Committee on Earth Observation Satellites

Atmospheric Composition Updates

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CEOS WGCV-49 Teleconference

June 29 - July 2, 2021

Working Group on Calibration and Validation

Atmospheric Composition Updates

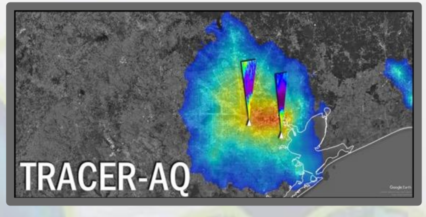
1. WGCV ACSG / AC-VC linkage
2. Fiducial Reference Measurements
3. Tropospheric Ozone Activity
4. Copernicus Cal/Val Solution (CCVS) / Atmosphere
5. Clouds, aerosols and radiation

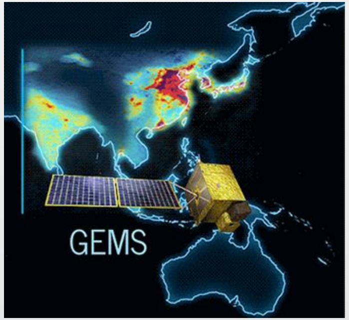
WGCV ACSG / AC-VC Linkage

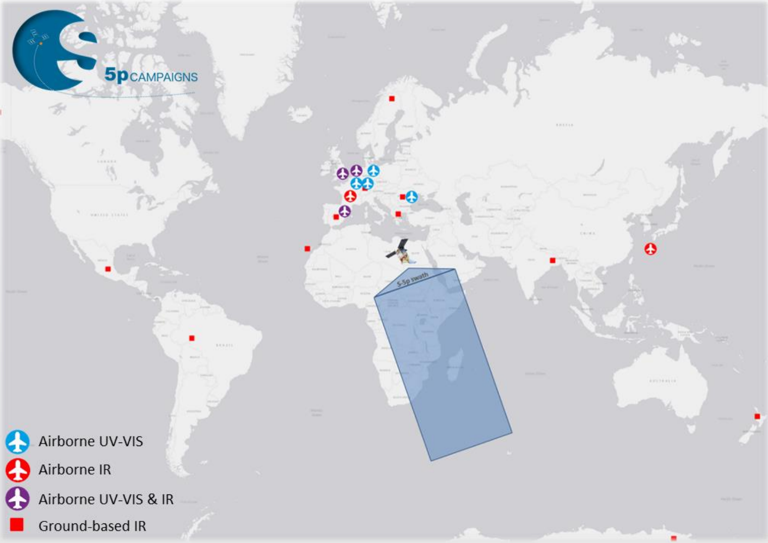
- AC-VC-16 and AC-VC-17 (and joint GEMS/Sentinel-4/TEMPO) meetings originally planned to be hosted by BELSPO and BIRA-IASB in Brussels => ONLINE MEETINGS (2020/06, 2021/06)
- AC-VC-18 meeting to be hosted by BELSPO and BIRA-IASB in Brussels, March 14-18, 2022
- Validation in cross-agencies harmonization efforts in AC-VC topics:
  - Air Quality: Aerosols (Lead S. Kondragunta, NOAA)
  - Air quality: Trace gases (Leads B. Lefer, NASA, B. Veheilmann, ESA)
  - Greenhouse gases (Lead D. Crisp, JPL)
  - Ozone (Lead D. Loyola, DLR)
  - GHG emission inventories for global stocktakes, reanalyses, CoViD-19 (fast response, dashboard), interdisciplinary (Chairs B. Lefer, NASA, H. Tanimoto, NIES, B. Veheilmann, ESA)
- General discussion at AC-VC-17: interleaved AC-VC / WGCV activities work well, enhanced collaboration wished on some topics like aerosols

Airborne and field campaigns

- 2020-2021 campaigns in Asia/Pacific, Europe and USA
- UV-Vis and IR spectrometers
- Mapping, enhanced horizontal resolution
- Inter/intra pixel experiments and (super)sites
- Geostationary peculiarities vs. LEO
- Surface BRDF, orography, clouds







GHG Cal/Val Roadmap (draft) toward global stocktake 2023 and 2028

2003 2008 2013 2018 2023 2028

Instruments

- Moderate spectral resolution
- High spectral resolution and wide coverage SWIR-TIR and pointing
- Imaging & high spectral resolution
- Imaging high spectral resolution & pointing
- Full spatial coverage
- GHG and NO_2
- Compact Geo

CAL

Challenge
(1) Mueller matrix

- Prelaunch Cross calibration: Intercomparison of radiometric standard
- Vicarious calibration, coincident observation of multiple sensors
- Cold site, uneven topography, thick aerosol

VAL (GHG Density)

- International commercial flights, sampling, in-situ
- **Column density with ground-based high-resolution FTS**
- **Vertical profile** : radiosonde, airplane (spiral flight)
- **Portable moderate resolution FTS at CAL/VAL sites**

VAL (Flux)

Challenge
(1) Global flux
(2) Windspeed and direction Accuracy

- Airplane: emission from different source sectors
  Mega cities
- Simultaneous NO_2 measurement

GHG Measurement Networks for Satellite Validation

NDACC IRWG

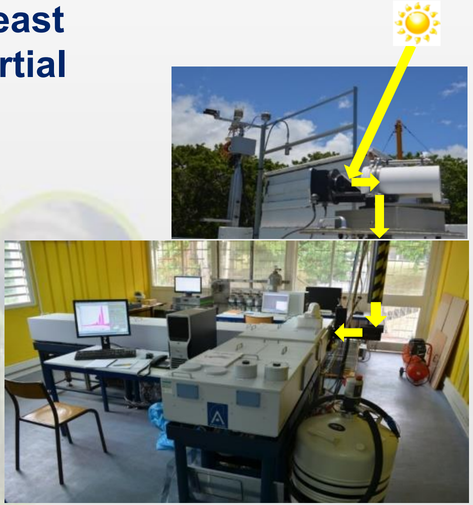
http://ndacc.org

- Bruker 120HR/125HR
- Resolution 0.0036 cm^{-1}
- Profile retrievals (limited vertical resolution, at least tropo/strato partial columns)

TCCON

http://tccon.org

- Bruker 125HR
- Resolution 0.02 cm^{-1}
- Profile scaling retrievals



COCCON

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

- Bruker EM27/SUN
- Resolution 0.5 cm^{-1}
- Profile scaling retrievals

Courtesy M.K. Sha, M. De Mazière and B. Langerock (BIRA-IASB)

