Recommendations for future work

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Gap Analysis for Integrated
Atmospheric ECV Climate Monitoring
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Executive summary

GAIA-CLIM was a Horizon 2020 project concerned with improving the utility of ground-based and airborne measurement systems to characterise and calibrate satellite measurements. The project brought together a broad range of relevant organisations, networks and institutions to address the challenge.

As a 3-year scientific project of finite resourcing, it was recognised from the outset that there would be a number of areas of investigation and exploration, in-situ network design and governance, as well as technical development that would either be left untouched or in which only partial progress could be attained within the project lifetime. Hence, throughout the project an iterative procedure to identify and catalogue gaps in observing capabilities and understanding was pursued via a living Gaps Assessment and Impacts Document.

This recommendations document builds upon this careful and meticulous collection and cataloguing process to produce a set of eleven overarching final recommendations for future work to close the most critical gaps identified. These are summarised thematically in Table ES1. The main text provides an outline of the approach to formulate these recommendations and an accessible textual summary of each, whilst Annex 1 provides more detailed 2-page summaries of each recommendation, sufficient to form the basis for future funding calls, projects and programmatic developments. Further specific detail is elaborated in the Gap Assessments and Impacts Document and associated gap traces[1].

The recommendations are thematically clustered around activities which:

- Ensure a sustainable workforce to develop and deploy capabilities;
- Improve the quality, coverage, and utility of the non-satellite data segment for satellite characterisation;
- Better optimise governance of non-satellite observations;
- Address shortcomings of knowledge in transferring between the non-satellite measurements and the radiance quantities sensed by satellites;
- Better quantify the effects of unavoidable measured quantity differences between satellite and non-satellite measurement techniques; and
- Provide user tools to enable exploitation.

While targeted at the thematic area of the project, many of the recommendations if enacted would undoubtedly have broader applicability, benefitting other application areas that use both satellite and non-satellite observations. For example, improved understanding of surface models resulting from the eighth recommendation (Table ES1) would positively impact both Numerical Weather Prediction (NWP) and climate modelling. Any consideration of the recommendations herein should naturally also consider such potential co-benefits.

[1] The online catalogue of gaps is available under: http://www.gaia-clim.eu/page/gap-reference-list

Education and training
Maintain and further develop a trained workforce competent in EO data characterisation and downstream applications to support Copernicus activities
Non-satellite data quality and availability
Improve the metrological characterisation of a suite of non-satellite measurement techniques: Striving for traceable, reference quality, fiducial measurement series
Augment and consolidate existing geographical coverage of fiducial reference quality observational networks to be more globally representative, including a range of surface types and climate zones
Improve time scheduling coherency of satellite and non-satellite measurements to minimise the need to account for co-location uncertainty effects
Instigate and sustain time-bounded access to a comprehensive set of harmonised fiducial reference data and metadata holdings under a common data model and open data policy that enables interoperability for applications
Observational network governance
Take steps to reassess, rationalise, and improve coordination of high quality observing networks
Conversion of non-satellite measures to Top Of Atmosphere radiance-equivalents and their use
Improve knowledge of fundamental spectroscopy and undertake associated innovations in radiative-transfer modelling
Improve quantification of the effects of surface properties to reduce uncertainties in satellite data assimilation and satellite to non-satellite data comparisons
Develop and provide tools that convert non-satellite fiducial reference quality measurements to Top-Of-Atmosphere radiance equivalents with associated rigorously quantified uncertainties
Understanding and quantifying irreducible co-location mismatch effects
Improve the basis for assigning co-locations and quantifying rigorously the associated uncertainties, including steps towards operational provision of co-location uncertainties
Provision of user tools that enable exploitation
Operationalise co-location match-ups, extraction and visualisation tools, such as the GAIA-CLIM Virtual Observatory, to facilitate user access to satellite to non-satellite match-ups

Table ES1. High level recommendation titles and thematic clustering.

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Version history

Version	Date	Authors	Comments
1.0	26/5/17	Peter Thorne, Anna Mikalsen	First draft for consideration by internal project partners and use in GRUAN meeting outreach activity
2.0	3/8/17	Peter Thorne, Fabio Madonna, Martine De Maziere, Anna Mikalsen	Incorporates feedback from GAIA-CLIM work package partners via teleconferences and from use in trial run at 9th GRUAN Implementation and Coordination Meeting
3.0	23/8/17	Peter Thorne, Martine De Maziere, Fabio Madonna, Karin Kreher, Stu Newman, Bruce Ingleby, Anna Mikalsen, Michiel van Weele	Feedback from authors listed incorporated plus from science advisory panel
4.0	2/9/17	Peter Thorne, Joerg Schulz, Stephanie Guedj, Tijl Verhoelst, Jean-Christopher Lambert, Stu Newman, Bruce Ingleby, Martine De Maziere	Further feedback incorporated. Version used in Outreach events to WMO and NIES
5.0	29/9/17	Peter Thorne, Gerrit de Leeuw, Anna Mikalsen	Final tidies and check for formal deliverable of public review version
6.0	14/2/18	Peter Thorne	First attempt at drafting a final version based upon feedback received upon the document on the road show and the revised set of GAID inputs from the underlying Work Packages
7.0	23/2/18	Peter Thorne, Tijl Verhoelst, Stu Newman, Martine De Maziere	Incorporation of feedback received including feedback from project reviewer in final project review.
8.0	25/2/18	Peter Thorne, Fabio Madonna, Bruce Ingleby, Anna Mikalsen, Karin Kreher	Incorporation of further feedback received
Final	28/2/18	Peter Thorne, Heather Lawrence, Stu Newman, Joerg Schulz, Tom Gardiner, Karin Kreher, Anna Mikalsen	Incorporation of final feedback received

1. Introduction

1.1 Project aims and context of the recommendations

The GAIA-CLIM project undertook to assess and improve global capabilities to use ground-based, balloon-borne and aircraft measurements (termed non-satellite measurements henceforth) to characterise space-borne satellite measurement systems. The work under GAIA-CLIM encompassed the following tasks:

1. Defining and mapping existing non-satellite measurement capabilities;
2. Improving the metrological characterisation of a subset of non-satellite (fiducial reference) observational techniques;
3. Better accounting for co-location mismatches between satellite observations and non-satellite (fiducial reference) observations;
4. Exploring the role of data assimilation as an integrator of information;
5. Creation of a '*Virtual Observatory*' bringing together all comparison data, including their uncertainties, and providing public access to the information they contain;
6. Identifying and prioritizing gaps in knowledge and capabilities.

The funding call for GAIA-CLIM (H2020 EO-3-2014[2]) explicitly requested a consideration of future strategy. The GAIA-CLIM project responded to this requirement through its outreach work package, which identified and prioritised currently unfulfilled user needs for satellite characterisation using non-satellite measurements in consultation with the user community. Over the first two years of the project, an iterative process of identifying, collecting, documenting and refining such gaps in capabilities, methods, governance etc. relevant to the project charge was undertaken (Section 1.2). Having identified a set of user needs, the present document identifies a prioritised set of recommended high-level follow-on activities (Section 1.3). A draft of this document was used in the user outreach (Section 1.4) and this feedback has informed the final set of recommendations. The final recommendations are summarised in Section 2, with detailed 2-page traces for each recommendation made available in Annex 1. Section 3 summarises.

1.2 The Gaps Assessment and Impacts Document

The Gaps Assessment and Impacts Document (GAID) [1], and associated set of traces[3], summarises the outcome of this collection of gaps and their proposed remedies. It further describes the gap identification process, as well as the way these findings are presented and made accessible to users. Each detailed gap traces clearly articulates:

- The nature of the gap
- The relevance and benefits of resolution, and risks of non-resolution; and
- One or more potential remedies. Remedies are laid out in a manner that is:
    - **S**pecific,
    - **M**easurable,
    - **A**ctionable,
    - **R**ealistic, and

[2] https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/eo-3-2014.html
[3] http://www.gaia-clim.eu/page/gap-reference-list

- **T**imebound.

Several cross-sections of gaps and remedies in the GAID can be identified through a series of selection criteria, which include aspects such as the gap type, remedy type, cost and likely actors.

During the GAIA CLIM project, the GAID was a living document that benefitted from both internal and external stakeholder input, which led to iterations both in which gaps were included and how they were documented. The GAID was informed by a user survey [2] undertaken in the early stages of the project, two dedicated user workshops [3,4], and the user feedback collection in the final year [5]. Drafting was also based upon sustained input by project participants [6-21], who cover a broad range of necessary expertise and are involved in several ground-based networks, international measurement programs and satellite validation programs.

In its final version [1], the GAID serves as a high-level overview of the gaps and remedies included in the on-line catalogue of gaps[3]. Detailed online traces of each gap and actionable remedies are formulated in a consistent manner. Users can select cross-sections of interest in the online catalogue, which shall remain available online.

1.3 Deriving recommendations from the underlying GAID

The GAID and accompanying detailed gap descriptions constitute a firm and traceable basis for the production of a set of recommendations. The challenge was how to achieve this to create recommendations that may be not just actionable, but also actioned. We foresaw three potential routes:

1. One option, which would lose no information relative to the GAID, would be simply to lift the remedies detailed in all the underlying gap traces and present these as a comprehensive wish list. However, even after significant efforts at rationalisation, there remain 41 gaps and 64 recommendations in the final version of the GAID.
2. Another option would be to elevate solely a small prioritised subset of the gaps and remedies, as they stand. Such an elevation of individual gaps ensures a direct traceability to the GAID but might lead to an unbalanced/biased presentation of overall needs.
3. A final alternative would be to further synthesise the information, leading to a more restricted set of recommendations that reflect broad thematic needs that the GAID has identified, but at a substantially higher level of abstraction than many of the individual, very specific, GAID gap traces permit.

While recognising that none of these approaches is perfect, we have chosen to pursue the final option as that most likely to meet the stakeholder needs. The initial selection of recommendations was undertaken by participants in the outreach work package, led by the scientific project lead and document owner, Peter Thorne, taking into account factors including:

- Gap types
- Gap impacts and resolution benefits
- Remedy types
- Remedy costs
- Remedy actors

These aspects have been consistently mapped across the 41 gap traces documented in the GAID. Consideration was given in the first instance to the use of an explicitly quantitative technique to formalise the selection criteria. However, there are several important caveats, which ultimately led us to discount this approach, principal amongst which were:

1. Not all those aspects which might inform prioritisation are necessarily quantifiable or clear in what order to rank (e.g. should high cost be prioritised over low cost? Quick over long-term?).
2. There is an inevitable and irreducible degree of compiler-to-compiler subjectivity in some aspects of the GAID traces.
3. In many cases, it makes compelling sense to generalise a family of gaps to create a more holistic recommendation that encapsulates several gaps.
4. Using any chosen purely quantitative approach may lead to an unbalanced set of recommendations that prioritised one or more area(s) of activities unduly over others.

The assessment thus considered the gaps qualitatively using informed expert judgement involving the range of GAIA-CLIM participants engaged in the work package in coming to a final selection of recommendations (Section 2). The final prioritisation takes into account feedback received from internal partners and external stakeholders through various outreach events, including a joint day discussion with partners of the FIDUCEO[4] project and the series of in-depth outreach events undertaken in the final project year [5]. To support broad applicability, attempts have been made to ensure that the recommendations cover a broad range of types of work, likely funders and actors who may address the work.

