the measured ground cell but integrated along the path of the light ray. Expressed in units of moles per meter-squared.
Dark current	Residual signal detected by a camera pixel even in the absence of light. Can be quantified by acquiring dark background images (shutter closed)

Term	Definition
	which are then subtracted from illuminated images to estimate photocurrent accurately.
Fabry Perot (FP)	Optical component made of a pair of closely-spaced partially reflective surfaces. Commonly used in spectroscopy for its transmission spectrum which is a periodic series of narrow wavelength bands (modes). It is the core component of the GHGSat imaging spectrometers.
Georeferencing	Process of mapping the pixel coordinates of an image to the geographic coordinates of the area that was imaged.
Ground cell	The smallest spatial unit in which methane concentration is retrieved. Equivalent of a pixel in the maps of retrieved quantities. We reserve the term "pixel" for raw camera-level quantities, as opposed to ground coordinates.
Gyrostabilized mount (GSM)	An active device used to stabilize the viewing angle of an imaging system when mounted on an aircraft.
Imaging spectrometer	Instrument which measures the intensity of light, both as a function of position (images) and wavelength (spectrum), at the basis of the GHGSat technological platform.
Inertial navigation system (INS)	An electronic device which estimates the position and attitude of an aircraft by combining inputs from global positioning system (GPS), accelerometers, and gyroscopes.
Nadir	Downwards vertical view angle, from the instrument towards the ground.
Order sorting filter (OSF)	Synonymous of "bandpass filter" used in the context of optical remote sensing.
Prior	In the context of inverse analysis and regression, refers to information known independently of the measurement data. For example, the mean concentration of methane at sea level is prior information.
Retrieval	The process of finding the values of unknown "state" variables (e.g. methane concentration, ground reflectance) that best explain the raw measurement (light intensity on the sensor).
Saturation	Maximum light intensity that can be collected by camera pixels, above which they stop returning an increasing signal with increased light stimulus.
Simple Storage Service (S3)	File storage system provided by Amazon Web Services (AWS), used by GHGSat to host measurement data for processing and delivery.

4 METHOD INTERFERENCES AND ENVELOPE OF OPERATION

External conditions and environmental factors provide some operational limitations to the measurements. Every survey day is started with a thorough Go/No-Go assessment. In cases of inclement weather, surveys may be postponed before or during data collection to ensure high data quality. Table 2 provides a list of environmental limitations for surveys.

Table 2. Operational envelope

Factor	Summary	Mitigation
Time of day	Solar zenith angle must be sufficiently high to provide enough illumination for optical absorption spectroscopy.	Solar angle is accounted for in flight planning.
Wind speed	High wind speeds can restrict safe flight and reduce detection sensitivity	Monitor weather forecast to determine if survey can be conducted. Reschedule in case of poor conditions.
Light path obscuration (Clouds, fog and smoke)	Optical measurements require direct line of sight from the instrument to the ground, and from the ground to the sun.	Monitor weather forecast to determine if survey can be conducted. Reschedule in case of poor conditions.
Onshore/Offshore	DATA.AIR gen 1 is applicable to onshore components only.	Offshore infrastructure is excluded from survey
Land cover	Infrastructure located under tree cover or obscured by tree shadows cannot be measured.	Tree-covered components are excluded from survey.
Flight elevation	Spatial resolution and methane sensitivity can depend on altitude above ground.	Flight trajectory is actively monitored during survey.
Ground surface reflectance	Low ground reflectance reduces the amount of signal collected by the spectrometer and increases measurement noise.	Discrete areas with low ground reflectance are quality-flagged in post-processing.
Reflectance and topography-induced artifacts	Local variability in ground reflectance and topography can induce measurement noise.	Discrete areas with elevated uncertainty on the methane concentration are quality-flagged in post-processing. Ground-correlated artifacts are ignored in manual retrieval inspection steps.

Note that GHGSat DATA.AIR measurements are not sensitive to ambient temperature and relative humidity.

5 SAFETY

[Reserved]

6 EQUIPMENT AND SUPPLIES

From a customer standpoint, only the final data products are delivered. No specific equipment or supplies are involved.

From the measurement provider perspective (GHGSat), the materials required for the measurement are:

- Spectrometer: the core instrument which comprises an optical imaging system to collect the backscattered light, disperse its spectral components, and form an image on a SWIR digital camera. It also includes an auxiliary visible-light camera, and an inertial navigation system (INS) for position and attitude measurements.
- Supporting electronics and portable computer, for data acquisition, control, and visualization by the GHGSat operator.
- Aircraft rigged for measurement surveys, with belly port through which the spectrometer images the ground.
- Gyrostabilized mount (GSM) and vibration dampers, on which the spectrometer is mounted, providing mechanically stable imaging conditions throughout the flight.
- Data processing and delivery to customers is performed in the cloud through an AWS S3 bucket and web application.