GHG Measurement Networks for Satellite Validation

NDACC IRWG

- Operational use in: EUMETSAT AC SAF IASI validation, ESA MPC TROPOMI validation, CAMS validation (RD delivery supported by CAMS27)
- Recent and ongoing harmonisation efforts in QA4ECV, GAIA-CLIM, CAMS27, C3S-311a-Lot3 (BARON)
  Upcoming SFIT/PROFFIT to improve harmonization of uncertainties evaluation, better spectroscopy
- Selected NDACC stations to join EU research infrastructure ACTRIS: with central processing facility, QA/QC, training…
- CO_2 retrieval strategy under development (IUP/UB & BIRA-IASB)

TCCON

- Operational use in: OCO-2/3 & GOSAT/2 Cal/Val, CAMS validation, ESA TROPOMI validation (limited RD delivery)…
- GGG2020 will improve prior profiles (shape and possible bias), verify CO calibration factor, improve spectroscopy, reduce remaining airmass and H_2O dependences, reduce scatter in CO product, improve diagnostics for instrumental issues.
- Negotiations ongoing for selected TCCON stations to join EU research infrastructure ICOS, with central processing facility
- Profile retrievals under development. Tropospheric partial columns can be derived indirectly

COCCON

- Operational usage in: OCO-2/3, GOSAT/2, S5P TROPOMI validation (started in 2020)…
- Planned update foreseen for PROFFAST, redefined spectroscopic descriptions + improved line lists
- EM27/SUN as travelling standard for TCCON, COCCON can complement TCCON, support by ESA for COCCON-PROCEEDS, follow-up crucial for current capabilities of COCCON
- Towards extension of COCCON with VERTEX70 and IRcube (2 other low resolution FTIR instruments – with higher spectral resolution and additional species) – ESA FRM4GHG project https://frm4ghg.aeronomie.be

Courtesy M.K. Sha, M. De Mazière and B. Langerock (BIRA-IASB)

Further details

Use in operational validation facilities:

- Copernicus Atmosphere Monitoring Service (CAMS): https://global-evaluation.atmosphere.copernicus.eu
- ESA/Copernicus Sentinel-5p MPC: https://mpc-vdaf-server.tropomi.eu
- EUMETSAT AC SAF trace gases validation: http://cdop.aeronomie.be/validation/valid-results

Intercomparisons (recent papers):

- CO: https://doi.org/10.5194/amt-12-5979-2019
- N_2O: https://doi.org/10.5194/amt-12-1393-2019
- CH_4 Profile retrievals from TCCON spectra: https://doi.org/10.5194/amt-12-6125-2019
- FRM4GHG paper – low resolution FTIR comparison to TCCON: https://doi.org/10.5194/amt-2019-371

Fiducial Reference Measurements

Fiducial Reference Measurements

- Asian/Pacific PGN and MAX-DOAS networks (GEMS, GOSAT-GW and S5P focus)
- ESA/NASA/USEPA/LuftBlick Pandonia Global Network (PGN) NO_2, O_3, SO_2, HCHO
- US EPA/NASA efforts to integrate remote sensing at existing AQ monitoring sites
- ESA FRM4DOAS, Mutual consistency between MAX-DOAS, direct-sun UV and FTIR (HCHO and NO_2)
- EUBREWNET uncertainty budget and enhancement
- EUMETSAT CO2M FRM study, ESA FRM4GHG, COCCON
- ACTRIS CLOUDNET, ESA FRM4RADAR, US ARM

FRM data distribution infrastructures

- 9 atmospheric Cal/Val data services assessed in CCVS T2.6
- ACTRIS, AERIS, ASDC, CEDA, EVDC, HALO, ICOS are FAIR
- Network data centers not assessed (GRUAN, NDACC, TCCON, WOUDC…)

CEOS Work Plan 2021-2023

VC-20-01	Tropospheric ozone dataset validation and harmonization	2022 Q4	AC-VC
VC-20-02	Air quality constellation validation coordination	2024 Q4	AC-VC WGCV
VC-20-03	Air quality constellation validation coordination: validation plans	2022 Q4	AC-VC WGCV
VC-20-04	Air quality constellation validation coordination: announcements of opportunity	2023 Q4	AC-VC WGCV

IGAC Tropospheric Ozone Assessment Report

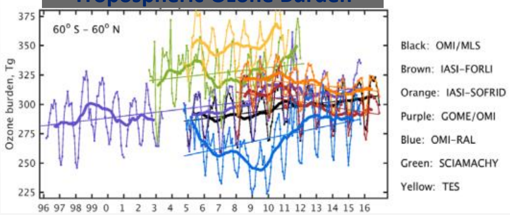
Questions from TOAR-I (Gaudel *et al.*, 2018)

- Why do measured distributions and trends differ (i) among satellites, and (ii) w.r.t. monitoring networks ?

TOAR-II Satellite Ozone Working Group goals

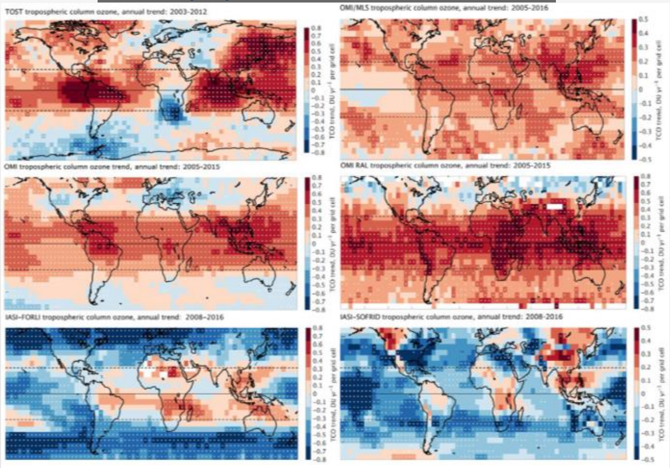
- Reconcile satellite-, ground- and aircraft-based data
- Global chemistry transport models as transfer standard
- Provide common methodology for validation of trends

