



GHGSAT-C1/WAF-P Quality Assessment Summary

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1. EXECUTIVE SUMMARY

In this study the quality assessment of methane CH₄ concentrations/plumes utilizing the high resolution (25 m) retrievals CH₄ from the GHGSAT-C1 satellite (the second generation of GHGSAT satellites launched on 2nd September 2020) on some specific targets that are related to the anthropogenic emissions are presented.

The Greenhouse Gas Satellite (identified as GHGSat-C1 or IRIS satellite), is a microsatellite build by UTIAS Space Flight Laboratory (SFL) for GHGSat Inc. as greenhouse gas monitoring demonstrator satellite, with the objective to measure methane (CH₄) abundances in a field of view of approximately 12 km x 12 km and spatial resolution of 25 m.

The satellite is equipped with an advanced miniature hyperspectral SWIR imaging spectrometer for monitoring targeted greenhouse gas emitters such as area fugitive sources (tailing ponds and landfills) and stacks (emissions such as flaring and venting). A secondary instrument will measure clouds and aerosols in order to enhance retrievals from the primary instrument. The satellite payload includes in fact two different sensors:

- a 2D Wide-Angle Fabry-Perot (“WAF-P”) imaging spectrometer that measures vertical column densities of CO₂ and CH₄;
- VIS-1: Visible Sensor.

The WAF-P spectral range is in the short-wave infrared (SWIR) at 1600-1700 nm, with multiple bands in a proprietary configuration.

The auxiliary imager is used to obtain a high-resolution image of the ground in the 500-550 nm region. The images acquired by the auxiliary imager can be used to guide the registration of SWIR image sequences or to identify structures on the ground. It is therefore important to characterize the auxiliary image spatial resolution and ensure that the auxiliary camera has a spatial resolution higher than the main SWIR instrument.

IRIS has a primary body measuring 20 x 30 x 40 cm, with a mass (payload included) of c.a. 16 kg. IRIS’s orbit is sun-synchronous at an altitude of 523 km, resulting in a site revisit period of approximately 14 days.

With reference to CLAIRE satellite (GHGSAT first satellite generation), IRIS is the evolution with the following improvements:

- Improved stray light / ghosting mitigation;
- Addition of onboard calibration features;
- Improved radiation mitigation;
- Optimized spectroscopy for primary instrument;
- Replacement of secondary instrument;
- Addition of experimental optical downlink.

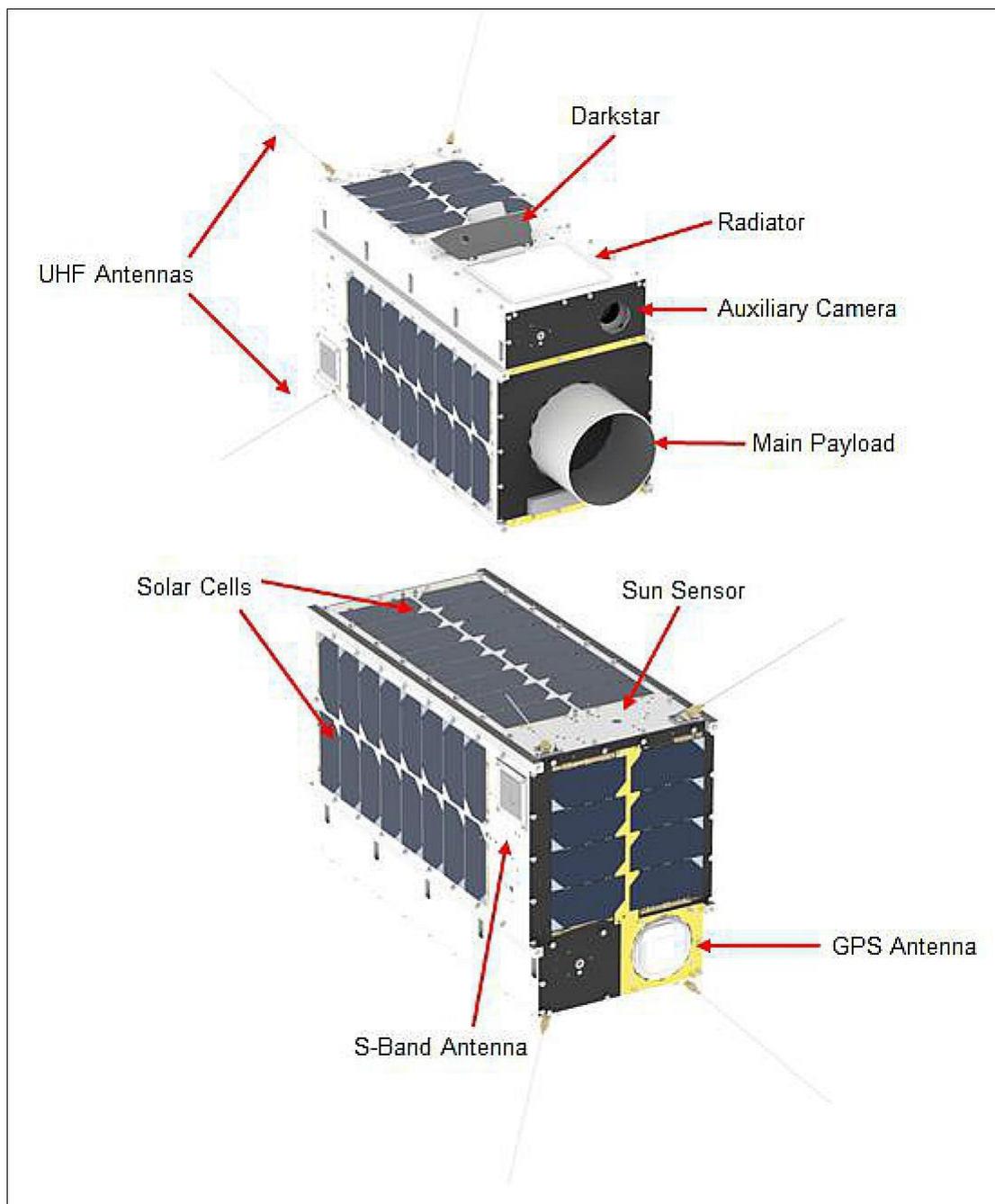


Figure 1 – GHGSAT-C1 (IRIS) Satellite and Payloads

GHGSAT-C1 instrument (Figure 1) can measure atmospheric methane columns from solar backscatter in the shortwave infrared (SWIR) with near-uniform sensitivity down to the surface.

There is considerable interest in using these measurements to quantify methane emissions: the data show that these measurements can successfully map regional methane emissions but have limited ability to resolve individual methane point sources, even with imaging capabilities, because the sources tend to be relatively small and spatially clustered (e.g., oil/gas fields, livestock operations, landfills, coal mine vents).



Atmospheric methane (CH₄) is the second most important anthropogenic greenhouse gas after carbon dioxide and contributes significantly to changes in radiative forcing and climate change.



1.1 Mission Quality Assessment Matrix

Product Information	Product Generation	Ancillary Information	Uncertainty Characterisation	Validation
Product Details	Sensor Calibration & Characterisation Pre-Flight	Product Flags	Uncertainty Characterisation Method	Reference Data Representativeness
Availability & Accessibility	Sensor Calibration & Characterisation Post-Launch	Ancillary Data	Uncertainty Sources Included	Reference Data Quality
Product Format	Retrieval Algorithm Method		Uncertainty Values Provided	Validation Method
User Documentation 	Retrieval Algorithm Tuning		Geolocation Uncertainty	Validation Results
Metrological Traceability Documentation 	Additional Processing			

Key
Not Assessed
Not Assessable
Basic
Intermediate
Good
Excellent

 Information Not Public

Figure 2 – GHGSAT-C1 Product Quality Evaluation Matrix

2. MISSION ASSESSMENT OVERVIEW

2.1 Product Information

Product Details	
Product Name	GHGSAT
Sensor Name	<ul style="list-style-type: none"> WAF-P VIS-1
Sensor Type	<ul style="list-style-type: none"> 2D Wide-Angle Fabry-Perot imaging spectrometer (in the short-wave infrared (SWIR) at 1600-1700 nm, with multiple bands) The auxiliary imager is used to obtain a high-resolution image of the ground in the 500-550 nm region.
Mission Type	Earth Observation Satellite – Methane Emission Detection
Mission Orbit	Sun Synchronous, altitude 523 km, inclination 97.5 deg.
Product Version Number	v1
Product ID	C1_XXXXXXXX_XXXXXXXX_XXXXXXXX_XXXXXX_CH4
Processing level of product	Level-1 and Level-2; additional info as Layer-3 and Layer-4
Measured Quantity Name	L-1: Surface Reflectance L-2: Abundance dataset CH4 L-3: Uncertainty L-4: Quality Flag
Measured Quantity Units	L-1: sr ⁻¹ L-2: ppb L-3: ppb L-4: integer
Stated Measurement Quality	1% as CH4 standard deviation
Spatial Resolution	c.a. 25 m per pixel
Spatial Coverage	Approx. 12 km x 12 km
Temporal Resolution	20 sec.
Temporal Coverage	Revisit period of approximately 14 days
Point of Contact	https://www.ghgsat.com/contact/
Product locator (DOI/URL)	DataMaster (web interface that GHGSat uses to deliver its products) https://datamaster.ghgsat.com/DMweb/login.go
Conditions for access and use	Commercial Data, conditions defined by contract
Limitations on public access	N/A (Conditions defined by contract)
Product Abstract	Numerical values: PRODUCT_TYPE_1: Surface Reflectance PRODUCT_TYPE_2: Abundance Dataset - CH4 PRODUCT_TYPE_3: Concentration Map - CH4 PRODUCT_TYPE_4: Quality flag

Availability & Accessibility	
Compliant with FAIR principles	Yes
Data Management Plan	<i>Not available to users</i>
Availability Status	<i>Data available via catalogue. Possibility to order specific acquisitions.</i>

Product Format	
Product File Format	<i>.tif</i>
Metadata Conventions	<i>v1</i>
Analysis Ready Data?	<i>Yes, available on request Level-3 and Level-4 data</i>

User Documentation		
<i>Document</i>	<i>Reference</i>	<i>QA4ECV Compliant</i>
Product User Guide	<i>GHGSAT Product Specifications GHG-1501-7003 (21/07/2021)</i>	<i>No</i>
ATBD	<i>GHGSAT-C1 ATBD GHG-1292-6003 (16/07/2021)</i>	<i>Yes</i>

Metrological Traceability Documentation	
Document Reference	<i>GHGSst-C1 CAL/VAL Plan and Errors Report</i> <ul style="list-style-type: none"> • <i>GHG-1292-6001-a (19/07/2021)</i> <i>GHGSat-C1 Ground Characterization and validation</i> <ul style="list-style-type: none"> • <i>GHG-1292-1002-a (19/07/2021)</i>
Traceability Chain / Uncertainty Tree Diagram Available	<i>Yes, partially</i>



2.2 Product Generation

Sensor Calibration & Characterisation – Pre-Flight	
Summary	<p>GHGSat-C1 uses an InGaAs camera as sensor for its SWIR spectrometer. Each pixel of the camera has a specific dark current, dark offset, gain, and might respond non-linearly to change in irradiance. Therefore, it is necessary to carefully calibrate the camera to be able to infer the incident irradiance from the digital signal output at given pixel.</p> <p>As the instrument spectral band of interest is close to the cut-off wavelength of InGaAs cameras, a careful measurement of each pixel quantum efficiency as a function of wavelength is required to be able to convert digital signal from the camera into input irradiance at a given wavelength.</p> <p>Measure the transmission of the order sorting (bandpass) filter (OSF) as function of wavelength and angle of incidence.</p> <p>The Fabry-Perot is the heart of GHGSat-C1 spectrometer. It is therefore characterized at the component level to assess its performance. The key parameters that are measured are the resonant wavelength (wavelength transmitted at 0-degree field angle), the free spectral range and the defect finesse. Those parameters will inform the wavelength mapping on the sensor as well as the spectral resolution of the instrument.</p> <p>Optical components such as lenses and mirrors induce some distortion of the ground image formed in the camera plane. The objective of this test is to determine the amount of distortion in the image. The same test setup is also used to quantify the angular field of view of the instrument.</p>
References	<p><i>GHGSat-C1 Ground Characterization and validation</i></p> <ul style="list-style-type: none"> • <i>GHG-1292-1002-a (19/07/2021)</i>

Sensor Calibration & Characterisation – Post-Launch	
Summary	<p>The payload contains a calibration system that can illuminate the sensor with known irradiance. This illumination is created using 4 LEDs whose light is reflected by the shutter when closed towards the sensor. The light from the LEDs goes directly to the sensor without going through any spectral component such as the Fabry-Perot or the order sorting filter. There is a need to calibrate for each LED the irradiance created at the FPA plane for varying drive current to be able to use the LED for the sensor calibration in orbit.</p> <p>Moreover, the auxiliary imager is used to obtain a high-resolution image of the ground in the 500-550 nm region.</p> <p>The images acquired by the auxiliary imager can be used to guide the registration of SWIR image sequences or to identify structures on the ground. It is therefore important to characterize the auxiliary image spatial resolution and ensure that the auxiliary camera has a spatial resolution higher than the main SWIR instrument.</p>
References	<p><i>GHGSat-C1 Ground Characterization and validation</i></p> <ul style="list-style-type: none"> • <i>GHG-1292-1002-a (19/07/2021)</i>



Retrieval Algorithm Method	
Summary	<p>The measurement vector contains the measured radiances in the Short Wave Infrared (SWIR) range 1633 nm to 1677 nm. A suitably chosen inverse method is then used to optimize the parameter with respect to the measurements after applying the forward model.</p> <p>This optimization is performed over a dense grid of “ground cells” which enables spatial reconstruction of methane column density enhancements (with respect to the background atmospheric state) and surface reflectance maps in the SWIR. To make the inverse problem numerically tractable, the retrieval is therefore performed in two stages. First, the scene-wide average atmospheric state is retrieved along with key instrument parameters. Once the scene-wide average state and instrument parameters have been inferred, the model is linearized with respect to this background. The linearized model is quick to evaluate and is used to infer methane column density enhancements (with respect to the background atmospheric state) and surface reflectance maps in the SWIR. Before these two retrievals stages, various corrections are applied to the observation image sequence. These corrections involve: field flattening (to remove detector gain and offset non-linearities), bad-pixel identification and ghost-image removal.</p>
References	<ul style="list-style-type: none"> • <i>GHGSat-C1 Algorithm Theoretical Basis Document for Methane Retrieval (GHG-1292-6003, 16 July 2021)</i> • <i>Sloan, J. J. (2016). Fabry-Perot interferometer-based satellite detection of atmospheric trace gases.</i> • <i>Varon, D. J. (2019). Satellite discovery of anomalously large methane point sources from oil/gas production. Geophysical Research Letters.</i> • <i>Patent. Rodgers, C. D. Inverse Methods for Atmospheric Sounding: Theory and Practice; World Scientific, 2000; Vol. 2</i>

Retrieval Algorithm Tuning	
Summary	<p>Errors in the spatially resolved column retrieval arise from several sources:</p> <ul style="list-style-type: none"> • Random error (Shot noise from photocurrent and dark current, Camera read noise); • Unmodelled instrument effects (Stray light from outside nominal field of view, Stray light from unwanted extra reflections internal to the instrument; Uncorrected anomalous pixel currents due to radiation damage and Camera persistence); • Unmodelled atmospheric effects (Clouds and Smoke/Aerosols); • Imperfect image registration.
References	<ul style="list-style-type: none"> • <i>GHGSat-C1 Calibration and Validation Plan and Description of Errors Document No.: GHG-1292-6001 (19 July 2021)</i> • <i>GHGSat-C1 Algorithm Theoretical Basis Document for Methane Retrieval (GHG-1292-6003, 16 July 2021)</i> • <i>McKeever, J.; Durak, B. O. A.; Gains, D.; Varon, D. J.; Germain, S.; Sloan, J. J. GHGSat-D: Greenhouse Gas Plume Imaging and Quantification from Space Using a Fabry–Perot Imaging Spectrometer. American Geophysical Union 2017 Fall Meeting, New Orleans, LA, 2017, Dec 11–15, 2017</i>