It has only been possible to elevate a subset of the remedies outlined in the GAID whilst simultaneously retaining a reasonably concise set of recommendations. Furthermore, these have often been merged to form a much wider (and hence more expensive and often longer-term) course of action than the underlying family of individual remedies available in the GAID traces. An alternative means to deliver progress would be via undertaking the set of remedies detailed within the underlying gap traces, which invariably constitute a richer population of potential approaches to be pursued of more varied costs, durations and work types.

1.4 User consultation on the draft recommendations

The recommendations document public consultation version [22] was used in the user outreach in the period over September 2017 to January 2018, which collected and considered feedback from a range of users [5]. This user consultation explicitly sought feedback upon the drafted recommendations, including, but not necessarily limited to:

- Whether, in the view of the consulted members of the broader user community, the most appropriate set of issues and ensuing recommendations had been elevated from the GAID.
- Whether the recommendations strategy and detail were fit for purpose or required further modification.
- Whether there were key unfulfilled user needs that were not addressed either in the recommendations or the underlying GAID, which required additional attention and potential elevation.

A substantial synthesis of feedback received on the public consultation draft [22] along with

[4] http://www.fiduceo.eu/

all underlying visit reports is presented in the roadshow final report [5; specifically, Section 2.3]. This feedback has been extensively used to draft the final version presented herein. For brevity the feedback is not further discussed here.

2. Recommendations

The recommendations exercise has led to the formulation of eleven specific recommendations. All recommendations are laid out in full in Annex 1 in a common format of maximum two pages to enable ease of interpretation and comparability. The template includes: A clear and succinct title; GAID trace(s) contributing; the nature of the issue to be addressed; and one or more possible pathways to resolution and the likely funders and / or actors, costs and timescales. Further formatting rationale is given in Annex 1.

The recommendations make certain implicit assumptions regarding the continuation of ongoing activities. Examples of such implicit assumption include, but are not limited to:

- Continued efforts by instrument manufacturers, research institutes, research infrastructures and observational networks to develop and deploy new instrumentation capable of sensing the atmosphere with lower uncertainty over a greater range, with greater vertical fidelity, and / or more continuously.
- Continued development by NWP and reanalysis centres to better exploit, integrate, and use the non-satellite segment, including for model validation and the characterisation of satellite measurements.

The recommendations, if adopted, would serve to augment such assumed ongoing activities.

In this Section, we highlight pertinent aspects of the recommendations. Table 1 provides an overview of the recommendations split into broad classes that show how they respond to different needs and application areas, likely timescales, costs, work type, actors, and how the recommendations map back to the underlying GAID traces. Following this, we provide a high-level text overview of each recommendation of around half a page. The recommendations are indexed numerically solely for the purposes of referencing between the main text and Annex 1. The numerical ordering should **not** be taken to infer prioritisation.

No matter how the recommendations are formulated, it is inevitable that they are inter-linked to a greater or lesser extent. Resolution of one or more given recommendations will have impacts upon the ability or chosen approach to address the remaining recommendations. Resolving multiple recommendations will also have synergistic benefits. However, the recommendations have been constructed in such a manner that there are no critical dependencies whereby one recommendation must be completed prior to addressing another. Within Annex 1 wherever there are recognised substantive overlaps these have been noted.

We would note that work on aspects of all the recommendations is already ongoing to a greater or lesser extent either within Europe, in the rest of the world, or both. This includes substantive progress in the GAIA-CLIM project in many cases. However, what is missing in all cases is the scale, coordination and resource required to fully address the issues raised within the recommendations.

Recommendation title and indexing	Timescale(s)	Costs	Work type (s)	Scale of work	Actors	Pertinent GAID gap traces
Education and training						
1. Maintain and further develop a trained workforce competent in EO data characterisation and downstream applications to support Copernicus activities	Continuous	Scalable dependent upon ambition	Training /academic	Single institution / small consortia	Academia, NMSs, NMIs, Copernicus (Academy), ESA, EUMETSAT	G6.12
Improvements to non-satellite data quality and availability						
2. Improve the metrological characterisation of a suite of non-satellite measurement techniques: Striving for traceable, reference quality, fiducial measurement series	>5 years	>10 million euros	Technical / Research / Field campaigns	Consortium / Programmatic	NMIs, NMSs, Academia, research institutes, SMEs / industry, WMO, measurement networks/research infrastructures	G1.10, G2.08, G2.11, G2.12, G2.13, G2.18, G2.22, G2.24, G2.26, G2.27, G2.30, G2.31, G2.36, G5.07
3. Augment and consolidate existing geographical coverage of fiducial reference quality observational networks to be more globally representative, including a range of surface types and climate zones	<10 years	>10 million euros	Governance / Technical / Deployment	Consortium / Programmatic	NMSs, NMIs, academia, research institutes, SMEs / industry, WMO, space agencies, measurement networks/research infrastructures	G1.10, G2.06, G2.10, G4.12, G6.02

Table 1. Summary of recommendations split out by thematic area and in the order presented in the remainder of Section 2 (note that indexing does not imply prioritisation). The gap trace identifiers uniquely denote a gap trace in the GAID. Full traces are available from http://www.gaia-clim.eu/page/gap-reference-list . Note that some gaps appear more than once, but not all GAID gaps have been included. Cont. overleaf.

Recommendation title and indexing	Timescale(s)	Costs	Work type (s)	Scale of work	Actors	Pertinent GAID gap traces
4. Improve time scheduling coherency of satellite and non-satellite measurements to minimise the need to account for co-location uncertainty effects	<10 years	Dependent upon ambition but at least 10 million euros	Governance / Technical / Network management	Programmatic	NMSs, NMIs, Academia, research institutes, SMEs/industry, observational networks/research infrastructures, WMO	G5.11, G6.03, G6.06
5. Instigate and sustain time-bounded access to a comprehensive set of harmonised fiducial reference data and metadata holdings under a common data model and open data policy that enables interoperability for applications	<5 years	Additional funding <2 million euros	Data management	Programmatic	NMSs, NMIs, WMO, Academia, Copernicus, research institutes, observational networks/research infrastructures, SMEs	G1.06, G5.01
Observational network governance						
6. Take steps to reassess, rationalise, and improve coordination of high quality observing systems	>10 years	<5 million for studies to ascertain options; costs (and cost-savings) of implementation unknown	Governance / Network management	Programmatic, Consortium to ascertain and quantify options	Observational networks/research infrastructures, WMO, Copernicus, NMSs, satellite agencies, SMEs	G1.03, G1.04, G5.01, G6.01, G6.02

Table 1. Cont.

	Recommendation title and indexing	Timescale(s)	Costs	Work type (s)	Scale of work	Actors	Pertinent GAID gap traces
Conversion of non-satellite measures to TOA radiance-equivalents and their use							
7.	**Improve knowledge of fundamental spectroscopy and undertake associated innovations in radiative-transfer modelling**	<5 years	<5 million euros	Technical / Research	Consortium / programmatic	NMIs, NMSs, academia, research institutes, SMEs / industry	G2.26, G2.27, G2.37
8.	**Improve quantification of the effects of surface properties to reduce uncertainties in satellite data retrieval, assimilation, and satellite to non-satellite data comparisons**	<5 years	<10 million euros	Technical / Research / Field campaigns	Consortium	NMSs, Satellite agencies, academia, NMIs, research institutes, SMEs / industry	G4.08, G4.09, G4.10
9.	**Develop and provide tools that convert non-satellite fiducial reference quality measurements to Top-Of-Atmosphere radiance equivalents with associated rigorously quantified uncertainties**	<5 years (development); Continuous (deployment)	<5 million euros (development only)	Technical / Research / Operations	Consortium / Programmatic	NMSs, Satellite agencies, NMIs, academia, research institutes, SMEs / industry	G4.01, G5.09

Table 1. Cont.

Recommendation title and indexing	**Timescale(s)**	**Costs**	**Work type (s)**	**Scale of work**	**Actors**	**Pertinent GAID gap traces**
Understanding and quantifying irreducible co-location mismatch effects						
10. Improve the basis for assigning co-locations and quantifying rigorously the associated uncertainties, including steps towards operational provision of co-location uncertainties	<5 years	<10 million euros	Research	Consortium	NMSs, Observing networks/research infrastructures, NMIs, WMO, academia, research institutes, SMEs / industry	G3.01, G3.02, G3.04, G3.05, G3.06
Provision of user tools that enable exploitation						
11. Operationalise co-location match-ups, extraction and visualisation tools, such as the GAIA-CLIM Virtual Observatory, to facilitate user access to satellite to non-satellite match-ups	Continuous	<2 million euros per annum, although dependent upon adopted scope	Development and operations	Single institution / consortium	Copernicus, Satellite agencies, NMSs, academia, research institutes, SMEs / industry	G1.05, G5.01, G5.06

Table 1. Cont.

2.1 Education and training

1. Maintain and further develop a trained workforce competent in EO data characterisation and downstream applications to support Copernicus activities

While it is necessary to address technical and organisational issues that reduce the availability, effectiveness, and quality of satellite characterisation data, doing so is moot unless there is sufficient capacity, both in terms of personnel, but also critical skills, to develop and deliver products and services to the marketplace. If Copernicus Services are to realise their full potential, additional training through formal and informal routes is required to provide the next generation of data providers, analysts and users with the skills and insights that can be used to fully exploit the substantive investment in space-based and non-space based observational assets. Thus allowing Copernicus to deliver the envisaged step-change in capabilities and services.

In terms of formal instruction and training, this requires the Commission to facilitate and promote a substantial increase in the number of relevant academic programs at undergraduate, masters and PhD levels across member states. Perhaps the most acute need to address is training at the doctoral level which provides the next generation of expert scientists capable of maintaining and improving the observational program, driving novel analysis, and delivering technological innovation. A pan-European targeted doctoral program addressing questions of mutual interest to host institutions and Copernicus would facilitate the provision of a sustainable programmatic capability while simultaneously better engaging academia across Europe within the programmatic structure of Copernicus.

The effective provision of services from Copernicus data also requires users to be able to have confidence in the quality of the service provider. This may result from a combination of proof of prior service engagement with users and / or successful completion of formal training course(s). Service providers need to show demonstrable competency in accessing relevant observational data and products, their appropriate and smart fusion, and the provision of advice to the user. A certificate of competency in Copernicus Service provision could be provided to accredited individuals and institutions by one or more recognised institutions providing training and appropriate assessment in required competencies.

2.2 Improvements to non-satellite data quality and availability

2. Improve the metrological characterisation of a suite of non-satellite measurement techniques: Striving for traceable, reference quality, fiducial measurement series

Formal closure of a comparison of any two measurement systems requires, as an absolute minimum condition, that the uncertainty in at least one of the two measurement systems be metrologically rigorously quantified and traceable either to SI or community standards (fiducial reference quality). Despite substantial progress under GAIA-CLIM for each of the six target measurement techniques (lidar, MWR, FTIR, MAX-DOAS, UV/Vis and GNSS-PW [25]) and for other measurement systems and / or species by related networks / programs / projects such as NDACC, GRUAN, QA4ECV, and ACTRIS, substantial work remains to be done to develop fully metrologically traceable measurements and their associated uncertainties for a broad suite of both satellite and non-satellite measurement techniques. Non-satellite techniques have the advantage of being accessible to allow calibration, maintenance etc. and in many cases already are available and providing high-quality measurements. The missing link is assuring traceability in processing back to SI or community standards, quantifying the associated uncertainties, and then processing the data to these specifications.

