

# **FRM4GHG 2.0**

## **Fiducial Reference Measurements for Greenhouse Gases**



Intercomparison update between TCCON and low-resolution spectrometers and S5P GHG validation

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|----------------------|---------------------------------------------------------------------------------------------------------------------|
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## **Table of contents**

|          |                                                                                  |          |
|----------|----------------------------------------------------------------------------------|----------|
| <b>1</b> | <b>Document change record .....</b>                                              | <b>3</b> |
| <b>2</b> | <b>Access list.....</b>                                                          | <b>3</b> |
| <b>3</b> | <b>Purpose .....</b>                                                             | <b>3</b> |
| <b>4</b> | <b>Document structure.....</b>                                                   | <b>3</b> |
| <b>5</b> | <b>Results.....</b>                                                              | <b>3</b> |
| <b>6</b> | <b>Validation of the GHG retrieval results against updated FRM4GHG data.....</b> | <b>4</b> |
| <b>7</b> | <b>Applicable documents .....</b>                                                | <b>7</b> |
| <b>8</b> | <b>Reference documents .....</b>                                                 | <b>8</b> |

## 1 DOCUMENT CHANGE RECORD

| Issue | Date       | Item | Comment         |
|-------|------------|------|-----------------|
| V0.0  | 2025-10-24 | -    | Initial version |
|       |            |      |                 |
|       |            |      |                 |
|       |            |      |                 |
|       |            |      |                 |

## 2 ACCESS LIST

This document is a deliverable “D2.6.2: Report on Intercomparison update between TCCON and low-resolution spectrometers and S5P GHG validation – created for the project FRM4GHG 2.0 and will be submitted to ESA. The document can be downloaded from the project webpage <http://frm4ghg.aeronomie.be>.

## 3 PURPOSE

The document describes the strategies for retrieving CH<sub>4</sub> vertical information from ground-based FTS near-infrared spectra, CO partial column information and improved CO column retrievals, and N<sub>2</sub>O tropospheric column information from standard TCCON spectra.

## 4 DOCUMENT STRUCTURE

See Table of Contents

## 5 RESULTS

The GGG code is the standard retrieval code for Total Carbon Column Observing Network (TCCON), which is used to perform profile scaling retrieval of greenhouse gases like carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) amongst others to retrieve their column concentrations in the atmosphere [Wunch et. al., 2011]. During the first phase of the FRM4GHG campaign GGG2014 [Wunch et. al., 2014] version of the code has been used for the analysis of the TCCON data. Meanwhile, the network released an updated version of the GGG code to version GGG2020 [Laughner et. al., 2024]. This updated version has reduced uncertainties in the retrieval results of the target trace gases. For example, the errors for XCO<sub>2</sub> and XCH<sub>4</sub> are below 0.16 % (~ 0.6 ppm) and 0.4 % (~ 7 ppb) for solar zenith angles less than 82 degrees, further details can be found in Laughner et. al., 2024.

The COllaborative Carbon Column Observing Network (COCCON) [Frey et al., 2019] uses PROFFAST to derive the column concentrations of CO<sub>2</sub>, CH<sub>4</sub>, carbon monoxide (CO) and water

vapour (H<sub>2</sub>O). PROFFAST v1.0 has been used for the analysis of the FRM4GHG dataset [Sha et al., 2021]. Since then several improvements have been made to the PROFFAST code and intermediate versions (2.0 – 2.3) were released for short periods of time with current version being v2.4.1. Details on the documentation and code can be found on the COCCON website <https://www.imkasf.kit.edu/english/3225.php> and in Feld et al., 2023. Herkommer et al., 2024 and Sha et al., 2024 also describes the results of side-by-side measurements performed by a traveling standard EM27/SUN, developed under the FRM4GHG2.0 project, at several TCCON stations and evaluated the consistency of the measurements on a global scale. The low-resolution spectrometers EM27/SUN, Vertex70/INVEION and IRCube uses PROFFAST to perform the retrieval of target gases.

The LHR data is processed by MORSE-GB retrieval code. The LHR instrument has undergone several instrumental upgrades changes since the FRM4GHG phase 1 campaign. These changes together with new level 1 and 2 processors have led to significant improvements in the quality of the LHR data as described in the report “D1.2 LHR instrumental improvements” by Berrington et al., 2025. The systematic bias has been reduced by one order of magnitude from -20 ppm to -2 ppm for XCO<sub>2</sub> and the artificial diurnal amplitude has been reduced from  $>\pm 30$  ppm to  $\pm 9$  mm. This is quite a major improvement since the first version of the data. However, the errors are still quite large and need to be further worked on. Moreover, the XCH<sub>4</sub> results do not show much improvement and need further investigation as well.