7 REAGENTS AND STANDARDS

[Reserved]

8 DATA COLLECTION AND METHOD INPUT SOURCING

Table 3. Data sources and uses

Input	Variables	Use
SWIR camera	Raw dark SWIR frames	Dark current and offset correction
SWIR camera	Raw illuminated SWIR frames	Methane concentration retrievals
SWIR camera	Camera settings (exposure time, frame period, gain)	Radiometric calibration
Auxiliary camera	Auxiliary visual images	Visual inspection
INS	Position and attitude variables (Latitude, longitude, altitude, orientation, heading)	Georeferencing
Data acquisition computer	Observation metadata (campaign, observation identifiers, etc.)	General data management and delivery

Input	Variables	Use
Weather database	Weather forecast (wind, cloud cover, precipitations)	Flight planning
Weather database	Wind speed at 10 m elevation (m/s) at the time of observation	Emission rate quantification
Weather database	Wind direction (degrees) at the time of observation	Q&A for ambiguous emission candidates
US Standard Atmosphere	Nominal vertical profiles for temperature, pressure and, mixing ratios (CH_4, CO_2 and H_2O)	Methane concentration retrievals
HITRAN	Absorption spectra for CH_4, CO_2, and H_2O	Methane concentration retrievals
TSIS-1 Solar Reference (Coddington et al., 2023)	Solar spectrum	Methane concentration retrievals

9 Quality Control

This section describes quality control at different steps of the data acquisition and processing pipeline.

9.1 Survey planning and go/no-go assessment

The following metrics are used upstream of the survey, to screen which sites can be reliably measured, determine flight hours, and assess if weather conditions are appropriate for flying. Every survey day starts with a thorough Go/No-Go assessment. In cases of inclement weather, surveys may be postponed before or during data collection to ensure high data quality.

Table 4.

Component	QC pass criteria	Mitigation and implications
Solar angle	Solar zenith angle > 20 degrees above the horizon)	Solar angle is accounted for in flight planning.
Forecasted wind speed	Average forecasted wind speed for flight day: - Wind speed < 6 m/s - Gusts < 10 m/s	Reschedule survey
Forecasted cloud cover	Go: - Clear sky - Light cloud coverage, - Thin diffuse overcast. No-go - Mostly cloudy	Reschedule survey if not passing “go/no-go” checks. Components obscured by isolated clouds, fog or smoke are flagged downstream and marked as invalid measurements.

Component	QC pass criteria	Mitigation and implications
	- Overcast - Ground-level fog	
Onshore/Offshore	Site is located onshore	Offshore infrastructure is excluded from survey
Land cover	The surveyed equipment and infrastructures must be at least 5 m away from tree coverage.	Tree-covered components are excluded from survey.

9.2 System checks

The following system checks are performed before the survey flight.

Table 5. QC: pre-flight system checks

Component	QC pass criteria	Mitigation and implications
INS	GPS signal received. Data transmitted. Estimator converged.	Power cycle, check connections. Service if required.
GSM	GSM initializes successfully (green light status indicator).	Refer to GSM operating manual for investigation and service.
Passive dampers	Dampers are flexible.	Replace malfunctioning part.
Shutter SWIR camera	Images are received and displayed. Images are dark/illuminated if shutter is closed/open.	Check lens cap is removed, check connections, power cycle. Service if required.
AUX camera	Images are received and displayed.	Power cycle, check connections. Service if required.
Data acquisition PC and software	PC boots successfully. Operator GUI displayed and reactive	Reboot, check connections. Service if required.
Multiple subsystems	Run pre-flight calibration sequence. All SWIR images, and, INS files, and software logs are successfully acquired.	Investigate; repair or service affected component.

9.3 QC performed during data collection

The following metrics are continuously monitored in-flight by the GHGSat technician operating the instrument.

Table 6. QC: data collection

Component	QC pass criteria	Mitigation and implications
GSM	Is in STABILIZE mode	Turn on STABILIZE. Service if required.
SWIR camera	Image saturation: less than 1% of pixels are saturated	Adjust camera settings. If saturation affected customer sites, re-do flight line.
SWIR camera, AUX camera	Cloud shadows: customer sites not obscured	Fly again over obscured sites later in the day or reschedule survey.
INS	Flight trajectory: lateral or vertical deviation from flight plan < 50 m	Adjust arajectory. If deviation resulted in missed targets, re-fly at intended location and elevation.

