



[GHGSat/ C-10 Vanguard CO2] Quality Assessment Summary

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AMENDMENT RECORD SHEET

The Amendment Record Sheet below records the history and issue status of this document.

ISSUE	DATE	REASON
1.0	10/12/25	First draft
1.1	25/02/26	Updated version including new dataset over Europe

REFERENCE

The following is a list of reference documents with a direct bearing on the content of this proposal. Where referenced in the text, these are identified as [RD-n], where 'n' is the number in the list below:

- RD-1. EDAP Best Practice Guidelines, EDAP.REP.001, v2.2, 6th December 2022.
- RD-2. Earth Observation Mission Quality Assessment Framework - Atmospheric Guidelines, EDAP.REP.061, v0.1, October 2021
- RD-3. GHGSat web page: <https://www.ghgsat.com/en/newsroom/ghgsat-to-launch-worlds-first-commercial-co2-satellite/>
- RD-4. GHGSat web page: <https://www.ghgsat.com/en/newsroom/ghgsat-unveils-carbon-dioxide-plume-images-from-vanguard-the-worlds-first-commercial-satellite-that-pinpoints-co2-to-individual-facilities/>
- RD-5. Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., ... & Zeng, J. (2024). Global carbon budget 2024. Earth System Science Data Discussions, 2024, 1-133.
- RD-6. United States Environmental Protection Agency (EPA). "Clean Air Markets Program Data." Washington, DC: Office of Atmospheric Protection, Clean Air and Power Division. Available from EPA's Air Markets Program Data web site: <https://campd.epa.gov/>.
- RD-7. GHGSAT-C10 PRODUCT INFORMATION. Document N. o. GHG-01800-2001-a, November 19, 2025
- RD-8. GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025
- RD-9. QA4ECV product user guide PUM guidelines. <https://knmi.sitearchief.nl/?subsite=qa4ecv#archive>
- RD-10. GHGSAT-C10 – METROLOGY - Document No. GHG-1790-3001-a (confidential).
- RD-11. Nikola Tesla Power Station information from Global Energy Monitor wiki: https://www.gem.wiki/Nikola_Tesla_power_station
- RD-12. Continuous Emissions Monitoring Systems: <https://www.epa.gov/emc/emc-continuous-emission-monitoring-systems>
- RD-13. Carbon footprint method – A case study for thermal power plants in republic of Serbia: <https://acta.fih.upt.ro/pdf/2018-2/ACTA-2018-2-23.pdf>

RD-14. CAMPD FAQs section <https://campd.epa.gov/help-support/faqs>

RD-15. Substitute data in EPA CAMD's Power Sector Emissions Data
<https://www.epa.gov/system/files/documents/2021-06/monitoring-insights-substitute-data.pdf>

RD-16. Barré, J., Aben, I., Agustí-Panareda, A., Balsamo, G., Bousseres, N., Dueben, P., ... & Ribas, R. (2021). Systematic detection of local CH₄ anomalies by combining satellite measurements with high-resolution forecasts. *Atmospheric Chemistry and Physics*, 21(6), 5117-5136.

GLOSSARY

AOI: Area of Interest

ATBD: Algorithm Theoretical Basis Document

CAMPD: Clean Air Markets Program Data

CEMS: Continuous Emissions Monitoring Systems

CO₂: Carbon Dioxide

DMP: Data Management Plan

EDAP: Earthnet Data Assessment Pilot

EO: Earth Observation

EPA: U.S. Environmental Protection Agency

ESA: European Space Agency

FOV: Field of View

GHG: Green House gases

GL: Gross Load

GUM: Guide to the Expression of Uncertainty in Measurement

LEO: Low Earth Orbit

MM: Maturity Matrix

PUG: Product User Guide

QA4ECV: Quality Assurance for Essential Climate Variables

SNR: Signal-to-Noise Ratio

SWIR: Shortwave Infrared

WAF-P: wide-angle Fabry-Perot Instrument

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1. EXECUTIVE SUMMARY

The GHGSat launched the first commercial CO₂ sensor in orbit in November 2023. The GHGSat-C10 Vanguard sensor is the precursor of a new generation of space instruments that will build on GHGSat experience with methane emissions. Its optical design is similar to the methane infrared sensors already in orbit but tuned to CO₂'s characteristic wavelengths. GHGSat-C10 Vanguard and future constellations will provide frequent, accurate and independent high-resolution CO₂ data from individual industrial sites that will help in addressing carbon dioxide emissions, reporting and trading.

The onboard instrument is a wide-angle Fabry-Perot (WAF-P) imaging spectrometer that measures CO₂ concentrations by collecting and spectrally filtering solar backscattered radiation in the shortwave infrared (SWIR). The distinguishing features of this instrument are high spatial resolution (~30 meters) and fine spectral resolution (~0.3 nm), see Figure 1.3. The measurement concept consists of a programmable number of closely overlapping two dimensional images (~200 in nominal operations) in which the atmospheric absorption spectrum is “imprinted” on the images in the form of spectral rings due to the angle-dependent Fabry-Perot transmission spectrum. During the observation sequence, the ground target traverses the FOV, sampling the full extent of the spectral information contained in the images. The instrument operates in a “target” mode in which GHGSat-C10's attitude is adjusted to keep the facility of interest within the FOV for much longer than it would if operated in nadir, thereby increasing the available integration time and hence the signal-to-noise ratio (SNR).

The high-resolution CO₂ data will complement the information of the Global Stocktake at the international level, improving the accuracy of emissions inventories and the CO₂ modelling emissions [RD-2].

- High-resolution instruments will monitor carbon-intensive industrial sites worldwide;
- Accurate, independent satellite CO₂ data at the source to be available for the first time;
- Supports efficient operations, better emissions reporting and global stocktake.

Given the high spatial resolution, Vanguard can detect individual sites such as steel mills, power plants, and petrochemical complexes, providing emissions data for monitoring as well as Continuous Emissions Monitoring Systems (CEMS) to optimise operations aimed at reducing emissions. Figure 1.2 reports all GHGSat-C10 Vanguard characteristic.

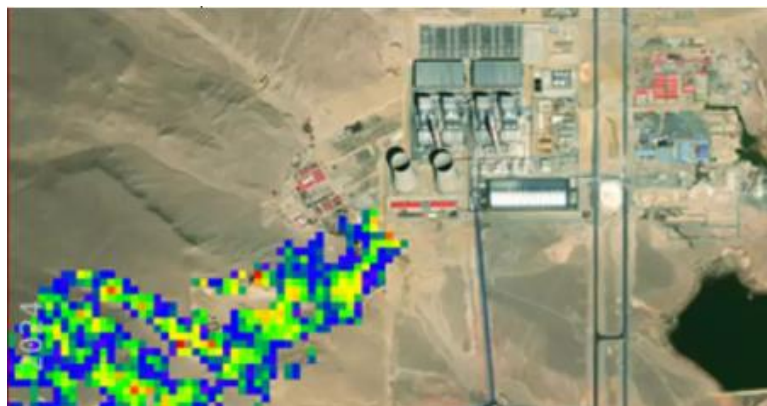


Figure 1.1 First Vanguard image released by GHGSat. It shows a carbon dioxide plume detected from a power-generating station, with an estimated rate of 12 Mt of CO₂ per year [RD-3].