The AirCore retrieval process consists of four steps: (1) PREPROCESS – calculates the sampling altitudes of the AirCore using ideal gas law and meteorological data, (2) QA/QC – curates raw files and applies corrections and calibration, (3) RETRIEVAL – matches the sampling and analysis data to derive vertical profiles of trace gases as well as removes contaminated measurements at the top and the bottom of the profiles, (4) SENSITIVITY TESTS – optimizes the AirCore retrievals by adjusting the starting point of the time series of concentration analysis. There are several updates done to the AirCore retrieval procedure, e.g., focusing on enhancing altitude attribution accuracy. The results of the updates and detailed discussions on the improvements are presented in the deliverable “D2.5.1 AirCore retrieval procedure updates”.

Towards the end of the FRM4GHG2.0 project the intercomparison results using the complete dataset of the project with the latest updates will be presented and perhaps a scientific publication will be pursued when the analysis results of the datasets from all instruments are finalized.

## 6 VALIDATION OF THE GHG RETRIEVAL RESULTS AGAINST UPDATED FRM4GHG DATA

The validation of S5P XCH<sub>4</sub> product using the updated COCCON data (v2.4) for the Sodankylä site are shown in this section. The S5P data of version 2.4.0 and above have been used in this study. The following coincidence criteria have been used for comparison against the COCCON data: S5P observations withing a radius of 100 km for CH<sub>4</sub> such as to ensure that a sufficient number of coincidence measurements and COCCON observations within  $\pm 1$ h of the S5P overpass were taken into account. The spatial and temporal colocation criteria chosen are similar to the validation of operational S5P CH<sub>4</sub> product using TCCON and COCCON networks [Sha et al., 2021, 2025]. An

average of all coincident S5P pixels was performed for each of the COCCON measurements co-located with the S5P measurements. Co-located pairs were created between the COCCON and averaged S5P only if a minimum of five pixels were found when applying the coincidence criteria. The S5P columns were also corrected to take the altitude variability for the collocated pixels into account.

The time series of the S5P bias-corrected XCH<sub>4</sub> product and COCCON data are shown in Figure 1. The ground-based COCCON data are represented in grey. The co-located COCCON and S5P data with a priori alignment are represented in black and green respectively.

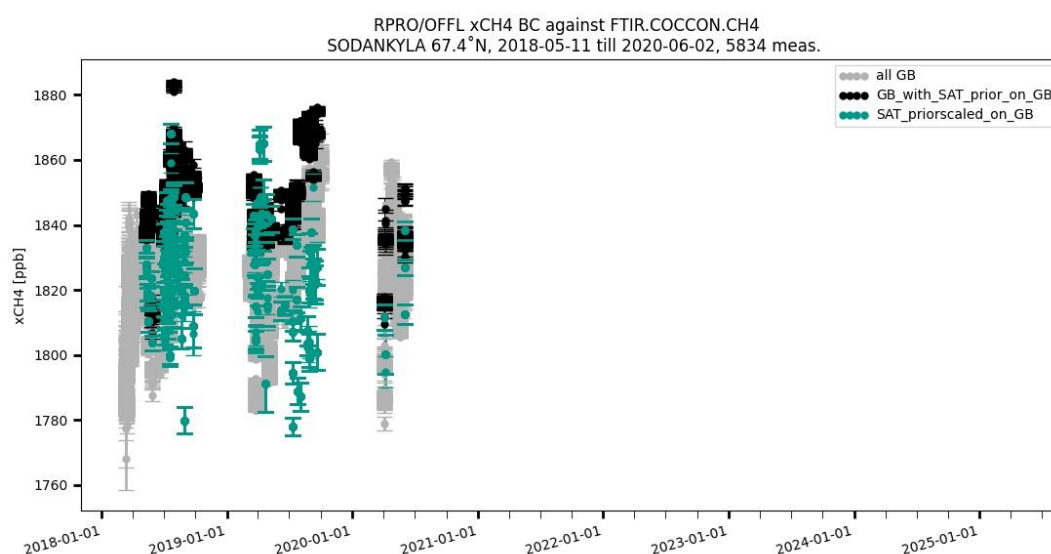


Figure 1: Timeseries of XCH<sub>4</sub> for all COCCON data (grey), S5P bias-corrected data co-located with COCCON data (green) and co-located COCCON data with a priori alignment (black) for Sodankylä site.

The time series of the relative bias plot is shown in Figure 2. The spring period shows high positive bias and summer period shows high negative bias, as seen clearly in 2019 data. Figure 3 shows the same plot as in Figure 2 but for COCCON v1.0 data.

Figure 4 shows the plot of the relative difference as a function of the solar zenith angles and the data is sorted in months for easy identification of the seasonal bias distribution. Figure 5 shows the same plot as in Figure 4 but for COCCON v1.0 data.

