

Methane Alternative Test Method – GHGSat DATA.AIR Gen 2 For Fugitive Methane Emission Monitoring

1. Scope and Application

1.1. Scope

This document describes the procedure associated with the GHGSat DATA.AIR Gen 2 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

1.2.1. 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.

1.2.2. 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.

1.2.3. 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 2 under this protocol can detect and quantify emissions of 10kg/hr with a 90% probability of detection (POD) at facility-level resolution. The detection threshold is determined through single-blind controlled releases, as 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 a facility owner/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.

2. Summary of Method

This section provides a high-level description of the processing steps.

2.1. Data acquisition

2.1.1. 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 spectrometers have high spatial and spectral resolution, to enable high-precision measurements of the methane concentration enhancement above local background.

2.1.2. The spectrometers can be mounted in any appropriate third-party aircraft and deployed with a GHGSat technician as required for aerial survey campaigns. Surveys are performed during daytime in clear weather conditions as the measurement is based on the analysis of backscattered sunlight.

2.2. 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.

2.3. Retrieval

2.3.1. 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 explain the measured data, including the methane enhancement and ground reflectance. There are two sub-steps:

1. Scene-wide retrieval: Full-physics retrieval on scene-wide averaged signal, in which instrument parameters and average methane concentration are retrieved.
2. Spatially resolved retrieval: The forward model is partially linearized, using the values from step 1 as the reference for Taylor expansion. A regression is performed for every ground cell based on this model, retrieving the methane enhancement and parameters of a reflectance model.

2.3.2. 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 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.

2.4. Georeferencing

The methane concentration map is georeferenced using the position and orientation measured from the inertial navigation system (INS) which integrates data from a Global Positioning System (GPS) and accelerometers. Retrievals are then reprojected to an orthorectified grid in Universal Transverse Mercator (UTM) coordinates.

2.5. Emissions Identification

Methane emissions are identified by qualified GHGSat analysts by inspecting the retrieved spatially resolved methane concentration. Primarily, emissions are identified as areas containing elevated methane concentrations compared to background level. Quality assurance against false positives is described in Section 9 of this document. The origin of the emission is also localized at this stage, based on wind direction, plume morphology, and visual imagery of the terrain (both our own and publicly available).

2.6. 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

$$Q = \frac{U_{\text{eff}}}{\sqrt{A}} \text{ IME} \quad (1)$$

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 weather forecast/reanalysis models.

2.7. Data delivery and alerting

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.

3. Definitions of Method

3.1. Definitions

3.1.1. *Albedo*: Fraction of the sun radiation reflected by the ground surface.

3.1.2. *Attitude*: The orientation (3D angles) of an aircraft, spacecraft or imaging platform.

3.1.3. *Concentration enhancement*: Difference in concentration of a gas species (e.g., methane) with respect to local background.

3.1.4. *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) which are then subtracted from illuminated images to estimate photocurrent accurately.

3.1.5. *Facility owner/operator*: The owner or operator of the oil and gas facility being surveyed, and the recipient of the emission reports and alerts generated under this method.

3.1.6. *Georeferencing*: Process of mapping the pixel coordinates of an image to the geographic coordinates of the area that was imaged.

3.1.7. *GHGSat analyst*: GHGSat personnel who inspect the retrieved methane concentration maps and associated data layers to identify emissions, attribute their origin, and perform the manual quality control described in Section 9.

3.1.8. *GHGSat technician*: GHGSat personnel on board the survey aircraft who install the imaging spectrometer, control it, set acquisition parameters during a survey, and log flight status and survey progress.

3.1.9. *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.

3.1.10. *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.

3.1.11. *Integrated mass enhancement (IME)*: the total amount of detectable methane enhancement that originates from a given source.

3.1.12. *Inertial navigation system (INS)*: An electronic device which estimates the position and attitude of an aircraft by combining inputs from GPS, accelerometers, and gyroscopes.

3.1.13. *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.

3.1.14. *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).

3.1.15. *Saturation*: Maximum light intensity that can be collected by camera pixels, above which they stop returning an increasing signal with increased light stimulus.

3.1.16. *Short-wave infrared (SWIR) region*: The wavelengths of light typically defined to be from 0.9 to 1.7 μm .