GHGSat-C10 (Vanguard)	
Satellite	
Launch Date	November 11, 2023
Spacecraft Mass	~20 kg
Spacecraft Dimensions	30×30×50 cm ³
Expected Design Lifetime	5 years (minimum)
Orbital Altitude	~470 km (LEO)
Orbital Inclination	97.4°
Orbital Period	94 min
Equator Crossing Time	10:30 LTDN
Orbits Per Day	15
Nominal Revisit Rate	~14 days
Daily Acquisition Capacity	Up to 60 observations per day
Instrument	SWIR: WAF-P Imaging Spectrometer
Gas Detection	carbon dioxide
Bands and Spectral Ranges	SWIR 1500-1700 nm Multiple bands in a proprietary configuration, unpolarized
Spectral Resolution	~0.3 nm
Spectral Sampling	0.0001-0.1 nm/pixel
Ground Sampling Distance	~30 meters
Retrieval Domain	15 km × 12 km
CO ₂ Detection Threshold	500-1,500 tonnes/hr (in 3 m/s wind)
CO ₂ Column Precision	3-8% of background
Sampling Depth	12 bit
On-Board Calibration Source	Yes

Figure 1.2 GHGSat-C10 (Vanguard) satellite and instrument specifications, from [RD-7]

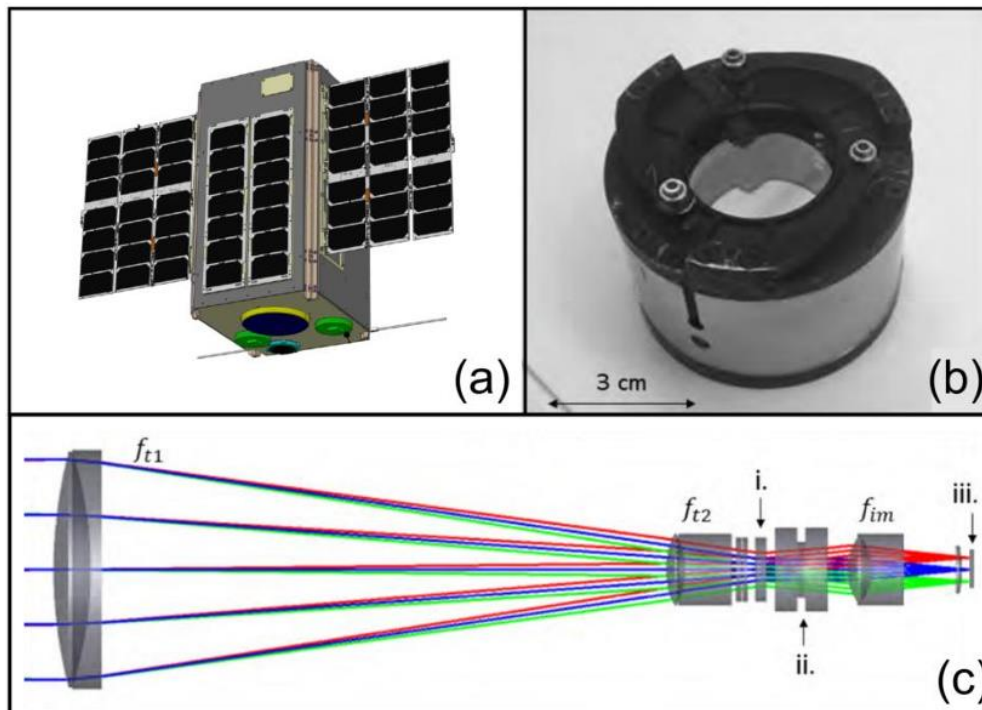


Figure 1.3 (a) The GHGSat spacecraft with the imaging spectrometer onboard. (b) The mounted Fabry, from [RD-7].

The main driver of climate change is greenhouse gas emissions, which demand a global response. Some counter measurements have been put in place. In late 2015, the Paris Agreement was signed, with the objective of enhancing the global response to climate change by limiting global warming to below 2 degrees Celsius above pre-industrial levels and pursuing efforts to limit the temperature



















increase to 1.5 degrees Celsius. However, some recent study indicates that the carbon dioxide emissions from fossil fuel combustion in 2023 are 8% higher those in 2015 [RD-4].

Data generated by sensors such as Vanguard, which provides emissions from industrial sites, are invaluable instruments for quantifying emissions and providing essential data to policy makers to address the climate change in years to come.

1.1 Cal/Val Maturity Matrices

1.1.1 Summary Cal/Val Maturity Matrix

Data Provider Documentation Review			Validation Summary
Product Information	Metrology	Product Generation	
Product Details 	Sensor Calibration & Characterisation 	Calibration Algorithm 	Measurement Validation Method 
Availability & Accessibility 	Geometric Calibration & Characterisation 	Geometric Processing 	Measurement Validation Results Compliance 
Product Format, Flags & Metadata 	Metrological Traceability Documentation 	Retrieval Algorithm 	Geometric Validation Method 
User Documentation 	Uncertainty Characterisation 	Mission-Specific Processing 	Geometric Validation Results Compliance 
Ancillary Data			


Key
Not Assessed
Not Assessable
Basic
Good
Excellent
Ideal
 Not Public

Figure 1.4 - Summary Matrix Cal/Val Maturity Matrix

1.1.2 Validation Cal/Val Maturity Matrix

GHGSat C-10 Vanguard CO2 Detailed Validation			
Measurement		Geometric	
GHGSat CO2 L4 emissions vs CAMPD database from U.S. EPA #1 Method	GHGSat CO2 L4 emissions vs CAMPD database from U.S. EPA #1 Results Compliance	GHGSat CO2 L4 emissions vs CAMPD database from U.S. EPA #1 Method	GHGSat CO2 L4 emissions vs CAMPD database from U.S. EPA #1 Results Compliance


Key
Not Assessed
Not Assessable
Basic
Good
Excellent
Ideal
 Not Public

Figure 1.5 – Validation Cal/Val Maturity Matrix

2. DATA PROVIDER DOCUMENTATION REVIEW

2.1 Product Information

Product Details	
Grade: Ideal	
Justification	<i>All required information available.</i>
Product Name	<i>Column averaged CO₂ concentration in excess of local background</i>
Sensor Name	<i>GHGSat C-10 Vanguard</i>
Sensor Type	<i>Spectrometer is based on a wide-angle Fabry-Perot (WAF-P) imaging concept</i>
Mission Type	<i>Single satellite – potential future constellation</i>
Mission Orbit	<i>LEO Polar sun-synchronous (~ 470 km altitude, inclination 97.4°)</i>
Product Version Number	<i>L0, L1A, L1B, L2A processor: "GHGSat-Toolchain", processor version: "17.0.0" L2B processor: "ghg.post_processing", no processor version L3/4 processor: "ghg.ops.srr, no processor version metadata version: "2.5" (all from *META.json file)</i>
Product ID	<i>All files are contained in a compressed archive named: C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_XXXXXXXX</i>
Processing level of product	<i>Level 2B and Level 4</i>
Measured Quantity Name	<p>Surface Reflectance (L2B Product): C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYY_ALB.tif Per-pixel Surface Reflectance in [sr⁻¹].</p> <p>Abundance Dataset: C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYY_CO2.tif Per-pixel abundances column average mixing ratio in units of [ppb] for CO2.</p> <p>C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYY_CO2ER.tif Per-pixel measurement error expressed as a standard deviation, for a single site, on a single satellite pass in units of [ppb] for CO2.</p> <p>C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYY_FLG.tif Per-pixel Quality flag layer.</p> <p>Concentration Map: C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYY_ZZZZ_CO2CM.pdf C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYY_ZZZZ_CO2CM.png High readability pseudocolor concentration map in PDF or PNG format in units of [ppb] overlaid on a MapBox image of the location.</p> <p>C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYY_ZZZZ_CO2PL.tif Foreground image of the plume is CO2 column-averaged concentration in excess of the local background level in units of [ppb] (plume).</p>