The systematic and random uncertainties of the S5P XCH<sub>4</sub> product at Sodankylä site against COCCON v2.4 is  $-1.16 \% \pm 1.11 \%$ . This is within the requirements of systematic uncertainty of 1.5 %, however, slightly over the 1 % range for the random uncertainty. These values are much improved against the previous validation results using COCCON v1.0 data of systematic and random uncertainties values of  $-2.36 \% \pm 1.03 \%$ .

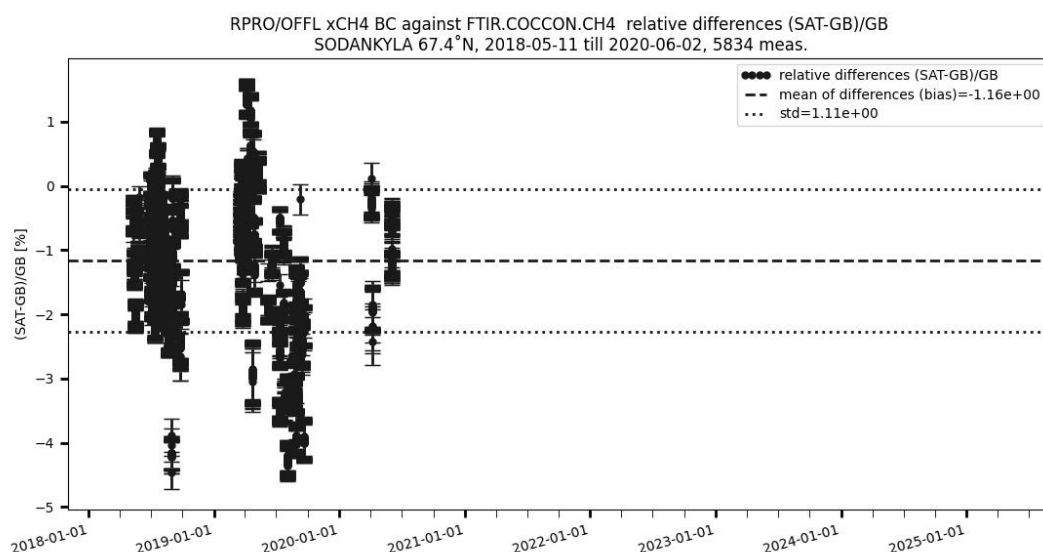


Figure 2: Relative difference ((satellite – ground-based)/ground-based) of XCH<sub>4</sub> time series for all co-located S5P bias-corrected data and COCCON data with a priori alignment as the reference data for Sodankylä site.

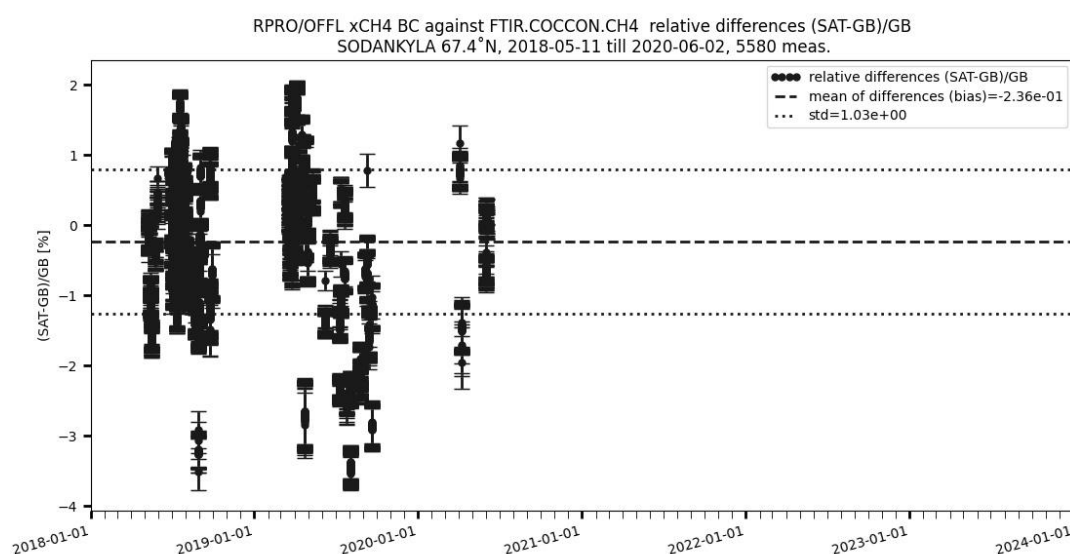


Figure 3: Same as Figure 2 but with COCCON v1.0 data.

