Copernicus Cal/Val Solution

D3.1 Recommendations for R&D activities on Instrumentation Technologies

Ref: CCVS.TAR.D3.1

Version : 1.1

Date: 02/06/2022

GA number: 101004242

Document Reference

	Company
Work Package	3
WP leader	S. Clerc
Deliverable Title	Recommendations for R&D activities on instrumentation technologies
Delivery Number	D3.1
Delivery Type	Report
Dissemination Level	Public
Version	1.1
Date of issue	02/06/2022
Lead beneficiary	UTARTU
Lead authors	M. Aun (UTARTU), M. K. Sha (BIRA-IASB), F. Tack (BIRA-IASB), C. Tison (CNES), A. Meygret (CNES), M. De Mazière (BIRA-IASB)
Contributors	M. Bachmann (DLR), C. Bes (CNES), K. F. Boersma (KNMI), S. Clerc (ACRI-ST), A. Dick (CNES), Y. Ferrec (ONERA), A. Fix (DLR), G. Hajduch (CLS), S. Holzwarth (DLR), E. Jakobson (UTARTU), J. Kuhn (Heidelberg University), S. Labroue (CLS), C. Lacrouts (ACRI-ST), M. Ligi (UTARTU), A. Merlaud (BIRA-IASB), F. Nencioli (CLS), B. Pflug (DLR), C. Pierangelo (CNES), M. Raynal (CNES), T. Raynal (CNES), G. Tilstra (KNMI)
Reviewed by	E. Jakobson (UTARTU), L. Bourg (ACRI-ST)

Changes Log

Version	Date	Changes
1.0	02/06/2022	Initial Version
1.1	02/06/2022	Final Version

This project has received funding from the European Union's Horizon 2020 programme under grant agreement No 101004242.

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1. Introduction

1.1. Scope of the Document

The Document identifies the gaps in instrumentation technologies for pre-flight characterisation, on-board calibration and Fiducial Reference Measurements (FRM) used for calibration and validation (Cal/Val) activities for the current Copernicus missions. It also addresses the measurement needs for future Copernicus missions and gives a prioritised list of recommendations for R&D activities on instrumentation technologies.

Four types of missions are covered based on the division used in the rest of the CCVS project: optical, altimetry, radar and microwave and atmospheric composition.

It also gives an overview of some promising instrumentation technologies in each measurement field for FRM that could fill the gaps for requirements not yet met for the current and future Copernicus missions and identifies the research and development (R&D) activities needed to mature these example technologies. The Document does not provide an exhaustive list of all the new technologies being developed but will give a few examples for each field to show what efforts are being made to fill the gaps. None of the examples is promoted as the best possible solutions. The selection is based on the authors' knowledge during the preparation of the Document.

The information included is mainly collected from the deliverables of work packages 1 and 2 in the CCVS project. The new technologies are primarily from the interviews with various measurement networks and campaigns carried out in tasks 2.4 and 2.5. Reference documents can be found in section 1.3.

DISCLAIMER

Examples of new technologies included in the Document illustrate possible solutions to the gaps in Cal/Val activities and are not promoted as the best or only ones under development.

1.2. Structure of the Document

The Document is divided into six sections.

Section 1 describes the scope of the Document, outlines the structure of this Document, identifies the reference documents, and explains the used acronyms and abbreviations.

Sections 2, 3, 4 and 5 are devoted to the gap analysis, recommendations and new technologies for Optical missions (Section 2), Altimetry (Section 3), Radar and Microwave (Section 4) and Atmospheric composition missions (Section 5).

In section 6, conclusions are presented with the main recommendations relevant for multiple mission types.

1.3. Reference documents

1.3.1. Deliverables of the CCVS project

Table 1: Reference documents

Id	Describtion
D1.1	Optical Missions Cal/Val requirements
D1.2	Altimetry Missions Cal-Val Requirements
D1.3	Radar and Microwave Imaging Missions Cal/Val requirements
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D2.1	On-board Calibration sources
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D2.3	Inter satellite comparisons
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D3.3	Copernicus Operational FRM network and Supersites
D3.4	Copernicus Cal/Val Data Distribution service

1.3.2. Other references

Abdalla, S., Kolahchi, A.A., Ablain, M., Adusumilli, S., Bhowmick, et al. (International Altimetry Team), 2021. Altimetry for the future: Building on 25 years of progress. *Advances in Space Research*, 68 (2), 319–363.

Adams, J., Gobron, N., Widlowski, J.-L., and Mio, C., 2016. A model-based framework for the quality assessment of surface albedo in situ measurement protocols. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 180, 126–146.

Alonso, K., Bachmann, M., Burch, K., Carmona, E., Cerra, D., de los Reyes, R., Dietrich, D., Heiden, U., Hölderlin, A., Ickes, J., Knodt, U., Krutz, D., Lester, H., Müller, R., Pagnutti, M., Reinartz, P., Richter, R., Ryan, R., Sebastian, I., and Tegler, M., 2019. Data Products, Quality and Validation of the DLR Earth Sensing Imaging Spectrometer (DESIS). *Sensors*, 19 (20).

Alonso-Montesinos, J., 2020. Real-Time Automatic Cloud Detection Using a Low-Cost Sky Camera. *Remote Sensing*, 12 (9).

Amediek, A., Ehret, G., Fix, A., Wirth, M., Büdenbender, C., Quatrevalet, M., Kiemle, C., and Gerbig, C., 2017. CHARM-F – a new airborne integrated-path differential-absorption lidar for carbon dioxide and methane observations: measurement performance and quantification of strong point source emissions. *Applied Optics*, 56 (18), 5182–5197.

André, G., Martín Míguez, B., Ballu, V., Testut, L., and Wöppelmann, G., 2015. Measuring Sea Level with GPS-Equipped Buoys: A Multi-Instruments Experiment at Aix Island. *The International Hydrographic Review*, (10).

Barriere, F.D.L., Ferrec, Y., Croizé, L., Ehrhardt, H., Gousset, S., and Coarer, E.L., 2021. Instrumental development of NanoCarb, a new spectro-imaging sensor. In: B. Cugny, Z. Sodnik, and N. Karafolas, eds. International Conference on Space Optics — ICSO 2020. SPIE, 1704–1717.

Biogeochemical-Argo Planning Group, 2016. The Scientific Rationale, Design and Implementation Plan for a Biogeochemical-Argo Float Array. https://doi.org/10.13155/46601.

Bonnefond, P., Haines, B.J., and Watson, C., 2011. In situ Absolute Calibration and Validation: A Link from Coastal to Open-Ocean Altimetry. In: S. Vignudelli, A.G. Kostianoy, P. Cipollini, and J. Benveniste, eds. *Coastal Altimetry*. Berlin, Heidelberg: Springer Berlin Heidelberg, 259–296.

Carberry, L., Roesler, C., and Drapeau, S., 2019. Correcting in situ chlorophyll fluorescence time-series observations for nonphotochemical quenching and tidal variability reveals nonconservative phytoplankton variability in coastal waters. *Limnology and Oceanography: Methods*, 17 (8), 462–473.

Chapman, L., 2007. Potential applications of near infra-red hemispherical imagery in forest environments. *Agricultural and Forest Meteorology*, 143 (1), 151–156.

Chen, H., Hooghiem, J., Brownlow, R., Kivi, R., Heikkinen, P., Leuenberger, M., Nyfeler, P., Ramonet, M., Lopez, M., Laemmel, T., Engel, A., Wagenhaeuser, T., Elvidge, E., Laube, J., Baier, B., Sweeney, C., Danis, F., Crevoisier, C., Zhou, M, Sha, M. K., de Maziere, M., Petri, C., Warneke, T., 2019. Specification for high accuracy in situ vertical profile measurements, Deliverable 3.1 for H2020 project RINGO (GA no 730944), Available from: https://www.icos-cp.eu/sites/default/files/2021-01/D3.1.%20Specification%20for%20high%20accuracy%20in%20situ%20vertical%20profile%20measurements.pdf [Accessed 12 May 2022].

Chupin, C., Ballu, V., Testut, L., Tranchant, Y.-T., Calzas, M., Poirier, E., Coulombier, T., Laurain, O., Bonnefond, P., and FOAM Project, T., 2020. Mapping Sea Surface Height Using New Concepts of Kinematic GNSS Instruments. *Remote Sensing*, 12 (16).

Claustre, H. & Co-Authors, 2010. Bio-Optical Profiling Floats as New Observational Tools for Biogeochemical and Ecosystem Studies: Potential Synergies with Ocean Color Remote Sensing. in Proceedings of OceanObs’09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, DOI:10.5270/OceanObs09.cwp.17.

Claustre, H., Johnson, K.S., and Takeshita, Y., 2020. Observing the Global Ocean with Biogeochemical-Argo. *Annual Review of Marine Science*, 12 (1), 23–48.

Concha, J.A., Bracaglia, M., and Brando, V.E., 2021. Assessing the influence of different validation protocols on Ocean Colour match-up analyses. *Remote Sensing of Environment*, 259, 112415.

Ermida, S.L., Trigo, I.F., DaCamara, C.C., Göttsche, F.M., Olesen, F.S., and Hulley, G., 2014. Validation of remotely sensed surface temperature over an oak woodland landscape — The problem of viewing and illumination geometries. *Remote Sensing of Environment*, 148, 16–27.

EURAMET SRNP 2020: European Metrology Network for Climate and Ocean Observation Stakeholder Needs Review Report 2020.

Goyens, C., De Vis, P., and Hunt, S.E., 2021. Automated Generation of Hyperspectral Fiducial Reference Measurements of Water and Land Surface Reflectance for the Hypernets Networks. In: 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS. 7920–7923.

Goyens, C., Ruddick, K., and Kuusk, J., 2018. Spectral Requirements for the Development of a New Hyperspectral Radiometer Integrated in Automated Networks - the Hypernets Sensor. In: 2018 9th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS). 1–5.

Gruber, N., Doney, S.C., Emerson, S.R., Gilbert, D., Kobayashi, T., Körtzinger, A., Johnson, G.C., Johnson, K.S., Riser, S.C., and Ulloa, O., 2007. The ARGO-Oxygen Program - A white paper to promote the addition of oxygen sensors to the international Argo float program.

Guanter, L., Kaufmann, H., Segl, K., Foerster, S., Rogass, C., Chabrillat, S., Kuester, T., Hollstein, A., Rossner, G., Chlebek, C., Straif, C., Fischer, S., Schrader, S., Storch, T., Heiden, U., Mueller, A., Bachmann, M., Mühle, H., Müller, R., Habermeyer, M., Ohndorf, A., Hill, J., Buddenbaum, H., Hostert, P., Van der Linden, S., Leitão, P.J., Rabe, A., Doerffer, R., Krasemann, H., Xi, H., Mauser, W., Hank, T., Locherer, M., Rast, M., Staenz, K., and Sang, B., 2015. The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation. *Remote Sensing*, 7 (7), 8830–8857.

Guillevic P., F. Göttsche, J. Nickeson, G. Hulley, D. Ghent, Y. Yu, I. Trigo, S. Hook, J. A. Sobrino, J. Remedios, M. Román and F. Camacho, 2018. Land Surface Temperature Product Validation Best Practice Protocol, CEOS WGCV LPV.

Göttsche, F.-M., Olesen, F.-S., and Bork-Unkelbach, A., 2013. Validation of land surface temperature derived from MSG/SEVIRI with in situ measurements at Gobabeb, Namibia. *International Journal of Remote Sensing*, 34 (9–10), 3069–3083.

Göttsche, F.-M., Olesen, F.-S., Trigo, I.F., Bork-Unkelbach, A., and Martin, M.A., 2016. Long Term Validation of Land Surface Temperature Retrieved from MSG/SEVIRI with Continuous in-Situ Measurements in Africa. Remote Sensing, 8 (5).

Huot, Y. and Babin, M., 2010. Overview of Fluorescence Protocols: Theory, Basic Concepts, and Practice. In: D.J. Suggett, O. Prášil, and M.A. Borowitzka, eds. Chlorophyll a Fluorescence in Aquatic Sciences: Methods and Applications. Dordrecht: Springer Netherlands, 31–74.

Johnson, K.S., W.M. Berelson, E.S. Boss, Z. Chase, H. Claustre, S.R. Emerson, N. Gruber, A. Körtzinger, M.J. Perry, and S.C. Riser. 2009. Observing biogeochemical cycles at global scales with profiling floats and gliders: Prospects for a global array. Oceanography 22(3):216–225, https://doi.org/10.5670/oceanog.2009.81. Kleipool, Q., Ludewig, A., Babić, L., Bartstra, R., Braak, R., Dierssen, W., Dewitte, P.-J., Kenter, P., Landzaat, R., Leloux, J., Loots, E., Meijering, P., van der Plas, E., Rozemeijer, N., Schepers, D., Schiavini, D., Smeets, J., Vacanti, G., Vonk, F., and Veefkind, P., 2018. Pre-launch calibration results of the TROPOMI payload on-board the Sentinel-5 Precursor satellite. *Atmospheric Measurement Techniques*, 11 (12), 6439–6479.

Joly, L., Coopmann, O., Guidard, V., Decarpenterie, T., Dumelié, N., Cousin, J., Burgalat, J., Chauvin, N., Albora, G., Maamary, R., Miftah El Khair, Z., Tzanos, D., Barrié, J., Moulin, É., Aressy, P., and Belleudy, A., 2020. The development of the Atmospheric Measurements by Ultra-Light Spectrometer (AMULSE) greenhouse gas profiling system and application for satellite retrieval validation. *Atmospheric Measurement Techniques*, 13 (6), 3099–3118.

Karion, A., Sweeney, C., Tans, P., and Newberger, T., 2010. AirCore: An Innovative Atmospheric Sampling System. *Journal of Atmospheric and Oceanic Technology*, 27 (11), 1839–1853.

Konarska, J., Klingberg, J., and Lindberg, F., 2021. Applications of dual-wavelength hemispherical photography in urban climatology and urban forestry. *Urban Forestry & Urban Greening*, 58, 126964.

Kuhn, J., Bobrowski, N., Wagner, T., and Platt, U., 2021. Mobile and high-spectral-resolution Fabry–Pérot interferometer spectrographs for atmospheric remote sensing. *Atmospheric Measurement Techniques*, 14 (12), 7873–7892.

Labsphere, Inc., 2019. “Top-of-Atmosphere reflectance calibration of satellite and airborne sensor systems using FLARE vicarious calibration network”, FLARE whitepaper. Available from: https://www.labsphere.com/wp-content/uploads/2021/09/FLARE.pdf [Accessed 12 May 2022].

Letu, H., Nagao, T.M., Nakajima, T.Y., and Matsumae, Y., 2014. Method for validating cloud mask obtained from satellite measurements using ground-based sky camera. *Applied Optics*, 53 (31), 7523–7533.

Merlaud, A., Tack, F., Constantin, D., Georgescu, L., Maes, J., Fayt, C., Mingireanu, F., Schuettemeyer, D., Meier, A.C., Schönardt, A., Ruhtz, T., Bellegante, L., Nicolae, D., Den Hoed, M., Allaart, M., and Van Roozendael, M., 2018. The Small Whiskbroom Imager for atmospheric compositioN monitorinG (SWING) and its operations from an unmanned aerial vehicle (UAV) during the AROMAT campaign. *Atmospheric Measurement Techniques*, 11 (1), 551–567.

Meygret, A., Santer, R.P., and Berthelot, B., 2011. ROSAS: a robotic station for atmosphere and surface characterization dedicated to on-orbit calibration. In: J.J. Butler, X. Xiong, and X. Gu, eds. *Earth Observing Systems* XVI. SPIE, 374–385.

Mitchum, G.T., 2000. An Improved Calibration of Satellite Altimetric Heights Using Tide Gauge Sea Levels with Adjustment for Land Motion. *Marine Geodesy*, 23 (3), 145–166.

Niro, F., Goryl, P., Dransfeld, S., Boccia, V., Gascon, F., Adams, J., Themann, B., Scifoni, S., and Doxani, G., 2021. European Space Agency (ESA) Calibration/Validation Strategy for Optical Land-Imaging Satellites and Pathway towards Interoperability. Remote Sensing, 13 (15).

Piegari, E., Gossn, J.I., Juárez, Á., Barraza, V., González Trilla, G., and Grings, F., 2020. Radiometric characterization of a marsh site at the Argentinian pampas in the context of HYPERNETS project (a new autonomous hyperspectral radiometer). *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-3/W2-2020, 95–100.

Rivera, G. and Healey, N. C., 2017. System Description Plan. Tower Instrumentation for Russell Ranch Site, Jet Propulsion Laboratory, California Institute of Technology. CL#17-0875.

Rouse J, Haas R, Schell J, Deering D., 1974. Monitoring vegetation systems in the Great Plains with ERTS. In: Paper presented at NASA. Goddard space flight center 3d ERTS-1 symposium, Greenbelt, MD.

Schiller, S.J., 2019. Demonstration of the Mirror-based Empirical Line Method (MELM), 18th Annual Joint Agency Commercial Imagery Evaluation (JACIE) Workshop, Reston, Virginia, Sept. 24-26.

Sha, M.K., De Mazière, M., Notholt, J., Blumenstock, T., Chen, H., Dehn, A., Griffith, D.W.T., Hase, F., Heikkinen, P., Hermans, C., Hoffmann, A., Huebner, M., Jones, N., Kivi, R., Langerock, B., Petri, C., Scolas, F., Tu, Q., and Weidmann, D., 2020. Intercomparison of low- and high-resolution infrared spectrometers for ground-based solar remote sensing measurements of total column concentrations of CO_2, CH_4, and CO. *Atmospheric Measurement Techniques*, 13 (9), 4791–4839.

Silny J., and Schiller, S., 2013. Method and system for spectral calibration of a remote sensing sensor and a synthetic target having a tunable spectral composition, US8507843, United States Patent and Trademark Office.

Skakun, S., Vermote, E.F., Artigas, A.E.S., Rountree, W.H., and Roger, J.-C., 2021. An experimental sky-image-derived cloud validation dataset for Sentinel-2 and Landsat 8 satellites over NASA GSFC. *International Journal of Applied Earth Observation and Geoinformation*, 95, 102253.

Tack, F., Merlaud, A., Iordache, M.-D., Pinardi, G., Dimitropoulou, E., Eskes, H., Bomans, B., Veefkind, P., and Van Roozendael, M., 2021. Assessment of the TROPOMI tropospheric \chemNO_2 product based on airborne APEX observations. *Atmospheric Measurement Techniques*, 14 (1), 615–646.

Tian, J., Zhang, Y., Klein, S.A., Wang, L., Öktem, R., and Romps, D.M., 2021. Summertime Continental Shallow Cumulus Cloud Detection Using GOES-16 Satellite and Ground-Based Stereo Cameras at the DOE ARM Southern Great Plains Site. *Remote Sensing*, 13 (12).

Werkmeister, A., Lockhoff, M., Schrempf, M., Tohsing, K., Liley, B., and Seckmeyer, G., 2015. Comparing satellite- to ground-based automated and manual cloud coverage observations – a case study. *Atmospheric Measurement Techniques*, 8 (5), 2001–2015.

Wolff, S., Ehret, G., Kiemle, C., Amediek, A., Quatrevalet, M., Wirth, M., and Fix, A., 2021. Determination of the emission rates of \chemCO_2 point sources with airborne lidar. *Atmospheric Measurement Techniques*, 14 (4), 2717–2736.

Woodgate, W., van Gorsel, E., Hughes, D., Suarez, L., Jimenez-Berni, J., and Held, A., 2020. THEMS: an automated thermal and hyperspectral proximal sensing system for canopy reflectance, radiance and temperature. *Plant Methods*, 16 (1), 105.

Vuilleumier, L., Harris, T., Nenes, A., Backes, C., and Vernez, D., 2021. Developing a UV climatology for public health purposes using satellite data. *Environment International*, 146, 106177.

