FRM4GHG

What Are Fiducial Reference Measurements for Greenhouse Gases (FRM4GHG) and How Reliable Are They For The Satellite Validation

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What are Fiducial Reference Measurements

- The **Quality Assurance Framework for Earth Observation (QA4EO)** provides a set of principles, guidance, and specific tools to encourage provision of internationally consistent quality indicators on the delivered data.

- **Fiducial Reference Measurements (FRM)** are a suite of independent, fully characterized, and traceable (to a community agreed reference, ideally SI) measurement of a satellite relevant measurand, tailored specifically to address the calibration/validation needs of a class of satellite borne sensor and that follow the guidelines outlined by the GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO) – CEOS-FRM definition, Goryl et. al., 2023

- **Satellite based Earth observation data** requires proper **calibration** (CAL) and **validation** (VAL) for ensuring that it provides reliable information on the measured variables

- There is a critical need to provide a coordinated and comprehensive assessment on the **quality**, **bias** and **uncertainty** of the measured variables by the satellites

- The **FRM Cal/Val data set** allows to achieve the above goal. Furthermore, there is also the benefit of **improved harmonization and interoperability between sensors**.

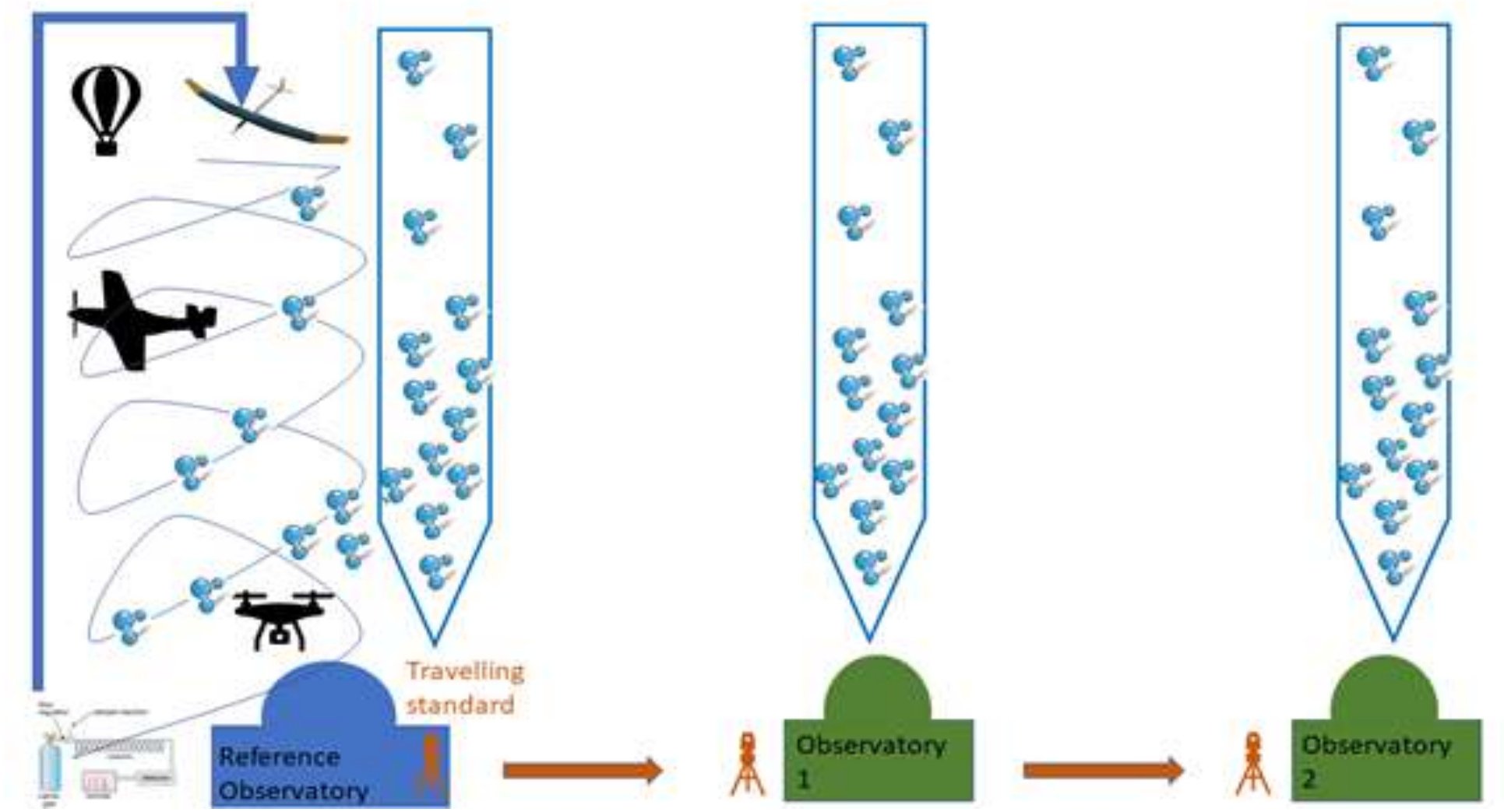
ESA's FRM4GHG project

https://frm4ghg.aeronomie.be/

- European Space Agency (ESA) initiated the Fiducial Reference Measurements for GreenHouse Gases (FRM4GHG) in 2016 with the aim to create **high quality reference measurements** of greenhouse gases (GHGs) for **supporting satellite validation**

- Aim: Test **several portable low-cost instruments against** reference Total Carbon Column Observing Network (**TCCON**; for gases retrieved in the near-infrared spectral range), Infrared Working Group of the Network for the Detection of Atmospheric Composition Change (**NDACC-IRWG**; for gases retrieved in the mid-infrared spectral range) and AirCore in-situ observations

- The **multi-year campaigns** (2017 – 2019 – phase I; 2020 – 2026 – phase II, 2026 – in planning) proved to be greatly beneficial for several of the tested instruments which **improved significantly** during the campaign, for some **other instruments improvements are still ongoing** for bringing them to the **level of FRM**