Additional Processing
Additional Processing 1



Description	<p>The GHGSat-C1 toolchain generates a level 2 data product from level 0 data acquired by GHGSat-C1. This level 0 consists of raw images from the SWIR sensor and visual AUX camera, by plus auxiliary data such as telemetry from the ADCS. The level 2 data consists of gas column density and surface reflectance maps. Various intermediate output is generated by the toolchain, which may be classified according to the following data processing levels:</p> <ul style="list-style-type: none"> • L1: If L0 data is the set of raw images (in digital units), then L0B data is corrected for dark noise, per-pixel offset and gain non-uniformity, and ghosting (L1 data is L0B data that had been radiometrically calibrated in order to convert into units of photocurrent). • L2: L2 data is the per ground-cell CH4 estimate obtained by comparison of a forward model to the L1 data using an optimal estimation procedure. • L3: L3 data is a 6 to 12 months monitoring product. • L4: L4 data is the emissions rate estimate that uses L3 data and auxiliary information (WRF-LES simulations and either wind information or plume morphology)
Reference	<ul style="list-style-type: none"> • <i>GHGSat-C1 Algorithm Theoretical Basis Document for Methane Retrieval (GHG-1292-6003, 16 July 2021)</i>

2.3 Ancillary Information

Product Flags	
Product Flag Documentation	<i>Reported in the metadata file related to the specific product.</i>
Comprehensiveness of Flags	<i>Yes, only quality flag is reported (1, 'Good'), (2, 'No data'), (3, 'Bad fit')</i>

Ancillary Data	
Ancillary Data Documentation	<i>The ancillary data necessary for the processing (telemetry data, calibration files, spectroscopy data and radiative transfer model info) are reported in the GHGSat-C1 Algorithm Theoretical Basis Document for Methane Retrieval (GHG-1292-6003, 16 July 2021)</i>
Comprehensiveness of Data	Yes
Uncertainty Quantified	Yes

2.4 Uncertainty Characterisation

Uncertainty Characterisation Method	
Summary	<i>A standard method of validating L2 data is to compare against a mature and well-validated third-party measurement. To take the S5P/TROPOMI methane retrieval as an example, comparisons of their methane retrieval have been made against the GOSAT remote methane retrieval (Hu et al., 2018) and</i>



	<p><i>TCCON ground-based retrieval (Hasekamp et al., 2019).</i></p> <p><i>Since the spectral irradiance and thus methane column density has known physical dependency on solar zenith angle and target elevation, an alternate route to validation besides comparison with third-party measurements is to measure the differences in retrieved methane column density under known and varying these two parameters and see if it varies in the expected way.</i></p> <p><i>The spectral radiance is the quantity that is used in the forward model and depends on the albedo of a ground cell. In the absence of error, an absorption measurement should be independent of albedo, but in practice, errors such as stray light and mischaracterized pixel dark current and offsets, for instance, can cause an albedo dependence of the retrieved methane column density. This phenomenon is calibrated empirically choosing a variety of scenes with a range of intra-FOV albedos that are not expected to have much methane column density variation in them.</i></p>
Reference	<ul style="list-style-type: none"> • <i>GHGSat-C1 Calibration and Validation Plan and Description of Errors Document No.: GHG-1292-6001 (19 July 2021)</i>

Uncertainty Sources Included	
Summary	<p><i>Errors in the spatially resolved column retrieval arise from several sources:</i></p> <ul style="list-style-type: none"> • <i>Random error (Shot noise from photocurrent and dark current and Camera read noise);</i> • <i>Unmodelled instrument effects (Stray light from outside nominal field of view and Stray light from unwanted extra reflections internal to the instrument);</i> • <i>Unmodelled instrument effects (Uncorrected anomalous pixel currents due to radiation damage, Camera persistence);</i> • <i>Unmodelled atmospheric effects (Clouds, Smoke/Aerosols);</i> • <i>Imperfect image registration;</i> • <i>Model error (due to things like turbulence and variable plume shape);</i> • <i>Wind speed error;</i> • <i>Measurement error (systematic errors).</i>
Reference	<p><i>GHGSat-C1 Calibration and Validation Plan and Description of Errors Document No.: GHG-1292-6001 (19 July 2021)</i></p>

Uncertainty Values Provided	
Summary	<p><i>The Methane column density precision (% of background) is c.a. 1% (an improvement of 10% has been obtained), with a Detection Threshold capacity 10 times better.</i></p>
Reference	<p><i>GHGSat-C1 Calibration and Validation Plan and Description of Errors Document No.: GHG-1292-6001 (19 July 2021)</i></p>
Analysis Ready Data?	No

Geolocation Uncertainty	
Summary	<p><i>The geolocation of the retrieved column enhancements is accurate to within ~30 m</i></p>
Reference	<ul style="list-style-type: none"> • <i>GHGSAT Product Specifications GHG-1501-7003 (21/07/2021)</i>

2.5 Validation

Validation Activity #1	
Independently Assessed?	No: this is the official validation results provided by GHGSAT
<i>Reference Data Representativeness</i>	
Summary	<p>A standard method of validating L2 data is to compare against a mature and well-validated third-party measurement (S5P/TROPOMI, GOSAT, TCCON ground-based retrieval, 10 ÷ 100 measurements).</p> <p>Additional 10 ÷ 20 measurements validation for solar zenith angle, albedo, and target elevation calibrations.</p>
Reference	<ul style="list-style-type: none"> GHGSat-C1 Ground Characterization and validation GHG-1292-1002-a (19/07/2021) GHGSat-C1 Calibration and Validation Plan and Description of Errors Document No.: GHG-1292-6001 (19 July 2021)
<i>Reference Data Quality & Suitability</i>	
Summary	<p>For controlled releases, the method is limited by the amount of CH₄ that is able to be released by facility operators, as well as by the wind speed at the time of release.</p> <p>The value of coincident measurements is limited by the combined uncertainties of both ground (TCCON) and satellite measurements (S5P and GOSAT). Additional measurements over defined targets at different sensing conditions and times increase the quality of data, especially in the post processing and auxiliary data preparation and corrections.</p>
Reference	<ul style="list-style-type: none"> GHGSat-C1 Ground Characterization and validation GHG-1292-1002-a (19/07/2021)
<i>Validation Method</i>	
Summary	<p>GHGSat is validating system performance through a series of such tests, including:</p> <ul style="list-style-type: none"> Detailed Pre-flight characterization and validation of payload; On-board calibration planning; Controlled / metered releases from test sites; Coincident ground/space measurements on TCCON and S5P; Measurement of well-characterized emissions sources, such as thermal generating stations.
Reference	<ul style="list-style-type: none"> GHGSat-C1 Ground Characterization and validation GHG-1292-1002-a (19/07/2021)
<i>Validation Results</i>	
Summary	<p>GHGSat has conducted an intensive on ground instrument characterization through testing campaigns and simulations. This analysis confirms the improvements of the measurement results, comparing results to both end-to-end instrument re-simulations.</p> <p>Moreover, the changed strategy in calibration has provided an improvement in the quality of data, together with the combination of the auxiliary instrument on board supporting the primary payload. Using on-</p>



	<p><i>orbit data, column errors is characterized by the following methods:</i></p> <ul style="list-style-type: none"> • <i>Cal/Val comparisons with satellites/ground data;</i> • <i>Statistical analysis of retrieval outputs in scenes where no plume is present.</i> <p><i>Considering that:</i></p> <ul style="list-style-type: none"> • <i>the TROPOMI methane retrievals have a bias and column-averaged mixing ratio precision of $-4.3 \text{ ppb} \pm 7.4 \text{ ppb}$ which amounts to approximately 0.23% and 0.40% of background, respectively.</i> • <i>The TCCON methane column density accuracy is of 0.4% (validated against in-situ aircraft campaigns).</i> <p><i>This uncertainty is well-below the expected GHGSat-C1 precision of 2%.</i></p>
Reference	<ul style="list-style-type: none"> • <i>GHGSat-C1 Ground Characterization and validation GHG-1292-1002-a (19/07/2021)</i> • <i>GHGSat-C1 Calibration and Validation Plan and Description of Errors Document No.: GHG-1292-6001 (19 July 2021)</i>

Validation Activity #2	
Independently Assessed?	Yes
<i>Reference Data Representativeness</i>	
Summary	<i>The dataset analysed in this report refers to 8 acquisitions over 6 specific targets (oil and gas infrastructures, landfills, and mine vent infrastructure).</i>
Reference	<i>This report</i>
<i>Reference Data Quality & Suitability</i>	
Summary	<p><i>The products analysed are referred to big infrastructures and targets that are clearly big methane emitters. The emissions are evident in the products, even if:</i></p> <ul style="list-style-type: none"> • <i>in two products the amount of the plume is not so intense if referred to the background;</i> • <i>the features as source of interference by GHGSAT seem to be present in some products.</i>
Reference	<i>This report</i>
<i>Validation Method</i>	
Summary	<i>The strategies used for the verification and the validation of the dataset are: 1) the intercomparison of the GHGSAT plumes with the recalculated plumes from the L2 products; 2) the intercomparison of products with the AIRS measured methane profiles.</i>
Reference	<i>This report</i>
<i>Validation Results</i>	
Summary	<p><i>The quality of the data is overall quite good: emission plumes are clearly identified, and the amounts are in line with the results provided by GHGSAT. Features different from plumes are anyway present and can induce confusion or additional wrong identifications.</i></p> <p><i>Clouds and humidity seem to have an impact on the quality of the product. Also, the presence of human infrastructure seems to provide interference in the retrieval and to be cause of plume emissions.</i></p> <p><i>Offset and Ghosting has been corrected respect to the previous mission, even if Gain non-uniformity is lightly present, and it is the cause of presence of lines in some cases in the borders of products.</i></p>



	<i>The emissions rates are not always of big intensity, and the sensor is anyway able to detect the plumes respect to the background.</i>
Reference	<i>This report</i>

3. DETAILED ASSESSMENT

3.1 Methodology

In this section the results of the quality assessments of the GHGSAT-C1 data are presented. Two methodologies have been adopted for the assessments of the data:

- 1) The emissions rates of GHGSAT-C1 provided by the GHG maps have been compared with the derivation of emissions from the products, to estimates and compare the presence of emitters, the peak values of the emitters, the difference from the background and the evidence of emission events from other “events”.
- 2) The intercomparison of the observations with CH₄ AIRS data (AIRS, the Atmospheric Infrared Sounder on NASA's Aqua satellite, gathers infrared energy emitted from Earth's surface and atmosphere globally, every day. Its data provides measurements of temperature and water vapor through the atmospheric column along with a host of trace gases, surface, and cloud properties)

3.2 Analysis of results

The following table shows the overall results found during this analysis:

Geographic Area	Emission Source	Intercomparison with CH ₄ Emissions	Noise, Issues, Features	AIRS Data
Turkmenistan#1 (multiple emissions)	Oil&Gas infrastructure	Yes (Low values)	No	Yes
Turkmenistan#2	Oil&Gas infrastructure	Yes (2 nd emission low)	Yes	Yes, Partially Appreciable
Argentina#1	Landfill	Yes	Yes	Yes, Partially Appreciable
Argentina#2	Landfill	Yes	Yes	NO data
Argentina#3	Landfill	Yes	No	Yes, Partially Appreciable
Pakistan#1	Landfill	Partially Appreciable	Yes	Yes
Australia	Mine Vent	Partially Appreciable	Yes	NO data
China	Mine Vent	Yes	No	Yes, Not evident

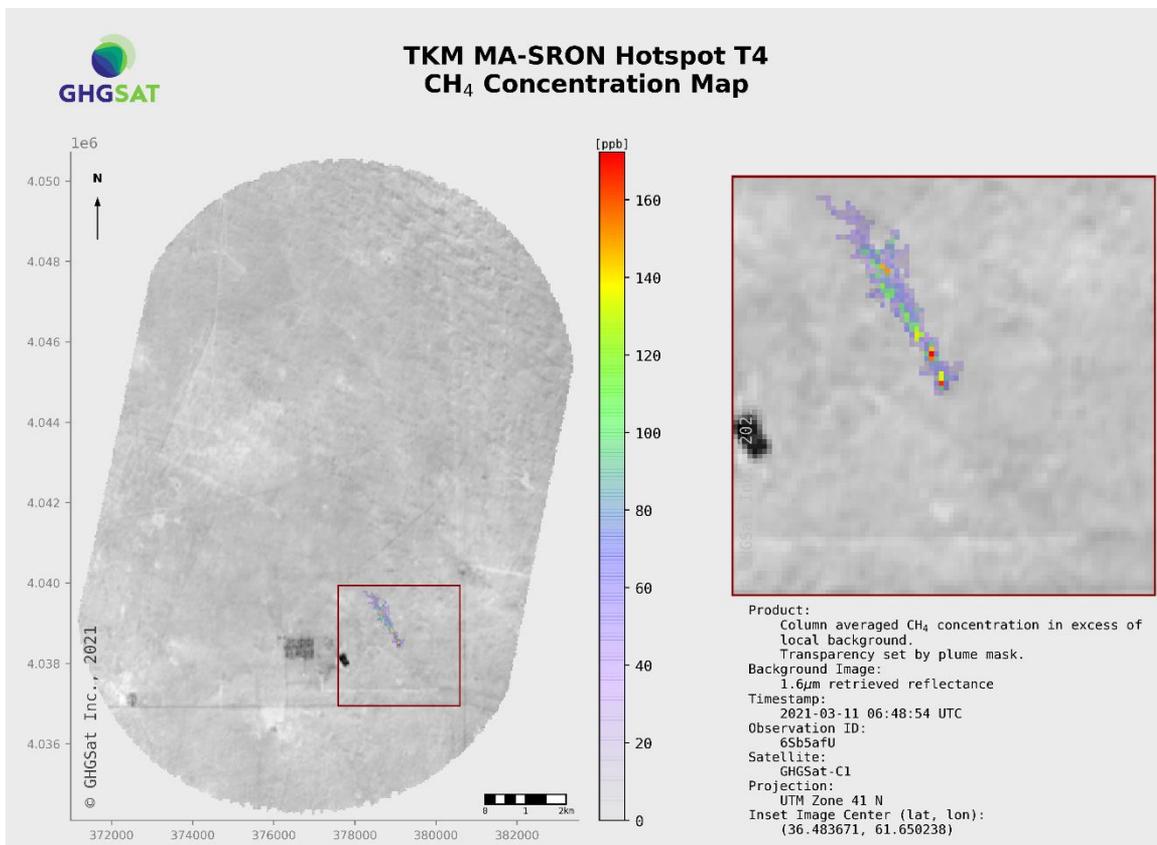
Table 1 – Summary of the results per analysed product

