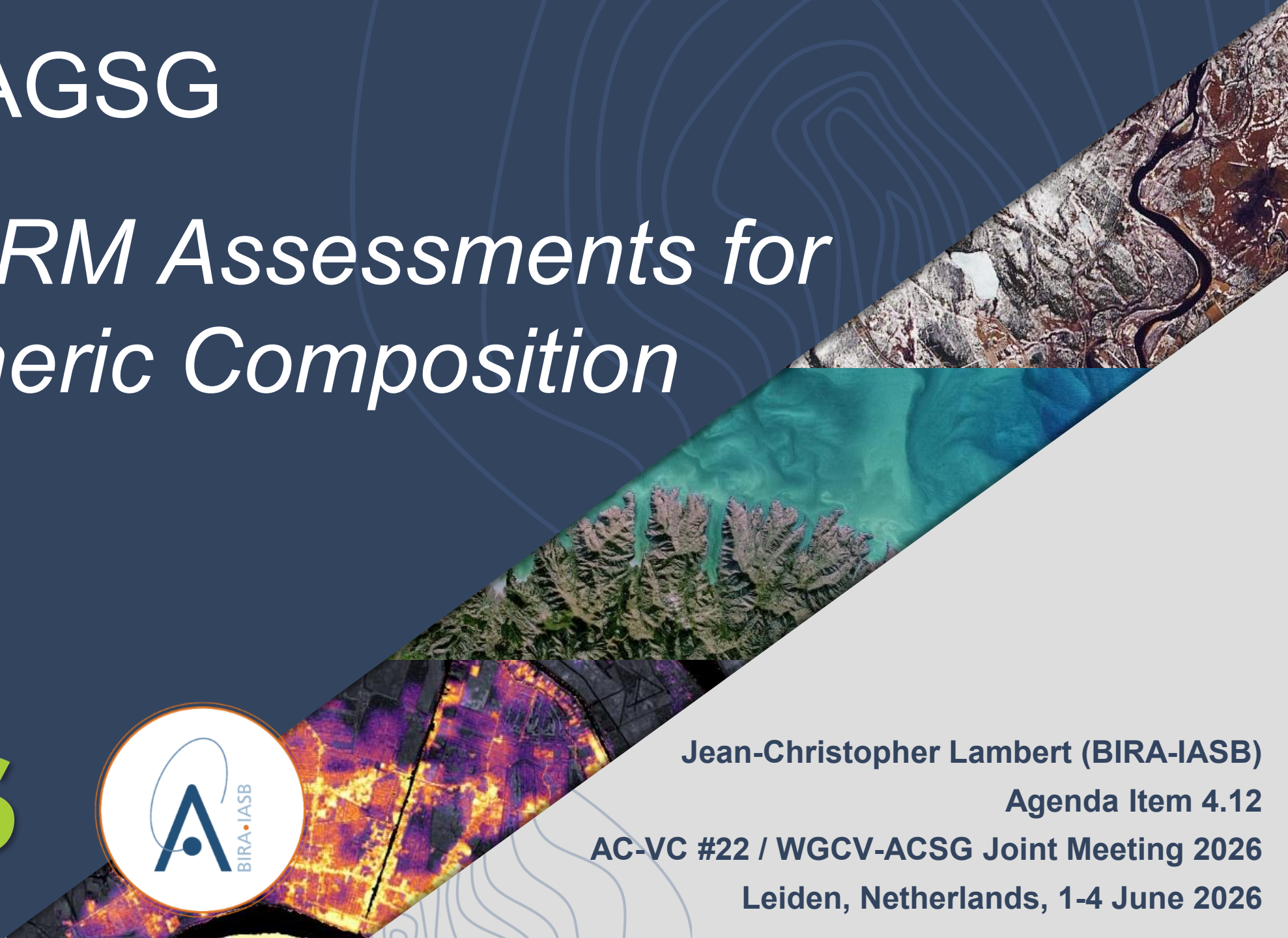
WGCV-AGSG

CEOS-FRM Assessments for Atmospheric Composition