9.4 QC performed during retrievals

9.4.1 Input validation: SWIR camera bad pixel detection

SWIR camera images are the main input to the retrieval toolchain, and each frame is analyzed to identify “bad pixels”, as described in the table below.

Table 7. QC: SWIR bad pixel exclusion for retrieval input

Component	QC pass criteria	Mitigation and implications
SWIR frames	Dark and illuminated raw SWIR signal (DU) < camera saturation threshold.	Ignore pixel in downstream retrieval subprocesses.
SWIR camera pixel gains	Outliers identified during factory calibration.	Ignore pixel in downstream retrieval subprocesses.

9.4.2 Output validation: Retrieval quality flagging

A second layer of quality flagging is performed on the retrieval outputs. Ground cells can be flagged as invalid if the amount of signal is too low, which results in a high measurement uncertainty. From an operational perspective, the following situations cause pixels to be marked as invalid:

- Water bodies
- Shadows of clouds, buildings, mountains, trees, sides of open-pit mines, etc.
- Transient events such as a cloud passing or a moving vehicle

The table below summarizes the quality flagging criteria.

Table 8. QC: ground cell quality flagging for retrieval outputs

Component	QC pass criteria	Mitigation and implications
Retrieved ground reflectance	Reflectance > 4%	Ground cell flagged as invalid
CH4 uncertainty	CH4 uncertainty < 0.15 mol/m^2	Ground cell flagged as invalid

Component	QC pass criteria	Mitigation and implications
Retrieved CH4	Signal/Uncertainty ratio > 3	Overrides other QC criteria (ground cell is valid despite low albedo or high error)*

* A high signal / uncertainty ratio indicates that a methane emission was detected with high confidence despite lower than usual data quality (e.g. super-emitter over weakly-reflective ground). This emission will be reported if it passes other downstream QC.

9.5 Manual QC of deliverables

Prior to delivering data to customers, GHGSat operators will perform the following verifications:

- High-level qualitative assessment of the spatially resolved methane retrieval.
- If a plume is identified, a second operator confirms the assessment (presence or absence of emissions) to ensure that no false positives are delivered. Edge cases where the assessment is uncertain can be ruled based on the following criteria:
    - Alignment with the wind direction
    - The methane enhancement is not correlated with features present in the albedo or its gradient
    - The location of the emission is close to infrastructure identifiable on standard satellite imagery or from a list of known sites.
    - The plume morphology does not match that of known instrument artifacts.
- Plume origin is tied to the appropriate facility if it is part of a list of known customer assets. Otherwise, the origin is localized within the limits allowed by the plume morphology (examples of factors affecting origin localization include diffuse VS well defined shape, overlap between multiple emissions in the same retrieval, etc.) and the instrument spatial resolution (ground sampling distance of 1.5 m).
- In the case where multiple emissions are found close to each other, close attention is paid to ensure the masks contain only emissions from the associated site.

The manual QC checks are summarized below.

Table 9. QC: deliverable inspection

Component	QC pass criteria	Mitigation and implications
Retrieval fields	Retrieval fields (albedo, CH4, uncertainty) are free of any unusual artifact, distortion, or aberrant values.	Investigate intermediate retrieval outputs (retrieved instrument parameters, optimizer logs, etc.), assess impact (affects customer sites or not). Reprocess failed retrievals if possible or report invalid measurements.
CH4 enhancement	Plume-like morphology. Aligns with wind direction. Not albedo-correlated.	False-positive enhancements are not reported.
Emission origin	Tied to customer facility	Emissions from customer sites are reported Emissions from non-customer sites are not reported

Component	QC pass criteria	Mitigation and implications
		Emissions with ambiguous origins are reported and investigated on a case-by-case basis
Plume mask	Free of ground-correlated artifacts. Unique emission.	Manual review and refinement

10 Calibration and Standardization

10.1 Factory calibration

Individual spectrometer units are factory-calibrated at the time of fabrication. A detailed characterization protocol is followed, which includes tests at the single-component, sub-assembly, and full-instrument level. The table below provides a summary of the factory calibration tests. This calibration remains valid throughout the lifetime of the instrument.