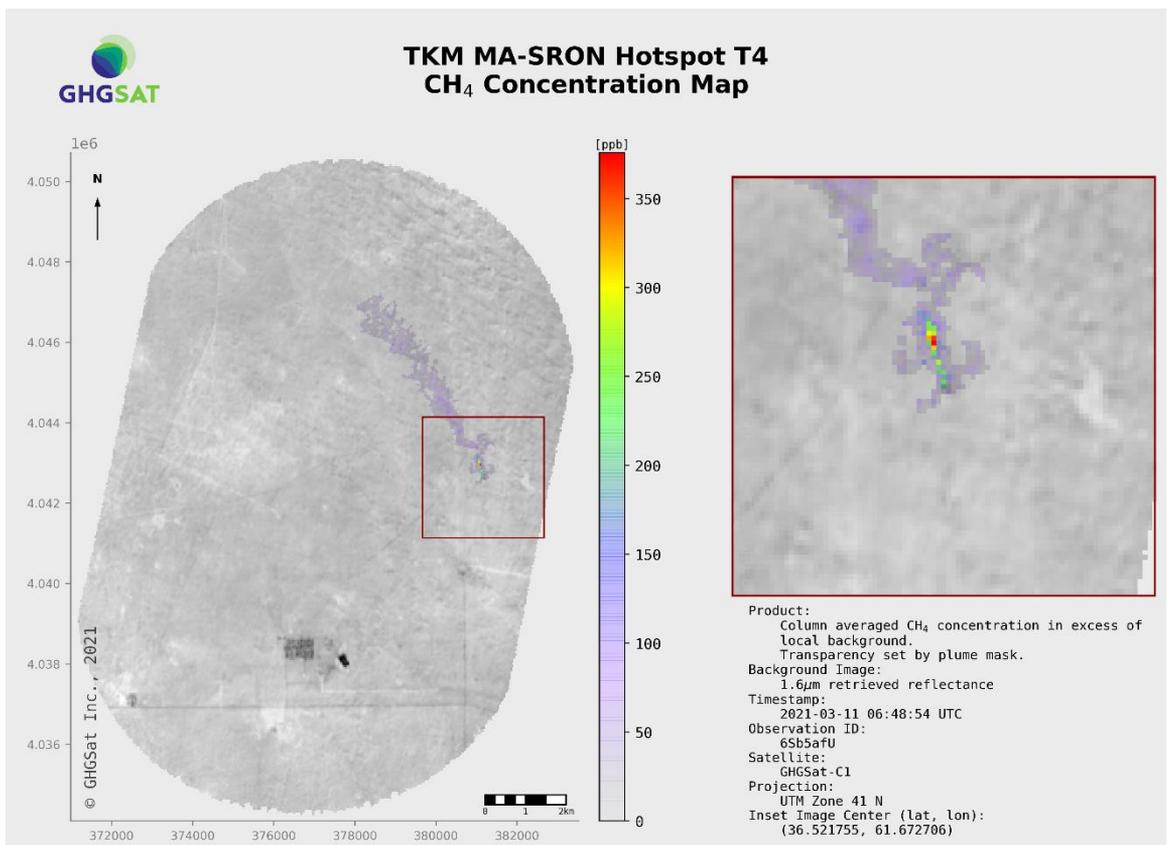
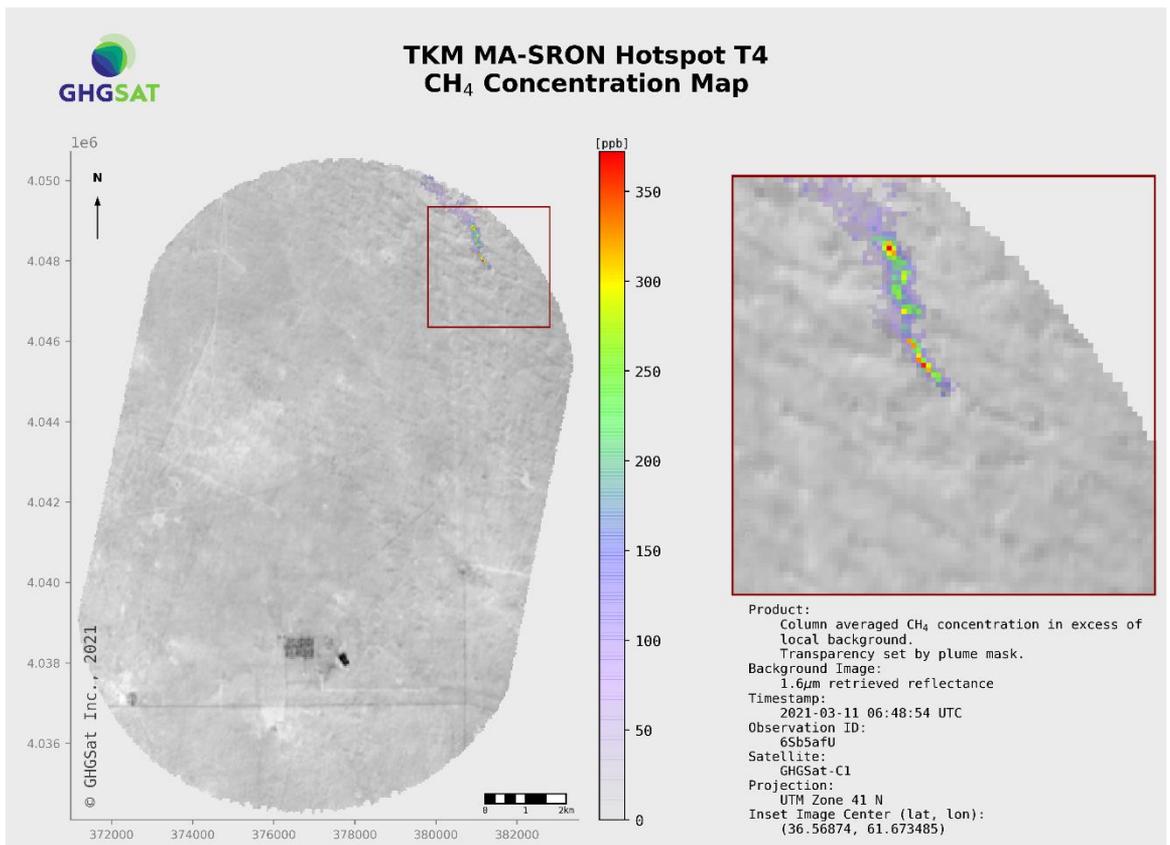
Starting from the list of products provided, the first analysis has been focused on the intercomparison of the CH₄ excess column and plumes derived by the abundance dataset. The official emissions are highlighted in red squares, artefacts and suspicious elements or additional not clear features with yellow arrows.



Figure 3 – Turkmenistan, Oil and Gas Mary Infrastructure site

In the Figure 3 above a satellite image of the Oil and Gas Mary Infrastructure site has been reported.





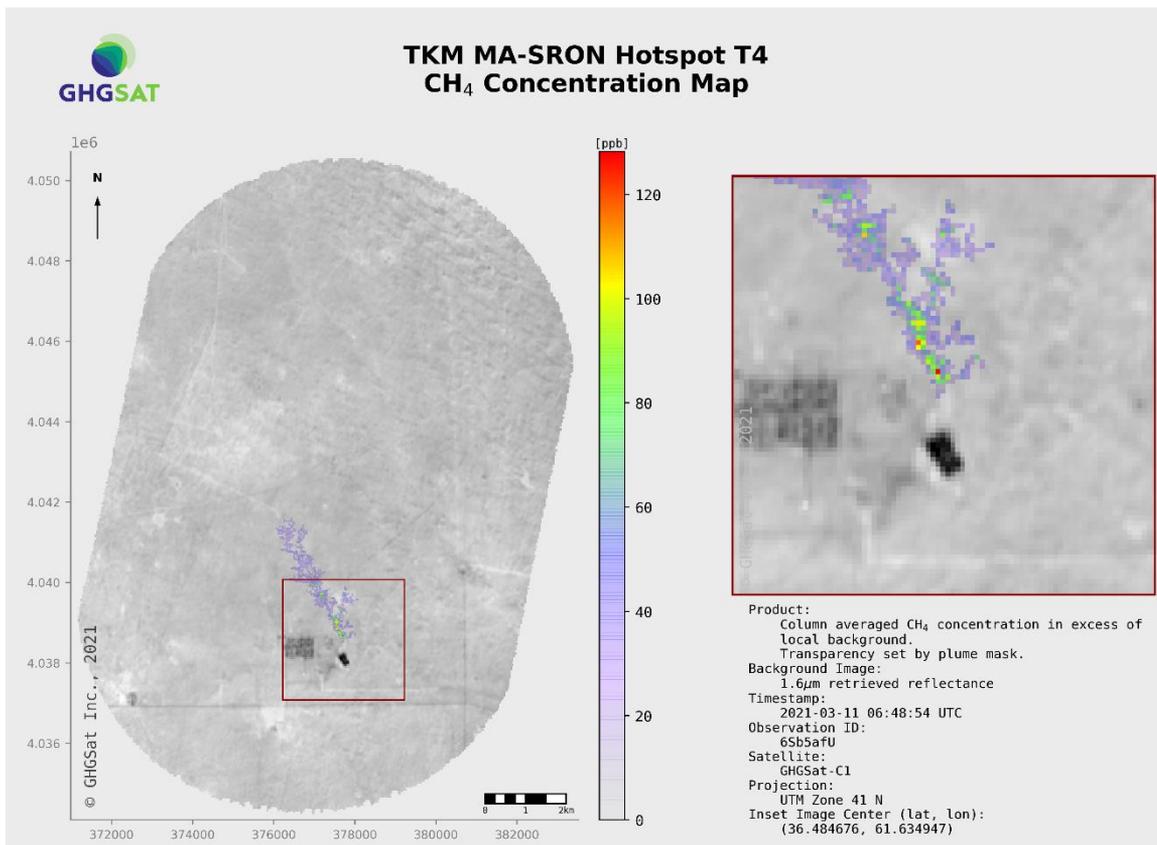


Figure 4 – GHGSAT-C1 Emission over Turkmenistan, Oil and Gas Mary Infrastructure site

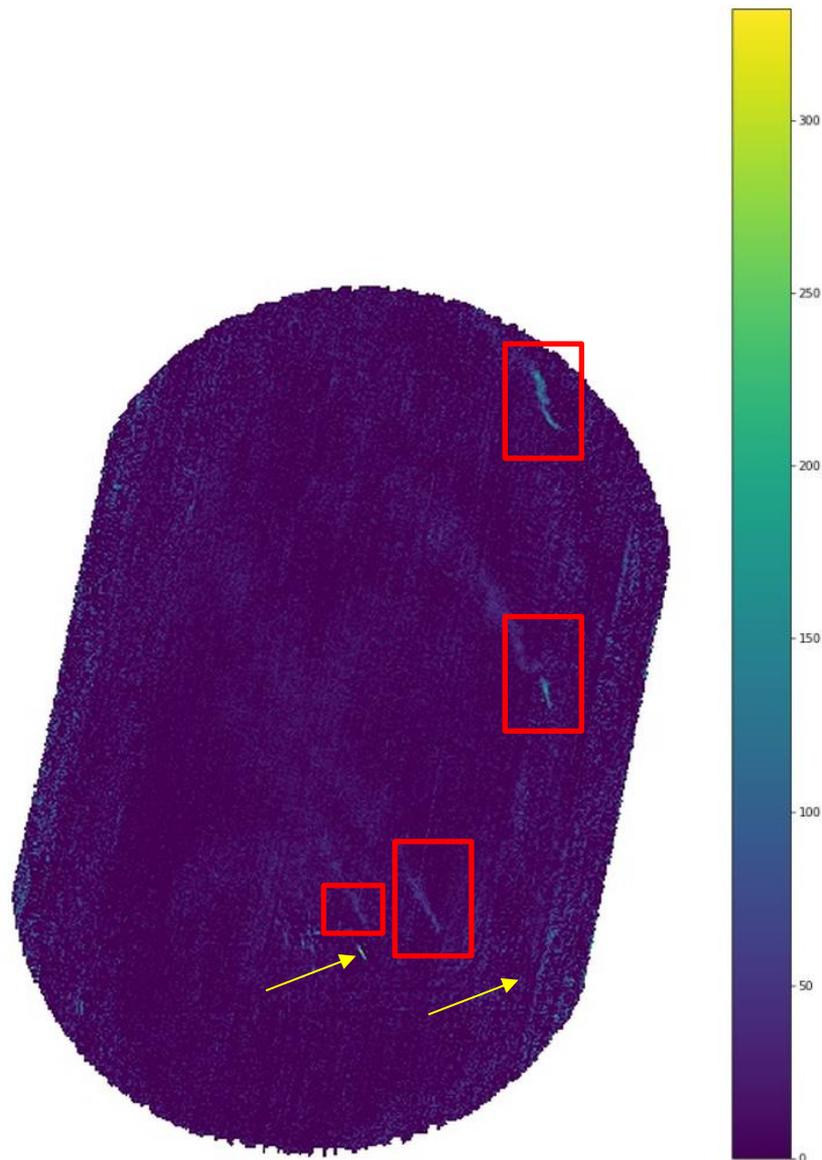


Figure 5 – Emission recalculated over Oil and Gas Mary Infrastructure site

The intercomparison of GHGSAT plume emissions (Figure 4) and the recalculated emission (Figure 5) shows a very good agreement (c.a. 350 ppb of max value). The product has been acquired during no very intensive emissions, but they are clearly visible since no particular features are present: the product is qualitatively good, low interference/noise present in the right part probably border straylight effect. In the products are present at least 2 areas probably related to the infrastructure.



Figure 6 – Turkmenistan, Oil and Gas Korpeje Up Shale Infrastructure site

The second product (Figure 7) has been acquired on another oil and gas infrastructure in Turkmenistan: there are two main emissions (Figure 8, the first with a peak at ~600ppb and well visible, the second at 250 ppb less evident), but especially there are three “features” in correspondence of pools. Clouds interference is present, in the upper part of the products that generate artifacts in the retrieval.