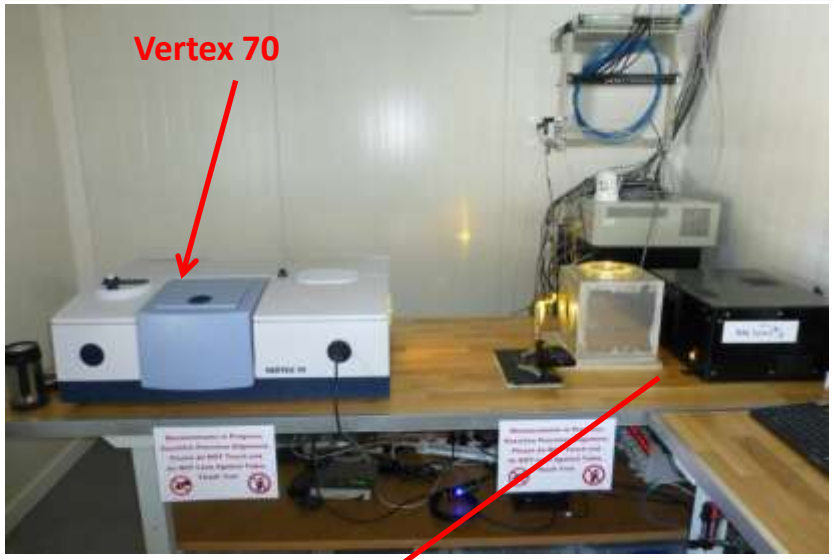


Intercomparison Intercomparison Intercomparison …

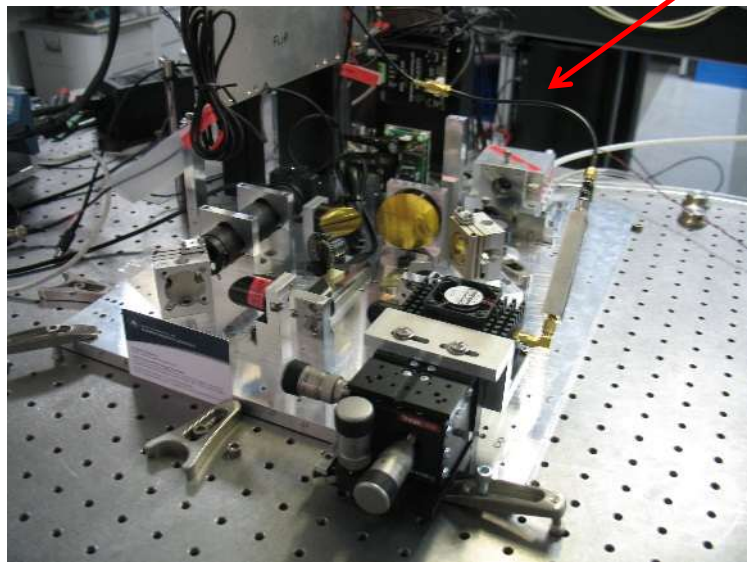
FRM4GHG campaign – characterizing low-resolution FTIRs

Fiducial Reference Measurements For Greenhouse Gases

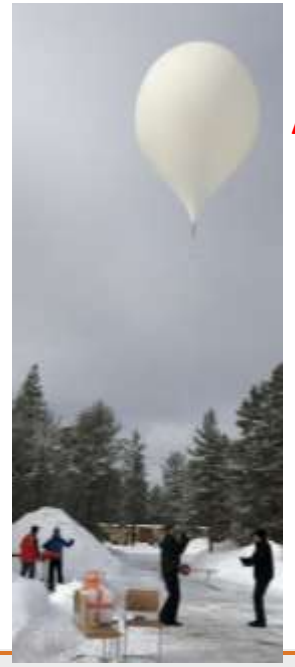
EM27/SUN with suntracker



Vertex70 spectrometer has been upgraded and is called **INVENIO**



LHR optical breadboard



AirCore launch

Instrumentation used during the ESA funded FRM4GHG project frm4ghg.aeronomie.be

Details in Sha et al., 2020, https://doi.org/10.5194/amt-13-4791-2020

EM27/SUN – COCCON providing FRM quality data

- https://www.imk-asf.kit.edu/english/COCCON.php

- Main species: **XCO_2, XCH_4, XCO, XH_2O** at **0.5 cm^{-1}**; data processing following COCCON recommendations
- Excellent agreement with TCCON – results shown in previous meetings
- Manual operation at majority of sites, setting it up in the morning and bringing it back to the shelter at the end of the day, data acquisition is automatic.

- Automatic operation, remote control, protection against rain/snow, rain sensor, heating & cooling systems – developed or under development by several groups

- Selected as **travelling standard** (FRM4GHG-2) for visiting TCCON stations (Europe, America, Asia-Oceania)