Wunch, D., Toon, G.C., Wennberg, P.O., Wofsy, S.C., Stephens, B.B., Fischer, M.L., Uchino, O., Abshire, J.B., Bernath, P., Biraud, S.C., Blavier, J.-F.L., Boone, C., Bowman, K.P., Browell, E.V., Campos, T., Connor, B.J., Daube, B.C., Deutscher, N.M., Diao, M., Elkins, J.W., Gerbig, C., Gottlieb, E., Griffith, D.W.T., Hurst, D.F., Jiménez, R., Keppel-Aleks, G., Kort, E.A., Macatangay, R., Machida, T., Matsueda, H., Moore, F., Morino, I., Park, S., Robinson, J., Roehl, C.M., Sawa, Y., Sherlock, V., Sweeney, C., Tanaka, T., and Zondlo, M.A., 2010. Calibration of the Total Carbon Column Observing Network using aircraft profile data. *Atmospheric Measurement Techniques*, 3 (5), 1351–1362.

1.3.3. Referenced internet web addresses

Internet web addresses referenced in the Document are presented in Table 2.

Table 2: Uniform Resource Locators (URL)

Id	Description	Reference
URL-1	TRUTHS mission website	https://www.esa.int/Applications/Observing_the_Earth/TRUTHS
URL-2	CLARREO Pathfinder website	https://clarreo-pathfinder.larc.nasa.gov/
URL-3	TENEVIA website	https://www.tenevia.com/en/
URL-4	The MetaSensing Electronic Corner Reflector webpage	https://www.geomatics.metasensing.com/ecr-c
URL-5	Sentinel-5P Campaigns website	https://s5pcampaigns.aeronomie.be/

1.4. Acronyms and abbreviations

Acronyms used in the Document are presented in Table 3.

Table 3: Acronyms

Acronym	Definition
AERONET	AErosol RObotic NETwork
AMULSE	Atmospheric Measurements by Ultra-Light Spectrometer
BGC-Argo	Biogeochemical-Argo Planning Group
BOA	Bottom-of-atmosphere
BRDF	The Bidirectional Reflectance Distribution Function
Cal/Val	Calibration and Validation
CCVS	Copernicus Cal/Val Solution
CDOM	Colored Dissolved Organic Matter
CH_4	Methane
CHIME	The Copernicus Hyperspectral Imaging Mission
CIMR	Copernicus Imaging Microwave Radiometer
CL	Close Loop
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CMIX	Cloud Masking Inter-Comparison Exercise

CNES	Centre National d'Etudes Spatiales
CNR	Consiglio Nazionale delle Ricerche
CO	Carbon monoxide
CO_2	Carbon dioxide
CO2M	Copernicus Carbon Dioxide Monitoring mission
COCCON	Collaborative Carbon Column Observing Network
CONICET	National Scientific and Technical Research Council - Argentina
CPF	The CLARREO Pathfinder
CSA	Canadian Space Agency
CSC	Copernicus Space Component
DHP	Digital Hemispherical Photography
DLR	Germany's research centre for aeronautics and space
DOAS	Differential Optical Absorption Spectroscopy
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DTM	Digital Terrain Models
ESA	European Space Agency
EUFAR	The EUropean Facility for Airborne Research
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FOV	Field of View
FRM	Fiducial Reference Measurements
FTIR	Fourier transform infrared
GBOV	Ground-Based Observations for Validation
GEO	Geostationary Orbit
GFZ	Helmholtz Centre Potsdam - German Research Centre for Geosciences
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
H2020	Horizon 2020
H_2O	Water
HAPS	High-Altitude Pseudo-Satellites
HCHO	Formaldehyde
HDO	Deuterium hydrogen monoxide
HF	High-Frequency
HySICS	HyperSpectral Imager for Climate Science
ICOS	Integrated Carbon Observation System
IFOV	Instantaneous Field of View
IGN	Institut National de l'Information Géographique et Forestière
IGS	International GNSS Service
IOP	Inherent Optical Properties
IoT	Internet of Things
JPL	NASA's Jet Propulsion Laboratory
KIT	Karlsruhe Institute of Technology
LAI	Leaf Area Index
LED	Light-Emitting Diode
LEO	Low Earth Orbit
LIDAR	Laser Image Detection and Ranging
LST	Land Surface Temperature
LSTM	The Copernicus Land Surface Temperature Monitoring Mission
MIR	Mid-infrared
MRD	Mission Requirements Document
MTF	Modulation Transfer Function
MWR	MicroWave Radiometer
N_2O	Nitrous oxide
NASA	The National Aeronautics and Space Administration
NASA GSFC	NASA Goddard Space Flight Center

NDACC-IRWG	InfraRed Working Group of the Network for the Detection of Atmospheric Composition Change
NIR	Near-infrared
NIST	National Institute of Standards and Technology
NO_2	Nitrogen dioxide
NPL	National Physical Laboratory
OCN	Ocean
OCS	Carbonyl sulfide
OL	Open Loop
OLTC	Open Loop Tracking Command
OSTST	Ocean Surface Topography Science Team
PC	Personal Computer
POCA	Point-Of-Closest-Approach
POD	Precise Orbit Determination
PSF	Point Spread Function
R&D	Research and Development
RAMOS	Technical Assistance For A Romanian Atmospheric Observation System
RBINS	Royal Belgian Institute for Natural Sciences
REGINA	GNSS Receiver Network for IGS and Navigation
RF	Radio Frequency
ROSAS	RObotic Station for Atmosphere and Surface characterization
ROSE-L	Radar Observation System for Europe in L-band
RS	Reflected Solar
RVL	Radial Velocity
SAR	Synthetic Aperture Radar
SI	International System of Units
SLR	Satellite Laser Ranging
SNR	Signal-to-Noise Ratio
SO_2	Sulfur dioxide
SPARC	the Specular Array Radiometric Calibration
SSH	Sea Surface Height
SU	Sorbonne University
SURFRAD	Surface Radiation Network
SVANTE	The Sentinel-5 Precursor VAlidatioN and calibraTion Experiment
SVF	Sky View Factors
SWH	Significant Wave Height
SWIR	Shortwave infrared
TAC	Thematic Assembly Center
TBD	To be determined
TCCON	Total Carbon Column Observing Network
THEMS	Thermal and Hyperspectral Monitoring System
TIR	Thermal Infrared
TOA	Top-Of-Atmosphere
TOPS	Terrain Observation with Progressive Scan
TRL	Technology Readiness Level
TRM	Transmit and Receive Module
TROPOMI	The TROPOspheric Monitoring Instrument
TRP	Transponder
TRUTHS	Traceable Radiometry Underpinning Terrestrial- and Helio-Studies
UAV	Unmanned Aerial Vehicles
UKSA	United Kingdom Space Agency
ULM	Ultra-Light Motorized
USO	Ultra-Stable Oscillator
UV	Ultraviolet

UV-VIS	Ultraviolet-visible
VIS	Visible
VNIR	Visible and Near-Infrared
WMO	World Meteorological Organization

2. Optical missions

2.1. Gaps and limitations in instrumentation capabilities

2.1.1. Instrumentation technologies used

Optical missions of the Copernicus Space Component are classified as Surface Colour missions (Sentinel2/MSI, Sentinel3/OLCI, Sentinel3/SYN, CHIME) and Surface Temperature missions (Sentinel3/SLSTR, LSTM). CHIME and LSTM are future missions still under development. Optical missions and their Cal/Val requirements are thoroughly described in D1.1.

Radiometric calibration starts with pre-launch characterisation activities that describe the sensor response in conditions mimicking space (Niro, 2021). As described in D2.1, many established sources (e.g., monochromators, tuneable lasers) are available for the on-ground characterisation and calibration of optical sensors in laboratories.

On-board calibration is set to update calibration factors once the instrument is in space. Here no full SI traceability is possible. Optical missions are calibrated with various on-board calibration subsystems and methods described in D2.1. Different technologies exist to provide absorption features regarding the means of spectral on-board calibration equipment. These include tunable laser diodes used in S5P and S5 (details in D2.1, Ch. 3.4 and Ch. 3.6.1.); doped Spectralon sphere (e.g., EnMAP mission, see Guanter et al., 2015); LEDs with specified emission (e.g., DESIS mission, see Alonso et al., 2019).

Another common spectral calibration source is a doped spectral diffuser, which is also used in combination with the solar Fraunhofer lines on the diffuser. This approach is described in D2.1 (Ch. 3.1, 4.2) for Sentinel 3 OLCI and is reported to provide good results.

For optical sensors in VIS and SWIR wavelength ranges, radiometric calibration is carried out using diffuser panels that should have nearly-Lambertian reflectance properties, but due to imperfections of coating material and ageing, they have not. Secondary diffusers are used to precisely characterise the ageing of the primary diffuser. (Niro, 2021). Vicarious targets are used in case of nonexistent or damaged on-board calibration devices or to validate on-board calibration devices.

A large part of the validation activities is done with on-ground measurements.

2.1.2. Gaps in pre-flight characterisation and on-board calibration technologies

2.1.2.1. Radiometric calibration

Radiometric calibration is performed through Sun diffusers working either in reflectance or transmission and active sources (diodes, lamps, black-bodies).

Solar reflectance diffusers are used for Sentinel-2 MSI, Sentinel-3 OLCI and SLSTR. While this technology ensures an efficient operational calibration which could probably not be obtained through other means, it can introduce radiometric calibration errors affecting the absolute radiometric uncertainty as well as the relative uncertainty (the error may not be constant spectrally or spatially and has a seasonal component linked to the Sun acquisition geometry). While the expected uncertainty of solar diffusers is a priori compatible with targeted radiometric performances (3% typically), it was not met for SLSTR A and B and OLCI-A. As described in deliverable D2.1, uncertainty on solar reflectance diffusers is dominated by BRDF characterization errors, as well as in-flight alignment uncertainty. Transmission diffusers may alleviate some of these issues.

2.1.2.2. Characterisation of straylight

The pre-flight characterisation includes the characterisation of straylight in the laboratory to generate straylight models and correction coefficients to correct these effects. Using a standard spectral characterisation bench can only manage spectral rejection. For straylight and crosstalk, special tests and strong optical engineering skills are needed to characterise them. It is also not a straightforward task to correct them by processing. Therefore, more emphasis must be put on these characterisations.

2.1.2.3. Spectral calibration and characterization

The main shortcomings of calibrations are not directly linked to limitations of the instruments but to the limited characterisation of the used on-board sources and their traceability to SI on which the accuracy depends (D2.1). Besides special systems, various vicarious calibration methods are used for optical missions, including radiometry, geometry and MTF. Limitations of these methods are discussed in D2.2 and do not include specific gaps in the instrumentation.

For spectral on-board characterisation, multiple technical solutions (tunable lasers, doped spectralon, LEDs) exist for fine spectral resolution instruments. These are used for multispectral (e.g., OLCI, S5 TROPOMI) as well as for hyperspectral (e.g., EnMAP, DESIS) missions, where these means are adequate within limitations (see D2.1 and D2.2).

There is indeed a gap for adequately characterising the spectral characteristic in-orbit for broad-band multispectral instruments, as the previously mentioned solutions are not suitable for these sensors. In particular:

- Tunable laser diodes are suitable for NIR-SWIR but are technically not usable for the UV and blue wavelength ranges. Also, the actual measurements are carried out only for narrow wavelength intervals (narrow tuning range). Thus, an interpolation between these specific points is required, causing significant uncertainties in the case of broad-band sensors.
- The usage of a doped integration sphere is adequate for fine spectral resolution instruments in the VNIR range, where multiple narrow-band absorption features can be used for spectral characterisation and calibration. But especially in the SWIR, the spectral features are relatively broad, thus allowing only for a rough check of the spectral stability. In the case of broad-band sensors, these spectral features can’t be adequately resolved, and a proper spectral characterisation can’t be conducted.
- LEDs emitting at different wavelengths can be used for assessing the spectral characteristics in orbit, but significant shortcomings have to be considered. For example, DESIS shows a non-uniform illumination of the focal plane and unknown temporal stability (short-term and long-term stability), which was also identified within CCVS D2.1, Ch. 3.3. As before, broad-band sensors can’t adequately resolve these emission features, so the limitations of this approach result in even higher uncertainty.

Consequently, an adequate technical solution for in-orbit spectral characterisation of broad-band instruments is currently missing.

2.1.3. Gaps in in-situ measurement technologies

The validation of optical missions is primarily carried out using ground measurements. Many of the gaps affecting these activities could be resolved or reduced by applying different methods and changes in measurement activities. First of all, in some cases, like vegetation measurements, there is suitable instrumentation available, but the limitations are from the uneven and sparse measurement sites across the globe. So, there is a strong need for new locations. While planning these new sites, the accessibility (cloud coverage), spatial homogeneity, atmospheric properties, reflectance dynamics, etc., must be considered. Considering the amount of data collected and needed and the required simultaneity with the satellite passes, automated systems should be encouraged. Special attention must be given to the quality/validation status of the radiative transfer codes used to get the best TOA values from BOA ones. These issues regarding methods, sites and data are thoroughly discussed in deliverables D3.2, D3.3 and D3.4 accordingly.

Several gaps in Cal/Val activities of optical missions are connected with instrumentation technologies, which divide mainly between temporal and spectral constraints. Several new developments are expected to improve the situation.

For various products, higher temporal sampling is needed. This is often a methodological question, but in some cases, the limit comes from technical issues, e.g., power supply issues for water measurements that restrict the frequency of measurements (D2.4). The temporal sampling should be high enough to cover atmosphere variations, BRDF variation for VNIR-SWIR spectral range, temperature variation and directional emissivity variations for TIR spectral range. For temperature variation in TIR spectral range, a very high temporal frequency is required to manage surface-level turbulences. A high temporal measurement cycle is another point that advocates for the use and development of automatic measurement systems that would also solve the issues with data handling and transmission. The focus should be on the automatic measurements supported by the campaign measurements.

Spectral gaps arise from the used range and resolution. The spectral range used for measurements has to cover all the Copernicus optical missions. CHIME is the most demanding for VNIR-SWIR (400 to 2500 nm) and LSTM for TIR (8-12µm). A similar or better spectral resolution is needed to support the validation of future missions. For VNIR, the most constraining targets for spectral resolution definition are inland and coastal waters, and the atmosphere, the resolution should be 2 nm or better. For SWIR bands, the constraining targets are land use and urban characterization, and the resolution should be better than 10 nm. For TIR spectral range, the exact resolution should still be discussed; the high resolution is unnecessary for temperature/emissivity retrieval. Still, it might be helpful for the atmosphere optical properties retrieval. To respect the Shannon sampling, the spectral sampling should be twice higher than the spectral resolution (5 nm or better for VNIR/SWIR, TBD for TIR). There is a need for the hyperspectral or multispectral instrument to meet these requirements. Several instruments and networks (e.g., Hypernets) are being developed that are discussed in Section 2.2.2. These devices could also benefit from shortwave radiation measurements where mainly broadband instruments are available. Currently, there is a lack of instruments for some variables like shortwave albedo.

Another aspect that must be considered in the optical domain is the problems with atmospheric corrections. There is a need for a simultaneous ground and atmosphere characterisations for better validation of the products. This is also a reason to support validation sites covered in D3.3. Different directional measurements could also benefit the process. The cloud screening of optical satellite data is strongly connected with the atmospheric correction. There is a crucial lack of independent reference data to validate cloud screening. A new technology to fill this gap is the use of a Hemispherical camera for cloud cover assessment.

In general, the instruments used for calibration need to be much more accurately calibrated (1-2% today, better tomorrow?) than the sensor to calibrate (3% target today, 1% tomorrow – cf. water colour missions). There should be traceability to SI for calibrations. In VNIR-SWIR spectral range, using the same instrument to measure the downwelling and upwelling flux for reflectance assessment allows partially getting rid of its calibration.

We need more focus on the importance of the calibration/characterization of instruments/artefacts (e.g., panels). Even when using panels, understanding Solar irradiance is important. The calibrations are based on radiance or reflectance (e.g., using an on-board diffuser). The latter does not need a solar irradiance spectrum. On the contrary, radiance-based calibration depends on the solar spectrum used. A spectral bias is introduced if a different solar spectrum is used between calibration measurements and the satellite sensor data. Therefore, efforts are needed and made by CEOS to standardize solar models.

Finally, there are issues with measurement coverage and access. Manually operated spectrometers cover only a limited area, disturb the field site, and have a limited height of measurements (wide FOV is required)) and they are not suitable for certain surface types like forests and water. These gaps could be solved using masts, towers, unmanned aerial and water vehicles. The necessary height of measurement towers to measure high enough over the canopy depends on the surface (Adams et al., 2016). They have to be tall, and multi-angular measurements from towers assume that a whole area around them has the same multi-angular properties. It is very likely not the case in the case of a low tower height above a forest. Also, the tower area is usually not representative of a satellite pixel. However, tower-based spectrometers are the only real way to have long term autonomous measurements. Limitations of the measurement towers can be partly overcome with UAV-s, e.g., UAV-hyperspectral push-broom imager for better ground coverage. UAVs are a good option for campaign-based measurements that do not demand high temporal frequency. The existing off-the-shelf instruments are generally not meant for Cal/Val activities and are therefore not characterised enough with a traceable calibration to answer our needs. Small and easily deployable instruments have to be developed for these different platforms. All instruments used should have better performance than the satellite sensor they are calibrating. With aerial instruments, legislation issues limiting their use must be considered.

In some cases, there are gaps due to limited manufacturers who offer specific instruments. There are very few instrument providers for inherent optical properties measurements, and the running of these instruments is difficult. There is a need for a European manufacturer, as calibration and maintenance time is extended if devices have to be sent far. Expertise is needed in Europe to handle IOP instruments.

2.1.4. Summary of gaps

2.1.4.1. Pre-flight characterisation and on-board calibration technologies

- Solar reflectance diffusers can introduce radiometric calibration errors due to errors in BRDF characterization and uncertainty in in-flight alignment
- On-board means for characterizing the spectral properties of broad-band multispectral instruments are insufficient

- Full characterisation of straylight and crosstalk is not fully implemented

2.1.4.2. In-situ measurements

- Existing instruments are generally not meant for Cal/Val activities and are therefore not characterised enough with a traceable calibration
- Accurate calibration is needed for the instruments developed for validation activities, and the calibration should be tracible to SI
- Full characterisation of straylight and crosstalk is not fully implemented for instruments used in validation activities
- There is a lack of instruments for reflectance assessment measuring the downwelling and upwelling flux with the same sensor at the same time for realizing that the achieved reference data are much more accurately than the data to validate/calibrate
- Independent reference data are required for validation of cloud screening
- Used temporal resolution is insufficient to validate some products as it does not cover atmospheric and temperature variations.
- There is a lack of data and simultaneity with satellite passes
- The current measurement systems' spectral resolution and range do not meet future needs.
- The current measurement systems’ viewing range does not satisfy future needs
- Manually operated spectrometers cover only a limited area, disturb the field site, have a limited height of measurements (wide FOV is required), and are not suitable for certain surface types like forests and water

2.1.5. Recommendations

2.1.5.1. Pre-flight characterisation and on-board calibration technologies

- The focus must be put on the importance of the calibration/characterization of instruments/artefacts. **Criticality – high, effort needed – medium**
- Full characterisation of straylight and crosstalk is needed. **Criticality - high, effort needed – high**
- Technical solutions need to be developed to characterise the spectral properties of broad-band multispectral instruments, as current means for on-board spectral characterization (tunable lasers, doped spectralon, LEDs) are *only* suitable for high spectral resolution instruments**. Criticality – high, effort needed – high**
- Radiometric calibration transmission diffusers should be investigated as possible alternatives to Solar reflectance diffusers. **Criticality – low, effort needed - medium**

2.1.5.2. In-situ measurements

- Technology with an extensive spectral range is needed to cover the spectral range of future missions. **Criticality – high, effort needed – low**
- New technology developments should be encouraged to allow measurements to generate reference data for cloud screening quality. **Criticality – high, effort needed – medium**

- The development of automatic systems should be endorsed. **Criticality – high, effort needed – high**
- Technical solutions need to be developed to measure the downwelling and upwelling flux with the same sensor at the same time **Criticality – medium, effort needed – low**
- To respect the Shannon sampling, the spectral sampling should be twice higher than the spectral resolution (5 nm or better for VNIR/SWIR, TBD for TIR). **Criticality – medium, effort needed – medium**
- BRDF or directional emissivity characterization needs to be done. **Criticality – medium, effort needed – high**
- Higher temporal sampling and continuous measurements should be encouraged to limit time interpolation in measurements and be as close as possible to simultaneous measurements between the sensor to calibrate or validate and the reference sensor. **Criticality – medium, effort needed – medium**
- Small and easily deployable instruments (UAVs etc.) should be developed to cover the limitations of area coverage, the height of measurements and site access. **Criticality -medium, effort needed – medium**
- Continuing development of different hyperspectral instruments is important to cover the spectral resolution of future missions. **Criticality – medium, effort needed – high**

2.2. Examples of new instrumentation technologies

2.2.1. BGC-ARGO

2.2.1.1. Overview

In situ measurement of the chlorophyll concentration is usually performed thanks to pigment analysis of water samples. However, this method is costly and time-consuming, and some regions remain under-sampled to the difficulty of accessing it. Autonomous profiling floats were developed to monitor several biogeochemical variables (chlorophyll concentration, CDOM, particulate backscattering, O_2, pH, etc.) on a global scale. It has been demonstrated that these floats have the potential to increase our knowledge and understanding of biogeochemical processes (Claustre et al., 2010; Gruber et al., 2007; Johnson et al., 2009). The BGC-Argo program, launched in 2016, aims to organize and support the development and sustained operation of a network of 1000 profiling floats (Biogeochemical-Argo Planning Group, 2016).