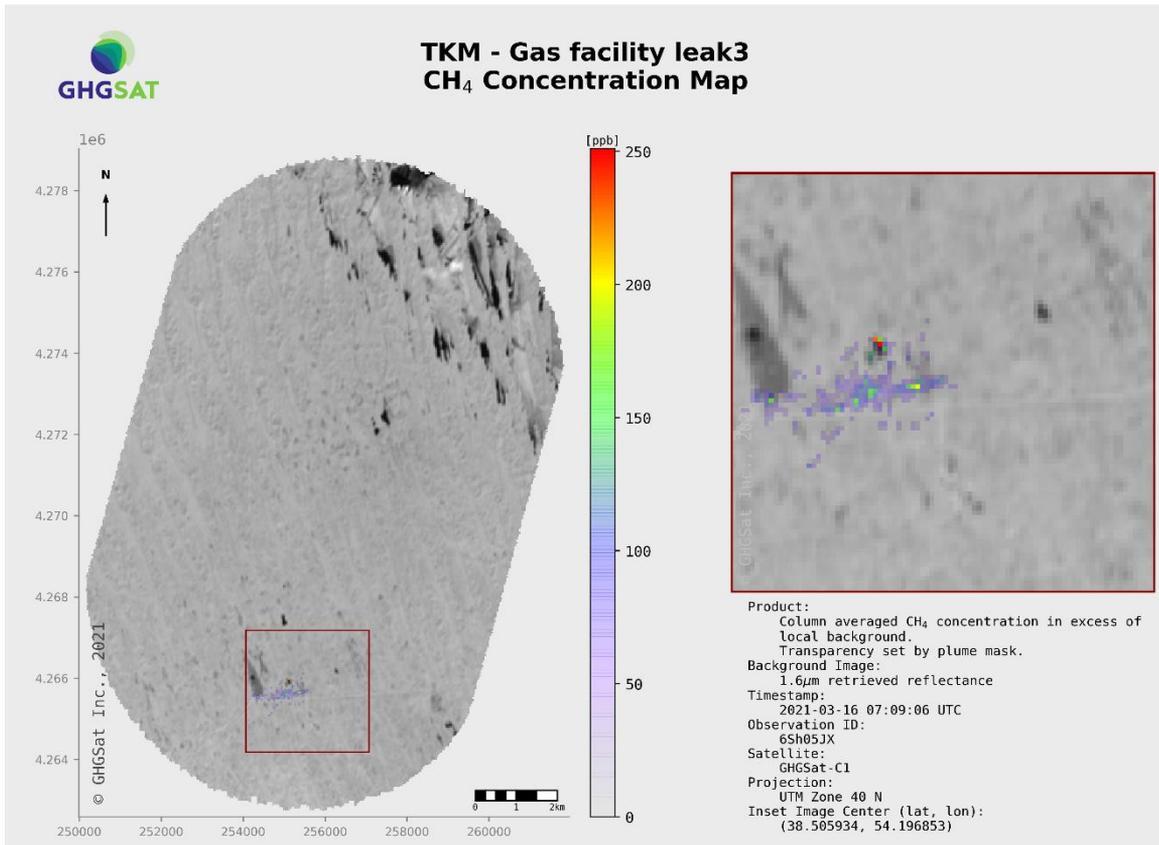
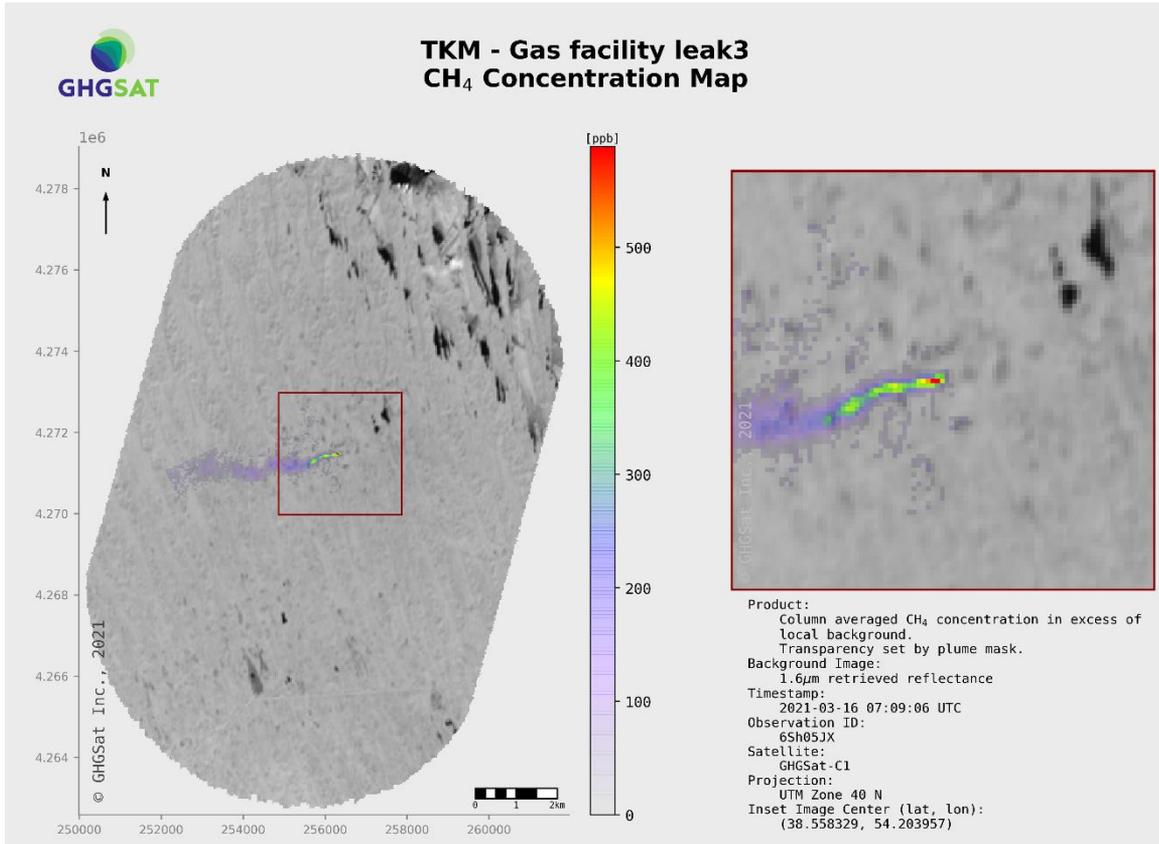


Figure 7 – GHGSAT-C1 Emission over Turkmenistan, Oil and Gas Korpjeje Up Shale Infrastructure site

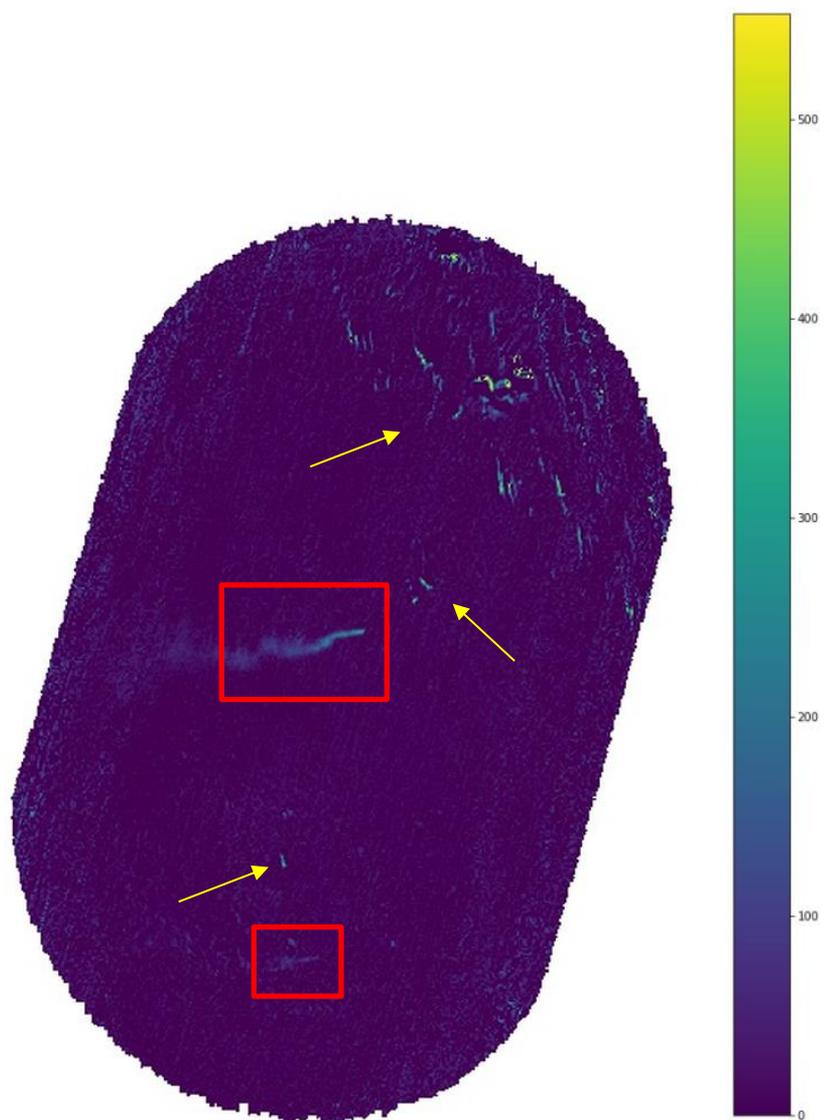


Figure 8 – Emission recalculated over Oil and Gas Korpeje Up Shale Infrastructure site

Three acquisitions (Figure 10, Figure 12, Figure 14) have been analysed over the Buenos Aires landfill. In the first product (even if it seems affected by noise and bad pixels) the main emission (Figure 11, over 1000 ppb) is clearly visible and the plume is well identified and distributed. The river is a feature identified and constitutes a source of interference in the evaluation of the emissions.

In the second product (Figure 13, very poor quality caused by clouds and ghosting / straylight effects) the main emission is recognizable, but many artifacts are present with the same intensity (1000 ppb).

In the third product (Figure 15), emission at c.a. 1100 ppb has been detected. This product is affected by non-uniformity of instrument gain causing the presence in the image of an alternance of stripes of less/more intense signal. The stripes present a longitudinal pattern (parallel to the flight direction of the satellite).



