Copernicus Cal/Val Solution

D3.3 - Copernicus measurement network and supersites

Ref: CCVS.TAR.D3.3

Version: 1.3

Date: 29/01/2023

GA 101004242

Document Reference

	Company
Work Package	3
WP leader	Sebastien Clerc
Deliverable Title	Copernicus operational FRM network and supersites
Delivery Number	3.3
Delivery Type	Report
Dissemination Level	Public
Version	1.3
Date of issue	29/01/2023
Lead beneficiary	UTARTU
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Changes Log

Version	Date	Changes
1.1	30.11.2021	
1.1	02.08.2022	The document was restructured according to the feedback of the draft document.
1.2	31.08.2022	Final changes according to the feedback to the version 1.1
1.3	29.01.2023	Revised version (editorial)

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

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Table 1. Acronyms used in this report

Acronym	Definition
BRDF	Bi-directional reflectance distribution function
Cal/Val	Calibration/Validation
CCC	Canopy Chlorophyll Content
CCVS	Copernicus Cal/Val Solutions
CDOM	Coloured Dissolved Organic Matter
CHL	Chlorophyll-a
CMEMS	Copernicus Marine Service
CNES	The National Centre for Space Studies
ESA	European Space Agency
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FCover	Fraction of green vegetation Cover
FRM	Fiducial Reference Measurement
GIM	Global Ionospheric Modelling
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IOP	Inherent Optical Properties
LAI	Leafe Area Index
LST	Land Surface Temperature
MTF	Modulation Transfer Function
MWR	MicroWave Radiation
NASA	The National Aeronautics and Space Administration
OSTST	Ocean Surface Topography Science Team
POD	Precise Orbit Determination
RI	Research Infrastructure
R&D	Research and development
SI	System of Units
SLR	Satellite Laser Ranging
SSH	Sea Surface Height
SWH	Significant wave height
SWIR	Short-Wave InfraRed

SWOT	the Surface Water and Ocean Topography
TAC	Thematic Assembly Centre
TBD	To Be Decided
TSM	Total Suspended Matter
WP	Work package

All the acronyms for measuring networks and institutions are provided in deliverables 2.4 and 2.5 and those tables are copied here as appendices.

1 Introduction

1.1 Scope of the document

- Identify measurement gaps, considering the existing ground-based Cal/Val measurement campaigns and networks (as outcome from Tasks 2.4 and 2.5) and the Copernicus missions Cal/Val requirements (as outcome of Tasl 1.1 to 1.4).
- Identify rationalization and optimization pathways: e.g., use of common instrumentation, protocols, and standards across sites; cross-Sentinel use of generic measurements; "supersite" approaches to minimize maintenance costs, as well as possible synergies with other European or international programs.
- Define a minimum set of requirements for a "Copernicus" label for measurement sites, addressing measurement protocols, documentation, availability, data policy; define a certification process.
- Principles and need to evaluate degree of equivalence between individual networks and sites (inter-comparisons) and for other comparison measurements.

1.2 Disclaimer

- The aim of this document is not to address the quality of networks analysed within this document, but to use these as examples of the future approaches for Cal/Val activities.
- Approaches mentioned here are discussed in the mind of Copernicus Cal/Val activities only. This means that the scientific benefit for other purposes (like time series analyses for example) is not under discussion but only the needs of Copernicus missions and services.
- The list of data providers is not complete but just serves as an overview of the current situation. If a data provider is missing from the current list, it is not in any way an evaluation of the quality of the data that they are providing.

2 Copernicus needs vs. current situation

In this chapter the mission validation needs, that are described in more detail in WP1 deliverables [D1.1-D1.4] are compared with the current situation, that was evaluated in WP2 [D2.4 and D2.5]. The aim of this chapter is to map the gap between the needs and deeds, find the main issues that need to be addressed in the future and also point out where synergies as to validation efforts for different satellite missions can be exploited, including the use of network/campaign data that were intended initially for a different satellite mission.

2.1 Optical missions

As the validation sites on water and over land are mostly measuring different parameters and are conducted by different parties of interest, they are covered here separately to also mimic the approach used in WP2. The parameters covered are taken from the mission requirements document [D1.1 Tables 31-33] and the possible gains for measuring different parameters together are addressed in the later parts of this document. As optical missions are strongly affected by the quality of the atmospheric correction (especially the case for water products) the number of stations available for validating the satellite products has to be large in order to have a statistically valid set of data for evaluating the state and drift of the sensor as well as of the products (routine Cal/Val activities ensuring systematic performance monitoring – at least during the commissioning period). It is important to keep in mind that the validated products are not measured by the satellite but are 2nd to n degree level of derivatives of the initial optical signal measured by the satellite. The same can apply for the in-situ validation measurements. Therefore, it is important to understand that we are at the same time validating both the measurement and the calculation procedure. In order to move forward in the most efficient way it is vital to address the components from where the highest error or uncertainty originates rather than fine-tune the parts which have a small effect on the end results. In addition, natural sites have often a lot higher uncertainty coming from the heterogeneity within one satellite pixel rather than from the uncertainty coming from the measurement procedure.

For some variables like directional surface reflectance, we need sampling at higher rate. in order to get match-up data also in areas where cloud coverage is often an issue.

The parameters retrieval information is based on the interviews conducted for tasks 2.4 and 2.5 [D2.4 and D2.5] so not all the available measurements are covered here.

2.1.1 MTF Cal/Val sites

The assessment of the MTF of optical sensors can make use of dedicated Cal/Val targets (checkerboard patterns). Although there is no such target currently maintained in Europe, the CCVS project does not consider this as a gap since alternative methods using “natural” targets (bridges, edges) can be used.

2.1.2 Land products

*Table 2. Comparison of how the in-situ and campaign measurements match the variables to be estimated for optical products. The * in the third column refers to campaigns.*

Parameter	Uncertainty specification	Conducted in-situ / Campaigns*	Temporal coverage	Data repositories	Comments
Aerosol Optical Thickness (550 nm)	10%	AERONET, AEROSPAN, ARM, EUBREWNET, SKYNET / JECAM*	Needed daily, measured in every 5 minutes	AERONET	Uncertainty specification to meet in range from 0.05 – 3.0. EUBREWNET uncertainty example (link)
Aerosol Angstroem Exponent at 550 nm					"by-products" of the atmosphere correction
Bare soil organic carbon (SOC) content		ONERA-TERRISCOPE*, ICOS Ecosystem	decadal	ICOS Carbon Portal	
Biodiversity		JECAM*, ONERA-TERRISCOPE*			physiological (e.g., pigments) morphological (e.g., specific LAI) functional plant traits species composition and others
Canopy and leaf nitrogen content		NEON, ICOS Ecosystem	yearly	ICOS Carbon Portal	
Composition and abundance of raw materials (minerals)					ferric oxide content, clay mineral compositions
Fire Disturbed Area	5% - 10%	INPE-Validation of Satellite Detected Vegetation Fires*	5 – 10 d		Range 0 - 1

Fire Radiative Power	TBD	Western States UAS Fire Imaging Missions*, FIDEX*	daily		Range (0 – 650) K
Fraction of Absorbed Photosynthetically Active Radiation, fAPAR	5% - 10%	FRM4VEG@Wytham Woods*, FRM4VEG@ Las Tiesas–Barrax*	weekly	GBOV	Uncertainty specification for range from 0 – 1 [µmol m^{-2} s^{-1}].
Land cover classification	85%	JECAM*/FLUXNET/ ICOS Ecosystem GeoWiki, LUCAS (up to 2018)		ICOS Carbon Portal	Assumed: Requirement is on Overall classification accuracy (OA)
Land Surface Emissivity	2%	SurfSense*, MACSSIMIZE*			
Land Surface Temperature	< 1K to 1,5K	Copernicus Law, ISMN, KIT LST, SurfSense*, MACSSIMIZE*	daily		At 1 km spatial resolution in range (210 – 350) K resp. (200 – 460) K
Leaf and canopy pigments		NEON, ICOS Ecosystem, FRM4VEG@Wytham Woods*, FRM4VEG@ Las Tiesas–Barrax*			Chlorophyll, Carotenoids, Anthocyanins (required), provided from networks: LMA, chlorophyll, Carbon, Nitrogen, lignin, isotopes
Leaf area index, LAI	5% - 10%	FLUXNET / ICOS Ecosystem / NASVF / JECAM*, FRM4VEG@Wytham Woods*, FRM4VEG@ Las Tiesas–Barrax*	weekly	ICOS Carbon Portal GBOV	Uncertainty specification for range from 0 – 10.
Leaf Chlorophyll Content, Cab [µg/cm^2]	10%	NEON / JECAM* FRM4VEG@Wytham Woods*, FRM4VEG@ Las Tiesas–Barrax*	Measured yearly to once in some years		Uncertainty specification for range from 0 – 90 µg/cm^2.
Leaf Dry Matter Content, C_{dm} [g/cm^2]	10%	DEMMIN/Moorfluxnet/ ICOS Ecosystem	Needed daily, measured several times per day	ICOS Carbon Portal	Uncertainty specification for range from 0.0005 – 0.1 g/cm^2.

Leaf Water Content, Cw[g/cm^2]	10%	JECAM*			
Leaf Water Content, Cw [g/cm^2]	10%	DEMMIN/Moorfluxnet	Needed daily, measured several times per day		Uncertainty specification for range from 0.0001 – 0.001 g/cm^2.
OTCI (former MERIS Terrestrial Chlorophyll Index (**MTCI))**	5% - 10%		weekly		At spatial resolution 0.3 to 1 km
Soil textural / structural composition Quantification		JECAM*			of non-photosynthetic vegetation (NPV)
Surface reflectance (Land)	5%	IMOS, FLARE, NEON, PEN, RadCalNet / ASTER/HISUI vicarious calibration*, Australian continental surface reflectance validation*, CHIME-SBG*, DLR-DESIS*, DLR-Sentinel2*, FlexSense*, ForDroughtDet*, JECAM*, NASVF*, Priscav*, Western States UAS Fire Imaging Missions*, WSN Sentinel-2 Val*	Needed daily, measured several times per day	GBOV	RadCalNet: site-to-site consistency and SI traceability
Water vapour	10%	ARM, COCCON, GRUAN, NDACC/FTIR, NDACC/Lidar, NDACC/MW, TCCON / JECAM*, Stratéole-2*, DLR-Sentinel2*	Needed daily, measured several times per day	EVDC, LAW	Uncertainty specification to meet in range from 0.1 – 4.0 g/cm^2. However, 4 g/cm^2 is too low for the tropics. Expected range is at least up to 5 g/cm^2, may be even up to 6 g/cm^2

**Parameter that should be included in the table but did not have enough information available include: Snow grain size; Snow, ice light absorbing impurities; and Canopy water content.