To realise the full benefits of existing non-satellite measurement capabilities, a sustained program is required to improve the metrological characterisation and measurement quality of a substantial range of instrumentation, attaining fully traceable reference quality measurements where possible and practicable. These instruments may include but not be limited to: various balloon-borne measurements (radiosondes, frostpoint hygrometers, ozonesondes etc.), active remote sensing techniques such as lidars, and passive remote sensing techniques such as microwave radiometers, FTIR, UV-visible spectroscopy etc., and eventually measurements of the oceanic and terrestrial domains. Significant synergies would be gained from a consideration of the metrological qualification of the broad range of measurement techniques under a common programmatic effort given the similarity in metrological aims. An alternative would be more piece-wise approaches on an instrument-by-instrument or network-by-network basis which could be provided through the reinforcement of existing measurement programs and research infrastructures.

3. Augment and consolidate existing spatial coverage of fiducial reference quality observational networks to be more globally representative, including a range of surface types and climate zones

Limited spatial availability of fiducial reference observations with traceable uncertainty estimates restricts their direct applicability to high-quality applications such as satellite data characterisation, model validation and reanalyses. What fiducial reference quality measurements exist tend to be geographically concentrated in Northern Hemisphere mid-latitude regions. There is a paucity of such measurements in areas such as South America, Africa and parts of Asia, as well as remote island locations. Such measurements are also often dispersed rather than co-located at a single central observing facility, which leads to undesirable non-co-location effects that serve to potentially diminish their value for certain applications. The challenge is thus two-fold: to improve coverage in geographically under-sampled regions; and, where appropriate, to co-locate infrastructure to realise synergies between existing fiducial reference quality instrumentation where it is locally dispersed across numerous facilities.

Reference-quality observational networks need to work both internally and with funders and partners to pro-actively increase both the number of fiducial reference observation locations and the volume of data arising from data sparse regions. Robust quantitative assessments of the impacts of geographical spatial gaps (including such aspects as vertical range, vertical resolution and temporal sampling) in the availability of fiducial reference quality measurement systems are required to inform such expansion choices. GAIA-CLIM has developed model-based [26] and statistically-based [27] techniques to evaluate these issues for a restricted subset of networks and ECVs, leading to a number of specific suggestions. Similar assessments have also been undertaken elsewhere. But, historically, these have variously considered a subset of ECVs and / or networks. These reviews need to be consolidated and as necessary augmented to consider aspects such as surface type (important for characterisation of satellite measurements with a significant surface sensitivity) to provide the rigorous scientific basis for the establishment or consolidation of facilities where the availability of fiducial reference quality measurements provides a clear benefit to multiple data stakeholders. Such analyses should be facilitated by targeted activities such as OSSEs, short period field campaigns or other activities which permit a quantitative assessment of the benefits of both co-locating existing observing capabilities and making observations in new locations.

4. Improve time scheduling coherency of satellite and non-satellite measurements to minimise the need to account for co-location uncertainty effects

There are many non-satellite measurement systems that, in principle, can be used for the purposes of satellite characterisation on a sustained basis. However:

1. Many of the measurement systems are by necessity discontinuous such as balloon borne measurement systems, and in such cases their scheduling is often made on an operational basis without specific regard to satellite overpass times.
2. Many other instruments such as various Lidar and FTIR instruments have the potential to be operated on a more sustained and continuous basis, taking measurements whenever geophysically possible, and thereby maximising opportunities for satellite cal/val applications. But, for various reasons - including scientific, technical, operational, organisational and financial reasons - this potential has not been fully realised to date.

Sustained funding and governance mechanisms need to be instigated and assured that optimise the observational scheduling of relevant high-quality non-satellite measurements for satellite characterisation. Care must be taken to avoid deleterious impacts on other operations and data users (see also Section 3.2).

The scientific benefits will be maximised if a sampling strategy for a periodic measurement series can be devised which optimizes, to the extent resources and competing user requirements allow, the ability of the non-satellite data segment to characterize satellite instrument performance across time, across platforms and across instrument types. This may include making (and funding) a number of additional specifically targeted measurements at the selected sites. An example is the ongoing JPSS cal/val / RIVAL campaign at the US ARM SGP facility whereby two flights are being released 50 minutes apart scheduled to coincide with a JPSS overpass on a sustained basis funded by the space agency.

For instruments that could in theory be operated continuously, an assessment on a per instrument and per site basis of the current impediments to either continuous or optimized operation is required. Such an assessment must consider questions of resourcing, logistics and governance amongst others. Work can then be undertaken to address these issues, prioritising instruments and sites that would provide greatest benefit to satellite cal/val.

5. Instigate and sustain time-bounded access to a comprehensive set of harmonised fiducial reference data and metadata holdings under a common data model and open data policy that enables interoperability for applications

Owing to presently dispersed data management, effective usage of the full range of reference quality measurements requires substantial investment of time and resources to instigate and maintain a large number of data access protocols and processing software facilities, as well as to fully understand and adhere to a broad range of data policies and data provision modalities (NRT, delayed mode, periodic, ad hoc). To make matters worse, data access, format and policy are subject to periodic change requiring a constant maintenance overhead on any applications that use data from a range of contributing networks. What is required is unified access to fiducial reference quality data and metadata in a time-bounded manner (within hours to days to at worst weeks) in a consistent format.

The C3S_311a_Lot 3 service contract, if successful, will make considerable strides in enabling users' access to harmonised reference and baseline data, metadata and time series of in-situ networks available under a common data model and with clear articulation of data policies that enable appropriate and seamless usage of data arising from multiple contributing networks and data streams. The work program builds upon many aspects of work within GAIA-CLIM. Data shall be served via the Climate Data Store (CDS) facility of C3S.

However, the C3S_311a_Lot 3 service development is limited to accessing data from a small number of atmospheric networks and a subset of atmospheric ECVs. It also does not consider unified access to intensive observational campaign data, which historically is highly dispersed, but has significant scientific potential. So, in the longer-term extension of such capabilities would be required to cover additional in-situ measured atmospheric ECVs and to the oceanic and terrestrial ECVs as well as archiving and assuring access to observational campaign data.

An open data policy for all networks in line with the new European policies for Copernicus and the US data policies, that are generally open already, would also be of great benefit. The open data policy that is applicable to the Copernicus program including the Sentinel missions is the model which all networks, data centres, and satellite agencies should be encouraged to adopt.

2.3 Observational network governance

6. Take steps to reassess, rationalise, and improve coordination of high quality observing networks

Current governance of global high-quality measurement programs remains highly fractured and lacks sustained coordination. In part, this arises because there is no universally agreed approach to categorising networks [23]. This dispersed governance leads to decisions which, although sensible on an individual network basis, are potentially sub-optimal on a more holistic basis e.g. investing in a new site close-by to a site that contributes to an existing network rather than co-locating these. Inevitable outcomes from a fractured governance and support mechanism include aspects such as:

- Geographical dispersal of capabilities;
- Heterogeneities in measurement technique practices and processing;
- Lack of coordination between activities managed by international funding and the various funding agencies; and

- Different networks taking different approaches to data processing and serving which reduces both accessibility to and comparability of the resulting data.

It follows that many of the remaining recommendations as well as the gaps identified within the GAID are symptoms of this issue remaining inadequately addressed. It is necessary to firstly use defensible metrics categorising networks based upon demonstrable aspects of their maturity [23]. It is then recommended to strengthen existing efforts to ensure meaningful collaboration between potentially synergistic or complementary networks via e.g. cross-pollination of governance bodies. Synergies can also be realised through involvement in joint research and infrastructure activities such as Horizon 2020 and Copernicus grants or service contracts, ESFRI, and similar activities outside of Europe. In the longer-term, it is also necessary to assess and, if possible, rationalise the number of networks involved in taking high-quality measurements by merging where feasible, on the basis of mission and capabilities similarities or enforcing collaboration mechanisms such as ESFRI. This would result in more unified governance and planning for these measurement programs both regionally and globally. This process must take into account available funding, geopolitical, network remit, the need for enhanced cooperation mechanisms and other relevant factors. Mergers should only proceed if it would strengthen the observing program and should not be enforced if funding support or other essential support would be weakened as a result of the decision.

2.4 Conversion of non-satellite measures to TOA radiance-equivalents and their use

7. Improve knowledge of fundamental spectroscopy and undertake associated innovations in radiative-transfer modelling

The vast majority of satellite monitoring of the Earth occurs via either passive or active measurement techniques, where the fundamental measurement is a radiance spectrum in some narrow portion of the electromagnetic (EM)-spectrum. Molecular spectroscopy provides the primary link between a given radiance and the underlying atmospheric gaseous composition and its properties. Historically, such uncertainties have been dwarfed by uncertainties in the satellite and non-satellite measurements and limitations in our ability to control for co-location impacts. As improvements have occurred in these, spectroscopic uncertainties have become increasingly important and in some spectral regions such as off-wing 183 GHz measurements [24] may now be dominant.

Therefore, spectroscopic knowledge limitations, if left unaddressed, shall compound many other issues inherent in a satellite to non-satellite comparison. Spectroscopic parameters are also an integral part of radiative transfer (RT) codes. RT codes constitute the core of radiometric or spectrometric physical retrievals, such as optimal estimation methods, and fast RT models are widely used in data assimilation for Numerical Weather Prediction and reanalyses. Any data intercomparison/validation method that includes the use of RT codes will also be influenced by uncertainties in the underpinning spectroscopic parameters.

Establishment of a high-level programmatic activity is needed to coordinate and review spectroscopic uncertainty activities across the range of spectral regions (with special attention on key spectral regions such as 1-50 GHz and the 183 GHz line) and measurement techniques, with the long-term goal of developing harmonised processes to establish spectroscopic traceability. This may be achieved either by a large-scale coordinated project or smaller, targeted activities for specific cases. A large-scale coordinated project approach would benefit from synergies and commonality of approaches and may be preferred. The activity should aim to strengthen cooperation between communities making laboratory-based spectroscopic investigations and the radiative transfer community which is perceived as weak presently.

8. Improve quantification of the effects of surface properties to reduce uncertainties in satellite data assimilation, retrieval and satellite to non-satellite data comparisons

Numerous space-based remote-sensing techniques sense the surface, and therefore are sensitive to surface emissions, albedo etc. The surface of the Earth does not have homogeneous emissivity characteristics. For example, over the land domain there can be strong spatial heterogeneity and seasonality and over ocean the emissivity can be strongly affected by waves. Considering portions of the radiance spectrum for which the atmosphere is relatively transparent, surface emissivity and its uncertainty can be the dominant source of uncertainty in the analysis and utilisation of the satellite measurements. Over all surface types, limitations in knowledge of surface emissivity and its spatio-temporal variability across a range of scales is therefore a significant challenge that requires addressing.

As a first step, it is necessary to undertake an in-depth intercomparison of available surface emissivity model outputs, for a carefully defined set of inputs. Such an intercomparison of emissivity models, in itself, would not achieve a validation of emissivity models, but the differences identified and quantified could shed light on the sources of bias in any given emissivity model and would yield avenues for further investigation and refinement.