2.2.1.2. Methodology

<u>**Profile acquisition**</u>

BGC-Argo floats measure the profile of different parameters with a regular frequency (~11 days). The timeline of BGC-Argo data is the following. First, the float dives down to a “parking depth” (about 1000 m), where it drifts for about nine days. The floats then dive to 2000 m and acquire a profile of physical and biogeochemical parameters while surfacing. Satellite communication transmits the data to the ground station when the float is at the surface (Figure 1a).

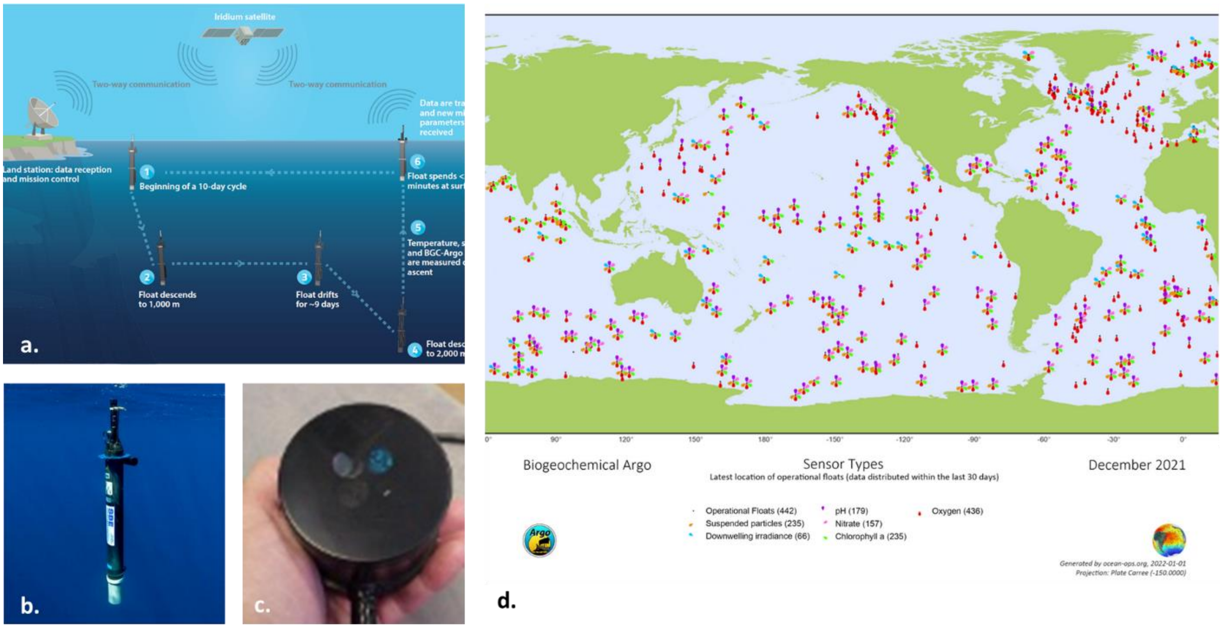

Figure 1: (a) Schematic of a BGC-Argo float cycle (Claustre et al., 2019), (b) BGC-Argo, (c) Sea-Bird ECO Puck sensor, and (d) map of BGC-Argo floats in operation in December 2021.

One of the precious advantages of BGC-Argo is that the data are available for users soon after their acquisition. Conversely, for pigments analysis, it may take several weeks or even months before the publication of the data.

<u>Sensor</u>

BGC-Argo floats are equipped with a bio-optical sensor for chlorophyll fluorescence (Sea-Bird ECO Puck Figure 1c). Fluorescence can be converted into chlorophyll concentration since chlorophyll molecules emit a fraction of the light they absorb as fluorescence (Huot and Babin, 2010).

It is generally considered that the chlorophyll concentration from BGC-Argo is given with an error of 50%. However, this error can be lower after applying the quality control in delayed mode. Three corrections are applied in delayed mode to improve the data retrieving: the dark correction, the quenching correction, and the slope correction (the slope used to extrapolate the data up to the surface).

New developments are being done by adding new parameters to measure, but every added instrument changes the characteristic of the float and must be carefully assessed. For example, adding a hyperspectral radiometer has been tested.

2.2.1.3. Ocean colour data validation

<u>Advantages</u>

BGC-Argo floats can be useful for validating ocean colour data and, notably, for a new mission. They cover a vast part of the ocean (and different water classes, Figure 1d), and data are available soon after the acquisition. As BGC-Argo floats are distributed globally and measure in every condition, the spatial and temporal biases in match-ups with ocean colour are reduced. That is why part of the European project EuroSea aimed to demonstrate the efficiency of BGC-Argo to validate S3A&B ocean colour observations.

Drawbacks

The mode quality control of the BGC-Argo floats is under development, and the use of ocean colour data to perform the QC of BGC-Argo is studied. Performing ocean colour observation validation with BGC-Argo data can lead to biased results.

Another point to raise is that the ratio between fluorescence and chlorophyll is not constant. This ratio varies in function of the phytoplankton taxonomy, cell size, pigment packaging and nonphotochemical quenching (Carberry et al., 2019).

To be used as valuable data for satellite data validation, further development of the quality control of the BGC-Argo measurement should be achieved. First, to improve the conversion from fluorescence to chlorophyll concentration, then to ensure that BGC-Argo and satellite data are independent.

2.2.2. FLARE

2.2.2.1. Description

The FLARE (Field, Line-of-sight Automated Radiance Exposure) system developed by LabSphere relies upon convex orientable mirrors (called SPARC, The SPecular Array Radiometric Calibration) to create two arrays of calibration targets for deriving absolute calibration coefficients of Earth remote sensing systems in the solar reflective spectrum. The first is an array of single mirrors used to oversample the sensor’s point spread function (PSF), providing the necessary spatial quality information to perform a sensor's radiometric calibration when viewing small targets. The second is a set of panels consisting of multiple mirrors designed to stimulate detector response with known at-sensor irradiance traceable to the exo-atmospheric solar spectral constant. The measuring concept is described in Figure 2. (Labsphere Inc, 2019; Schiller, 2019; Silny and Schiller, 2013).

In addition, a Solar Irradiance radiometer is used to estimate atmospheric transmission conditions.

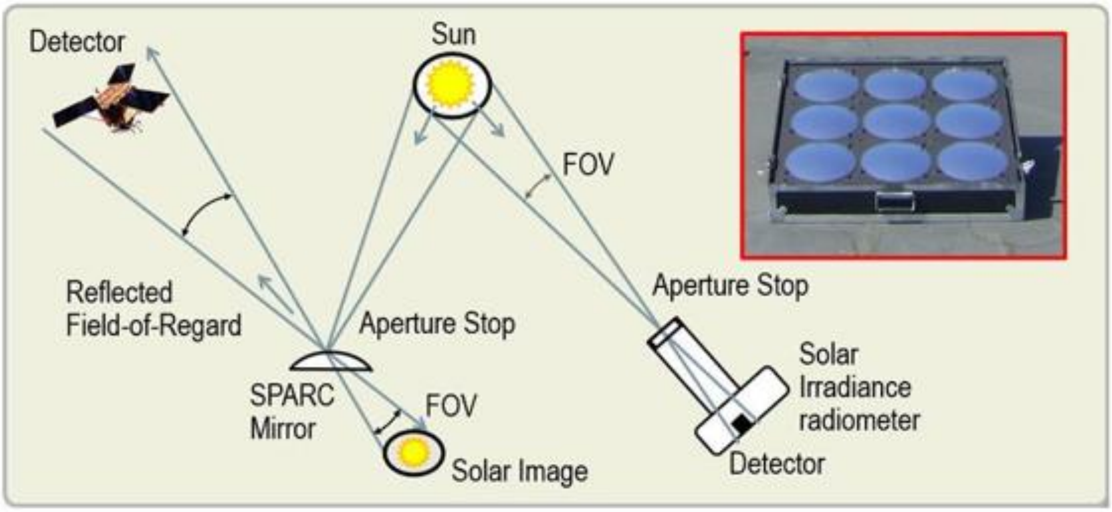

Figure 2: SPARC vicarious calibration concept (courtesy Labsphere).

The system can be used to:

- Characterize the PSF
- Verify the response linearity (using an increasing number of identical mirrors)
- Monitor the sensor's radiometric response

The general uncertainty of the FLARE system is about 5%, and it is dependent on atmospheric conditions. The aim is to have the uncertainty closer to 3% in the future. The quality control has been manual, but some automated algorithms have been developed for clouds.

There are two operational units, one in South Dakota and one in Texas. The latter one will be moved to Hawaii.

2.2.2.2. R&D activities required

The system is currently pre-operational, and the estimated TRL level is 6. Some preliminary measurements with Landsat 9 and Sentinel-2 have been reported (e.g. Sentinel-2B Image Data Quality Report, Jan-March 2021). The preliminary results showed relatively strong temporal dispersion and discrepancies with assessment from other methods (especially for radiometry). The use of L1C data may explain some of these discrepancies. Systematic tests using L1B data should be carried out. There is a significant error source from simulated radiances and irradiance. The 5% accuracy has not yet been demonstrated.

The company wants to increase the mobility of the instrument and is trying to decrease its size.

2.2.3. Hemispherical camera for cloud cover assessment

2.2.3.1. Overview

To improve the accuracy of satellite products, accurate cloud masks are needed (Letu et al., 2014). The validation of cloud masks in satellite images is currently primarily performed using reference images labelled using a manual or semi-automatic approach. This methodology is highly time-consuming, not usable for systematic online validation and provides no reference data independent from satellite data.

The use of ground-based sky cameras could present an interesting alternative. Cloud detection is arguably simpler using sky images than satellite images, and reported accuracy is generally higher (94% accuracy typically, Alonso-Montesinos, 2020). Werkmeister et al. (2013) showed generally good agreement between satellite-derived estimates compared to hemispherical Sky Imager. Examples of satellite and SkyCam images are presented in Figure 3. Such devices are routinely used to monitor cloud cover over solar electric power plants, which opens potential synergies with satellite Cal/Val needs. A study on detecting shallow cumulus clouds from Geostationary Operational Environmental Satellite (GOES)-16 reflectance data, with cross-validation by observations from ground-based stereo cameras, was done by Tian et al. (2021), presenting a new promising method for it thanks to the ground validation.

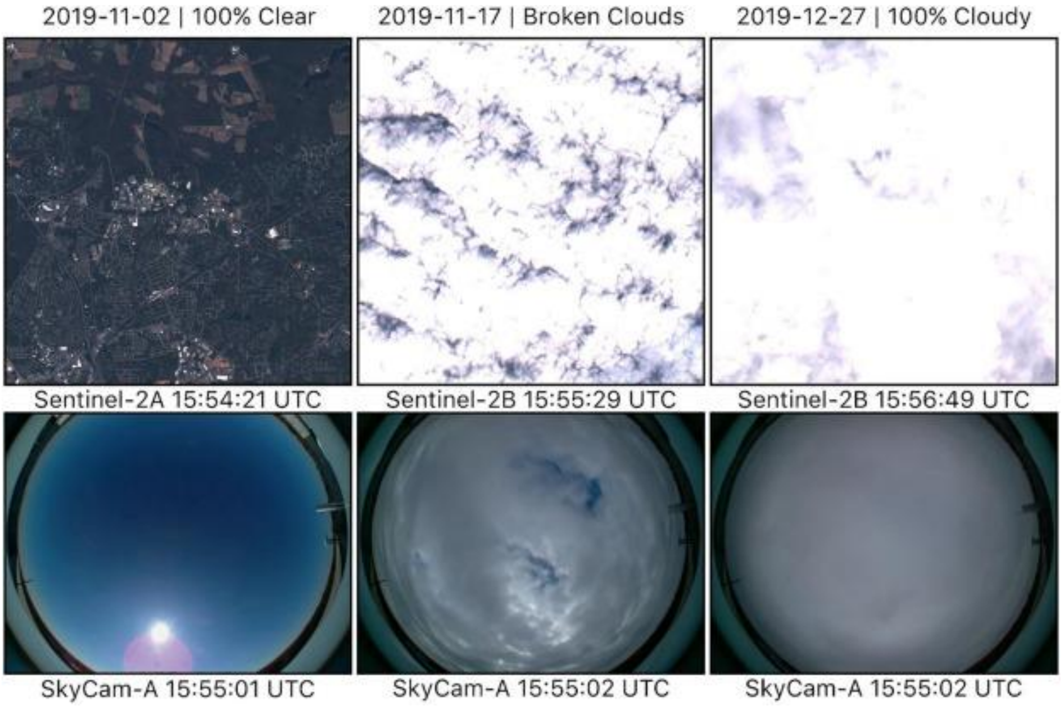

Figure 3: Example of Sentinel-2 images (top row) and ground-based sky images acquired with the SkyCam system over NASA GSFC for various cloud conditions, from Skakun et al. 2021.

2.2.3.2. R&D activities required

The first problem to be solved is providing a clear definition of a cloud for earth observation. A link between this definition and the sky images is to be established. To compare the ground-based image to the satellite image, the altitude of the cloud needs to be estimated. This can be done by stereo-vision using two sky imagers or a complementary sensor (ceilometer). Strictly simultaneous acquisitions are also required, especially in windy conditions.

Several R&D efforts are ongoing to develop methodologies for cloud mask validation based on sky cameras. The NASA GSFC team has set up the first site, while the University La Sapienza is currently deploying a similar system in the frame of the IDEAS-QA4EO project. Collaborations between the teams are organized in the frame of the CMIX initiative. A study about the use of sky cameras for cloud mask validation is also included in the CNES R&T plan for 2022. Such initiatives should be continued to assess the potential of the approach further.

To reach operational maturity, quality control and accuracy assessment questions should be addressed, and the satellite validation methodology should be consolidated.

In parallel, the deployment over measurement sites should be studied, taking advantage of existing synergies with existing measurement networks either dedicated to satellite Cal/Val (AERONET, GBOV, RadCalNet), scientific (e.g. ICOS, SURFRAD), or operational (electric power plants).

2.2.4. HYPERNETS

2.2.4.1. Description

The objective of the HYPERNETS project is to develop a new lower-cost hyperspectral radiometer and associated pointing system with an embedded calibration device for automated measurement of water and land bidirectional reflectance. It is meant to validate all optical bands on all optical satellite missions, including Sentinel 3A and 3B, Sentinel 2A and 2B, MODIS AQUA and TERRA, VIIRS, Landsat-8 and -9, PROBA-V, CHRIS-PROBA, ENMAP, Pléiades, etc.

HYPERNETS system will include, among other things, an innovative VIS-NIR spectrometer and an optional additional SWIR spectrometer, the integration of a simple RGB imaging camera alongside hyperspectral measurements, a calibration device, a pan-tilt mechanism, site-dependent auxiliary infrastructures (solar/wind power, acquisition PC, data transmission, mounting frame/mast, etc.) and complementary application-dependent optical instruments, a standardized data stream according to HYPERNETS protocols for easy and systematic exploitation by downstream validation networks. The units are 1.5 to 3 kg in weight. The needed power supply is 12 V, and solar power could be used. The system has 360 degrees range, with the mast being the black spot. The general schemes of the radiometer and measuring system are described in Figure 4.

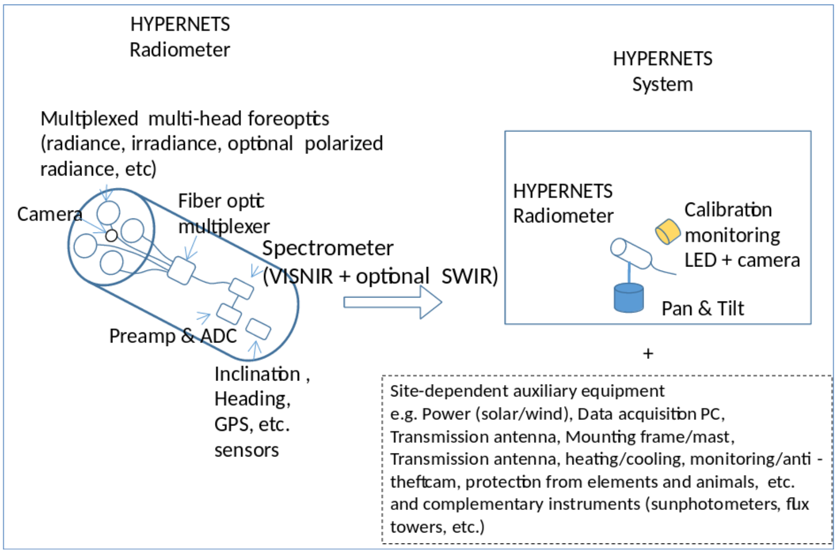

Figure 4: Schemas of the HYPERNETS radiometer and system (courtesy HYPERNETS).

The price of the instruments is not yet set but should be in the medium range (10k – 100k EUR).

HYPERNETS project is carried out by a consortium consisting of RBINS (coordinator), TARTU, SU, CNR, NPL, GFZ and CONICET. The technology readiness level is very high; the first instruments are already doing regular measurements. HYPERNETS will demonstrate instrument performance by deployment at 24 sites, covering a range of water and land types and climatic (cold/temperate/hot, dry/wet) and logistic (accessible/remote, European/non-European) conditions. They provide quality-controlled data of known uncertainty from the validation sites to the international user community (including Copernicus services, space agencies and validation entities) via networks according to user requirements and following internationally agreed standards, protocols and quality control. The project will end by May 2023; by then, commercial production of the instrument will be on the market under the brand Hypstar, including regular maintenance and calibration services.

More information is available from Goyens et al. (2021), Concha et al (2021), Piegari et al (2020), Goyens et al (2018).

2.2.4.2. R&D activities required

The HYPERNETS measuring system is still under development, and some work needs to be done before full deployment. Some instruments are already measuring, and the system has achieved TRL 7.

The complete characteristics and uncertainty budget will be made by the end of the project. So far, only a few preliminary satellite matchups have been done, but they look promising. There are also some gaps in the data processing chain as some instrumental corrections are missing.

The signal to noise ratio at shorter wavelengths is poor, so it will be decided how to solve it or what the usable spectral range will be.

The system shows great potential for Copernicus Cal/Val activities. Still, an assessment of suitability can be done after more testing has been done, and documentation has been provided with all the necessary information.

2.2.5. Hyperspectral evolution of ROSAS (CNES)

2.2.5.1. Overview

ROSAS (RObotic Station for Atmosphere and Surface characterization), an automated station deployed at La Crau in France, and Gobabeb, in Namibia, is dedicated to on-orbit sensor calibration and L2a products validation (Meygret et al., 2011). These two stations are part of the Radiometric Calibration Network (RadCalNet) and freely provide atmospheric and surface data to the public. ROSAS measurement protocol and data processing provide the BRDF of the site and the optical properties of the atmosphere.

