



**DATA.AIR Gen 2**

## **Description of Technology**

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## GHGSAT PRODUCT/DOCUMENT APPROVAL

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## CHANGE HISTORY

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## ACRONYMS

|      |                                       |
|------|---------------------------------------|
| GPS  | Global Positioning System             |
| GSD  | Ground Sampling Distance              |
| GSM  | Gyro Stabilized Mount                 |
| INS  | Inertial Navigation System            |
| ISRF | Instrument Spectral Response Function |
| LFM  | Linearized Forward Model              |
| LM   | Levenberg-Marquardt                   |
| OSF  | Order Sorting Filter                  |
| O&G  | Oil and Gas                           |
| QE   | Quantum Efficiency                    |
| RGB  | Red, Green, Blue                      |
| SSD  | Solid State Drive                     |
| SWIR | Shortwave Infrared                    |



## 1 OVERVIEW

GHGSat provides monitoring services to detect and quantify methane emissions from sources of various sectors including Oil and Gas (O&G), mining, and waste management. The measurements are based on the principle of optical absorption spectroscopy, using remote-sensing instruments that can be carried out by instruments aboard microsatellites (DATA.SAT) or small aircraft (DATA.AIR) which survey the target facilities as they orbit or fly above them. This document focuses on second generation airborne instruments (DATA.AIR Gen 2).

The imaging spectrometers measure wavelength-dependent backscattered sunlight, in the shortwave infrared (SWIR) portion of the electromagnetic spectrum. This data is analyzed to produce a two-dimensional map of methane concentration enhancement above local background, integrated vertically along the optical path. Areas of high methane concentration indicate the presence of emissions. Emission rates are then quantified by combining excess concentration with information on gas dispersion and transport (wind speed).

Example concentration maps measured by GHGSat DATA.AIR are provided in Figure 1 below, which shows two methane emissions: one large, (left:  $Q \sim 1100$  kg/hr), and one smaller (right:  $Q \sim 20$  kg/hr). Both examples are emissions attributed to the O&G sector in the United States.

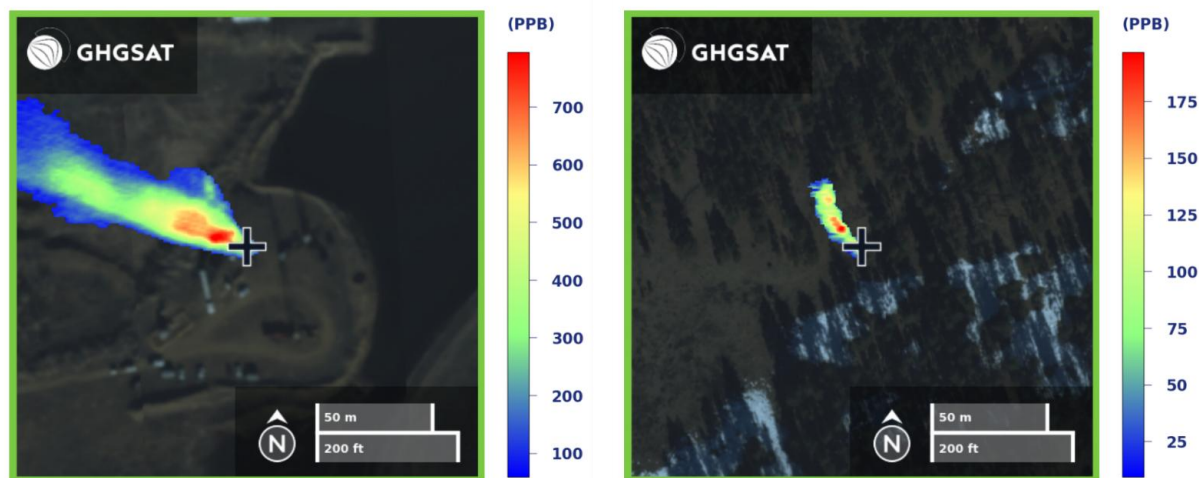


Figure 1. Sample methane concentration maps from GHGSat DATA.AIR Gen 2, for two O&G sites located in the United States. Methane concentrations are expressed as column-averaged mixing ratio in excess of local background, represented using the colored heatmap, overlaid over the visual imagery from the instrument auxiliary camera.