After merging the requirements from 1.1 with the survey results obtained from 2.4 and 2.5, the following picture emerged:

- Some of the parameters considered within the land products are not measured directly, but are derived values from different measurements.
- No performance requirements addressing some of products from satellite data available (mainly concerning so called application products). This needs to be defined in future. Also, requirements for the products need to be translated into instrument requirements, i.e., define requirements from higher-level products down to lower-level products (many simulations are necessary to do so). The working group within CEOS, WGCV Land Product Validation, is already doing excellent preparatory work in this regard. Their focus areas are:
  - Biophysical (LAI and fAPAR)
  - Fire/Burned Area
  - Phenology
  - Vegetation Index
  - Land Cover
  - Snow Cover
  - Surface Radiation
  - Soil Moisture
  - LST and Emissivity
  - Aboveground Biomas
- Concerning the high number of parameters, focussing on land core-products is recommend, as e.g. defined by GBOV (Ground-Based Observations for Validation (GBOV) of Copernicus Global Land Products):
  - Top-of-canopy reflectance
  - Surface albedo
  - fAPAR
  - LAI
  - FCover
  - Land Surface Temperature
  - Soil Moisture
- FRM4VEG is focused on the vegetation-related parameters surface reflectance, FAPAR and CCC. FRM4VVEG protocols are currently being developed on two sites (Barrax, Wytham Woods)
- Some of the parameters are not clearly defined if they are integrated over the spectrum or if they are spectrally resolved (e.g., surface radiation, albedo). This fact needs to be considered when formulating the requirements.
- Most Cal/Val activities concerning land products are using imaging and/or field spectrometers (radiance measurements). SI traceability is given for RadCalNet. But so far,

there are only three RadCalNet sites available to the community (La Crau, Gobabeb, Railroad Valley).

- 5% uncertainty is the requirement for surface reflectance; therefore, it would be necessary to have in-situ data available for validation with less than 5% uncertainty. So far this is only the case for the RadCalNet sites.
- Surface reflectance reference data are required for different viewing directions. Therefore, BRDF characterization should be addressed. This is foreseen in the HYPERNETS project.
- In addition to RadCalNet sites, further instrumented sites acquiring data under higher aerosol conditions would help understanding potential errors. The provision of a full AOT profile provided by a Lidar would be helpful in this context.
- Traceability of measurement results: Uncertainty information is rarely provided with the measurements. The specification of uncertainty, however, is not always straightforward, especially when it comes to higher level products ("Proper treatment of uncertainty in the validation data requires understanding of the measurement equation and experimentation to determine which factors need to be considered" [Origo, NPL]). The uncertainty of a measurement does not only depend on the characteristics of the optical sensor but also on the measurement condition. However, it is worth mentioning, that most of the in-situ/campaign data is at least quality controlled.
- The number of variables for land products in combination with the different possible land cover on different ecosystems/biomes would require an incredible number of in-situ stations for the validation of products. Therefore, there is a focus on a small number of representative sites (e.g., ICOS ecosystem station network consists of 87 stations in 12 countries). Accordingly, additional data collection on a campaign basis is unavoidable.
- When it comes to Leaf optical properties (LOP), the variation over biological, spatial and temporal scales needs to be accounted for within the validation design.
- Apart from the above-mentioned parameters in table 2, typical by-products like snow cover, cloud cover, etc should also be validated, and validation sites could be developed accordingly (incl. Instrumentation).
- It is important to ensure the sustainability of existing and future networks. The availability of well documented measurements is necessary for a proper validation. Also, a common file-format of the sites data would be convenient. For all this effort, financial support of the sites is required.
- Ideally, regular inter-calibration of the site's instrumentation (depending on the degradation) should be performed.
- Connected methodical aspects for validation of retrievals from satellite data like necessary upscaling to pixel size is discussed in chapter 2.6 "Gaps in ground-based Cal/Val methods" of D3.2 - Recommendations for R&D on Cal/Val Methods.
- Even if no measurements or campaigns are given for some products, this is due to the fact that within 2.4 and 2.5 there is certainly no completeness.

2.1.3 Water products

*Table 3. Comparison of how the in-situ and campaign measurements match the variables to be estimated for optical water products. The * in the third column refer to campaigns.*

Parameter	Uncertainty specification	Conducted in-situ / Campaigns*	Spatial coverage	Temporal coverage	Data repositories	Comments
Chlorophyll-a concentration, Chl [mg/m3]	threshold 30% (70% for CASE-2) goal 10 %	Aquaspectus, LéXPLORE/Thetis, ICOS Ocean / AMT*, AWI-Lake_Constance*, AWI-Polarstern*, DLR-Shipborne field campaigns*, UTARTU-EMI*, MOSES-REEBUS Eddy Hunt*, SU*, SYKE*, UTARTU-TO*, BGC-ARGO	Routine measurements are done in a few fixed locations	1 minute –1 month	Mostly available on request and sometimes additional conditions apply CMEMS OC-TAC, EUMETSAT OC-DB	Uncertainty specification to meet in range from 0.001 – 150. Concentration measurements are mostly campaign based and happen at best twice per month. More frequent measurements are derivatives of reflectance measurements. There are also government monitoring measurements done, however these parameters are usually not entered to any known database and have to be retrieved from reports.
Coloured Dissolved Organic Material, CDOM (a_{442}[m^{-1}])	threshold 50% (70% for CASE-2) goal 10 %	BOUSSOLE, IMOS Ocean Colour Sub-facility / AWI-Lake_Constance*, DLR-Shipborne field campaigns*, UTARTU-EMI*, MOSES-REEBUS Eddy Hunt*, SU*, SYKE*, UTARTU-TO*	Routine measurements are done in a few fixed locations	Needed daily, measure 1-2 times per month	Mostly available on request and sometimes additional conditions apply	Uncertainty specification to meet in range from 0.01 – 2. Campaign data is often gathered in coastal areas, affected by rivers and therefore have values strongly exceeding the expected range.
Diffuse attenuation coefficient (turbidity), K [m^{-1}]	5%	Aquaspectus, LéXPLORE/Thetis, IMOS Ocean Colour Sub-facility / AWI-Lake_Constance*, AWI-Polarstern*, UTARTU-	Routine measurements are done in a few fixed locations	Needed daily, measured several times per day	Mostly available on request and sometimes additional conditions apply	Uncertainty specification to meet in range from 0.001 – 0.1.

		EMI*, SU*, SYKE*, UTARTU-TO*				
Harmful Algae Bloom [mg/m^3]	threshold 30% (70% for CASE-2) goal 20% (30% for CASE-2)	Aquaspectus, MRI KU*		Needed daily, measured constantly		Uncertainty specification to meet in range from 0.1 – 100. Presence of algal bloom is mostly evaluated from reflectance spectra.
Photosynthetically available radiation, PAR [µmol m^{-2}s^{-1}]	5%	BOUSSOLE, DEMMIN/Moorfluxnet, LéXPLORE/Thetis, FLUXNET, ICOS Ecosystem, NASVF, NEON		Needed daily available in every 5 minutes		Uncertainty specification to meet in range from 0 – 1400. In situ uncertainty only available for NEON (5%).
Surface reflectance	5 $\times 10^{-4}$	AERONET-OC, Aquaspectus, BOUSSOLE / AMT*, AWI-Lake_Constance*, AWI-Polarstern*, DLR-Sentinel2*, DLR-Shipborne field campaigns*, UTARTU-EMI*, MRI KU*, MONOCLE*, MOSES-REEBUS Eddy Hunt*, PRIMEWATER*, PRISCAV-water Garda*, PRISCAV-water Trasimeno*, SU*, SYKE*, UTARTU-TO*	Global coverage but CASE-2 waters coverage is weak. Routine measurements are done in a few fixed locations	Needed daily, measured several times per day	Mostly available on request (Apart from AERONET-OC) and sometimes additional conditions apply	442 nm has often issues with atmospheric correction – for coastal and inland waters. Range from 0.001 – 0.04 is expected. Data is usually collected in multi- or hyperspectral form. However, it is mostly gathered during the campaigns and there are very few constant measurements.
Total Suspended Matter, TSM [g/m^3]	threshold 30% (70% for CASE-2)	Aquaspectus, BOUSSOLE, LéXPLORE/Thetis, IMOS Ocean Colour Sub-facility /	Routine measurements are done in a	Needed daily, measured	Mostly available on request and sometimes	Uncertainty specification to meet in range from 0 – 100.

	goal 10 %	AMT*, AWI-Lake_Constance*, DLR-Shipborne field campaigns*, UTARTU-EMI*, MOSES-REEBUS Eddy Hunt*, SU*, SYKE*, UTARTU-TO*	few fixed locations	several times per day	additional conditions apply	Concentration measurements are mostly campaign based and happen at best twice per month. More frequent measurements are derivatives of reflectance measurements.
Water leaving radiance Lw (λ) [mW/cm2/µm/Sr]	5%	AERONET-OC, Aquaspectus, BOUSSOLE, IMOS Ocean Colour Sub-facility, MOBY/ AMT*, AWI-Lake_Constance*, AWI-Polarstern*, UTARTU-EMI*, MOSES-REEBUS Eddy Hunt*, SU*, SYKE*, UTARTU-TO*	Global coverage but CASE-2 waters coverage is weak. Routine measurements are done in a few fixed locations	Needed daily, measured constantly		Range from 0 – 1 is expected. In situ uncertainty examples: AERONET-OC (link) BOUSSOLE (link)
Sea Surface Temperature	0.1 - 0.5 K			6h		At spatial resolution 50 km to <0.5 km

It is expected that validation measurements follow the FRM principles, that must include full uncertainty estimation. As the standard rules of how to apply these calculations are currently being developed for ocean colour measurements within the ongoing FRM4SOC-2 project, the uncertainty estimation is not included in the current analyses. In practice most parties do not provide any uncertainty evaluation, and even if they do, the validity of the estimation is not confirmed.

For water products retrieved from the optical missions, the only product that is commonly validated in an automated measurement form is the surface reflectance and this is only the case when we leave the atmospheric correction issues aside at the moment. It is important to state this, as usually the product providers who provide parameters like CHL, TSM etc on daily bases together with reflectance values actually measure radiance/irradiance and calculate the reflectance and from there the parameter of interest. Therefore, this does not provide validation data as such on these parameters but only compare the different calculation methods compared to the laboratory measurements from collected water samples that actually measure the target of interest. Nevertheless, these sites are still very valuable as they enable the validation of the base product – reflectance.

The other provides like BGC-Argo and ICOS Ocean do provide continues direct (calculated from the measurements of the specific optical instruments) measurements for parameters like CHL, TSM, Turbidity or CDOM. However, these measurements are usually not paired with other apparent or inherent optical properties which makes the use of these products for Cal/Val activities a bit difficult. The second issue is that these sensors are sent on long missions in the ocean and sometimes are being lost during the deployment. This means that the condition of the sensor cannot be evaluated or is being evaluated after a long time series. However, these kinds of networks collect data in the amount of measuring points that is not feasible in any other way. This means that they provide an approach to statistically validate satellite products over time and space in a matter that is not possible with any other approach. If these measurements could be coupled with time-to-time water sample measurement in the close proximity to validate the current state of these instruments, then these measurements would already be in almost ideal position if the real-world restrictions are considered.

The other option to increase the quality assurance for these deployments is to add reflectance measurements to them. It is only possible when the devices are mounted to a buoy (in comparison to gliders). Even then there are several uncertainties that need to be addressed (including tilt and azimuth viewing angle) and need more research. ICOS-Ocean is looking into possibilities of providing these kind of test sites and data from these would be essential to have a longer plan for Copernicus Cal/Val activities.

Until then, to validate the concentration parameters, we must turn to campaign type products. Some of these might be regular and reasonably frequent (1-2 times per month) whereas most of these measurements are conducted either seldomly or even just once for current location. Either way these kinds of measurements can easily occur during cloudy days or just when there is no satellite overpass. The latter can sometimes be overcome with better communication as in several cases the routine measurements can be shifted to better dates, if the weather (wind/waves) allows it. The communication improvements have to be addressed by the remote sensing community as the people/institutes/agencies conducting these measurements are well within their needs and the change can only come when the need and potential positive outcome is first demonstrated to them.