CEOS Committee on Earth Observation Satellites

BIRA-IASB

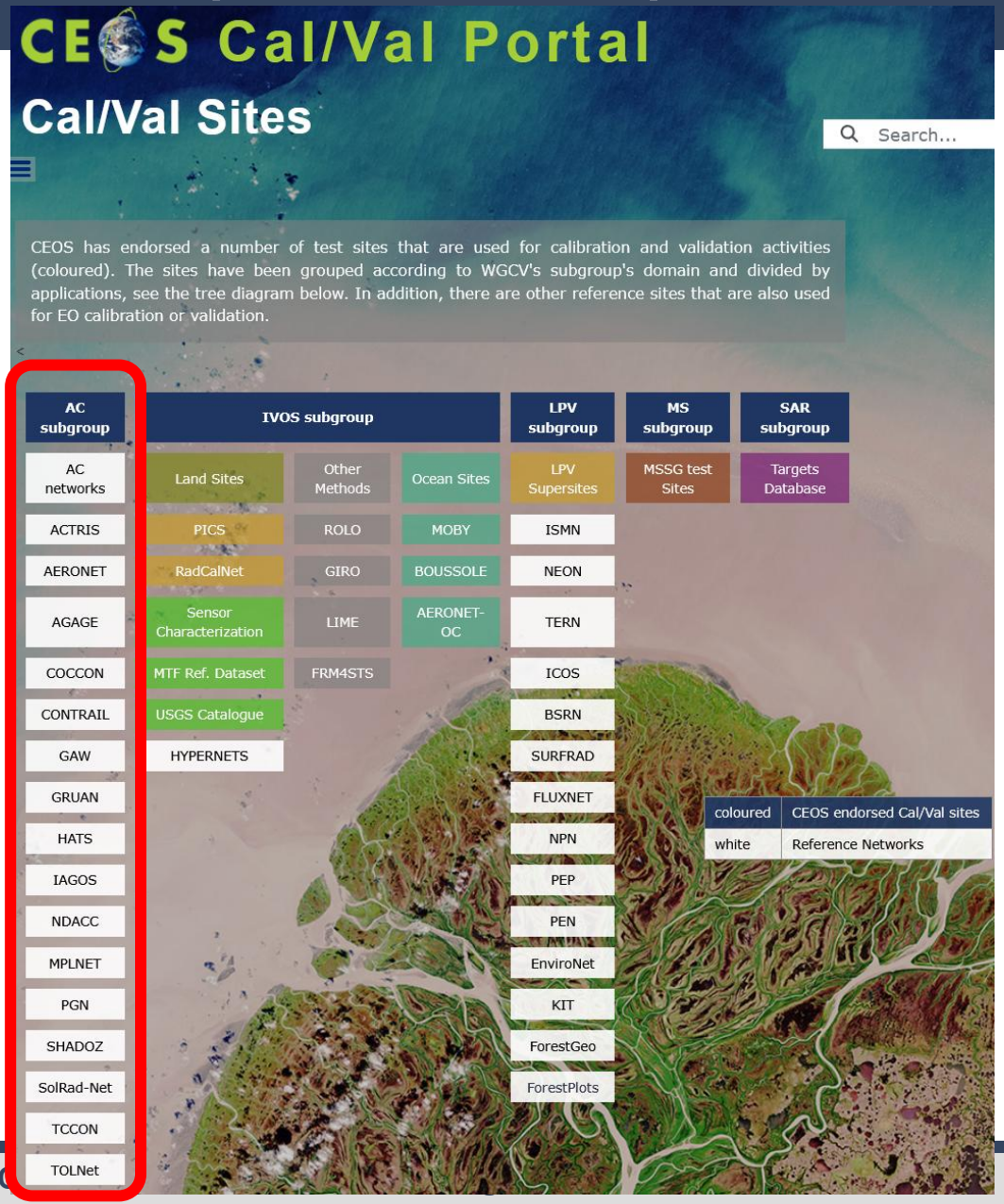
Jean-Christopher Lambert (BIRA-IASB)