## 2 MEASUREMENT CONCEPT

GHGSat sensors are based on the principle of absorption spectroscopy. The measurement concept is illustrated in Figure 2. Broadband light from the sun traverses the atmosphere towards the ground, where a portion of it is backscattered towards the instrument. The collected light signal is dispersed spectrally, and the different wavelength components are quantified by the instrument's pixel array (SWIR camera). Methane absorbs specific wavelengths of the light, a spectral signature defined by molecular vibrational energy levels. A reduction in the light intensity at those wavelengths compared to a normal atmosphere indicates the presence of excess methane.

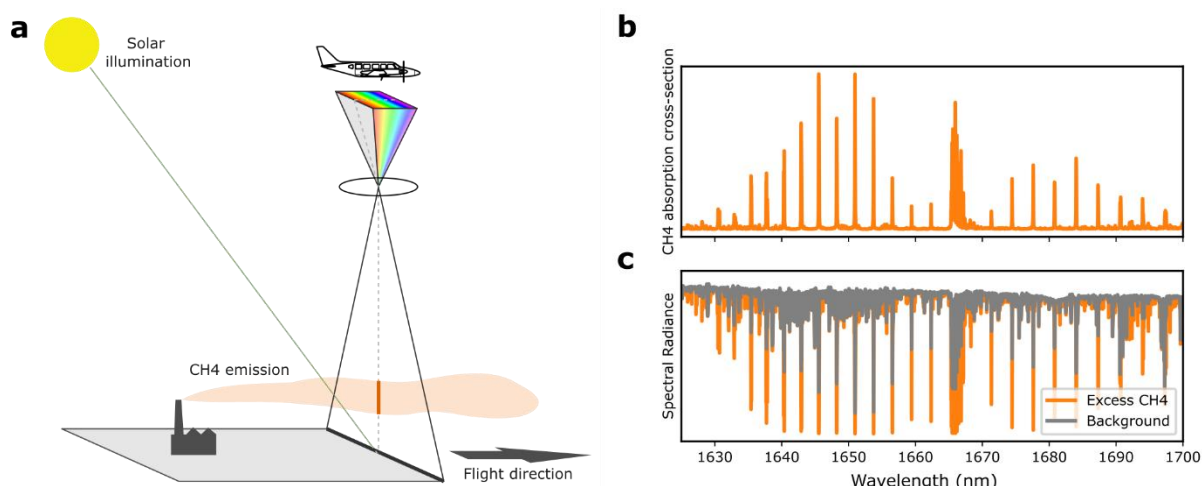


Figure 2. GHGSat DATA.AIR measurement concept. (a) Schematic of the measurement procedure illustrating backscattered sunlight that traverses a methane plume and is collected by the airborne instrument, where it is spectrally dispersed. (b) Absorption cross section of CH<sub>4</sub>. (c) Spectral radiance collected by the instrument, for the atmospheric background (grey) and in the presence of excess methane (orange) which has deeper absorption lines.

The instruments are installed in nadir viewing configuration and operated in “pushbroom” mode: only light from a narrow line of the ground passes through the spectrometer entrance slit and is collected by the instrument at a given time. This line is scanned forward by the motion of the aircraft, allowing to rapidly survey large areas containing multiple methane-emitting targets.

The light intensity signal measured by the instrument can be converted to a methane concentration by using a variant of standard inverse methods. A mathematical forward model is constructed, which describes the wavelength-dependent transmission of light through the atmosphere and the instrument, given a set of known state parameters (methane concentration, ground reflectance, instrument parameters, etc.). Nonlinear regression is then used to solve the inverse problem of retrieving the state parameters from measured light transmission. A spatially resolved methane concentration map is obtained from this algorithm, which is used to identify emissions which appear as high-concentration hotspots, and to calculate the emission rate.

### 3 INSTRUMENTATION

The instrument comprises 3 main data collection subsystems: SWIR spectrometer, auxiliary (AUX) camera, and inertial navigation system (INS). The flow of information related to instrument control, data acquisition, and processing is illustrated in Figure 3.