Listed within this document, only AERONET-OC and Aquaspectus provide constant comparison measurement from several different sites. For AERONET-OC the issue is that the product is multispectral and at the moment there are also some question marks about the durability of the network. For Aquaspectus, the sites are currently only located in Europe and the data is not freely accessible, although these sensors have a common database so having arranged the data access with instrument owners, the data extraction is the same for every instrument. The data is hyperspectral and therefore cover all the optical missions. On the positive side, there are several emerging networks (like HYPERNETS) that cover constant hyperspectral reflectance measurements. These are in detail discussed in Deliverable 3.1.

In order to constantly validate remote sensing products, measurement buoys with above and in water measurements have to be used. Parameters like absorption, fluorescence and backscattering can only be measured below the surface but radiance (both upwelling and downwelling) and irradiance should also be measured above the surface. Ideally these systems would include profiling measurements. Currently there are only few of these complete systems around the world and as their deployment is expensive and needs regular maintenance, it is not seen that the number would be rapingly increasing. Therefore, it is vital that the ones measuring now will be maintained. With that comes another issue. Main provider for these systems is Seabird that cut the service and construction in May 2022. Already before that it was clear that a service provider, or even manufacturer, is needed in Europe, as maintenance and calibration including oversea shipments carved into deployment periods. Now, as the main manufacturer is not within the market anymore, this need was lifted from necessary to essential. Without the properly maintained instruments it is hard to keep and impossible to increase the number of locations where inherent optical properties are measured in an automated way together with surface reflectance. Parameters that are used for calculations within Copernicus standard products.

From the parameters listed in the Table 3 only TSM and harmful algal blooms sensors are not available. However, TSM can be estimated through turbidity sensor and blooms can be calculated from above water reflectance measurements, especially if the buoys stay in one location and the local knowledge can be used for algorithm tuning.

2.2 Altimetry mission

The in-situ measurements are critical for the calibration and the validation of the **products** of altimetry missions. Indeed, these measurements are not used to tune the instruments of altimetry missions (altimeters, radiometers and POD). There are used only for Cal/Val of products and thus improvement of the ground processing. As explained in [D2.1], the instruments have their own on-board calibration modes. These modes are sufficient to tune the instruments and to monitor their good health all along the mission lifetime. As a consequence, no campaigns are mandatory for the instruments during the commissioning phase. They all address the product validation.

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 list of the geophysical parameters estimated from altimetry missions is obtained from [D1.2, table 1]. In this section, we have cross-checked the requirements on the mission parameters and the ability to validate them from in-situ networks [D2.4] and from campaigns [D2.5]. We have also added some information obtained from direct feedback of users (readers of the previous reports or participants of the CCVS workshop).

The aim here is to identify gaps either on the observations of some variables or on accuracies and associated uncertainties of observations.

As stated in [D1.2], the requirements for each variable are not always in agreement from one mission to another. We **indicate the lowest numbers** here which are key to determine the usefulness of the in-situ measurements. The readers can refer to [D1.2] for the discrepancies between missions.

Altimetry is very demanding on accuracy and precision and thus on the uncertainty associated with in-situ instruments. For a satellite uncertainty requirement of 1 cm, the in-situ measurements should have an accuracy of, at least, 0.5 mm to be able to be used as the ground truth. For most of the parameters, the requirements are within the same level of accuracy and uncertainty as the parameters to be validated. This requires the use of multiple sites and statistical approaches to mitigate the errors associated with in-situ measurements.

For some parameters, the requirements are also expressed in terms of temporal drifts [D1.2]. They are usually one order of magnitude below the requirements on the variable itself. For instance, the requirement on SSH (Sea Surface Height) uncertainty is around 3 cm, depending on the kind of product. The requirement on the SSH drift is 1 mm/year (over 1 year, the uncertainty measurements is of the order of 3 cm while the drift of 1 mm, leading to very different sensitivity ratio). The drift issue is very tricky to address from in-situ measurements. These measurements often have the same accuracy as the spaceborne instruments as well as their own drifts. Characterization (both detection and quantification) requires a very stable or monitored environment which is less easy to achieve on Earth than in Space. In-situ means deploy, in average, less monitoring of surrounding environment than on-space instruments. The Earth environment is changing a lot (temperature, pression, humidity) which impact the accuracy of the in-situ measurements.

Using in-situ observations to retrieve uncertainty estimates at scales between the individual measurements and the long-term trends (e.g. mesoscale) is difficult.

For POD, stations are needed at high latitudes, especially for polar altimeter missions: currently no SLR station above 60° N and 30° S!

2.2.1 Link between variables and observables

*Table 4. How the in-situ and campaign measurements match the variables to be estimated? The * in the third column refers to campaigns. The "req. order" is the order of magnitude of the requirements coming from the Mission Requirements Documents. The "meas. Accuracy" is the accuracy achieved by the ground instrument.*

Parameter	Uncertainty expected	Conducted in-situ / Campaigns*	In-situ uncertainty	Spatial coverage	Temporal coverage	Data repositories	Comments
Sea Surface Height (SSH)	3cm	Specific sites: FRM- BASS STRAIT, FRM-CORSICA, FRM-CRETE, FRM-HARVEST	1 cm	Only specific sites, close to the coast	Continuous	Restricted / Available on-demand only	With at least one comparison (two in case of a crossover) between the satellite and in-situ measurements per cycle, it usually requires a dataset of several years to reach a level of uncertainty below the 1 mm/yr. In addition, the in-situ and satellite measurements are not perfectly collocated, dedicated methodology and precise geophysical information are used to compensate for the ocean and atmosphere spatial variability. However, the small-scale variations of the oceanic topography remain unknown. This effect increases the level of uncertainty. It can be reduced, cancelled out by averaging a large number of observations sampled over several cycles. These sites are localized at agencies/labs place only.
		GNSS-based instruments (CalNaGeo, Cyclopée) + Lidar measurements	~cm	Only specific sites, close to the coast or in-land waters	Few days (on-demand)	Available on-demand only	Very accurate but deployed on small areas. Lots of initiatives (mostly in the framework of SWOT preparation). It can be deployed over rivers, lakes and ocean.

		Tide gauges' networks: GLOSS, REFMAR	1 cm (every 1 s)	Worldwide, coastal area	Continuous	Freely available	Almost only accessible in coastal areas. Use of models and inter-satellite comparisons for open water.
		Portal of networks: INSTAC	Same as above.	Worldwide, coastal area	Continuous	Freely available	Gathers all the available networks. Very valuable to have a unique and clear access for all oceanic in-situ data.
		SWOT US moorings, drifters etc		Only specific site			
		SWOT Adopt a crossover		Only specific site			
SSH drift	1 mm/year						Issues to characterize the drifts. The verification of the 1 mm/yr requirements on the SSH drift requires the accumulation of a large amount of data to reduce the effect of instrumental noises (from both satellite and in-situ sensors).
Land Ice Elevation	?	CRYOVEX*		Artic and Antarctic	Once or twice a year	Freely available	
Water Level Height (hydro)	~10 cm	Specific sites: AMAZON, FRM-ISSYKKUL	Few cm	Only very specific sites	Continuous	Restricted / Available on-demand	Specific sites under satellite tracks are very useful but they are very heterogeneous. A labelling of FRM sites will be useful to harmonize the in-situ instruments and available data.
		Gauges' Networks:	Few cm	Mostly North	Continuous	Freely available	

		GRDC, HYDRODATEN		America and Europe			
		Citizen science: LOCSS, OECS	Few cm	Mostly North America and Europe	Continuous	Freely available	
		VorteX.io (lidar on drone, on-demand deployment)*	Few cm	Deployment on demand	Few days (on-demand)	Restricted / Available on contract	
Freeboard Height	(~1cm ?)	CRYOVEX*	?	Artic and Antarctic	Once or twice a year	Freely available	
Ice thickness	~10cm	CRYOVEX*	?	Artic and Antarctic	Once or twice a year	Freely available	
Water Vapor	~1cm	Specific sites: FRM-BASS STRAIT, FRM-CORSICA, FRM-CRETE, FRM-HARVEST, FRM-ISSYKKUL	<1cm	Only very specific sites	Continuous	Restricted / Available on-demand	
		Portal of networks: INSTAC		Worldwide, coastal area	Continuous	Freely available	

Wet tropospheric Path Delay	~1cm	Specific sites: FRM-BASS STRAIT, FRM-CORSICA, FRM-CRETE, FRM-HARVEST, FRM-ISSYKKUL		Only very specific sites	Continuous	Restricted / Available on-demand	
		GPS data		Worldwide , coastal area			
		Radio Sonde					
		On-ground radiometers					
		Portal of networks: INSTAC		Worldwide , coastal area	Continuous	Freely available	
Wind speed modulus	~1m/s	Specific sites: FRM- BASS STRAIT, FRM-CORSICA, FRM-CRETE, FRM-HARVEST, FRM-ISSYKKUL	<1m/s	Only very specific sites	Continuous	Restricted / Available on-demand	
		Portal of networks: INSTAC		Worldwide , coastal area	Continuous	Freely available	

		SUMOS*	?	Bay of Biscay	Once	Restricted / Available on-demand	
Significant wave height	~5 cm	Specific sites: FRM-BASS STRAIT, FRM-HARVEST	?	Only very specific sites	Continuous	Restricted / Available on-demand	
		Networks: DBCP, IMOS, NDBC	Very variable (from 10 cm to 50 cm)	Worldwide, coastal area	Continuous	Freely available	
		Portal of networks: INSTAC		Worldwide, coastal area	Continuous	Freely available	
		SUMOS*	?	Gascogne Golfe	Once	Restricted / Available on-demand	
		VorteX.io (lidar on drone, on-demand deployment)*	On-going development	Deployment on demand	Few days (on-demand)	Restricted / Available on contract	
Backscatter coefficient	~0.1 dB	Specific sites: FRM-CRETE (transponder capability under development), FRM-	On-going demonstration	Only very specific sites	Continuous (for FRM)	Restricted / Available on-demand	A corner reflector may be added at the FRM-CORSICA (under study). The transponder dedicated to sigma0 calibration/validation needs to be associated to an on-ground radiometer to also calibrate the part of the altimeter signal due to the atmosphere attenuation (signal of 0.2 dB magnitude). This

		HARVEST, Italy ESA transponder, CNES transponder					is under development in the ESA S3 Land Altimetry MPC project for the future Italian site.
		Corner reflectors*	~0.2 dB (may not be	Only very specific sites	Few days	Restricted / Available on-demand	
		SUMOS*		Gascogne Golfe	Once	Restricted / Available on-demand	
		CRYOVEX*		Arctic and Antarctic	Once or twice a year	Freely available	
Range	~cm	Specific sites: FRM-CRETE, Italy transponder		Only very specific sites	Continuous	Restricted / Available on-demand	Harmonization as much as possible between the "FRM" sites through OSTST partnerships. The labelling as FRM is only put on the CRETE sites by ESA. → extension of labelling could help for better harmonization. The TRP facility (FRM-CRETE) allows to measure and monitor the altimeter range bias. However, it is derived from a specific processing that slightly differs from the one implemented in the ground segment. Therefore, the result is not strictly comparable to the range values provided in the Level-2 products.
Ionospheric correction	~0.1cm	Networks: IGS		Worldwide	Continuous	Freely available	Networks satellite-oriented. GPS data are used to compute GIM model that can be compared with altimeter dual frequency ionospheric correction.