	<p>C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYYY_BRW.png Browse image.</p> <p>Emission Rates: C10_XXXXXXXX_YYYYMMDD_YYYYMMDD_YYYYYYYY_ZZZZ_CO2SR.csv Emission rate and associated error from targeted source estimated using abundance dataset(s) and applying integrated mass enhancement techniques with auxiliary information.</p>
Measured Quantity Units	See above
Stated Measurement Quality	CO2 Column Precision: 3-8% of background
Spatial Resolution	~50 m (Depends on altitude and viewing angle, up to GSD of ~30m), with ~25x25 m ² effective pixel resolution
Spatial Coverage	Scenes of order 10 km x10 km
Temporal Resolution	~14 days revisit time, up to 60 observations per day
Temporal Coverage	November 2023 - ongoing
Point of Contact	operations@ghgsat.com
Product locator (DOI/URL)	https://spectra.ghgsat.com
Conditions for access and use	Public but available upon request
Limitations on public access	Limited access
Product Abstract	GHGSat-C10 Abundance, concentration, and emission datasets for carbon dioxide (CO2)

Availability & Accessibility	
Grade: Excellent	
Justification	DMP not available but many information required in the DMP are present in GHGSAT-C10 PRODUCT INFORMATION [RD-7].
Compliant with FAIR principles	Yes
Data Management Plan	Not available to users
Availability Status	Data catalogues available. The default delivery mechanisms will be GHGSat's online data platform called SPECTRA. Data products will be made available around five days after downlink for new taskings and about two days for archive dataset deliveries (larger archive orders may take longer).

Product Format	
Grade: Excellent	
Justification	<i>Data are organized a well-documented standard file format, meeting community naming convention standards. Comprehensive set of metadata and data flags.</i>
Product File Format	<i>GeoTIFF</i>
Metadata Conventions	<i>Metadata well documented but not specific convention used.</i>
Analysis Ready Data?	<i>NO</i>

User Documentation		
Grade: Excellent		
Justification	<i>ATBD available meeting QA4ECV standard. PUG mostly follows QA4ECV guidelines except for one point. Documents are up-to-date.</i>	
<i>Document</i>	<i>Reference</i>	<i>QA4ECV Compliant</i>
Product User Guide	<i>GHGSAT-C10 PRODUCT INFORMATION. Document N. o. GHG-01800-2001-a, November 19, 2025 [RD-7]</i>	<i>Partially, according to [RD-9] the PUG comprises all requirement except for "Using the Product"</i>
ATBD	<i>GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025 [RD-8]</i>	Yes

2.2 Metrology

Sensor Calibration & Characterisation	
Grade: Good	
Justification	Pre-flight and post-launch measurement calibration & characterisation documents cover most important aspects of instrument behaviour at a level of quality to be judged fit for purpose. The documentation received cover all the important aspects of sensor pre-flight and in-flight characterization and calibration, with validation performed against notes Cal/Val sites and Landsat data over the same area. The grade could be raised to Excellent if references in literature for the Cal/Val techniques applied is added to the documentation.
References	<i>GHGSAT-C10 – METROLOGY - Document No. GHG-1790-3001-a (confidential) [RD-10]</i>

Geometric Calibration & Characterisation	
Grade: Good	
Justification	Geometric calibration & characterisation covers most important aspects of instrument behaviour at a level of quality to be judged fit for purpose. The grade could be increased if references for geometric calibration are provided with calibration sites used.
References	<i>GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025 [RD-8]</i>

Metrological Traceability Documentation	
Grade: Good	
Justification	Traceability chain documented identifying most important steps and sources of uncertainty. Uncertainty tree diagram not available.
References	<i>GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025 [RD-8]</i>

Uncertainty Characterisation	
Grade: Good	
Justification	Limited use of GUM approach, and an expanded comparison to measurements by other sensors. Most important sources of uncertainty are included.
References	<i>GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025 [RD-8]</i>

Calibration Algorithm	
Grade: Excellent	
Justification	Calibration algorithm documented. The calibration applied is considered “fit for purpose” in terms of the mission’s stated performance for all expected use cases.
References	<i>GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025 [RD-8]</i>

Ancillary Data	
Grade: Excellent	
Justification	Ancillary data used in product generation, fully specified per product, and traceable. Ancillary data used are of sufficient quality to be judged “fit for purpose” in terms of the mission’s stated performance.
References	<i>GHGSAT-C10 PRODUCT INFORMATION. Document N. o. GHG-01800-2001-a, November 19, 2025 [RD-7]</i>

2.3 Product Generation

Geometric Processing	
Grade: Good	
Justification	Geometric processing documented. Missing part of the input calibration parameters. Reasonable retrieval algorithm used. Confidence in the calibration quality is considered sufficient.
References	<i>GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025 [RD-8]</i>

Retrieval Algorithm	
Grade: Excellent	
Justification	Retrieval algorithm documented. Retrieval algorithm “fit for purpose” in terms of the mission’s stated performance all expected use cases and validated performance against known emissions for L4 data.
References	<i>GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025 [RD-8]</i>

Mission-Specific Processing	
Grade: Excellent	
Justification	Additional processing for L4 retrieval steps documented. All additional processes steps considered fit for stated purpose.
Reference	<i>GHGSat-C10 Product generation and validation. Document No. GHG-1790-4001, 1 October 2025 [RD-8]</i>

3. DETAILED VALIDATION

This section details the methodology and the results of the cross-comparison of GHGSat Level 4 CO2 emissions rate data with reference measurements.

3.1 GHGSat Dataset

The CO2 emission rates from target source are estimated from Level 2 products (abundance datasets) applying dispersion modelling techniques. The Level 2 abundance dataset is a set of per-pixel abundances column average mixing ratio provided in ppb for CO2 with associated per-pixel error (standard deviation) given for a single site for a given satellite acquisition. GHGSat dataset is accessible through the GHGSat SPECTRA platform. The CO2 data is provided in ZIP file that comprises both Level 2 and Level 4 product when the detection happened. Level 2 data include: abundance dataset in GEOTIFF, concentration maps in PDF; and Level 4 emission rates in CSV.