The current photometer is derived from AERONET instruments developed by CIMEL. It has two collimators equipped with two detectors (one for VNIR and one for SWIR bands) and 12 spectral bands. To improve in-situ measurements and prepare for the calibration needs of future hyperspectral missions, CNES is working to replace the current instrument with a hyperspectral instrument.

This new system, also developed with CIMEL, includes 3 OEM spectrometers provided by HORIBA with the following features presented in Table 4.

Table 4. The features of OEM spectrometers.

Item	HYJ Specifications VNIR	HYJ Specifications SWIR 1	HYJ Specifications SWIR 2
Spectral range	350 – 1050 nm	1000 – 1700 nm	1600 - 2500 nm
Spectral resolution	<2 nm	<5 nm	<10 nm
Sensor Type	Si detector	InGaAs detector	InGaAs detector

The project is divided into several continuous phases. A preliminary laboratory mock-up will be assembled and tested during the year 2022. This mock-up aims to develop the first design of this new hyperspectral instrument (spectrometers, optical path, filters, etc.), work on its performance, and run numerous laboratory and field calibration tests. Then, a prototype will be produced, in 2023, with an instrument weight and space optimization. Operational field constraints, such as instrument stability in a real temperature range or a new robot regarding the instrument features, will also be considered. This prototype will be deployed at the La Crau site at the beginning of 2024 to provide hyperspectral BRDF and atmosphere optical properties.

2.2.5.2. R&D activities required

The main objective of this project is to replace the current instrument with this new hyperspectral instrument keeping the same measurement protocol. Even if the processing chain has been consolidated over more than 20 years of operations, it must be adapted to these new data.

The current photometer uses sky and in-situ sun measurements to calibrate itself. The irradiance calibration is based on the solar irradiance extinction and the Bouguer-Langley law, whereas the radiance calibration is based on molecular scattering. The radiance calibration is propagated for other wavelengths thanks to the irradiance cross-calibration. This new instrument design needs to validate these calibration principles based on the IFOV spectral stability.

The manufacturing itself of this new instrument is an important challenge as its performances have to be much better than the satellite optical sensors to calibrate. Miniaturization of three spectrometers, the temperature stability of detectors (especially for the SWIR detector), high radiances dynamics between ground, sky and sun observations, weight and the design of a new robotization, power supply, laboratory calibration and in-field calibration tests are the main issues at stake during the development.

The project is fully funded by CNES with a CIMEL contribution.

2.2.6. Infrared hemispherical camera for enhanced LAI retrieval

2.2.6.1. Overview

Digital hemispherical photography (DHP) is widely used to measure the radiative environment and estimate sky view factors (SVF) in urban areas and leaf area index (LAI) in forests. However, it is challenging to distinguish trees from buildings or leaves from stems and branches. Several authors (Chapman 2017, Konarska et al. 2021) have considered photographs with visible and NIR channels to classify pixels into the sky, and green and woody plant elements in urban areas.

The Konarska et al. study used a modified Nikon D5100 digital camera. The camera’s Bayer-filter sensor is made of pixel sensors sensitive to red, green and blue (R, G, B) light. These three channels are combined to create a full-colour RGB image. As in most digital cameras, however, the image sensor is sensitive not only to visible light but also to NIR, which is thus blocked by a filter called a hot mirror to produce images in the visible range. For the study, the hot mirror was professionally replaced with an NDVI Blue IR glass filter, model ZB2 (Kolari Vision, Raritan, New Jersey, USA). Several companies offer such camera conversion services worldwide for around 250–350 USD, depending on the camera model and the chosen filter.

An example of images acquired by the modified camera is displayed in Figure 5 below. The approach could be beneficial in determining the LAI of evergreen trees. It should also improve the accuracy of LAI retrieval for deciduous vegetations (accounting for the partial masking of woody elements by leaves). In urban areas, changes in the landscape due to human activity may interfere with RGB-based LAI retrieval algorithms, while the NIR channel provides a more robust identification of leaves. Finally, note that all satellite vegetation retrieval algorithms use information from NIR channels.

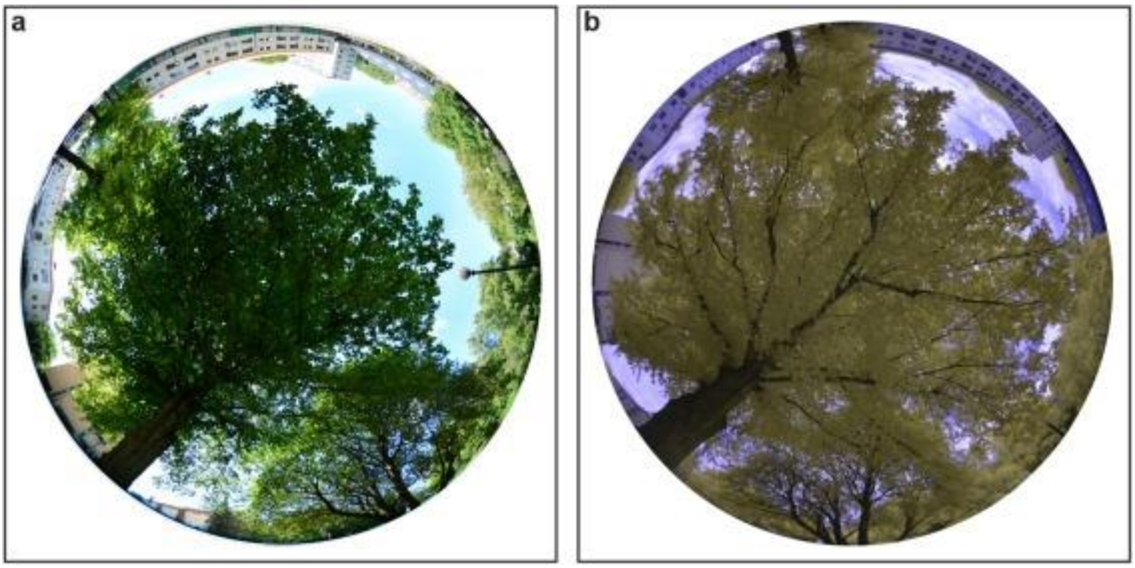

Figure 5: An example of a) a standard hemispherical photograph taken under an urban tree and b) a dual-wavelength photograph taken in the same spot, with blue light recorded in the blue channel and near-infrared (NIR) in the green and red channels. In the second image, leaves appear yellow due to lower reflectance in the blue channel (blue light) than in red and green channels (NIR). From Konarska et al. 2021.

2.2.6.2. R&D activities required

The technology could be tested in evergreen and deciduous forest sites and compared with a standard RGB camera. This would require an adaptation of the standard LAI retrieval algorithms.

2.2.7. KIT stations

2.2.7.1. Overview

Karlsruhe Institute of Technology (KIT) stations were designed to allow the continuous validation of LST products over several years. The stations were set up in large, flat areas with homogenous surface cover to minimise complications from spatial scale mismatch between ground-based and satellite sensors (Figure 6). Furthermore, the stations are located in different climate zones to analyse LST products under different atmospheric conditions and over broad temperature ranges: Evora (Portugal), Dahra (Senegal), Gobabeb (Namibia) and Farm Heimat (Namibia).

The core instruments of KIT's stations are Heitronics KT15.85 IIP (KT15) infrared radiometers that measure radiances between 9.6 and 11.5 µm (Guillevic et al., 2018). The temperature resolution of the KT15.85 IIP is given as 0.03 K with an uncertainty of ±0.3 K over the relevant range and high stability with a drift of less than 0.01 % per month (Goettsche et al., 2013). This is achieved by linking the radiance measurements to internal reference temperature measurements.

From 25 m height, the KT15's field of view of 8.5° results in a footprint of about 14 m^2. An additional KT15 faces the sky at 53° with respect to the zenith and measures the channel-specific downwelling longwave radiance, which is used to correct for the reflected component in the down-looking measurements. All measurements are provided at a sampling interval of 1 min.

The radiometers are initially calibrated by the manufacturer (Heitronics GmbH, Wiesbaden, Germany). Re-calibration against a blackbody is performed by KIT about every two years and after deployment.

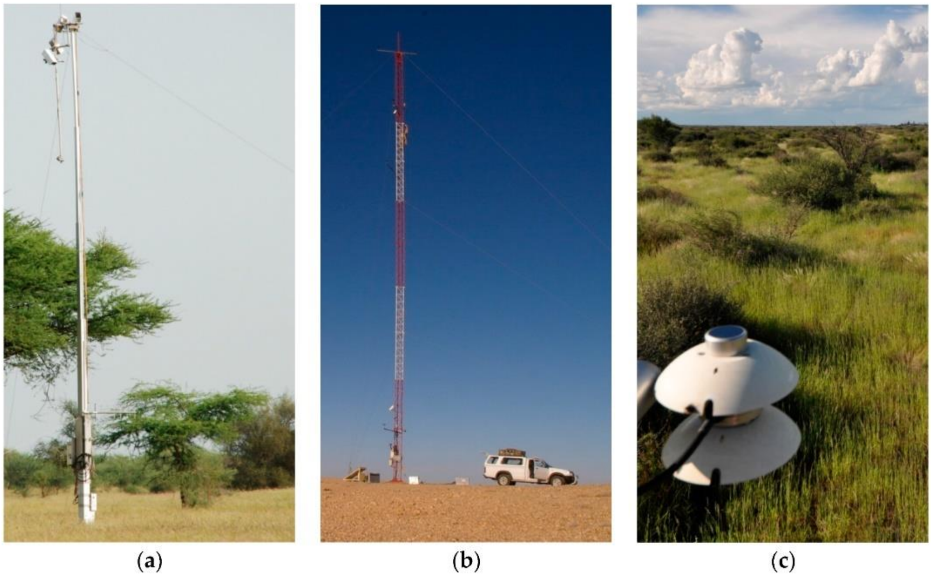

Figure 6. African stations at a) Dahra, Senegal, b) Gobabeb, Namibia and c) Farm Heimat, Namibia. From Göttsche et al. 2016.

The IR radiance measurements from KIT stations have been used to validate satellite LST products derived from MODIS (Ermida et al., 2014) and SEVIRI (Goettsche et al., 2013).

2.2.7.2. R&D activities required

Lack of in situ emissivity measurement.

2.2.8. NASA JPL thermal infrared radiometer

NASA's Jet Propulsion Laboratory (JPL) has deployed two permanent 9 m tower systems at Russell Ranch Sustainable Agricultural Facility (Figure 7). The towers support a set of instruments that collect thermal properties of the surface and incident, reflected, and emitted light/energy from the atmosphere, crop foliage, and soil. Each station has a JPL-built self-calibrating thermal infrared radiometer that measures surface brightness temperature in the 8-14 µm spectral domain (Figure 8). (Rivera et al., 2017).

Figure 7: JPL tower. From Rivera and Healey 2017 (courtesy NASA/JPL-Caltech).

Figure 8: JPL radiometer. From Rivera and Healey 2017 (courtesy NASA/JPL-Caltech).

The radiometers are calibrated using a laboratory blackbody. The systems are NIST traceable. In addition, JPL has developed a portable cone blackbody for field calibration. After calibration, the radiometers have accuracies of ± 0.1 °C.

2.2.8.1. R&D activities required

Lack of emissivity measurements

2.2.9. ESA TRUTHS & NASA CLARREO - Optical in-orbit missions dedicated to cross-calibration

2.2.9.1. Overview

For underpinning decision-making, reliable satellite data records are critical. A new ESA mission, TRUTHS (Traceable Radiometry Underpinning Terrestrial- and Helio-Studies), will be launched in 2030. It is dedicated to climate measurements and will carry a cryogenic solar absolute radiometer, a hyperspectral imaging spectrometer and a novel onboard calibration system. The main aim is to make continuous measurements of incoming solar radiation and reflected radiation with high accuracy. It will enable to evaluate Earth's energy-in to energy-out ratio to improve our understanding of climate change and help increase the precision of climate models. (URL-1).

The second similar mission is the CLARREO (Climate Absolute Radiance and Refractivity Observatory) Pathfinder (CPF) mission. The mission's main objectives are to measure Earth-reflected sunlight with extremely high accuracy of 0.3% (k=1) – a 5-10x improvement over existing reflected solar (RS) sensors and serve as an on-orbit inter-calibration reference to other orbiting sensors. The main instrument is an RS spectrometer HySICS (HyperSpectral Imager for Climate Science). It will be mounted on International Space Station (ISS) in the first half of the 2020s and will measure for a year. (URL-2).

2.2.9.2. R&D activities required

- Detailed instrument specifications and design (currently in progress for TRUTHS)
- Improved Lunar calibration approach
- Full traceability and specified uncertainty for all data products at all levels

2.2.10. THEMS Thermal & Hyperspectral imaging camera

2.2.10.1. Description

THEMS (Thermal and Hyperspectral Monitoring System) is a prototype system developed by Woodgate et al., 2020 for CSIRO. It was successfully deployed on TERN/CSIRO Tumbaramba supersite in South Western Australia.

A main feature of the system is the co-location of a visible and near-infrared 'VNIR' hyperspectral line scanner 'HLS' (model VNIR N-Series, Headwall Photonics Inc., MA, USA), and the thermal camera (model A655SC, FLIR Systems Inc.) in the main sensor enclosure. The sensors are mounted in a custom-built enclosure attached to a pan-tilt unit 'PTU' (model PTU-D48E, FLIR Systems Inc.) for multi-angular acquisition (Figure 9a, b). These sensors acquire multi-angular observations of spatially resolved canopy radiance (W m^{-2} sr^{-1} μm^{-1}) and temperature (K). A full description of the system is provided in Woodgate et al., 2020.

Figure 9: An internal view of the main sensor enclosure. (1) thermal camera, (2) VNIR hyperspectral line scanner with cooling fan, (3) shutter motor and mechanism, (4) 24 VDC to 12 VDC converter, and (5) shutter controller with temperature sensor. b External view of the main sensor enclosure on the pan-tilt unit tilted downward at the canopy. The white cover is a radiation shield with ventilation. c Contextual view of the THEMS sensor enclosure (number '1' insert). Other inserted numbers are 2) the command PC enclosure and 3) the all-sky camera and irradiance sensor location. (Extract from Woodgate et al. 2020).

Figure 10 provides some example outputs of the NVIR and thermal camera.

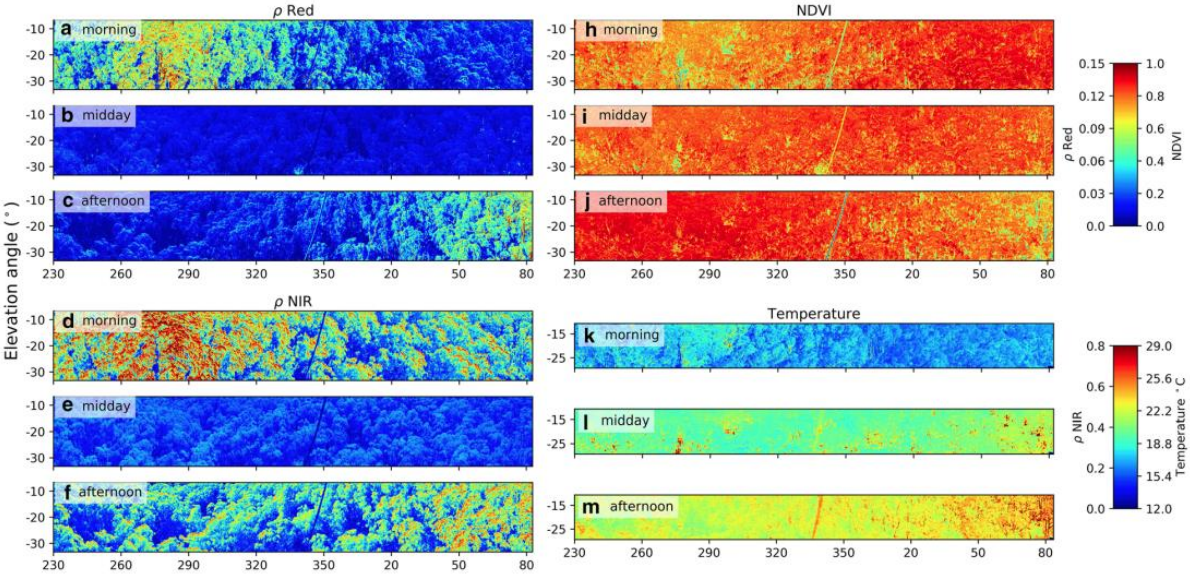

Figure 10: Diurnal variation image panoramas at three times of day on Jan 1st, 2018: morning (07:45), midday (12:11, solar noon) and afternoon (16:40) for the −20° elevation scan angle. Subplots: a–c red reflectance 'ρ Red'; d–f NIR reflectance 'ρ NIR'; h–j NDVI calculated as (ρ NIR−ρ Red)/(ρ NIR+ρ Red) (Rouse et al., 1974); k–m range corrected canopy temperature. (Extract from Woodgate et al. 2020).

2.2.10.2. Potential use for Cal/Val

THEMS has been used so far to assess the leaf content of the canopy. Its high spatial resolution and temporal sampling could be of high interest in characterising canopy BRDF. Existing systems like RALCALNET designed for sensor calibration perform remarkably well on homogeneous surfaces, but these systems were not designed for heterogeneous environments such as forest canopy and vegetated soils.

2.2.10.3. R&D activities required

The dataset has not yet been exploited for BRDF characterisation. Complimentary data analysis and research shall be founded to do so.

Protocol adjustment may be needed to optimize its value for BRDF characterisation.

The system, including too high-quality NVIS and the thermal camera, remains relatively expensive but could be reduced to a hyperspectral camera for BRDF characterisation.

3. Altimetry missions

3.1. Gaps and limitations in instrumentation capabilities

3.1.1. Instrumentation technologies used on-board

All Altimetry Missions rely on three on-board instruments, a radar altimeter, a microwave radiometer and a POD instrument, to measure the surface topography characteristics [D1.2]. Satellites in the Copernicus system that currently carry altimeters are Sentinel-3 and Sentinel-6. In the future, CRISTAL will be added.

As stated in [D1.2], in altimetry, most of the Cal/Val activities are related to the **validation of the products**. The instruments require a very minimum tuning (or even no tuning) after launch. It is still vital to monitor their behaviours all along the mission and to intercalibrate them with the other altimetry missions. The ground processing includes the instrument parameters to reach accurate inversions.

The altimeter design includes several calibration modes that enable measuring on a very regular basis most of the instrument characteristics (impulse response, thermal noise level). The radiometer also has its own on-board calibration path to monitor the RF losses of the reception chains.

For the altimeter, we also make a specific focus on the acquisition modes which require updates on the continental surface during the mission lifetime:

- The OLTC (Open Loop) mode enables measurements over hydrological and glaciological bodies. It relies on an on-board DTM defined under the satellite tracks. This DTM has to be updated to correct any misvalue of water elevations or to add new Virtual Stations.
- The CL (Close Loop) is automatic, without using any DTM. Trade-offs have been made on Sentinel-3 and Sentinel-6 missions to choose the most appropriate mode with respect to the surfaces. The OL mode has been selected over the Ocean and the Continents.

The long-term stability of the MWR is a key issue for the global performance of the altimetry system (as a reminder, it is one of the main sources of uncertainty in the altimeter climate data record)

The POD instrument is calibrated from ground measurements. For the POD, three technics (on-board and on-ground) are required:

- GNSS (both ground and board)
    - GNSS receiver antennae should minimize multipath to reduce the necessity of calibrating the antenna phase maps in flight.
- DORIS

- The only independent tracking technic from GNSS to compute reduced dynamic orbits.
- A new manoeuver (yaw-flip manoeuver) has been added to Sentinel-6 to characterize the phase centre of the instrument better. This manoeuvre has been recommended by the OSTST.
- GNSS-DORIS USO hybridation on board and on the ground (CNES/IGN IGS REGINA network) should be generalized to track inter-techniques systematisms and improve the along-track observability of DORIS.