3.1.17. *Simple Storage Service (S3)*: File storage system provided by Amazon Web Services (AWS), used by GHGSat to host measurement data for processing and delivery.

3.2. Abbreviations

3.2.1. *GPS*: Global Positioning System

3.2.2. *GSM*: Gyro-stabilized Mount

3.2.3. *IME*: Integrated Mass Enhancement

3.2.4. *INS*: Inertial Navigation System

3.2.5 *POD*: Probability of Detection

3.2.6. *S3*: Simple Storage Service

3.2.7 *SWIR*: Short-wavelength Infrared

4. Method Interferences and Envelope of Operation

Table 1. Interference factors and mitigation

Factor	Summary	Mitigation
Time of day	Solar zenith angle must be > 20 degrees above the horizon to provide enough illumination for optical absorption spectroscopy.	Solar angle is accounted for in flight planning. (See Table 3).
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 cases of wind speeds above 6 m/s and gusts above 10 m/s. (See Table 3).
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 mostly cloudy skies, overcast, and ground-level fog. (See Table 3).
Water bodies	Specular reflection from water (as opposed to diffuse reflection from solid ground) can result in insufficient collected signal.	For temporary flooding around sites (from heavy rain or snow melt), survey is rescheduled. Low-signal ground cells are quality-flagged, marking them invalid. (See Table 7).
Land cover	Infrastructure located under tree cover or obscured by tree shadows cannot be measured.	Tree-covered sites are excluded from survey and must be measured using different technology. (See Table 3)
Ground surface reflectance	Low ground reflectance reduces the amount of signal collected by the	Discrete areas with low ground reflectance are quality-flagged in

Factor	Summary	Mitigation
	spectrometer and increases measurement noise.	post-processing, marking them invalid. (See Table 7).
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, marking them invalid. (See Table 7). Ground-correlated artifacts are ignored in manual retrieval inspection steps (See Table 8).

5. Safety

5.1. Flight operations under this method are conducted in accordance with applicable FAA regulations, including but not limited to 14 CFR Part 91 (General Operating and Flight Rules). The flight provider operating the aircraft has established rules, regulations, and safety policies and procedures which must be followed for internal and general aviation compliance. Prior to each deployment, weather conditions, airspace status, and aircraft airworthiness are evaluated as part of a Go/No-Go assessment (Section 9.1). Flights are not initiated or continued when conditions fall outside the applicable safety envelope of the aircraft, pilot, or operating regulations.

5.2. This method may not address all potential safety scenarios associated with its use. It is the responsibility of the user of this test method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to performing this test method.

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:

6.1. *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 INS for position and attitude measurements.

6.2. *Supporting electronics and portable computer*: used for data acquisition, control, and visualization by the GHGSat technician.

6.3. *Aircraft*: GHGSat typically operates on small, fixed-wing aircraft rigged for measurement surveys, with a belly port through which the spectrometer images the ground. Both single-engine and twin-engine aircraft can be used, provided they can maintain a consistent surveying speed and altitude and accommodate the associated equipment.

6.4. *Gyrostabilized mount (GSM) and vibration dampers*: The GSM is an actively controlled mechanical platform on which the spectrometer is installed, using onboard gyroscopes and motorized actuators to compensate for aircraft roll, pitch, and yaw in real time. This maintains the spectrometer's line of sight in a near-nadir orientation throughout the flight, decoupling it from aircraft motion and preserving consistent imaging geometry. Passive vibration dampers between the GSM and the aircraft airframe further attenuate high-frequency vibrations that would otherwise degrade image quality.

6.5. *AWS S3 bucket and web application*: used for data delivery to customers performed in the cloud.

7. Reagents and Standards

[Reserved]

8. Data Collection and Method Input Sourcing

The data inputs used by this method (see Table 3) come from two categories of sources: (1) internal instrument subsystems that collect measurements during the survey flight, and (2) external reference data used for flight planning, retrievals, and emission rate quantification. Table 3 summarizes each input, the variables it provides, and its use in the measurement and processing pipeline.