Agenda Item 4.12

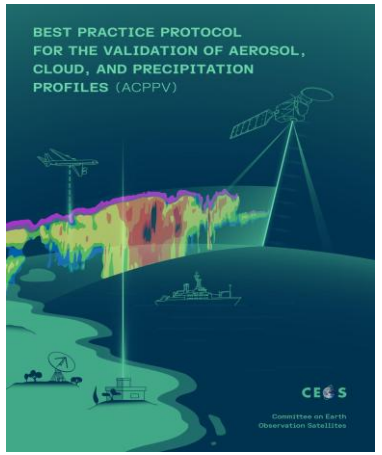
AC-VC #22 / WGCV-ACSG Joint Meeting 2026

Leiden, Netherlands, 1-4 June 2026

Atmospheric Composition Data used as a FRM



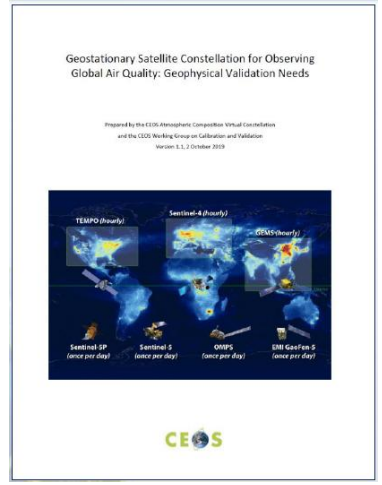
Aerosol, Cloud & Precipitation



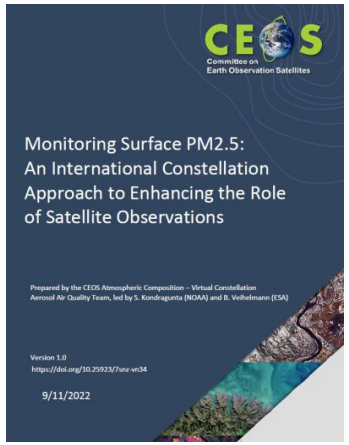
+

CO_2 & CH_4

Air Quality



PM 2.5



Atmosphere Pilots for CEOS-FRM Maturity Assessment v1: 1st Round of Exercise (2024)

- **FRM4DOAS** (Ground-Based DOAS Air-Quality Observations) – Michel Van Roozendael (BIRA-IASB)
- **FRM4GHG – COCCON** (EM27/SUN) XCO_2, XCH_4, and XCO data – Mahesh Kumar Sha (BIRA-IASB)
- **PGN** (Pandonia Global Network) – Stefano Casadio (Serco)
- **ACTRIS CREGARS** (Centre for Reactive Trace Gas Remote Sensing) – Martine De Mazière (BIRA-IASB)
- **Brewer Spectrometer - NO2 Vertical Column Densities (VCDs) Measurements** – Henri Diémoz (ARPA Valle d'Aosta) – BAQUNIN project

- **RadCalNet** (Radiometric Calibration Network) – Marc Bouvet (ESA/ESTEC)
- **ICOS** (Integrated Carbon Observation System – Ecosystem Component) - Fabrizio Niro (Serco)
- **BAQUNIN** (PREDE-POM LUNAR) – Stefano Casadio (Serco)
- **CSIRO DION** – Janet Anstee and Matt Garthwaite (CSIRO)

Atmosphere Pilots for CEOS-FRM Maturity Assessment v1: 1st Round of Exercise (2024)

FRM4DOAS and FRM4GHG CEOS-FRM v1 self-assessments published

Special Issue

Copernicus Sentinels Missions Calibration, Validation, FRM and Innovation Approaches in Satellite-Data Quality Assessment