Table 10. Factory calibration tests

Test	Description
Dark offset and dark current	Component-level test. Dark frames at multiple exposure times for available camera gains are captured. Outputs: Dark offset and dark current for every camera pixel. Note that field-collected darks (see field calibration section below) are preferred for data processing.
Flat field	Component-level test. A diffuse and uniform illumination with broadband light is sent to the camera, at different light intensities. Outputs: Gain coefficient for each pixel. Used to correct the pixel response non-uniformity (PRNU) of the camera in the pre-processing step of the retrieval, (a.k.a. “flat field” correction)
Quantum efficiency	Component-level test. Diffuse uniform illumination with monochromatic light, at varying wavelength. Outputs: Model coefficients for each pixel describing the quantum efficiency as a function of wavelength, over the optical passband of the instrument. Used in retrieval as part of the forward model.
FP Reflectivity	Component-level test. Measure the reflectivity of the coating of the Fabry-Perot (FP) etalon as a function of wavelength Outputs: Reflectivity coefficients, used in the forward model.
FP Spacing and finesse	Component-level test. Measure the wavelength response of the FP. Outputs: FP finesse and gap spacing are derived from the wavelength response. Used in the forward model
Bandwidth filter transmission	Component-level test. Measure the wavelength response of the order sorting filter (OSF).

Test	Description
	Outputs: OSF spectrum, used in the forward model.
Instrument spectral response	System-level test. Diffuse monochromatic illumination is sent to the instrument at varying wavelength. Outputs: FP spacing, FP defect finesse, FP tilt angle, imaging assembly focal length, OSF transmission band (redundancy with component-level test). Used in the forward model.
Focal length, field of view, distortion and co-registration	System-level test. Collimated, broadband illumination is sent to the instrument at varying angles of incidence. Outputs: Instrument focal length and field of view. Used in the forward model and georeferencing.

10.2 Field calibration

Dark frames are collected by the SWIR camera prior to every flight. This is done with a mechanical shutter which is closed to prevent light from reaching the sensor. In the pre-processing steps of the retrieval, the dark frames will be subtracted from the observation (non-dark) frames to remove the dark current and offset of the camera from the light-induced photocurrent.

10.3 Retrieval self-calibration

Additionally, the retrieval algorithm acts as a form of self-calibration based on the measurement data itself, as instrument-related parameters can be retrieved in addition to methane concentration and ground reflectance. A small number of global atmospheric state and instrument parameters are retrieved as part of the scene-wide retrieval step:

- Scene-wide CH4 average concentration
- Gap spacing of the Fabry-Perot etalon
- Bandpass filter transition wavelengths

11 Analytical Procedure

11.1 Flight Planning

The scope of the survey is defined with the customer and a list of targets is compiled. The optimal flight lines to survey the targets are then determined, accounting for requested coverage and revisit. Weather forecast is also considered at this stage, as measurements will not be performed in cloudy conditions or in case of hazardous weather.

11.2 Flight personnel

The crew for a survey flight consists, at a minimum, of a pilot (GHGSat subsidiary), and a GHGSat operator who handles the instrument installation, control, and settings. The operator also logs flight status, survey progress, conditions, and other events.

11.3 Installation

The imaging spectrometer and associated materials described in section 6 are installed in the aircraft.

11.4 Acquisition settings

Data acquisition settings (gain, frame rate and exposure time) are adjusted by the operator to optimize signal quality. They are adjusted as necessary before flight lines. The general guidelines are to maximize gain and exposure time while avoiding overexposed (saturated) regions and maximize the frame rate for the chosen exposure within hardware constraints.

11.5 Data acquisition

The instrument is flown above the target facilities, in accordance with the flight plan. They operate in “nadir” mode, continuously capturing images while their line-of-sight points downwards. The collected data and metadata are saved on solid state drives (SSD). Measurements are not collected during transit to and from the airport, between flight blocks, and during turns between flight lines.

11.6 Processing and delivery

After the flight, data from the SSDs is uploaded to an Amazon S3 bucket for processing as described in Section **Error! Reference source not found.**. The raw data and generated products that are derived through the processing are stored within Amazon S3 and synced to the data delivery portal for each customer via API.

12 DETECTION AND ALERTING

12.1 Method Overview

This section provides a high-level description of the processing steps. An in-depth, formal description of the retrieval algorithm is provided in the document “Description of Technology” included in this application.

12.1.1 Pre-processing

Camera-level signal is corrected for dark offset (field-collected dark frames) and pixel gain non-uniformity (factory-calibrated flat field). The raw camera signal is scaled to physical radiometric units (photons per second per pixel area). Initial quality control is performed at this step, which includes identifying saturated or faulty pixels, and ensuring all data and metadata have been successfully collected by the instrument.