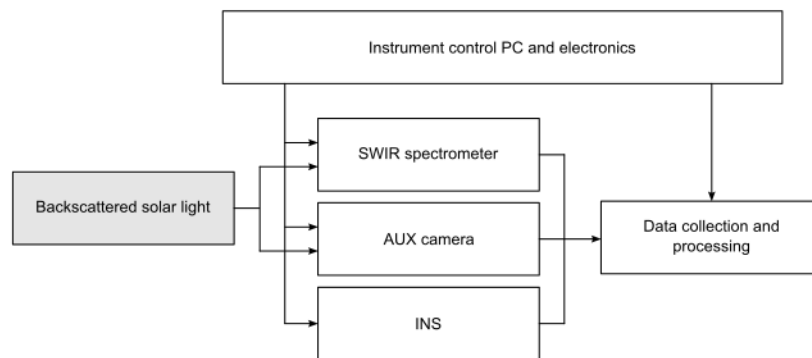


Figure 3. Schematic representation of the main hardware subsystems and the flow of information and data.

The SWIR spectrometer is 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. Methane concentration enhancements are retrieved based on the wavelength-resolved intensity measurements from the SWIR spectrometer.

In addition to the main SWIR spectrometer, an auxiliary (AUX) camera in the visible range provides standard RGB aerial imagery of the surveyed facilities. The AUX images are used for visual inspection, quality assurance, and provide additional context in the case of emissions.

The position and attitude of the instrument are tracked by an inertial navigation system (INS) which includes a global positioning system (GPS) and accelerometers. This information is used to localize the measurements geographically.

All 3 data-collecting subsystems (SWIR, AUX and INS) are controlled by a GHGSat technician via custom instrument-control software. The collected data is collected by an external computer and stored on solid state drives (SSD) before processing.

The sensors can be deployed on any appropriate third-party aircraft rigged with a camera port for measurement surveys. The mounting assembly includes passive vibration dampers and a commercial motorized gyro-stabilized mount (GSM), which isolate the optical system orientation from the aircraft and provides uniform viewing angle throughout each flight line.

## 4 RETRIEVAL METHOD

The goal of the retrieval algorithm is to estimate the instrument and atmospheric state vector  $\mathbf{x}$  from a measurement vector  $\mathbf{y}$ . The measurement vector is the photocurrent  $\Phi$  collected by the pixel array of the SWIR spectrometer, in units of electrons per second per pixel. The state vector includes methane concentration as the main quantity of interest, expressed as the vertically integrated column density  $\Omega_{\text{CH}_4}$  in units of moles per meter-squared, as well as other unknown variables that influence the measured signal, such as the ground albedo  $A$  and instrument parameters.

A forward model  $\mathbf{F}(\mathbf{x})$ , which describes light propagation in the atmosphere and instrument, is constructed, making the association (Rodgers, 2000):

$$\mathbf{y} = \mathbf{F}(\mathbf{x}) + \epsilon_y + \epsilon_F \quad (1)$$

where  $\epsilon_y$  represents the measurement error and  $\epsilon_F$  represents error in the forward model.

The inverse problem of retrieving the unknown state parameters from known measurement is solved by non-linear regression, minimizing the cost function:



$$\chi^2(\mathbf{x}) = (\mathbf{y} - \mathbf{F}(\mathbf{x}))^T \mathbf{S}_0^{-1} (\mathbf{y} - \mathbf{F}(\mathbf{x})) \quad (2)$$

where  $\mathbf{S}_0$  is the measurement covariance matrix.

Because  $\mathbf{F}(\mathbf{x})$  is a nonlinear function of  $\mathbf{x}$ , we must solve for the state vector iteratively. This requires knowledge of the Jacobian  $\mathbf{K}(\mathbf{x}) = \frac{\partial \mathbf{F}(\mathbf{x})}{\partial \mathbf{x}}$  to weight the state vector step  $\Delta \mathbf{x}^i$  taken during the  $i^{th}$  iteration. Evaluating the forward model and Jacobian is computationally expensive and impractical for the large amounts of data collected by the instrument. Instead, we use a two-step procedure:

1. Scene-wide average retrieval using the full forward model to estimate the scene-wide average state vector  $\hat{\mathbf{x}}$
2. Per-column retrieval done using a linearized forward model (LFM) evaluated at the linearization point  $\hat{\mathbf{x}}$ .