Secondly a reference ocean emissivity model should be developed for the spectral region of 1 – 200 GHz, supported by reference-quality laboratory measurements of the seawater dielectric constant. The development of reference land surface emissivity models for these frequencies, for different surface types, is also a long-term aspirational goal. Developing reference emissivity models would allow for future scientific developments and aid in the estimation of uncertainty.

Finally, emissivity models and their uncertainty estimates should be validated by comparison to field campaign measurements. Typically, validation of emissivity models has been carried out using airborne (and, over land, ground-based) campaigns. However, to date these campaigns have not generally used traceably calibrated radiometers, since there have not been primary reference standards available. To enable full metrological closure requires development and deployment of traceably calibrated radiometers for field campaigns and in laboratory experiments. These should be targeted at regions of the spectral domain and surface types / seasons identified as being highly uncertain.

9. Develop and provide tools that convert non-satellite fiducial reference quality measurements to Top-Of-Atmosphere radiance equivalents with associated rigorously quantified uncertainties

The validation of satellite measurements in terms of the measured radiance (level 1) is more straightforward than a validation of retrieved (or analysed) quantities (level 2). This is because the forward calculation to top-of-atmosphere (TOA) radiance from the geophysical profile is uniquely conditioned, whereas the solution to the inverse problem is always non-unique in that several distinct geophysical profiles can simultaneously satisfy a given TOA radiance measurement. It would therefore greatly facilitate satellite to non-satellite validation activities were the non-satellite reference measurements and their uncertainties able to be transformed into TOA radiance equivalents and uncertainties in radiance units. This, in turn, requires knowledge of the vertical, horizontal and/or temporal correlation structures present in the non-satellite reference measurement and any covariate information that may affect the implied TOA radiation (e.g. aerosol, clouds, surface emissivity, albedo, spectroscopy, surface height). It almost inevitably requires recourse to NWP analyses to fill gaps.

GAIA-CLIM has developed such a TOA radiance simulator capability - the GRUAN processor – for radiosonde profile measurements as a proof of concept. The tool is able to simulate measurements for many satellite instruments that are sensitive to temperature and/or humidity operating in the infrared and microwave spectral ranges consistent with GRUAN radiosonde profiles and their uncertainties via a fast RT model and ingestion of NWP fields. This provides a working model that would enable development of similar tools for measurements arising from other non-satellite reference quality measurements (including those from other domains such as the ocean, cryosphere etc.). Further development of the concept is required in the following ways:

- Uncertainty covariance information from the non-satellite measurements needs to be made available and used appropriately within applications that convert from geophysical profile data to TOA radiances
- Extension to other data of demonstrated quality, such as selected radiosondes and GNSS radio occultations, in order to sample a larger subspace of NWP regimes.
- Exploitation of ensembles from NWP and reanalysis systems

2.5 Understanding and quantifying irreducible co-location mismatch effects

10. Improve the basis for assigning co-locations and quantifying rigorously the associated uncertainties, including steps towards operational provision of co-location uncertainties

Atmospheric fields of ECVs vary in space and time, both at the scale of the individual measurements, and at the scale of the co-locations between multiple measurements, leading to additional terms in the uncertainty budget of a validation or intercomparison exercise. Those additional terms often have the same order of magnitude as -or even exceed - the combined uncertainty of the measurements being compared. Their amplitude depends on the actual 3-D/4-D spatio-temporal sensitivity of each measurement (i.e. the smoothing properties); on the spatio-temporal sampling properties of satellite instrument and ground-based network; the spatio-temporal variability of the geophysical property being measured; and on the co-location criteria for the selection of measurements to be compared. Inevitably, decisions have to be made as to the ‘acceptable’ degree of co-location mismatches, which arise from both smoothing and sampling, and the remaining co-location uncertainties need to be quantified. In practice, co-location methods and criteria are often based on community habits and are rarely optimized, with only a few pioneering studies that have quantified co-location mismatch uncertainties.

Dedicated studies comparing and exploring in detail the advantages and disadvantages of several co-location methods and criteria are required. Remaining (irreducible) co-location mismatch uncertainties can be estimated either from Observing System Simulation Experiments (OSSEs) with explicit description of the 3-D/4-D sensitivity of the measurements to the atmospheric variability, or by statistical modelling on the measured differences. These approaches were explored successfully for selected pilot ECVs and measurement instruments within GAIA-CLIM and elsewhere (e.g. double differencing in a data assimilation setting). They need now to be further elaborated and extended to other ECVs and measurement techniques. Climatological behaviour of the derived co-location uncertainties can be used to infer look-up tables of expected co-location mismatches for real-time applications, and in the longer-term with methodological and computational innovations it should be possible to operationalise the provision of measurement-specific co-location uncertainties under either approach.

2.6 Provision of user tools that enable exploitation

11. Operationalise co-location match-ups, extraction and visualisation tools, such as the GAIA-CLIM Virtual Observatory, to facilitate user access to satellite to non-satellite match-ups

Users need to be able to discover, access, manipulate and ultimately apply co-location match-ups with confidence if the value of the non-satellite EO segment to satellite EO measurements is ultimately to be realised. One or more means of accessing co-location match-ups and attendant information to enable robust scientifically based inferences are required. This set of tools must be operational, such that any innovations in underlying tools and capabilities will be encouraged and seamlessly integrated into the facility. Historically, such tools have tended to be piecemeal, project based and limited in consideration to either a subset of ECVs or a subset of the space program, or both. This lack of integrated user tools has served to inhibit the uptake of non-satellite measurements to characterize satellite observations.

An operational facility is required that considers all relevant satellite missions, a broad suite of ECVs, level 1 and level 2 data products plus comparisons, and enables a versatile range of tools to guide users to make appropriate choices. These analysis tools must have flexibility, such as interchanging the reference in a comparison and the ability to perform analyses at different time and eventually space scales. Visualisation tools need to be capable of displaying geographical co-location discovery, and multiple co-located parameters to circumvent the complexity of comparing datasets of varying types and geometries, e.g. time series and instantaneous, spatially localised and large spatial extent observations, column-integrated observations and vertical profiles, etc. Special attention must be paid to the specification of graphical representation of individual parameters and various uncertainty measures.

The GAIA-CLIM Virtual Observatory, as it has been delivered, constitutes a proof-of-concept and is not updated in near-real-time. Many other ECV reference measurements / satellite data combinations exist, e.g. for terrestrial and oceanic ECVs that were outside the scope of the GAIA-CLIM project. But these could be accommodated via operationalization and extension of the Virtual Observatory or a similar service in the future. Such an operational service should involve unified access to the underlying reference quality non-satellite measurements used.

3. Summary

3.1 Summary of recommendations

A total of 11 recommendations have been prepared and presented, which cover a broad range of potential avenues to improve the future utility of non-satellite segment observations to characterise satellite observations. The recommendations cover a range of thematic areas and also a range of types of work, timescales, costs and plausible actors. Taken together, if enacted, they would enable a step-change in our collective ability to utilise the non-satellite data segment to characterise future satellite missions. Several recommendations would also permit better understanding and exploitation of existing observations. The recommendations, while they cover a broad range of work, are not intended to be holistic. Nor are the recommendations necessarily the only plausible pathway to addressing the underlying issues identified. Users interested in a given recommendation are strongly encouraged to read and use not just the associated detailed trace in Annex 1 but also the much richer set of information presented in the associated gap traces referred to in Table 1 arising from the underlying GAID.

Although specifically a deliverable to the European Commission, the recommendations should have applicability to other European entities (such as ESA, EUMETSAT, ECMWF and EEA), national agencies and other international interested parties and agencies. GAIA-CLIM shall endeavour to share broadly this final version of the document in the hope that it provides a basis for future decision making in this domain of Earth Observation science.

3.2 A cautionary note: Maintaining existing critical capabilities

The danger inherent in any exercise that creates a set of recommendations is that, in reality, there is a finite financial resource available to support Earth Observation related activities. Hence, to fund a given recommendation one option is to reduce available funding elsewhere. While, undoubtedly, there are real cases where such a reallocation is possible without a deleterious effect on fundamental observational and analysis capabilities, this clearly cannot be guaranteed. Particularly with a view to climate applications, great care must be taken in deciding how to allocate resources to support the recommendations herein without placing existing capabilities in unnecessary jeopardy. If in enacting a recommendation, the net effect is to cause new unintended issues that then require to be addressed, then little if any additional value shall have accrued. There is always a case to be made for funding something new and exciting, whereas the case to continue funding key long-term capabilities is often harder.

3.3 Common themes

Finally, there are common themes that underpin very many of the recommendations and the gaps from which they arise:

- If the true value of the multi-billion-Euro space-segment Copernicus program and those of other satellite agencies is to be realised, then due attention to, and commensurate resource allocation is required for the ground segment and tools that enable a comparison of the two. The presence of a high-quality ground segment should not be taken as a given by those funding the space segment activities. National and project budgets that typically support the ground-segment are not secure and lead to piecemeal investment decisions that do not tend to serve well uses such as satellite cal/val, which requires a sustained and coordinated approach.
- As we improve both space-based and ground-based measurement capabilities, a better understanding of hitherto ignored effects is becoming increasingly important. There is therefore an increasing need to focus on areas of investigation which have received scant recent attention.
- Realising the full value of the Copernicus program investment requires a mix of training, innovation, governance, technological and underpinning scientific investigation activities on a long-term and sustained basis, as well as the active coordinated engagement of industry, academia and the research community.

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Annex 1: Detailed traces of recommendations

The recommendations build directly upon the underlying GAID process, which has iteratively collected and refined an analysis of gaps in knowledge and capabilities throughout the course of the three-year GAIA-CLIM project. The template for each recommendation trace is formatted as follows:

- The title clearly and succinctly lays out the nature of the recommendation.

- Next, we delineate those underlying GAID gap traces which have informed the recommendation and form the initial basis for the text herein. The recommendation in each case should be interpreted together with the identified underlying gap traces in the GAID. In the majority of cases, the recommendation arises from multiple underlying gap traces, in which case this field contains multiple gap identifiers and titles. The gap traces can be found either in the 5th and final version of the GAID or online at http://www.gaia-clim.eu/page/gap-reference-list and searched via http://www.gaia-clim.eu/cross-section-search?Submit=Search+along+cross-section

- Then, we highlight the nature of the issue to be addressed. This information is distilled from Sections 1 and 2 of the underlying gap traces from which the recommendation arises and serves to give a flavour of the nature of the problem/challenge to be addressed (Section 1) and the potential risks and benefits (Section 2).

- Finally, we summarise one or more possible pathways to resolution and the likely funders and / or actors, costs, and timescales. This information arises from Section 3 of the underlying gap traces, which in all cases contain one or more proposed remedies. By necessity, only a subset of the remedies have been included. The reader is encouraged to consider the rich information in the underlying gap traces in addition.

1. Maintain and further develop a workforce competent in EO data characterisation and downstream applications to support Copernicus activities

Underlying gap traces of relevance

G6.12 - Under-capacity of workforce to exploit satellite data and satellite characterisation

Issue to be addressed

While it is necessary to address technical and organisational issues that reduce the availability, effectiveness and quality of satellite characterisation data, doing so is moot unless there is sufficient capacity, both in terms of personnel, but also critically skills, to develop and deliver products and services to the marketplace. If Copernicus Services are to realise their full potential, additional training through formal and informal routes is required to train the next generation of data providers, analysts and users with the skills and insights that can be used to fully exploit the substantive investment in space-based and non-space based observational assets. Thus allowing Copernicus to deliver the envisaged step-change in capabilities and services.

