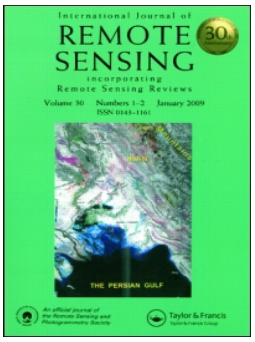

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Towards a European Cal/Val service for earth observation

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ABSTRACT

Societal dependence on, and commercial and scientific exploitation of Earth-Oriented remote sensing from satellites is growing at an exponential rate. The comprehensive EU Copernicus programme provides a major contribution to the global effort, but even so, to achieve the necessary global and temporal coverage requires synergistic cooperation and associated interoperability of the Worlds sensors. For a user to exploit Earth Observation (EO) data there must exist confidence in data characteristics, quality and reliable delivery. Although long-term data records for climate may be the most demanding in nature, generation of analysis-ready operational data sets for applications, as diverse as food security to pollution monitoring, all require the user to have some quantitative level of confidence in the data and derived information. A long-term Calibration/Validation (Cal/Val) vision necessitates clear ownership and long-term funding. Delineating the roles of the European Commission (EC), space agencies and member states in long-term Cal/Val would provide clarity. It is clear that the space agencies have the responsibility to meet the mission requirement of their spaceborne instruments but long-term validation is often entrusted to interested parties bringing their own resources to the task. Furthermore, there is a critical need for Fiducial Reference Measurements (FRMs), acquired in operational mode, and comprehensive in coverage both spatially and temporally, to assure that the satellite product accuracies are met. This paper discusses the current status, gaps and challenges regarding long-term Cal/Val of EO satellites and recommends the creation of a European coordinating entity for satellite product calibration and validation. The proposed entity would be an integrative organization coordinating the European Cal/Val activities in partnership with the member states and the space agencies and working together with existing data providers to secure access to satellite and in-situ data of traceable FRM standards.

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1. Introduction

To sustain leadership in Earth Observation (EO), Europe is investing billions of Euros into the Copernicus Earth Observation Programme. These EO data are an essential component of all Copernicus services. It follows that these services depend strongly on the quality of the satellite data being delivered. Hence the effectiveness of this investment depends critically upon sustained Calibration and Validation (Cal/Val) activities. Calibration is the practice of assuring instrument performance to SI (International System of Units) or community accepted standards. Validation is the practice of quantifying the accuracy of the satellite-derived geophysical products (Justice et al. 2000).

Cal/Val activities must span the whole lifetime of the mission from pre-launch characterization to the de-orbiting phase and should continue even after the mission's lifetime in view of the creation of long-term consistent climate data records (CDRs) (National Research Council, 2011; Hollman et al., 2013). Cal/Val consists of in-situ infrastructure, product evaluations, reprocessing activities, the analysis of long-term series and efforts to obtain consistency between multiple missions. There must be a sufficient array of Cal/Val capabilities to assure long-term characterization of satellites i.e. Cal/Val cannot rely upon single entities, measurement programme or funding sources, but rather must consist of a broad range of coordinated activities. Measurements made for Cal/Val purposes are also valuable in their own right.

The EO landscape is changing and faster than ever before. Ever more actors, including commercial companies, are launching an increasing array of satellites, including hundreds of small-sized EO platforms, such as cubesats and nanosats. It is expected that in the near future Small Satellites (SmallSats) will increasingly be employed in operational and science missions. While most of the large-scale missions are equipped with onboard calibration devices, small satellites often lack these devices due to constraints on size, weight and power consumption (Sterckx et al. 2014). Furthermore SmallSats will mainly operate in constellations, which means that there will be many overpasses per day at most locations. All this puts additional challenges on Cal/Val to ensure that the quality expectations of SmallSats are met. Failure to ensure adequate Cal/Val will decrease the confidence that can be attributed to the products resulting from such missions.

Given the envisaged step-change in satellite-based monitoring capabilities and the increasing use of Copernicus Services, it is essential to revisit the current Cal/Val capabilities and ask whether they are fit for purpose. In Section 2 we outline the theoretical basis underpinning satellite Cal/Val. In Section 3 the current status of Cal/Val activities is outlined and critically discussed. Section 4 reviews in detail current and emerging challenges in Cal/Val and the gaps which are commonly encountered. These include uncertain long-term funding, scarcity of in-situ data of sufficient quality, lack of cross-cutting in-situ coordination, fragmentation, unclear stewardship and lines of responsibility. Finally, in Section 5 we make recommendations for the implementation of a sustainable European Cal/Val strategy that can be used as a template by global partners.