In the following sections, we describe the instrument and atmospheric forward model and describe the two-step inversion used to estimate  $\mathbf{x}$ .

#### 4.1 Forward Model

The forward model  $\mathbf{F}(\mathbf{x})$  represents our best knowledge of the instrument, atmosphere, and ground reflectance, with approximations used to evaluate the model more efficiently when performing retrievals. The modeled camera signal  $F_{i,j}$  at detector pixel  $(i, j)$  in photocurrent units [ $e^- s^{-1}$ ] is expressed as a convolution between the spectral radiance received by the instrument  $L(\lambda)$ , and the instrument spectral response function  $R(\lambda)$  (ISRF, also known as the instrument line shape or slit function):

$$F_{i,j} = \int L(\lambda') \cdot R(\lambda_{i,j} - \lambda') d\lambda' \quad (3)$$

The imaging spectrometer disperses wavelengths along the vertical axis (row index:  $i$ ), while the horizontal axis (column index:  $j$ ) maps to the across-track dimension on the ground. As such, wavelength and row can be used interchangeably in the computations provided a wavelength mapping function  $\lambda_{i,j} = f_\lambda(i, j)$ .

#### 4.2 Atmospheric Model

The spectral radiance  $L(\mathbf{x}, \lambda)$  is calculated from the spectral irradiance  $I(\lambda)$  assuming Lambertian surface reflectance:

$$L(\mathbf{x}, \lambda) = \frac{a(\lambda) \cdot \cos(\theta_{sza})}{\pi R_{E-S}^2} I(\mathbf{x}', \lambda) \quad (5)$$

where  $a(\lambda)$  is the spectrally-dependent surface albedo,  $\theta_{sza}$  is the solar zenith angle,  $R_{E-S}$  is the relative Earth-Sun distance,  $\mathbf{x}'$  is the state parameter vector without the albedo, and the spectral irradiance is the solution to a simplified radiative transfer equation where thermal emission, aerosol and molecular scattering have been neglected (Chandrasekhar, 2013):

$$\mu \frac{\partial I(\mathbf{x}', \lambda)}{\partial z} = -\alpha_{abs} I(\mathbf{x}', \lambda). \quad (6)$$

This equation is integrated along the downwelling and upwelling light path. Here  $\mu = \cos(\theta)$ ,  $\theta$  is the angle that the light travels through the atmosphere with respect to the Earth's surface normal,  $z$  is the altitude,  $\alpha_{abs}$  is the pressure, temperature, wavelength, and species dependent absorption coefficient.

We justify excluding thermal emission and molecular scattering from the atmospheric model because both are small effects for the wavelengths within our spectral bandpass region.



Previous studies of simulated carbon dioxide retrievals using only the 1563 - 1585 nm band have found that neglecting aerosol and molecular scattering can lead to a few percent error, depending on the surface albedo and aerosol optical depth (Aben et al., 2007). This error can be either positive or negative, depending on whether the presence of aerosols – in combination with the surface albedo - leads to an increase or decrease in the average optical pathlength. An analysis of SCIAMACHY retrievals in this same spectral region found that errors decrease for aerosol vertical distributions that are narrow and closer to the Earth's surface (Houweling et al., 2005). GHGSat retrievals are primarily intended to measure local plume enhancements. Therefore, we are especially concerned with any unmodeled effects with spatial structure on the length scales of emission plumes. This could potentially include aerosol scattering, such as aerosols that might conceivably be co-emitted with methane plumes. However, since the presence of these aerosol plumes would be much closer to the surface and narrower in vertical profile than the aerosol profiles retrieved in (Aben et al., 2007; Houweling et al., 2005), we expect that errors arising from neglecting scattering should be small compared with other sources of measurement error, similar to what is assumed in AVIRIS airborne methane retrievals (Thorpe et al., 2014). We also note a recent study in which the effect of neglecting aerosols in an AVIRIS airborne methane plume retrieval was shown to be < 5% for representative methane plume enhancements and a significant aerosol optical depth (Huang et al., 2020).