12.1.2 Retrieval

A map of methane concentration is obtained from the spectrally resolved intensity measurements using a variant of standard nonlinear regression methods. A forward mathematical model describes the light propagation through the atmosphere and instrument and predicts how much irradiance is sensed at the instrument’s pixel array. An optimization algorithm is used to infer the model inputs (state vector) that best explains the measured data, including the methane column density (concentration integrated along the light ray path) and ground reflectance. There are 3 sub-steps:

1. Alignment: In the WAFP measurement concept, obtaining the full spectral information about a given point on the ground requires this point to be imaged multiple times, each one from a slightly different view angle as the instrument moves. An image registration algorithm is used to convert from camera pixel coordinates to fixed-ground coordinates.
2. Scene-wide retrieval: Full-physics retrieval on scene-wide averaged signal, in which instrument parameters and average methane concentration are retrieved.

3. Spatially resolved retrieval: The forward model is partially linearized, using the values from step A as the reference for Taylor expansion. A regression is performed for every ground cell based on this model, retrieving the methane column density and parameters of a reflectance model.

The retrievals do not use a priori distributions (in other words, a uniform prior is assumed). Reasonable initial guesses for the optimization sub-steps are taken from onboard telemetry (alignment step) and US standard atmosphere (scene-wide retrieval step). Results of the scene-wide retrieval are the initial guess for the individual ground cell of the spatially resolved retrieval step.

12.1.3 Georeferencing

The methane column density map is georeferenced in two steps. (1) A projective transformation is estimated using the position and orientation measured from the inertial navigation system (INS) which integrates data from a GPS and accelerometers. (2) This georeferencing is refined using image coregistration from the retrieved albedo to standard satellite imagery. Retrievals are then reprojected to an orthorectified grid in Universal Transverse Mercator (UTM) coordinates.

12.2 Emissions Identification and Reporting

12.2.1 Identification

Methane emissions are identified by qualified GHGSat personnel who inspect the retrieved methane column density maps, its associated uncertainty estimate, as well as ground reflectance. This step includes the manual quality checks described in section 9, as well as identifying methane emissions.

Emissions are mostly identified based on the strength of the methane enhancement relative to the uncertainty (high signal to error ratio). To distinguish real methane enhancements from noise and artifacts, the operator assesses the spatial structure of the plume (general morphology, alignment with the wind direction), and ensures the enhancement is not correlated with features present in the albedo or its gradient. Knowledge of the infrastructure (or lack-thereof) also factors in the decision process, which can come from customer-provided site lists and by inspection of the albedo field or standard satellite imagery of the surveyed sites. All identified emissions and borderline cases are reviewed by a second GHGSat operator to provide quality assurance against false positives.

When an emission is detected, the operator identifies its origin based on wind direction, plume morphology, and location of potentially emitting infrastructure. Additionally, a binary mask of the plume is computed using an algorithm based on image filtering, thresholding, and a flood-fill algorithm. This mask identifies which connected ground cells have a methane concentration above the measurement uncertainty and originate from the defined source.

12.2.2 Reporting

DATA.AIR is a detection-first method: every emission identified which passes the quality assurance and validation checks listed in section 9 of this document, and which is attributed to a customer site, is reported to the operator. Emissions that are not tied to a customer facility do not constitute an alert. Detected emissions should be promptly inspected and mitigated if confirmed on the ground.

12.3 Emissions quantification

The methane mass emission rate is calculated using the method of integrated mass enhancement (IME) (Varon et al., 2018). IME measures the local accumulation of methane, which is driven by two factors: the emission rate, and the rate at which the methane dissipates in the surrounding atmosphere, which in turn is driven by wind speed. The source rate is calculated using the equation

$$Q = \frac{U_{\text{eff}}}{\sqrt{A}} \text{IME}$$

where Q is the emission rate, U_{eff} is the effective wind speed, and A is the plume mask area. The effective wind speed is an empirically calibrated function of the local wind speed at 10 m above ground U_{10}, obtained from a third-party database.

13 METHOD PERFORMANCE

GHGSat uses controlled releases as its primary technique for calibration and validation. This approach is appropriate to quantify two key performance metrics: detection threshold and quantification accuracy.

13.1 Methodology

The validation data presented in this document is from independent single-blind controlled releases led by Stanford University (El Abbadi et al., 2023; Rutherford et al., 2023), and uses methodologies that were also successfully applied to validating satellite platforms including GHGSat DATA.SAT service (Sherwin et al., 2024, 2023).

The study design is a single-blind, multi-staged experiment. The auditor (Stanford University) performs a series of controlled releases at various rates (including possible nulls). The measurement provider (GHGSat) is aware of the test campaign and of the approximate release location, but does not know the exact equipment configuration, if methane is being released at any given time, or the true flow rate.