Figure 9 – Argentina, Buenos Aires Landfill Infrastructure site

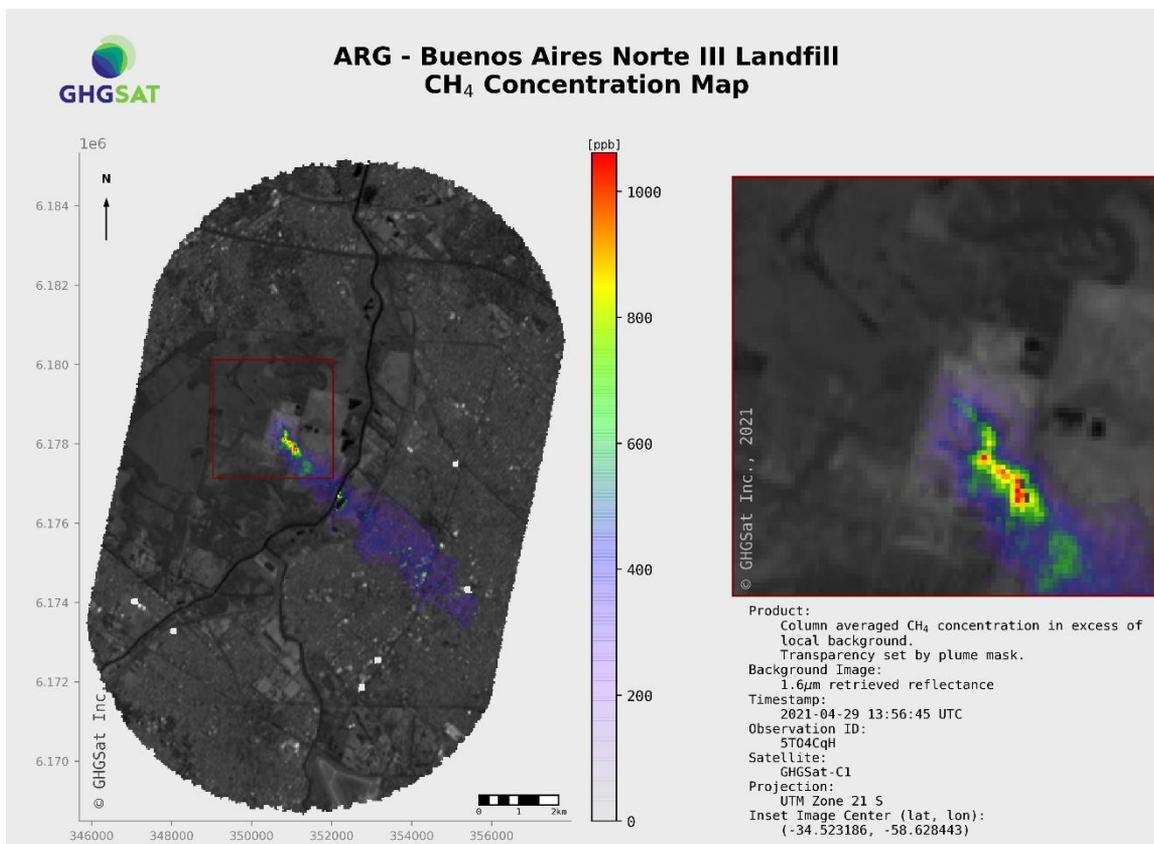


Figure 10 – GHGSAT-C1 Emission over Argentina, Buenos Aires Landfill#1

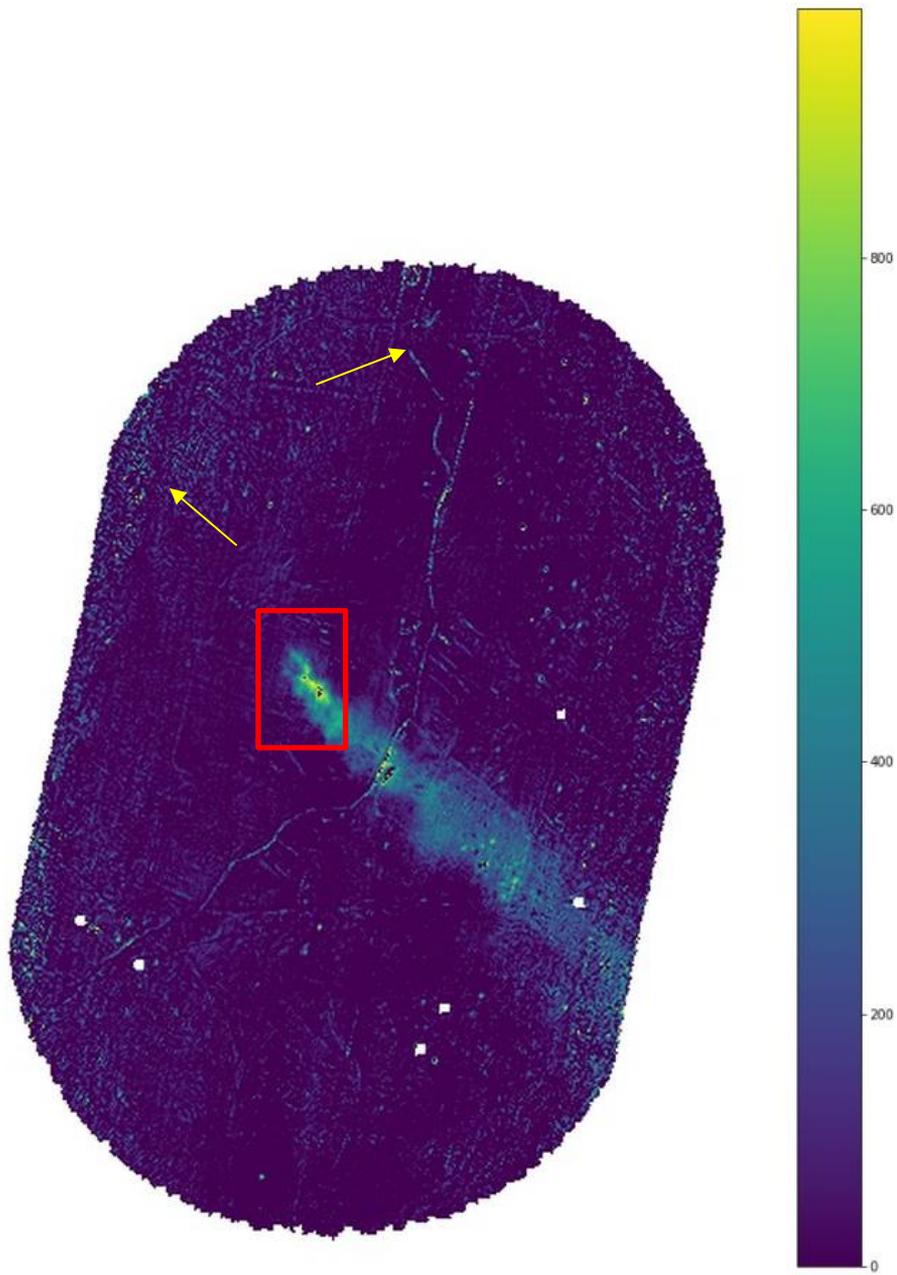


Figure 11 – Emission recalculated over the Buenos Aires Landfill site#1

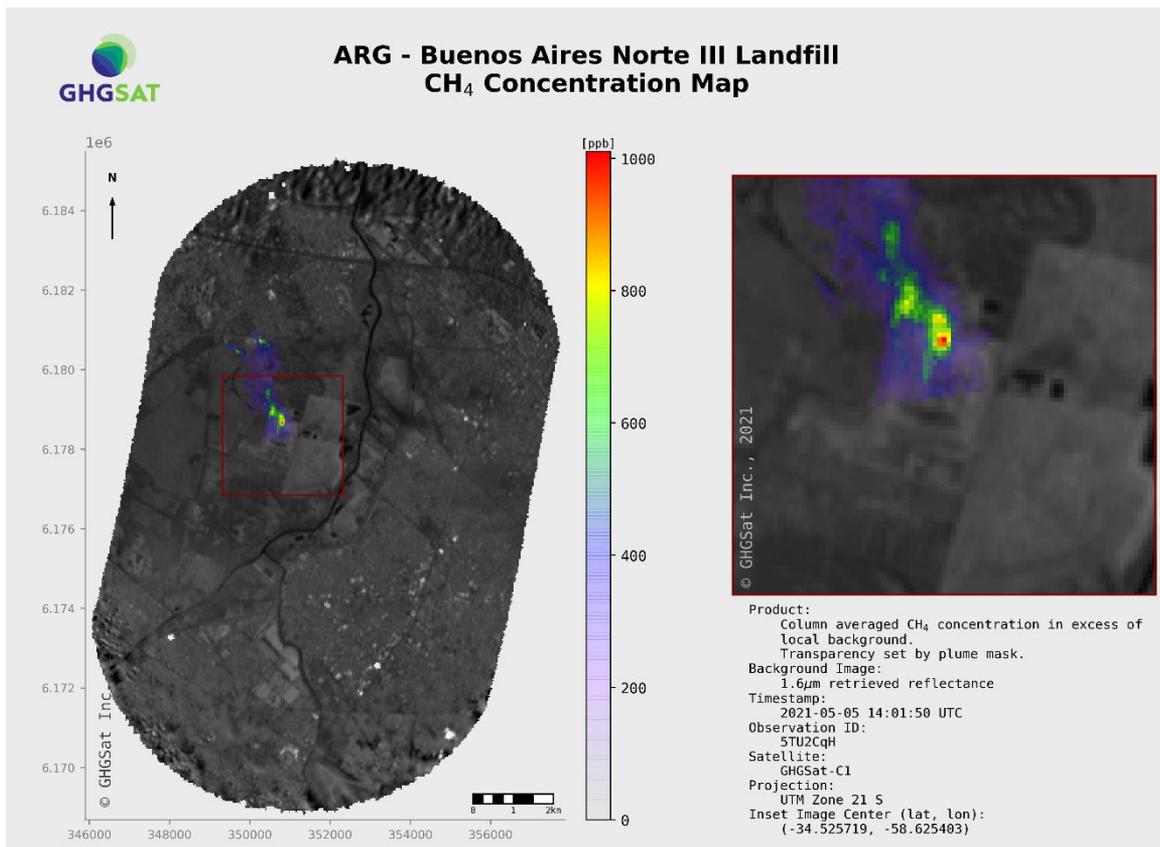


Figure 12 – GHGSAT-C1 Emission over Argentina, Buenos Aires Landfill#2

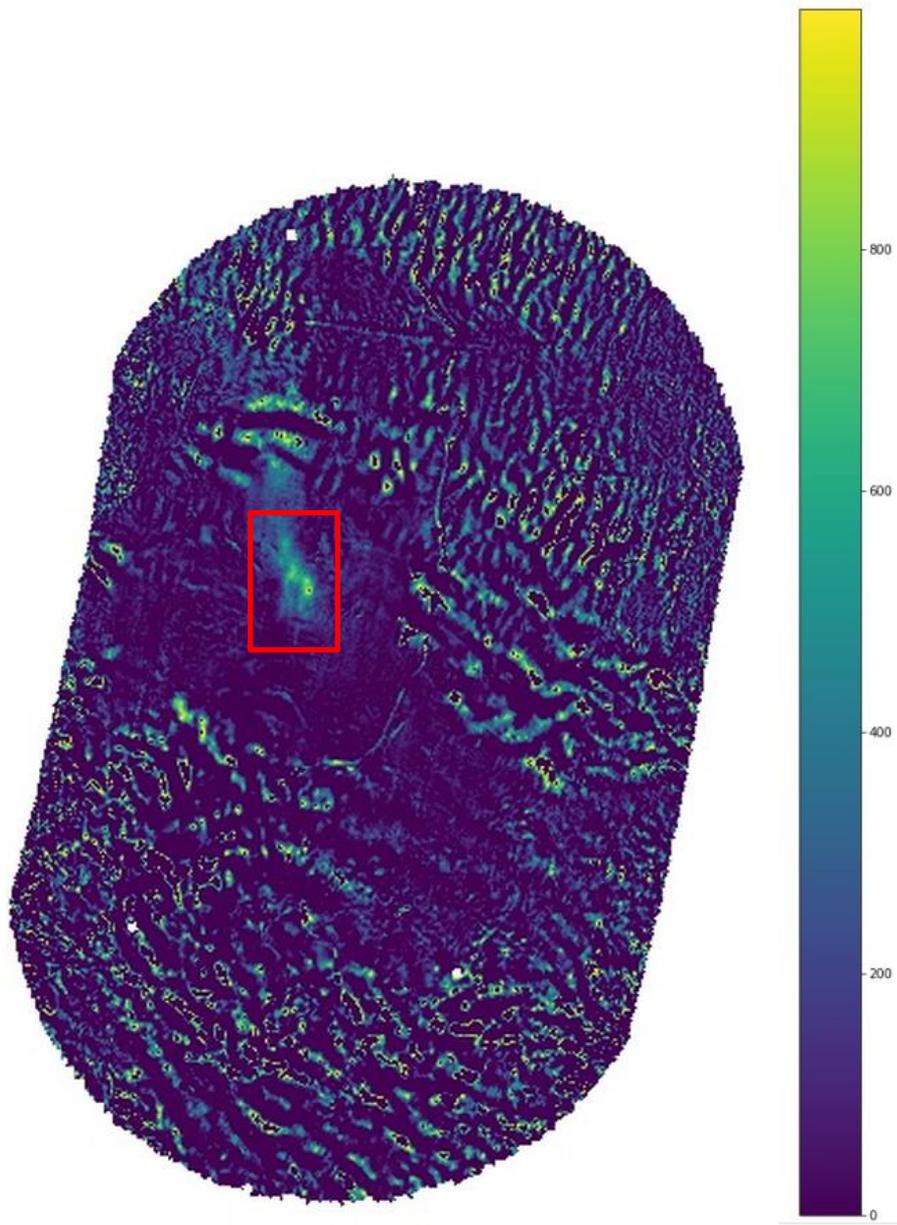


Figure 13 – Emission recalculated over the Buenos Aires Landfill site#2

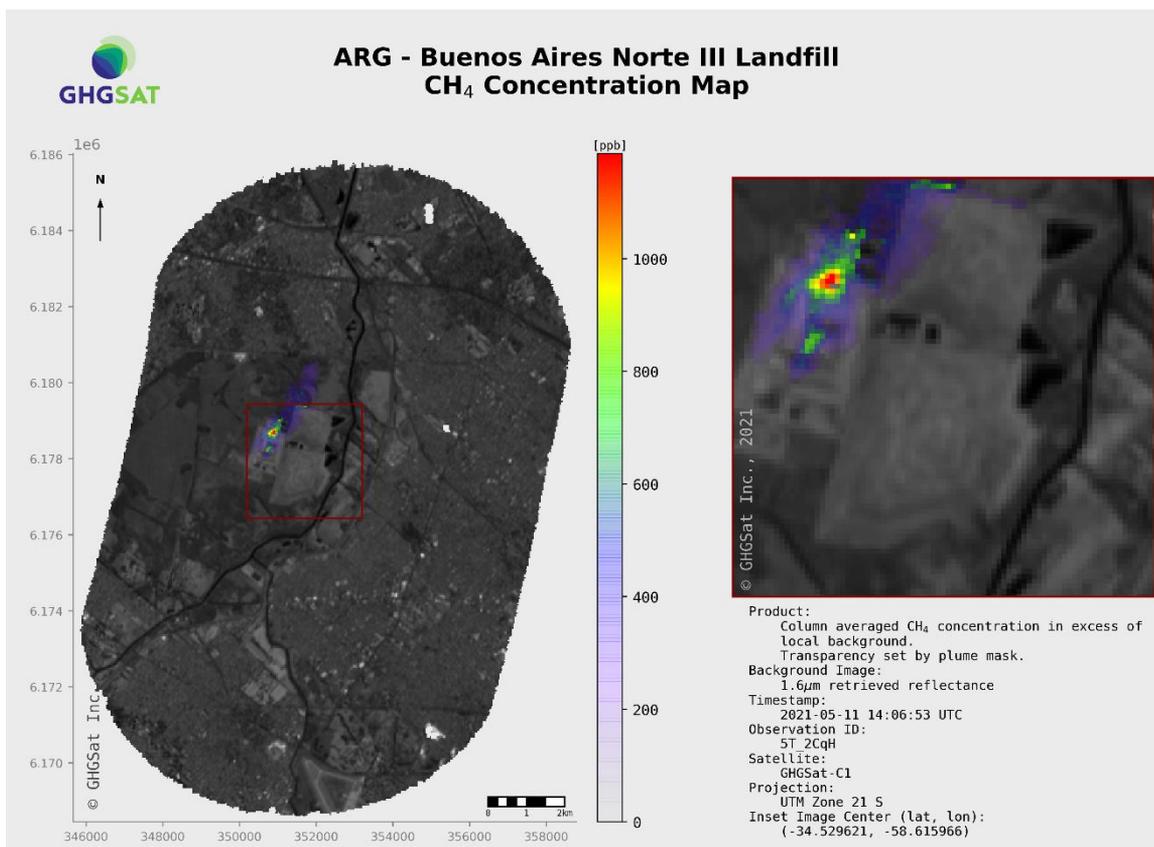


Figure 14 – GHGSAT-C1 Emission over Argentina, Buenos Aires Landfill#3

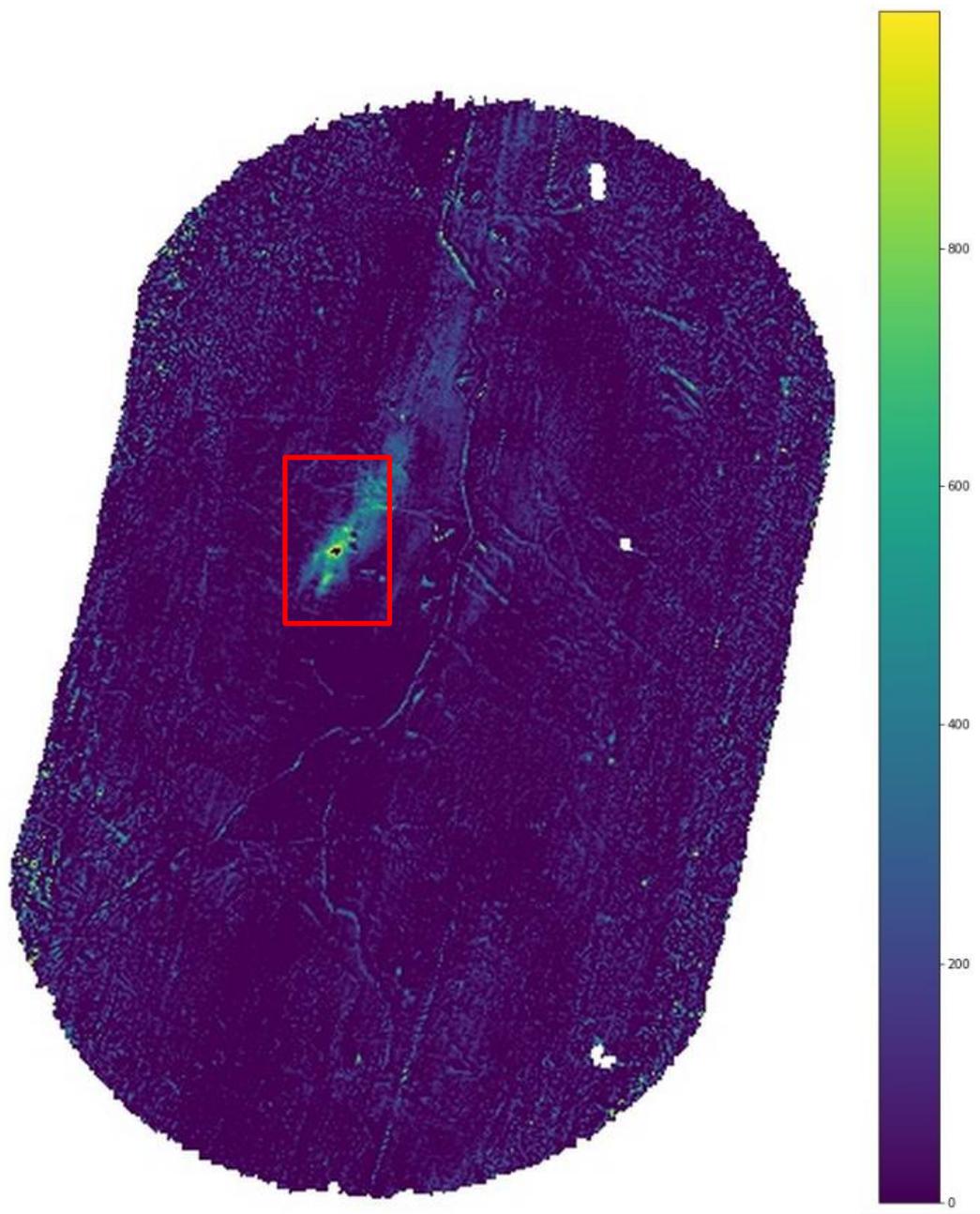


Figure 15 – Emission recalculated over the Buenos Aires Landfill site#3

The landfill emission on the Pakistan in Figure 17 shows a very good agreement in the retrieval of the emission and plume. Even if the intensity is not very high, the product is not characterized by artefacts. However the product analysed in Figure 18 shows clearly an emission in correspondence of the river, probably caused by biologic processes and a stripes pattern similar to that of Figure 15 revealing a non-uniformity of gain along the satellite flight direction.