Remote Sensing

remote sensing MDPI

Article

Fiducial Reference Measurements for Air Quality Monitoring Using Ground-Based MAX-DOAS Instruments (FRM4DOAS)

Michel Van Roozendael [1,*], Francois Hendrick [1], Martina M. Friedrich [1], Caroline Fayt [1], Alkis Bais [2], Steffen Beirle [3], Tim Bösch [4], Monica Navarro Comas [5], Udo Friess [6], Dimitris Karagkiozidis [2], Karin Kreher [7], Alexis Merlaud [1], Gaia Pinardi [1], Ankie Piters [8], Cristina Prados-Roman [5], Olga Puentedura [5], Lucas Reischmann [3], Andreas Richter [4], Jan-Lukas Tirpitz [6,†], Thomas Wagner [3], Margarita Yela [5] and Steffen Ziegler [3]

Remote Sens. **2024**, *16*(23), 4523; https://doi.org/10.3390/rs16234523

CEOS FRM

Grade
Not assessed
Not assessable
Basic
Good
Excellent
Ideal
Non-public

Table 11. Self-established Maturity Matrix for the FRM4DOAS service.

Self-Assessment					
Nature of FRM	FRM Instrumentation	Operations/Sampling	Data	Metrology	Verification
Descriptor	Operator expertise	Automation level	Data completeness	Uncertainty characterisation	Guidelines adherence
Range of instruments	Instrument documentation	Measurand sampling/ representativeness	Availability and usability	Traceability documentation	Utilisation/ feedback
Complementary observations	Evidence of traceable calibration	ATBD on processing/software	Data format	Comparison/ calibration of FRM	Metrology verification
Location/availability of FRM assessment	QA/maintenance	Guidance on transformation to satellite sensor	Ancillary data	Adequacy for class of instrument/measurand	Independent verification

remote sensing MDPI

Article

Fiducial Reference Measurement for Greenhouse Gases (FRM4GHG)

Mahesh Kumar Sha [1,*], Martine De Mazière [1], Justus Notholt [2], Thomas Blumenstock [3], Pieter Bogaert [1], Pepijn Cardoen [1], Huilin Chen [4], Filip Desmet [1], Omaira García [5], David W. T. Griffith [6], Frank Hase [3], Pauli Heikkinen [7], Benedikt Herkommer [3], Christian Hermans [1], Nicholas Jones [6], Rigel Kivi [7], Nicolas Kumps [1], Bavo Langerock [1], Neil A. Macleod [8], Jamal Makkor [2], Winfried Markert [2], Christof Petri [2], Qiansi Tu [3,9], Corinne Vigouroux [1], Damien Weidmann [8] and Minqiang Zhou [1,10]

Remote Sens. **2024**, *16*(18), 3525; https://doi.org/10.3390/rs16183525

Table 4. Maturity Matrix for COCCON XCO_2, XCH_4, and XCO data. The meaning of the colors is defined in Table 5 and follows the CEOS-FRM standards. The header for the self-assessment section and the grade (Table 5) are provided in blue color following the CEOS-FRM standards.

Self-Assessment				
Nature of FRM	FRM Instrumentation	Operations/Sampling	Data	Metrology
Descriptor	Instrument documentation	Automation level	Data completeness	Uncertainty characterization
Location/availability of FRM	Evidence of traceable calibration	Measurand sampling/ representativeness	Availability and usability	Traceability Documentation
Range of instruments	Maintenance plan	ATBD on processing: algorithm/ software	Data Format	Comparison/ calibration of FRM
Complementary observations	Operator expertise	Guidelines on transformation to satellite pixel	Ancillary Data	Adequacy for intended class of instrument/ measurand

Atmosphere Pilots for CEOS-FRM Maturity Assessment v2: 2nd Round of Exercise (2026)