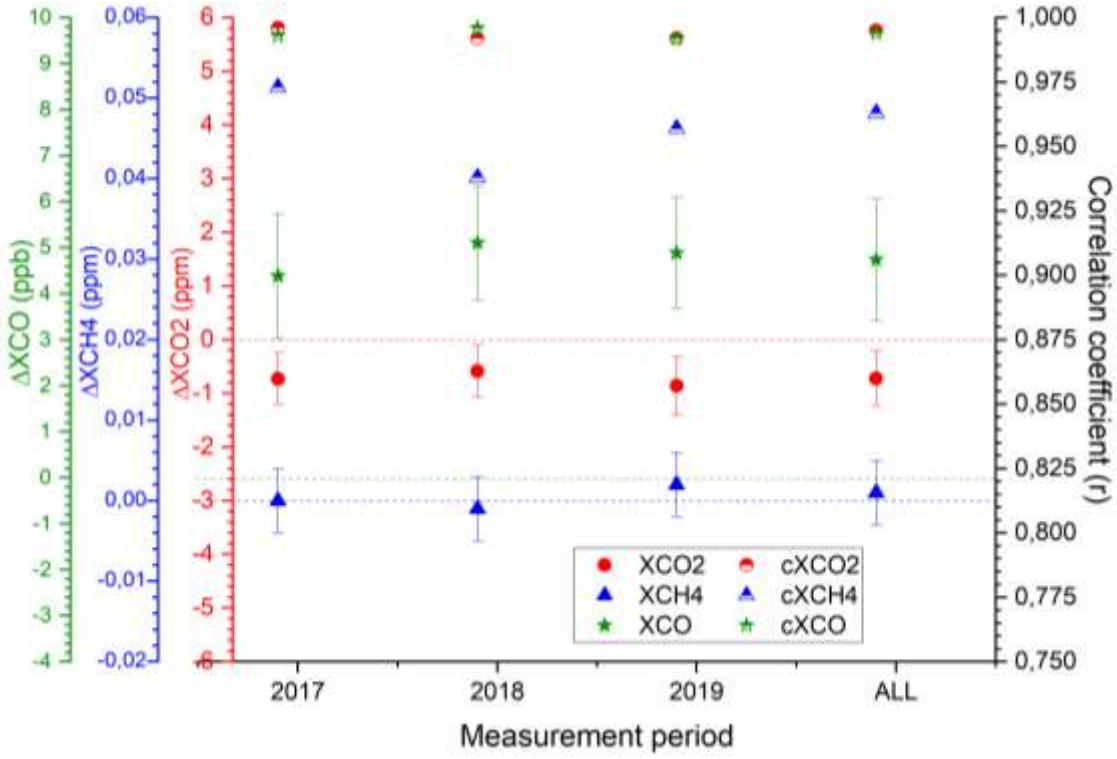
Long-term stability of EM27/SUN @ Sodankylä

Species	Duration	XCO_2 / ppm	XCH_4 / ppm	XCO / ppb
Bias (mean standard ± deviation) and correlation coefficient (r)				
EM27/SUN vs TCCON	2017	-0.727±0.474 (0.996)	0.000±0.004 (0.973)	4.384±1.361 (0.993)
EM27/SUN vs TCCON	2018	-0.587±0.485 (0.992)	-0.001±0.004 (0.938)	5.101±1.234 (0.996)
EM27/SUN vs TCCON	2019	-0.859±0.548 (0.992)	0.002±0.004 (0.957)	4.886±1.210 (0.992)
EM27/SUN vs TCCON	2017 – 2019	-0.722±0.510 (0.995)	0.001±0.004 (0.963)	4.738±1.321 (0.994)

TCCON precision requirements (GGG2014): XCO_2: < 0.25% ~ 1 ppm
XCH_4: 0.5% ~ 0.009 ppm; XCO: < 4% ~ < 4 ppb