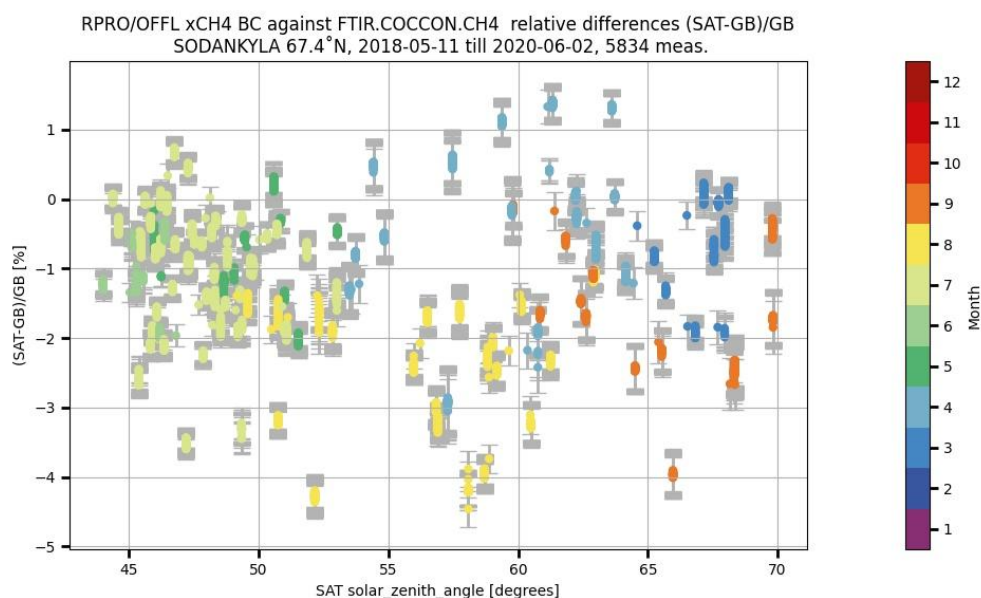


Figure 4: Relative biases between co-located S5P XCH<sub>4</sub> and TCCON XCH<sub>4</sub> with a priori aligned are plotted as a function of the S5P measurement solar zenith angles retrieved at Sodankylä site for the period shown in Figure 1. The colours represent the different months from January (1) until December (12) of a year.

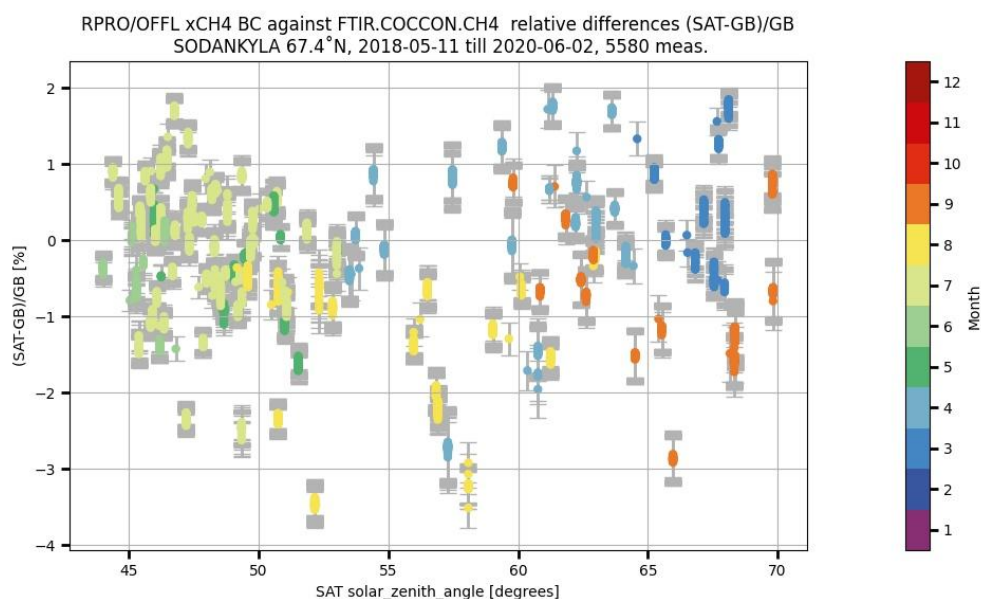


Figure 5: Same as in Figure 4 but with COCCON v1.0 data.

## 7 APPLICABLE DOCUMENTS

Statement of Work: Fiducial Reference Measurements for Ground-Based IR Greenhouse Gas Observations (FRM4GHG 2.0)

Prepared by: EOP-GMQ, Reference: ESA-EOPG-EOPGMQ-SOW-21

## 8 REFERENCE DOCUMENTS

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