Table 2. 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 and observation identifiers)	General data management and delivery
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 ₂ O)	Methane concentration retrievals
HITRAN	Absorption spectra for CH ₄ , CO ₂ , and H ₂ O	Methane concentration retrievals
TSIS-1 Solar Reference (Coddington et al., 2023)	Solar spectrum	Methane concentration retrievals

9. Quality Control

This section describes quality control (QC) at different steps of the data acquisition and processing pipeline. QC performed before and during data acquisition (Sections 9.1, 9.2, and 9.3) are designed to maximize the chance of collecting high-quality emissions data. Failing a pre- or in-flight QC requires adjusting flight parameters, repeating a measurement overpass, or rescheduling a survey when conditions are more favorable. Because operational conditions are complex and not perfectly predictable, further QC is performed after data acquisition (Sections 9.4 and 9.5). A facility that fails post-flight QC is not considered measured under this method and the associated data are marked invalid. The facility must be re-measured, either in a repeat survey or by another approved method.

Post-flight QC failures are infrequent and are limited to the affected facilities; valid measurements of other facilities in the same survey are unaffected.

9.1. Survey planning and go/no-go assessment

Table 3 presents metrics that are used upstream of the survey to screen which sites can be reliably measured, determine flight hours, and assess whether weather conditions are appropriate for flying. Every survey day starts with a go/no-go assessment, and surveys may be postponed before or during data collection to ensure high data quality. In particular, the wind envelope is enforced at the go/no-go stage, at the level of the flight day: flight days with forecast average wind speed above 6 m/s or gusts above 10 m/s are rescheduled, and no data are collected or delivered.

Table 3. QC: survey planning

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 in case of high winds.
Forecasted cloud cover	Go: - Clear sky - Light cloud coverage, - Thin, diffuse overcast. No-go: - Mostly cloudy - Overcast - Ground-level fog	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.
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. All checks must pass before the survey can take place.

Table 4. 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.

Component	QC pass criteria	Mitigation and implications
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. GUI displayed and reactive	Reboot, check connections. Service if required.
Multiple subsystems	Capture test frames. SWIR images, 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 5. 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 trajectory. 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 6. 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

9.4.2.1. 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 may cause pixels to be marked as invalid:

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

9.4.2.2. The table below summarizes the quality flagging criteria.

Table 7. QC: ground cell quality flagging for retrieval outputs

Component	QC pass criteria	Mitigation and implications
Retrieved ground reflectance	Reflectance > 1%	Ground cell flagged as invalid
CH ₄ concentration uncertainty	CH ₄ uncertainty < 0.1 mol/m ²	Ground cell flagged as invalid
Retrieved CH ₄ concentration	Signal/Uncertainty ratio > 3	Overrides other QC criteria (ground cell is valid despite low albedo or high error) *

*A high signal to uncertainty ratio indicates that a methane emission was detected with high confidence despite lower than usual data quality. This emission will be reported if it passes other downstream QC (see Table 8).

9.5. Manual QC of deliverables

9.5.1. Prior to delivering data to customers, GHGSat analysts will perform the following verifications:

- a) Visual inspection of the retrieval output layers (methane concentration, uncertainty, and ground reflectance) to identify unexpected artifacts, distortions, defocus, or aberrant values that fall outside the automated quality controls described in Section 9.4. This step is intended to catch previously uncharacterized failure modes and provides a final human-in-the-loop check before deliverables are released.
- b) Edge cases where the assessment (presence or absence of an emission) is uncertain are ruled based on the following criteria:
 - a. Alignment with the wind direction
 - b. The methane enhancement is not correlated with features present in the albedo or its gradient
 - c. The location of the emission is close to infrastructure identifiable on standard satellite imagery or from a list of known sites.
 - d. The plume morphology does not match that of known instrument artifacts.
- c) 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 1.0 m).
- d) 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.
- e) Quality assurance for every detected emission and ambiguous non-detection is performed by a second analyst, who confirms the assessment, localization, and plume mask meet the quality requirements listed in Table 8.