Tropospheric Ozone Burden



TOAR tropospheric ozone assessment report

Tropospheric Ozone Annual Trend



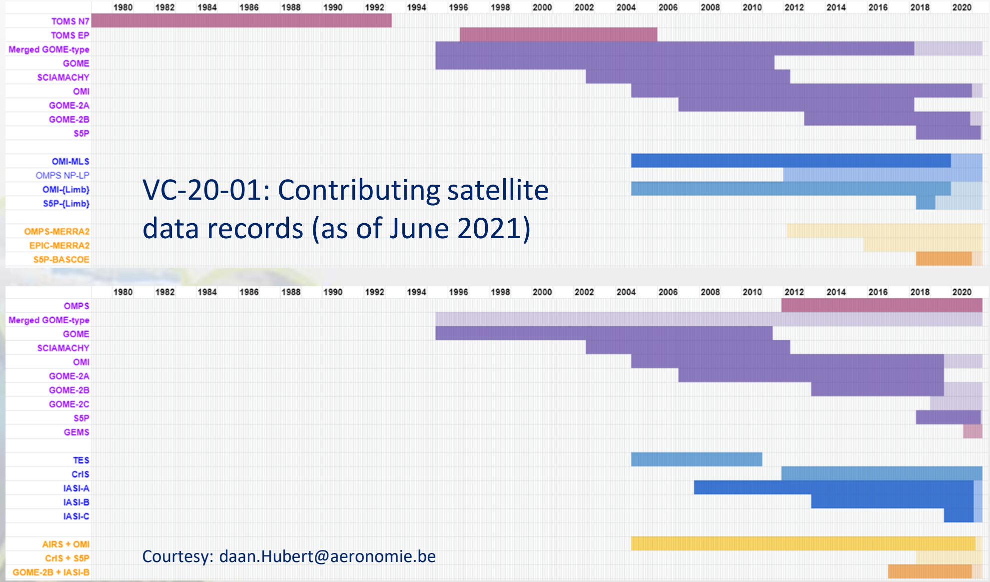
CEOS VC-20-01 Tropospheric Ozone Activity

- **VC-20-01:** ***'Tropospheric ozone dataset validation and harmonization'***
- **Lead: D. Loyola (DLR), support G. Labow (NASA) and J.-C. Lambert (BIRA-IASB)**
- **CEOS (AC-VC / WGCV) response to IGAC TOAR-II needs**
- **Coordination with TOAR-II Satellite Ozone WG and HEGIFTOM WG**
- **WC-20-01 schedule:**
  - ✓ **Kick-off at AC-VC-16 (June 2020)**
  - ✓ **Initial results at AC-VC-17 (June 2021)**
  - **Progress Meeting (Jan 2022)**
  - **TOAR-II Workshop (2022, TBD)**
  - **Results at AC-VC-18 (March 2022, Brussels)**
  - **Contributions to TOAR-II publications (2022+)**

CEOS VC-20-01 Tropospheric Ozone Activity

Status at AC-VC-17 (June 2021):

- Data harmonisation and validation protocol for satellite tropospheric ozone
- Gap analysis for cross-constellation validation
- Initial validation results
- Feedback to ground-based data providers



VC-20-01: Contributing satellite data records (as of June 2021)

Courtesy: daan.Hubert@aeronomie.be

Residual technique (UV-VIS sensors)

- Convective Cloud Differential
- Nadir - Limb
- Nadir - Reanalysis

Profile retrieval

- UV-VIS
- IR-NIR
- VIS+IR synergy

Copernicus Cal/Val Solution (CCVS) – Atmosphere

- EC H2020 project to elaborate a holistic Cal/Val solution for the Copernicus Sentinel missions, overcoming current limitations:
  - Lack of cross-Sentinel synergies: methodologies, data collection, distribution, processing and inter-validation,
  - Insufficient handling of inter-operability requirements within the Copernicus programme,
  - Excessive dependency on data obtained from external entities without any long-term operational commitments to the Copernicus programme,
  - Global lack of reference data compliant with internationally endorsed good practice methods for operational Cal/Val, both from permanently maintained sites and campaign-based acquisitions.
- Coordinator ACRI-ST + 13 partners
- Advisory committee: EEA, ESA, EUMETSAT
- Partners/stakeholders: Copernicus, EC, JRC, space agencies, WGCV and GSICS members, Cal/Val experts, measurement networks & infrastructures
- Atmosphere: BIRA-IASB, ACRI-ST, CNES, JRC, KNMI, U. Antwerp, U. Tartu.
- CCVS addresses GHG Roadmap CV-2 and CV-5, and is also relevant to CV-6.

Copernicus Cal/Val Solution (CCVS) – Atmosphere

CCVS – Atmosphere: requirements and status (December 2020 – May 2021)

- D1.4 – Cal/Val Requirements for Atmospheric Composition Missions
- D2.1 – On-board calibration
- D2.2 – Vicarious methods
- D2.3 – Inter-satellite comparisons
- D2.4 – Systematic ground-based measurements
- D2.5 – Field and aerial campaigns
- D2.6 – Cal/Val data distribution services

Reviewed by ACRI-ST, Copernicus, EC/JRC, EEA, ESA, EUMETSAT, U. Tartu, revised, delivered on June 1, 2021

More details tomorrow

Copernicus Cal/Val Solution (CCVS) – Atmosphere

Current CCVS – Atmosphere activities (June 2021 – June 2022): gap analysis and solution

- T3.1 – Needs for new/enhanced instrumentation
- T3.2 – Audit of Cal/Val methods per product, compliance with Cal/Val requirements, need for further developments
- T3.3 – Evaluation and optimization of ground-based networks configuration
- T3.3 – Concept of supersite
  - End-to-end validation of Level-1-to-2 data production
  - Synergies with other EO Cal/Val domains: PICS, RadCalNet, surface BRDF…
- T3.4 – Cal/Val data distribution
- T3.5 – Impact of Level-1/2 Cal/Val on Level-3 data quality
- T3.6 – CCVS Solution

Next (by end 2022): Reference scenarios for implementation

Copernicus Cal/Val Solution (CCVS) – Atmosphere

Task 1.4 – Atmospheric Cal/Val Requirements

CCVS

Table 5: Sentinel-5p data products available to users, for which validation is necessary: data product (measurand, uncertainties, quality flags…), product identifier, useful range over which validation must be performed, and mission requirements on bias (from systematic effects) and uncertainty (from random effects).