Risks to non-resolution:

- Lack of capability to uptake and use Copernicus data services;
- Long-term operational programs compromised;

Benefits to resolution:

- Innovative research and product development;
- Increase in practitioners capable of delivering user services

Possible pathways to resolution

Enhanced provision of academic courses and training at tertiary level

The exploitation of Copernicus data and services requires the training of a competent workforce of data providers, analysts, managers and service provision experts. This requires a substantial increase in the number of relevant degree programs at undergraduate, masters and PhD levels across member states. Via the Copernicus academy system, ERASMUS+ or other avenues innovative teaching courses could be pursued and shared to help develop competency in use of Copernicus data to derive products and services including the use of satellite and non-satellite data and their appropriate synthesis.

Perhaps most acute is training at the doctoral level which provides the next generation of expert scientists capable of maintaining and improving the observational program and driving innovative analysis. In many countries within Europe there is very limited, if any, access to doctoral funding program support for Copernicus relevant activities. There hence exists a looming expert capability capacity issue as the existing EO expert workforce is not being adequately refreshed to account for career changes and retirements. Many of the gaps and remedies identified by both GAIA-CLIM through its GAID and elsewhere are amenable to doctoral thesis type work. Doctoral studentships are relatively inexpensive and offer an opportunity to explore issues in depth, including possible high-risk high-reward proposed work. A targeted doctoral program addressing questions of mutual interest to host institution and Copernicus would facilitate the provision of a sustainable programmatic capability while simultaneously better engaging academia across all member states, including academic institutions which have traditionally not had high participation in Copernicus-related activities within the programmatic structure of Copernicus.

Viability: High

Timebound: Continuous

Scale: Individual / single institution (per project / course but with potential synergistic aspects)

Investment: Dependent upon scale of ambition

Potential funding actors: Copernicus funding, national funding agencies

Potential actionees: Universities and academic not-for-profits

Instigation and roll-out of a formal qualification of professional competency in Copernicus EO-related service provision

For Copernicus services to be effective requires users to be able to access recognised practitioners in the marketplace, with confidence about the quality of the service to be provided. Currently such a means of recognition does not exist. Such recognition may result from a combination of proof of prior service engagement with users and / or formal training course(s) attendance. Service providers should show competency in accessing relevant observational data and products, their appropriate fusion, and the provision of advice to the user. A Copernicus service provision certificate could be provided by one or more accredited institutions providing training in required competencies with appropriate assessment. Training should be provided in a range of languages and need not be limited to the European domain.

Viability: High

Timebound: Three years to develop, continuous revision and deployment

Scale: Individual / single institution (per course but with potential synergistic aspects)

Investment: <5 million euros (but dependent upon degree of ambition)

Potential funding actors: Copernicus funding, national funding agencies

Potential actionees: National Meteorological Services, ESA, EUMETSAT, Space agencies, Academia, SMEs/industry, National Measurement institutes, existing summer and winter schools (e.g. ESA, ERCA) and grants (e.g. ACTRIS TNA grants)

2. Improve the metrological characterisation of non-satellite measurement techniques: Striving for traceable, reference quality, fiducial measurement series

Underlying gap traces of relevance

G1.10 - Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons
G2.08 - Need for a metrologically rigorous approach to long-term water vapour measurements from Raman lidars in the troposphere and UT/LS
G2.11 - Lack of rigorous tropospheric ozone lidar error budget availability
G2.12 - Lack of rigorous pure rotational temperature lidar error budget availability limits utility for applications, such as satellite characterisation
G2.13 - Missing microwave standards maintained by National/International Measurement Institutes
G2.18 - Better agreement needed on systematic and random components of the uncertainty in FTIR measurements and how to evaluate them
G2.22 - FTIR cell measurements carried out to characterize Instrument Line Shape have their own uncertainties
G2.26 - Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27 - Lack of understanding of random uncertainties, Air Mass Factor calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30 - Metrologically incomplete uncertainty quantification for Pandora ozone measurements
G2.31 - Incomplete metrological understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements
G2.36 - Lack of traceable uncertainties in MWR measurements and retrievals
G5.07 - Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems

Issue to be addressed

Formal closure of a comparison of any two measurement systems requires, as an absolute minimum condition, that the uncertainty in at least one of the two measurement systems be metrologically rigorously quantified and traceable either to SI or community standards (fiducial reference quality). Presently, there exists a relative paucity of such measurements either for the satellite segment, or for the non-satellite segment. Despite substantial progress under GAIA-CLIM and by related networks / programs / projects such as QA4ECV, FIDUCEO and ACTRIS, work remains to be done to develop metrologically traceable estimates and propagate their operation for a broad suite of satellite and non-satellite measurement techniques.

Non-satellite techniques have the advantage of being accessible to allow calibration, maintenance etc. and in many cases already are available and making/providing high-quality measurements. The missing link is assuring traceability in processing back to SI or community standards and quantifying the associated uncertainties. Work Package 2 of GAIA-CLIM has worked on six measurement systems (Lidar, MWR, FTIR, UV/vis, MAX-DOAS, and GNSS-PW). The gaps arisen speak solely to these techniques, but give a good flavour of the range of issues and challenges that exist. There are, however, many additional measurement techniques that can, in principal, be developed further.

Risks to non-resolution:

- Restricted set of reference quality non-satellite observations suitable for satellite

characterisation persists.
- Currently unrecognised or unquantified uncertainties in measurement systems remain, reducing their utility.
- Heterogeneity in observing techniques and processing chains persists reducing comparability of non-satellite systems.

Benefits to resolution:
- Improved metrological characterisation of measurements leading to better services and measurement system innovations.
- Increased pool of reference quality measurements for satellite characterisation with improved coverage.

Possible approaches to address

Sustained program to improve metrological characterisation and qualification of potential fiducial reference quality measurement systems

To realise the full benefits of existing measurement capabilities a sustained program is required to improve their metrological characterisation, attaining fully traceable reference quality measurements where possible and practicable. The work needs to bring together manufacturers, measurement networks, metrologists, and experts in each measurement system to be considered. As evidenced by the extensive articulation of gaps associated with this recommendation the specific short-comings in current understanding are highly instrument specific. Nonetheless, there exist essential core requirements of:
- understanding the measurement processing chain / measurement equation(s),
- quantifying measurement and product uncertainties,
- ensuring comparability of measurement operations between locations, instruments, and techniques,
- consistent processing of the data streams across all contributing instruments / series.

This suggests that significant synergies would be gained from consideration of the metrological qualification of a range of measurement techniques under a common programmatic effort. Ideally this effort would consider not just atmospheric domain measurements but also cryospheric, oceanic and terrestrial domains. An alternative would be more piece-wise approaches on an instrument-by-instrument or network-by-network basis.

Viability: Medium to high

Timebound: >5 years

Scale: Consortium / Programmatic multi-year, multi-institution activity

Investment: High >10 million euros (depending upon ambition)

Potential funding actors: EU H2020 funding, Copernicus funding, National Funding agencies, ESA

Potential actionees: National Measurement Institutes, National Meteorological Services, Academia, individual research institutes, SMEs / industry, WMO, existing measurement networks

3. Augment and consolidate existing spatial coverage of fiducial reference quality observational networks to be more globally representative, including a range of surface types and climate zones

Underlying gap traces of relevance

G1.10 - Relative paucity and geographical concentration of reference quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons
G2.06 - Current poor spatial coverage of high-quality multi-wavelength lidar systems capable of characterising aerosols
G2.10 - Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G4.12 - Lack of reference quality data for temperature in the upper stratosphere and mesosphere
G6.02 - Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services

Issue to be addressed

Limited spatial availability of fiducial reference observations with traceable uncertainty estimates limits their direct applicability to high-quality applications such as satellite data characterisation, model validation and reanalyses. What fiducial reference quality measurements exist tend to be geographically concentrated in Northern Hemisphere mid-latitude land regions. There is a paucity of such measurements in South America, Africa, parts of Asia and remote island locations. Numerous climatic zones and surface scene types (important for satellite instruments with substantive sensitivity to surface characteristics) are poorly sampled. For example, to characterise Microwave measurements there is a critical need for measurements over ocean scenes. In order to achieve progress, it is critical to have sufficient coverage of fiducial reference quality data records that are stable over time, across the various methods of measurement, uniformly processed worldwide, and traceable to calibration standards. This will allow us to establish the robust scientific basis for using such data as a transfer standard in satellite dataset characterization and other activities, such as trend analysis, and for assessing the cost-effectiveness of potential observing system enhancements.

Risks to non-resolution:

- Restricted set of reference quality observations persists
- Continued lack of strategic placement of research infrastructure leading to diminished scientific value across the range of application areas.
- Threat to instrument long-term continuity arising from not realising full value of assets
- Reduced ability to bridge across catastrophic satellite failure or to manage changes in satellite missions.

Benefits to resolution:

- Improved characterisation of state of atmospheric column characteristics at well-located sites
- Improved capacity in areas where observational capabilities have traditionally been weak or non-existent

Possible approaches to address

Expand and reconcile reference network capabilities to improve spatial representativity and sampling completeness

Reference networks need to work both together and with donors and partners to pro-actively increase the number of locations and volume of data arising from data sparse regions. Examples of twinning (e.g. KNMI and Paramaribo, MeteoSwiss and Nairobi, MeteoFrance at La Reuniòn), the recent ESFRI infrastructures, and targeted programs (e.g. SHADOZ) exist as potential working models of means to initiate and maintain long-term capabilities in such regions. These are not necessarily the only potential models, and alternatives should also be investigated. Regardless of the exact mechanism, such solutions require a long-term commitment at international, regional, national and local levels. They include training, provision of equipment and logistical support and provision of expendables. Successful programs have generally required a partnership with the host country / institution and this also speaks to the need for a capacity building component through education and training. Europe through historical ties with many of the target countries and regions in question could take a leading role in the action required to enact this remedy.

Robust assessments of the impacts of geographical spatial and temporal gaps in the availability of fiducial reference quality measurement systems are required to inform expansion. GAIA-CLIM has developed model and statistically-based techniques to evaluate these issues for a restricted subset of networks and ECVs. Similarly, other assessments have been undertaken elsewhere. But, historically, these have variously considered a subset of ECVS and / or networks. What is required is a holistic assessment approach that considers the issue across the range of fiducial reference quality networks and ECVs. In assessing against competing stakeholder needs a robust means to quantify the cost-benefit trade-offs of different measurement capability expansion options (including both locations and scheduling of measurement strategies) that considered the problem more holistically (across ECVs and networks) would lead to more optimal configurations (or reconfigurations) of networks (this is intrinsically linked with Recommendations 4 and 6). Specifically, such reviews would lead to steps towards consolidation of facilities where a clear benefit to multiple data stakeholders is identified. The analysis may be facilitated by activities such as OSSEs, short period field campaigns, investigation of underexploited datasets collected in the past, or other activities which permit a quantitative assessment of the benefits of co-locating capabilities. It may also make use of a number of existing highly instrument rich sites.