2. The theoretical basis underlying Cal/Val

Satellite Cal/Val starts at the manufacturing stage and should continue well beyond decommissioning (National Research Council 2000; Zhou, Divakarla, and Liu 2016; Yoon

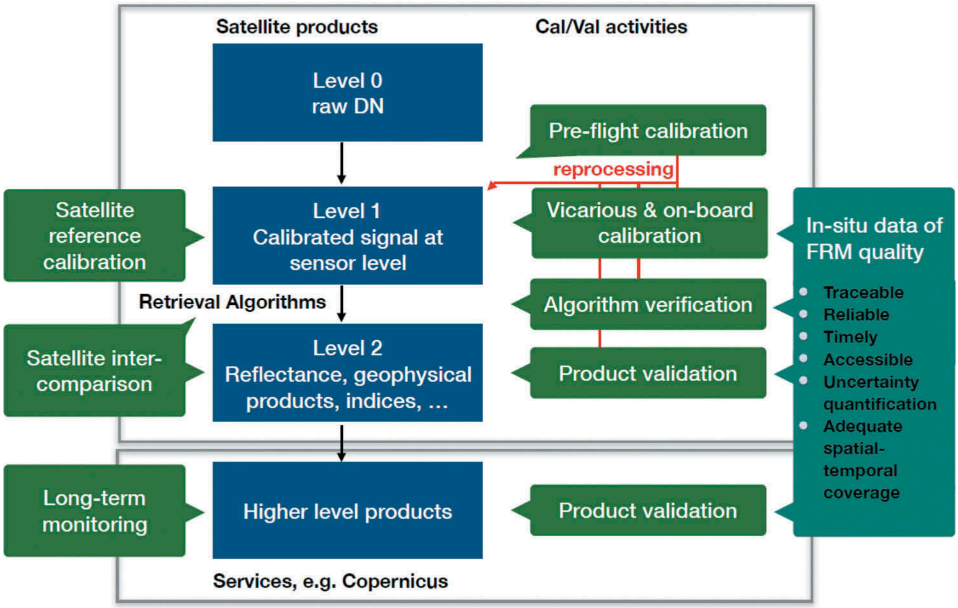

Figure 1. Pictorial representation of the steps necessary for comprehensive Cal/Val activities for satellite missions on a sustained basis. Green boxes indicate specific Cal/Val activities, blue boxes the steps in producing geophysical satellite data products and red lines reprocessing activities.

and Kacker 2015). The typical steps as currently undertaken are outlined in Figure 1 and described in this Section. This is the theoretical state-of-the-art practice (the ideal), but is rarely accomplished presently.

All satellite missions should undergo comprehensive pre-launch calibration and characterization (Datla et al. 2011). The pre-launch calibration constitutes the only opportunity by which the instrument can be physically directly calibrated and characterized and is applied, to varying degrees, for almost all satellite missions.

However, due to outgassing after launch, ageing of the instrument, and energetic particle damage, changes to these pre-flight characterizations may occur in orbit. In orbit calibration is often performed using on-board calibration devices, but currently no on-board calibration device attains strict metrological traceability, they are prone to drift or degradation (Sun, Chu, and Wang 2016), and several examples (Sayer et al. 2017; Skokovic, Sobrino, and Jimenez-Munoz 2017; Fu and Haines 2013) highlight that relying only on on-board calibration alone is not sufficient to reach the mission accuracy requirements. Vicarious calibration practices, making use of some combination of: 'invariant' natural targets on the Earth or in space (such as the moon); absolutely traceable satellite 'reference calibration' measurements; and high-quality in-situ based observational capabilities, have to be put in place (e.g. Neigh, McCorkel, and Middleton 2015).

Post-launch calibration verification and/or correction is an essential prerequisite to obtain reliable and calibrated Level-1 data (e.g. radiance, reflectance, transmittance, radar backscattering coefficient, radar-echo time delay) which form the basis for the derivation of geophysical Level-2 products (i.e. derived geophysical and geochemical parameters at the same resolution and location as Level 1 source data). With the aim to generate CDRs, biases, within and between successive sensors need to be quantified and accounted for. Reprocessing of Level-1 data is required based on new insights gained in calibration activities (Goryl et al. 2016). This means that adequate resources should be allocated to maintain the calibration efforts and to ensure that reprocessing can be done regularly based on the improved knowledge.

The Cal/Val of a mission is not limited to the sensor calibration. It includes also algorithm verification, validation of the geophysical data, and inter-comparison with other missions, all leading to the quantification of uncertainties. This can be best assured via multi-source truly independent comparisons that serve to build confidence in the verity of the data.

Validation of Level-2 data (ideally based upon absolutely calibrated Level-1 data) is a comparison between independent estimates of the same measurand. Ideally there are multiple paired comparisons of the form (Immler et al. 2010):

$$|m_1 - m_2| < k\sqrt{u_1^2 + u_2^2 + \Delta^2} \quad (1)$$

where m_1 and m_2 are two independent measurements of the same measurand, u_1 and $u_2$are (ideally) fully traceable uncertainty estimates associated with these measurements, and Δ denotes an additional irreducible uncertainty due to non-coincidence in space, time and measurement geometry. Depending upon what level of k, the coverage factor (BIPM 2008., see also Immler et al. 2010; their Table 1), is obtained, the measurements can be concluded to be consistent or otherwise to be within given level of confidence. In the real-world such comparisons are challenging and the mismatch term can never be fully eliminated. Multiple such comparisons are necessary to identify and quantify discrepancies and would ideally include a broad range of Fiducial Reference Measurements (FRMs) (see Sect. 3.4) from in-situ platforms. FRMs are a specific sub-set of commissioned 'in-situ' measurements with specific characterization tailored to meet the needs of satellite validation (Mertikas et al. 2019; Ruddick et al. 2019).