For the reference altimetry missions (Jason series and now Sentinel-6), a **tandem phase** is always planned during Cal/Val between the new satellite and the previous one. For instance, the last tandem phase is between Jason-3 and Sentinel-6. The two satellites are in the same orbit during all the commissioning phase. The comparison of the products between the tandem phase enables to get climate series continuities and is mandatory to validate the new instruments.

In addition, the altimetry missions are compared on cross-overs, either among the same mission (between ascending and descending paths) or between several missions. Cross-overs are defined with a maximum time and space sampling to ensure homogeneity of the observed surface and thus the validity of the comparison. The comparisons are performed at level 1 (on MWR brightness temperatures) and level 2 (sea level height, surface roughness, SWH, backscatter coefficient, mispointing, water level height, sea ice, etc.).

3.1.2. Gaps in pre-flight characterization

3.1.2.1. Altimeter

The altimeter design has strongly evolved into digital architecture over the past ten years. This architecture has the advantage of including corrections of instruments defaults. The tuning of the RF parts can be relaxed to a certain extent and compensated in the reception chain.

The pre-flight characterizations are very important for all the RF paths which are not covered with the on-board calibration. This includes the antenna gains and the non-common paths (between measurement and calibration paths). The ground measurements are vital to getting the proper instrument description which will not be available after launch.

The recent evolution of digital architecture leads the path to a new trade-off between ground measurements and ground compensations in the processing. The question is now to optimize the ground operations to get the required level of knowledge while accelerating the AIT process.

The antenna gain characterization on the ground could be improved to reach higher inversion precisions.

The backscattering coefficient accuracy depends on the RF paths measurements. There is still a demand to improve it. This accuracy is relatively high (around 0.5 dB or 1 dB depending on the instruments).

3.1.2.2. Radiometer

For the radiometer instruments, the ground calibration is also a field where improvements are needed. Combined with the simplest instrumental design possible, it is the way of obtaining a better accuracy of the brightness temperatures.

Some recommendations can be pointed on the instrumental design:

- simplify instruments to decrease calibration uncertainty related to the various elements' losses in the instrumental chain (feedbacks of SARAL/AltiKa and ENVISAT missions)
- Focus on technological improvements
    - to favour the same path of the signal for calibration and measurement (prospective work)
    - to reduce MWR observation resolution

The design of the AltiKa radiometer and ENVISAT radiometer are good references, with a simplified RF path.

The antenna pattern should be made available for in-flight calibration. This feedback has been provided by the S3 Cal/Val team. The Cal/Val group has also recommended performing functional validation and internal calibration on the ground.

3.1.2.3. POD

Calibration phases of the different instruments on board the satellite could be defined to see the impact on the orbit of turning on/off them (in terms of power/thermal emissions and associated accelerations). This could be done by on-board calibration but also through better modelling of the instruments and pre-flight measurements.

3.1.3. Gaps in on-board calibration technologies

The on-board calibrations are now very well defined. We can recall here the importance of the new concepts which are not implemented in all the altimeters:

- Dedicated calibration pulse to estimate thermal noise (interleaved with "normal" pulse)
- Internal calibration acquired and downloaded in I&Q.

For the radiometer:

- Absolute calibrations (cold sky/hot target):
    - keep short sequences but frequent ones to limit the impact of a short-term drift of the instrumental gain (AltiKa, …, S3 feedback) and avoid gaps when interpolated on the altimeter. Compromises have to be found for a higher sampling rate.
    - Cold sky calibration: best on natural and stable targets, further studies on geographical/environment dependence for calibration with the main antenna

From an operation point of view:

- Calibrate the nominal and the redundant RF paths in tandem phase (done for the first time with Sentinel-6 but crucial for the climate series)
- Importance of the tandem phase both for the altimeter and the radiometer
    - essential to intercalibrate MWR with the highest possible accuracy (=radiometric sensitivity)
    - need to follow S3 feedbacks (30 s gaps between both satellites/duration≥ 2 months)
- Yaw-flip manoeuvres for the POD (Attitude flips at low beta angles (0°, 10°) should be implemented to disentangle the centre of phase errors from time-tagging, dynamic modelling errors)
- The number of CAL1/CAL2 per day has to be optimized regarding the instrument design. The usual numbers of calibrations per day may be relaxed if the instruments prove to be very stable.
- It is important to keep AutoCal every 6 months (calibration of the Automatic Gain Control steps) and keep a long CAL2 (half an orbit) every year.

3.1.4. Gaps in in-situ instrumentation capabilities

The missions also rely on sites, networks and airborne campaigns to contribute to the validation of the products. There are only very few measurement sites (6) accounted for as FRM sites - so far, only transponder data. There is also data available and used in validation activities that are not considered FRM. In altimetry, validation methods focus on different surfaces like the ocean, ice, inland, and coastal waters.

3.1.4.1. Gaps in airborne measurement technologies

Airborne instruments are developed for new instrument concepts, and they can then follow the mission life. Specific airborne radars (ASIRAS, KAREN, AirSWOT, KaRADOC, KuROS) are being developed and tested that help in preparation for future missions.

New developments with drones and ULM open new possibilities which must be encouraged. In particular, LIDAR embarked on drones are critical assets for hydrological and glaciological issues.

3.1.4.2. Gaps in in-situ measurement technologies

The available technologies can cover already a large variety of measurements and assure a proper Cal/Val, at least for the ocean ones. Ground measurements are available for most of the parameters estimated by altimetry missions.

We can underline the use of in-situ Argo data, which is essential to validate the steric sea-level component. Combined with the ocean mass component (from gravimetry missions or models), the total sea-level estimates can also be validated by this approach with a better spatial coverage than using tide gauges.

3.1.4.2.1. *For level 1 altimeter products (instrument characterization)*

As stated previously, the level 1 validation is done through intercomparison with transponders (TRP). TRP can be seen as the only altimeter oriented in-situ instrument. The ground processing can be improved to reach even higher precision. This processing shall take into account all the instrument characteristics of the TRP (especially the losses and its variations in the temperature). It is more difficult to use it directly to validate the instrument, as its accuracy is of the same order as the spaceborne instruments (or even more prone to degradation due to atmospheric variations). There are several limitations connected to TRP:

- TRP does not allow to validate the L2 processing.
- It is difficult to guarantee the TRP thermal stability and thus its internal delay (the goal is to have stability much better than the spaceborne instrument, which is tricky).
- Replica induced by the electronic system often contaminates the TRP radar signal.
- Are the range drifts identified relevant and consistent with those measured over the ocean using multi-mission approaches? No altimeter drift could be detected by TRP so far (for instance, the drift of 1.3 mm/year on the Sentinel-3A mission was not detected by Crete transponder).
- Maintenance and exploitation costs are non-negligible.

Nonetheless, the TRP bring valuable measurements, and new TRPs are currently deployed to provide more observations.

A perspective to complete this reference ground measurement would be to further test and develop (CNES campaign under Sentinel-3A ground track to be detailed) the use of Corner reflectors. Corner reflectors have a much lower cost, have no electronic components, and have thus stable characteristics. It is possible to equip various sites with them (and make synergy with other sensors (optical, imaging radar). Corner reflectors also have lower SNR than the TRP technique: sufficient to calibrate the instrument but less precise than a TRP. This new in-situ means is now deployed in Spain (Pyrénées) and studied for deployment in Corsica (Senetosa).

3.1.4.2.2. *For level 1 radiometer products (instrument characterization)*

The in-situ measurements for MWR CAL/VAL are mostly based on GPS, which are the most reliable instruments for this topic. Actually, the radio sondes are not reliable enough and are barely used in the CAL/VAL activities of the MWR of altimetry missions.

The in-situ measurements useful for radiometer validation are mainly distributed along coastal regions of the North Hemisphere. The first major gap is the poor coverage of the Earth, which does not represent lots of atmospheric situations. In addition, the low resolution of the MWR inducing land contamination in coastal areas prevents accurate results.

3.1.4.2.3. *For level 1 POD products (instrument characterization)*

For POD, it is necessary to pay particular attention to the laser network and to the GNSS antenna.

- Laser network

    - In terms of noise (precision) and biases (accuracy): today, only 5 to 8 SLR stations have a satisfactory accuracy (less than 5 mm biases and 1 cm noise) to validate the short-term orbit accuracy.
    - In terms of long-term stability: laser measurements need to reach new standards of stability to address the challenges of long-term radial orbit stability at regional scales (0.1 mm/y per decade).
    - Stations are needed at high latitudes, especially for polar altimeter missions: currently no SLR station above 60° N and 30° S!
    - This points toward the need for automatic SLR stations.
- GNSS
    - GNSS receiver antennae should minimize multipath to reduce the necessity of calibrating the antenna phase maps in flight.

3.1.4.2.4. For geophysical products (topography over ocean, water bodies and ice)

The main issue for ocean validation is **that the coverage is very local compared to the scale of the oceanic processes.** The ground truth of oceanic surfaces at medium and large scales cannot be built with in-situ measurements only.

More specific problems involve measurements for specific ground types, especially coastal areas, ground and ice.

For coastal areas, issues arise from the signal interference from the land and complex dynamics (D1.2, Chupin et al., 2020). There are similar problems with estuaries. The data quality from these areas needs improvement. So far, mainly tide gauges have been used to measure relative sea-level variations at the coast and calibrate satellite data (Mitchum et al., 2000). However, they are usually grounded at the coast, and their location is not always near the satellite ground track. The latter is necessary for correcting for local hydrodynamics and knowing the fine-scale spatial variations of the geoid. The measurements might also be affected by vertical land movements. (Chupin et al. 2020). To overcome some of the shortcomings, different GNSS systems attached to the tide gauges and buoys have been tested and used in Cal/Val activities (André et al., 2013, Bonnefond et al., 2011, IAT 2021). But these solutions still offer measurements at a single point. French DT-INSU has developed a floating towed carpet named CalNatGeo and an autonomous platform with a Cyclopée system for larger flexibility.

Further development of GNSS reflectometry for coastal measurements improvement has been recommended to provide sea level measurements in the coastal area (IAT 2021). Nonetheless, the GPS carpet cannot capture quickly enough the signal dynamic. The actual design measures mainly the geoid.

For ice sheets, the limitations of altimetry are related to too steep topography, which shifts the POCA too far from the nadir. As stated in D1.2: "it is essential to define in the MRD a range of "operability" for the altimeter" as it is done for CRISTAL, MRD-150: "The altimeter shall include tracking ability over steep terrain and as a minimum be able to track ice surfaces/glaciers with slopes <1.5 ". Another issue regarding ice sheets is the limited information on snow loading due to instrumentational limitations. For the solution, dual-frequency altimeter systems using Ka/Ku bands are being developed with altimeters in tandem and complimentary orbits (IAT 2021), but these are out of this project's scope.

Many improvements do not need new technology but changes in methodology and merging altimetry measurements with in situ data, models and optical sensors, for example, to study river discharge in hydrology (IAT 2021). These developments are not included in this Document.

As stated in document D2.3, although the in-situ measurements provide valuable ground truth, their comparisons to altimetry measurements present several limitations for a detailed description of the data quality. For example, although highly accurate, FRM measurements have limited spatial coverage. Thus, they do not allow us to assess altimeter performances over the broad range of possible orbit configurations (altitude and radial velocity), sea (waves, winds, ocean tides, etc.) or atmospheric conditions (temporal and spatial variability of the atmospheric pressure, of the liquid water content, etc.). On the other hand, although global networks provide a much wider (although unevenly distributed) coverage, their usage remains limited by their lower level of precision as well as by the fact that their corresponding uncertainty levels are not always rigorously documented (indeed, none of these existing global networks is labelled as FRM yet). Therefore, inter-comparisons using other altimetry missions and models remain a key approach of the altimetry Cal/Val methods.

The HF radar could be an interesting technology for validation in the coastal environment. Some attempts have been made. Nonetheless, the main limitation comes from the type of parameters provided by the HF radar, which is no more sea surface height but current observations. Therefore, it does not address Level 2 altimetry products but rather the validation of geostrophic currents derived from altimetry SSH.

For the POD, the core laser network is sufficient to reach the required accuracy. The efforts have to be put into a better colocation of DORIS beacons with satellite tracking techniques. The hybridisation of methods is very important. Three independent tracking techniques (SLR, DORIS, GPS) are essential for the next decade's challenges.

3.1.5. Summary of gaps

3.1.5.1. Pre-flight characterization and on-board calibration technologies

- Altimeter: Improve the antenna calibration to better estimate the backscattering coefficient.
- MWR: trade-offs on the radiometer calibration sequence for the cold sky calibration.

3.1.5.2. Platform accommodation and instrument design

Altimeter

- Dedicated calibration pulse to estimate thermal noise (interleaved with “normal” pulse).
- Internal calibration acquired and downloaded in I&Q.

POD

More thoughts should be devoted in the future to the design of the platforms for POD:

- Troubles with the Sentinel-6 platform:
    - solar panels are not always perpendicular to the sunlight direction (problems with the Solar Radiation Pressure modelling),
    - "roof shape" of the solar panels, which would require to have access to the power supplied by the solar panels to improve the knowledge of the re-emitted fluxes by the radiators,
    - cavities below the solar panels (self-shadow area and drag modelling difficulties),
    - huge nadir surface (up to 5 times bigger than Jason-3, which exposes the orbit to consequent albedo modelling errors) with almost all the radiators located on this face (unmodeled thermal fluxes).
- Solar panel and central body temperature measurements are useful to improve the modelling of solar radiation pressure.
- Multi-constellation GNSS receivers should be the baseline for future missions.

Radiometers

- Simplify instruments to decrease calibration uncertainty related to the various elements' losses in the instrumental chain (ex: AltiKa, Envisat feedbacks)
- Special care about the accommodation of the MWR on the platform (to avoid targets around the MWR: Envisat, Sentinel-3)
- Focus on technological improvements:
    - to favour the same path of the signal for calibration and measurement (prospective work)
    - to reduce MWR observation resolution

3.1.5.3. In-situ measurements

- The use of opportunity networks remains limited due to the low level of precision and insufficient documentation of uncertainty
- Sparse data for coastal, hydrology and glaciology with variable qualities
- Signal interference from the land and complex dynamics limit measurements in coastal areas and at estuaries
- Limitations of measurements over ice sheets and sea ice due to steep topography
- The incapability of transponders to calibrate both the phase and the backscattering coefficient
- There are several gaps related to TRP:

  - TRP does not allow to validate the L2 processing.
  - It is difficult to guarantee the TRP thermal stability and thus its internal delay (the goal is to have stability much better than the spaceborne instrument, which is tricky).
  - Replica induced by the electronic system often contaminates the TRP radar signal.
  - Are the range drifts identified relevant and consistent with those measured over the ocean using multi-mission approaches? No altimeter drift could be detected by TRP so far (for instance, the drift of 1.3 mm/year on the Sentinel-3A mission was not detected by Crete transponder).
  - Maintenance and exploitation costs are non-negligible.
- For radiometers, the gaps in the in-situ instruments are the following:
  - Radio sondes: they are not reliable, and they do not play a significant role for MWR Cal/Val
  - GPS is extensively used for MWR Cal/Val. But the network needs to be densified in the South Hemisphere (more scarce than in the North Hemisphere).

3.1.6. Recommendations

For altimetry, we have gathered some recommendations on the instrument's designs and on-board calibrations, as well as strong recommendations on operations (tandem phase, yaw flip manoeuver for the POD).

For in-situ, the instruments are quite good. Improvements can be reached in the instrument's calibration (delay, backscattering coefficient) with corner reflectors and transponders. The issue is more on the density of the networks. In addition, the ground truth for the Ocean cannot be reached by in-situ only. The meso and large oceanic scales can be accessed only through a combination of in-situ, models and satellite data.

3.1.6.1. On-board calibration

- Calibrate the nominal and the redundant RF paths in the tandem phase (done for the first time with Sentinel-6 but crucial for the climate series). **Criticality – high, effort needed – medium**
- Importance of the tandem phase both for the altimeter and the radiometer
  - essential to intercalibrate MWR with the highest possible accuracy (=radiometric sensitivity). **Criticality – high, effort needed – medium**
  - need to follow S3 feedbacks (30 s gaps between both satellites/duration≥ 2 months). **Criticality – high, effort needed – medium**
- Radiometer absolute calibrations (cold sky/hot target): keep short sequences but frequent ones to limit the impact of a short-term drift of the instrumental gain (AltiKa, …, S3 feedback). **Criticality – medium, effort needed – low**
- Yaw-flip maneuvres for the POD (Attitude flips at low beta angles (0°, 10°) should be implemented to disentangle the centre of phase errors from time-tagging, dynamic modelling errors). **Criticality – medium, effort needed – medium**

- Trade-offs to optimize the Altimeter CAL1/CAL2/AutoCAL number of acquisitions and durations to be made (based on REX of in-flight missions). **Criticality – low, effort needed – low**

3.1.6.2. In-situ measurements

- Airborne capabilities
  - Drones and ULM open new capabilities (easier and cheaper but with other limitations). **Criticality – low, effort needed – medium**
  - LIDAR is a key technology for topography which use has been very limited so far. **Criticality – low, effort needed – high**
- Improvement of transponders and merging with corner reflectors for Altimeter calibrations
  - Improve L1 validation: improve transponders to calibrate both the phase and the backscattering coefficient. **Criticality – medium, effort needed – medium**
  - Deploy more corner reflectors. **Criticality – medium, effort needed – low**
- Improvement of Argo data
  - The validation of the steric sea level component relies strongly on Argo in-situ data. We need to get deeper Argo data (< 2000 m) to improve the validation.
- Address ice sheets, sea ice and hydrology validation issues
  - Analysis on-going in ESA STR3TART project with different aspects including in-situ instrument capabilities, network densification etc. **Criticality – high, effort needed – high**
- Address laser network issues for precise orbit validation
  - Improvement needed:
    - In terms of noise (precision) and biases (accuracy): today, only 5 to 8 SLR stations have a satisfactory accuracy (less than 5 mm biases and 1 cm noise) to validate the short-term orbit accuracy. **Criticality – medium, effort needed – high**
    - In terms of long-term stability: laser measurements need to reach new standards of stability to address the challenges of long-term radial orbit stability at regional scales (0.1 mm/y per decade). **Criticality – high, effort needed – medium**
  - Stations are needed at high latitudes, especially for polar altimeter missions above 66°: currently no SLR station above 60° N and 30° S! **Criticality – high, effort needed – high**
  - This points toward the need for automatic SLR stations. **Criticality – high, effort needed – high**

3.2. Examples of new instrumentation technologies

3.2.1. Autonomous Underwater Vehicle (AUV)

3.2.1.1. Description

To measure the sea-ice thickness from below the water surface is possible. It allows mapping the ice when conventional techniques are not possible (boat, airborne techniques). The measurement principle uses a pressure sensor to calculate the depth (equivalent to the distance to the surface) coupled with a bathymetry sonar to measure the distance to the bottom of the ice surface. The difference between these two distances gives the sea-ice thickness. Comparison with conventional measurements gives an error difference of up to 15%.

3.2.2. Corner Reflectors

3.2.2.1. Description

Corner reflectors are metal trihedrons. The radar view angle of trihedrons is extensive. The radar signal is thus always in the good direction for being acquired by the sensor. In addition, the backscattering coefficient of the trihedrons is fully determined by the object's width. This technology is very performant for the calibration of SAR imagery. It is more complicated for altimetry as the spatial resolution is much wider than in SAR.

Nonetheless, in SAR altimetry, it is possible to detect corner reflectors. The condition is to deploy them in an environment which will minimize the clutter in the corner reflector radar gate. This means that the location has to be far from any water bodies and, preferably, at the summit of a small hill.

3.2.2.2. R&D activities required

- Determine appropriate locations to implement corner reflectors.
- Manufacture corner reflectors and deploy them in pre-determined locations.
- Process the signals to improve the inversion method and the locations.