		Networks: DORIS	Too large for altimetry validation.	Worldwide	Continuous	Freely available	DORIS derived correction is not directly comparable to altimetry since it is not a measure of electron content at nadir but on the path between DORIS station and the satellite. Jason-1 grounds segment included dedicated processing to compute a derived correction for altimetry but the associated uncertainty was larger than the GIM correction so the calculation of this correction was stopped.
		CATALINA transponder		Catalina Island, 30 km off shore Los Angeles	Done by NASA on a best effort basis	Under NASA responsibility	Indirect measurement through Ku-band and C-band range. Still to be assessed for Sentinel-3 mission. Note that funding for Sentinel-3 operations is not secured.
Sea State bias correction	~cm	Towers					Very difficult to retrieve by in-situ means since it deals with the interaction between radar altimeter signal and distribution of waves specular facets, and the way it is modelled in the ground segment.
		Aircraft campaigns					
Altitude	~1cm (mm ?)	Networks: DORIS, IGS, IRLS		Worldwide	Continuous	Freely available	Networks satellite-oriented
Ocean Tide correction		Tide gauges' networks: GLOSS, REFMAR	1 cm (every 1 s)	Worldwide , coastal area	Continuous	Freely available	Almost only accessible in coastal areas. They are used for the validation of ocean tide models and are sometimes assimilated in the ocean tide models used in the Sentinel products.
Rain flag / rain rate	?	Specific sites: AMAZON, FRM-BASS STRAIT, FRM-		Only very specific sites	Continuous	Restricted / Available on-demand	

		CORSICA, FRM-CRETE, FRM-HARVEST, FRM-ISSYKKUL					
		Networks: GLOSS, REFMAR		Worldwide, coastal area	Continuous	Freely available	
		Portal of networks: INSTAC		Worldwide, coastal area	Continuous	Freely available	
Ice flags		CRYOVEX*		Artic and Antarctic	Once or twice a year	Freely available	
Leads and floe flag	~1cm	CRYOVEX*		Artic and Antarctic	Once or twice a year	Freely available	
MWR brightness temperature	~1K						

2.2.2 Conclusion

First of all, this state-of-the-art review points out three main kinds of in-situ measurements:

the permanent sites dedicated to the altimetry missions gathering many instruments to characterize the sites and, in some cases, the altimeter signals

the temporary sites associated to campaign deployment (with or without airborne components),

the global networks, generally not designed for space missions but used on a routine basis for Sentinel product validation

2.2.2.1 FRM versus non FRM

This first observation leads to the discussion on Fiducial Reference Measurement. We have first to define what is a "FRM". Tentatively, we state here the following definitions:

> FRM are considered "critical for the mission" as they bring an independent observation that cannot be obtained in any other way.

FRM are "Super Sites" data gathering several instruments to fully characterize the site surrounding and its atmosphere. The site is permanent and acquires data all over the mission lifetime. It brings observables that can directly be used to calibrate one of the payloads or the mission products. It can include an on-ground instrument facilities specifically designed for the spaceborne instruments (e.g., transponder for radar), but this is not mandatory.

FRM implies that all the measurements are performed with a high-quality level. This means that the traceability is assured as well as a complete uncertainties budget. The instruments have a high accuracy with a measured level in agreement with the mission or product requirement. Additional campaigns are often required to maintain the accuracy and the perfect characterisation of the site surroundings. Thus, FRM sites gather permanent acquisition and occasional deployments.

Non FRM in-situ data include all the opportunity data coming from in-situ networks or campaigns. The in-situ networks may not be specifically designed for Cal/Val objectives, nor be maintained, nor be at the level of accuracy expected/needed. Nonetheless, they benefit greatly the mission due to their spatial and temporal coverages. The Cal/Val activities shall cope with the discrepancies in design, accuracy or traceability which are not always clearly documented.

Finally, field campaigns are usually of a high level of accuracy and traceability but they can be one shot or on sparse temporal slots. They certainly are carried out over very specific sites selected for the purpose of the validation exercise. One important recommendation is to secure and maintain the access to the acquired data and associated documentation (uncertainties, conditions of the campaign measurements, data limitations etc.) to be able to exploit the campaign observations for qualifying regularly (I.e. every 2 or 3 years) the quality of the Sentinel mission.

To summarize, on the one hand, there are few FRM sites but they are very accurate. On the other hand, there are lots of non-FRM measurements but they are heterogeneous (e.g. in their design, uncertainty etc.).

At this stage, there is only one official FRM-class data for altimetry, and it is specifically dedicated to the altimeter range (the Crete site including a transponder). It has been identified as FRM through the FRM4ALT study of ESA. However, we have identified here other sites as “FRM-like”, since they bring the same valuable information with the same high standard of measurements. Many sites (e.g. Corsica, Harvest, Bass Strait) have been used as absolute calibration sites for altimetry for several years. **We recommend to label them as FRM for the Copernicus Sentinel-3, Sentinel-6 and CRISTAL missions** to secure continuity of funding. They all have the particularity to be over flown by several altimetry missions and/or to be at cross-overs of one given mission. After being evaluated by ESA and EUMETSAT as valid references for Cal/Val activities, Copernicus program should consider supporting these sites financially.

What does altimeter FRM bring and which is not accessible with other measurements?

Compared punctual campaigns that usually provide well documented results and uncertainty estimations, the current altimetry FRM sites (including the Harvest, Corsica, Bass-Strait calibration sites) collect high quality (and well documented) measurements on a long time period, covering the mission lifetime. This recurrence allows to set up dedicated routine activities (as it is the case, for example, of the ESA Sentinel-3 Mission Performance Cluster project) to regularly process the data and perform the comparison with the altimetry measurements. In case of instrument or processing anomaly (or planned change in the ground processing), the impact can be assessed through the comparison with FRM. With punctual campaign datasets, the satellite instruments and processing performances can be assessed, ground processing improvements can also be evaluated (with reprocessing activities) but they do not allow to monitor the temporal evolution of the performances.

Compared to opportunity in-situ data, the altimetry FRM sites, although being more localized, have the advantage of bringing a higher level of confidence in the comparison between satellite and in-situ measurements. This can be explained by the following points:

First of all, one important characteristic that defines FRM measurements is the traceability of the error associated with the measurements.

Current FRM altimetry sites have been conveniently selected to be located specifically under the satellite ground-track. On the other hand, the distance between the altimeter measurement and the (opportunity) in-situ facility can reach tens of kilometres. The longer is the distance between measurements (from satellite and in-situ facility) the higher the errors induced by the spatial variability of the environment.

The geophysical environment of the FRM sites is well characterized. Such instrumentation sometimes can provide accurate correction for atmospheric and/or oceanic perturbations. When direct observations are not available, these corrections can be also derived from regional numerical models designed specifically for the FRM-site area.

The analyses of the altimetry FRM-sites datasets and their comparison with the altimetry measurements are usually performed by teams of experts with extensive knowledge of the instrumentation system (and most of the time by teams who deployed the facility). Indeed, the altimetry FRM measurements are not widely distributed to the altimetry community which limits potential wrong usages. This point can also be considered a limitation, since these regular high quality in-situ measurements could be used more widely by the altimetry community for other validation activities.

2.2.2.2 Transponders

In the constellation of in-situ measurements, transponders have a well-defined role: they have been specifically designed to characterize the radar range and backscattering. Historically, the first altimeter transponders only measured the Ku-band range. Nonetheless, some have been recently upgraded to address not only the backscattering accuracy in Ku-band (ESA, NASA, CNES' ones), but also range and backscattering accuracy in Ku-band. At first, transponders were dedicated to range only.

A second major upgrade is the addition of the C-band to the Ku-band. This is the case of the NASA Catalina transponder, that can be thus considered the most complete existing facility: it allows the calibration of both Ku-band and C-band range and therefore the absolute calibration of the dual frequency ionospheric correction for the first time in altimetry. In the same manner, simultaneous calibration of both Ku-band and C-band backscatter coefficients could be also used for a more thorough validation of the rain flag. This type of observations can be theoretically used for Sentinel-6 and Sentinel-3 missions, but so far, acquisitions have only been performed for Sentinel-6 mission. Acquisitions for Sentinel-3-A mission have been set up by the ESA S3 Land Altimetry MPC.

One important drawback of transponders is that they are difficult to calibrate themselves, in range and in radiometry. The backscattering measurement require a strong monitoring of any temperature variations and associated compensation. Note that a full calibration of the backscattering requires an additional equipment with on-ground radiometer to properly measure the atmosphere attenuation in the transponder acquisition.

Furthermore, it is important to remind that the transponder calibration ignores any effect that the various reflecting surfaces have on the returning echo. As such, transponders provide access to only one part of the altimeter sensor characterisation and do not address the validation of the on-ground processing that is needed to estimate the range over the different surfaces. Therefore, transponders should not be considered to provide the full answer to the uncertainty assessment of the final altimetry product.

The main recommendations regarding transponders are the following:

Select common sites between the different Sentinel ground tracks so that a given site allows the calibration of at least 2 satellites (this allows cost reduction).

Make available the uncertainty budget of the various equipment on the different sites along with the calibration approach and monitoring used for each site since this is the critical issue for qualifying the transponder accuracy.

Identify the outcome expected from several transponders operating for the same mission and during the same period. In other words, how many transponders do we need to calibrate Ku-band and C-band at the requested level of accuracy?

Note that the definition of the FRM site for altimetry cannot be reduced to presence of a transponder. We acknowledge that to be classified as FRM site, one must follow the official FRM standard. On the other hand, we recommend that the altimetry FRM standard should be revised to include sites without transponders.

2.2.2.3 Lack of on-ground observables

2.2.2.3.1 Summary: observability matrix

The following table summarizes the parameters which can be validated through in-situ means or a campaign. It does not discuss the accuracy of these observations (see 2.2.1).

Table 5. Observability matrix. The crosses indicate that the parameter is observed either in an in-situ device or during a specific campaign.

Sea Surface Height	In-situ	Campaigns
Sea surface height	x	
Water Level Height (hydro)	x	x
Land Ice Elevation	x	x
Freeboard Height		x
Ice thickness		x
Water Vapor	x	
Wet tropospheric Path Delay	x	
Wind speed modulus	x	x
Significant wave height	x	x
Backscatter coefficient	x	x
Range	x	x
Ionospheric correction	x	
Altitude	x	

Rain flag / rain rate	x	
Ice flags		
Leads and floe flag		
MWR brightness temperature		

2.2.2.3.2 Ocean

The oceanic parameters are all well covered, except for the MWR brightness temperature. However, this level 1 variable can be addressed through the validation of some level 2 variables on atmosphere properties. Over the ocean, the limitations of in-situ observations are mostly related to their spatial coverage. Obviously, most of the in-situ devices are near the coasts, except for drifting buoys (Argo). For this reason, the models and the inter-comparison with satellites are the baselines of the product Cal/Val [D3.2].

The in-situ measurements of SWH are not accurate enough, and mostly they are in coastal areas. Near the coast, the wave heights evolve very rapidly over short distances. Because of that, buoys information is difficult to use to validate the SWH product, especially when buoys are away from the satellite tracks. For this topic, specific campaigns in off-shore conditions should be a great asset.