Emission ID	Observation ID	Site Name	Site Grounds	Observation Date / Time	Gas Type	Emission Detection	Emission Rate (kg/h)	Emission Error Ra	Wind Speed	Emission Latitude	Emission Longitude	Zone	Sensor
47487	fmF2Kdc	NA		2024-12-24 16:48:22	CO2	Y	1258271	40	1.24	33.63407	-87.06001	United States (I)	GHGSat-C10
51873	fm3L1V	NA		2024-11-29 18:15:15	CO2	Y	572985	42	1.82	36.68686	-108.47796	United States (I)	GHGSat-C10
52868	fm3DZZ	NA		2024-11-26 17:57:23	CO2	Y	137399	93	0.08	38.20794	-104.57712	United States (I)	GHGSat-C10
51943	fmY2CJN	NA		2024-11-09 17:15:26	CO2	M	905519	35	4.02	31.18167	-96.48871	United States (I)	GHGSat-C10
53225	fmP1xqp	NA		2024-10-31 16:12:15	CO2	Y	1050763	33	2.98	33.37005	-80.11365	United States (I)	GHGSat-C10
47494	fmC2Kdc	NA		2024-10-18 16:38:12	CO2	Y	2665898	35	2.52	33.63332	-87.05618	United States (I)	GHGSat-C10
51708	fm62KF7	NA		2024-10-11 17:43:26	CO2	Y	382339	40	1.49	47.37795	-101.15844	United States (I)	GHGSat-C10
51862	fm52q1V	NA		2024-10-10 18:09:19	CO2	Y	372388	45	1.33	36.68652	-108.47785	United States (I)	GHGSat-C10
47977	fm07L1V	NA		2024-10-06 18:06:57	CO2	Y	709734	39	1.33	36.68675	-108.47811	United States (I)	GHGSat-C10
53218	fm2KF7	NA		2024-10-02 18:00:21	CO2	Y	630325	34	5.28	47.37787	-101.15686	United States (I)	GHGSat-C10
52856	fm3DZZ	NA		2024-09-28 17:58:13	CO2	M	288514	63	1.97	38.20797	-104.57806	United States (I)	GHGSat-C10
50095	fm40jd	NA		2024-09-27 18:21:55	CO2	M	349972	51	2.24	33.34447	-112.86379	United States (I)	GHGSat-C10
50844	fm3CV6	NA		2024-09-27 18:18:29	CO2	Y	735902	40	2.28	45.88317	-106.61254	United States (I)	GHGSat-C10
53223	fm9Qfk	NA		2024-09-23 18:14:28	CO2	M	172231	42	2.12	40.08762	-109.28405	United States (I)	GHGSat-C10
53224	fm5ihX	NA		2024-09-22 18:36:39	CO2	Y	2184817	47	2.22	39.51267	-112.57851	United States (I)	GHGSat-C10
51960	fm3GhX	NA		2024-09-18 18:30:18	CO2	M	528361	36	4.12	39.51117	-112.58044	United States (I)	GHGSat-C10
52707	fm7IZZ	NA		2024-09-15 18:01:50	CO2	Y	488205	62	1.32	38.209235	-104.58033	United States (I)	GHGSat-C10
64452	fmY2hV6	NA		2024-09-06 18:05:28	CO2	Y	1931088	32	5.06	45.882858	-106.61435	United States (I)	GHGSat-C10
50075	fm3yZU	NA		2024-09-05 18:30:06	CO2	Y	1134491	32	7.2	33.34467	-112.86412	United States (I)	GHGSat-C10
64266	fm9CV6	NA		2024-09-01 18:17:11	CO2	Y	1834663	31	6.1	45.883169	-106.61321	United States (I)	GHGSat-C10
53217	fm6Vjd	NA		2024-08-23 18:20:11	CO2	Y	572345	37	2.57	33.34448	-112.8641	United States (I)	GHGSat-C10
52705	fm3CIZ	NA		2024-08-15 17:54:59	CO2	Y	867634	57	1.62	38.20821	-104.5764	United States (I)	GHGSat-C10
51947	fm4mmX	NA		2024-08-10 18:01:12	CO2	Y	754020	46	2.97	42.10902	-104.8805	United States (I)	GHGSat-C10
52930	fm74xRd	NA		2024-08-09 18:21:27	CO2	Y	847810	35	4.72	41.73891	-108.78731	United States (I)	GHGSat-C10
50590	fm1Gvrk	NA		2024-08-06 18:07:44	CO2	Y	398185	40	1.37	40.08647	-109.28524	United States (I)	GHGSat-C10

Figure 3.1 GHGSat-C10 CO2 L4 emission rates dataset CSV structure.

The GHGSat L4 data are categorized and flagged on whether the emission are detected. Data is flagged accordingly: emission detected (flag “Y”, YES), emission not detected (flag “N”, NO), and emission probably detected (flag “M”, MAYBE). According to GHGSat, When one or more emissions are identified in an observation, a status is assigned to each one. An emission can have one of the following statuses:

- YES: A methane emission was detected at or above our detection threshold.
- MAYBE: A potential methane emission was detected, but our level of confidence in the detection is low. The emission might be from an unknown source or conditions at the time of the measurement might result in the detection being marginally distinguishable above the background noise.
- Observations where no emissions are detected are known as Null observations. The emission status of Null observations is NO.

For the evaluation we received two datasets: one with CO2 emissions over the U.S power plants, and a second dataset with acquisitions over Europe.

The total dataset is made of 236 GHGSat observations: 34 emission detection (Y), 6 probably detection (M) and 196 no detection (N), see Table 3.1

Table 3.1 GHGSat datasets received for the Assessment

GHGSat Dataset	Emission detection			N° observations
	YES	MAYBE	NO	
U.S	33	6	181	220
EU	1	0	15	16
TOT	34	6	196	236

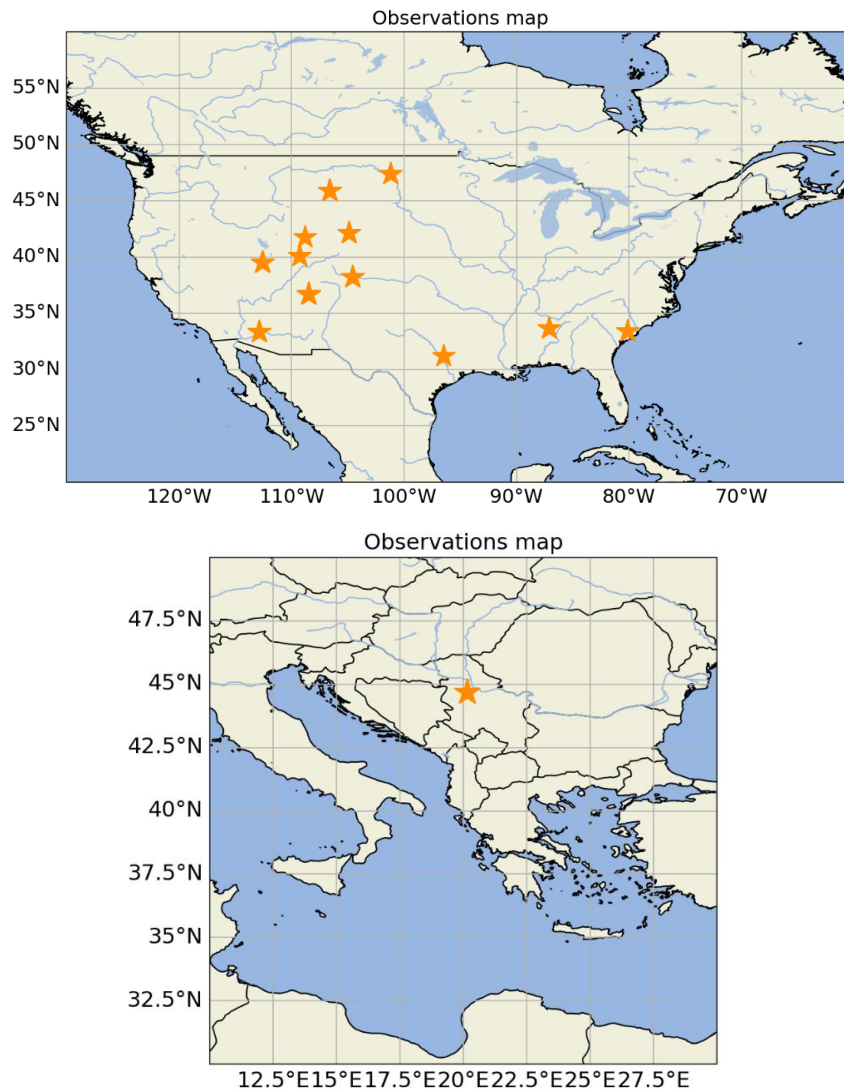


Figure 3.2 Location of U.S. and European sites where 39 CO2 plumes were observed and used in the analysis. 13 locations are in the U.S. territory; 1 location is placed in Serbia.