Data product (measurand)	Processing level/ identifier	Useful range of measurand value	Bias (systematic)	Uncertainty (random)
Solar spectral irradiance	L1B_IR	Detailed requirements in [MRD-S-4-5]		
TOA UV spectral radiance	L1B_RA_UV	Detailed requirements in [MRD-S-4-5]		
TOA VIS spectral radiance	L1B_RA_VIS	Detailed requirements in [MRD-S-4-5]		
TOA NIR spectral radiance	L1B_RA_NIR	Detailed requirements in [MRD-S-4-5]		
TOA SWIR spectral radiance	L1B_RA_SWIR	Detailed requirements in [MRD-S-4-5]		
Ozone total column	L2_O3_TC	100 – 550 DU (1)	5%	2.5%
Ozone tropospheric column	L2_O3_TCL	0-70 DU (1)	25%	25%
Ozone vertical profile	L2_O3_PR	0-12 ppmv	30%	10%
Nitrogen dioxide tropospheric column	L2_NO2_TCL	0-150 Pmolec/cm2 (2)	50%	0.7 Pmolec/cm²
Nitrogen dioxide stratospheric column	L2_NO2_SC	0.5-7 Pmolec/cm2	10%	0.5 Pmolec/cm²
Nitrogen dioxide total column	L2_NO2_TC	0-150 Pmolec/cm2	10% (clean) 50% (polluted)	0.9 Pmolec/cm²
Formaldehyde total column	L2_HCHO_TC	0-20 Pmolec/cm2	80%	12 Pmolec/cm²
Sulphur dioxide column	L2_SO2_TC	0-25 DU (1)	0.5 DU 30% (SCD>1.5 DU)	1 DU 30% (SCD>1.5 DU)
Carbon monoxide total column	L2_CO_TC	0.5-4 10^{18} molec/cm2	15%	10%
Methane total column	L2_CH4_TC	1.6-2.0 ppm (XCH_4) (3)	1.5%	1%

(1) Traceability of Dobson Unit (DU) to SI: 1 DU is equivalent to 2.1415 10^{-5} kg[O_3]/m_2, or 0.4462 mmol/m², or 2.687 10^{20} molecules/m²

(2) Traceability of Pmolec.cm⁻² to SI: 1 Pmolec.cm⁻² is equivalent to 16.605 µmol/m²

(3) Traceability of ppm and ppb to SI: 1 ppm is equivalent to 1 µmol mol⁻¹, l ppb is equivalent to 1 nmol mol⁻¹.

Data product (measurand)	Processing level/ identifier	Useful range of measurand value	Bias (systematic)	Uncertainty (random)
Radiometric Cloud Fraction	L2_CLOUD_CF	0 - 1	20%	0..05
Radiometric Cloud Height	L2_CLOUD_CH	0 - 15 km	20%	0.5km (P<30hPa)
Radiometric Cloud Albedo	L2_CLOUD_CA	0 - 1	20%	0.05
Radiometric Cloud Optical Thickness	L2_CLOUD_COT	1 - 250	20%	10
Lambertian equivalent reflectivity	L1B_SURF_LER	< 0 (absorbing dust) to > 1 (high clouds)		5%
Surface Albedo	L2_SURF_AL	0 - 1		
Aerosol UV Absorbing Index	L2_AER_AI	-5 to +10	1 AAI	0.1 AAI
Aerosol Layer Height	L2_AER_LH	0 - 15 km	100 hPa	50 hPa
Surface UV radiance	L2_UV_SURF		20%	20% (UVAI > 1)

Table 6: Sentinel-5p influence quantities and their range over which validation should be performed and Quality Indicators assessed, and ancillary parameters for which validation measurements are needed.

Influence quantity	Spectral domain	Range	Rationale
Spectral emissivity of surface	SWIR-TIR	0.65 to 1	Decreases surface thermal radiance and increases reflection of downwelling atmospheric radiation.
Spectral albedo of surface	UV-VIS-NIR	0 to 1	Increases reflection/scattering of downwelling scattered radiation.
Spectral BRDF of surface	UV-VIS-NIR	at angles from 0° to 90°	Influences reflection/scattering of downwelling scattered radiation.
Snow/ice flags	All		Snow-ice influences heavily LER, cloud and AMF retrievals.
Solar zenith angle (SZA)	All	20° to 90°	Conversion from slant to vertical column sensitive to scattering geometry, vertical profile of absorber…; shortcomings of DOAS retrieval technique for optically thick atmosphere (large SZA).
Viewing/scan angle (VA/SA)	All	0°±15° wrt nadir	Various sources, introduces scan dependent biases (striping).

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Towards a generic validation protocol for atmospheric (L2) data products ?

- Standards and traceability
- Cardinal validation targets
- Mission and user requirements
- Data product content
- Documentation
- Validation approaches
- Data analysis
- Domain specifics
- Planning, organization and inte rnational collaboration
- Tools and services

5 Summary: Matrix of Cal/Val requirements

This section summarises in the form of a matrix the key Cal/Val requirements identified in the previous sections. Quantitative requirements specific to the Sentinel missions are not reproduced. The matrix describes shortly the requirement and indicates the section(s) describing or referring to this requirement.

Table 12 : Overview of Cal/Val requirements for the atmospheric composition Copernicus Sentinels.