In-situ measurements can only provide a local validation of the satellite measurements. They can be compared with a spatially averaged value (of a given parameter) measured by the satellite at an individual point. However, an uncertainty assessment for scales from ten to hundreds of kilometres cannot be performed. The validation of these medium/small scales, is usually performed via dedicated in-situ glider campaigns. However, the slow horizontal and vertical speed of such platforms (compared to both the satellite ground speed and the temporal scales of variability of ocean topography) represent a major limitation for these type of applications: the observed vertical sections through the water column (required to reconstruct the ocean surface topography) are never truly synoptic (for instance processes such as internal tides are strongly aliased), so that the comparison is rarely accurate enough for validating the altimeter signal at those scales.

In-situ measurement from large networks of moorings along a satellite track or quick airborne flights located under the satellite tracks represent a more promising solution. These in-situ validation methods have been designed and will be tested in 2023 to validate the SWOT short scale signal contents.

All the work in the framework of the SWOT missions for Cal/Val preparation should also be adopted by to the Copernicus missions. It will bring new in-situ measurements and campaigns for ocean (https://www.swot-adac.org).

2.2.2.3.3 In-land waters and ice surfaces

As explained above, the FRM sites are mostly for the ocean variables. The altimetry missions open new tracks on in-land waters and ice. The in-situ measurements shall follow this trend to validate the products. For the moment, there are not enough measurements and models cannot supply this information.

The ice parameters cannot be validated with systematic in-situ measurements. This thematic is only covered by the CRYOVex campaigns, which is not enough to validate thoroughly the ice observations.

The spatial and temporal variability are very high for these surfaces. It is thus very important to have acquisitions at the exact satellite tracks. The objective is to have very reliable observations to assess the measurement accuracy (mostly of Level 2 product).

We need more FRM sites over land surfaces. The ESA St3TART initiative will identify and develop new sites. The actual ones (such as Issykkul Lake, Parintins, etc.) could be classified as FRM.

All the work in the framework of the SWOT missions for Cal/Val preparation should also be aggregated to the Copernicus missions. It will bring a lot of in-situ measurements for in-land waters (https://www.swot-adac.org).

2.2.2.4 Centralized access

As explained in [D2.4] the access of in-situ data may be tricky, mostly for networks and networks of networks. The centralized access proposed by the CMEMS in-situ TAC is very valuable and should be encouraged. As it is fostered by CMEMS this portal address only ocean measurements.

The same need exists for land and ice. The ESA St3TART project will provide a first answer by gathering all in-situ data for land and ice validation of Sentinel-3.

We recommend to extend these initiatives to ease the use of the in-situ data.

We have also pointed out that the data from the FRM sites are not freely available at the moment. This is an improvement point to be discussed with the owners of the site.

2.3 Radar and Microwave missions

Two types of FRM are used for calibration of Sentinel-1 SAR: Corner Reflectors and Transponders.

- The Corner Reflectors are used to validate and whenever appropriate to calibrate the absolute geolocation accuracy of the product and to some extent to validate and calibrate the absolute radiometry.
- The Transponders are used to validate and calibrate the absolute radiometry of the products.

There have been several flight campaigns and campaign-based surface stations for Copernicus radar mission Cal/Val activities. However, there are only 2 regularly maintained sites that are being used for this purpose. One is in Germany (DLR) and the other in Australia (AGOS). These sites are truly purpose built for radar satellites validations but there are a couple of restrictions.

Only a limited set of Transponders are used for now, operated by DLR in Germany. They are pointed toward the Sentinel-1 unit during overpass.

The collection of data over those FRM quality sites is performed depending on actual mission acquisition plan. The Sentinel-1 mission can operate using four exclusive acquisition modes (Extra Wide Swath, Interferometric Wide Swath, Stripmap and Wave modes) using a set of configurable polarization configuration (Single polarisation H or V, Dual polarization H or V). The objective of the mission leads to (almost) constant acquisition plan over dedicated area to ensure continuity of measurements. For instance, over Europe mainland (out of the northern part), the acquisitions are performed in Interferometric Wide Swath Mode in Dual Polarisation V (IW DV) configuration. The data acquired over the DLR transponders and corner reflectors in Germany are then nominally acquired in this configuration, excluding the other ones.

The other modes are then calibrated using opportunistic measurements out of Europe (over corner reflectors or rain forest) using variability of acquisitions in different modes and extending the calibration of IW DV performed over European measurements. This is however an indirect calibration using IW DV as a reference. The direct absolute calibration of all mode will require placing acquisitions over FRM in all the operated modes, that can only be possible for very limited period as conflicting with the nominal acquisition scenario. A short period of acquisition of IW Dual Polarization H (IW DH) over the DLR Transponders was set up in January/February 2021.

Operating Transponders in other areas of the globe for which there are no strong restrictions on switching from one acquisition mode to another will benefit to the overall calibration of the mission. This means that there is a need for a test site outside of Europe, where temperatures stay above zero, that does not have so high priority. There a set of corner reflectors can be installed and different acquisition modes could be activated at different overpasses to validate all of these. The site would be of interest for other radar missions also, which means that there is strong potential for international collaboration.

A set of transponders are operated by the Canadian Space Agency for the calibration and validation of the Radarsat Constellation Mission. Ensuring operation of those transponders and the acquisition of corresponding Sentinel-1 data could be a way forward.

To increase spatial coverage, mobile transponders can be used to increase the radiometric accuracy but it has to be remembered that geometry/geolocation accuracy is at the same time lost, when mobile transponders are used independently.

Multiple Corner Reflectors are used either as opportunistic targets (For instance, fields of corner reflectors deployed in the Surat Basin in Australia, without dedicated pointing matching the Sentinel-1 orbit) or optimised targets (Corner Reflectors operated by DLR in Germany and pointed specifically toward Sentinel-1 unit during overpass).

2.4 Atmospheric composition missions

Referring to deliverable D1.4, the products of the atmospheric composition Sentinel missions include concentrations (total columns, tropospheric columns and vertical profiles) of atmospheric species, aerosol and cloud products, surface albedo/reflectivity, solar irradiance and spectral radiances, and (for CO2M) Solar Induced Fluorescence (SIF). D1.4 also highlights the so-called 'influence quantities' that affect the accuracy of the primary data products: they will be discussed in section 3.4.

As far as the atmospheric species concentrations, aerosol, albedo and radiance products are concerned, several global monitoring networks are delivering reference data to their central data host facilities and to European Research Infrastructures for validation (see D2.4) that fulfil the requirements and are the backbone for Copernicus Cal/Val activities. The network data are complemented with campaign data to validate more specific mission requirements, to fill some gaps in the geographic and vertical coverage of the networks, and to address auxiliary data and ancillary data required by the Copernicus missions. About ancillary data, the situation is a bit less fortunate regarding the cloud products: vertical cloud profile information and cloud height is measured in an automated way by Cloudnet and ARM radar-lidar-radiometer networks, but the data available at EVDC and ACRTIS is mainly restricted to European stations. This could partially be alleviated if more ARM sites would contribute to the central Cloudnet processing and/or other international networks would contribute.

So generally speaking, we can say that most requirements are met per single parameter for the current (S-5P) and near-future (S4 and S5) Sentinels and CO2M atmospheric composition missions. Nevertheless, some gaps must be highlighted:

Atmospheric measurements are often restricted to a certain aspect of the product, for example, only total columns, or only the vertical distribution or horizontal distribution in the case of atmospheric constituents. The reasons are that it often requires different platforms, instruments and different communities to encompass all required validation measurements. For the data retrievals of, for example, the horizontal distribution, a priori information on the horizontal evolution of the vertical distribution is needed. More efforts are needed to address such gaps and bring together different types of instruments and different communities during measurement campaigns.

We need more systematic measurements on mobile platforms like HAPS, aircrafts, drones, ships, buses, trams, maintenance cars or Google Street View cars to acquire more systematic data for performing 'mapping' at high spatial and temporal resolution

There are obvious gaps in the spatial and temporal coverage of the network data.

Spatial coverage:

The locations of the stations do not cover the full range of the influence quantities.

For example: for the greenhouse gas measurements in the SWIR range, it is known that the albedo, aerosol load and clouds strongly affect the retrieval. We lack reference data from stations with low and very high albedo, variable aerosol loads and the full humidity range.

We also miss reference data for continents like Africa, South America and South-east Asia.

Most network data are representative of 'background' conditions. We need better coverage of urban / polluted conditions.

Network data often suffers from a spatial mismatch problem due to the course spatial resolution of atmospheric spaceborne missions. Basically (slightly) different airmasses are sampled by the satellite and ground-based instrument. This becomes significant in the case of species with strong spatiotemporal variability like tropospheric NO_2. Validation of such species requires additional validation measurements from aircraft, drone, ship, car, etc.

Temporal coverage

Some measurements, mostly the ones that are automated, are carried out on a quasi-continuous basis during the day. Others still require human attendance or manual intervention like the lidar and ozone sonde measurements. This issue will become particularly important for the geostationary satellites (S4) where we need full coverage during the day.

In many cases, the measurement sites belong to one single network and therefore don't cover the ensemble of parameters that are measured by the satellite, or the ensemble of auxiliary, ancillary and influence quantities. This aspect is discussed in more detail in Sec.4.

Especially for the CO2M mission, R&D work is required to meet the very demanding requirements as to accuracy and precision of the greenhouse gas data, as well as to the timeliness of the reference data delivery. The capabilities of the current reference network data are getting tight compared to the requirements.

The most direct match between the satellite data and the reference data is achieved with the ground-based (or airborne) remote sensing data. Nevertheless, we also need and use the ground-based and airborne in-situ reference data (surface concentrations and vertical profiles). But here we meet some issues related to the calibration:

(1) intra-network calibration: to ensure that all network sites are calibrated to the same standard, travelling standards must be developed and deployed on a regular basis. A good example is the development and deployment of the traveling standard for total column measurements of CO2, CH4 and CO in the framework of the FRM4GHG-2 project. Currently, we do not yet have such travelling standard instruments in all networks nor for all species; also, the associated procedures require further development.

(2) cross-network calibration: there are still inconsistencies between data delivered by different networks for the same parameter, e.g., between NDACC and TCCON for greenhouse gases, even when the measurement techniques are very comparable, as well as between the in-situ and the remote sensing components (e.g., HCHO measured by in-situ sensors onboard aircraft and NDACC). Some known causes are: uncertainties in the spectroscopic reference data (e.g., NDACC and TCCON measure in different spectral domains and therefore use different spectroscopic reference data that are not necessarily

consistent), uncertainties linked to the retrieval procedures and influence quantities, lack of calibration of the in-situ and remote sensing data to a common agreed standard.

Therefore, we need some dedicated laboratory spectroscopic studies to get improved, traceable spectroscopic reference data, as well as miniaturized stable sensors for deployment on mobile/airborne platforms associated with a travelling standard approach as explained in D3.1 – Fig. 15. The latter cross-calibration approach is a concept that has been applied to some extent in the TCCON community (Wunch et al., 2010), but it requires extension to other networks/parameters, improved procedures and more regular implementation.

Enhanced collaborations between the atmospheric measurement communities and the metrology and spectroscopy communities must be promoted.

It is important to have well-documented calibration procedures and to make the calibration data easily available to the data users, together with the calibrated and non-calibrated data. This must ensure full traceability of the calibrated data, reproducibility of the calibration procedure and – as calibration itself is charged with some uncertainties – the opportunity to revise the calibration if needed.

