DATA.AIR Gen 1

Formal Alternative Test Method

Document No. GHG-21850-6103

30 May 2024

GHGSAT Product/Document Approval

Title:	**DATA.AIR Gen 1** **Formal Alternative Test Method**
Document No.:	**GHG-21850-6103-a**
Submission Date:	**30 May 2024**
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CHANGE HISTORY

Version	Release Date	Notes
a	30 May 2024	Initial submission

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).

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
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).
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.

4 Interferences

The following aspects can affect our ability to detect and quantify methane emissions:

- Data will not be collected in case of high winds or other extreme weather conditions that represent a flight hazard.
- Weather: Low altitude clouds or haze
- Seasonal effect: Snow cover and low solar elevation angle
- Industrial effect: Smoke, lit flares, elevated background methane
- Background: Ground features can affect our ability to detect emissions. Homogenous and arid scene allows a better precision and lower detection threshold than mountain, farmland and urban scenes or areas with a complex topography.
- Wind speed: Lower wind speed allows us to detect fainter emissions. Higher wind speed dissipates methane emissions faster in the atmosphere and makes it more challenging to detect fainter emissions.

5 Safety

From a customer perspective, only the final data products are delivered. There are no safety considerations.

From the measurement provider perspective (GHGSat), the risks are those inherent to commercial survey flights and are not specific to this protocol or instrumentation, since measurements are remote (aircrafts are typically flown at 10,000 ft above ground) and use no active light source (e.g. lasers). All airborne operations are performed by qualified personnel and in accordance with local, national and international regulations.

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

9.1 Automatic QC performed during data collection

The data acquisition software automatically performs the following verifications:

- Camera configuration is appropriate for the surveyed terrain (images are not underexposed or overexposed)
- 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 Automatic QC performed during retrievals

The retrieval processing toolchain performs the following QC steps automatically:

- Identify saturated or faulty camera pixels.
- Ground cells with high fit residuals or insufficient measurements are flagged as invalid.

9.3 Manual QC

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.
- Plume origin is tied to the appropriate facility. In the case of a point source, its origin is localized within the limits of the instrument spatial resolution (ground sampling distance of 1.5 m) and plume morphology.
- Emission masks include only “true positive” methane enhancements and are free of reflectance-correlated noise. 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

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. This calibration remains valid throughout the lifetime of the instrument.

In the field, dark frames are collected prior to every measurement, with the shutter in closed position preventing light from reaching the sensor.

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. In particular, the gap distance between the two reflecting surfaces of the Fabry-Pérot component changes over time, and is retrieved as part of the “scene-wide retrieval” sub-step (see Description of Technology 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.

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 and pixel gain non-uniformity, and the raw camera signal (digital units) 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 using position and orientation measured from an inertial navigation system (GPS and accelerometers), and refined using standard image-based alignment. Retrievals are reprojected to an orthorectified grid.

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. Methane emissions are identified based on the strength of the methane enhancement relative to the uncertainty (high signal to error ratio), and the spatial structure of the plume (general morphology, alignment with the wind direction, uncorrelated with ground reflectance features).

When an emission is detected, its origin is located, and a mask is produced using a flood-fill algorithm to label which ground cells contain high methane concentration (above the measurement noise) that originate from this source. As described in section 9, detected emissions are reviewed by a second operator.

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 NASA's GEOS-FP database and interpolated to the time and coordinates of the emission.

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 data. The uncertainty is defined as the sum in quadrature of individual error components:

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

where ΔQ_{meas} is the measurement error determined from the variance of retrieved methane concentration, ΔQ_{wind} is the error on the wind speed (whether it was locally measured or sourced from GEOS-FP), and ΔQ_{mod} quantifies the uncertainty of the IME to source rate conversion (Varon et al., 2018).

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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