9.5.2. The manual QC checks are summarized below.

Table 8. QC: deliverable inspection

Component	QC pass criteria	Mitigation and implications
Retrieval fields	Retrieval fields (albedo, CH ₄ , 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.
CH ₄ 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 facilities are reported. Emissions from non-customer facilities are not reported.
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 for the lifetime of the instrument, unless factory service involving the optical components is required, in which case the relevant calibration tests are repeated before the instrument returns to operation. In addition, the key elements of the calibration are continually refined in the field: dark calibration is re-measured on every flight (Section 10.2), and the spectral calibration is verified on every flight line as part of the retrieval (Section 10.3).

Table 9. Factory calibration tests

Test	Description
Dark offset and dark current	Component-level test. Measures dark offset and dark current for every camera pixel.
Flat field	Component-level test. Measures 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. Measures quantum efficiency of the sensor as a function of wavelength, over the optical passband of the instrument.
Spectral response	System-level test. Measures the response of the whole instrument as a function of wavelength.
Focus	System-level test. Measures the along-track and across-track point spread function (PSF).

Test	Description
Angular response	System-level test. Measures the instrument's focal length and field of view.

10.2. Field calibration

10.2.1. Dark frames are collected in flight by the SWIR camera using a mechanical shutter. 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.

10.2.2. Additionally, the quality of the geometric calibration (angular response) is monitored as part of the QC (section 9.5) and is updated when geometric artifacts in the retrieval output layers (spatial distortion, defocus, or misregistration) are identified and are consistent with a change in the instrument's angular response.

10.3. Retrieval self-calibration

The retrieval algorithm additionally acts as a per-scene calibration, as key instrument parameters are re-estimated from the measurement data itself. A small number of global atmospheric and instrument parameters are fitted during the scene-wide retrieval step described in Section 2.3:

- Scene-wide average methane concentration
- Spectral line shape and wavelength mapping
- Spectrometer slit position

This self-calibration is performed automatically for every overpass. If the optimization routine fails to converge at the calibration step, no methane emission measurement is made, and the overpass must be repeated, either on the same day or in a follow-up survey.

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 forecasts are 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 technician who handles the instrument installation, control, and settings. The technician 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 technician 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 (i.e., downwards vertical view angle, from the instrument towards the ground), continuously capturing images while their line-of-sight points downwards. The collected data and metadata are saved on solid state drives (SSD). Measurements are generally not collected during transit to and from the airport, between flight blocks, and during turns between flight lines.

11.6. Data Processing

Raw data collected by the instrument is analyzed by the GHGSat proprietary processing toolchain. Key steps of the process are outlined in Section 2.

11.7. Data delivery

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.

12. Detection and Alerting

12.1. Detection

12.1.1. Methane emissions are identified by qualified GHGSat analysts who inspect the retrieved methane concentration 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.

12.1.2. 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 GHGSat analyst 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 analyst.

12.1.3. When an emission is detected, the analyst 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 ground cells have a methane concentration above the measurement uncertainty and originate from the defined source.

12.2. Alerting

DATA.AIR Gen 2 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 facility owner/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.

13. Method Performance

GHGSat uses controlled releases as its primary technique for calibration and validation. The aggregate detection threshold for DATA.AIR Gen 2, quantified using this approach, is 7.1 kg/hr, with 90% POD at a wind speed of 3 m/s.

13.1. Methodology

13.1.1. The validation data presented in this document is from experiments that were organized and executed by GHGSat at a partner facility located in Southern Alberta in 2024. The methodology borrows heavily from previous studies that were successfully applied to validate GHGSat’s first generation of airborne sensors (El Abbadi et al., 2023; Rutherford et al., 2023), and satellite platform (Sherwin et al., 2024, 2023).

13.1.2. Methane is released from cylinders through a pressure regulator, mass flow controller, and thermal conditioner. It is then released from a vertical stack at about 5 m above ground. A 3D anemometer measures the local wind speed. Flow and wind data from the ground supporting instruments is timestamped and logged electronically, providing accurate measurements that are used as “ground truth” values in downstream analysis.

13.1.3. 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.

13.2. Detection threshold

13.2.1. The probability of detection model is inferred from a set of 110 measurements, ranging from 2.5 to 22.5 kg CH₄ / hr. The average wind speed was 3.4 m/s, ranging between 0 and 6.2 m/s.