There is still a worrying issue as to the sustainability of the networks. Most network PIs feel that they are under-funded, and that their efforts for producing high-quality, long-term homogeneous data sets is not sufficiently recognized. Consequently, networks have a hard time to improve and implement calibration procedures, to develop and implement improved retrievals, to verify new spectroscopic reference data, to achieve a complete network-wide reprocessing of the data to maintain intra-network and long-term consistency, as well as to deliver the data in a timely and continuous way. The concept of the European Research Infrastructures (RI) provides an answer to this problem, but has its limitations in the practical implementation: (1) the RI are limited in scope and do not necessarily cover all the stations and parameters required for Copernicus Cal/Val, (2) the commitments from the Member States are also limited (they do not necessarily support all national contributions to the monitoring activities) and not guaranteed (there is often an internal national competition; the Member States can withdraw, etc., and (3) they are not dedicated to Cal/Val support only and must serve research and other users.

3 Parameter specific recommendations

In the previous chapter it was discussed what Copernicus missions' products need regular validation with in-situ data. Using the input from the experts of the field who collect and analyse these parameters we concluded the best practices for single parameters so that different communities would benefit the most from these measurements. These outputs include suggested measurement frequency, spatial coverage and complementary parameters.

Complementary parameters: There are two levels. One is the vital parameters that need to be measured with the listed one so it could be properly used for validation. The second is for parameters that would make the measurement used for wider audience. Spatial coverage is the target area at site, not global coverage. In-situ uncertainty is referred to measurement uncertainty and if needed then also uncertainty about site heterogeneity.

3.1 Optical missions

3.1.1 Land products

For optical land products, there is a need to validate surface reflectance and geophysical products. Different networks or sites may be selected for these two objectives.

Surface reflectance (at least directional surface reflectance) is not a very scientifically relevant quantity for environment monitoring. However, validation of surface reflectance is a critical step to ensure that the atmospheric correction is correctly performed. Surface reflectance needs to be measured together with atmospheric properties (at least AOD and water vapour concentration) and solar irradiance. The BRDF and spatial homogeneity (at a scale of 5 pixels of the Spatial Sampling Distance of the target satellite) of the measurement site shall be characterized. For surface reflectance it is necessary to acquire measurements within 20 minutes of the satellite overpass.

Geophysical variables of interest are listed in 2.1.2. For the geophysical sites, simultaneous measurement of ancillary variables (atmospheric properties and solar irradiance) is desirable but not strictly necessary. Concurrent measurement of several vegetation parameters (LAI, FAPAR) and surface temperature is also desirable (leading to a "supersite") but again not strictly necessary for current Sentinel data products. This will however become necessary for the validation of future LSTM Evapo-Transpiration products. The inhomogeneity of the measurement site needs again to be fully characterized: for instance, by regular field campaigns with handheld DHP cameras for vegetation sites. Some parameters cannot be measured by automatic instruments and need to be acquired through field campaigns (e.g. Chlorophyll Content). It would be desirable to have such measurements periodically available from the target sites equipped with automatic sensors.

We remind some additional generic requirements for land validation sites:

- ❖ The site also needs to be flat at the scale of several SSD of the target satellite.

- The cloud cover shall not be too high (sites in tropical regions are often not usable for validation).
- The site needs to be accessible to allow maintenance activities and field campaigns.

Land validation sites should not be limited to arid/bright sites with new validation sites being complimentary to existing sites. This could be related to the geographic location of the site (global coverage), the cover type (range of cover types, representative of a certain ecosystem), the atmospheric condition (set of different AOT up to 0.5 or even 0.7) as well as to the actual measurement (setup of instrumentation). Spectroradiometric in-situ measurements must be repeatable and SI-traceable, including an associated uncertainty budget. Site characterization should be comprehensive. In the case of e.g. forested areas, the structure of the site can be captured by airborne measurements (Lidar). Models of dynamic scenes (e.g. 3D models of vegetated scenes or ocean biogeochemical models) are currently not used routinely for optical missions but could become a reference source in the future. Existing data protocols (incl. site description, instrumentation, data recording method, ...) are necessary to use – best would be to have common protocols for each parameter being validated. All targets should include adequate data management / storage /delivery.

Finally, we recall that measurement networks which can contribute to land product validation are in detail analyzed in deliverables 2.4 and 2.5:

3.1.2 Water products

The ideal site for a water Cal/Val activity must include hyperspectral surface reflectance measurements. If azimuth control is not possible then sophisticated filtering has to be added to filter out any possible glint issues. When sensors are not mounted on a fixed structure, tilt sensors with automated filtering are also needed.

Reflectance measurements should be a base for a proper Cal/Val site. In addition, it should be coupled with IOP and concentration measurements. As was mentioned earlier (section 2), then several IOP measurements are hard to manage as automatic measurement, especially when a site is harder to reach. Therefore, if automatic measurements are not possible then at least regular campaign measurements should be conducted to calibrate the site. One IOP parameter – absorption – can be measured from water samples which makes it a bit easier as periodic water samples should be anyway taken for Cal/Val sites.

To validate the Copernicus standard products, reflectance measurements are not enough and these have to be paired with concentration measurements. For clear waters, only CHL measurements can be enough as the others are related to it, although there is hesitation also to this point nowadays. For coastal and inland waters, CHL measurements have to be taken together with CDOM and TSM as they all behave independently from each other and have independent sources. If the concentrations are measured with optical instruments on site, then it would be proper if these are periodically intercompared with laboratory measurements where the procedures and uncertainties are better described. If the concentrations are only measured during field campaigns, then special care has to be taken in order to match these campaigns with satellite overpasses and with clear skies.

We cannot rely only on coastal sites/campaigns to validate Copernicus products. Some open ocean measurements can be done with automated devices but measurements acquired during cruises are really essential for validation. In this respect, it could be good to have systematic measurement campaigns performed by one Copernicus member state rather than outside partners.

In addition to these direct parameters that are used for validation, some auxiliary parameters should be measured, that can help the use of the main ones:

- Wind speed – to estimate the surface roughness
- Water and air temperature – to check if the measurements are within the calibration range
- Aerosol optical thickness – for atmospheric correction evaluations
- Hemisphere photos – for latter data analyses and filtering

3.2 Altimetry mission

Table 6. Products of altimetry missions and their target acquisition format. The most challenging issues are underlined in red in the following table.

Parameter	Measurement frequency	Spatial coverage	In-situ uncertainty	Complementary parameters
Altitude	Continuous	On all in-situ sites		GNSS position
Backscatter coefficient	At satellite acquisition	Some sites (can be continental sites)	<0.25 dB (absolute) <0.1 dB (knowledge)	Atmospheric parameters (TWC, wind speed) GNSS position
Freeboard Height	daily	Campaign – specific sites	Few cm	Atmospheric parameters (TWC, wind speed) GNSS position
Ice thickness	daily	A set of test sites in Arctic and Antarctic	Few cm	Geoïd Atmospheric parameters (TWC, wind speed) GNSS position
Ionospheric correction	Continuous	On all in-situ sites		GNSS position
Land Ice Elevation	daily	A set of test sites in Arctic and Antarctic	Few cm	Geoïd Atmospheric parameters (TWC, wind speed) GNSS position
Range	At satellite acquisition	Some sites (can be continental sites)	<1cm	Atmospheric parameters (TWC, wind speed) Geoïd GNSS position

Significant wave height	Continuous	Good coverage on coastal areas / to be improved in South Hemisphere and in open water	<20 cm (this is an issue today)	(Not mandatory but nice combination) Atmospheric parameters (TWC, wind speed) GNSS position
Water Level Height (hydro)	At least daily / ideally, at the exact time and location of the satellite acquisition (for water bodies with high variability)	A set of test sites with different topology (worldwide) - best = on cross-overs or multi-missions	Few cm	Geoïd Atmospheric parameters (TWC, wind speed) GNSS position
Water Vapor	Hourly	On all in-situ sites		GNSS position
Wet tropospheric Path Delay	Hourly	On all in-situ sites		GNSS position
Wind speed modulus	Continuous	On all in-situ sites	<5m/s	GNSS position
Ice flags	Not covered by in-situ measurements			
Leads and floe flag				
MWR brightness temperature				
Rain flag / rain rate				

Thanks to our analysis done in section 2.2, we have identified the following recommendations:

Identify key in-situ means for Cal/Val activities when different solutions exist for the same parameter. This implies identifying their complementarity, if any, or selecting the means with the uncertainty that is the most adapted to the validation exercise.

Convert existing on-ground facilities in FRM class data to assure the same quality level, a large access and a sustainable funding. This recommendation is also coupled with the previous one since it would allow identifying as FRM-class one of the key facilities among the existing ones. Note that FRM for altimetry may not have all the same sets of instruments. There can be several kinds of FRM sites (mostly with or without transponders).

Create FRM data for the product parameters that are not validated by any independent mean.

Reduce uncertainty of the on-ground means to reach their capability in answering product requirement

Optimise the localisation of the networks to maximise the benefits for the product validation

Develop, promote and improve usage of some of the existing networks that are not much used by the altimetry Cal/Val community

3.2.1 Identification of key on-ground facilities

The aim of this section is to identify some recommendations when, for a single parameter, several means of validation are available.

This is the case for the range validation for which several transponder sites are available for the purpose of Cal/Val activities. Similarly, some corner reflectors are also emerging. Therefore, it appears reasonable to discuss the pros and cons of the different facilities to better understand and outline their complementarity in the whole Cal/Val Sentinel framework.

At least, the following questions shall be addressed for the range and backscatter validation:

Identify the outcome expected from several transponders operating for the same mission and during the same period. In other words, how many transponders do we need to calibrate Ku-band and C-band at the requested level of accuracy?

Identify the respective uncertainty between the different transponders

Identify the uncertainty between the different transponders and corner reflectors

Identify the capability to detect altimeter drifts (on range and backscatter coefficient) which means assess the facility uncertainty in stability over different considered time series length. Are the transponders able to detect drifts with 0.3 mm/year uncertainty over 1 year of data or rather 10 years of acquisition?

3.2.2 Conversion of existing facilities into FRM sites

As explained in 2.2.2.1, FRM sites already exist for ocean even if they are not labeled as such. It is important to secure them for the validation of the Copernicus Sentinel missions. Only the Crete site is labeled as FRM at the present time.

We identified the following facilities and/or sites to be labelled as FRM sites:

- Corsica Site
- Harvest Site
- Bass Strait Site
- Issykkul Lake Site
- Catalina transponder Site
- Italian transponder Site

In addition, the question is also raised for other types of on-ground measurements:

- Tide gauge data since there are identified as of today as the on-ground mean with the lowest uncertainty to detect drift on SSH on altimetry payload (as a whole without the possibility to distinguish between altimeter, radiometer or GNSS sensor). In addition, they are also used for the validation of ocean tide models used in the ground segment for SSH computation.
- Buoy data since this is the only on-ground means to validate and monitor a long time the SWH and Wind Speed parameters.
- Laser Network that is identified as of today as the on-ground mean with the lowest uncertainty for orbit validation

3.2.3 Creation of FRM data for filling the gaps in the requirements

The most critical issue deals with in-land waters and ice surfaces, since no FRM data exists. Nonetheless, some hydrological sites and/or networks could already be labeled and developed.

The needs and demands on in-land and ice are increasing and the validation is even trickier than for ocean parameters. Therefore, the in-situ data has an important part to play in the Cal/Val activities over these surfaces, pushing for more sites and networks.