### 4.3 Scene-wide Retrieval

The scene-wide retrieval uses the full instrument model  $\mathbf{F}(\mathbf{x})$  from Eq. (3) in the optimization procedure. The measurement vector  $\mathbf{y}^{\text{SR}}$  is constructed by averaging multiple frames which suppresses the variations of ground reflectance on the signal and the difference between camera columns (cross-track positions). This average 2D frame is then “flattened” to construct a unique measurement vector (as opposed to a per-column retrieval where each cross-track position is solved independently) that is compared against a likewise flattened forward model vector in the optimization.

$$\mathbf{y}^{\text{SR}} = \{\bar{\Phi}_{0,0} \dots, \bar{\Phi}_{i,j}, \dots\} \text{ for } i = \{1 \dots N_{\text{rows}}\}, j = \{1 \dots N_{\text{cols}}\} \quad (4)$$

where  $\bar{\Phi}_{i,j}$  is the time-averaged photocurrent for pixel  $i, j$ .

The result of the scene-wide retrieval is the state parameter estimate  $\hat{\mathbf{x}}^{\text{SR}}$  which includes the scene-wide averaged albedo and methane column density.

### 4.4 Spatially Resolved Column Retrieval

A linearized forward model (LFM) can be constructed by expanding the full-physics model defined by Eq. (3) around the linearization point  $\hat{\mathbf{x}}$  defined by the scene-wide average retrieval results:

$$F_j^{\text{LFM}}(\mathbf{x}) = A \cdot (K_0 + K_{\text{CH}_4} \delta\Omega_{\text{CH}_4}) \quad (5)$$

where  $A$  is the ground reflectance,  $K_0$  is the derivative (Jacobian) of the full model with respect to signal,  $K_{\text{CH}_4}$  is the methane Jacobian, and  $\delta\Omega_{\text{CH}_4} = \Omega_{\text{CH}_4} - \hat{\Omega}_{\text{CH}_4}$  is the difference between the column-specific  $\text{CH}_4$  column density and the scene-wide average.

The signal Jacobian can be interpreted as the measured spectrum obtained in scene-wide average state  $\hat{\mathbf{x}}$  and over unit albedo. It can be expressed as:

$$K_0(\lambda_i) \equiv \left. \frac{\partial F_{ij}}{\partial A} \right|_{\hat{\mathbf{x}}^{\text{SR}}} = F_{ij}(\hat{\mathbf{x}}^{\text{SR}}, A = 1) \quad (6)$$

and the  $\text{CH}_4$  Jacobian as



$$K_{CH_4}(\lambda_i) \equiv \frac{\partial F_{ij}}{\partial \langle \delta \Omega_{CH_4} \rangle} \Big|_{\lambda^{SR}} \quad (7)$$

The LFM is applied to each column  $j$  of the sensor (cross-track pixel) separately. For each column, the measurement vector  $\mathbf{y}_j^{CR}$  is comprised of the measured photocurrent  $\Phi_{i,j}$  at each wavelength  $\lambda_i$  corresponding to row  $i$  of the sensor:

$$\mathbf{y}_j^{CR} = \{\Phi_{0,j}, \dots, \Phi_{i,j}, \dots\} \text{ for } i = \{1 \dots N_{rows}\} \quad (8)$$

Solving equation (5) for each camera column provides a spatially-resolved estimate of methane column density enhancement  $\delta \Omega_{CH_4}$ , as well as the ground albedo. Camera columns map to the cross-track coordinate on the ground, a 1D line corresponding to the image of the spectrometer entrance slit. To construct a 2D image, this line is scanned in the along-track direction by the motion of the aircraft (so-called “push broom” configuration).

## 5 EMISSIONS IDENTIFICATION

Emissions are identified by visual inspection of the spatially resolved methane density retrieved at the previous step. 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 auxiliary RGB images or publicly available background imagery. All identified emissions and uncertain 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 by successively applying a band pass filter, intensity threshold, and rejecting isolated pixels disjoint from the main body of the plume. This mask identifies which connected ground cells have methane concentration above the measurement uncertainty and originate from the defined source.