The map of power plants observed is shown in Figure 3.2.

From GHGSat SPECTRA platform it is possible to download the L4 dataset in a compact format as CSV spreadsheet file. Figure 3.1 shows the document structure with comprehensive information of the emission rates uncertainty, the wind speed, and geolocation site.

3.2 Reference dataset

The GHGSat L4 CO₂ emissions rate U.S. dataset was compared with the hourly emissions rate *Clean Air Markets Program Data (CAMPD)* [RD-6] provided by the U.S. Environmental Protection Agency, the EPA dataset, from now on. The EPA dataset reports emissions data in the local standard time of each facility, converted in UTC to perform the analysis. No uncertainty is provided for the reference dataset. The CAMPD aggregated rates (daily, monthly, quarterly, ozone, annual) are calculated as straight averages, (e.g., hourly rates are added up and then divided by the count).

Under the Clean Air Act, most fossil fuel-fired power plants must continuously monitor and report their emissions of carbon dioxide, nitrogen oxides, and sulfur dioxide to EPA. Emissions are monitored by Continuous Emission Monitoring Systems (CEMS) [RD-12], or equivalent that power plants install and maintain. The power plants collect and report the hourly emissions data to EPA every calendar quarter and EPA publishes those data. While the CEMS measure continuously, there may be operating hours when a CEMS does not provide valid data due critical system malfunctions, missed or failed quality assurance tests, routine maintenance, or other problems. When data is missing or invalid, data are substituted with calculated emissions values, classified as “reported” [RD-14][RD-15].

The EPA dataset reports for each site separate emissions from single units (subsite/chimney), for performing the analysis each unit are summed together to compared with GHGSat data. The conversion factor $1 \text{ short ton} = 0.907 \text{ metric ton}$ was used to convert data, and a constant emission rate during any measured hour is assumed. The GHGSat powerplant emission rate is the measured emission during the hour that corresponds to the time at which the observation took place divided by 1 hour (e.g. acquisition time 2024-10-11 17:43:26.437000+00:00 refers to the EPA emission rate reported for 17.00-18.00). These aspects need to be taken into account during the intercomparison because GHGSat acquire data over each site on a narrow time window and it might catch plumes coming from partial plant and not from the entire powerplant. On the other hand, the EPA dataset report hourly emissions generated from all powerplant. Therefore, we would expect GHGSat emissions rate to be generally lower than the EPA reference.

The GHGSat dataset acquired over Europe was analysed with a different approach since CO₂ emissions rate reference dataset is not available for European sites. In this case we calculated the CO₂ emissions rate $ER [CO_2 \text{ t/h}]$ for each site starting from the total electric power generated $P_G [MW/h]$, using fixed conversion factor C_f based on the fuel type emplaced.

$$ER [CO_2 \text{ t/h}] = C_f \cdot P_G [MW/h]$$

For more details on the approach used for the reference emission rate computation over European site and validation over a small set of U.S. sites see the ANNEX 1. The GHGSat EU dataset reports one emission detected over Nikola Tesla power based in Serbia, which is powered by lignite coal mined from Kolubara Mine complex [RD-11]. For this site the tailored conversion factor used to evaluate the CO₂ emission rate is $C_f = 1.16 [kg \text{ CO}_2/kWh]$ [RD-13].

This observation is identified by ID number *fmH0pcr*, date (23-10-2024), and it is reported in the analysis and plots with the other data from U.S. dataset.

3.3 Analysis result

For the analysis we matched spatially and temporally the GHGSat data with reference measurements, finding a total of 230 matches out of 236 GHGSat observations. A total of 39 GHGSat observations reporting emissions were used in the analysis (38 over U.S sites and 1 over EU), including both emissions detection (Y) and probably detection data (M), see Table 3.2 with details of GHGSat data used for the validation.

Table 3.2 GHGSat products used in the validation. Data are matched spatially and temporally with reference datasets for the assessment.

GHGSat Dataset	Emission detection used for the analysis		TOT
	YES	MAYBE	
U.S	32	6	38
EU	1	0	1
TOT	33	6	39

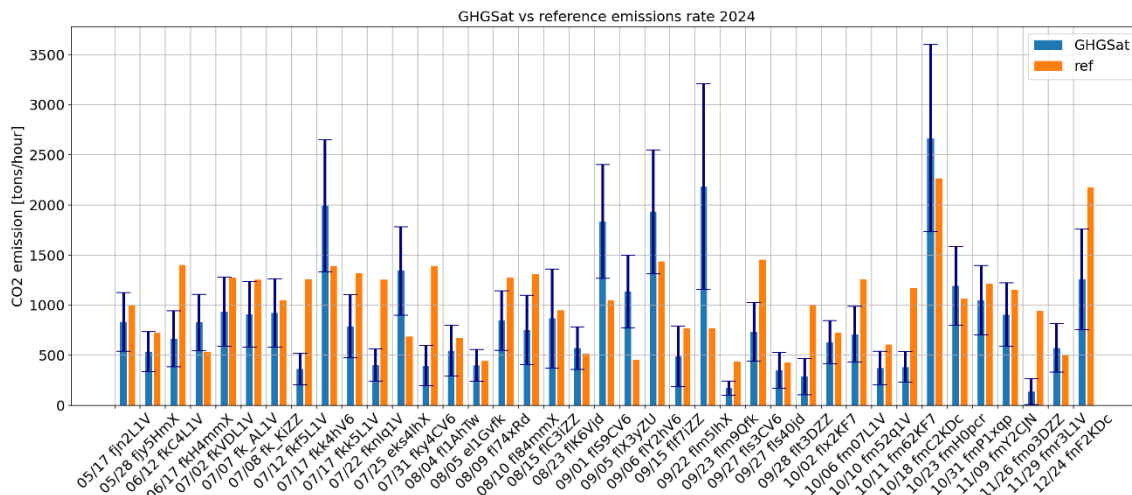


Figure 3.3 Comparison of GHGSat CO2 emissions rate and its uncertainty (blue data) with reference data (orange data).