Viability: Medium to high

Timebound: less than 10 years to implement, long-term for operation

Scale: Programmatic multi-year, multi-institution activity

Investment: >10 million euros

Potential funding actors: EU H2020, Copernicus, WMO, ESA, EUMETSAT or other space agency

Potential actionees: National meteorological agencies, National measurement institutes, academia, individual research institutes, SMEs / industry, WMO, space agencies

4. ## Improve time scheduling coherency of satellite and non-satellite measurements to minimise the need to account for co-location uncertainty effects

Underlying gap traces of relevance

G5.11 - Non-operational provision of reference measurement data and some (L2) satellite products reduces their utility for Copernicus operational product monitoring
G6.03 - Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06 – Provision of reference-quality measurements where technically feasible on a continuous basis, to maximise opportunities for the validation of satellite and derived products

Issue to be addressed

There are many non-satellite measurement systems that, in principle, can be used for the purposes of satellite characterisation on a sustained basis. However:

1. Many of the measurement systems are by necessity periodic, such as balloon-borne measurement systems, and in such cases their scheduling is often made without specific regard to satellite overpass times.
2. Many other instruments such as various lidar and FTIR instruments have the potential to be operated on a sustained and continuous basis, taking measurements whenever geophysically possible, and thereby maximising opportunities but for various reasons - including scientific, technical, operational, organisational and financial reasons - this potential has not been fully realised to date.

Risks to non-resolution:

- Insufficient number of high quality co-locations in the future that meet co-location match-up criteria to meaningfully constrain (at least some) satellite missions.
- Inability to use non-satellite segment to effectively bridge across any unplanned gap in spaceborne EO capabilities.
- Reduction in perceived utility and value of measurements leading to reduction in funding.

Benefits to resolution:

- Better intra-satellite and inter-satellite data characterization using the ground segment through increased pool of co-locations to common non-satellite tie-points.
- Operational quality control and delivery of non-satellite reference measurements would allow for better characterisation of satellite and reanalysis products offered in close to real time and vice-versa.

Possible approaches to address

Schedule observations that can be made only intermittently to better match satellite overpass

Sustained funding and governance mechanisms need to be instigated and assured that optimise the observational scheduling of relevant high-quality non-satellite measurements and their provision for satellite characterisation while simultaneously avoiding deleterious impacts on other operations and data users. To be effective space agencies and non-satellite high-quality observing networks need to work together to design, instigate and fund a sustained program of targeted measurements. The scientific benefits will be maximised if a strategy can be devised which optimizes the ability of the non-satellite data segment to characterize satellite instrument performance (and vice-versa) across time, across platforms and across instrument types. This, in turn, points to individual non-satellite observational segments being tasked with helping to characterise across multiple satellite missions, rather than this support being extended and decided on a per mission basis. Care must be taken for any changes not to impact deleteriously upon existing functions and purposes of the non-satellite segment. This implies that in at least some cases the remedy will need to involve funding support commensurate with undertaking new or additional measurements that supplement rather than replace existing capabilities. Examples of such dedicated campaigns include the ongoing JPSS validation campaign being undertaken at the ARM facility Southern Great Plains site.

Viability: High

Timebound: Under 10 years to instigate, continuous for operations

Scale: Programmatic multi-year multi-institution

Investment: Medium cost (<5 million) with annually recurring costs thereafter (cost per site / measurement are significantly lower)

Potential funding actors: Copernicus, National Meteorological services, ESA, EUMETSAT, other satellite agencies

Potential actionees: National Meteorological Services, Satellite agencies, Academia, SMEs/industry, observational networks, WMO

Operationalise the measurement programs and data exchange for measurements that can be made continuously

The work required will be specific to individual cases. But, in general, it requires an assessment on a per instrument and per site basis of the current impediments to continuous operation and time-bounded provision of the measurements from the asset. Once reason(s) underlying are known then work can be undertaken to address which shall typically include:

- Technical innovations or modifications to the instrumentation to enable continuous operations
- Modifications to instrument housing
- Funding increases to enable continuous operation

Resolution of these issues shall require the participation of instrument scientists, site operators, networks and funding agencies. An initial holistic survey may identify the impacted instruments and help inform prioritization of targeted sites and / or instruments.

Viability: High

Timebound: Under 5 years (dependent upon ambition)

Scale: Programmatic multi-year multi-institution (although resolution of each issue is single institution / small consortium)

Investment: More than 10 million to solve global issues, much smaller on individual cases

Potential funding actors: National funding agencies, National Meteorological Services, ESA, EUMETSAT and other satellite agencies

Potential actionees: National Meteorological Services, National Measurement Institutes, Academia, research institutes, SMEs/industry, observational networks, WMO

5. Instigate and sustain time-bounded access to a comprehensive set of harmonised fiducial reference data and metadata holdings under a common data model and open data policy that enables interoperability for applications

Underlying gap traces of relevance

G1.06 - Currently heterogeneous metadata standards negatively impact data discoverability and usability

G5.01 - Plethora of data portals serving data under distinct data policies in multiple formats for reference quality data inhibits their discovery, access and usage for applications such as satellite Cal/Val

G6.07 - Distinct data policies across different networks harm the use of complementary data from different networks

Issue to be addressed

Presently, access to high-quality reference network data is obtained through a variety of portals, using a broad range of access protocols and the data files are available in an array of native data formats adopting different standards that compromises their interoperability. Metadata protocols are also diverse which substantially inhibits both discoverability and understanding. Finally, there also exists a broad range of data policies from open access through delayed mode restricted access. To make effective usage of the full range of reference quality measurements, e.g., for the characterisation of satellite data therefore presently requires substantial investment of time and resources to instigate and maintain a large number of data access protocols, processing software, and to fully understand and adhere to a broad range of data policies and data access modalities (NRT, delayed mode, periodic, ad hoc). To make matters worse, portals, formats, metadata and data policies are subject to periodic change requiring a constant maintenance overhead on any applications that use data from a range of contributing networks. Thus, the current situation is a substantial impediment to their effective usage in applications such as satellite data characterisation.

Risks to non-resolution:

- Continued impediments to interoperability between networks and communities
- Continued need for repeated development of bespoke data format conversion tools
- The use of multiple locations with different setups for data access continues to complicate work on data comparison and increases cost to delivery and analysis / exploitation of data
- Certain data sets remain hidden for some time or fully unexploited

Benefits to resolution:

- Access to reference measurements organised via a brokering system service makes discovery and access easy.
- Full data interoperability and availability of full metadata records for reprocessing of CDRs
- Increase in the usage of multiple non-satellite datasets for research study, operational and downstream services.
- Enable cross-validation between observing platforms and with models

Possible approaches to address

Instigate and maintain a single point of access service to reference quality non-satellite data holdings

The C3S 311a Lot 3 service contract, if successful, shall make considerable strides in enabling the users' access to harmonised reference and baseline data, metadata and time series from a subset of in-situ networks data available under a common data model and with clear articulation of data policies that enables appropriate and seamless usage of data arising from multiple contributing networks and data streams. Work is envisaged to cover aspects of

- data access brokering,
- data and metadata harmonisation under a common data model, and data provision
- Harmonization of time series through the implementation of physically and statistically based adjustment applied to the measurements
- Provision of ancillary products to support the data interpretation

The work program builds upon many aspects of work within GAIA-CLIM. Data shall be served via the CDS facility of C3S. The work is funded through 2018 with extension to 2021. However, the service development is limited to accessing data from a limited number of atmospheric networks and a subset of atmospheric Essential Climate Variables within the current contract period. It also does not consider access to observational campaign data So, in the longer-term extension would be required to additional atmospheric ECVs and the oceanic and terrestrial ECVs measured in-situ, and to access to campaign data as required for satellite cal/val.

Viability: High

Timebound: Less than 5 years (current activity); Less than 10 years (extension)

Scale: Programmatic multi-year, multi-institution activity

Investment: Medium cost (<5 million)

Potential funding actors: Copernicus (funded initial work), satellite agencies, national agencies

Potential actionees: National Meteorological services, WMO, academia, research institutes, SMEs / industry, GEO

Advocate with reference quality networks for adoption of open data policies

An open data policy for all networks in line with the new European policies for Copernicus and the US data policies that are already generally open, would be of great benefit. The open data policy that is applicable to the Copernicus program including the Sentinel missions should be the model which all networks, data centres, satellite agencies should adopt. This is a political (and economic) decision, but it must be made clear to the data providers that there is a benefit for them and they must be assured that the data acquisition is secured by their funding organisations, and that they get credit for their data.

Viability: Medium to high

Timebound: Less than 5 years

Scale: Institutional

Investment: Low cost (<1 million)

Potential funding actors: WMO, Copernicus, Satellite agencies

Potential actionees: Observing networks, WMO, National meteorological services, research institutes, academia

6. Take steps to reassess, rationalise and improve coordination of high quality observing networks

Underlying gap traces of relevance

G1.03 - Lack of internationally recognised and adopted framework for assessment of fundamental observation capabilities
G1.04 - Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs across domains
G5.01 - Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access and usage for applications, such as satellite Cal/Val
G6.01 - Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.02 - Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services

Issue to be addressed

Current governance of high-quality measurement programs is highly fractured. There is also no agreed set of best practices or set of criteria by which to assess networks. This dispersed governance and lack of coordination leads to decisions which, although sensible on an individual network basis, are sub-optimal on a more holistic basis. This fractured governance both results from but also augments a diversity in historical and present-day funding support, authority, and observational program priorities. Inevitable deleterious results accrue from a fractured governance and support mechanism which include:

- Geographical dispersal of capabilities
- Heterogeneous processing choices
- Heterogeneities in measurement technique practices
- Competition between otherwise synergistic activities
- Different networks take different approaches to data processing and serving which reduces both accessibility to and comparability of the resulting data.

As such many of the remaining recommendations as well as the gaps identified within the GAID are symptoms of this issue remaining unaddressed.

Risks to non-resolution:

- Continued fractured governance leading to sub-optimal management and development of high-quality measurement networks.
- Reduction in funding opportunities for high-quality measurements owing to fractured and competing demands.

Benefits to resolution:

- More unified voice for non-satellite data management
- More efficient use of resources
- Consistency of data provision

Possible approaches to address

Improve cross-network governance coordination

Strengthen existing efforts to ensure meaningful collaboration between potentially synergistic or complementary networks and research infrastructures. This could be achieved via several means. Improved cross-governance group representation could be implemented between networks that have similar aims / remits which may start to enforce a degree of collaboration and cross-fertilisation of best practices. A more formal approach, which may be relevant in certain cases is a more formal network memoranda of understanding. On a more practical and working level, synergies can be realised through involvement in joint research and infrastructure activities such as Horizon 2020 and Copernicus grants and service contracts and similar activities outside of Europe. An example is represented by ENVRIplus Horizon 2020 project bringing together Environmental and Earth System Research Infrastructures, projects and networks with technical specialist partners to create a more coherent, interdisciplinary and interoperable cluster of Environmental Research Infrastructures.