Cal/Val requirement by category	Sections	Identifier
Standards and traceability		
EO Cal/Val activities shall adhere to the general EO data quality strategy established in the QA4EO framework.	3.1.1	CCVS-REQ-AC-001
Traceable Quality Indicators shall be produced to enable users to evaluate readily the fitness-for-purpose of the EO data.	3.1.1	CCVS-REQ-AC-002
EO Cal/Val activities shall adopt standards and best practices for terminology. The expression of terms ambiguously used across teams and communities (e.g. accuracy) shall be clarified.	1.3.1	CCVS-REQ-AC-003
EO Cal/Val activities based on data comparisons shall adopt community endorsed processes of generic operations and specific operations.	3.3	CCVS-REQ-AC-004
Maturity of the EO Cal/Val shall be assessed against the CEOS WGISS Data Management and Stewardship Maturity Matrix for satellite data validation.	3.4	CCVS-REQ-AC-005
Traceability of the validation process, methods, tools and data shall be documented.	3.1.1	CCVS-REQ-AC-006
Validation reporting shall include traceability information on the Sentinel data product, the validation processing, and the validation teams having performed the work and issued the report.	3.1.1	CCVS-REQ-AC-007
Cardinal validation targets		
Quality indicators shall be established for Level-1b data (radiance, reflectance and irradiance) and for their radiometric calibration, spectral assignment and geolocation.	3.1.2	CCVS-REQ-AC-008
Quality indicators shall be established for Level-2 geophysical quantities (column and profile of atmospheric constituents).	3.1.1, 3.1.2	CCVS-REQ-AC-009
Validity of the ancillary and auxiliary parameters used by the Level-1-to-2 data processors shall be verified.	3.1.2	CCVS-REQ-AC-010
Theoretical ex-ante uncertainties associated with the Level-1b and Level-2 data products shall be given quantitative evidence of their validity.	3.1.1, 3.1.2	CCVS-REQ-AC-011
Quality flags and of data usage recommendations associated with the data products shall be given evidence of their validity and efficiency.	3.1.1, 3.1.2	CCVS-REQ-AC-012
Compliance of actual quality of the data product shall be evaluated with respect to mission requirements and core user requirements.	3.1.2	CCVS-REQ-AC-013
Compliance of actual quality of the data product shall be evaluated with respect to product specifications.	3.1.2	CCVS-REQ-AC-014
Mission and user requirements		
Cal/Val activities shall establish quality indicators enabling to judge the fitness-for-purpose of the Sentinel data quality comply with product specifications and mission requirements.	3.1.1	CCVS-REQ-AC-015
Cal/Val activities shall establish quality indicators enabling the Copernicus services to readily evaluate the fitness of the Sentinel data for their purposes.	3.1.1, 4.2.1	CCVS-REQ-AC-016
Cal/Val activities shall establish quality indicators enabling to readily evaluate whether the Sentinel data comply with interoperability requirements within the Copernicus constellations and within the CEOS and CGMS constellations.	4.2.2 , 4.7	CCVS-REQ-AC-017
Cal/Val requirements for the atmospheric composition Sentinels shall be adapted during mission lifetime and beyond to reflect the evolution of core user data quality requirements.	1.1.3, 4.2, 4.2.1.2	CCVS-REQ-AC-018
Requirements on Sentinel data content and documentation		
Each Sentinel data product shall be provided with full identification of the data processing chain: data processor versions, but also identification of the ancillary and auxiliary data used in the processing.	3.1.1	CCVS-REQ-AC-019
Each Sentinel data product shall have associated with it a full uncertainty budget described in detail in an Algorithm Theoretical Basis Document (ATBD), with identification of the intermediate parameters, influence quantities and ancillary parameters influencing data quality.	2.4, 3.1.2	CCVS-REQ-AC-020
Each Sentinel data product shall include intermediate retrieved quantities, diagnostic data (averaging kernels…) and other quality information required to perform data content and information content analysis.	2.4, 3.3, 3.1.2	CCVS-REQ-AC-021
Validation approaches		
Sentinel Level-1b radiance and reflectance data shall be compared to natural targets for validation of geolocation, of calibration, of long-term stability, and of mutual consistency with other missions.	3.1.2	CCVS-REQ-AC-022
Sentinel Level-1b radiance and reflectance data shall be inter-compared with other satellite measurements.	3.1.2, 3.2.4	CCVS-REQ-AC-023
Sentinel Level-1b data shall be compared to (ground-based) Fiducial Reference Measurements.	3.2.2	CCVS-REQ-AC-024
Sentinel-1b extra-terrestrial spectral irradiance data shall be compared to other satellite measurements.	3.1.2	CCVS-REQ-AC-025
Sentinel Level-2 data shall be compared to (ground-based) Fiducial Reference Measurements tailored to Cal/Val needs of traceability, documentation, uncertainty assignment, timeliness of delivery, and long-term continuity.	3.2.2	CCVS-REQ-AC-026

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Towards a generic validation protocol for atmospheric (L2) data products ?

- Objectives of Cal/Val
- Terminology
- Mathematical formulation
- Validation metrics
- Advanced methods and strategies
- Referred to in ISO 19124-1

AGU PUBLICATIONS

Reviews of Geophysics

REVIEW ARTICLE
10.1002/2017RG000562

Validation practices for satellite-based Earth observation data across communities

Alexander Loew[1,2], William Bell[3], Luca Brocca[4], Claire E. Bulgin[5], Jörg Burdanowitz[6], Xavier Calbet[7], Reik V. Donner[8], Darren Ghent[9], Alexander Gruber[10], Thomas Kaminski[11], Julian Kinzel[12], Christian Klepp[13], Jean-Christopher Lambert[14], Gabriela Schaepman-Strub[15], Marc Schröder[12], and Tijl Verhoelst[14]

[1]Department of Geography, Ludwig-Maximilians-Universität München (LMU), Munich, Germany, [2]Deceased 2 July 2017,, [3]MetOffice, Reading, UK, [4]Research Institute for Geo-Hydrological Protection-National Research Council, Perugia, Italy, [5]Department of Meteorology, University of Reading, Reading, UK, [6]Max Planck Institute for Meteorology, Hamburg, Germany, [7]Spanish Meteorological Agency, AEMET, Madrid, Spain, [8]Potsdam Institute for Climate Impact Research, Potsdam, Germany, [9]Department of Physics and Astronomy, University of Leicester, Leicester, UK, [10]Department of Geodesy and Geoinformation, TU Wien, Vienna, Austria, [11]Inversion Lab, Hamburg, Germany, [12]Deutscher Wetterdienst, Offenbach, Germany, [13]Initiative Pro Klima, University of Hamburg, CliSAP/CEN, Hamburg, Germany, [14]Royal Belgian Institute for Space Aeronomy (BIRA-IASB), Brussels, Belgium, [15]Department of Evolutionary Biology and Environmental Studies, University of Zurich, Zurich, Switzerland

Key Points:
- First review of EO validation approaches across different Geoscience communities
- Validation approaches depend on the intermittency and inhomogeneity of the geophysical variables
- Enhanced traceability in EO validation approaches required

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Citation:
Loew, A., et al. (2017), Validation practices for satellite-based Earth observation data across communities, *Rev. Geophys.*, *55*, doi:10.1002/2017RG000562.