ESA has already identified this gap and has started the STR3TART project in 2021 to address these needs and establish the basis for in-situ facilities deployment for inland waters, sea ice and land ice parameters. Below are the main outcomes and recommendations for inland waters at this stage of the project:

- Some basins (Europe, North America) are well monitored, whereas others are not covered. So, there is a discrepancy between the different lakes and rivers typology that can be validated.
- In-situ sensors can be very different from one site to another.

- There is no real harmonization between sites at the moment. FRM label could help to federate several sites. How to harmonize national initiatives?
- The campaigns with drones are very good opportunities. They are quite easy to deploy and reach a high accuracy. The drone can follow the exact path of a river, which enables to capture the high spatial variability of rivers. A balance between in-situ permanent sites and drone campaigns should be found.

Nonetheless, over ocean we have identified the need for on-ground observations that would support the validation of ocean short scale structures between 10 and 80 km.

3.2.4 Reduction of uncertainties of the on-ground facilities

In altimetry, the reduction of uncertainty is certainly the key question to better benefit from the on-ground observations. Indeed, their level of uncertainty is often too large to support the validation activities in a very efficient way and to do **quantitative assessment**.

This is the case for several types of in-situ measurements:

- tide gauge networks
- radio sonde networks
- buoys networks

3.2.5 Optimization of the existing networks

The aim of this section is to discuss recommendations on potential ways and benefits coming from the optimization of some of the global networks such tide gauges, buoys, GPS data for water vapor validation.

We distinguish two different approaches:

A better harmonized localization of the networks to improve the coverage of the different environment situations

A better tradeoff between uncertainty level and the localization. Indeed, the optimal solution could come from a few more accurate facilities within the network coupled with suitable localization while keeping the entire network to access to a global coverage but dealing with some larger uncertainties.

3.2.6 Focus on tide gauge networks

The link between tide gauge networks community and the altimetry community is very strong. Common work reaches some strong recommendations towards the networks:

(https://eurogoos.eu/download/eurogoos-tgtt-nov2016-report-and-recommendations/?wpdmdl=10740&refresh=62679806e324f1650956294)

List of recommendations from the altimetry community:

Vertical land movements: they request more co-location of GNSS stations with existing tide gauges to monitor vertical land motion.

Tide gauges are needed in the open ocean for validation of altimetry in ocean circulation studies.

There is a demand also of coastal tide gauges, including estuarine gauges to the extent of the tidal influence, for validation of altimetry near the coast.

Quality controlled time series to minimize undocumented datum or reference changes and clock errors: datum control within a month (or less for near-real time validation in altimetry) and metadata with information about the origin of the error.

A homogenous product, with standard format (e.g. CF compliant) and a one-click download data bottom is required. Tidal predictions in the data have been also asked for.

Homogeneous sampling: hourly data should always be provided, independently of what other high frequency samplings are available for other applications.

Whenever possible, optimizing the location of stations with respect to altimetry ground-tracks and improving the spatial coverage of the in-situ network.

Redundancy (double or multiple) of sea level sensors would be appreciated for avoiding gaps in the historical tide gauge time series.

3.2.7 Promotion of existing networks

All the work in the framework of the SWOT missions for Cal/Val preparation should also be aggregated to the Copernicus missions. It will bring new in-situ measurements and campaigns for ocean (https://www.swot-adac.org).

3.2.8 Networks

The Cal/Val activities shall cope with the heterogeneities of the in-situ networks. It is already integrated in the Cal/Val methods. This will continue as it is a utopia to try to harmonize all these large sets of data. The need is more on the access to the data. The INSTAC initiative of CMEMS should be extended to other surfaces.

3.2.9 Synergies with other missions / common sites

Altimetry Cal/Val is using some data which can be acquired in synergies with other missions. At this stage, we identify:

- Atmospheric: water vapour content, wind speed, rain rate
- Orbit (DORIS, ISLR)
- Ionospheric delay
- Sea states (SWH, wind speed)

Information coming from other thematic is also useful for altimetry (but not in-situ):

- River and lake contours
- Models (oceanic, wind, rain)

3.3 Radar and Microwave missions

Radar missions have a few parameters that are used for Cal/Val activities. These parameters and how these should be joined together were already discussed in chapter 2.3 and do not need any elaboration.

3.4 Atmospheric composition missions

As already introduced in Section 3.2, a proper validation of the primary Copernicus data products often requires the availability of reliable data for the auxiliary and ancillary parameters and influence quantities.

A regularly met problem is that these data are most often provided by different networks than the atmospheric composition networks themselves and therefore aren't available at the same location / temporal scale.

To solve that issue, we can either rely on other global datasets (Copernicus Sentinel or services, or other satellite data) in as far as these deliver the required parameters and have been validated, or we can perform dedicated, but punctual, campaigns involving complementary instruments and measurement techniques. The former approach is implemented on an ad-hoc basis; a better collaboration between the different communities (atmosphere, land, ocean, optical) should be promoted. The latter approach requires the necessary infrastructure and organization, which is hard to get on a systematic basis.

4 Copernicus Supersites

Copernicus Supersite is a term that is understood differently within different fields. One of the most known versions being the one from CEOS-WGCV-LPV:

- ❖ Super characterized (canopy structure and bio-geophysical variables) site following well- established protocols useful for the validation of satellite land products (at least 3) and for radiative transfer modelling approaches.
- ❖ Active, long-term operations, supported by appropriate funding and infrastructural capacity.
- ❖ Supported by airborne LiDAR and hyperspectral acquisitions (desirable).

Second topic that has to be made clear is the purpose of Copernicus Supersite labelling. Currently it is not clear what the site or network will gain from being one. It should be confirmed over different missions either the supersite is something that contributes to Copernicus mission in some way or it is part of the mission, as a ground segment, or is it part of Copernicus Cal/Val infrastructure. At the moment the labelling purpose is vague.

Copernicus Supersite term can be misleading as it suggests that these sites/networks are funded/organized by Copernicus program. If the use of the term is to be continued it should include some Copernicus funding (several issues) or some other practical benefits when aiming for that labelling (currently unclear benefit). If Copernicus is funding some sites, then there is a risk that the other sites are neglected from Copernicus side. There is also the risk of bad relationships when some get Copernicus support when others don't.

It has to stated that the focus should not be finding new places to collect additional data but first double check if the currently available options are maximally benefitted. In example, evaluate if the potential of the Research Infrastructures is used in the Cal/Val activities, as they are fully operational, long term funded and applying full FAIRness.

We need more than the supersites alone: many other sites are also indispensable to complete the coverage. The main aim has to be to collect FRM quality data to validate Copernicus products. This means that the data cannot be collected only from single locations but have to cover a variety of conditions. To do so, we recommend not to build some new structures but to build on the already existing stations/networks and further develop the relationships between those and the Copernicus program. One option would be to have a Copernicus presenter/scientific advisor in the management body of the networks to better plan the future activities for collaboration.

In the current document we are not covering Copernicus supersites as such, as these can have a wider purpose, but sites that are suitable for Copernicus Cal/Val. For that we recommend the following approaches (We don't recommend providing too many additional terms. The terms used in this document are just used to clarify the point made):

"Copernicus Cal/Val Reference site" will be Copernicus site, with easy access, where there is history of certain measurements so that new technologies can be tested together with existing devices (e.g., currently almost all new automatic radiometer systems for water are tested at

AAOT Tower near Venice which has been the Aeronet-OC station for some time already.) – perhaps not a Supersite but recommendation to have this kind of sites.

"Copernicus Cal/Val site"– target for every site that wants that their data is being used in Copernicus Cal/Val activities. This is parameter specific and means that the site can have this label per parameter if the measurement of this parameters is having FRM standard or is following some other agreed measurement and data handling standard that is being recognised by Copernicus.

For these parameters, there is Standard Travelling Instrument that is maintained together with Copernicus and its partner laboratory. These devices are well characterised and calibrated and will be used to compare different sites regularly to make sure that there is site-to-site consistency. This is done in addition to regular calibration and maintenance and the main principle is to have different sensors/measurement methods to provide same (within uncertainty) results for Copernicus.

4.1 Optical missions

4.1.1 Water

Fixed position sites (Towers or anchored buoys) are needed where low uncertainty measurements can be made regularly with auxiliary inherent optical properties measurements (e.g. Boussoule or AAOT) and regular water samples for water constituents' analyses. This means that these locations have to have low cloud coverage and mostly stable water properties.

In addition, there is need for a network of measurements covering variety of different water sites, both marine and lacustrine waters. As the most of the user interest is focused on waters that are close to inhabited areas, then this mostly includes complex coastal waters and inland waters.

4.1.2 Land

Supersites that are covering several parameters are not often recommended as different parameters need different site characteristics (e.g. Homogeneity). Therefore. it is recommended to classify a network, that measures different parameters at different locations, as a Supersite, rather than focusing on a single or a couple of locations.

4.2 Altimetry mission

4.2.1 Conversion of existing facilities into FRM sites

As explained in 2.2.2.1, FRM sites already exist for ocean even if they are not labeled as such. It is important to secure them for the validation of the Copernicus Sentinel missions. Only the Crete site is labeled as FRM at the present time.

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Buoy data since this is the only on-ground means to validate and monitor a long time the SWH and Wind Speed parameters.
Laser Network that is identified as of today as the on-ground mean with the lowest uncertainty for orbit validation

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The most critical issue deals with in-land waters and ice surfaces, since no FRM data exists. Nonetheless, some hydrological sites and/or networks could already be labeled and developed.

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In-situ sensors can be very different from one site to another.
There is no real harmonization between sites at the moment. A FRM label could help to federate several sites. How to harmonize national initiatives?
The campaigns with drones are very good opportunities. They are quite easy to deploy and reach a high accuracy. The drone can follow the exact path of a river, which enables to capture the high spatial variability of rivers. A balance between in-situ permanent sites and drone campaigns should be done.

Nonetheless, over ocean we have identified the need for on-ground observations that would support the validation of ocean short scale structures between 10 and 80 km.

4.3 Radar and Microwave missions

There is already well-maintained site in Germany and a good collaboration with Australians. These sites, however, cover only one acquisition mode, which is why there is a need for international collaboration to create a calibration site outside of main target areas that could be used for different acquisition modes (4 for S1). Different size corner reflector would enable also collaboration between satellites that are measuring using different bands.

4.4 Atmospheric composition missions

As mentioned already in Section 2.4, it must be ensured that the ground-based monitoring networks cover the space of target parameter values and data influence parameters: surface albedo value range, surface and atmospheric temperature, aerosol load, environmental conditions, pollution levels, …That doesn't mean necessarily that all target parameters and influence parameters must be measured at all network locations together.

Still there is a need for some well characterised 'supersites' where the properties of the site and the environmental conditions as well as the sources are well-known and where there is a large availability of ground-based instruments measuring several aspects of the atmospheric composition, complemented by airborne instruments to map the horizontal and/or vertical distribution. Such sites may best serve the validation of the retrieval algorithms under different viewing and environmental conditions, and the interferences between different parameters in the retrieval algorithms. Having the complementary airborne mapping data and/or vertical profiling data supports the validation of the information content of the satellite data.