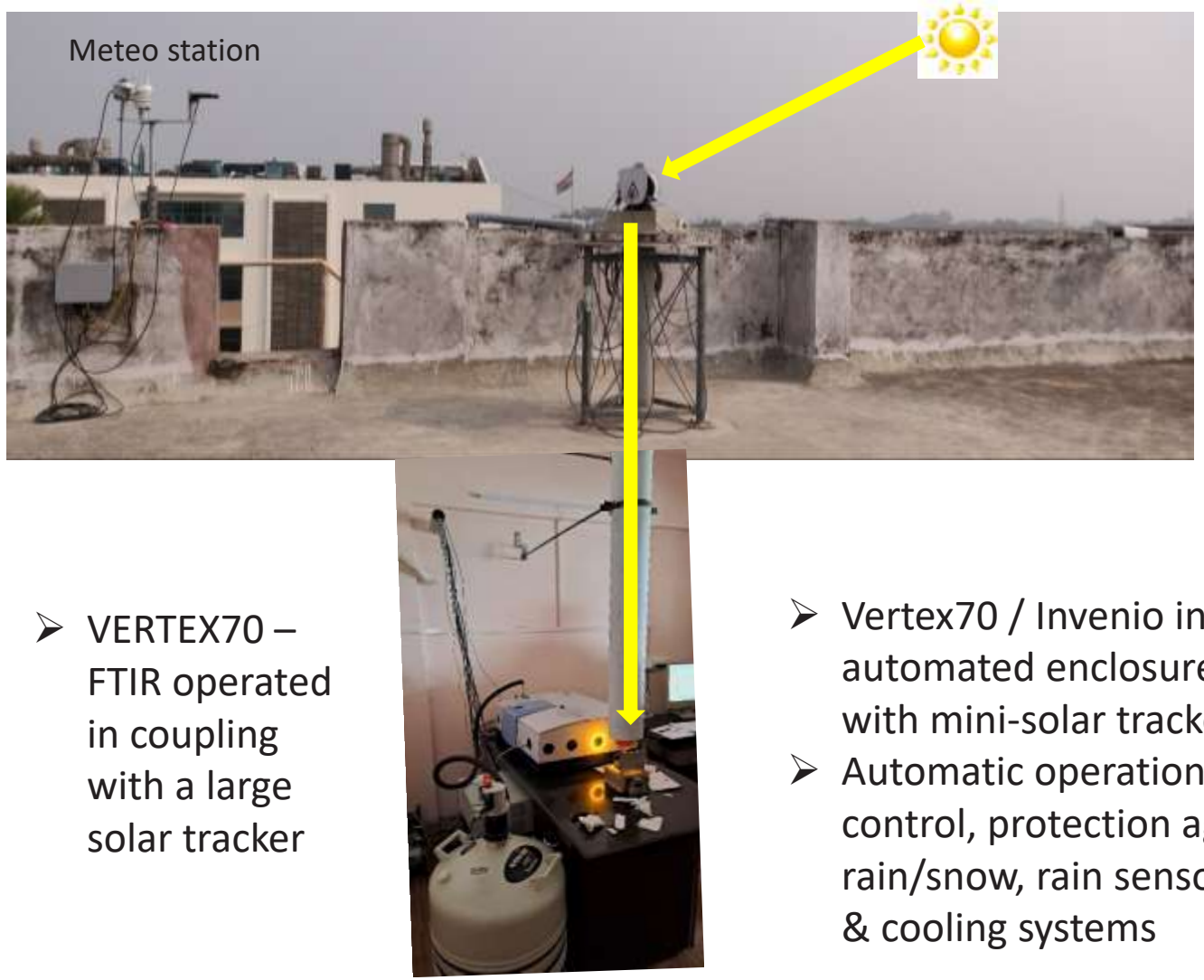
The bias values are very close to each other and the small diffeence seen from year-to-year is due to the data representative issue.
Year-to-year variability (**Sha et al. 2024** – 3 y @ Sodankylä)
https://doi.org/10.3390/rs16183525
XCO_2 – 0.137 ppm (0.03%) with 1σ (0.5 ppm)
XCH_4 – 0.001 ppm (0.05%) with 1σ (0.004 ppm)
XCO – 0.363 ppb (0.4%) with 1σ (1.32 ppb)

Year-to-year variability (**Frey et al. 2019** – 3.5 y @ Karlsruhe)
https://doi.org/10.5194/amt-12-1513-2019
XCO_2 – 0.02 ppm (0.005%) with 1σ (0.6 ppm)
XCH_4 – 0.001 ppm (0.05%) with 1σ (0.004 ppm)
The constant bias will be scaled following the strategy developed in COCCON