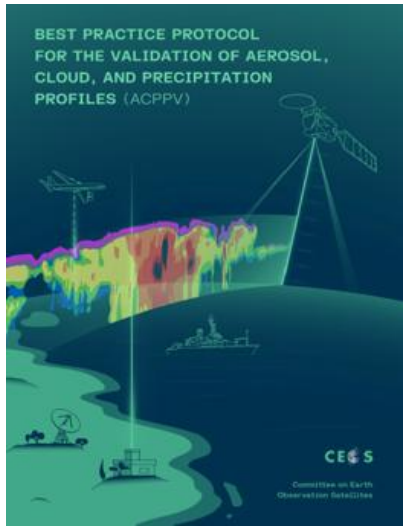
- ACTRIS-CREGARS-FTIR HCHO ⇔ NDACC FTIR HCHO
- COCCON
- NDACC
  - Brewer O_3 ⇔ EUBREWNET
  - FTIR CH_4
  - Lidar T, O_3 ⇔ TOLNet
  - MWR H_2O, O_3
  - Ozonesonde ⇔ SHADOZ
  - UV-Vis NO_2 ⇔ FRM4DOAS ⇔ ACTRIS-CREGARS-UVVIS
- Pandora (PGN)

FRM Fitness-for-purpose for Constellations

QA4EO: Validation relies on FRMs to produce Quality Indicators enabling users to judge fitness for purpose of the satellite data.

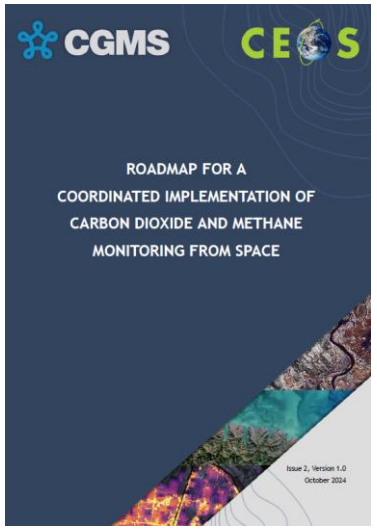
1. FRM requirements for an individual mission ⇨ metrology, data comparability
2. FRM requirements for the constellations ⇨ 1. + interoperability