13.2.2. The POD function is modelled as the composition of a predictor function $g(\mathbf{x}; \boldsymbol{\phi})$ and an inverse-link function $f(g(\mathbf{x}; \boldsymbol{\phi}); \boldsymbol{\theta})$, where $\mathbf{x} = \{Q, U\}$ is a vector containing the variables which influence detection threshold (emission rate Q and wind speed U), and $\boldsymbol{\phi}$ and $\boldsymbol{\theta}$ are vectors of model parameters (Conrad et al., 2023). A log-normal inverse link function is used as follows:

$$p = f(g(Q, U; U_0); \mu, \sigma) = \frac{1}{2} \left(1 + \operatorname{erf} \left(\frac{\ln g(Q, U; U_0) - \mu}{\sigma} \right) \right) \quad (2)$$

where p is the probability of detection erf is the error function, μ and σ are the fitted parameters of the lognormal link function. The predictor function uses a rational form:

$$g(Q, U; U_0) = \frac{Q}{U - U_0} \quad (3)$$

13.2.3. This form captures the first order physical behavior of methane mass balance, which accumulates proportionally to Q and dissipates at a rate proportional to U (Jacob et al., 2016; Jervis et al., 2021). The wind offset parameter U_0 reflects the fact that even at zero average wind speed, small-scale turbulence and diffusion cause some amount of dissipation.

13.2.4. The parameters μ , σ and U_0 are fitted to the results of the controlled releases, using maximum likelihood optimization, which minimizes the negative log-likelihood of observing the sequence of detection events given the POD model parameters:

$$L(\mathbf{D} | \mu, \sigma, U_0) = - \sum_{i=1}^N D_i \ln(F_i) + (1 - D_i) \ln(1 - F_i) \quad (4)$$

where $\mathbf{D} = \{D_1, D_2, \dots, D_N\}$ is the vector of binary detection events and $F_i = f(g(Q_i, U_i; U_0); \mu, \sigma)$ is the POD function evaluated with the corresponding predictor variables (Q_i, U_i) and parameters (μ, σ, U_0) for detection event i .

13.2.5. Results are shown in Figure 1, where markers represent individual outcomes of the experiment (blue diamonds represent successful detections, green crosses represent misses), and the shaded greyscale represents the fitted POD model. To quote a single value for detection limit from this distribution, one must specify the desired probability of detection and wind speed. For POD = 90% and $U_0 = 3$ m/s, a detection threshold of 7.1 kg/hr was determined.

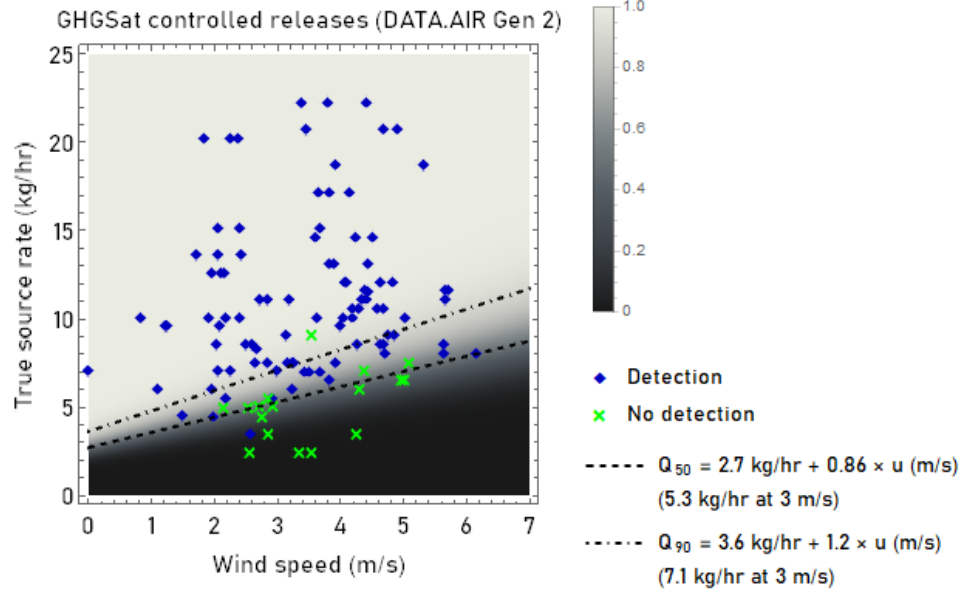


Figure 1. DATA.AIR Gen 2 emission detections from blind controlled releases and probability of detection model fit. Markers indicate individual detection attempts (blue diamonds = detections, green crosses = missed detections), scattered in a 2D space of wind speed (x) and true source rate (y). The background color represents the fitted probability of detection model. Dashed lines represent the fixed POD contours for 50% and 90% detection probability.