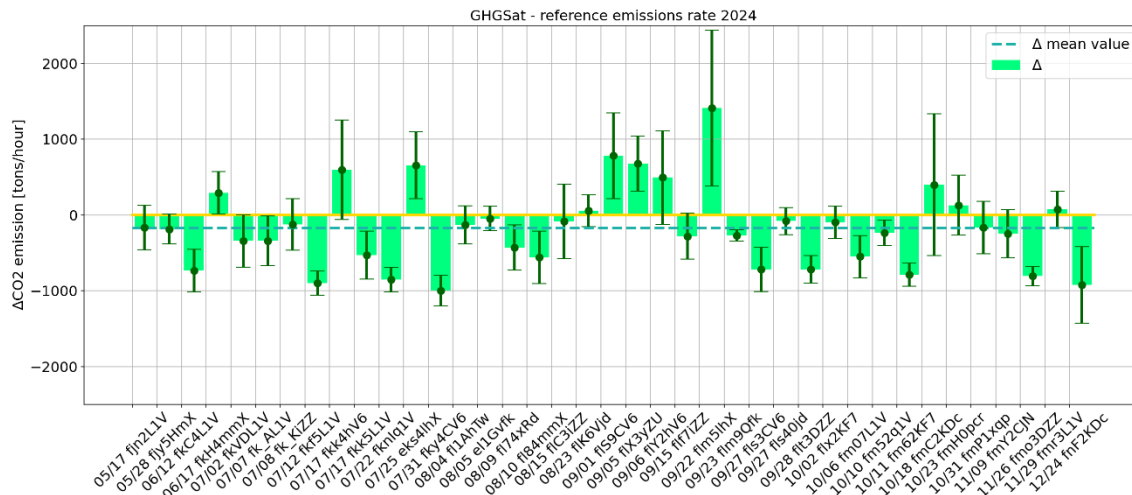


Figure 3.4 CO2 emissions rate difference (Delta) evaluated between GHGSat data and reference. The errorbars indicate the GHGSat data uncertainty. The yellow horizontal line indicate the value 0, while the horizontal dashed line indicates the delta mean value.

Figure 3.3 shows the comparison between GHGSat measurements at power plants sites with the corresponding reference emission rates. The figure also shows error bars with the GHGSat uncertainties. The bars plot in this work reports as x-axis label the observation data in form of MM/DD and the observation identifier.

There is a general agreement between the two datasets within 2σ , with some measurements reported by GHGSat being much higher than the reference. The GHGSat-reference difference graph (delta) shown in Figure 3.4 reveals how for 72% of cases GHGSat reports a lower value than reference, with a negative delta value. In the remaining 11 cases, the difference between GHGSat and reference data reports positive values.

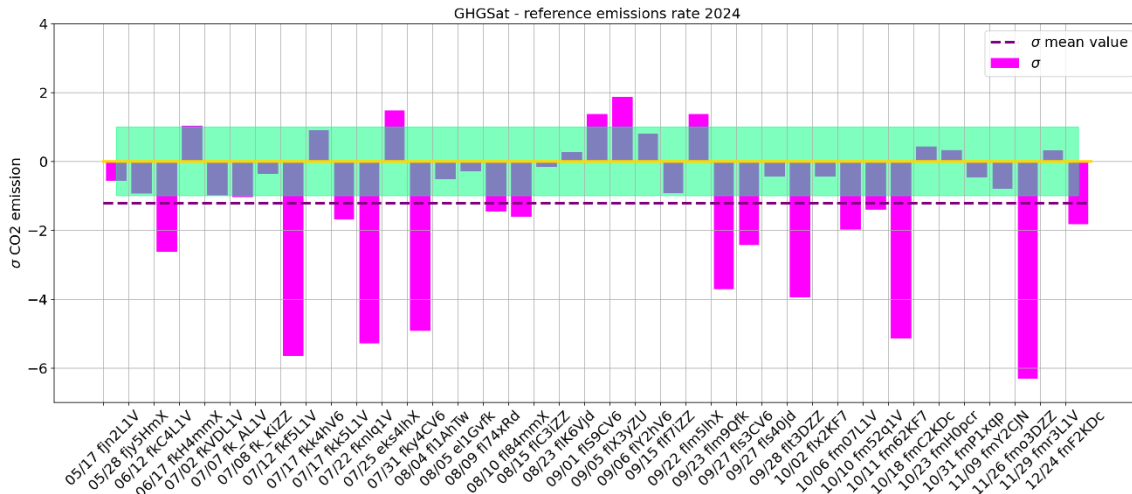


Figure 3.5 Ratio between GHGSat-reference difference and the GHGSat uncertainties (sigma). The horizontal dashed line indicates the sigma mean value. The horizontal yellow line indicates the value equal to 0, and the green box indicates where the difference is lower than the GHGSat uncertainty.

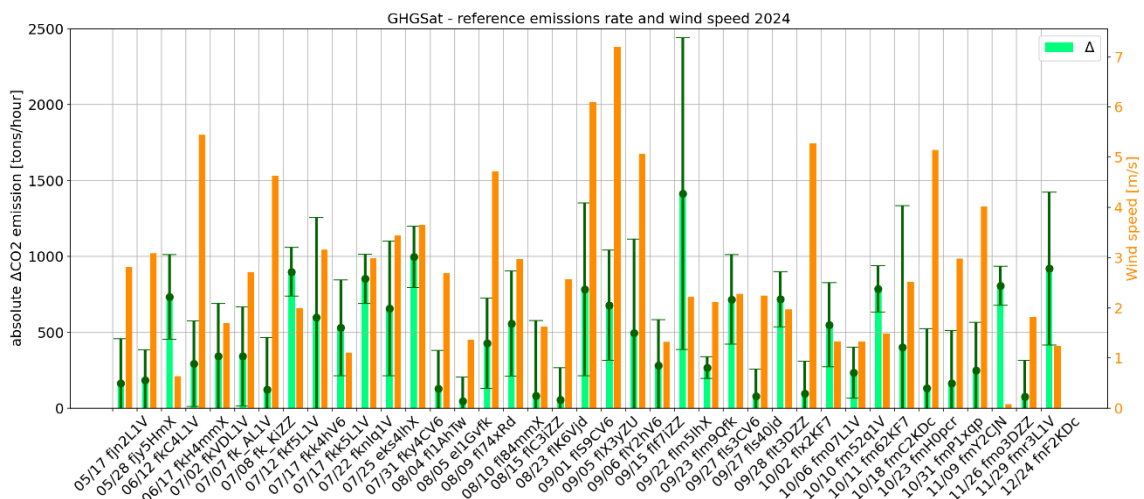


Figure 3.6 Delta CO₂ emissions rate GHGSat-reference (green bars) and wind speed (orange bar) used by GHGSat for the plume evaluation and emissions rate estimation.

To provide more information regarding delta and measurement uncertainty, the sigma graph is in Figure 3.5 (i.e., the ratio between GHGSat-reference delta and the GHGSat uncertainties). When $|\text{sigma}| > 1$, the uncertainty is much smaller than the difference between the measurements. The green region highlights the area where the GHGSat-reference differences are smaller than the GHGSat uncertainty (-1,+1). The analysis shows sigma tending to be lower than 1, meaning the uncertainty in the GHGSat measurements is larger than the difference between GHGSat and reference.