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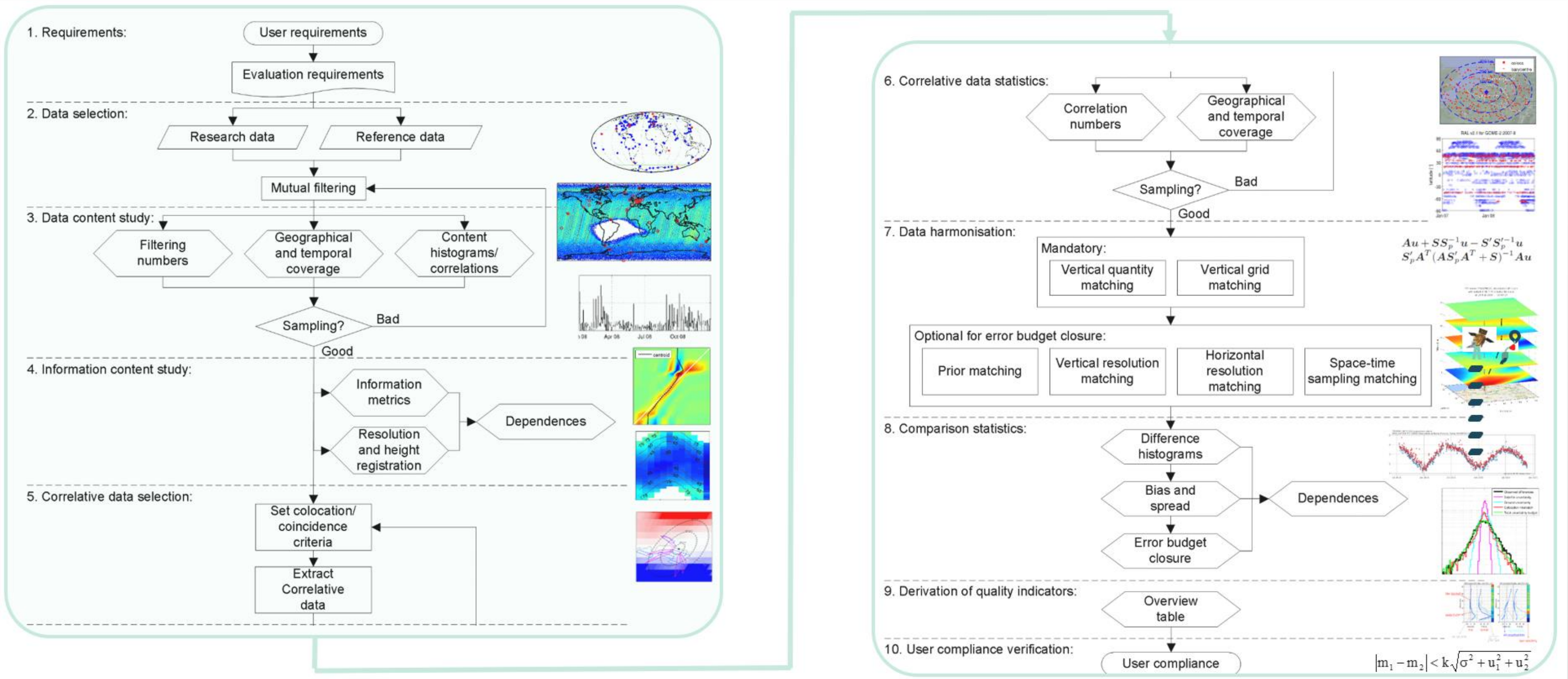
Abstract Assessing the inherent uncertainties in satellite data products is a challenging task. Different technical approaches have been developed in the Earth Observation (EO) communities to address the validation problem which results in a large variety of methods as well as terminology. This paper reviews state-of-the-art methods of satellite validation and documents their similarities and differences. First, the overall validation objectives and terminologies are specified, followed by a generic mathematical formulation of the validation problem. Metrics currently used as well as more advanced EO validation approaches are introduced thereafter. An outlook on the applicability and requirements of current EO validation approaches and targets is given.

Towards a generic validation protocol for atmospheric (L2) data products ?

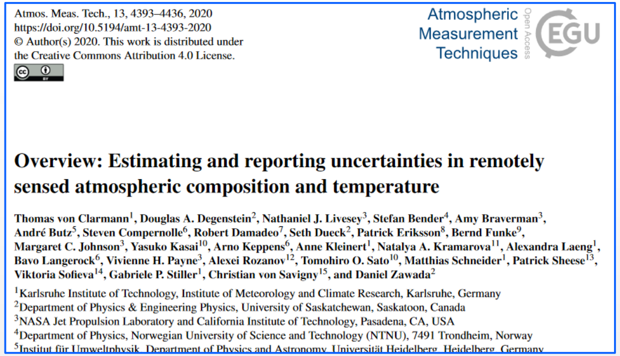
Generic nadir satellite validation protocol (including round-robin functions)

(Keppens et al., AMT, 2015; AC-VC-10, College Park, 2014)



Towards a generic validation protocol for atmospheric (L2) data products ?

SPARC TUNER activity: Data harmonization and uncertainty budget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Atmospheric Measurement Techniques
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Overview: Estimating and reporting uncertainties in remotely sensed atmospheric composition and temperature

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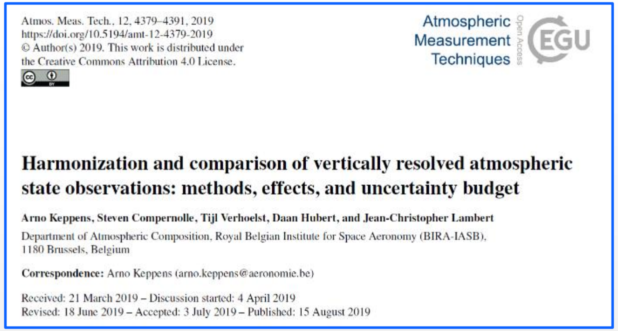
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Harmonization and comparison of vertically resolved atmospheric state observations: methods, effects, and uncertainty budget