Aerosol, Cloud & Precipitation

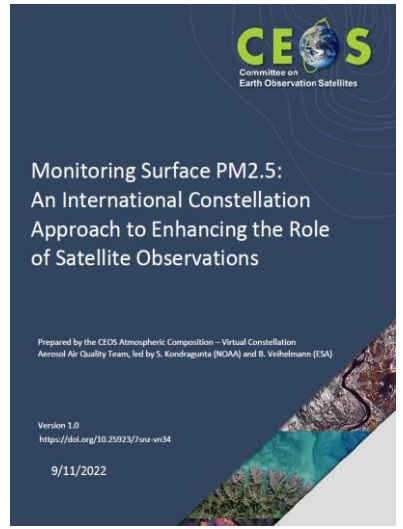


Air Quality

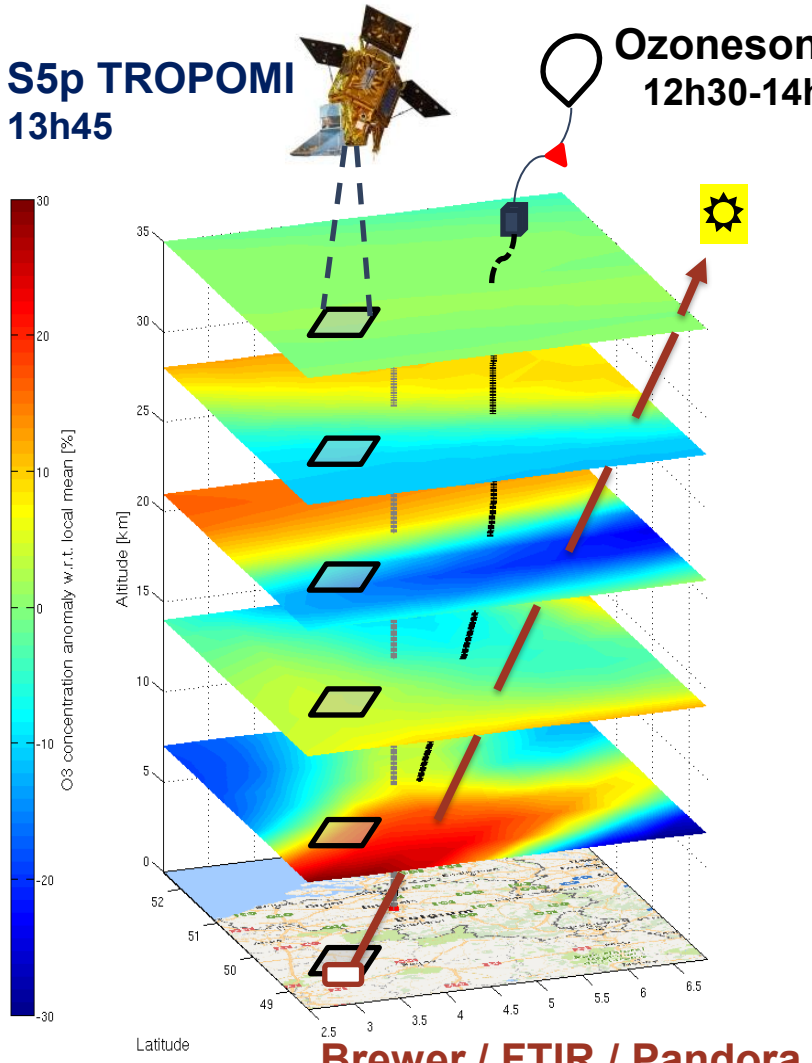
CO_2 & CH_4



PM 2.5



Data Comparability ⇨ Representativeness



$$|m_1 - m_2| < k\sqrt{u_1^2 + u_2^2}$$

Loew *et al.*, RG 2017
ISO/TS 19124-1:2023

Verhoelst *et al.*, AMT 2015

$$|m_1 - m_2| < k\sqrt{\sigma^2 + u_1^2 + u_2^2}$$

Mismatch uncertainty:

- Mixes spatiotemporal **co-location** mismatch and **smoothing** differences of atmospheric variability and gradients
- Random and systematic components

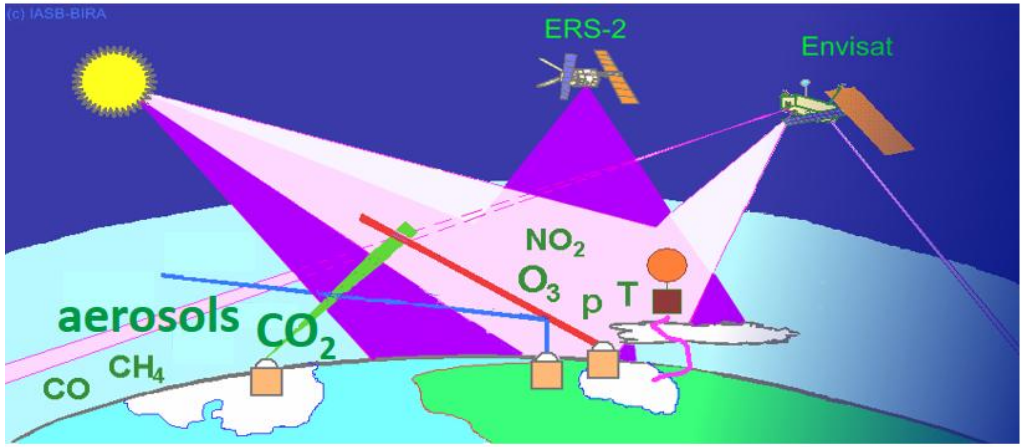
Data Comparability ⇨ Representativeness

test: range of measurand quantity value and of influence quantities values

Measurand sampling/representativeness	PGN FRM products are acquired for very different climatic areas and under almost all illumination conditions, i.e. day/night (lunar)

test: horizontal representativeness (smoothing)