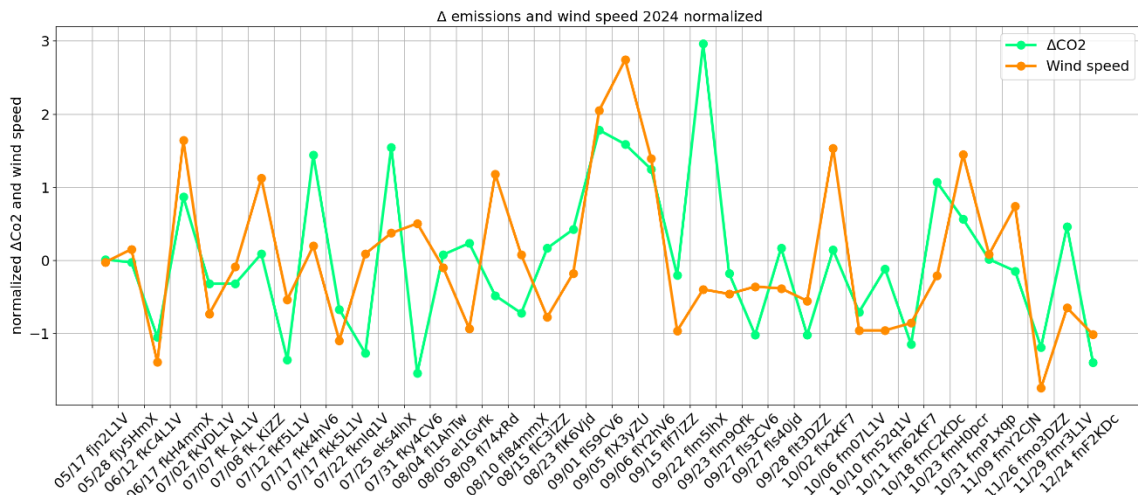


Figure 3.7 Normalized Delta CO2 emissions rate GHGSat-reference and normalized wind speed obtained by subtracting the mean value and dividing by the standard deviation respectively.

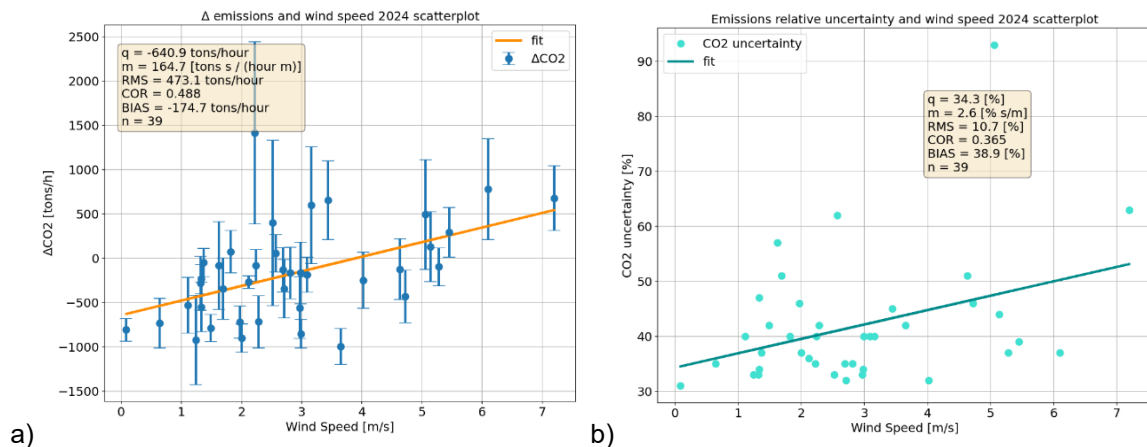


Figure 3.8 a) Delta CO2 emissions rate GHGSat-reference vs wind speed at each site. The errorbars are GHGSat CO2 emissions rate uncertainties. The orange curve indicates the trend, with a correlation coefficient of 0.49. b) GHGSat CO2 emissions rate uncertainties vs wind speed measured at each site.

The impact of wind speed on measurements was evaluated. Figure 3.6 shows the wind measurements at the individual sites at the time of GHGSat acquisition and the difference between GHGSat and reference. The two quantities were also reported in the form of a scatterplot (Figure 3.8a), which shows that for higher wind values, there tends to be a difference between the highest measurements, with the delta changing from negative values for moderate wind speeds to positive differences as the wind increases. The correlation coefficient between delta and wind speed is 49%, always keeping in mind that wind is an extremely challenging variable to measure and can locally change in intensity and direction. Figure 3.8b shows the same analysis performed between GHGSat uncertainties and wind speed.

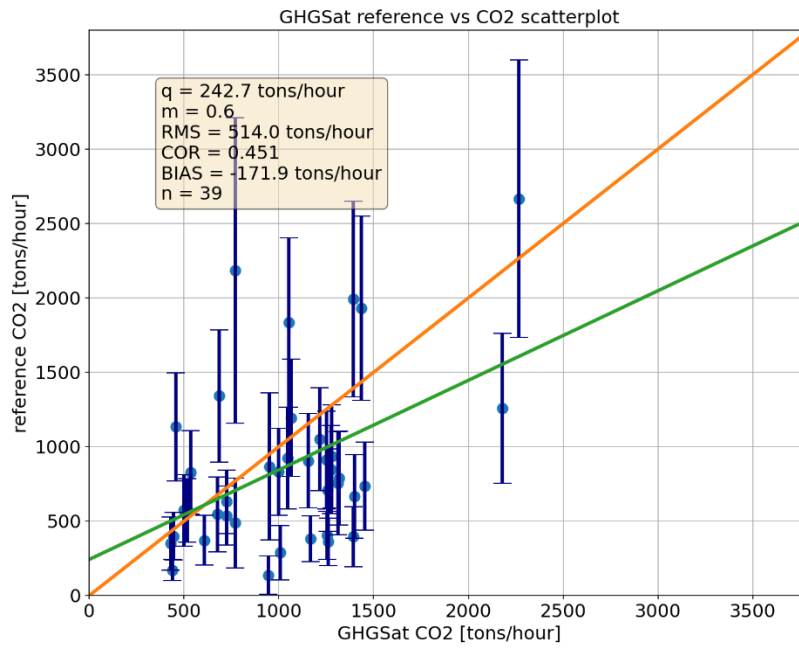


Figure 3.9 GHGSat - reference CO2 emissions rate scatterplot and fit results.

Finally, the scatterplot between the GHGSat and reference measurements is shown in Figure 3.9.

The overall analysis indicates a fair agreement between the GHGSat CO2 emissions rate, and the reference data. The correlation coefficient between the two datasets is 49.8%, with a bias of approximately -172 tons/hour calculated on a dataset of 39 measurements.

4. CONCLUSIONS AND RECOMMENDATIONS

In this technical note are reported methods and results of GHGSat L4 CO₂ emissions rate data analysis and the validation against the reference data. The first GHGSat CO₂ dataset delivered was made of 220 acquisitions over U.S. known power plants, categorized as 33 emissions detected, 6 probably detected, and 181 not detected. Data were validated using the *Clean Air Markets Program Data* from U.S. EPA. A second dataset from GHGSat was requested covering the European region and added to the analysis. 16 observations received with only 1 emission detected that was incorporated in the analysis. The reference CO₂ emission rate data used for the European acquisition was calculated applying a tailored conversion coefficient to the power plant energy generated.