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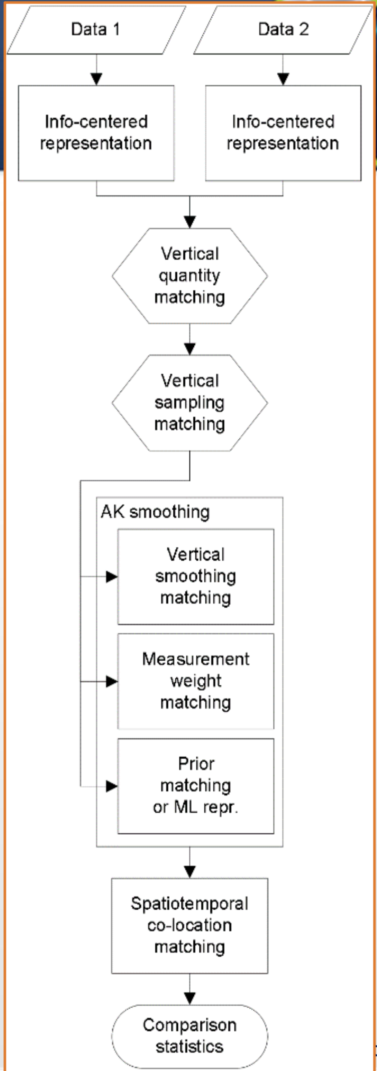
Matching operation	$\boldsymbol{x}'$	Removed covariance	Converted covariance $\mathbf{S}'$	Introduced and residual covariance
Vert. quantity matching	$\mathbf{M}\boldsymbol{x}$	–	$\mathbf{MSM}^T$	$\mathbf{S}_Q$
Vert. sampling matching	$\mathbf{W}\boldsymbol{x}$	–	$\mathbf{WSW}^T$	$(\mathbf{V}_1-\mathbf{V}_2')\mathbf{S}_C(\mathbf{V}_1-\mathbf{V}_2')^T$
Vert. smoothing matching	$\mathbf{V}\boldsymbol{x}$	$\mathbf{S}_{\Delta\mathrm{Vsm}}$	$\mathbf{VSV}^T$	$(\mathbf{V}_1-\mathbf{V}_1\mathbf{V}_2)\mathbf{S}_C(\mathbf{V}_1-\mathbf{V}_1\mathbf{V}_2)^T$
Meas. weight matching	$\mathbf{W}^{\mathrm{M}}\boldsymbol{x}$	$\mathbf{S}_{\Delta\mathrm{MW}}$	$\mathbf{S}$	–
Prior matching (PM)	$\mathbf{S}'(\mathbf{S}^{-1}\boldsymbol{x}-\mathbf{R}_a\boldsymbol{x}_a+\mathbf{R}_a'\boldsymbol{x}_a')$	$\mathbf{S}_{\Delta\mathrm{PS}}$ and/or $\mathbf{S}_{\Delta PC}$	$(\mathbf{S}^{-1}-\mathbf{R}_a+\mathbf{R}_a')^{-1}$	$\mathbf{S}'_{\Delta\mathrm{MW}}$
Re-optimized PM	$\mathbf{P}[\boldsymbol{x}-(\mathbf{I}-\mathbf{A})\boldsymbol{x}_a]+\mathbf{PS}(\mathbf{A}^T)^{-1}\mathbf{R}_a'\boldsymbol{x}_a'$	$\mathbf{S}_{\Delta\mathrm{Vsm}}+\mathbf{S}_{\Delta\mathrm{PS}}+\mathbf{S}_{\Delta PC}+\mathbf{S}_{\Delta\mathrm{MW}}$	$\mathbf{PSP}^T$	$(\mathbf{A}-\mathbf{PA})\mathbf{S}_C(\mathbf{A}-\mathbf{PA})^T$
AK smoothing (for s on r)	$\mathbf{A}_\mathrm{s}\boldsymbol{x}_\mathrm{r}+(\mathbf{I}-\mathbf{A}_\mathrm{s})\boldsymbol{x}_{\mathrm{a,s}}$	$\mathbf{S}_{\Delta\mathrm{Vsm}}+\mathbf{S}_{\Delta\mathrm{PS}}+\mathbf{S}_{\Delta PC}+\mathbf{S}_{\Delta\mathrm{MW}}$	$\mathbf{A}_\mathrm{s}^1\mathbf{S}_\mathrm{r}(\mathbf{A}_\mathrm{s}^1)^T$	$(\mathbf{A}_\mathrm{s}-\mathbf{A}_\mathrm{s}\mathbf{A}_\mathrm{r})\mathbf{S}_C(\mathbf{A}_\mathrm{s}-\mathbf{A}_\mathrm{s}\mathbf{A}_\mathrm{r})^T$
Maximum likelihood repr.	$\mathbf{S}'(\mathbf{S}^{-1}\boldsymbol{x}-\mathbf{R}_a\boldsymbol{x}_a)$	$\mathbf{S}_{\Delta\mathrm{Vsm}}+\mathbf{S}_{\Delta\mathrm{PS}}+\mathbf{S}_{\Delta PC}+\mathbf{S}_{\Delta\mathrm{MW}}$	$(\mathbf{S}^{-1}-\mathbf{R}_a)^{-1}$	$\mathbf{S}'_{\Delta\mathrm{Vsm}}+\mathbf{S}'_{\Delta PC}$
Information-centered repr.	$\mathbf{W}(\mathbf{S}^{-1}-\mathbf{R}_a)^{-1}(\mathbf{S}^{-1}\boldsymbol{x}-\mathbf{R}_a\boldsymbol{x}_a)$	$\mathbf{S}_{\Delta\mathrm{Vsm}}+\mathbf{S}_{\Delta\mathrm{PS}}+\mathbf{S}_{\Delta PC}+\mathbf{S}_{\Delta\mathrm{MW}}$	$\mathbf{W}(\mathbf{S}^{-1}-\mathbf{R}_a)^{-1}\mathbf{W}^T$	$\mathbf{S}'_{\Delta\mathrm{Vsa}}$
Co-location matching	$\boldsymbol{x}-\boldsymbol{\Delta m}$	$\mathbf{S}_{\Delta\mathrm{Hsa}}+\mathbf{S}_{\Delta\mathrm{Tsa}}+\mathbf{S}_{\Delta\mathrm{Hsm}}+\mathbf{S}_{\Delta\mathrm{Tsm}}$	$\mathbf{S}$	$\mathbf{S}_{\Delta m}$

(Keppens *et al.*, AMT 2019)



Level-1 / Reflectance / Surface

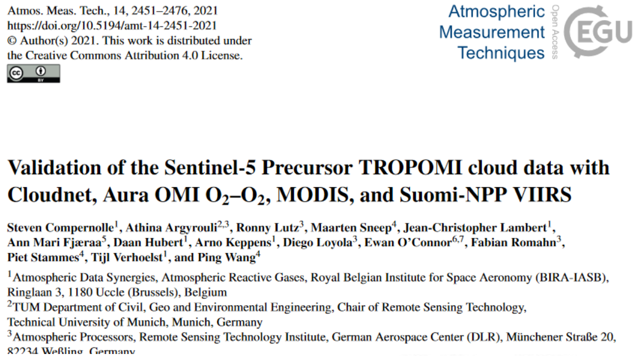
Emerging interest in validation of Level-1 FCDRs (calibration validation), in validation of LER/DLER/GLER/GELER retrievals and climatologies, in use of PICS, in directional properties of surface, in validation of pixel geolocation… from UV-Vis to SWIR and TIR