Flow rate was held constant during individual passes of the instrument but varied between passes and from day to day, allowing to probe detection sensitivity over the dynamic range of the instrument and under varied wind conditions.

The data collected by the auditor includes precisely metered flow rate, local wind speed and direction, and their associated uncertainties. At stage 1, the measurement provider has no access to this information, and therefore only has data obtained through the measurement system under test. Auditor data is progressively revealed at later stages of the experiment, allowing finer analysis of quantification accuracy, for example related to wind speed uncertainty. Limit-of-detection results presented in this document are from stage 1 (fully blinded).

13.2 Detection threshold

The aggregate detection threshold for DATA.AIR is 13.4 kg/hr, with 90% probability of detection at a wind speed of 3 m/s. The probability of detection model for is inferred from a set of 140 fully blinded measurements, ranging from 1.05 to 1140 kg CH_4 / hr (El Abbadi et al., 2023). The average wind speed was 2.5 m/s, with 90% of the trials having wind speed between 0.9 m/s and 5.6 m/s.

The detection threshold is inferred by fitting a probability of detection (PoD) model to experimental detection events. The PoD model is a lognormal cumulative probability distribution (CDF) of the wind-normalized emission rate Q/U:

$$PoD = F(Q, U; \mu, \sigma) = \Phi\left(\frac{\ln(Q/U) - \mu}{\sigma}\right) \tag{14}$$

where

$$\Phi(x) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{x}{\sqrt{2}}\right)\right] \tag{15}$$

is the CDF of a standard normal distribution, erf is the error function, μ and σ are model parameters (fitted coefficients). Wind speed has a strong influence on detection probability, which is why it must be accounted for explicitly. A linear relationship between Q and U is considered a good approximation for point sources (Jacob et al., 2016; Jervis et al., 2021), which the Q/U normalization derives from.

Note that other common probability models such as logistic and probit could also be used and were found to yield similar results. The lognormal distribution has the advantage of predicting the PoD from a non-negative predictor function (Q/U), as opposed to a mapping from any real number. This enforces a detection probability of zero for an emission rate of zero. Additionally, it provides a conservative estimate of PoD at high emission rates with a slow asymptotic behavior.

The parameters μ and σ are fitted to the results of the stage 1 (fully blinded) controlled releases, using maximum likelihood optimization, which minimizes the negative log-likelihood of observing the sequence of detection events given the PoD model parameters:

$$L(\boldsymbol{D}|\mu, \sigma) = -\sum_{i=1}^{N} D_i \ln(F_i) + (1 - D_i)\ln(1 - F_i) \tag{16}$$

where $\boldsymbol{D} = \{D_1, D_2, \dots D_N\}$ is the vector of binary detection events and $F_i = F(Q_i, U_i; \mu, \sigma)$ is the PoD function evaluated with the corresponding predictor variables (Q_i, U_i) and parameters (μ, σ) for detection event i.

Results of the regression are plotted in Figure 1 either as a function of (a) normalized emission rate Q/U, or (b) actual emission rate Q. Grey vertical markers represent the data vector (individual detection events) and the full red line represents the fitted PoD model.

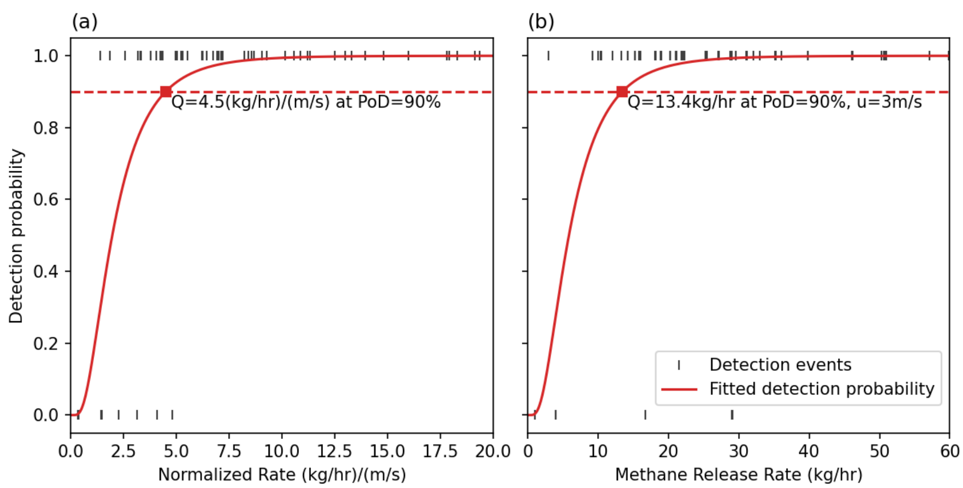

Figure 1. DATA.AIR emission detections from blind controlled releases and probability of detection model fit, expressed as a function of (a) normalized emission rate, and (b) emission rate.