It is critical that the in-situ FRMs have sufficient spatial and temporal coverage, and that their spatio-temporal representativeness is well known. Access to the FRM data should be guaranteed over the entire mission (including the commissioning phase), in a sustainable, timely, open, and accessible way. An understanding of the measurement uncertainty of the FRM data is critical, and these data are by definition well-validated themselves. Furthermore uncertainties due to non-perfect spatial and temporal co-location between satellite and in-situ measurements need to be accounted for in the error-budgets (e.g. Verhoelst et al. 2015). Finally, not only the Level-2 products need to be validated, but also validation of the ancillary data that satellite retrievals depend upon is necessary. Ideally, FRM capabilities should be collocated to collect a multitude of reference data (for example geophysical, geochemical and atmospheric datasets) allowing the validation of various products and multiple sensors.

3. Current status of Cal/Val

3.1. Quality assurance framework for earth observations

The Committee on Earth Observation Satellites (CEOS) on behalf of the Group on Earth Observations (GEO) established and endorsed the Quality Assurance Framework for Earth

Observation (QA4EO, qa4eo.org), which established a core principle, supported by a set of guidelines, which agencies should adopt to aid interoperability and usability of EO data and derived products. The core principle was that Quality Indicators (QIs) should be ascribed to data products, at each stage of the data processing chain – from collection and processing to delivery (e.g. Nightingale et al. 2018). A QI should provide sufficient information to allow all users to readily evaluate a product's suitability for their particular application, i.e. its 'fitness for purpose'. To ensure that this process is internationally harmonized and consistent, the QI needs to be based on a documented and quantifiable assessment of evidence demonstrating the level of traceability to internationally agreed (where possible SI) reference standards. Such standards may be man-made, natural or intrinsic in nature. The documented evidence should include a description of the processes used, together with an uncertainty budget (or other appropriate quality performance measure). The principles of this framework are being widely adopted across the global scientific community.

In Europe, QA4EO has been particularly strengthened by various EU and ESA (European Space Agency) funded research and development projects such as QA4ECV (Quality Assurance for Essential Climate Variables), Gaia-Clim (Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring), Fiduceo (Fidelity and uncertainty in climate data records from Earth Observations) and the FRM series. Aspects of these projects in turn have started to be implemented in operational services like Copernicus Climate Change Service (C3S). Important developments include:

- Development of a measurement maturity assessment approach (Thorne et al. 2017) which formalizes the need for documentation, metadata, uncertainty quantification and sustainability and assignment of a broad range of existing observational capabilities into a system of systems architecture where the peak are FRM quality reference measurements.
- Employing a framework to improve the metrological rigour of uncertainty quantification (e.g. Nightingale et al. 2018) and documentation for selected candidate reference measurement series.
- Quantification of co-location uncertainties with regard to viewing geometry, measurement type, spatio-temporal mismatches etc., and associated development of co-location matchup database (Verhoelst et al. 2015)
- Harmonization of historical Level-1 data

3.2. *Mission performance centres*

For the Copernicus Sentinel missions, the nominal Level-1 and Level-2 product quality is under the responsibility of their respective Mission Performance Centres (MPCs), which are part of the Copernicus space component. With the creation of the MPCs the various aspects of the Cal/Val chain are overseen with the aim to ensure that the mission requirements are met at all product levels. As Cal/Val experts in the various domains are directly involved in each MPC, anomalies in the quality of the data can be detected in an early phase and timely mitigation actions can be taken. The MPC also serves as a point of contact for external Cal/Val teams. Feedback from external activities is formalized in the Sentinel Validation Teams, which can have members from the global user communities.

The Sentinel Validation Teams support the missions through independent analyses as well as through the collection of in-situ data.

While the MPCs have all the Cal/Val expertise in-house, they are critically dependent on timely and sustainable availability of sufficient quality (ideally FRM) in-situ measurements provided by in-situ networks and research infrastructures funded through multiple sources. As no direct funding is allocated to in-situ data, as part of the MPC, there is no mechanism to ensure a sustainable supply of timely delivered high quality in-situ data throughout the whole mission life-time.

The MPC experts are often associated to a specific mission, while in view of inter-mission consistency essential to the creation of long-term homogeneous time series, a measurand-based approach instead of mission based-approach should be adopted with expertise spanning multiple missions and knowledge transfer between the missions. Such a coordinated approach may also reduce redundancy between MPC activities and thus realize synergies and cost efficiencies freeing up resources for further development.