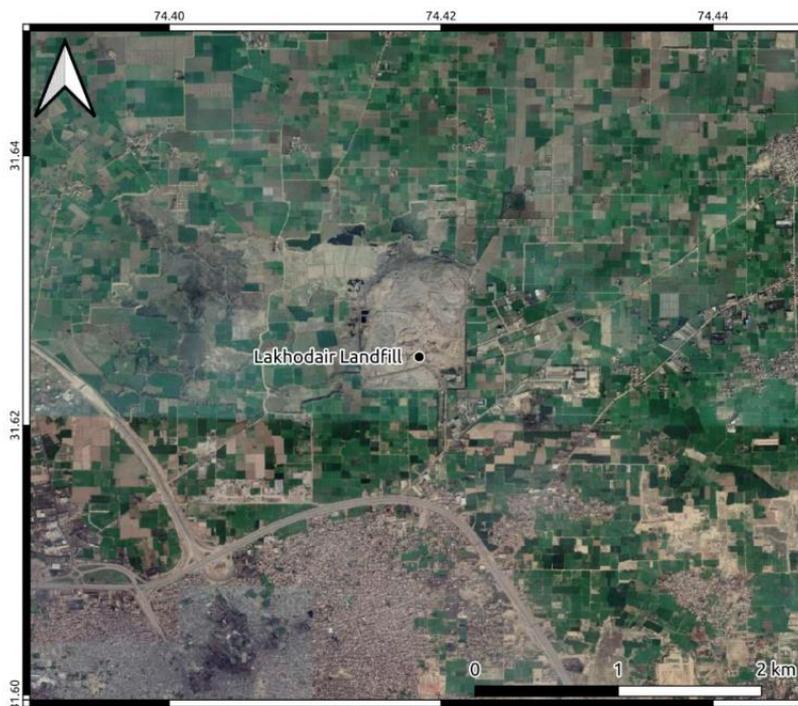


Figure 16 – Pakistan, Lakhodair Landfill Infrastructure site

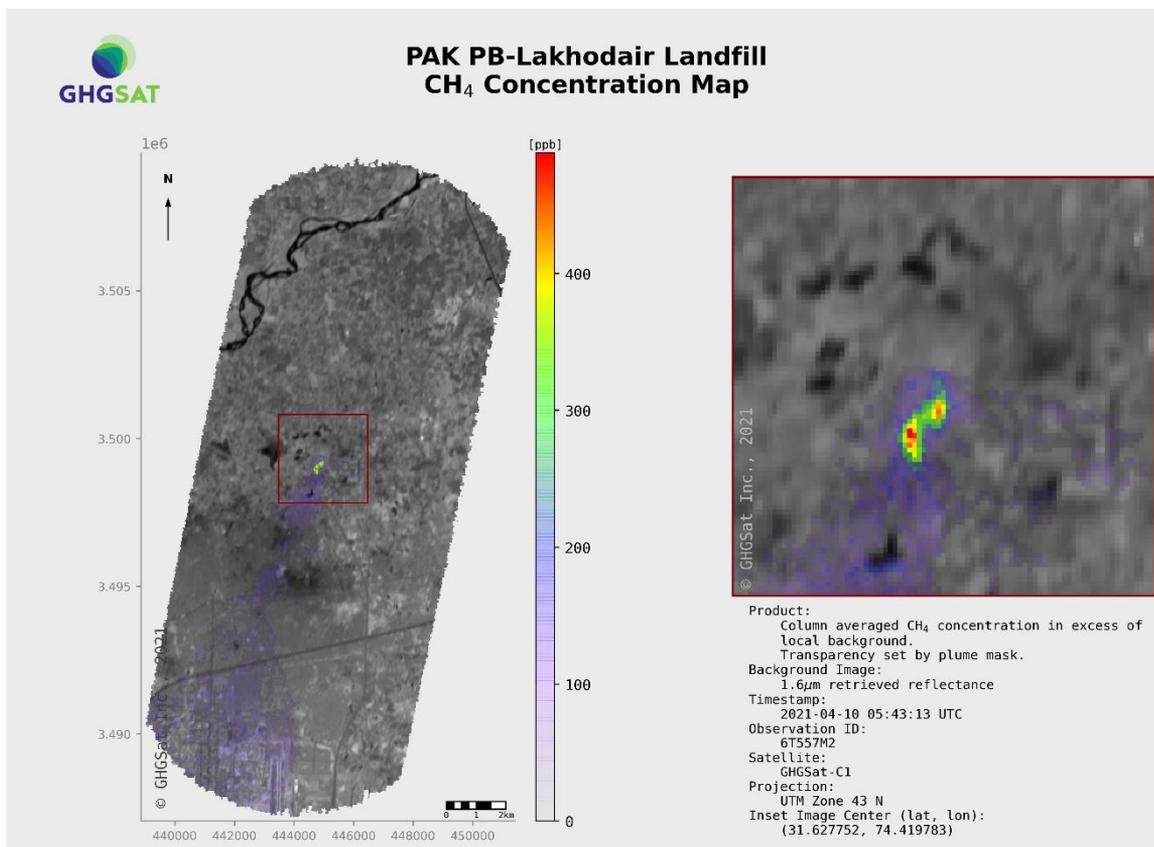


Figure 17 – GHGSAT-C1 Emission over Pakistan, Lakhodair Landfill

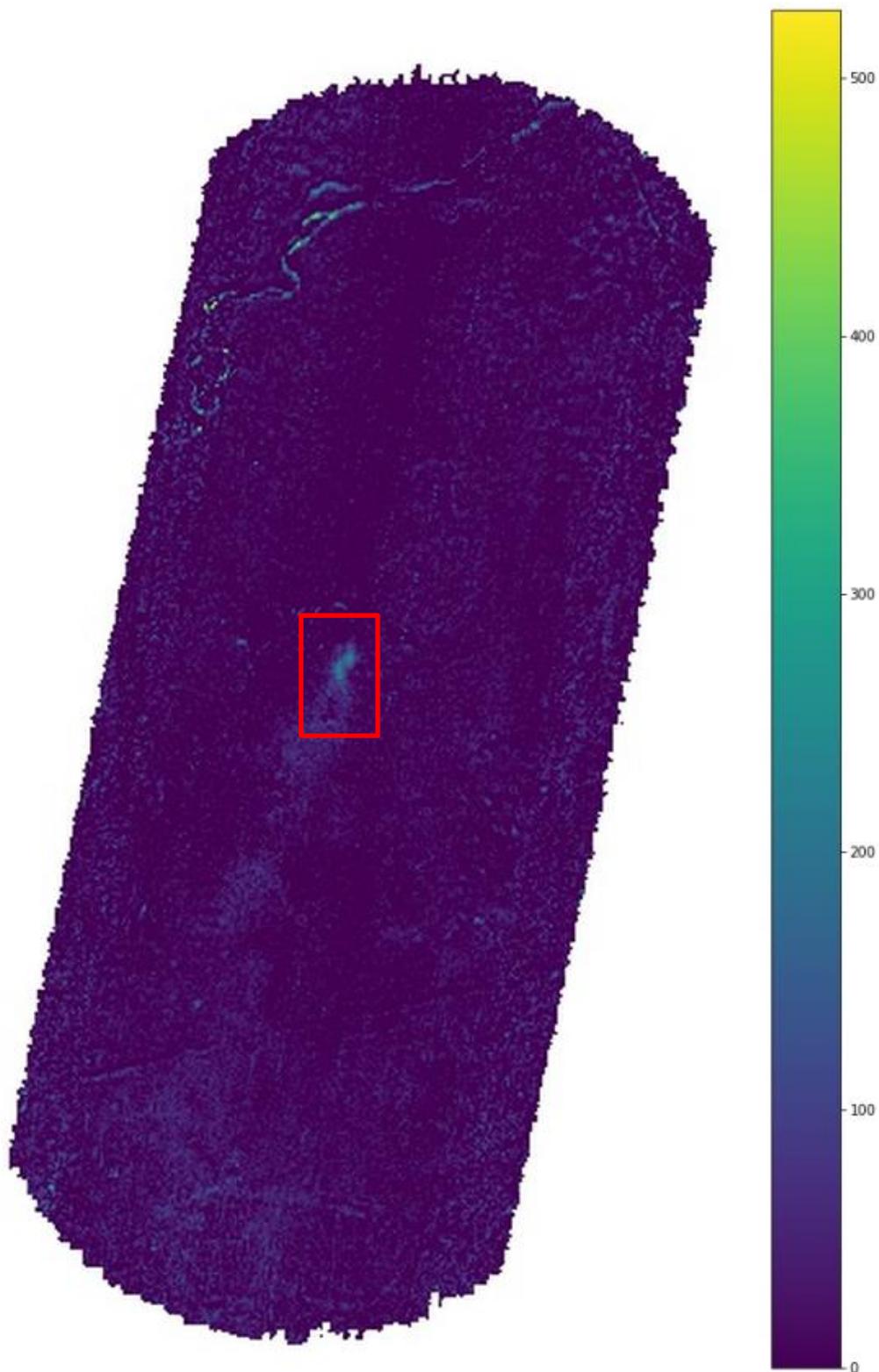


Figure 18 – Emission recalculated over the Lakhodair Landfill site

The product related to the Australia Mine Vent (Figure 20) seems to be quite problematic in terms of emission rate (not very high c.a. 350 and 300 ppb, Figure 21) since in the data seems to be present artifact generated by clouds, presence of infrastructures and non-uniformity of gain very persistent at the borders of the product.

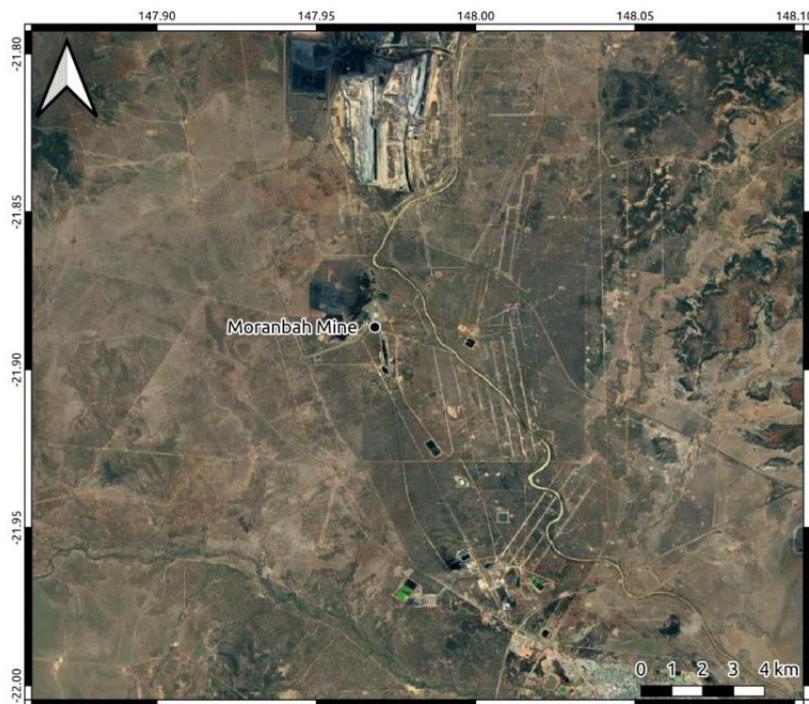
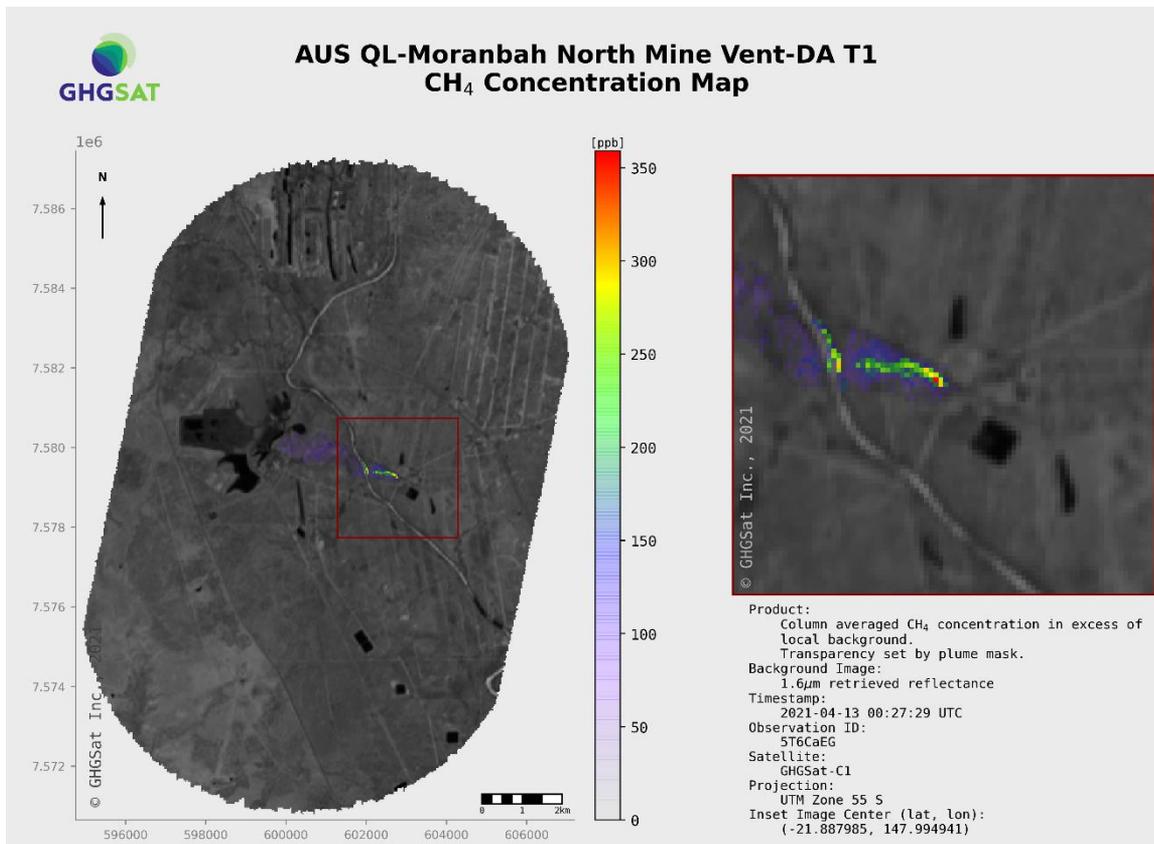