- **Investigate opportunities for a future WGCV activity cataloguing existing methods and data and exploring new possibilities ?**

(Radiometric) Clouds as Influence Quantities for L2 Trace Gas Retrievals

- Clouds modify the radiance measured by atmospheric composition sounders and influence the L2 retrieval of trace gases by masking and by modified sensitivity.
- Effective (or radiometric, not geometric) cloud fraction, cloud top height and/or cloud optical thickness are retrieved in the NIR (O_2-A), VIS (O_2-O_2) and with imagers with several key assumptions (reflecting boundaries, multi-layered…)
- Intercomparison study published: ground-based validation (vs. CLOUDNET and ARM) of all S5P TROPOMI cloud processors + OMI O_2-O_2, MODIS and S-NPP VIIRS
- ESA study of impact of cloud retrievals on TROPOMI L2 trace gas retrievals, coordinated by IUP/UB
- ESA study on 3D cloud effects, coordinated by NILU

➢ Interest on ACIX and CMIX process and outcome



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Validation of the Sentinel-5 Precursor TROPOMI cloud data with Cloudnet, Aura OMI O_2–O_2, MODIS, and Suomi-NPP VIIRS

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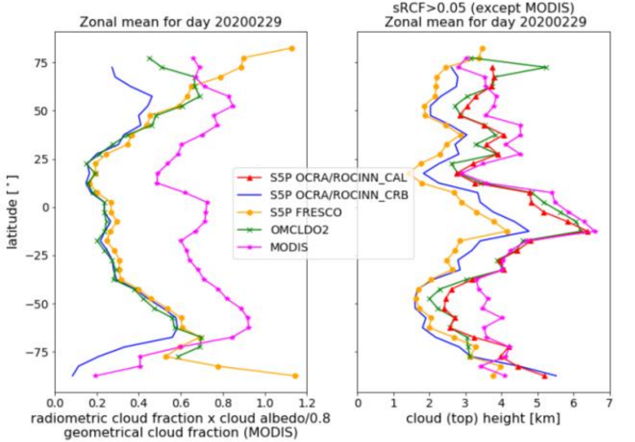
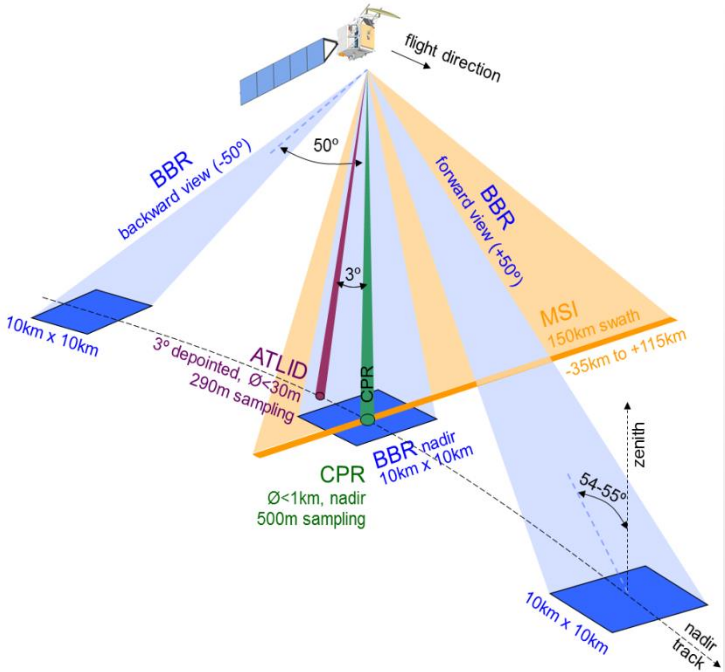


Development of validation protocols for atmospheric aerosol and cloud profiles

- EarthCARE = Earth Clouds, Aerosols and Radiation Explorer
- Joint ESA-JAXA mission.
- For scientific background, see [B.A.M.S. special issue on the EarthCARE Mission]
- Launch in June 2022. 6-Months Commissioning Phase
- ESA and JAXA each organize the validation of their own data products.
- Validation Research Announcements for the JAXA products in 2013 and 2019
- Validation Announcement of Opportunity for the ESA products in 2017: 33 proposals accepted and reviewed at the 1st ESA EarthCARE Validation Workshop: programme considered adequate but areas of improvement remain (see workshop conclusions in the workshop report at same URL): better coverage in tropics and Oceania, better coverage of cloud-profiling radars.

Futher validation contributions are welcome (contact ecvt-esa@earthcare.esa.int). Please spread the word



EarthCARE Validation Portal at https://earthcare-val.esa.int

Development of validation protocols for atmospheric aerosol and cloud profiles

Specific difficulties for EarthCARE validation:

- Extremely narrow-swath → fewer overpasses
- In particular for clouds: small correlation scale in time and space → stringent collocation criteria
- Broad suite of complex (including synergistic) products → Great variety of correlative instrumentation needed for validation
- Limited validation heritage compared to for example Atmospheric Chemistry. (Cloudsat, CALIPSO, Aeolus, CERES, MERIS heritage applicable to only few of the EarthCARE products)

- EarthCARE Validation <> CEOS WGCV
- How to address the issues in red?
- CEOS WGCV subgroups have developed validation best practices and protocols for many fields (including Atmospheric Composition).
- Some related activity in the domains of EarthCARE is in progress (FRM4RADAR, and GEOMS correlative metadata harmonisation) or completed (EARLINET aerosol)
- Need for further fostering of common practices and definition of protocols in the fields validation of cloud profiles, aerosol profiles and radiation products: EarthCARE <> WGCV(ACSG) interaction and collaboration

→ EarthCARE contact point: Rob.Koopman@esa.int

Development of validation protocols for atmospheric aerosol and cloud profiles

2nd EarthCARE validation workshop May 25-28, 2021, recommended to proceed with the development of validation protocols for aerosols, clouds and radiation

→ Proposal for a new WGCV / ACSG activity to develop these validation protocols

- **Time frame: two years**
- **Work plan currently in development for the EarthCARE subgroups, including development of validation protocols**
- **Good participation from ACCP, clearly a broader perspective (at least ESA and NASA)**
- **WGCV / ACSG to advise on QA4EO, generic protocols, best practices…**
- **Contact: Rob Koopman (ESA)**

Thank you for your attention!