3.3. In-situ networks and research infrastructures

Several global in-situ observation networks exist providing current and historical in-situ data records. For example, in the atmospheric domain, there are many well-established networks covering various atmospheric variables, like the Total Carbon Column Observing Network (TCCON) (http://www.tccon.caltech.edu/) focusing on greenhouse gases, the Network for the Detection of Atmospheric Composition Change (NDACC) (http://www.ndacc.org), the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) (http://www.gruan.org) and (Southern Hemisphere ADditional OZonesondes) SHADOZ (https://tropo.gsfc.nasa.gov/shadoz/) focusing on atmospheric composition and temperature, the Baseline Surface Radiation Network (BSRN) (https://bsrn.awi.de/) for radiation measurements, the Atmospheric Radiation Measurement (ARM) sites (https://www.arm.gov) which provide important in-situ observations for temperature/moisture sounding validations, etc. Many of these have been established with a research aim. This focus is starting to change to better consider satellite Cal/Val needs.

There are also a handful of dedicated networks for satellite Cal/Val. For example, in the land domain the CEOS Working Group on Calibration & Validation (WGCV) has recently created RadCalNet (Radiometric Calibration Network) (http://www.Radcalnet.org), a network of well-characterized surface targets, equipped with automated instruments to allow SI traceable radiometric Cal/Val of the GEOSS (Global Earth Observation System of Systems) high spatial resolution optical sensors. The automated systems of RadCalNet increase the number of potential sensor match-ups and reduces overall uncertainty. With its open access policy, the network provides the opportunity to perform vicarious calibration of their satellite sensors to agencies, commercial operators and organizations lacking resources and expertise. Individual member sites remain responsible for their own infrastructure and Quality Assurance (QA) with centralized processing and coordination from one or more lead agencies who are able to provide the necessary expertise. This initiative is similar to the longstanding AErosol RObotic NETwork (AERONET) (https://aeronet.gsfc.nasa.gov/) for aerosols operated by NASA.

Major challenges associated with the use of some existing networks for satellite Cal/Val are (1) that most of them are not explicitly dedicated to satellite Cal/Val activities, (2) that the measurement quality is not always at the level of traceable reference data, (3) that the data are not necessarily 'open access', (4) that sustainability is not guaranteed on the long term, (5) that point in-situ data are often sparse and not always representative of a satellite pixel/spatial resolution and coverage, and can be at different vertical levels from the satellite observation, and (6) that interoperability and comparability between networks are not necessarily assured.

The environmental research infrastructures (RIs) that are set up at the European level, build upon the existing global networks while providing a clear governance structure and strict quality requirements. The aim is to ensure a sustainable European infrastructure for in-situ observations, serving user communities with easily accessible reference data – through a single data portal per RI – and associated services, building on satellite dedicated networks such as RadCalNet and Aeronet-OC (Ocean Colour). The user communities include the research community, Copernicus, international assessments, policy makers, and the satellite community. ENVRI is the community of major European Environmental Research Infrastructures. Examples of current operational RIs are IAGOS (In-service Aircraft for a Global Observing System) and ACTRIS (Aerosol, Clouds and Trace Gases Research Infrastructure in the atmospheric domain), Coriolis, Euro-ARGO (European contribution to the International Argo Programme) and EMSO (European Multidisciplinary Seafloor and water column Observatory) in the ocean domain, and ICOS (Integrated Carbon Observation System covering the carbon cycle (ecosystem, atmosphere and ocean).

Again, the RIs are not dedicated to satellite Cal/Val and the sustainability depends on the interests and commitments from the Member States. Not all parameters currently measured from space are covered by the European RIs.

3.4. *Fiducial reference measurements*

A number of ESA funded FRM projects have been established in recent years with the express aim of establishing SI traceable reference methods and standards to support the validation of EO sensor products, with an emphasis on the Copernicus programme. These projects have coordinated with experts in the relevant domains to establish robust protocols, and to carry out comparisons to assess the state of the art, develop rigorous uncertainty budgets, and provide training with the aim to build a coherent internationally consistent validation network. They have variously developed the protocols, and pioneered the inaugural comparisons for performing FRM measurements in different domains. However, the operational implementation, i.e. the sustainable provision of FRM data to support the Cal/Val of the Sentinel fleet and other missions, is not part of these projects, nor is it envisaged to be sustainable from the current developers' resources.

Taking the FRM philosophy further, it is essential that maximum benefit can be obtained from investments in efforts that build upon activities and infrastructure with the aim of addressing multiple Cal/Val measurands allowing vicarious validation of multi-missions and multi-products. For example, supersites which provide validation for a minimum of three different satellite products are being established. First initiatives have come from CEOS WGCV Land Product Validation (LPV) (Figure 2) but opportunities for hosting temperature, radiometry and atmospheric measurements in the same locations, could be stimulated further with improved coordination and a strategic vision. In the first instance these efforts should explore synergies with existing networks and RIs.