Viability: High

Timebound: Less than 3 years

Scale: Programmatic multi-year, multi-institution activity

Investment: Low cost (<1 million)

Potential funding actors: Copernicus, WMO, satellite agencies, National meteorological services, national funding agencies

Potential actionees: Observing networks

Longer-term rationalisation of observational network governance

Take steps to assess and as necessary rationalise the number of networks involved in taking high-quality measurements by merging where possible, leading to more unified governance and planning for these measurement programs both regionally and globally. To undertake this robustly requires an initial analysis of the current observational capabilities and governance structure which should take into account funding, geopolitical, network remit and other relevant factors. This may be facilitated by undertaking an agreed assessment against quantifiable criteria that identifies to which tier in a system-of-systems approach each network contributes. It may also include in-depth survey interviews and other means to fully understand the role, support-model, and uses of each network. Then a rationalisation plan would need to be produced, circulated and gain broad buy-in amongst the affected networks and associated global oversight bodies. Mergers should only proceed on a no-regrets basis and should not be enforced if funding support or other essential support would be weakened as a result of the decision. Merged entities must be scientifically more robust, complete and sustainable.

Viability: Medium

Timebound: More than 10 years

Scale: Programmatic multi-year, multi-institution activity

Investment: Medium cost (<5 million) to undertake analysis. Currently unknown cost / benefit from implementation

Potential funding actors: Copernicus, H2020, National funding agencies, WMO, satellite agencies

Potential actionees: Observing networks, WMO, satellite agencies

7. Improve knowledge of fundamental spectroscopy and undertake associated innovations in radiative-transfer modelling

Underlying gap traces of relevance

G2.26 - Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27 - Lack of understanding of random uncertainties, Air Mass Factor calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.37 - Need for more complete metrological characterisation of spectroscopic information

Issue to be addressed

The vast majority of satellite monitoring of the Earth occurs via either passive or active measurement techniques, where the fundamental measurement is a radiance spectrum in some narrow portion of the EM-spectrum. Molecular spectroscopy provides the primary link between a given radiance and the underlying atmospheric gaseous composition and its properties. Fully traceable knowledge of the spectroscopic properties of a given measurement could, in theory, provide a route to formal traceability for that measurement. The exact nature of the influence of spectroscopic uncertainties on the derived ECV products will vary according to the spectral region being measured and the specific details of the measurement technique being employed.

So, spectroscopic knowledge limitations if left unaddressed, serve to compound many other issues inherent in a satellite to non-satellite comparison. Hence, there would be a clear benefit in steps to improve spectroscopic knowledge that identifies and disseminates common issues and solutions, including a harmonised process for dealing with spectroscopic uncertainties and establishing spectroscopic traceability. Historically, such uncertainties have been dwarfed by uncertainties in satellite and non-satellite measurement techniques and co-location impacts. As improvements have occurred in these, spectroscopic uncertainties have become more acute, particularly so in certain spectral bands such as off-wing measurements of the 183 GHz line and 1-50 GHz region.

Spectroscopic parameters are also an integral part of radiative transfer (RT) codes which represent the cumulative contribution of all molecular transitions to the total atmospheric attenuation within the spectral range of interest. RT codes constitute the core of spectrometric physical retrievals, such as optimal estimation methods and fast RT models are widely used in data assimilation for Numerical Weather Prediction and reanalyses. Any data intercomparison/validation method that includes the use of RT codes will also be influenced by uncertainties in the underpinning spectroscopic parameters. Such uncertainties will contribute to the overall uncertainty of the data intercomparison, and could be the source of, potentially unexpected, correlation between different data sources if the same RT model is applied to both measurements.

Risks to non-resolution:

- If a coordinated activity is not carried out then the situation will remain as a series of separate activities linked to individual techniques / instruments with varied quality of spectroscopic information.
- The potential effects of correlated uncertainties in the comparison of results from different techniques due to spectroscopic issues are not identified.

Benefits to resolution:

- A robust and consistent approach to the handling of uncertainties and traceability in spectroscopic measurements would significantly extend the availability of reference quality data across a wide range of techniques and ECVs.

- An improved understanding of the common issues in spectroscopic measurements would identify sources of correlated uncertainties between different measurement and modelling techniques.

Possible approaches to address

Renewed focus upon the improved metrological qualification of spectroscopic information

Establishment of a top-level cooperation and networking activity is needed to coordinate and review spectroscopic uncertainty activities across the range of spectral regions and measurement techniques, but with a particular focus on spectral regions identified as constituting key current uncertainties such as 183Ghz and the 1-50GHz range, with the long-term goal of developing harmonised processes to establish spectroscopic traceability. This may be achieved either by a large-scale coordinated project or piecemeal for specific cases. A large-scale coordinated project approach would benefit from synergies and commonality of approaches and may be preferred. Experts in spectroscopy, metrology and the specific instruments would be required.

Spectroscopic measurements of sufficient quality for this task require specialised laboratory instrumentation and (for their interpretation) an in-depth knowledge of fundamental quantum chemistry. The establishment of databases such as HITRAN, GEISA and ATMOS has made strides towards a robust description of spectroscopic parameters; however, the availability of error estimates is incomplete and information on error covariances between parameters is lacking. Furthermore, it is known that the commonly-used Voigt line shape model is inadequate for some applications, yet more sophisticated line shapes are not in widespread use, leading to an additional source of uncertainty. It will be necessary to engage with the laboratory spectroscopy and line-by-line modelling communities to agree on appropriate standards and best practices.

The activity should aim to strengthen cooperation between those communities making laboratory-based measurements and the radiative transfer community. This is currently identified as being a weak link within the expert community that was highlighted on several occasions by roadshow event attendees.

Viability: Medium / High

Timebound: More than ten years

Scale: Programmatic multi-year, multi-institution activity

Investment: Medium cost (<5 million)

Potential funding actors: H2020, space agencies, Copernicus, National funding agencies

Potential actionees: National Measurement Institutes, National Meteorological Services, academia, research institutes, SMEs / industry

8. Improve quantification of the effects of surface properties to reduce uncertainties in satellite data assimilation and satellite to non-satellite data comparisons

Underlying gap traces of relevance

G4.08 - Estimates of uncertainties in ocean surface microwave radiative transfer

G4.09 - Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer

G4.10 - Incomplete estimates of uncertainties in land surface infrared emissivity atlases

Issue to be addressed

Numerous space-based remote-sensing observations sense the surface, and therefore are sensitive to surface emissions, albedo etc. The surface of the earth does not have homogeneous emissivity characteristics. Considering those portions of the radiance spectrum for which the atmosphere is relatively transparent, surface emissivity and its uncertainty can be the dominant source of uncertainty in how to analyse and utilise the satellite measurements. The accuracy of retrievals of atmospheric state variables and trace gas concentrations in these EM-spectrum regions is intrinsically tied to making improvements in handling these issues. Such measurements have high potential utility in NWP and reanalysis applications if this issue can be addressed.

Risks to non-resolution:

- High uncertainties associated with surface emissivity modelling persist
- Sub-optimal validation of new EO data that has high surface sensitivity

Benefits to resolution:

- Through lower cost, effective and timely validation of new surface emissivity sensitive missions, of which there are >10 planned over the next 2 decades.
- Greater ability to use affected satellite channels in applications

Possible approaches to address

Better understand differences between existing surface emissivity models

Undertake an in-depth intercomparison of available surface emissivity model outputs, for a carefully defined set of inputs. Differences identified and quantified can shed light on the sources of bias in any given emissivity model. This approach thus constitutes a useful first step in the validation of surface emissivity estimates. The exercise can be coordinated through the appropriate international working groups (*e.g.* International TOVS Working Group, International Precipitation Working Group, GSICS, X-Cal), and supported by national and/or international agencies.

Viability: High

Timebound: Less than 5 years

Scale: Consortium project

Investment: <5 million euros

Potential funding actors: H2020, national funding agencies, satellite agencies, national meteorological services

Potential actionees: National meteorological services, satellite agencies, academia, national measurement institutes

Development of reference models for microwave surface emissivity

For calculating the microwave ocean emissivity, the FAST Ocean Emissivity (FASTEM) model is used widely across Europe, including in the Copernicus C3S Reanalysis system. This model was derived from best fits to a Physically-based reference model which has since been lost. In order to both further improve the accuracy of FASTEM and to estimate uncertainties in the underlying assumptions, a new Physically-based ocean emissivity model needs to be developed. This should be supported by new, reference-quality laboratory measurements of the dielectric constant of seawater. The development of reference models for the land surface requiring physical inputs from either land surface models or remotely sensed variables is also needed. Unlike microwave ocean emissivity, the land surface emissivity is currently estimated in NWP and Reanalysis models using retrievals from satellite window channel observations. The development of accurate models for different land surface types would advance the scientific understanding of land surface emissivity and improve our ability to calculate the land surface emissivity uncertainty, including identifying the areas where uncertainty is high.

Viability: Medium

Timebound: Less than 5 years

Scale: PhD or post-doctoral student (dielectric constant measurements), Consortium project (emissivity model development)

Investment: <5 million euros

Potential funding actors: H2020, national funding agencies, national meteorological services

Potential actionees: National meteorological services, academia, national measurement institutes

Campaign based validation of and innovations to surface emissivity models

Typically, validation of emissivity models has been carried out using airborne (and over land ground-based) campaigns. To date these campaigns have not generally used traceably calibrated radiometers. However, primary reference standards are beginning to be developed. We propose using these traceably calibrated radiometers for field campaigns and in laboratory experiments. Note that the determination of emissivity will be reliant on sufficiently characterised co-located estimates (from models) or *in-situ* measurements, of relevant co-variates. Over land, such campaigns would need to be undertaken across a sufficiently diverse set of land surface types and meteorological seasons to provide representative results that enabled broad applicability. The campaigns should be targeted at regions of the spectral domain and surface types / seasons identified as being highly uncertain.

Viability: Medium

Timebound: Less than 5 years

Scale: Consortium project

Investment: <5 million euros

Potential funding actors: H2020, national funding agencies, satellite agencies, national meteorological services

Potential actionees: National meteorological services, satellite agencies, academia, national measurement institutes

9. Develop and provide tools that convert non-satellite fiducial reference quality measurements to Top-Of-Atmosphere radiance equivalents with associated rigorously quantified uncertainties

Underlying gap traces of relevance

G4.01 - Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity

G5.09 – Need to propagate various reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable robust characterisation of satellite FCDRs

Issue to be addressed

The validation of satellite measurements in terms of the measured radiance (level 1) is more straightforward than a validation of retrieved (or analysed) quantities (level 2). It would therefore greatly facilitate satellite to non-satellite validation activities were the non-satellite reference measurements and their uncertainties able to be transformed into TOA radiance equivalents and associated uncertainties. This, in turn, requires knowledge of the vertical and / or horizontal correlation structures present in the non-satellite reference measurements and any covariate information that may affect the implied TOA radiation (e.g. clouds, surface emissivity, surface height). There is currently no readily accessible, maintained, online tool (except for the GRUAN processor under development as part of GAIA-CLIM) that would enable the broader scientific community to contribute to the quality evaluation of satellite TOA FCDRs.

Risks to non-resolution:

- Lack of penetration, and acceptance, of proposed methodology (NWP, coupled to GRUAN, for the validation of meteorological EO data) into wider user community.
- Limited uptake of non-satellite data in satellite cal/val activities as comparisons not possible at level 1 radiance space.

Benefits to resolution:

- Integration of a forward radiative transfer capability into satellite validation activities enables direct comparison of satellite radiances to non-satellite reference measurements.
- The forward radiative transfer capability provides the potential for further development of general satellite cal/val facilities.