Vertex70 / Invenio – COCCON providing FRM quality data

- Solar beam path from the roof to the FTIR lab in Kolkata, India



- VERTEX70 – FTIR operated in coupling with a large solar tracker

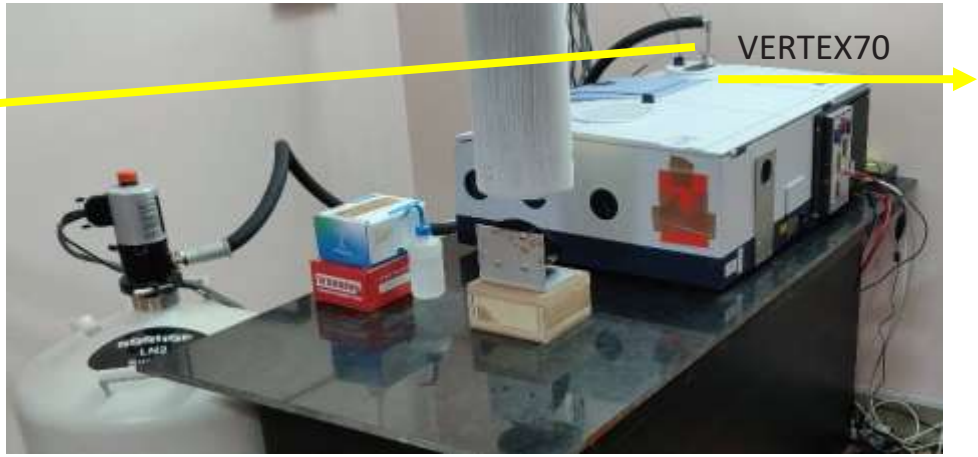
- Vertex70 / Invenio in an automated enclosure system with mini-solar tracker
- Automatic operation, remote control, protection against rain/snow, rain sensor, heating & cooling systems

Details in Sha et al., 2024
https://doi.org/10.3390/rs16183525

Vertex70 / Invenio – COCCON providing FRM quality data

- Vertex70/Invenio has the possibility to host two detectors with the possibility to fill liquid nitrogen

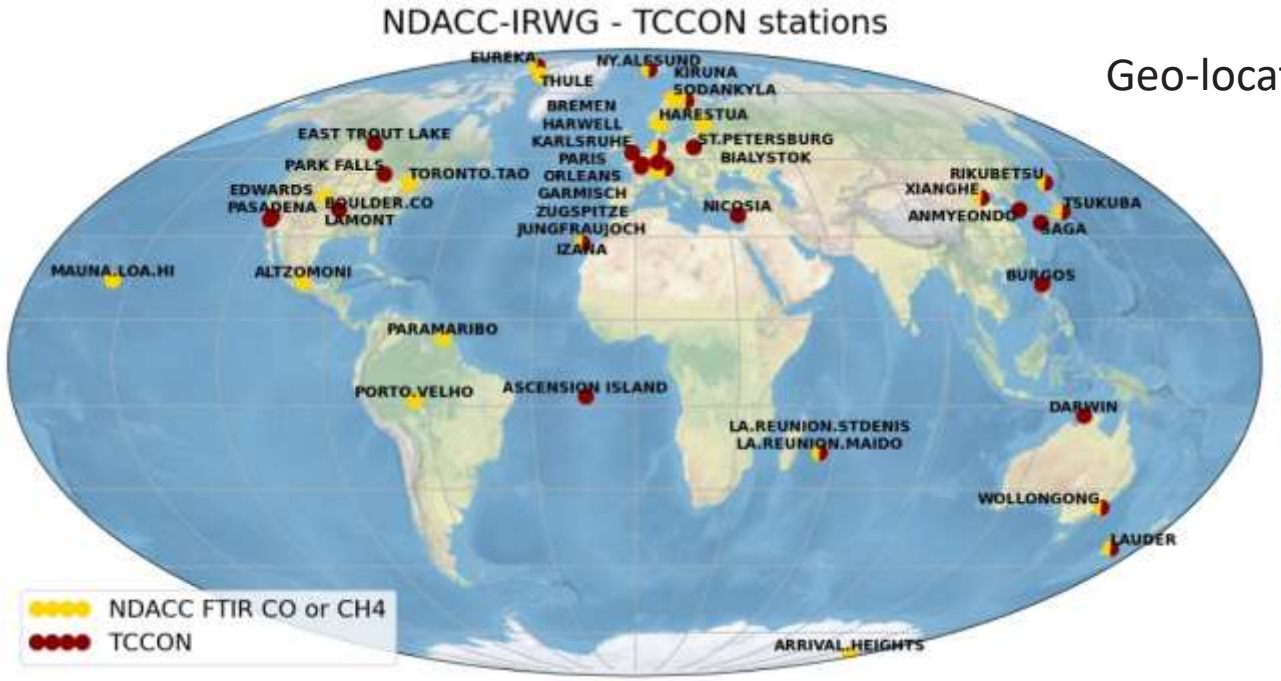
- Liquid nitrogen cooled InSb detector
- **OCS (total), HCHO (total), N_2O (tropospheric, total), CH_4 (total)** at 0.2 cm^{-1} (already published, retrieval other gases are under testing)
- Next to try – C_2H6, NH_3, …
- Measurements frequency = 52 sec