Next to these, additional complementary sites dedicated to certain single or few parameters must complete the global picture, to confirm the quality of the data at several geographical locations and under different viewing conditions. For example, Cloudnet and ARM cloud property data from EVDC is currently mainly restricted to European stations and should be extended to at least Asia and Africa. This could partially be alleviated if more ARM sites and other international networks in Asia and elsewhere, could contribute to the central Cloudnet processing or an equivalent. Put more generally, more FRM data exchange between different international networks can improve the global picture.

Attention must be paid also to the historical value of the site: we definitely need sites that have long-time series available, especially for serving as transfer standards between successive satellites.

For the upcoming CO2M mission, investigations as to the best network configurations are ongoing in the context of an EUMETSAT-funded study. Here we must pay specific attention to the capability of the network to validate the final products of the mission that are the anthropogenic greenhouse gas emissions.

5 Conclusions

There are already well-established research infrastructures but there has to be an improved cooperation with that RI and the Copernicus program. This collaboration would enable to better plan the developments of those existing structures to better handle the needs of the Copernicus Cal/Val. Input from higher institution would also enable to coordinate the measurement in this way that several missions could benefit from one measurement network/site. This means both the different mission types but also different satellites for the same type (e.g. measurements at different wavelengths for the same parameter)

This improved collaboration would also be a good point for governing the comparison measurements between different parties (like the travelling standard mentioned in the chapter 4) in order to ensure the even quality of the measurements done by different institutions.

Although the existing RI network is vast, then there is still need for new sites that could fill the gaps in space or heterogeneity of targets. Establishing new sites should be done at least under the guidance of Copernicus (probably with some financial support) to ensure that these sites would be maximally beneficial.

Cal/Val activities use temporary and long-term instrumentation. This means that the emerging technologies should be taken into use as soon as possible. Several of those instruments are being developed using EU funding. Copernicus program should take advantage of this and demand a testing of these instruments at well-known sites. This means, that when the instruments hit the market, there is already a comparison of how they behave compared to other instruments and side by side measurements can be used for extending the time series analyses.

6 Acronyms for in-situ sites

6.1 Systematic Ground-Based Measurements – Table 2 from D2.4

Network acronym	Network full name	Network Website
Optical		
AERONET-OC**	The Aerosol Robotic Network - Ocean Color	https://aeronet.gsfc.nasa.gov/new_web/ocean_color.html
Aquaspectus	Network of WISPstations	Water Insight
BOUSSOLE	BOUée pour l'acquiSition d'une Série Optique à Long termE	http://www.obs-vlfr.fr/Boussole/html/home/home.php
BSRN	Baseline Surface Radiation Network	https://www.bsrn.awi.de
Copernicus LAW	Copernicus Space Component for Land Surface Temperature, Aerosol Optical Depth and Water Vapour Sentinel-3 Products Project / LAW LST sites	https://law.acri-st.fr/home
DEMMIN & Moorfluxnet		https://www.moorflux.net/#Das%20Netzwerk
eLTER RI	European Long-Term Ecosystem, critical zone and socio-ecological Research Infrastructure	https://www.lter-europe.net/elter-esfri
FLUXNET		Fluxnet.org
ICOS Ecosystem	Ecosystem part of the European infrastructure Integrated	www.icos-etc.eu www.icos-ri.eu

	Carbon Observation System	
ICOS Ocean	Marine part of the European infrastructure Integrated Carbon Observation System	https://otc.icos-cp.eu/ www.icos-ri.eu
IMOS Ocean Colour Sub-facility	Integrated Marine Observing System – Ocean Colour Sub-facility	https://imos.org.au/facilities/srs/oceancolour http://thredds.aodn.org.au/thredds/catalog/IMOS/SRS/OC/LJCO/catalog.html http://thredds.aodn.org.au/thredds/catalog/IMOS/SRS/OC/BODBAW/catalog.html http://thredds.aodn.org.au/thredds/catalog/IMOS/SRS/OC/radiometer/VMQ9273_Solander/catalog.html http://coast-rs-1.it.csiro.au/
ISMN	The International Soil Moisture Network	https://ismn.earth/en/
FLARE		https://flare-network.com/
KIT LST	Karlsruhe Institute of Technology Land Surface Temperature	https://www.imk-asf.kit.edu/english/skl_surfacetemperature.php
LéXPLORE/Thetis		https://lexplore.info
MOBY	Marine Optical BuoY	https://mlml.sjsu.edu/moby
NASVF	North Australian Satellite Validation Facility	https://www.ozcalval.org/
NEON	National Ecological Observatory Network	https://www.neonscience.org/
PEN	Phenological Eyes Network	http://pen.envr.tsukuba.ac.jp/
PEP725	PEP725 PanEuropeanPh	http://www.pep725.eu/

	enology Data Base	
RadCalNet**	Radiometric Calibration Network	https://www.radcalnet.org/#!/
SIOS	Svalbard Integrated arctic earth Observing System	https://sios-svalbard.org/
SMEAR	The Station for Measuring Earth surface - Atmosphere Relations	https://www.atm.helsinki.fi/globalsmear/index.php
TERN	Australian Terrestrial Ecosystem Research Network	https://www.tern.org.au/tern-observatory/tern-ecosystem-processes/
Altimetry		
AMAZON	Altimetry measurements at Amazon river	N/A
DBCP**	Buoys network	https://www.ocean-ops.org/DBCP/
DORIS	International DORIS service	https://ids-doris.org
FRM-BASS STRAIT**	Altimetry FRM site at Bass Strait (Australia)	N/A
FRM-CORSICA	Altimetry FRM site in Corsica (France)	N/A
FRM-CRETE	Altimetry FRM site in Crete (Greece)	https://www.frm4s6.eu/ https://www.frm4alt.eu/
FRM-HARVEST**	Altimetry FRM site ah Harvest oil platform (US)	N/A
FRM-ISSYKKUL	Altimetry FRM site at Issykkul lake (Kyrgyzstan)	N/A
GLOSS**	The Global Sea Level Observing System	https://www.gloss-sealevel.org

GRDC**	The Global Runoff Data Centre	https://www.bafg.de/GRDC/EN/01_GRDC/grdc_node.html
HYDRODATEN	Switzerland hydrological network	https://www.hydrodaten.admin.ch/fr/
IGS	International GNSS Service	https://www.igs.org
ILRS	International Laser Ranging Service	https://ilrs.gsfc.nasa.gov/
IMOS Ocean Colour Sub-facility	Integrated Marine Observing System	https://imos.org.au/facilities/nationalmooringnetwork/wave-buoys
INSTAC	Copernicus Marine Environment Monitoring Service In Situ Thematic Assembly Centre	http://www.marineinsitu.eu
LOCSS	Lakes Observations by Citizen Scientists & Satellites	https://www.locss.org/view-lake-data
NDBC**	National Data Buoy Center	https://www.ndbc.noaa.gov
OECS	Observations des Eaux continentales par des Citoyens et des Satellites	http://oecsmap.org/
REFMAR	Reseaux de reference des observations marégraphiques	http://refmar.shom.fr/en/home
Atmospheric composition		
AERONET	Aerosol Robotic NETwork	https://aeronet.gsfc.nasa.gov
AEROSPAN	AERONET Australian part	https://research.csiro.au/acc/capabilities/aerospan/aerospan-data/
AGAGE**	The Advanced Global	https://agage.mit.edu

	Atmospheric Gases Experiment	
ARM	Atmospheric Radiation Measurement	https://www.arm.gov/
CLOUDNET/ ACRTIS		
COCCON	Collaborative Carbon Column Observing Network	https://www.imk-asf.kit.edu/english/COCCON.php
enerMENA	enerMENA Meteo-Network	https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-8680/12865_read-32404/
EUBREWNET	European Brewer Network	http://www.EUBREWNET.org
GRUAN	GCOS Reference Upper Air Network	www.gruan.org
IAGOS	In-service Aircraft for a Global Observing System	https://www.iagos.org
ICOS Atmosphere	Atmospheric part of the European infrastructure Integrated Carbon Observation System	www.icos-atc.eu www.icos-ri.eu
Meteo-France	Meteo-France operational radiosonde network	http://www.meteofrance.fr/prevoir-le-temps/observer-le-temps/moyens/les-radiosondages
NDACC	Network for the Detection of Atmospheric Composition Change	http://www.ndacc.org
PGN	Pandonia Global Network	https://www.pandonia-global-network.org/
SHADOZ	Southern Hemisphere Additional Ozonesondes	https://tropo.gsfc.nasa.gov/shadoz/

SKYNET		http://atmos3.cr.chiba-u.jp/skynet/
SNO-IFA	SNO-IFA ICOS-France-Atmosphére	Under development
TCCON	Total Carbon Column Observing Network	http://www.tccon.caltech.edu/
TOLNet**	Tropospheric Ozone Lidar Network	https://www-air.larc.nasa.gov/missions/TOLNet/
WMO/GAW Ozone column and sonde profiles network	World Ozone and Ultraviolet Data Centre under Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO)	https://woudc.org/home.php

6.2 Acronyms for institutes conducting campaign-based measurements – Table 2 from D2.5

Acronym	Institustion
AEMET	Agencia Estatal de Meteorología
AGH	University of Science and Technology Krakau
AIST	Advanced Industrial Science and Technology
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
AWI	Alfred-Wegener -Institut
BIRA-IASB	Royal Belgian Institute for Space Aeronomy
CEA-LSCE	Commissariat à l'énergie atomique - Laboratoire des sciences du climat et de l'environnement
CESBIO	Centre d'Etudes Spatiales de la Biosphère (Center for the Study of the Biosphere from Space)
CNES	Centre national d'études spatiales
CNR	Consiglio Nazionale delle Ricerche
CNRS	Centre national de la recherche scientifique
CNRM	Centre National de Recherches Météorologiques
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center)
EMI	Estonian Marine Institute
ESA	European Space Agency
EUFAR	The EUropean Facility for Airborne Research
FAAM	Facility for Airborne Atmospheric Measurements
FZJ	Forschungszentrum Jülich
GFZ	Deutsches Geoforschungszentrum (German Research Center for Geoscience)
INCAS	National Institute for Aerospace Research "Elie Carafoli"
INOE	National Institute for Research and Development in Optoelectronics INOE 2000
INPE	Instituto Nacional de Pesquisas Espaciais (National Space Institute of Brazil)
INTA	Instituto Nacional de Técnica Aeroespacial
IUP	Bremen Institute of Environmental Physics, University of Bremen
KIT	Karlsruher Institut für Technologie
LATMOS	Laboratoire atmosphères, milieux, observations spatiales
LERMA	Laboratoire d'Etudes du Rayonnement et de la Matière en Astrophysique et Atmosphères
LMD	Laboratoire de Météorologie Dynamique
NASA	National Aeronautics and Space Administration
NIER	National Institute of Environmental Research
NIWA	National Institute of Water and Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
ONERA	Office national d'études et de recherches aérospatiales
PML	Plymouth Marine Laboratory
RAL	Rutherford Appleton Laboratory
RHUL	Royal Holloway, University of London
RUG	RUG Rijksuniversiteit Groningen
SNSA	Swedish National Space Agency
SNU	Seoul National University

SYKE	Suomen ympäristökeskus (Finnish Environment Institute)
TUM	Technische Universität München
UFZ	Helmholtz-Zentrum für Umweltforschung (Centre for Environmental Research)
UHEI	Heidelberg university
VITO	Vlaamse Instelling voor Technologisch Onderzoek (Flemish institute for technological research)
MRI KU	Marine Research Institute of Klaipeda University
UTARTU	University of Tartu

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