Possible approaches to address

Implement forward radiative transfer model capabilities to enable sustained satellite characterisation at Level 1 TOA radiances

GAIA-CLIM oversaw the development of the GRUAN processor that is able to simulate measurements for many satellite instruments operating in the infrared and microwave spectral ranges consistent with GRUAN radiosonde profile measures and their uncertainties via a fast RT model with NWP fields. This provides a working model that would enable development of similar operators for measurements arising from other non-satellite reference quality measurements (including those from other domains such as the Ocean, cryosphere etc.).

Viability: High

Timebound: Less than 5 years (development); Continuous (deployment)

Scale: Consortium / programmatic multi-year multi-institution activity

Investment: Low to medium cost (<5 million euros); development only

Potential funding actors: H2020, Copernicus, satellite agencies, national funding agencies

Potential actionees: national meteorological services, national measurement institutes, academia, research institutes, SMEs/industry

Improve knowledge of uncertainty covariance in reference quality non-satellite measurement techniques

Uncertainty covariance information needs to be made available and used appropriately within applications that convert from geophysical profile data to TOA radiances. Firstly, the profile information needs to contain the uncertainty and the correlation structure in a usable format. Within GAIA-CLIM simple parametrised versions of the vertical error covariances have been developed as a workaround. Alternative approaches based on methods routinely used to characterise errors in data assimilation systems should also be tested.

Viability: High

Timebound: Less than 3 years

Scale: Single institution / Consortium

Investment: Low cost (<1 million)

Potential funding actors: National funding agencies, H2020, National Meteorological services

Potential actionees: national meteorological services, national measurement institutes, academia, research institutes, SMEs/industry, observational networks

Evaluate quality of NWP and reanalysis fields through comparisons with reference data as a means of establishing direct traceability.

The GRUAN processor developed for GAIA-CLIM offers the means of traceable evaluation of the quality of NWP fields at the GRUAN site locations. It is proposed to extend the assessment of NWP fields using other data of demonstrated quality, such as selected GUAN radiosondes and GNSS radio occultations, in order to sample a larger subspace of NWP regimes. Additionally, NWP and reanalysis systems now make use of ensembles. uncertainties from which should be evaluated using available NWP minus reference data differences. It is also desirable to extend the assessment to include atmospheric composition, for which reference composition measurements and their uncertainties are required.

Viability: High

Timebound: Less than 5 years

Scale: Single institution / Consortium

Investment: Low cost (<1 million)

Potential funding actors: National funding agencies, H2020, National Meteorological services

Potential actionees: national meteorological services

10. Improve the basis for assigning co-locations and quantifying rigorously the associated uncertainties, including steps towards operational provision of co-location uncertainties

Underlying gap traces of relevance

G3.01 - Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and of their co-location
G3.02 - Missing standards for, and evaluation of, co-location criteria
G3.04 - Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.05 - Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements
G3.06 - Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences

Issue to be addressed

Many ECVs vary in space and time at the scale of the individual measurements, and at the scale of the co-locations between measurements, leading to additional terms in the uncertainty budget of a validation exercise, often comparable to -or even surpassing- the measurement uncertainties. These depend on the actual 3-D/4-D spatio-temporal sensitivity of each measurement to atmospheric variability and structures (i.e. the smoothing properties), on the spatio-temporal sampling properties of satellite instrument and ground network, and on the co-location criteria for the selection of measurements to be compared. Inevitably, decisions have to be made as to the 'acceptable' degree of such co-location mismatches, and the remaining (irreducible) co-location uncertainties need to be quantified. In practice, co-location methods are rarely optimized, and only a few pioneering studies quantify co-location mismatch uncertainties. Consequently, there exists a need to (1) better understand the full spatio-temporal sampling and smoothing properties of the measurements systems, (2) to quantify small-scale atmospheric variability, (3) to include co-location mismatch uncertainty in the total uncertainty budget of a comparison, and (4) to evaluate and optimize the adopted co-location methods and criteria so as to minimize the uncertainties while maintaining robust statistics sampling the full range of geophysical and instrumental influence quantities. Exploratory work has been undertaken within GAIA-CLIM for pilot ECVs and instruments, and they need now to be further extended to other ECVs and measurement techniques.

Risks to non-resolution:

- Incomplete uncertainty budget for comparisons limits utility of and confidence in satellite to non-satellite Cal/Val activities
- Poor feedback on data quality (in particular on the reported uncertainties) from validation studies due to unknown/unquantified influence of atmospheric variability.
- Difficulty to compare validation results on similar products obtained by different teams

Benefits to resolution:

- Improved understanding of the impact of the instrument smoothing and sampling properties
- Improved definition of appropriate co-location criteria for validation work, minimizing errors due to co-location mismatch.
- Improved interpretation of comparison results because co-location mismatch errors can be quantified.
- Facilitates intercomparison of different validation studies

Possible approaches to address

Instigate a more formalised and rigorous approach to co-location selection

Dedicated studies comparing and exploring in detail the advantages and disadvantages of several co-location methods and criteria are required, assessing the robustness and coverage of the resulting statistics, and the impact of co-location mismatch. It would be beneficial to establish first a generic protocol, and then to derive specific settings for each ECV. For studies requiring measurement expertise, working groups or activities could be set up within the framework of the ground-based networks. The establishment of such protocols as well as the dissemination among and acceptance by the key stakeholders may be challenging and can probably best be achieved in the context of overarching frameworks such as the CEOS Working Group on Calibration & Validation (WGCV). Also, the space agencies and service providers should insist on sufficient attention for co-location criteria and remaining co-location mismatch in the validation protocols followed by their validation teams.

Viability: High

Timebound: Less than 3 years

Scale: Consortium

Investment: Low (<1 million euros)

Potential funding actors: WMO, H2020, national funding bodies, satellite agencies

Potential actionees: Observing networks, National meteorological services, National measurement institutes, WMO, academia, research institutes

Use of dynamical model and statistical techniques to estimate co-location effects striving for operational service provision

Observing System Simulation Experiments (OSSEs) including explicit description of the 3-D/4-D smoothing and sampling properties of the measurements, such as those performed e.g. with the OSSSMOSE system, can be used to estimate co-location mismatch uncertainties. Implicit is the need for sustained research on small-scale atmospheric variability and instrument smoothing and sampling properties. An alternative to estimating co-location mismatch from such simulations, is to apply statistical models on the measured differences. In certain applications, this approach also allows one to disentangle measurement from co-location mismatch uncertainties. For either approach, climatological behaviour can be used to infer look-up tables of expected co-location uncertainties, and there should be a long-term goal to operationalise the provision of measurement-specific co-location uncertainties.

Viability: Medium to high

Timebound: Less than five years

Scale: Consortium

Investment: <10 million euros

Potential funding actors: H2020, Copernicus, Satellite agencies

Potential actionees: National meteorological services, National measurement institutes, academia, research institutes, SMEs / industry

11. Operationalise co-location match-ups, extraction and visualisation tools, such as the GAIA-CLIM Virtual Observatory, to facilitate user access to satellite to non-satellite match-ups

Underlying gap traces of relevance

G1.05 - Lack of integrated user tools showing all the existing observing capabilities for measuring ECVs with respect to satellite spatial coverage

G5.01 - Vast number of data portals serving data under distinct data policies in multiple formats for reference-quality data inhibits their discovery, access and usage for applications such as satellite Cal/Val

G5.06 - Extraction, analysis and visualization tools to exploit the potential of fiducial reference measurements are currently only rudimentary

Issue to be addressed

Users need to be able to discover, access, manipulate and ultimately apply co-location match-ups with confidence if the value of the non-satellite EO segment to satellite EO measurements is ultimately to be realised. One or more means of accessing co-location match-ups and attendant information to enable robust scientifically based inferences are required. This set of tools must be operational, such that innovations in underlying tools and capabilities can be seamlessly integrated into the facility and made available quickly. Historically, such tools have tended to be piecemeal and project based and limited in consideration to either a subset of ECVs, a subset of the space program, or both. This lack of integrated user tools has served to inhibit the uptake of non-satellite measurements to characterize satellite observations. The GAIA-CLIM Virtual Observatory, or other similar portals such as e.g. FRM4ST.org, if further developed could provide a more comprehensive facility considering a broad suite of ECVs, level 1 and level 2+ comparisons, and using a broad range of tools to guide users to make appropriate choices.

Risks to non-resolution:

- Lack of uptake of non-satellite EO data to characterise satellite data inhibits future investments for the EO.
- Non-satellite reference measurements will have limited value for the characterisation of satellite measurements leading to lower-quality satellite products than could, theoretically, be achievable and vice-versa.

Benefits to resolution:

- Users to be able to fully exploit the content of surface-based and sub-orbital data and metadata
- To provide user-friendly open-source tools in support of a powerful strategy to interact with users and communicate science
- Access to reference measurements co-located to satellite measurements in operational mode, in particular at level 1 could boost satellite retrieval development and comparison and applications e.g. NWP.
- Data extraction tools allow the export of data in user friendly formats.

Possible approaches to address

Operationalise one or more co-location discovery, analysis and visualisation tools such as the GAIA-CLIM Virtual Observatory

The diverse sources of reference quality non-satellite data need to be integrated and appropriately associated with the suite of satellite sensors and platforms, with resulting co-location data made available through one or more operational exploitation portals. GAIA-CLIM provides this via the Virtual Observatory for a selected set of atmospheric ECVs and associated TOA brightness temperatures. The Virtual Observatory has been developed to demonstrate the use of non-satellite reference data and NWP model data for the characterisation of satellite data. The Virtual Observatory achieves this through integrating the different measurements, their metadata, quantified uncertainty for the measurements, and the uncertainty arising from the comparison process. It contains a data extraction capability that allows the export of data from in user friendly formats such as NetCDF. Data extraction tools also are capable of sub-setting each data source contained in the co-location data base by ECV / Brightness Temperature, time and location, observing system and other boundary conditions such as surface type, clouds etc..

To exploit the co-location data base analysis tools must be developed to provide statistics and various indicators for a comparison that meet user needs. These analysis tools must have flexibility, such as interchanging the reference in a comparison and the ability to perform analysis at different time and space scales. Visualisation tools need to be capable of displaying geographical co-location discovery, and multiple co-located parameters to circumvent the complexity of comparing datasets of varying type and geometries, e.g. time series and instantaneous, spatially localised and large spatial extent observations, column-integrated observations and vertical profiles, etc. Special attention must be paid to the specification of graphical representation of individual parameters and the various relevant uncertainty measures.

But, the GAIA-CLIM virtual observatory as delivered taken together with other relevant precursor and ongoing programs (e.g. NORS, QA4ECV, ESA SSP MPC) constitutes a proof-of-concept and is not updated in near-real-time. Many other ECV reference measurements – satellite data combinations exist, e.g., for terrestrial and Oceanic ECVs which are as yet not addressed by such tools. But these could be accommodated via operationalization and extension of such a co-location service in the future. Such an operational service should involve unified access to the underlying fiducial reference quality non-satellite measurements used.

Viability: High

Timebound: Operational

Scale: Single institution / consortium

Investment: c.2 million euros per annum

Potential funding actors: Copernicus, satellite agencies, national meteorological services, national funding agencies

Potential actionees: Satellite agencies, national meteorological services, academia, research institutes, SMEs / industry