After matching spatially and temporally GHGSat data with reference dataset, only 39 observations were used for the validation analysis (34 Y, 5 M). Results show:

- **A general agreement between GHGSat and reference data, with a correlation coefficient of 45.1% and agreement within 2 σ in many cases.**
- **The tendency of GHGSat value to be lower in 72% cases than the reference**, as expected. This result can be explained taking into account that each power plant is made of different units. The EPA reference dataset reports hourly CO₂ emissions rate for each units that we summed together to evaluate the total emission rate per power plant. This is also valid for the reference data retrieved over Nikola Tesla site in Serbia, for which the hourly power generated was reported individually for each power units, summed together to get the total hourly CO₂ emission rate. GHGSat acquisition is a snapshot in time, and the acquisition lasts less than 1 hour. For this reason, it may have detected a partial plume from the selected site. The analysis of wind speed in relation to GHGSat measurements and the differences with reference dataset might indicate that higher discrepancies are associated with higher wind speed values, but also to other factors such as local albedo and scattering parameters [RD-16], reporting a correlation of 49% between delta and wind speed variables.
- **The detection rate is a parameter that needs further investigation** and improvements. Of the 236 observations received, only 34 identified an emission event, leading to a **detection rate of 14.4%**. 6 observations were flagged as potentially detectable, for which an emission rate was retrieved. If these are added to the confirmed observations, the detection rate rises to **16.9%**. At the current state, 1 out of 8 GHGSat observations detect an occurring emission.

Regarding the **documentation**, we find it **of good quality, with comprehensive information covering all required aspects**. A recommendation we provide is to add missing information about metrology, in order to reach Excellent grade (uncertainty tree diagram, following the GUM approach, etc).

Regarding the **Sensor Calibration & Characterisation**, we graded it as **Good**, but it can potentially become Excellent just adding the reference literature in the documentation, evidencing how calibration methods employed are traceable to SI or standard reference.

The product was tested and internally validated using U.S. sites; therefore, the algorithm is tailored to that specific dataset. The provider currently has limited data coverage over European territory, as they are still refining the algorithm and the detection thresholds for this region. Considering these factors, our assessment is positive, with the recommendation to further optimize the algorithm and detection thresholds to increase the detection rate.

5. ANNEX 1

The validation analysis of GHGSat CO2 data was carried out with two different reference datasets, where the reference data used for European acquisition was evaluated with a different method than the reference used for U.S. sites. This annex details the approach we used to verify the procedure fairness and to validate results of European data, against a small set of U.S. sites.

The CO2 emission rate of selected U.S. sites was retrieved from gross load of EPA dataset applying the same method used for the European reference. The CO2 emission rate from gross load ER_{GL} is calculated as follows:

$$ER_{GL} [CO_2 t/h] = GL [MW] \cdot E_{f(CO_2)} [CO_2 t/MWh]$$

where $GL [MW]$ is the power plant gross load, and $E_{f(CO_2)}$ is the CO2 power plant emission factor calculated from yearly CO2 mass $M_{Y(CO_2)} [short tons]$ and Gross load $GL_Y [MWh]$ provided for each power plant. $\alpha = 0.907185$ is the factor to convert short tons in tons. Reference yearly data used is 2024 since GHGSat dataset used in the analysis were acquired in 2024.

$$E_{f(CO_2)} [CO_2 t/MWh] = \frac{\alpha \cdot M_{Y(CO_2)} [short tons]}{GL_Y [MWh]}$$

Figure 5.1 shows results of CO2 emission rate from gross load ER_{GL} with EPA CO2 emissions rate and GHGSat acquisition. Results from these two methods are comparable, with mean difference of $-29.3 \pm 68.2 [CO_2 t/h]$ reported in Figure 5.2 and in agreement within 2σ with GHGSat data except for one observation.

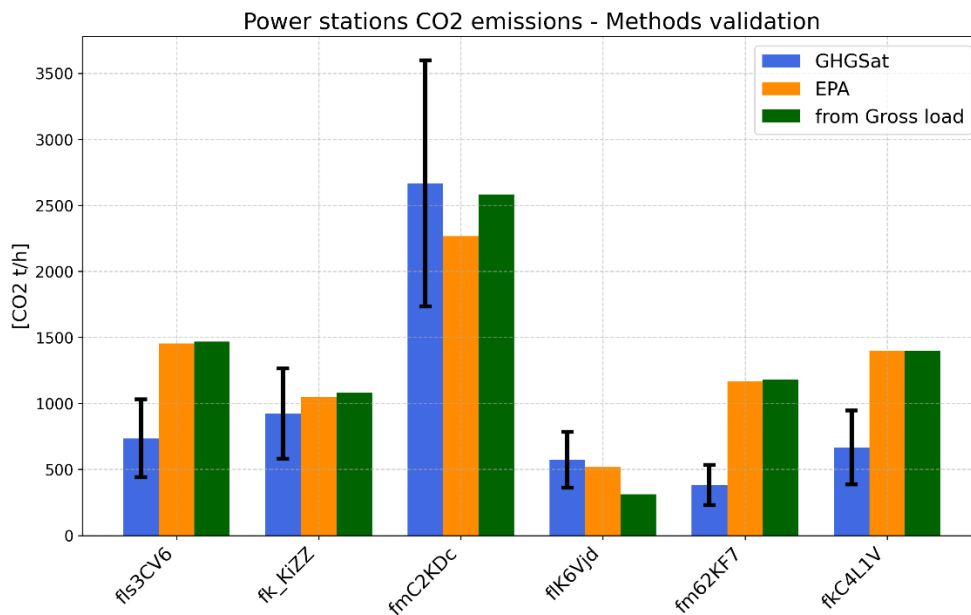


Figure 5.1 CO2 emission rate calculated from Gross load on EPA dataset (green bar) and compared with EPA CO2 emission rate (orange bar) and GHGSat detection (blue bar). The black errorbar is GHGSat uncertainty.

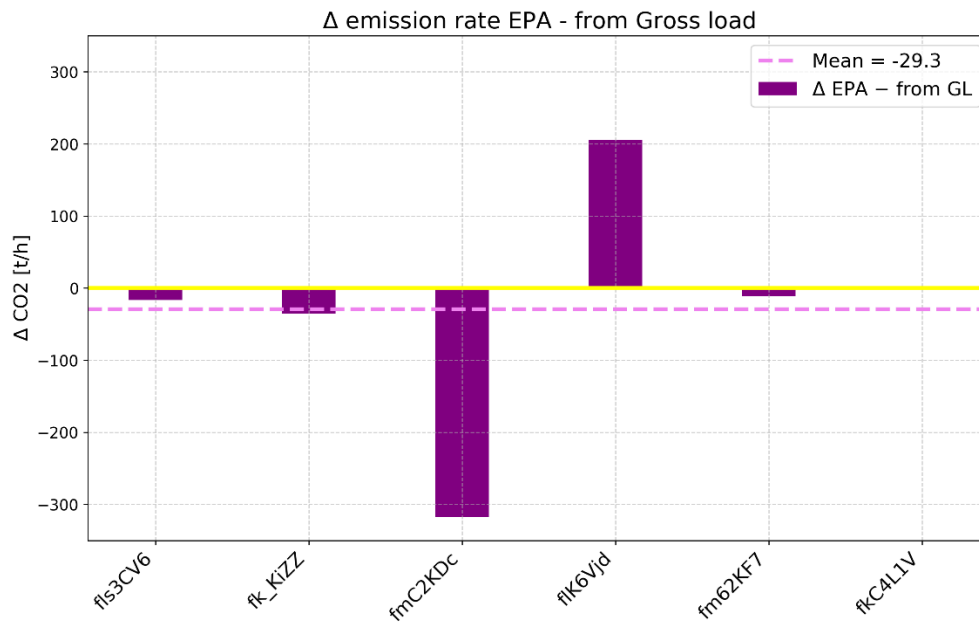


Figure 5.2 CO2 emission rate difference between EPA data and emission rate evaluated from Gross load. The dashed purple line identify the difference mean value equal to $-29.3 \pm 68.2 [CO_2 t/h]$.



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