3.2.3. GNSS carpet

3.2.3.1. Description

The French DT-INSU laboratory has developed an innovative kinematic GNSS instrument named CalNatGeo (https://doi.org/10.3390/rs12162656). This solution can be towed for SSH mapping at high speed and on rough seas. Installed onto a 100 m long and 2 m wide deformable carpet, a GNSS sensor has been installed to precisely measure the elevation of the sea surface in motion (Figure 11). The carpet can measure the current, flow, or depth in option. The sea surface height can be provided with centimetre accuracy. This solution has been tested on rivers, lakes and reservoirs with similar good results.

CalNatGeo shows comparable results in static mode with the classical GNSS buoy system. In kinematic mode, no height bias dependency with velocity has been shown (Chupin et al., 2020).

Due to its large dimensions, the GNSS carpet is not easily transportable, and it is hard to manoeuvre in areas with heavy marine traffic.

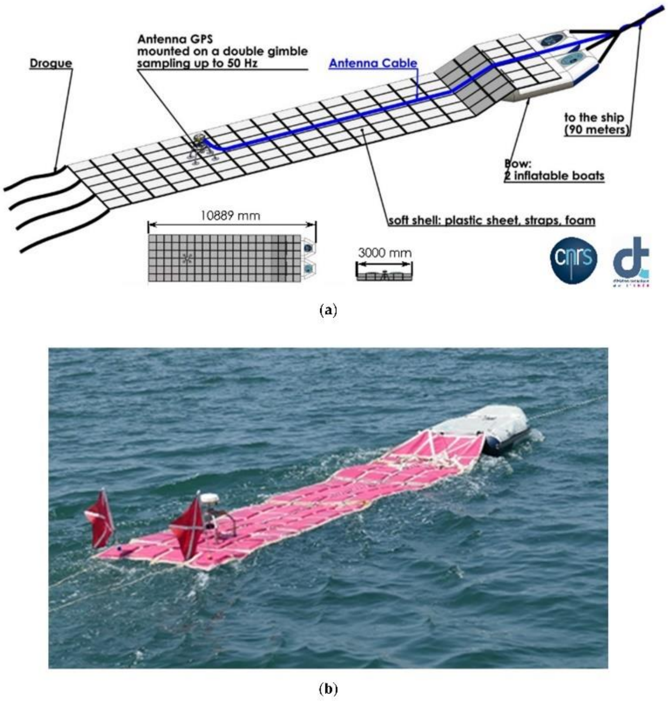

Figure 11. (a) A general drawing of the original CalNaGeo offshore towed carpet with a double inflatable boat in front (© M.Calzas—DT-INSU); (b) CalNaGeo coastal carpet in the Pertuis Charentais area. From Chupin et al. 2020.

3.2.3.2. R&D activities required

There are still uncertainties regarding the accuracy of GNSS systems due to systematic biases and GNSS processing. Positioning accuracy can be limited by the sea and weather conditions, GNSS satellite coverage, etc. Some improvements could be achieved using multi-constellation GNSS, orbit/clocks product development and integer ambiguity resolution. The information is from Chupin et al. (2020).

3.2.4. Micro-station

3.2.4.1. Description

Proposed by VorteX.io, a micro-station has been developed to monitor the water level height for hydrology and provide in-situ measurements collocated with an altimeter. Based on the LiDAR technology coupled with a camera, the micro-station measures the water surface height with the associated standard deviation with the LiDAR sensor. In addition, the camera estimates the water speed and temperature. The VorteX.io micro-station is innovative in that it is a compact, low-cost solution. The station is installed on a bridge or infrastructure over a watercourse. The micros-station is also easy to maintain and deploy. They are autonomous in energy, as they have their battery and solar panel and are connected via 4G and IoT Spatial. The water height is measured with a centimetre level accuracy.

3.2.5. Optical sensor

3.2.5.1. Description

Another innovative sensor to measure the water level elevation has been developed by Tenevia (CamLevel sensor). They have developed a solution combining a camera with a limnimetric scale. The principle of measurement is based on the automatic detection of the waterline in image sequences received from a fixed video surveillance camera installed near the water body in interest. Images are taken both day and night. Then, machine learning algorithms are used to identify the waterline on the images to read the corresponding height on the fixed scale pointed by the camera (Figure 12).

The water height can be provided with a centimetre level accuracy, depending on the camera resolution and the distance to the limnimetric scale. TENEVIA recommends a 5MP camera. If installed 20 m from an optical target, a pixel represents 0.4 to 1 cm in the real world, depending on the zoom level.

Maintenance of the system is the standard for an image-taking device. However, clearing of the field of few might be needed.

More information is available at URL-3.

Figure 12: Image caption from the system working at The Métropole Toulon Provence Méditerranée region. Source: URL-3

3.2.6. Unmanned Aerials Vehicles and Airborne LiDAR

3.2.6.1. Description

VorteX.io also proposed to embed a LiDAR (coupled with a camera and a GNSS sensor) on a UAV to measure the water surface along a river. Instead of the micro-station, this solution has the advantage of covering a larger water surface and studying the water extend and roughness, the local slope of a river, the presence of additional water bodies around, and the surrounding terrain. The water height is measured with a (sub-)centimetre level accuracy.

Another technique used to acquire in-situ measurements is installing a laser-based system (LiDAR) to acquire topography on an airborne platform. The system usually weighs around 100 kg and is composed of the scanner sensor with the associated electronic system, a GNSS receiver and antenna, and a system to attenuate the vibration of the airborne platform. The LiDAR solution is usually used to measure the land-ice topography, but some tests have been realised over rivers to identify the usefulness of this technique for hydrology issues.

3.2.7. Unmanned Surface Vehicle (USV)

3.2.7.1. Description

Developed by La Rochelle University and DT-INSU, the Cyclopée sensor comprises a geodetic GNSS antenna with an acoustic altimeter allowing air-draft corrections. The sensor is installed on a gyro-stabilised arm to compensate for the vehicle's motion (Figure 13). The Cyclopée sensor can be mounted on a USV or a boat, and it can be used to measure the sea surface height over coastal areas and on hydrology surfaces (lakes, rivers, reservoirs). The height accuracy depends on the surface motion (decimetre to centimetre accuracy). Several complementary instruments (temperature, salinity, bathymetry, etc.) can be installed to study hydrodynamics in the coastal area and help Cal/Val of current and future missions.

The measurements of SSH from Cyclopée are consistent with tide gauges. It can provide reliable results up to a speed of 7 knots, but the final results are affected by the acoustic altimeter dependent on air temperature.

Mini-Cyclopée mounted on a USV, or a boat is compact and manoeuvrable, an advantage compared to GNSS carpet.

Information from Chupin et al., 2020.

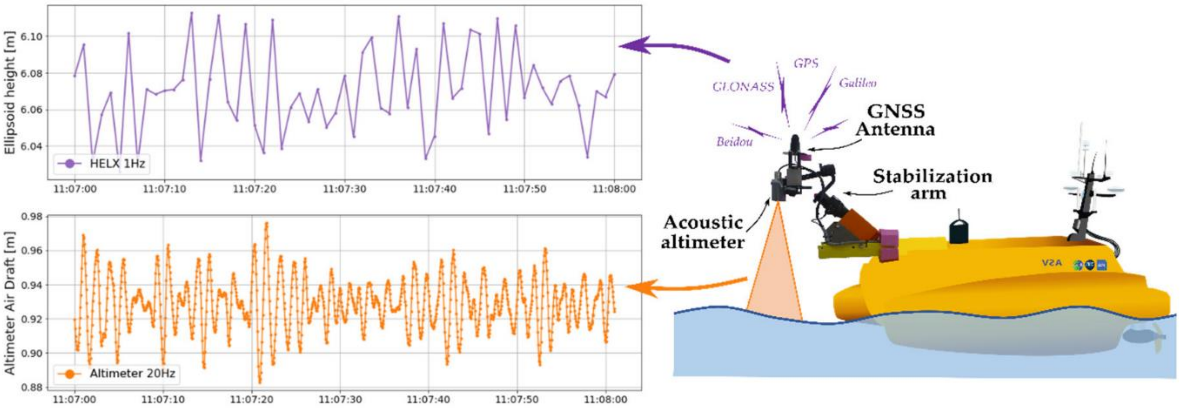

Figure 13. Mini-Cyclopée measuring system used on PAMELi unmanned surface vehicle (USV): To continuously monitor the sea surface height, this sensor combines a geodetic Global Navigation Satellite Systems (GNSS) antenna with an acoustic altimeter which allows for air-draft corrections. Note that for all our datasets, altimeter measures at 20 Hz, while GNSS is programmed to make 1 Hz measurements. From Chupin et al. 2020.

3.2.7.2. R&D activities required

As mentioned above, the results of Cyclopée are dependent on the acoustic altimeter. Therefore, the choice of the sensor should be carefully considered based on the estimated measurements range, and field constraints and full qualification of the sensor are needed for reliable measurements.

As for the GNSS carpet, there are uncertainties regarding the accuracy of GNSS systems due to system biases and GNSS processing.

Information from Chupin et al., 2020.

4. Radar and Microwave missions

4.1. Gaps and limitations in instrumentation capabilities

4.1.1. Instrumentation technologies used in Microwave Radiometry

Microwave radiometer instruments are passive devices used primarily for weather and climate studies. The instruments are thoroughly described in D1.3. Multiple microwave radiometers are currently under operation, but for now, none of them is a part of the Copernicus Sentinel constellation.

For radiometer Cal/Val activities in situ, inter-satellite and model comparisons are used. Both passive (corner reflectors, large artificial targets) and active (radar transponders) ground truths are used.

4.1.2. Gaps in technologies of Microwave Radiometry

Microwave sensors are sensitive to their operational temperature, and therefore there are usually blackbodies onboard the satellites. Due to the changes in sizes of sensors and satellites, there is a need to develop smaller, high-emissivity blackbody targets. To reduce uncertainty and ensure traceability development of integrating transition cells into the blackbodies for SI traceable fixed-point references is underway. Microwave traceability should be achieved for the provision of suitable blackbody sources but also for sub-system characterisation (antenna performance and detector linearity) and end-to-end characterisation (with a > 1 m diameter calibration target). (EURAMET SRNP 2020).

Some of the gaps in Microwave Radiometry are related to the available satellite measurements. One crucial indicator for microwave radiometers is the footprint resolution, where improvements are needed. There is a need for multifrequency microwave radiometry at a medium resolution in polar areas. In the future, CIMR aims to reduce the resolution for most channels. One exception is L-band, which is used for estimating sea ice thickness. Available L-band microwave radiometer technologies cannot meet the requirement of 10 km for thin Sea Ice Thickness (D1.3). Like in Altimetry, these gaps are out of the scope of the current project and will not be discussed any further.

4.1.3. Instrumentation technologies used in SAR missions

SAR is an active microwave instrument. This type of instrument is thoroughly described in D1.3. SAR missions are used for various applications addressing land, snow, sea ice, and sea monitoring. Currently, Sentinel-1 is using SAR technology. In the future, Sentinel-1 NG and ROSE-L will be added.

4.1.4. Gaps in pre-flight characterisation and on-board calibration technologies of SAR missions

No major instrumental issues have been detected regarding the calibration of current SAR concerning the initial objectives of the missions (regarding the mission design). The pre-flight on-board calibration of the SAR instrument of Sentinel-1 can be considered sufficiently mature to provide the required accurate and precise instrument characterisation at the time of launch. As a complement, dedicated acquisition modes are designed to monitor the instrument's status for each Transmit and Receive

Module (TRM). The instrument timing allows collecting regular calibration and noise pulses that enable characterising the instrument between and during nominal data acquisitions, considering ageing.

However, some improvements may be put in place either to go beyond the initially planned performances or to streamline the calibration of the data. For Sentinel-1C, for instance, improvement with the on-board instrument will be put in place by changing the instrument timeline allowing direct noise measurements with higher frequency (for each burst in TOPS modes and each imagette for Wave Mode). In addition, it was shown that a better accuracy on attitude knowledge would benefit the calibration of the level 2 radial velocity measurements and their performance. However, this involves changes in methodologies that are not covered in this Document.

The effective antenna pattern characteristics depend on the combination of each TRM and their status and can be estimated using the so-called Antenna Model. It was shown that the Antenna Model does not allow to derive the antenna pattern completely with the required accuracy to ensure smooth radiometric calibration among the whole instrument swath and to avoid beam to beam offset. However, alternative calibration methodologies and validation of the antenna pattern in elevation were defined to mitigate this.

Considering this on-ground calibration, no significant gaps can be identified regarding the on-board calibration of the Sentinel-1 instrument. The on-board calibration of the ROSE-L instrument is not considered in this analysis as the instrument is still under design.

No inter-calibration methods are available for SAR missions. Reasons are not related to unavailable instrumentation technologies but the uniqueness of each mission. As said in D2.3, "Intercomparison of SAR observation requires acquisition with the same radio frequency, bandwidth, acquisition geometry and processing. It also requires that the observed scenes are stable between successive observations." Close tandem configurations are possible for SAR in bistatic configuration (one active, multiple passive). However, a close tandem configuration for sensors active simultaneously may lead to mutual interference. Again, changes needed for future missions are out of the current document's scope.

The Level 2 OCN products of Sentinel-1 contain an RVL (Radial Velocity) measurement over the ocean. This measurement is performed by measuring the Doppler Centroid from the acquired data and compensating for the predicted Doppler Centroid derived from sensor geometry (orbit, attitude, earth rotation). This RVL component is still not calibrated due to insufficient accuracy in the knowledge of spacecraft attitude (and its variation along the orbit and with time). Calibrating this component would require collecting better attitude knowledge that is currently not achievable with the Attitude and Orbit Control System in place with the Sentinel-1 A/B/C units.

4.1.5. Gaps in in-situ measurement technologies of SAR missions

SAR external calibration is performed by deploying passive (e.g., corner reflectors, Amazon rainforest) and active (e.g., transponders, ground receivers) calibration targets. Several of these with high performances are produced, tested and maintained by DLR. Some experiments were done with networks of lower performance transponders like "Electronic Corner Reflectors" from Meta Sensing (https://www.geomatics.metasensing.com/ecr-c) designed. However, those low-performance transponders are not designed to support the absolute radiometric calibration of SAR instruments but as an active target for measuring vertical displacement thanks to InSAR analysis.

Validation and calibrations of SAR missions require systematic and automated measurement on the ground and benefit from case studies.

SAR measurements are done over a large swath, the absolute calibration and validation are performed only on subsamples, and the results are translated to the entire swath. A limited number of absolute ground truth (transponders) is used to achieve absolute measurement on a subset together with relative ground truth (e.g., rain forest) with extensive coverage to achieve continuity of the performance (D1.3).

4.1.6. Summary of gaps

- **Currently used on-board blackbodies do not satisfy the needs for future missions**
- **There is no microwave traceability in Europe**
- **No close tandem with two active instruments due to signal interference**
- **Limitations of transponders due to bandwidth**
- **Restrictions of transponders due to the frequency**

4.1.7. Recommendations

- Microwave traceability should be achieved for the provision of suitable blackbody sources but also for sub-system characterisation (antenna performance and detector linearity) and end-to-end characterisation (with a > 1 m diameter calibration target). **Criticality – medium, effort needed – high.**
- New suitable blackbodies need to be developed to satisfy the need for future missions regarding the size, uncertainty and traceability to SI. **Criticality – medium, effort needed – high.**
- There is a need for high-quality microwave calibrations. **Criticality – medium, effort needed – high.**

4.2. Examples of new instrumentation technologies

4.2.1. Low-performance transponders

4.2.1.1. Electronic Corner Reflectors

Description

A compact active transponder Electronic Corner Reflector in C-band (ECR-C) is developed by MetaSensing Electronic (Figure 14). It is a user-deployed device that amplifies the weak signal received from the satellite and transmits it back. It is mainly used for Differential Interferometric Synthetic Aperture Radar (DInSAR) measurements, where precise knowledge of the location and relative displacements are needed. It can also provide information about the atmosphere. Compared to corner reflectors, ECR-C is much more compact and has an active design. The operational frequencies are compatible with Sentinel-1A and –B. Information from URL-4.

Figure 14: The ECR-C enclosure (From URL-4)

These reflectors are designed to act as corner reflectors to ease the mapping of subsidence, land slide, etc. However, they do not include thermal control and cannot be directly used to perform fine radiometric measurements required for radiometric calibration of the sensor and processing.

4.2.2. High-performance transponders

4.2.2.1. Description

DLR is developing new transponders for future missions that need to address challenges that the currently used ones cannot do. For example, for the HRWS mission, high bandwidth is used (X-band (BW 1.2 GHz). The instrument needs an ultra-fast digital unit for pulse recording. For the ROSE-L mission, the challenges are low frequency and full polarimetric regarding L-band. The first challenge needs large antennas, and therefore, weight issues must be addressed. The second challenge requires dual-antennas with analogue electronics and a digital unit.

4.2.2.2. R&D activities required

Design of transponders with high bandwidth, low frequency and full polarimetric capability.

5. Atmospheric composition missions

5.1. Gaps and limitations in instrumentation capabilities

5.1.1. Instrumentation technologies used

Atmospheric composition missions primarily rely on remote sensing measurements of optical radiances in which signatures of absorption, emission and/or scattering by atmospheric constituents are detected and quantified. The Copernicus Space Component (CSC) identifies two families of Earth observation satellite missions for measuring atmospheric composition, namely, the Sentinel missions (Sentinel-4, Sentinel-5, Sentinel-5 Precursor, and the high priority candidate mission CO2M), which are developed and operated by ESA and EUMETSAT. The second category consists of the contributing missions operated by other space agencies and organisations and contributes to the Copernicus services. An overview of past, present and planned atmospheric composition missions has been provided in "D1.4 – Atmospheric Composition Missions Cal/Val Requirements". This report focuses on the Sentinel missions for measuring atmospheric composition.

The Sentinel missions for atmospheric composition are all nadir viewing and flying in a sun-synchronous Low Earth Orbit (LEO) or Geostationary Orbit (GEO). They typically cover a spectral range from the ultraviolet (UV) and ultraviolet-visible (UV-VIS) to the near-infrared (NIR) and shortwave infrared (SWIR). The data products and ranges for which the validation is required are mentioned in detail in D1.4.

5.1.2. Gaps in pre-flight characterisation and on-board calibration technologies

The currently only active Sentinel dedicated to the atmosphere, Sentinel-5P, carries the TROPOMI instrument. The calibration strategy for TROPOMI laid out in Kleipool et al. [2018] has been to:

(1) characterise the instrument on the ground prior to launch with dedicated calibration measurements to establish the so-called calibration key data that are used in the level 0-1b processor,

(2) update the calibration key data by in-flight calibration measurements in the first years of data collection, and

(3) focus on the data products' irradiance and radiance, whereas the calibration of the reflectance has been left to the data user. The absence of a reliable calibration of reflectance spectra can be considered a serious 'gap' since most level-2 retrieval algorithms use reflectance and require well-calibrated reflectances from TROPOMI.

The absolute irradiance calibration for TROPOMI has been complex because the sun simulator proved to be unstable. The angular dependence of the solar diffuser is not well-calibrated, causing viewing angle dependent biases in level-2 data products. Wavelength calibration has been successful with a 0.01-0.02 nm spectral knowledge accuracy, well within the mission requirements.

During and after TROPOMI's commissioning phase (from January to June 2018), in-flight calibration measurements have been made and analysed to update TROPOMI's calibration key data and document degradation in the devices used for calibration [Ludewig et al., 2020]. These measurements have resulted in a better calibration of the absolute irradiance. However, consistent improvements have not been achieved for the radiance calibration, so reflectances from TROPOMI are still not well-calibrated. The updates in the calibration key data have recently been implemented in the new level 0-1b processor version 2.

The TROPOMI level0-1 calibration team (via Antje Ludewig, interviewed on 18 October 2021) highlights the following main gaps in TROPOMI on-ground calibration methods:

"Several calibration light sources (Sun simulator, lasers, bandfilters) had severe shortcomings. The availability of additional spare calibration sources with a different design would have helped".

"For absolute radiometric calibration, a source with a persistent calibration validity and less straylight was missing. This needs to be developed for future instrument calibration, although this is not trivial and possibly beyond the scope of a single mission, as such new sources will need to be adaptable to the instruments at stake".