To quote a single value for detection limit from this distribution, one must specify the desired probability of detection and wind speed. A PoD of 90% and a reference wind speed of U_0 = 3 m/s are used in this document. The corresponding detection threshold is 13.4 kg/hr.

13.3 Measurement uncertainty

Each emission quantification Q is delivered accompanied by a measurement uncertainty estimate ΔQ , which accounts for variability in observation conditions such as ground reflectance, sun illumination, terrain, and wind. The uncertainty is defined as the sum in quadrature of 3 individual error components which are assumed to be weakly or non-correlated:

$$\Delta Q = \sqrt{\Delta Q_{\text{meas}}^2 + \Delta Q_{\text{wind}}^2 + \Delta Q_{\text{mod}}^2}$$

A brief description of the error components is provided below.

13.3.1 Measurement error

ΔQ_{meas} is the measurement error associated with imperfect methane concentration retrieval, which include shot noise, camera read noise, and other ground-correlated noise sources. Because correlated noise cannot be easily predicted from theory, we estimate this error component using an empirical approach, by moving the plume mask over the full retrieval domain and retrieving dummy source rates for each position. The error is estimated as the variance of the dummy rates.

13.3.2 Wind error

ΔQ_{wind} is the error on the wind speed, which arises from using a coarse resolution meteorological database to estimate the local 10-m wind speed U_{10}. It is generally the dominant source of uncertainty. We estimated this error through a comparison against weather stations.

13.3.3 Model error

ΔQ_{mod} is as model error which associated with the use of the same effective wind speed model (conversion from U_{10} to U_{eff}) for plumes of varying shapes and sizes in different meteorological conditions. An error analysis was conducted in the original publications that introduced the IME method for plume quantifications (Varon et al., 2019, 2018), using a large ensemble of simulated plumes in various atmospheric conditions. The average relative error was found to be around 7% for the IME method, which is the value used for ΔQ_{mod}.

13.4 Quantification accuracy and biases

The absolute accuracy of the quantification can be evaluated from the same controlled release data used to establish the detection threshold, by comparing the true emission rate with the GHGSat measurement. Results are shown in Figure 2 for two stages of the unblinding: (a) fully blinded, and (b) the locally measured wind speed is known. At stage 1, the results show the true source rate is generally contained within the measurement uncertainty ΔQ (expressed here as a 95% confidence interval), with a modest negative bias (under-estimation). This bias is removed at stage 2 when more accurate wind information is available.

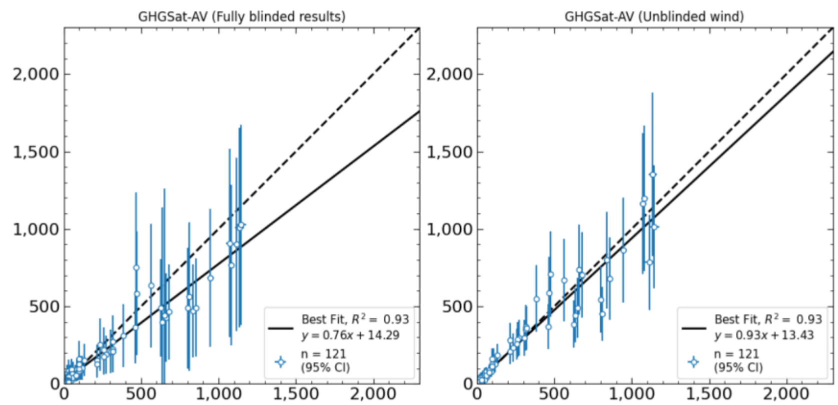

Figure 2. Comparison of the GHGSat emission rate measurement with ground truth at two stages of unblinding: (a) fully blinded, (b) locally measured wind speed unblinded. Markers and error bars represent individual measurements with the associated 95% confidence intervals. The full line is the linear regression, and the dashed line represents the ideal 1:1 ratio. Adapted from (El Abbadi et al., 2024).

14 Pollution Prevention

Carbon dioxide and other air pollutants are emitted form the combustion engines of the instrument-carrying aircraft, and during deployment of the personnel to the survey regions. While this pollution cannot be completely avoided, it can be mitigated by careful flight planning and optimization, in alignment with considerations of time and cost efficiency.