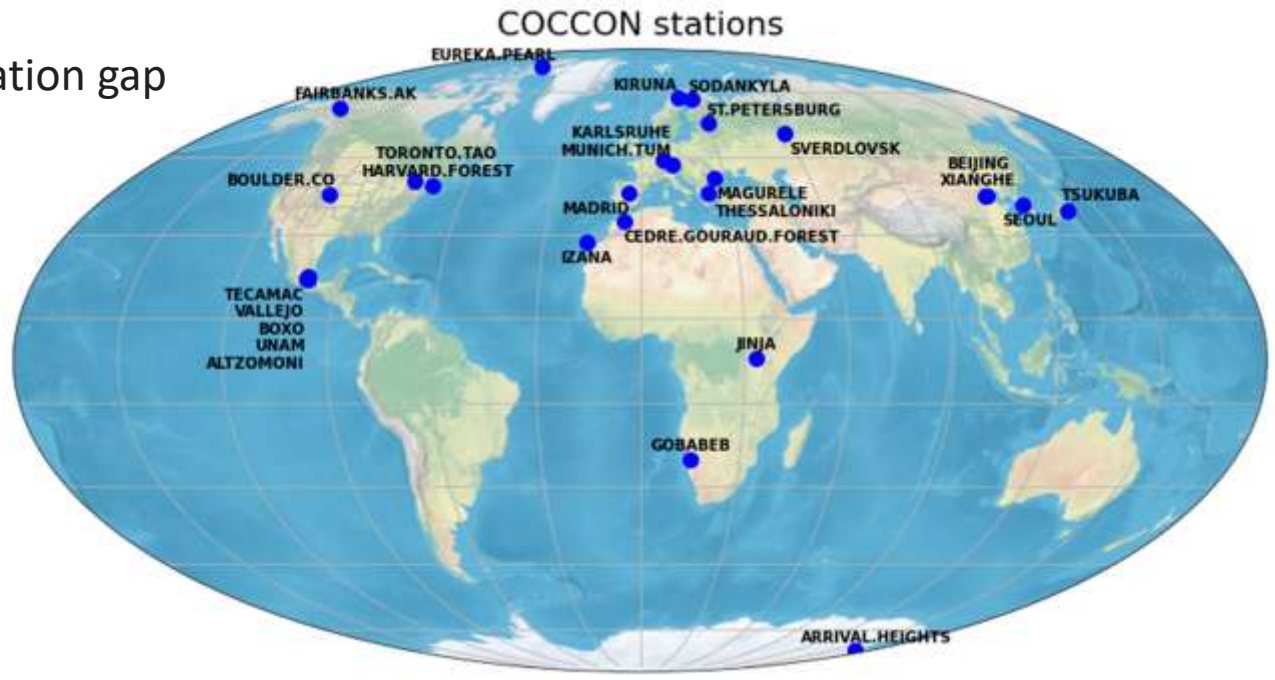
- Room temperature operated InGaAs detector
- Providing – **XCO_2, XCH_4, XCO, XH_2O** at 0.2 cm^{-1}
- Measurements frequency = 52 sec