For the TROPOMI in-flight calibration methods, these gaps have been identified:

The main issue of the largely successful in-flight (re-)calibration period is the timing of the release of the new results. Ludewig indicated that "*many improvements based on insights from the commissioning phase (November 2017-April 2018) only became operational* (with the release of version 2 TROPOMI lv1b data) *in July 2021*".

Another 'gap', which is actually an unforeseen windfall, was the high signal in TROPOMI's UV and VIS channels, which allows for shorter detector co-addition times while still reaching the mission signal-to-noise requirements. This resulted in an improvement of TROPOMI's spatial resolution (from 3.5 km x 7 km to 3.5 km x 5.5 km at nadir, a 20% smaller pixel), but the revised "*settings could only be implemented after 1.5 years (August 2019) because of limitations in the ground segment's capacity to handle larger data volumes*".

5.1.3. Gaps in in-situ measurement technologies

Ground-based remote sensing measurements provide the best reference measurements for the validation of total column products, such as CO, CH_4, and CO_2, as they probe the whole atmosphere, similar to what is done by the satellite. However, there are gaps in such measurement networks regarding the coverage for the useful range of parameters and possible measurement scenarios. The reference measurements are provided by measurements performed by networks, typically globally distributed, and dedicated campaign-based observations. Regarding tropospheric products like tropospheric nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and formaldehyde (HCHO), airborne and car-based remote sensing instruments are well-suited to complement ground-based stationary measurements. They can cover a larger area than stationary measurements, and therefore they increase the spatial coverage of the Cal/Val networks. Airborne imaging spectrometers can be considered similarly to satellite sensors. When operated well above the planetary boundary layer during the satellite's overpass, and as long as the bulk of the tropospheric column is located in the lowest layers of the atmosphere, they can measure approximately the same tropospheric columns as the satellite but at much higher spatial resolution. The satellite products can be validated by averaging these measurements within the larger satellite pixels. The same holds for spectrometers mounted on mobile platforms like cars.

There are significant gaps in Cal/Val discussed in the following paragraphs.

The traceability of remote sensing measurements to the world meteorological organisation (WMO) references or another internationally accepted standard. It is a big challenge for remote sensing data and is handled differently in different networks. The lack of traceability to one standard significantly contributes to the systematic uncertainty of the measurements at a given site and to the network-wide consistency, making it difficult to distinguish the real site-to-site variability related to the varying environmental conditions from inconsistencies between measurements from different sites because of calibration differences.

Joint standards are needed (at a European level) for 1) instrument calibration, 2) operation, 3) data acquisition, and 4) data analysis. While this is reasonably well developed for systematic ground-based measurements, this is not yet the case for airborne instruments deployed for Cal/Val purposes. Many instruments are usually operated in a rather experimental mode, and common practice is sometimes missing for the different instruments/scientific teams. Possible reasons are that technologies such as airborne imaging systems and their operation are less mature than, for example, ground-based network technologies. Currently, some efforts are made in this direction in the framework of the QA4EO/SVANTE/RAMOS projects, funded by ESA or Copernicus. However, funding mainly focuses on data acquisition and less on the harmonisation and standardisation aspects.

There is a need to characterise better the different sources of uncertainties (input parameters of the air mass factor, temporal variation of the trace gases fields) in airborne observations to fully appreciate its validation potential with respect to, for example, ground-based measurements and close the error budget with satellite measurements. This can be tackled by both R&D laboratory activities and intercomparison campaigns.

More systematic measurements are needed for airborne campaigns. Airborne campaigns are usually restricted in time (a few weeks) and focus on the spring/summer months. Campaigns with a more recurrent nature over the entire year allow insight into the spaceborne sensors' capabilities under different environmental conditions, such as meteorological conditions, sun position, and different pollution levels. It also provides a larger data set of statistically relevant reference measurements. However, both technical and financial issues are faced, as instruments need to be integrated more or less permanently into the aircraft. In this direction, some efforts are made in the ESA RAMOS and SVANTE projects to build an infrastructure to do regular measurements over Bucharest (Romania) and Berlin (Germany) with airborne in-situ and remote sensing instruments.

More systematic measurements are also needed for mobile measurements. Mobile platforms such as cars can be equipped with in situ and remote sensing instruments and are valuable and complementary as they can target much larger areas than stationary measurements. Such measurements are often performed in the framework of short campaigns. More systematic measurements could be achieved by installing such devices on buses, trams, maintenance cars or Google Street View cars to acquire more continuous data.

High resolved vertical profiles are beneficial as a reliable reference for validating satellite products. Atmospheric samplers under meteorological balloons or AirCore can produce vertical gas profiles to finely characterise the gas concentration between 0 and 30 km, the layer that contains most of the atmosphere's mass. The AirCore consists of a long tube system ascending with a balloon to reach the mid-stratosphere (typically 20 – 30 km). The tube pre-filled with a reference gas of known concentrations is emptied during its ascend and starts collecting the surrounding air when descending from the high altitude to the surface. After landing, the sampled air inside the tube is quickly analysed, before mixing, by a gas analyser to get the vertical profile of the atmospheric composition of the target gas. The AirCore systems are currently typically used to obtain vertical profiles of CO_2, CH_4, and CO. However, the AirCore technique at present covers only a few species with long lifetimes like CO_2, CH_4, and CO and cannot be deployed easily everywhere. The latter limitation is due to the fact that in the current state-of-the-art set-up, the AirCore is launched with a balloon and comes down after the balloon bursts with a parachute. The observation site, therefore, must dispose of balloon launching facilities. Also, the landing location of the payload depends strongly on the prevailing winds and can occur at a location that is difficult to access (marshes, mountains, etc.) or a place where the AirCore is lost (lake, sea, etc.).

Unmanned Aerial vehicles (UAV) and High-altitude pseudo-satellites or stratospheric drones (HAPS) have great potential both for vertical and horizontal mapping and sounding of the atmospheric composition. Although UAV technology is widely available, legislation usually doesn't allow it to operate out of sight for safety reasons, restricting the area that can be covered. However, validation of atmospheric products requires covering large areas due to the typically coarse resolution of the spaceborne measurements and seeing gradients in the spatial distribution of the atmospheric components. Again, for safety reasons, operations over urban and industrial areas are usually restricted. At the same time, these are the most interesting areas due to the high concentrations and the high exposure of the population to pollutants.

Another problem is that many UAVs are not equipped with payloads for atmospheric composition sensing. If there are some, neither the payloads nor the measurement procedures are standardised, and the systems are not usable in an operational mode. Therefore, R&D activities are needed before UAVs can fully be used in Cal/Val activities.

In Sect. 3.2, examples are given of emerging technologies with high potential for Copernicus Cal/Val as potential solutions to the current gaps with the respective R&D activities required to bring these technologies to an operational level.

5.1.4. Summary of gaps

5.1.4.1. Pre-flight characterisation and on-board calibration technologies

- A reliable calibration of reflectance spectra is absent for TROPOMI
- The absolute irradiance calibration of TROPOMI is not perfect due to the instability of the sun simulator
- The angular dependence of the solar diffuser for TROPOMI is not well-calibrated, which is causing viewing angle dependent biases in level-2 data products
- Several calibration light sources (Sun simulator, lasers, band filters) used for TROPOMI have severe shortcomings

5.1.4.2. In-situ measurements

- There is a lack of traceability of remote sensing measurements to one standard, which adds to the systematic uncertainty of the measurements at a given site and the network-wide consistency.
- The sources of uncertainties in reference Cal/Val data are not sufficiently characterised to close the error budget with satellite measurements.
- Current technology and legislation hamper systematic mobile, UAV and HAPS measurements over urbanised/industrialised areas, restricting the number of measurement points and area covered by atmospheric measurements. Neither available off-the-shelf payloads for atmospheric composition sensing nor the measurement and analysis procedures are standardised, and the systems are not directly usable in an operational mode.

- There is a lack of instruments capable of vertical profile measurements.

5.1.5. Recommendations

5.1.5.1. Pre-flight characterisation and on-board calibration technologies

- New calibration light sources with different designs could be useful. **Criticality - low, effort needed - high**
- There is a need to develop a calibration source with a persistent calibration validity and less straylight. **Criticality - low, effort needed - high**

5.1.5.2. In-situ measurements

- Efforts must be taken to agree on procedures that ensure that all measurements are tracible to one internationally accepted standard. **Criticality – high, effort needed – high**
- More systematic measurements for airborne and mobile (car, tram, ship, etc.) observations are needed. The development of operational off-the-shelf instruments should be encouraged. This might complement stationary measurements and increase the spatial coverage of the Cal/Val networks. **Criticality – high, effort needed – high**
- Further efforts to bring airborne and mobile spectrometers and in-situ instrument technologies to the FRM level should focus on 1) best practice documents, standards, protocols, etc., 2) harmonisation of data analysis based on centralised processors and automatic independent validation tools. Joint standards are needed for instrument calibration, operation, data acquisition, and analysis. There is also a need for better characterisation of different sources of uncertainty. **Criticality – high, effort needed – medium**
- New instruments should be developed, or existing ones should be miniaturised for better area coverage with UAV and HAPS, horizontally and vertically. The restrictions on battery lifetime, the possibility to fly out-of-sight and legislation have to be dealt with, especially to perform over urbanised/industrialised areas where most of the emissions are produced. **Criticality – medium, effort needed – medium**
- Improvement of the atmospheric sampler under balloon (AirCore, AMULSE): increase precision, develop a standard procedure for measurements and calibration, technological developments to enable measurements of additional species of interest, fit the instruments in other platforms (UAV) to ensure easier and more global deployment and controlled landing. **Criticality – high, effort needed – high**

5.2. Examples of potential gap solutions and new instrumentation technologies

To overcome the lack of traceability of remote sensing measurements to one standard, the ideal solution would be to calibrate the remote sensing measurements to in-situ measurements that are themselves calibrated to an internationally accepted standard – as sketched in Figure 15 below and as performed in the TCCON network (see section 3.2.1). In this approach, the remote sensing measurements of the atmospheric species' concentrations at one reference site are compared to in-situ vertical profile measurements of that same species' concentration above that reference site, covering as much as possible the total column range of the remote sensing measurements. The in-situ measurement system has been calibrated to the international standard beforehand on the ground. A portable version of the remote sensing instrument performs a simultaneous measurement at the reference site; this measurement is then calibrated identically. The portable instrument can then be considered a travelling standard that is moved to the other similar remote sensing observatories in the network for ‘transferring’ the calibration and making the network internally consistent and calibrated to the international standard used at the reference observatory. There are, of course, two caveats: (1) the in-situ measurements onboard the airborne platform must be reliable and keep their calibration level throughout the whole altitude range of the vertical profile. (2) The travelling standard must be stable enough to maintain its calibration when moving from one observatory to another.

In case it is difficult to obtain a calibrated vertical profile measurement at the reference site, one can still make a side-by-side remote sensing measurement with the travelling standard at the reference site and then use the travelling standard to the other network sites to perform an intra-network calibration. This will make the network internally consistent but not necessarily traceable to an internationally accepted standard and therefore not necessarily consistent with other networks (e.g., not ensuring the consistency between in-situ and remote sensing measurements.

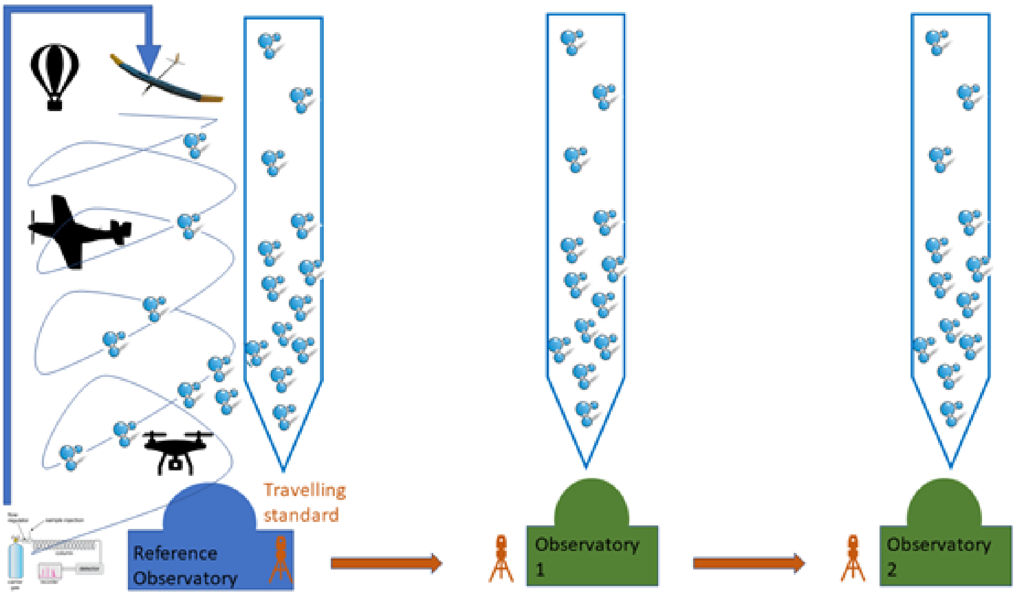

Figure 15. The concept for ensuring calibration of remote sensing measurements.

We need technological developments (1) to enable calibrated airborne vertical profile measurements of all atmospheric species of interest, (2) to ensure that these in-situ measurements are still reliable and maintain the calibration at high altitudes in the atmosphere and (3) to develop portable instruments that deliver sufficient data quality and that are sufficiently stable to make them suitable as travelling standards. For example, we need a portable, compact and stable FTIR instrument designed as a travelling standard for covering the FRM provided by the NDACC FTIR instruments with sufficient precision and accuracy.

5.2.1. Travelling standard for calibration of remote sensing measurements to WMO scale

5.2.1.1. Description

The Total Carbon Column Observing Network (TCCON) represents a network of ground-based Fourier transform infrared (FTIR) spectrometers that records direct solar absorption spectra in the near-infrared (NIR) to retrieve accurate and precise column-averaged abundances of atmospheric constituents, including carbon dioxide (CO_2), methane (CH_4) carbon monoxide (CO) and water vapour (H_2O and HDO) amongst other species. These measurements are the current golden standard for calibrating and validating space-based greenhouse gas measuring sensors. TCCON uses network-wide in-situ calibration factors for the trace gases to scale its products to the WMO reference scale. These calibration factors were calculated from several measurement campaigns where reference in-situ measurement profiles were taken from aircraft campaigns or AirCore launches at the sites (Wunch et al., 2010). However, not all sites are covered in this calibration exercise due to remote locations or difficulties in launching AirCore from those sites. The FTIRs used in the TCCON are large spectrometers, which are very difficult to move and not ideal for inter-site calibration. Portable FTIR spectrometers with similar capabilities are therefore needed to perform side-by-site measurements at all TCCON sites.

The Collaborative Carbon Column Observing Network (COCCON) is a network of portable low-resolution FTIR spectrometers of the type EM27/SUN that records direct solar absorption spectra in the NIR to retrieve accurate and precise column-averaged abundances of CO_2, CH_4, CO, and H_2O. The low-resolution COCCON instruments have shown similar performances for the retrieved CO_2, CH_4, CO, and H_2O products as the high-resolution TCCON (Sha et al., 2020). COCCON uses the reference measurements performed at the TCCON site to scale the measurements to the WMO scale. The high accuracy and precision and the instrument's portability make it a suitable candidate as a travelling standard.

The InfraRed Working Group of the Network for the Detection of Atmospheric Composition Change (NDACC-IRWG) is a network of high-resolution FTIR spectrometers that records solar absorption spectra in the mid-infrared spectral range. The solar absorption spectra are used to retrieve the atmospheric concentrations of several gases, including ozone, methane, ethane, nitrous oxide, carbon monoxide, and formaldehyde. The spectroscopic uncertainty contributes most to the systematic uncertainty of the retrievals. In-situ vertical profile measurements above the network sites and/or comparable remote sensing measurements with a portable low-resolution spectrometer would be needed to calibrate the high-resolution data and reduce the systematic uncertainty contribution to the total error budget.

5.2.1.2. R&D activities required

Additional low-resolution travelling standard instruments must be developed, and side-by-side measurements using these instruments are needed at the high-resolution FTIR sites (TCCON and NDACC-IRWG). These measurements will help to verify the in-situ calibration factors (if) used by the network, reduce inter-site biases and increase the network consistency.

In addition, we need R&D to ensure the availability of in-situ sensors that can be embarked on airborne platforms and measure the concentrations of atmospheric species along with the vertical profile in the (whole) troposphere and – if possible – also the stratosphere – and of which the reliability at high altitude can be guaranteed.

5.2.2. Low resolution remote sensing instruments for partial columns retrievals of atmospheric compositions

5.2.2.1. Description

Remote sensing measurements, either from the ground or from space, have different sensitivities. Retrievals of partial column profiles are therefore useful to compare the respective partial columns of the two instruments.

5.2.2.2. R&D activities required

Retrievals of partial columns (e.g., CH_4, CO_2) from NIR measurements performed with the TCCON instruments will enhance the use of the data. Further studies on the retrievals using CO_2 windows that are sensitive to different altitudes are needed.

Retrievals of partial columns from mid-infrared (MIR) measurements performed with the low-resolution portable FTIR instruments (e.g., Vertex and Invenio type spectrometers, Figure 16) will enhance the use of the data, and in combination with in-situ profile measurements, make it perhaps suitable as a travelling standard for some of the NDACC-IRWG species.

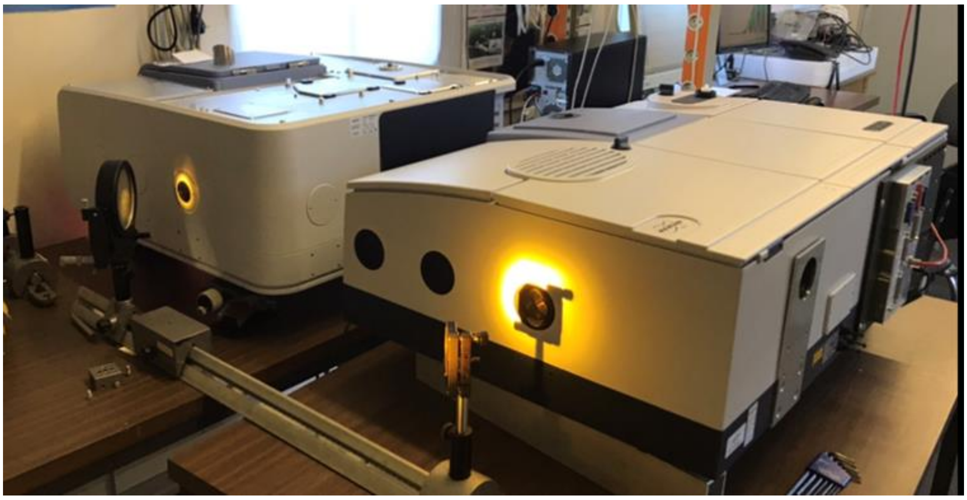

Figure 16: Bruker Invenio (left spectrometer) and Bruker Vertex70 (right spectrometer) performing solar absorption measurements. The solar beam coming from the sun tracker is falling on the entrance aperture of the two spectrometers.

5.2.3. AirCore

5.2.3.1. Description

The AirCore technique (Figure 17) gathers high-altitude profiles of atmospheric concentrations of trace gases. They are currently typically used to obtain vertical profiles of CO_2, CH_4, and CO. The AirCore technique has undergone several development stages since its invention by NOAA in 2010 (Karion et al., 2010). This includes the testing with variable tube lengths, different diameters, a combination of diameters focusing on different vertical resolutions in the troposphere and stratosphere, different coatings of the inner layer of the tubing, etc. Many development activities were performed as part of the H2020 RINGO project (GA no 730944) (Chen et al., 2019). In the context of the ESA-funded FRM4GHG-2.0 project (frm4ghg.aeronomie.be), the University of Groningen is working on the development of AirCore for measurements of nitrous oxide (N_2O) and carbonyl sulfide (OCS).

Some institutes or companies (e.g., Stratodynamics) are working on developing a glider that can carry an AirCore, and that be launched with a balloon up to 25 km latitude and come down in a remotely controlled way at a well-defined landing location.