Figure 19 – Australia, Moranbah Mine Vent Infrastructure site



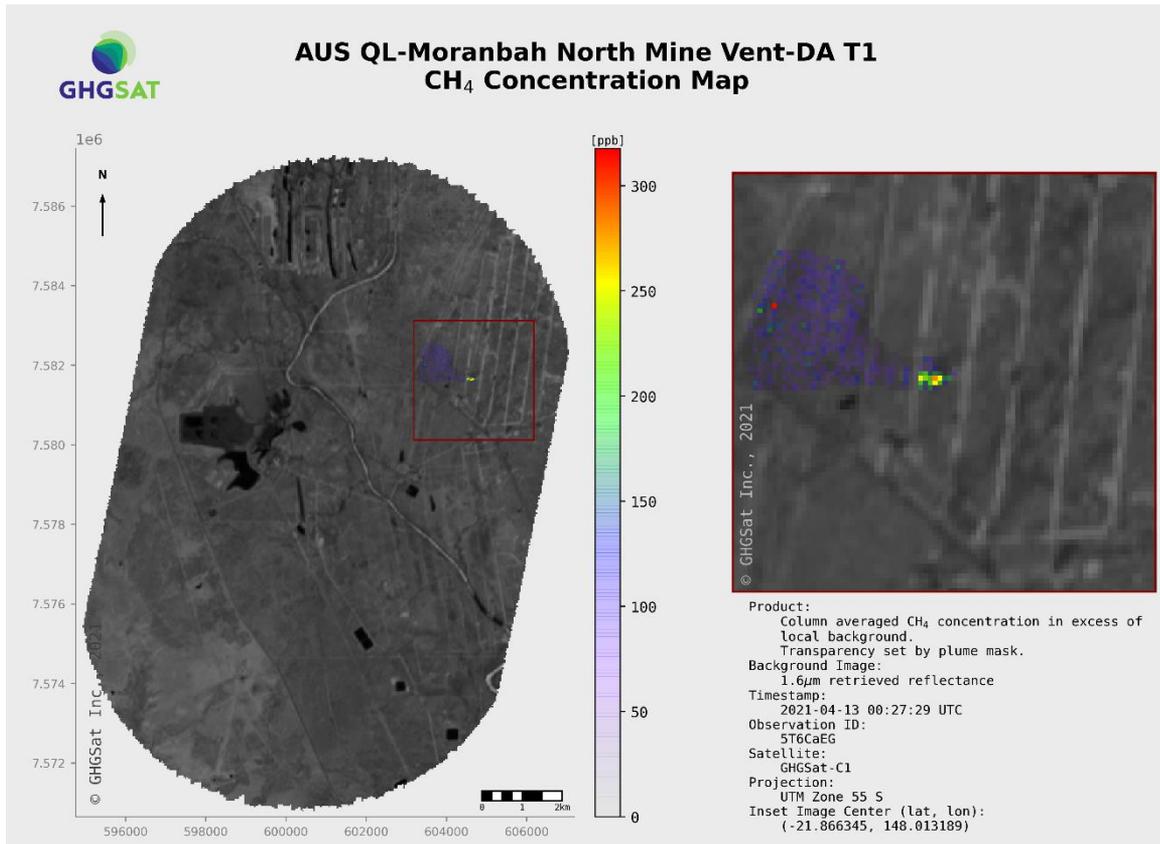


Figure 20 – GHGSAT-C1 Emission over Australia, Moranbah North Mine Vent

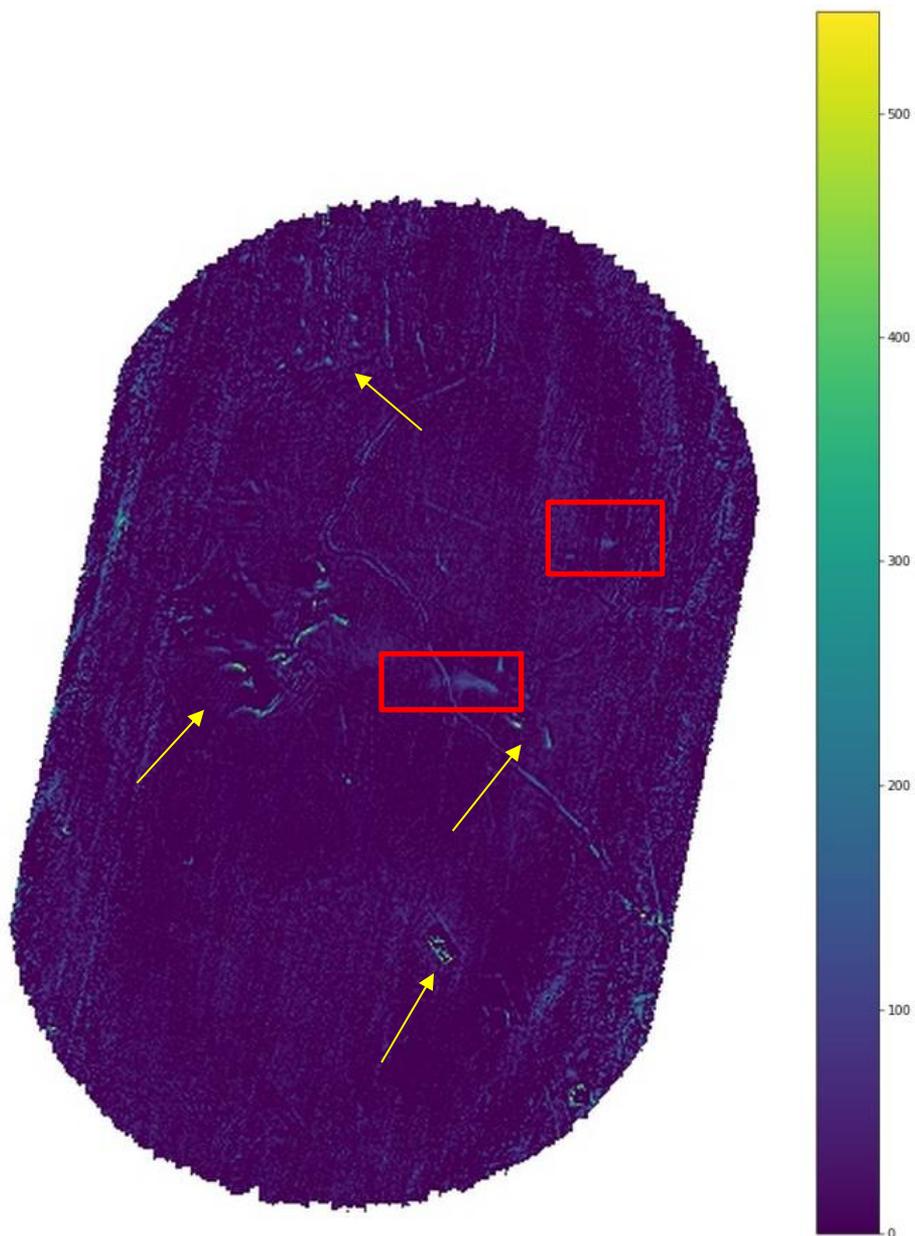


Figure 21 – Emission recalculated over the over Australia, Moranbah North Mine Vent

The last product of the dataset is on a Chinese Mine Vent infrastructure (Figure 23), which shows evidences of a middle intensity emission, with some additional elements related to river and probably other emissions sources (Figure 24).



Figure 22 – Cina, Changzhi Mine Vent Infrastructure site

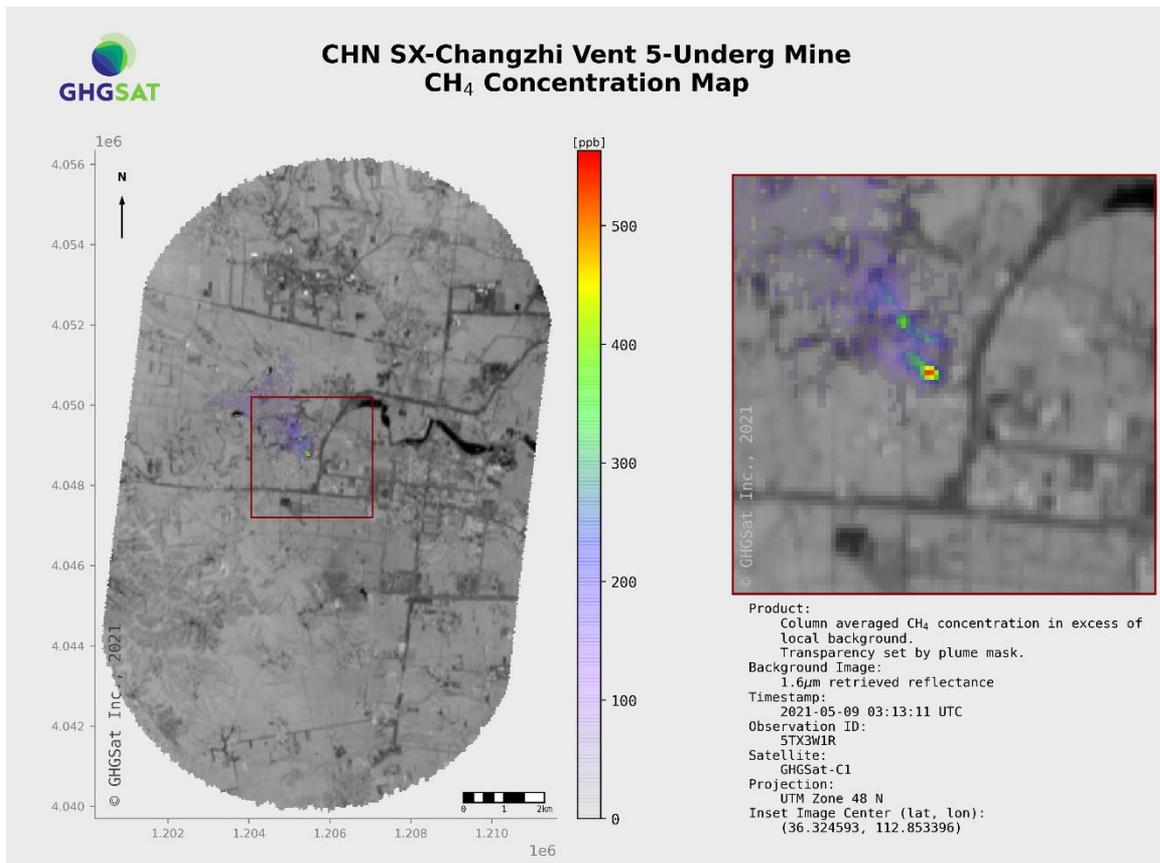


Figure 23 – GHGSAT-C1 Emission over China, Changzhi Vent Underground Mine

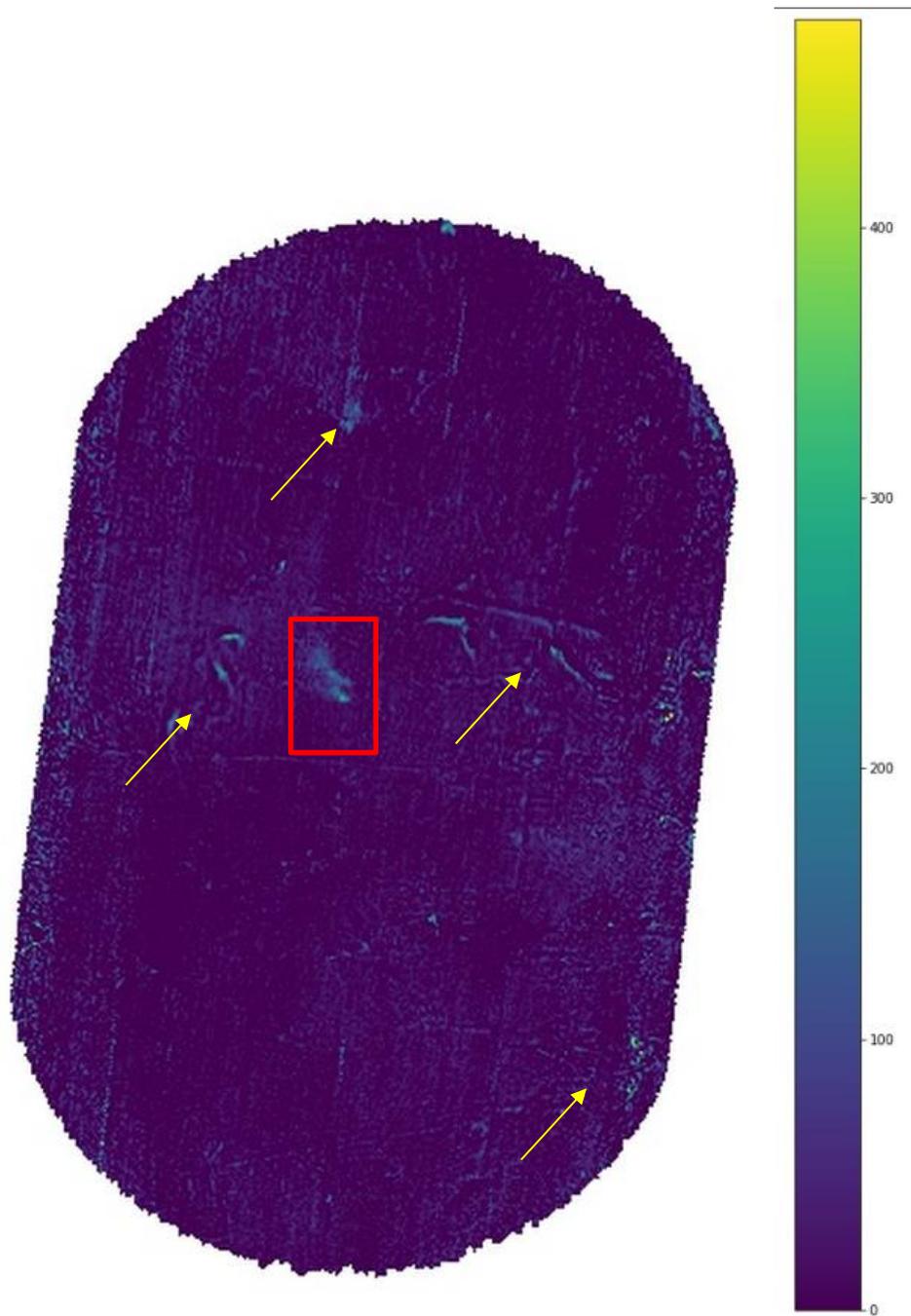


Figure 24 – Emission recalculated over the over China, Changzhi Vent Underground Mine



3.2.1 Intercomparisons with AIRS emissions

The AIRS is one of six instruments aboard NASA's Aqua satellite, which in turn is part of a constellation of satellites that make up NASA's Earth Observing System. Together with the microwave instrument the Advanced Microwave Sounding Unit (AMSU-A), these instruments observe the global water and energy cycles, climate variation and trends, and the response of the climate system to increased greenhouse gases.

The Atmospheric Infra-Red Sounder (AIRS) instrument is a

- hyperspectral – measures a large number of wavelengths over a two-dimensional field of view, creating a 'data cube'
- infrared – observes in the wavelengths redder than the eye can see
- atmospheric sounder – uses multiple, simultaneous wavelength measurements to understand the atmosphere as a function of altitude.

With 2378 spectral channels, AIRS has a spectral resolution more than 100 times greater than previous infrared sounders and provides more accurate information on the vertical profiles of atmospheric temperature and moisture. AIRS can also measure trace greenhouse gases such as ozone, carbon monoxide, carbon dioxide, and methane.

The AIRS L3 products are gridded mean geophysical parameters on 1°x1° latitude/longitude grid cells. Grid map coordinates range from -180.0° to +180.0° in longitude and from -90.0° to +90.0° in latitude. The selected temporal resolutions of the AIRS L3 products are daily, and they can be used to address the high frequency climate variability.

The AIRS products are vertical profiles (intercomparisons have been performed considering the total column of methane over a cell) and have two limits:

- 1) daily products can have gores (cells with no data) between the satellite paths where there is no coverage for that data;
- 2) spatial resolution is a cell of 1°x1° (110km x 110 km worst case) that implies a qualitative intercomparisons with GHGSAT emissions, trying to detect border cells variation.

With reference to the first product over Turkmenistan (Figure 25 and Figure 3), in the red square the area where are located the four emissions captured by GHGSAT highlights a small variation of 5÷10% respect to the values in the adjacent cells. There is with good probability a correlation with the emissions from oil&gas infrastructure, even if the wide area seems to be affected by this gradient of methane profiles and total column.

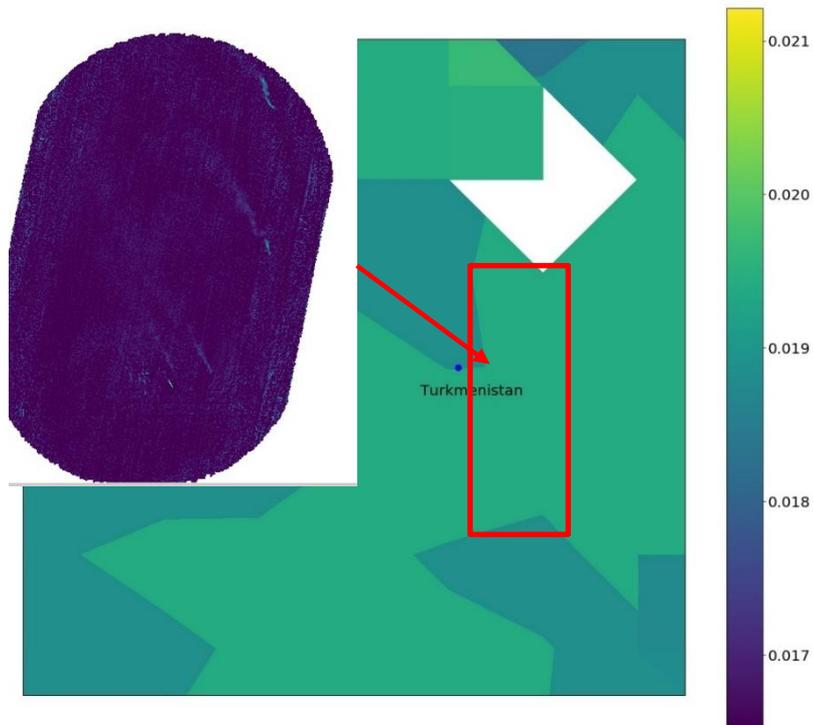


Figure 25 – AIRS vertical column (mol/m2) over Turkmenistan#1

The second product over Turkmenistan (Figure 6 and Figure 26) highlights a variation of 5% between the adjacent cells where is positioned the emission revealed by the GHGSAT acquisition. The all-AIRS product seems not be able to provide clear indications on this emission considering the uniformity of background and the values of the total column provided in all cells.

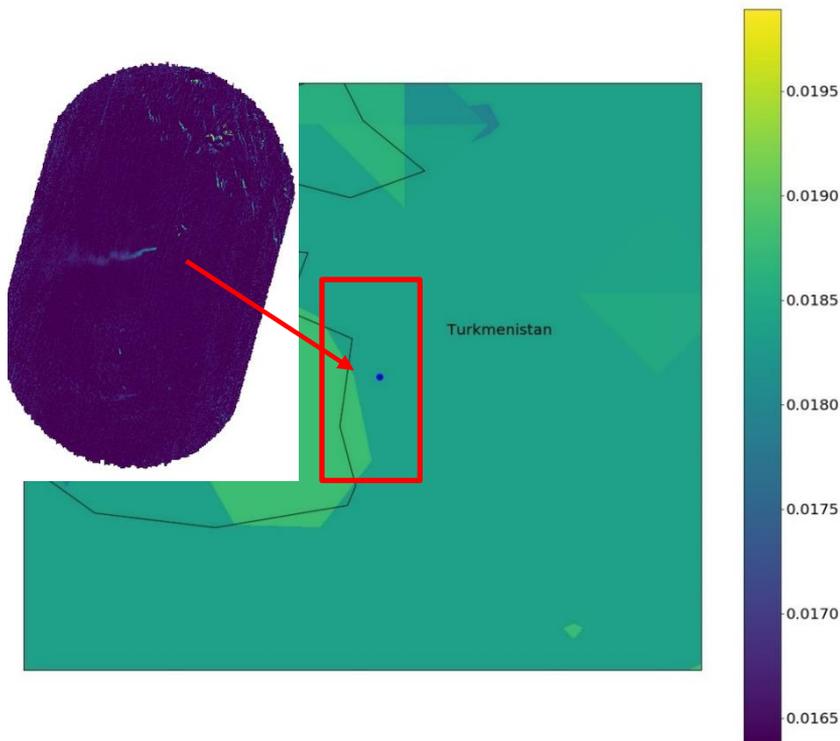


Figure 26 – AIRS vertical column (mol/m2) over Turkmenistan#2

The third product (Figure 10 and Figure 27) has been acquired over the landfill on Buenos Aires: there is a value in the cell containing the landfill 6% greater than the adjacent cells that can be in general associated to the urban areas, including the contribution of the landfill.