- Perform side-by-side measurements at COCCON central facility at KIT, Karlsruhe for NIR data calibration
- Perform side-by-side measurements at NDACC-IRWG sites to study the variability of the MIR data calibration
- Traceability of the measurements and output

Coverage of open access FTIR data used for satellite validation



Geo-location gap



NDACC-IRWG & TCCON stations used in S5P quarterly validation report submitted to ESA – Sha and Langerock et al.,

Sha, M.K.; Langerock, B.; et al., - Validation of methane and carbon monoxide from Sentinel-5 Precursor using TCCON and NDACC-IRWG stations, Atmos. Meas. Tech., 14, 6249–6304, https://doi.org/10.5194/amt-14-6249-2021

COCCON stations used in validation of S5P, OCO-2 and GOSAT

Sha, M.K.; Das, S.; Frey, M.M.; Dubravica, D.; et al. Fiducial Reference Measurements for Greenhouse Gases (FRM4GHG): Validation of Satellite (Sentinel-5 Precursor, OCO-2, and GOSAT) Missions Using the COllaborative Carbon Column Observing Network (COCCON). Remote Sens. 2025, 17, 734. https://doi.org/10.3390/rs17050734

COCCON as FRM data provider for satellite validation

- COCCON data which are public is hosted at **EVDC (ESA Validation Data Center)**; a **DOI** is minted per site
- **Central facility** for data handling and processing facility hosted at KIT assist site PIs in data processing and quality checks – funded by ESA
- **Validation of multiple GHG satellite** performed using COCCON data; S5P (BIRA-IASB), OCO-2 (JPL) and GOSAT (NIES)
  - Sha, M.K.; Das, S.; Frey, M.M.; Dubravica, D.; et al. Fiducial Reference Measurements for Greenhouse Gases (FRM4GHG): Validation of Satellite (Sentinel-5 Precursor, OCO-2, and GOSAT) Missions Using the COllaborative Carbon Column Observing Network (COCCON). Remote Sens. 2025, 17, 734. https://doi.org/10.3390/rs17050734
- Possible to **expand** the usage of COCCON data to other GHG satellites (**traditional and new space missions**)
- **Maturity Matrix** completed with the current status of COCCON for the main target gases – Sha et al., 2024
- Profile measurements at the COCCON sites would be needed to determine the **independent scaling factor**
- Warning: The **number of EM27/SUNs are growing fast** ➔ key to follow **the standardized procedures** established under COCCON
  - check new spectrometer before delivery, side-by-side solar measurements collocated at KIT TCCON site and reference EM27/SUN, alignment check and ILS meas., determination of Xgas scaling factors to establish the indirect traceability to WMO via TCCON
    - If you are a data user using data from private data providers, then please check if these conditions are strictly followed

Thank you for your attention!

Questions / comments to mahesh.sha@aeronomie.be

FRM4GHG 1.0

- Characterization of various portable low-resolution spectrometers for GHG measurements
- Inter-comparison w.r.t. reference TCCON data and collocated AirCore observations
- Suitability for campaign deployment or for long-term measurements from any site
- Results were excellent, some of the investigated portable low-resolution spectrometers offer the capability to further complement the TCCON while others need further improvements
- Expand the global coverage of ground-based FRM of the target GHGs

FRM4GHG 2.0

- Further improve the low-resolution instruments with respect to hardware and software (alignment, portability, precision of solar tracking, noise characterization, …) and of the AirCore observations
- Improve the associated data analysis algorithms, optimization of retrievals of additional species (OCS, HCHO, N_2O, CH_4), develop additional AirCore observations (N_2O, OCS)
- Further establish the links with TCCON and complementary COllaborative Carbon Column Observing Network (COCCON)