Figure 17: Preparation from an AirCore launch during the FRM4GHG project from the Sodankylä site (67.37 deg N, 26.63 deg E) in Finland.

5.2.3.2. R&D activities required

A low-cost, standardised procedure for the regular measurements of vertical profiles of the standard products (CO_2, CH_4 and CO) is needed. Furthermore, an extension of the technique to other gases is needed. These measurements will be useful in calibrating the remote sensing measurements. They can be used to directly validate the satellite data products and to support the traceability of the ground-based remote-sensing measurements.

Furthermore, it is important to have an AirCore system that is easily and surely recoverable. Therefore, developing a steerable platform to bring the AirCore back to a pre-defined location is strongly recommended (for replacing the current descent with an uncontrollable parachute). In addition, technological developments to make the AirCore fit in other platforms (UAV) will enable easier and more global deployment with controlled landing possibility.

Not all atmospheric species of interest can be measured in-situ on-board UAVs or HAPS because the standard sensors are not always adapted to these platforms. Current Aircores are limited to CO2, CH4 and CO measurements.

The deployment of the Aircore is limited to selected observation sites

5.2.4. Further development of AMULSE

5.2.4.1. Description

The AMULSE (Atmospheric Measurements by Ultra-Light Spectrometer, Figure 18) instrument is based on tuneable diode laser absorption spectroscopy in the mid-infrared spectral region. This instrument is dedicated to in situ CO_2, CH_4, and water vapour measurements (H_2O). (Joly et al. 2020).

AMULSE can be carried by a meteorological balloon, which allows measuring the vertical profile concentrations of the greenhouse gases, from 0 to around 30 km, with very good accuracy and precision. AMULSE can also be carried by a UAV platform that allows characterising spatial repartition of the gases in a given place up to 3 km.

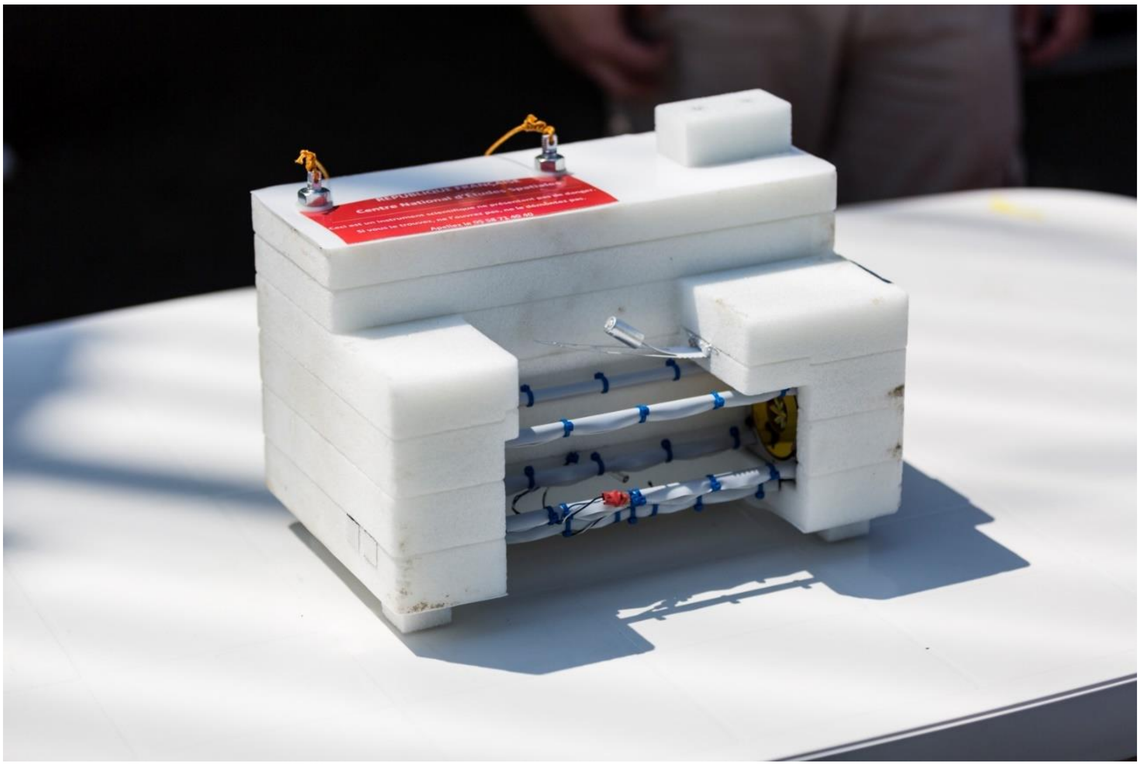

Figure 18: The Amulse instrument. Photo: Alexandre Ollier

5.2.4.2. R&D activities required

Improving the accuracy of the measurements made by Amulse requires precise characterisation of the instrument. For this purpose, a $1m^3$ atmospheric chamber is under construction, but the operating costs (maintenance, gas, filter) are not financed yet.

5.2.5. Further development of CHARM-F

5.2.5.1. Description

CHARM-F is an airborne integrated path differential absorption (IPDA) lidar for airborne operation developed by DLR as an airborne demonstrator for the upcoming German-French methane mission MERLIN. It simultaneously measures the column concentration of methane (XCH_4) and carbon dioxide (XCO_2) below the aircraft (Amediek et al., 2017; Wolff et al., 2021). CHARM-F can be routinely deployed onboard the German research aircraft HALO operated by DLR (Figure 19). Recently the system received certification for the ATR42 aircraft operated by SAFIRE in France.

5.2.5.2. R&D activities required

An IPDA lidar system with a higher repetition frequency operated on board a smaller, more agile aircraft will allow resolving plumes better and thus improve quantifying emissions from localised emission sources. Such a system is currently under development.

Figure 19: CHARM-F installed inside the German research aircraft HALO.

5.2.6. NanoCarb

5.2.6.1. Description

NanoCarb (De La Bariere et al., 2021) is a miniature spectral imager that measures specific gas signatures, such as CO_2, CH_4, NO_2, CO, etc. (Figure 20). It has been partially developed thanks to the H2020 Scarbo project. Nanocarb is based on an array of Fabry-Perot interferometers used in a multiplex mode. The main features of Nanocarb are to be very compact and stable, snapshot, and with a two-dimensional field-of-view. NanoCarb thus reduces the constraints on the platform, like mass and volume capacity or line-of-sight stability.

5.2.6.2. R&D activities required

NanoCarb is still under development: during the Scarbo project, the first airborne demonstrator was developed, and an airborne campaign occurred in October 2020. It was shown that the multiplexed signal measured by the Fabry-Perot array contains the relevant information. Nevertheless, efforts are still needed to validate the quality of the Nanocarb products in terms of geophysical parameter estimation. This may be done through experimental comparison with reference instruments, either in a laboratory or on the field, with ground-based or airborne data. Some improvements to the concept also need to be assessed by simulations and models before an experimental validation. Moreover, a dedicated approach to data processing has to be addressed to cope with a vast amount of data.

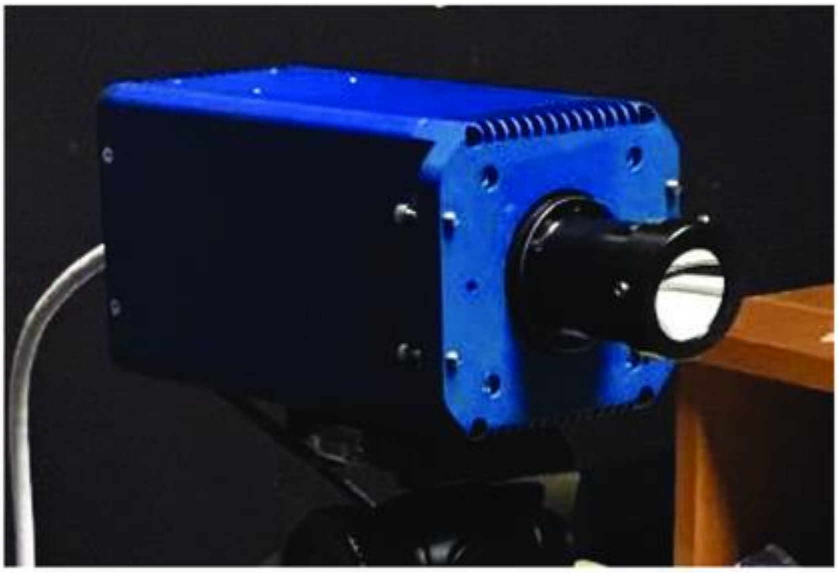

Figure 20: NanoCarb airborne prototype.

5.2.7. Airborne proof of concept SCALE

5.2.7.1. Description

SCALE (Short Comb Atmospheric Experiment) is an airborne proof of concept using a short comb LIDAR. This technique allows resolving a characteristic spectral line of CO_2 with several wavelengths coming from a single laser source. The demonstrator will fly in mid-2023. It is expected to measure the CO_2 total concentration of the atmospheric column under the aircraft with reasonable accuracy.

5.2.7.2. R&D activities required

Several R&D activities are being considered for further development of the instrument. The first activity might be to develop a multipoint detection that would allow switching from a current nadir measurement to a "swath" measurement thanks to a push-broom detector. This would improve the spatial resolution of the instrument. This new acquisition mode would be valuable for satellite validation as it would allow characterising an entire satellite on-ground pixel at once.

In addition, a study of the Doppler shift of the received ground echo would allow simultaneous measurement of the partial column of CO_2 and the wind.

5.2.8. Airborne remote sensing instruments

5.2.8.1. Description

Airborne hyperspectral imaging systems such as APEX, AirMAP, Spectrolite and SWING (Tack et al., 2019) have a high potential to complement stationary measurements for Cal/Val activities. Such instruments are currently deployed for TROPOMI validation objectives (Tack et al., 2021). They can cover a larger area than stationary measurements, and therefore they increase the spatial coverage of the Cal/Val networks. Airborne imaging spectrometers can be considered similar to the satellite sensors and therefore well suited for Cal/Val activities of tropospheric products. When operated well above the planetary boundary layer during the satellite's overpass, they can measure approximately the same tropospheric columns as the satellite but at a much higher spatial resolution.

5.2.8.2. R&D activities required

Joint standards are needed at a European level for 1) instrument calibration, 2) operation, 3) data acquisition, and 4) data analysis. While this is reasonably well developed for systematic ground-based measurements, this is not yet the case for such airborne instruments. Many instruments are under development at universities and institutes and are usually operated in a rather experimental mode. Common practice is sometimes missing for the different instruments/scientific teams, while this is strongly needed for providing reference measurements for Cal/Val purposes. Possible reasons are that technologies such as airborne imaging systems and their operation are less mature than, for example, ground-based network technologies. Currently, some efforts are made in this direction in the framework of the QA4EO/SVANTE/RAMOS projects, funded by ESA and/or Copernicus. However, funding mainly focuses on data acquisition and less on the harmonisation and standardisation aspects. Further efforts to bring this technology to the FRM standard should focus on 1) operationalisation of such instruments, 2) best practice documents, standards, protocols, etc., for example, through intercomparison campaigns, 3) harmonisation of data analysis based on centralised processors and automatic independent validation tools to compare the reference measurements with the satellite measurements. An appropriate platform for the exchange of information, harmonisation and standardisation could, for example, be further developed in the framework of EUFAR.

The Small Whiskbroom Imager for atmospheric compositioN monitorinG (SWING; Merlaud et al., 2018) is an example of an airborne imaging instrument. Several prototypes of the instrument have been developed to fly on fixed wing UAVs, octocopters and manned aircraft (Figure 21). The instrument has been demonstrated during several campaigns to measure emission plumes from industrial and urban point sources (e.g. AROMAT (Merlaud et al., 2018) and AROMAPEX (Tack et al., 2019) and for S5P satellite validation (Figure 22, see URL-5). One strength of the instrument is its compact size and weight, allowing it to integrate on various platforms easily. The cost of the instrument varies between

30k and 60k euros, mainly depending on the choice of the spectrometer. Further developments are needed to develop an industrial-grade/space-grade off-the-shelf SWING instrument.

Figure 21: Wingpod version of SWING, integrated on a motorglider ASK 16 from Free University of Berlin (FUB)

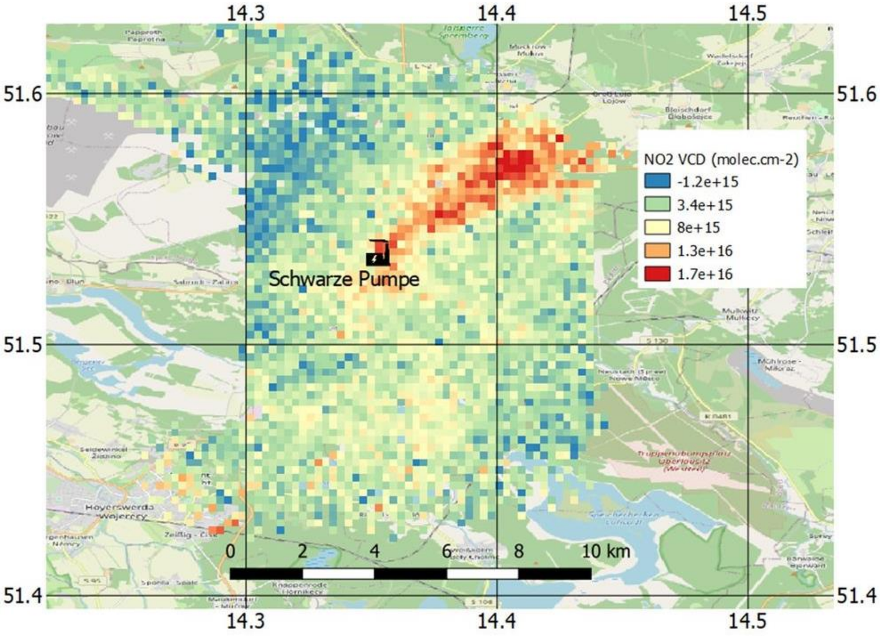

Figure 22: NO_2 plume detected with SWING over Schwarze Pumpe, Germany.

5.2.9. Unmanned Aerial vehicles (UAV) and High-altitude pseudo-satellites or stratospheric drones (HAPS)

5.2.9.1. Description

Unmanned Aerial vehicles (UAV) can be small or large fixed-wing or multi-rotor platforms that can operate at low (few meters) or high altitudes (1-3 km). Multi-rotor platforms are well suited for performing vertical profiling of the troposphere equipped with in-situ instruments. In contrast, fixed-wing platforms are rather suited to operate at higher altitudes, well above the planetary boundary layer, to map the atmospheric composition based on remote sensing instruments. Both types of measurements can be performed during the satellite's overpass and can avoid the deployment of more expensive manned aircraft. High-altitude pseudo-satellites or stratospheric drones (HAPS) will operate at higher altitudes (20-30 km). They can be a fixed-wing platform to map larger areas (Figure 23) or perform soundings with an AirCore system. It can also be a stratospheric balloon or zeppelin that can be geostationary over a specific area of interest.

5.2.9.2. R&D activities required

UAVs and HAPS have great potential both for vertical and horizontal mapping and sounding of the atmospheric composition and thus for validation of the satellite component. They have the potential to complement the existing fleet of manned aircraft and eventually perform operations at a lower cost. Although UAV technology is largely available, shown in several campaigns and experiments, legislation usually doesn't allow it to operate out of sight and above populated areas for safety reasons, restricting the area of interest that can be covered. Although operations with larger UAVs seem to be more easily allowed for applications such as military purposes or border control, it is not the case for scientific research and thus not for satellite validation purposes. Efforts are needed 1) to improve the legislation for UAV operations (for scientific research) at the European level, 2) to improve the technology in terms of safety (e.g. safety procedures in case of loss of contact, parafoil in case of potential crash) and telecommunication (e.g. transponders and UAV traffic management systems), 3) to miniaturize and operationalize hyperspectral (imaging) spectrometers and similar payloads to fit on a wide range of UAV. Regarding HAPS, the technology is less mature. ESA's Directorates of Telecommunication, Earth Observation and Navigation are currently working together to establish a HAPS Programme.

Figure 23: Example of a fixed wing UAV developed by Reev River Aerospace and operated with the BIRA SWING instrument during the AROMAPEX campaign (Merlaud et al., 2018).

5.2.10. Increasing the performance of DOAS measurements with novel Fabry-Pérot interferometer spectrographs

5.2.10.1. Description

DOAS measurements in the UV-VIS commonly undersample the spectral structures (rovibronic lines) of the trace gas absorption since dense bands of vibrational transitions are observable with the spectral resolution of compact, off-the-shelf grating spectrographs. However, the undersampling affects the effective absorption cross-section of the trace gases. In most cases, it implies the need for the evaluation with a reference spectrum recorded with the same instrument. By increasing the spectral resolution of the measurement and resolving trace gas absorption and solar Fraunhofer lines on their intrinsic resolution, measurements without a reference spectrum would be possible. The thereby enabled direct retrieval of absolute column densities of trace gases is more similar and thus likely to be better comparable to satellite measurement geometries. Further, high spectral resolution enables a much higher sensitivity for many trace gases and reduces cross-interferences to other trace gases or inelastic scattering effects. Thereby, the quality of ground-based data for satellite validation is likely to be dramatically enhanced.

Novel Fabry-Pérot interferometer based high-resolution spectrographs allows increasing the spectral resolution of DOAS measurements by more than two orders of magnitude. Their superior light-throughput, robustness and mobility are presented by Kuhn et al., 2021.

5.2.10.2. R&D activities required

High-resolution Fabry-Pérot interferometer-based spectrographs rely on a simple and robust optical design, which can readily be built from available and relatively low-cost optical components. A proof-of-concept study with a prototype instrument and yet not optimised optical components (Kuhn et al., 2021) show the expected and thus promising results. Developing a field-ready device with the performance described in 3.2.10.1 requires custom-made static air-spaced etalons at low to medium cost. The remaining components are low-cost. Once the instrument is characterized, there is no need for calibration (as in other DOAS applications). This technology opens the door to observations with a spectral resolution enhanced by 2-3 orders of magnitude compared to typical UV-VIS spectroscopic applications. Entering this new field has the potential to raise UV-VIS spectroscopy to a whole new level but naturally is subject to residual risk.

6. Conclusions

Instrumentation technology is an essential part of Cal/Val solutions. It corporates the technology used in pre-flight characterisation, on-board calibration and in-situ validation. The technology used must be of the highest possible quality to serve as reference measurements and cover the aspects of Cal/Val activities. With new space instruments and missions, the existing technology needs updating, and new developments are expected to cover the gaps. Also, existing prototypes require more R&D to be deployed in an operational context for Cal/Val. New technologies often incorporate available or slightly modified existing instruments on new platforms like automated floats or unmanned aerial vehicles like drones. The latter is an inexpensive and flexible solution for supporting Cal/Val activities, especially during campaigns. However, there are legal issues when operating drones, especially in urbanised or industrialised areas [D2.5].

The nature of gaps and, therefore, the recommendations vary across the mission types as presented in the previous chapters. However, some gaps are common in different fields, and actions should be taken to overcome them.

- Efforts must be made to bring technology used in Cal/Val activities to the FRM level. That includes 1) providing best practice documents, standards, protocols, etc., and 2) harmonising data analysis based on centralised processors and automatic independent validation tools.

- Common standards are needed for instrument calibration, operation, data acquisition, and analysis.

- The focus must be put on the importance of the calibration and full characterisation of instruments/artefacts.

- Efforts must be taken to agree on procedures that ensure that all measurements are tracible to one internationally accepted standard.

- More systematic measurements for airborne (e.g., UAVs, AirCores, etc.) and mobile (car, tram, ship, etc.) observations are needed. The development of off-the-shelf operational instruments should be encouraged. This might complement stationary measurements and increase the spatial coverage of the Cal/Val networks.

- The development of automatic systems should be endorsed to cover the temporal resolution needs and simultaneity with satellite passes.

- If new technology is being developed with EU funding, there should be an obligation to test in known sites to compare measurements with other reference measurements.

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