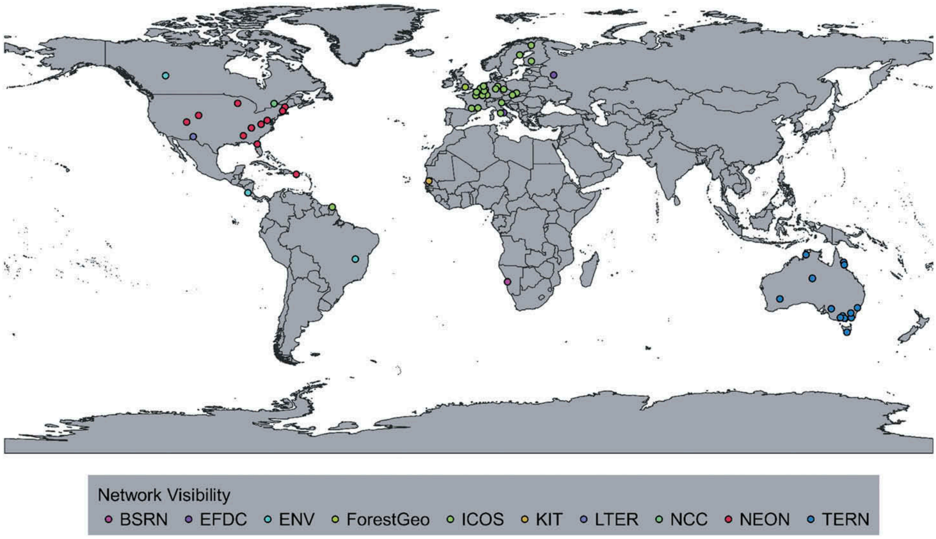

Figure 2. Location of LPV Supersites (reproduced from https://lpvs.gsfc.nasa.gov/LPV_Supersites/LPVsites.html).

3.5. Inter-agency Cal/Val efforts

The last decade or so, with the rapid increase in the number of satellites on-orbit, has made this coordination and joint development of Cal/Val infrastructure the primary focus of CEOS activities. In particular the establishment of 'test-sites' with associated methods of use, have served as an increasing focus for satellite operators. Identifying a subset of possible sites encourages common usage and consequently facilitates cross-comparison and interoperability. Interoperability is a characteristic of a product or system, whose interfaces are completely understood, to work with other products or systems, at present or in the future, in either implementation or access, without any restrictions. For EO this not only requires interchangeable formats but also the means to combine data of potentially different quality and/or biases in a transparent and meaningful manner. It also allows CEOS WGCV members to concentrate their research efforts in a combined manner to improve understanding of these endorsed sites.

The stimulus of this increased coordination stems from the recognition that meeting societal needs requires the combined efforts of all space agencies. This also requires that their data can be readily combined and 'interoperable'. The needs of climate time series place the greatest demands on this interoperability, requiring trustable long-term (multi-decadal) measurements to detect trends with sufficient fidelity.

Whilst climate is most demanding, operational services in meteorology, marine and land applications are all increasingly dependent on the assimilation and/or integration of multiple data sets from different sources. In fact the meteorological community has established its own complimentary group to CEOS to create a Global Space-based Inter-Calibration System (GSICS), where it seeks to harmonize predominantly meteorological satellite Level-1 products through cross-calibration to a common set of reference satellites (different spectral domains). In this way, data from all contributing agencies can be readily used in their local regional weather models and, although the ultimate goal is SI-traceability, in the near-term consistency and interoperability to a 'good' sensor meets the immediate operational needs.

An example of a coordinated Cal/Val infrastructure in the land domain, funded by multiple-agencies is RadCalNet. Many other inter-agency efforts can be found on the CEOS Cal/Val portal (http://calvalportal.org) and whilst they show significant progress and community commitment to work together for common societal goals, they are each dependent on the goodwill and continuing resources of a few agencies to provide leadership, common integrating infrastructure and expertise. Loss of this for some areas makes it difficult to ensure long-term continuity and thus reliance for an operational system like Copernicus. It should be noted that all activities of CEOS are undertaken on a 'best efforts' basis by each of the members as there are no mechanisms for formal long-term coordination or commitment of resources.

In addition to establishing common reference targets/methods for vicarious calibration, CEOS and the member space agencies also organize 'round-robin' comparisons to ensure that instrumentation and methods are also harmonized. This is particularly important where more transient campaign-based satellite validation is required, such as for ocean temperature. Round Robin efforts have proved to be very useful to identify areas for (retrieval) improvement (e.g. Lorente et al. 2017). These are often, but not per definition, done as inter-agency or multi-group efforts.

4. Cal/Val gaps, challenges and opportunities

4.1. Scarcity of data, spatio-temporal coverage, data quality, and data delivery

A large amount of in-situ data is collected by those observation networks and European Research Infrastructures and other networks supporting the Copernicus Services. However, within the in-situ community, there is limited awareness of the required coverage (in parameter space as well as spatially and temporally) and the requirements for FRM quality and documentation of the measurements in order to be useful for satellite Cal/Val. Of the large volume of in-situ data collected, only a limited portion is actually directly suitable for Cal/Val, and often there is a need for 'translational' techniques to enable the exploitation of in-situ data such that they do become useful for satellite validation (e.g. from surface concentration to column, or upscaling from small footprint to large pixel) which is either not recognized or the technique insufficiently developed. Despite the significant efforts that have been undertaken by space agencies through CEOS and EU H2020 projects on defining guidelines and protocols and implementing procedures for performing in-situ measurements fit for the purpose of Cal/Val (Figure 3), the level of understanding in the in-situ community of the needs for satellite calibration and validation is still low.