## 6 EMISSION RATE RETRIEVAL

The methane emission rate is calculated using the method of integrated mass enhancement (IME) (Varon et al., 2018). IME is defined as the total amount of detectable methane enhancement that originates from a given source. For an observed plume comprising  $N$  ground cells of area  $A_j$  ( $j = 1 \dots N$ ) and column density enhancement  $\Delta \Omega_j$  (output of step 4.4),

$$IME = \sum_{j=1}^N \Delta \Omega_j A_j \quad (9)$$

IME measures the local accumulation of methane, which is driven by two factors: the emission rate  $Q$ , and the rate at which the methane dissipates in the surrounding atmosphere characterized by its residence time  $\tau$ . One can express  $\tau$  dimensionally in terms of an effective wind speed  $U_{eff}$  [m s<sup>-1</sup>] and a plume size  $L$  [m]:

$$Q = \frac{1}{\tau} IME = \frac{U_{eff}}{L} IME = \frac{U_{eff}}{L} \sum_{j=1}^N \Delta \Omega_j A_j \quad (10)$$

$U_{eff}$  and  $L$  would have simple physical meanings of wind speed and plume length if dissipation of the plume occurred by uniform transport to a terminal distance downwind of the source.



But the actual mechanism for plume dissipation is turbulent diffusion, which takes place in all directions.  $U_{\text{eff}}$  and  $L$  must therefore be viewed as operational parameters to be related to observations of wind speed  $U$  and plume extent. These relationships take the following empirical form:

$$L = \sqrt{A_M} \quad (11)$$

$$U_{\text{eff}} = \alpha_1 U_{10} + \alpha_2 \quad (12)$$

In the equations above:  $A_M$  is the area of the plume mask (connected ground cells where the enhancement is above the measurement uncertainty level);  $U_{10}$  is the wind speed at 10 m above ground, obtained from a third-party weather provider;  $\alpha_1$  and  $\alpha_2$  are model parameters inferred from controlled releases. More information on the source rate calculation is provided in the SI document and in (Varon et al., 2018).

## 7 LIMITATIONS

The measurement technique has limitations that are inherent to passive optical absorption spectroscopy. In particular:

- Measurements during the night or in overcast weather are not possible. In partly cloudy conditions, obscured areas with insufficient signal will be flagged as invalid.
- Offshore measurements require a specific observing configuration to capture the direct sun glint reflection (predominantly specular reflection as opposed to diffuse reflection on land). At this moment, GHGSat only provides offshore measurements from its satellite platform (DATA.SAT), and not for aerial surveys (DATA.AIR).
- Underground leaks can be detected after they reach the surface.

Variations in wind speed affect the sensitivity and quantification accuracy, because the local concentration of methane from a leak is driven not only by the emission rate, but also the rate at which wind dissipates methane in the surrounding atmosphere. High wind speeds increase the detection threshold. On the other end, very low wind speed will favor detection of small leaks, but makes quantification more difficult as the relative uncertainty of the emission rate is dominated by that of local wind. Both of those effects are accounted for in the methane quantification uncertainty.

Geographic and seasonal variability of the ground reflectance affects the amount of light collected by the instrument and therefore modulates the signal to noise ratio due to shot noise. For example, dry land tends to be more reflective than humid ones, or regions with heavy tree cover. Snow is also poorly reflective in the SWIR band. Such conditions are not excluded from commercial operations but will result in higher measurement uncertainty.

In addition to average reflectance effects described above, retrieved methane concentration can be spatially correlated with ground reflectance, resulting in some degree of systematic noise in the measurement. Scenes with uniform reflectance therefore allow a better precision and lower detection threshold than heterogeneous ones including mountains, urban scenes, or areas with a complex topography. Such effects are also accounted for in the measurement error.

It is worth noting that reflectance effects, both via shot noise and correlated noise, matter mostly in a short range (tens of meters) around potential methane-emitting facilities, where a plume would be located.

Finally, other gas species ( $\text{CO}_2$ , water vapor) do not interfere in a significant way with  $\text{CH}_4$  measurements. The main reasons are (1) the GHGSat instruments use a narrow spectral band which is largely dominated by methane absorption lines, and (2) the weak absorption lines of other species do not overlap significantly with  $\text{CH}_4$  within the limit of spectral resolution. As a



result, GHGSat does not restrict its operations with relative humidity conditions, provided that the sun is not covered.

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