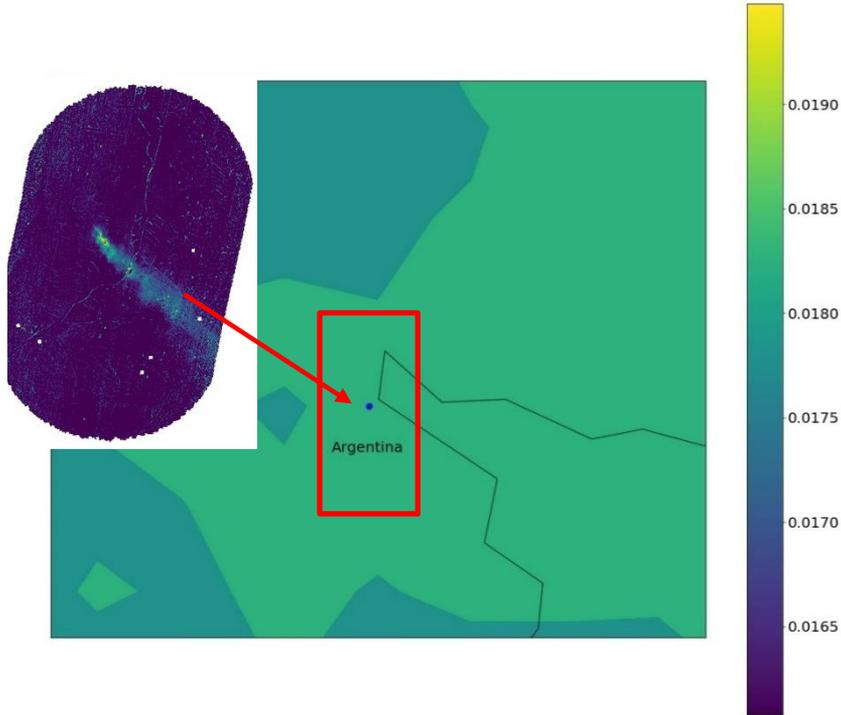


Figure 27 – AIRS vertical column (mol/m2) over Buenos Aires#1

The second acquisition over Buenos Aires can not be compared since there are no data from AIRS (Figure 28).

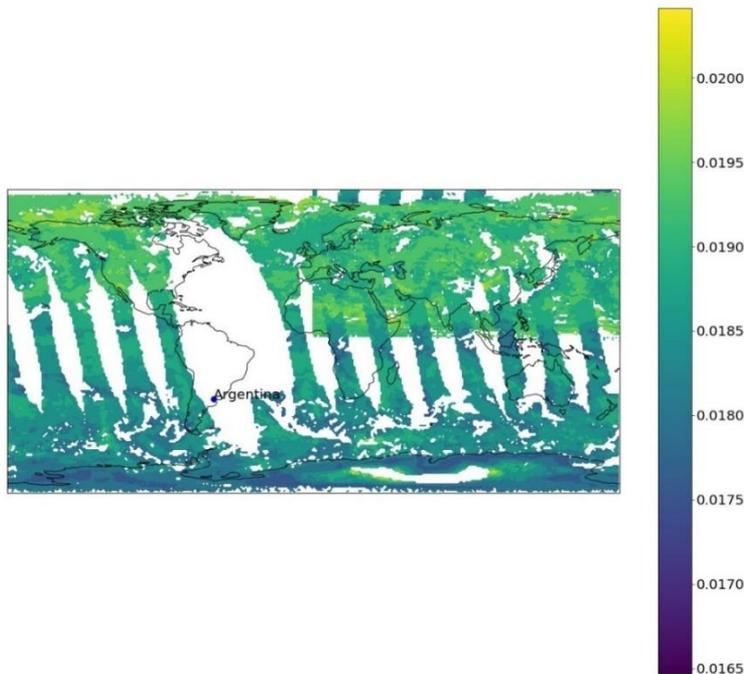


Figure 28 – AIRS vertical column (mol/m2) over Argentina#2 – No data over Buenos Aires



Finally, also for the third acquisition (Figure 14 and Figure 29) over Buenos Aires there is a variation of 6% in agreement with the first product. The analysis seems to indicate an impact related to the human activity and infrastructures related to the urbanization, with the contribution of the landfill site.

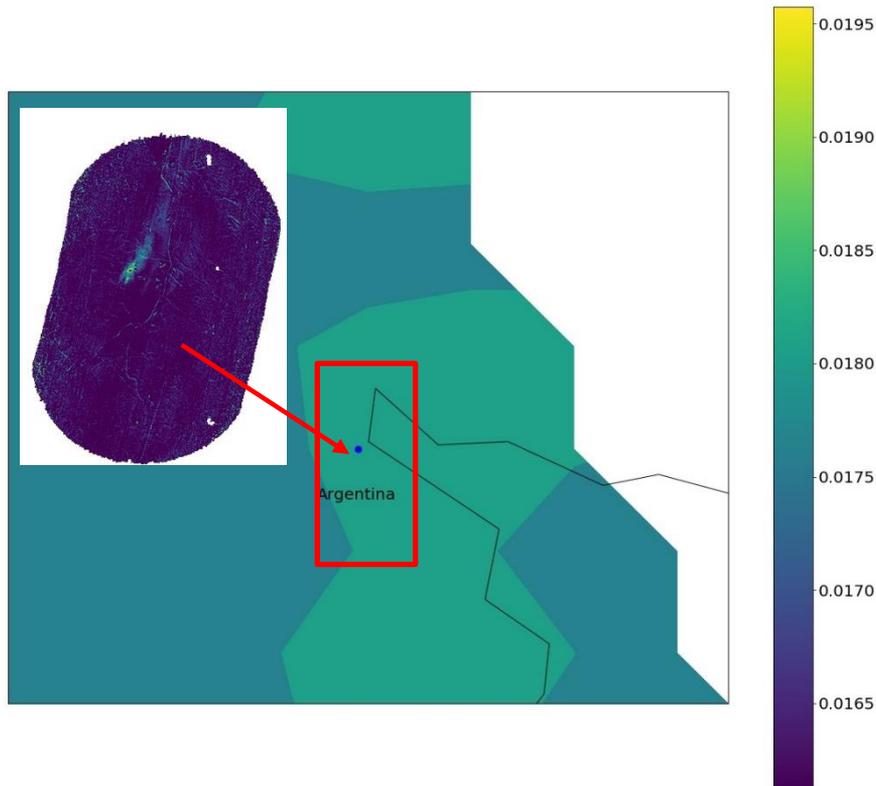


Figure 29 – AIRS vertical column (mol/m²) over Argentina#3

The product acquired over Pakistan (Figure 17 and Figure 30) landfill highlights a cell variation of 7% in the adjacency of the landfill area. In general, the area seems homogeneous with a small cell variation that could be associated to the landfill activity.

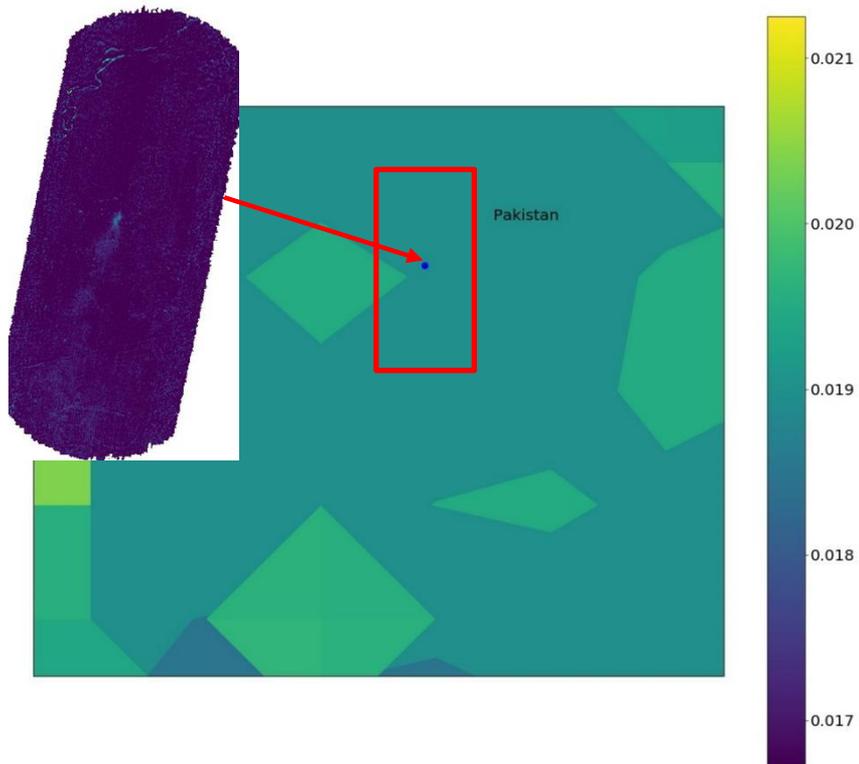


Figure 30 – AIRS vertical column (mol/m2) over Pakistan

Unfortunately, the acquisition over the Australia cannot be compared since there are no data from AIRS (Figure 31).

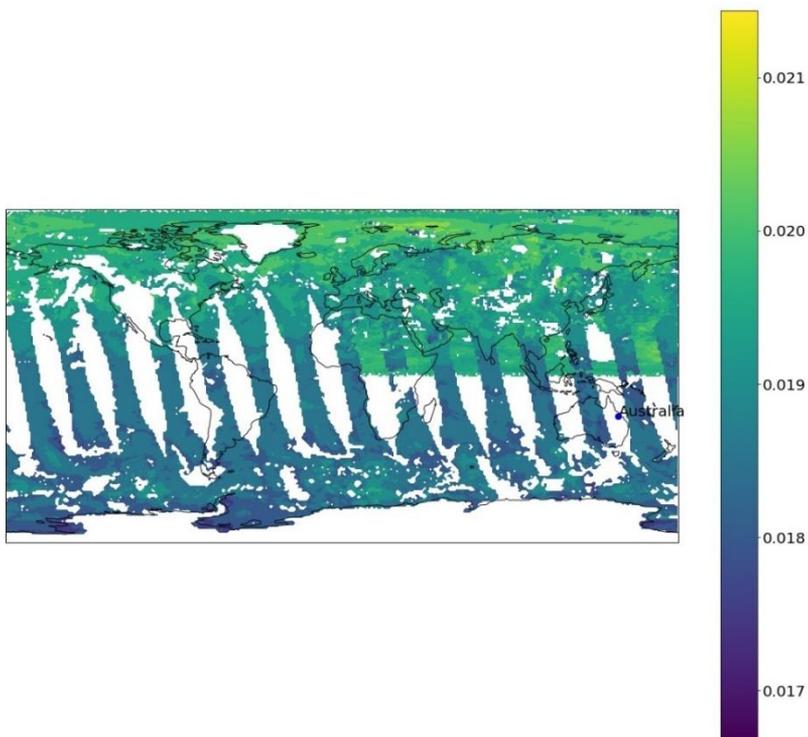


Figure 31 – AIRS vertical column (mol/m2) over Australia – No data available over the site



The last product analysed is over the mine vent over China: the AIRS data highlight a homogeneous status of the methane levels, with a positive variation of 5% in the north area, which is difficult to correlate with specific mine emissions: concretely, the entire area seems to be affected by same levels of methane (Figure 23 and Figure 32).

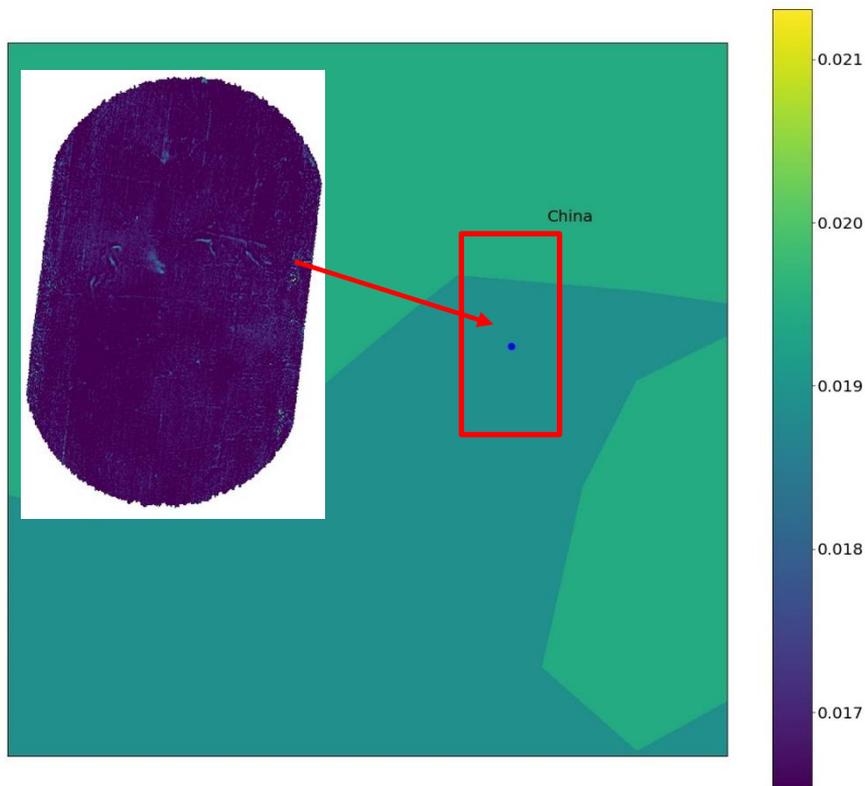


Figure 32 – AIRS vertical column (mol/m2) over China



4. CONCLUSION

Methane (CH₄), the second most important manmade greenhouse gas (GHG) after carbon dioxide (CO₂), is responsible for more than a third of total anthropogenic climate forcing. It is also the second most abundant GHG accounting for 14 percent of global GHG emissions.

Methane is emitted during the production and transport of coal, natural gas and oil. Emissions also result from the decay of organic matter in municipal solid waste landfills, some livestock manure storage systems, and certain agro-industrial and municipal wastewater treatment systems.

The performed assessment has been based on the intercomparison between the GHGSAT-C1 methane emissions and the recalculated emissions from the data provided; and the intercomparison with the AIRS methane profiles vertical and obtained column datasets.

The GHGSAT-C1 instrument has demonstrated the capacity to reveal emissions, with some evident improvements in terms of sensitivity and quality of products related to the calibration strategy that has been better defined respect to GHGSAT-D: in the dataset provided, there are emissions with low rate of methane that are detected, there are still features that can be correlated to the not completely corrections of errors (probably related to the gain) and to the conditions of acquisitions (clouds, interferences generated by infrastructures and natural elements as the rivers).

Respect to the AIRS dataset used as additional validation with space data, with the limitations related to the difference in spatial resolution of the products and typology of data (vertical profiles and columns), in some areas seems noticeable the impact of emissions with a methane cell variation > 7% respect to the other cells that characterise the area.