Moreover, many of the existing networks and RIs have been built bottom-up and the site locations have not been optimized for the needs of satellite Cal/Val. As a couple of examples: i) the locations of the current TCCON sites do not cover the range of surface albedos for which satellite validation is crucial; ii) high-altitude mountain sites are useful for specific research purposes but are not suitable for the validation of satellites with an extended footprint. The locations in space and time of the in-situ Cal/Val data should cover the uncertainty space of the satellite data, i.e. they should cover all parameters that

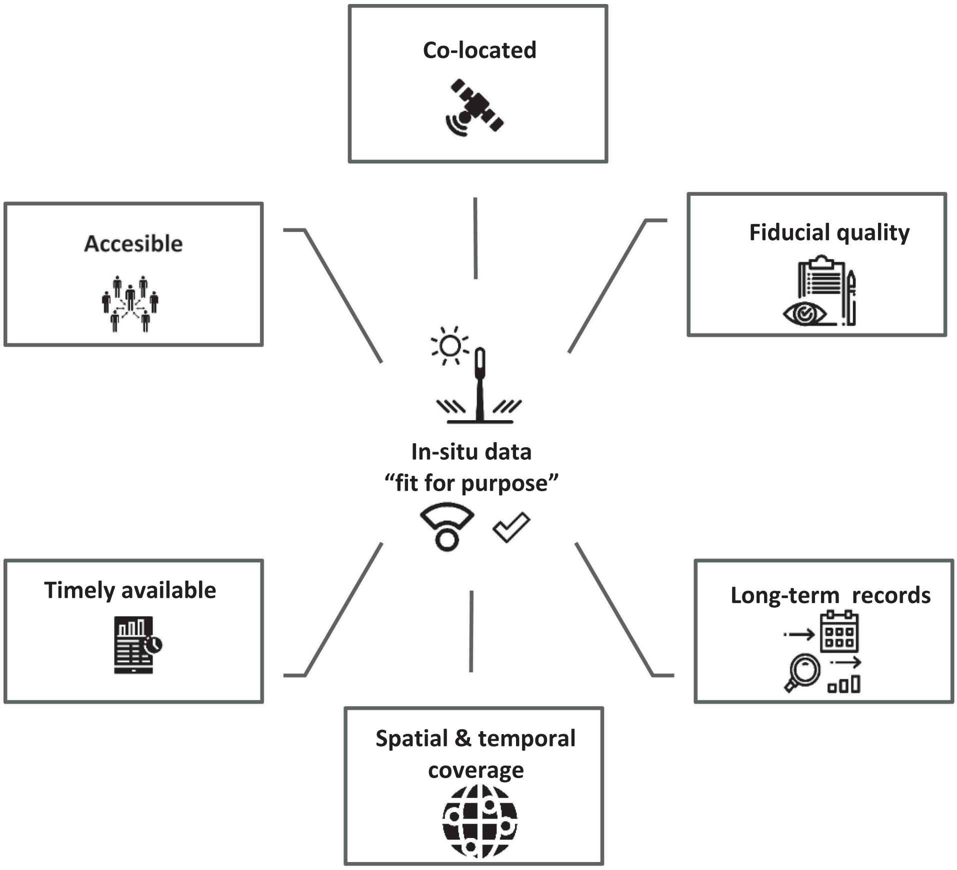

Figure 3. Conceptual outline of the requirements imposed on in-situ data in order to be fit for the purpose of Cal/Val.

may have an impact on the performance of the satellite, such as latitude, season, solar zenith angle, viewing angle, surface albedo, aerosol load, cloud cover etc.

To minimize co-location uncertainties, wherever possible, the in-situ data must be collected at times close to the satellite overpass. This implies that in some cases, the acquisition of the in-situ observations must be scheduled otherwise than what is adopted routinely. However, this may entail extra costs and logistics issues. Furthermore, some techniques are intrinsically tied to physics such as optical techniques which can limit substantively any flexibility.

Additional concerns are the lack of open data access and delayed delivery of the data. The in-situ data should be made available as soon as possible after the measurements have been made to the MPCs and other centres and institutes involved in the Cal/Val of satellite missions. Delays in the availability of in-situ data will result in delays in the Cal/Val activities, which in turn might lead to an unwanted extension of the commissioning phase or, in the operational phase, to costly and timely reprocessing of the data if validation indicates that the specified product accuracies are not met. As Cal/Val activities span the entire end-to-end duration of a satellite mission, the timely provision of in-situ data should be guaranteed during the entire mission.