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 three individual error components which are assumed to be weakly or non-correlated:

$$\Delta Q = \sqrt{\Delta Q_{\text{meas}}^2 + \Delta Q_{\text{wind}}^2 + \Delta Q_{\text{mod}}^2} \quad (5)$$

13.3.1. Measurement error

ΔQ_{meas} is the measurement error associated with imperfect methane concentration retrieval, which includes shot noise, camera read noise, and other ground-correlated noise sources. Because correlated noise cannot be easily predicted from theory, the error component is estimated 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. This error has been estimated through a comparison with weather stations.

13.3.3. Model error

ΔQ_{mod} is as model error which is 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. The results show the true source rate is generally contained within the measurement uncertainty ΔQ (expressed here as 1-sigma error bars), with a modest positive bias (over-estimation).

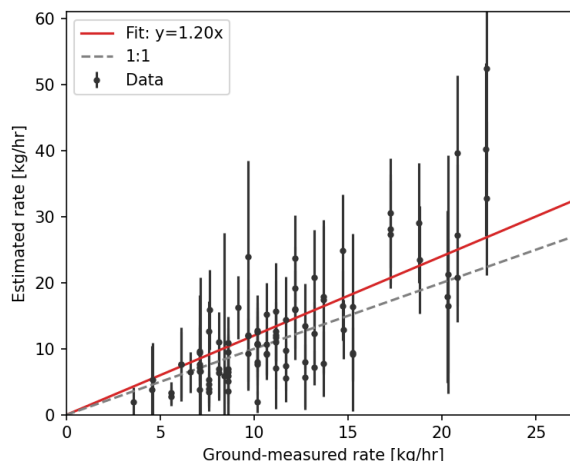


Figure 2. Quantification performance for the GHGSat AV Gen 2 sensor inferred from controlled releases. Quantified emission rates, with associated 1-sigma error bars, are plotted against the “ground truth” emission rate measured at the release site with a mass flow controller. A linear regression (red line) and 1:1 line (grey dashes) are also shown.

14. Pollution Prevention

Carbon dioxide and other air pollutants are emitted from 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 optimal flight planning, in alignment with considerations of time and cost efficiency.

15. Data Management and Recordkeeping

15.1. In-flight data collection

15.1.1 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 analysis and delivery.

15.1.2. 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 uses a suite of software and tools that produce 2D map of methane concentration, 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

15.3.1. 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 endpoints or link to their own GIS client software solutions. An application programming interface (API) is available for retrieving data products or parameters.

15.3.2. Data is delivered on SPECTRA within 48 hours after the flight where it remains accessible for an indefinite time. If a customer ends their contract with GHGSat, the SPECTRA account is maintained for six 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 10 and Table 11.

Table 10. 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 11.
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 content into an image.
Additional Information	Any associated processing files and documentation to help the user to understand the product and facilitate data use.

Table 11. 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 given 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 concentration GeoTIFF shows methane concentration of the entire observation. Note that this layer can contain artifacts (false positive methane enhancements); enhancements associated with real methane emissions are identified in the methane plume layer.	GeoTIFF
Methane concentration measurement error	Per-pixel methane measurement uncertainty. The uncertainty is for a single flight pass and includes	GeoTIFF

File	Description	Format
	instrument errors and the quality of the model fitted on the data. The error is defined as the standard deviation.	
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-color 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: this pixel meets the quality requirements outlined in section 9.4.2.. 2. No Data: There was no data available in the raw data at this location. 3. Low quality: this pixel does not meet the quality requirements outlined in section 9.4.2.	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]