Measurand sampling/representativeness	The representativeness of FRM4DOAS measurements for comparison with satellite measurements, strongly depend on the variability of the target molecules and on the native spatial resolution of the satellite sensor. Current atmospheric composition sensors, such as Sentinel-5 Precursors/TROPOMI have a ground-pixel size that matches the typical horizontal extend of airmasses sampled by ground-based MAX-DOAS measurements (typically a few kilometers). This is usually not the case for historical sensors, which results in larger comparison uncertainties due to non-representativeness.



$$\varepsilon_{smoothing} = f\left((A_1 - A_2).S_{atmos}.(A_1 - A_2)^T\right)$$

$$|m_1 - m_2| \le k\sqrt{\sigma^2 + u_1^2 + u_2^2}$$

Other highlights

- Adequacy: Need to define precisely the satellite measurand and the Quality Indicators (bias, precision, stability, diurnal cycle, altitude registration…) for which the measurement is an adequate FRM.
- Self-assessors have to provide evidence for each cell in the CEOS-FRM maturity matrix.
- The portfolio of satellite products, QIs and FRM candidates is wide. Need governance and tools to manage CEOS-FRM assessments.
- Subjectivity:
  - Separate classical metrology, data comparability, and validation capacity.
  - Provide illustrative test cases illustrating the CEOS-FRM guidelines.
  - Interaction between self-assessor and verifier is essential ⇨ Strengthen the verification of the self-assessment as an interactive peer-review process.

Other highlights

- Self-assessors tend to assess multiple species in one round
  ⇨ clarification needed
- CEOS-FRM = CEOS WGCV tool fostering interoperability; does not preclude mission specific FRM concepts and criteria.
- CEOS-FRM is appreciated as a guide to understanding and improvement. However, curiosity/fears about the result, meaning and purpose of the overall classification (A/B/C/D).

Discussion on CEOS-FRM V2

https://calvalportal.ceos.org/web/guest/frms-assessment-framework

- Feedback from this assembly ?
- Systematic assessments ?
- FRM'ization of Cal/Val campaigns, non-network data, higher level data…
- Better understanding and optimization of comparability
  - 1D to 3D representativeness,
  - methods and tools for state/pixel transformation,
  - uncertainty budget of data comparison.

Atmospheric Composition Data used as a FRM

Global measurement networks (several contributing to WMO Global Atmosphere Watch and GCOS)

- Multiple techniques: DOAS, ECC, FTIR, lidar, MWR, radar, sonde, UV spectrophotometry
- Ground-based : GRUAN, NDACC, PGN, SHADOZ, TOLNet, TCCON, COCCON…
- Airborne : AirCore, CONTRAIL, IAGOS
- Maturity: SOP, SI/community traceability, ancillary, uncertainty estimates, QA/QC… & utilisation

Dedicated instrumentation, processing and campaigns

- **Instruments/facilities**, e.g., EUBREWNET, FRM4AER, FRM4DOAS, FRM4AQ, FRM4GHG, COCCON, ACTRIS topical centres, cross-domain "supersites" (RRV, BAQUNIN Cal/Val Park…)
- **Cal/Val campaigns**, e.g., CINDI-3 intercalibration campaign, AQ airborne campaigns…

Higher level products: AQ tomography, Age of Air, fluxes, controlled release experiments…

Clouds as influencing tropospheric retrievals: ACTRIS-Cloudnet, ARM

Level-1B: emerging use of PICS, RadCalNet, HYPERNETS, future TIRCalNet