4.2. Long-term records and sustainability

Long-term data records are essential for monitoring global change, such as ozone hole recovery or climate change. While satellites nowadays play an essential role for global monitoring, most of the geophysical parameters that can be observed from satellites have a longer heritage of measurement by in-situ sensors. The comparison of satellite data to in-situ is therefore not only relevant for the Cal/Val of the satellite data record, but also to be able to understand the changes occurring before the satellite era and place satellite measurements in context. Also, in-situ data are crucial to intercalibrate between previous and current satellite missions, as a newer generation of satellite sensors often have better spatial, spectral and/or vertical resolutions compared to previous generations. This is especially important when the satellite missions do not have a sufficient overlap (or even in the worst case any overlap) period during which they are both operational. The in-situ data can be used to harmonize the multi-mission satellite data record, but only if made in a sustainable way and to FRM-principles. To link to the period before the satellite data record, as well as to link the different satellite missions, long-term in-situ FRM data are essential.

There are several challenges regarding the long-term in-situ data records:

- Historical in-situ measurements are often not well-documented, which makes quality assessment and the generation of harmonized long-term records difficult.
- Instrumentation, protocols, site locations and algorithms may have changed over time, which could introduce spurious trends and jumps in the historical data records.
- Due to the highly fragmented in-situ landscape, with in-situ data often collected at national or regional level and the paucity of openly accessible centralized databases, it is often very complicated to find and/or access the data to generate long-term records.
- Collection of in-situ data may stop because of lack of funding or often short-term prioritization, which breaks the long-term data record.

Some initiatives pose very nice examples, such as the efforts to provide consistent, quality-assured validation data for satellite measurements of the ozone layer (NDACC), aerosol properties (AERONET), upper-air meteorological data (GRUAN), ocean colour radiances through MOBY (Marine Optical BuoY) and altimetric sea-level via the OSTST (Ocean Surface Topography Science Team) Cal/Val group.

The central position of in-situ data in Cal/Val calls for actions ensuring a long-term perspective for handling the in-situ data, including quality control, preservation and accessibility. There is a clear need to collect, to quality control and to harmonize the historical data relevant for Cal/Val. Furthermore, the requirements for long-term in-situ data records for satellite Cal/Val should be brought to the attention of the providers of the in situ data and their funding bodies. The way forward to achieve this is through a central cross-cutting coordinating in-situ Cal/Val facility.

4.3. Fragmented landscape and lines of responsibility

Cal/Val is a shared responsibility of many organizations and entities. The space agencies have the responsibility to meet the mission requirements of their spaceborne instruments. To meet these requirements, sustainable access to in-situ data is needed. However it is unclear who is responsible for the timely and sustained provision of these data beyond the initial commissioning phase of the mission. Data collection by networks, campaigns, and RIs is not specifically dedicated to Cal/Val of the Copernicus Space Component (see previous section). Differences between various in-situ networks may even remain unnoticed when no regular inter-comparison is performed. On top of this, many of the in-situ activities are of a limited duration and there is no ensured continuity, either of availability of in-situ data or of timely access to the data. A stewardship plan to guarantee the sustainable provision of key in-situ data is clearly lacking.

Cal/Val activities are often tied to a single mission with mission specific requirements defined. However, for the generation of long-term ECV data records, data from past, current and future missions have to be combined. This requires inter-calibration and reprocessing efforts to harmonize the satellite observations of the different missions, which can fall under the responsibility/auspices of different agencies. The establishment of long-term stewardship, through for instance an independent authority with appropriate expertise in Cal/Val, would be a way forward to assure consistency between missions.

4.4. Future challenges

Currently, Earth Observation is dominated by the large satellite programmes of (inter) national players, such as the Copernicus programme. However, Earth Observation is rapidly evolving with the emergence of new actors and new technologies including innovative constellations of Cube- and Nano-satellites. ESA is also exploring the domain of High-Altitude Pseudo Satellites (HAPS). The opening of these new markets and opportunities is adding complexity, and increasing the urgency with which Cal/Val must be optimized. At present there is little quality assurance or transparency on products from these smaller satellites. To ensure that European entrepreneurs have an open marketplace to offer services in a competitive manner requires a good public infrastructure to independently assess quality.

In addition, constructing accurate long-term climate records puts increasing demands on the quality of the data, in order to meet the uncertainty and decadal stability requirements for many parameters. This should be carried out in a coordinated manner to minimize duplication of effort. Achieving this would have clear benefits for all applications of Earth Observation.

One step towards improving this situation is the creation of an 'in-orbit SI traceable calibration system' where a few specially designed SI traceable reference satellite sensors such as CLARREO (Climate Absolute Radiance and Refractivity Observatory) and TRUTHS (Traceable Radiometry Underpinning Terrestrial- and Helio- Studies) could provide cross-calibration to other sensors. The use of innovative orbits can permit comparisons in all latitudes. Although steps towards this are envisaged and under development, it will take some time before they are realized in practise and even then will be unlikely to be comprehensive and will not remove the need for complementary in-situ infrastructure and measurements.