15 Data Management and Recordkeeping

15.1 In-flight data collection

Data collected by all sub-components of the instrument (SWIR camera, AUX camera, and INS) is collected by custom instrument control and data acquisition software. Data is saved to a solid state drive (SSD) during the flight. After landing, the raw data is copied to two locations:

1. Backup to tape for long-term archiving.
2. Upload to an S3 server for processing.

The data acquisition software is version-controlled. The version is saved as metadata for traceability.

15.2 Data processing

Processing from raw data to deliverables occurs in the cloud (AWS S3). The suite of software and tools responsible for producing the 2D map of methane concentration is referred to as the *retrieval toolchain*. The version of the toolchain and other downstream processes (plume masking and source rate retrieval) are saved as metadata for traceability. A unique identifier is attributed to each flight line and data processing subset.

15.3 Data Delivery to End-Users

Search, discovery, and data access capabilities are provided through GHGSat's secure HTTPS online data system called SPECTRA, which provides both visibility to GHGSat's catalogue as well as access to user-specific observation products and data. Each approved user is provided with unique and password-protected access credentials to SPECTRA, and e-mail notifications for emissions detected in the data can be enabled. The SPECTRA interface enables customized data visualization in which users can import or export data layers through ArcGIS REST enpoints or link to their own GIS client software solutions. An application programming interface (API) is available for retrieving data products or parameters.

Data is delivered on SPECTRA within 5 business days after the flight where it remains accessible for an indefinite time. If a customer ends its contract with GHGSat, the SPECTRA account is maintained for 6 months, during which the data is available for download. GHGSat will maintain an indefinite record of all collected data independent of customer account status.

15.4 Product description

The file packages delivered to the user's SPECTRA account are detailed in Table 11 and Table 12.

Table 11. Product delivery package

Item	Contents
Imagery / Data	The image or data product, order as per call-up, with unique ID for each image / data product. The details of these images or data products are found in Table 12.
Metadata	The metadata and ancillary information for each image are provided in the JSON file format. This metadata includes the size, description, units, spatial coordinates (latitude and longitude) and pixel size, which is sufficient to allow a qualified programmer to read the volume and transform its contents into an image.
Additional Information	Any associated processing files and documentation to help the user to understand the product and facilitate data use.

Table 12. Data files and products

File	Description	Format
Albedo	The per-pixel short-wave infrared (SWIR) surface reflectance. The pixel values represent the fraction of light received on a surface that is reflected. A value of zero indicates that no light is reflected and a value of one indicates that all the light received on a surface is reflected.	GeoTIFF
Reduced resolution albedo and World file	Resolution of the image is reduced compared to the albedo layer. The World file provides reference information for the geographic location of the data.	PNG, WLD
Methane concentration measurement	The methane concentration values in each pixel represent how many methane particles are in a give volume of air compared to the local background. The background is set to a value of zero. The concentration of the methane particles is measured in parts per billion (ppb) and is a column averaged concentration. The methane	GeoTIFF

File	Description	Format
	concentration GeoTIFF shows methane concentration of the entire observation. Note that this layer can contain artifacts (false positive methane enhancements); enhancements associated to real methane emissions are identified in the methane plume layer.	
Methane concentration measurement error	Per-pixel methane measurement uncertainty. The uncertainty is for a single flight pass and includes instrument errors and the quality of the model fitted on the data. The error is defined as the standard deviation.	GeoTIFF
Methane concentration measurement isolated for each emission plume	This layer shows the methane concentration reported in the methane concentration measurement layer only at the location where a plume was detected.	GeoTIFF
Methane emission concentration map	High readability pseudo-colour map combining background imagery and the isolated emission plume identified in the methane plume layer.	PNG
Flags	This is a layer that presents the quality of each pixel in the methane concentration measurement layer. All the values in the flag layer are 1, 2, or 3: 1. Good: The pixel is considered to have good quality data. The values obtained at this location can be trusted. 2. No Data: There was no data available in the raw data at this location. 3. Bad Fit: The pixel is considered to have poor quality data. Typically, this means that the error at this location is high and/or that the signal is low. The value obtained at this location cannot always be trusted and need to be interpreted with caution.	GeoTIFF
Information about an identified emission	This file includes the spatial coordinates (latitude, longitude), detection time, wind speed, estimated source rate and uncertainty on the estimated source rate of the identified plume. Multiple methane emissions can be detected in one observation and each emission has its own ID.	CSV

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17 TABLES, DIAGRAMS, FLOWCHARTS AND VALIDATION DATA

[Reserved]