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 following review by the EPA

Content

1 Scope and Application

This document describes the procedure associated with the GHGSat DATA.AIR Gen 1 product, which aims to detect, localize, and quantify methane emissions. Methane (CAS# 74-82-8) is the is the unique chemical analyte quantified by this method. Other quantities of interest such as ground reflectance (albedo) are also estimated. The method sensitivity is 13.6 kg/hr, defined as the smallest methane emission rate it can reliably detect (90% probability of detection) in standard conditions (wind speed of 3 m/s).

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. The aircrafts are nominally flown at an altitude of 10,000 ft above ground level, providing a swath width of about 750m. Surveys are performed during daytime in clear weather conditions as the measurement is based on the analysis of backscattered sunlight.

2 Summary of Method

The key steps of the measurement procedure are listed below.

1. **Data acquisition**: GHGSat DATA.AIR is a remote-sensing technology based on optical absorption spectroscopy, The instrument is an airborne imaging spectrometer, which measures the solar illumination backscattered from the ground as it is flown above sites of interest (potential methane emitters).
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 methane concentrations, which indicate the presence of emissions sources.
4. **Source rate quantification**: If one or more emissions are found, the emission rate is calculated for each of them.
5. **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.

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

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) 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 delivery.

4 INTERFERENCES

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. Interference factors are described in the table below. Further details are provided in the supplementary information (SI) document.

Factor	Description
Time of day	Measurements are based on solar illumination and thus cannot be performed at night or at very low solar elevation angles.
Wind	Data will not be collected in case of high winds or other extreme weather conditions that represent a flight hazard. Wind speed also modulates the sensitivity and quantification accuracy of the measurement (see Description of Technology). This effect is reflected in the emission rate uncertainty associated with the data.
Light path obscuration (Clouds, fog and smoke)	To obtain a valid measurement, the light path between the sun and ground, and from ground to instrument must be clear. GHGSAT limits deployment during cloudy or foggy days. In partly cloudy conditions, some sites may be obscured by cloud shadows and flagged as invalid in downstream analysis. The same applies if a site is obscured by smoke (e.g. from lit flare).
Land cover and topography	Ground features can affect the ability to detect emissions. Homogenous and arid scenes allows a better precision and lower detection threshold than urban areas, heavy tree cover, snow, or mountains. The increased measurement error associated with these effects is reflected in the uncertainty associated with column density and source rate estimate.
Diffuse emissions	Diffuse emissions such as from open pit mines or landfills can be detected, but with reduced sensitivity and higher uncertainty. Instrument performance specifications (detection threshold and quantification accuracy) are benchmarked for point source emissions.

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 (for background imagery, not used in methane spectroscopic analysis), 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 Sample Collection, Preservation and Storage

No physical sample are collected. Section 11 describes the data collection procedure.

9 Quality Control

This section describes quality control at different steps of the data acquisition and processing pipeline. More information is provided in the SI document.

9.1 QC performed during data collection

Some quality checks are performed in-flight by the GHGSat technician operating the instrument.

- Camera configuration is appropriate for the surveyed terrain (images are not underexposed or overexposed).
- Measurements require direct sun illumination, if a site is cloud-covered during a measurement pass, it may be revisited later in the day in the case of isolated clouds, or on another date in the case of worsening overcast conditions.
- The flight path is monitored to ensure that target sites are surveyed.

The data acquisition software automatically performs the following basic verifications:

- The expected number camera frames has been collected.
- All expected ancillary data and metadata files have been collected (e.g. position and attitude measurements, timestamps, identifiers).

9.2 QC performed during retrievals

9.2.1 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". A camera pixel is labeled as bad for one of the following reasons:

- Saturated pixels: The signal measured by the pixel is above saturation threshold (the response of the pixel to light input is suppressed). This can be caused by sub-optimal adjustment of the camera gain or exposure time, or when flying over a particularly reflective patch of ground.
- High dark current (hot pixel): Some pixels display a high signal even when not exposed to light stimulus. This can be caused by manufacturing defects in the pixel array, or damaged by solar radiation. The contribution of radiation damage is small for airborne instruments but significant for satellites.
- Gain coefficient outlier: Each camera pixel is characterized by its gain coefficient, which describes the response in digital units per photon illuminating the pixel. Those

coefficients are measured during pre-operational testing. A pixel where the gain coefficient is an outlier, quantified by its absolute deviation compared with the median of all pixels, is excluded from retrievals.

Camera bad pixels are identified at the start of the retrieval toolchain and are masked out of all downstream subprocesses.

9.2.2 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

9.3 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.

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.

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). 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

Calibration in the field is minimal. 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 instrument parameters are retrieved as part of the scene-wide retrieval step (more information is provided in the SI document):

11 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. Further details are provided in the SI document.

11.5 Data acquisition

The instrument is flown above the target facilities, in accordance with the flight plan. Aircrafts are flown at a typical elevation of 10,000 ft above ground level, providing a swath width of around 750 m. 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 12. 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 DATA ANALYSIS AND CALCULATIONS

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 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.

12.2 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.

12.3 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. Further details are provided in the SI document.

12.4 Inspection and emissions identification

Qualified GHGSat personnel 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 9.3, 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.

12.5 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

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

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

13.1 Aggregate detection threshold

The aggregate detection threshold for DATA.AIR is 13.6 kg/hr, with 90% probability of detection at a wind speed of 3 m/s.

This value was determined through independent single-blind controlled releases led by Stanford University (El Abbadi et al., 2023; Rutherford et al., 2023; Sherwin et al., 2023a, 2023b).

13.2 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:

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

A brief description of the error components is provided below. More details on the calculation and methodology by which those errors are estimated is included in the SI document.

13.2.1 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.

13.2.2 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.

13.2.3 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 (D. J. Varon et al., 2019; Varon et al., 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}.

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 Waste Management

No physical samples or waste are generated in this procedure.

16 References

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17 Tables, Diagrams, Flowcharts and Validation Data

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