In the meantime the vicarious in-situ data used for Cal/Val are also evolving. Different in-situ instrumentation are being developed at finer space and time scales and their data are being used to locally validate satellite instruments and products. These Cal/Val data are not always incorporated and archived into European in-situ networks or RIs. The development of Cal/Val instrumentation on drones is also advancing. Today, the Cal/Val data from dedicated sites or new instrumentation are not being centrally stored in RIs or linked in a consistent way to their appropriate satellite missions.

For several applications, the current satellite observations that use a limited number of spectral bands will be superseded by instruments with hyperspectral capabilities. New in-situ infrastructure is required to calibrate the additional spectral information. Also, more instruments will be observing from geostationary orbits, providing high temporal sampling of the geophysical field. To validate these geostationary data, the in-situ information should also be acquired with a high temporal resolution. Furthermore, accurate auxiliary information on the angular dependence of the surface reflection as a function of wavelength should be available, as this is an important piece of ancillary information needed in many satellite retrievals.

5. Recommendation: a european coordinating entity for satellite calibration and validation

Our analysis, above, and recent and persistent calls for action from stakeholders in the EO community (GCOS-WMO 2016), lead us to conclude that there is a need for a European coordinating entity for satellite product calibration and validation. The proposed entity would be an integrative organization coordinating the European Cal/Val activities in partnership with the member states and the space agencies and working together with existing data providers to secure access to satellite and in-situ data of traceable FRM standard alongside necessary ancillary data as to fully understand the geophysical state of each co-location provided.

We envisage an entity providing an architecture to service the European Earth Observation system meeting the goals of the European Commission, it's partners and the global community. The entity would leverage existing investments in infrastructure, including RIs and networks, but would not claim ownership of measurements or data; the entity would complement and enhance, rather than replicate or replace current activities. We do not propose a data warehousing or database organization but rather an expert facility/grouping acting both as a knowledge repository and coordinating body. It would advocate for quality assurance in calibration and validation measurements, promote FRM compliance and assist in achieving FRM status where lacking, facilitating access to metrological expertise and traceability to international standards for comparisons and uncertainty analysis. Elements of the organizational tasking would include capacity building advocacy, recommendation for reprocessing activities, identifying synergistic solutions to Cal/Val problem and securing and allocation of funding across missions and networks. Forward-looking, there would be actions to support new technologies and observations to reach FRM candidacy and ultimately FRM status expanding the observables and QA of satellite datasets and analysis. The entity would be a template for other actors or regions enhancing European leadership in EO and EO QA.

Such an entity would need to coordinate between space agencies and other stakeholders, including the European Environment Agency (EEA), the European Commission, and EU member states. There is currently no organization with the necessary expertise, coordination and planning capabilities, engaged in this kind of activity. As noted by the In

Situ State of Play report, the EEA, whilst responsible for coordinating Copernicus In Situ is not a specialist in satellite Cal/Val organization and does not have the necessary familiarity with FRM-quality standards or certification. The proposed entity could assume a role complementary to Copernicus In Situ activities. The entity would become the de facto contact point for international coordination of Cal/Val activities, liaising with international partners including CEOS. It would help define and disseminate best practice across and between domains, and in particular, support harmonization of the Cal/Val approaches adopted in the various MPCs and their equivalents elsewhere. In supporting the propagation of FRM standards and attainment of QA the body would become a de facto certification entity with the data recommended by the entity known to be of high and traceable standards and fit for the purpose of Cal/Val. This certification by inclusion also meets a user need for open and accessible standards in an increasingly complex data provision landscape. We would anticipate that the entity would also act to encourage the timely and free delivery of data in time-critical situations leveraging its inherent authority as a community resource.

To maintain a user base and gain the acceptance of the community, a sustained approach is needed. Operating at longer timescales than projects or campaigns the entity could play an important role in helping the transition from developing FRMs to facilitating their operationalization and sustainable deployment. Sustainability in FRM observations remains a challenge. The entity should therefore have some capacity to support FRM expansion and to provide gap-filling support in an emergency. We propose a limited role in resourcing critical observations, commissioning targeted and supplementary observations that meet the needs of priority Cal/Val activities. This might see the organization acting as facilitator of last resort to ensure the continued delivery of a minimum set of validation capability should the existing infrastructures demise. We do not propose a funding agency, but rather a capabilities driven organization that has the resourcing and leverage with stakeholders to maintain and strengthen infrastructure critical to European Space Policy.

Such an entity will require resourcing commensurate with its established mandate. Furthermore, it will require access to specialist expertise that may, today, be lacking outside of national metrology institutes, space agencies and major aerospace concerns. Specification of resourcing and staffing of such an entity is beyond the scope of this whitepaper. However, we would emphasize that the success of Copernicus QA will be largely dependent on access to in situ data of traceable standards and data processing performed by specialists with the confidence of end-users. As such, a Cal/Val entity must retain the confidence of the community and international peers. Achieving such a solution would secure the future of European Earth Observation, the Copernicus Services and the legacy of the largest cohesive global monitoring programme.

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