Gaps Assessment and Impacts Document

(Version 4.0)

GAIA-CLIM
Gap Analysis for Integrated
Atmospheric ECV Climate Monitoring
Mar 2015 - Feb 2018

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Lead Beneficiary: KNMI

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Work Package 6; Edited by Michiel van Weele (KNMI)

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Executive Summary

The GAIA-CLIM project aims 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 encompasses the following tasks:

1. Defining and mapping existing non-satellite measurement capabilities;
2. Improving the metrological characterisation of a subset of non-satellite (reference) observational techniques;
3. Better accounting for co-location mismatches between satellite observations and non-satellite (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.

Under its work package 6, GAIA-CLIM performs an assessment of gaps in capabilities or knowledge relevant to the use of non-satellite data to characterise satellite measurements. This Gaps Assessment and Impacts Document (GAID) 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, stakeholders and actors. The current set of gaps and remedies provides a firm basis for providing costed and prioritised recommendations for future work to improve our ability to use non-satellite data to characterise satellite measurements.

In each of the project tasks outlined above, presently unfulfilled user needs ('gaps') are being identified. The gaps assessment exercise therefore predominantly considers gaps identified as relevant to these GAIA-CLIM project aims. The identified key user communities for whom the impact of the identified gaps would be most relevant include:

- Service providers (e.g. ECMWF for NWP, CAMS and C3S)
- Users and providers of ECV climate data records (e.g. space agencies and satellite data user communities)
- Users of reference observations
- Users of baseline network observations
- Users of the 'Virtual Observatory'

This document provides a snapshot of the gaps status as per May 2017. The on-line '*Catalogue of Gaps*' provides the full content of the gaps and the proposed remedies. The catalogue is available from: http://www.gaia-clim.eu/page/gap-reference-list.

Input from external parties continues to be invited through the GAID website. A designated e-mail address[1] and a specific template for gap reporting is provided at the website. Further user engagement shall be achieved through a series of visits to key stakeholders through summer and autumn of 2017. This user feedback will be important in refining the GAID and ensuring its usefulness to the broader scientific and policymaker communities, as well as space agencies and international organisations and funding bodies.

[1] Email address for GAID feedback: gaid@gaia-clim.eu

The purpose of the GAID is two-fold. (1) to provide an overview of the most recent version of the on-line Catalogue of Gaps[2], and (2) to provide an analysis of the gaps by taking cross-sections through the catalogue along type of gap and suggested remedies, instrument technique, costs and time scale of the remedies, and the potential actors addressed. Importantly, the catalogue is not limited solely to those gaps, which are envisaged to be (to some extent) remedied within the project. Part of the assessment includes an analysis of scientific and societal impacts of the gaps and identified potential remedies. This holistic approach serves as a starting point for prioritization to assess the feasibility of resolution.

This fourth version of the GAID (GAIDv4) exclusively provides the basis for the derivation of a set of recommendations for future work to be delivered to the Commission and other relevant stakeholders. The final version (v5) of the GAID will be produced in February 2018 together with this final set of recommendations by GAIA-CLIM.

Key innovations in this GAIDv4 compared to earlier versions include:

- Formulation of the gaps in a *SMART* fashion, i.e. specific or actionable, with a measurable outcome and clear relevance, with one or more remedies in given time bounds, and assigned to potential actors with an indicative cost estimate;
- Increased use of menu selections to allow greater user-driven exploitation;
- Remedies have been drafted such that they may constitute a plausible description of work in a funding call;
- Substantial efforts at rationalisation of gaps to focus on generic issues that inhibit our ability to characterise satellite observations using the non-satellite observing segment, and programmatic level responses to remedy.

[2] Online catalogue available under: http://www.gaia-clim.eu/page/gap-reference-list

GAID versions history

Version	Principal updates	Owner	Date
0	Framework document	KNMI	9 April 2015
1.0	First version including the inputs received per work package by end of June 2015 through D1.1, D1.2, D1.3, D1.4, D1.5, and D6.1 and reviewed by work package leads in September 2015.	KNMI	10 September 2015
1.1	Interim version including author suggestions in preparation of v2.0	KNMI	4 November 2015
2.0	Version 2 is based on all inputs received by December 2015, including the results of the first user workshop, and reviewed by work package leads in January 2016; The public version does not indicate the personal e-mail addresses of the gap owners	KNMI	24 February 2016
3.0	Version 3 is rather drastically restructured and simplified compared to GAID versions 1 and 2. The Catalogue of Gaps which has been defined is kept up-to-date online at the project website. The most recent copy of the catalogue is included here. The new content in GAID Version 3 is based on the input materials received until early August 2016 and this includes the set of deliverables D1.4, D2.2, D3.3, D4.3 and D5.2. An updated list of governance gaps has been included by work package 6.	KNMI	31 August 2016
4.0	Version 4 is updated from version 3 to include in Section 2 the template used to identify the gaps and their remedies. The cross-sections through the list of gaps and remedies in Section 3 have been updated and extended. An updated and consolidated list of gaps is included in the Annex. Texts in the different sections have been updated and modified.	KNMI	16 May 2017

1 Introduction

The GAIA-CLIM project aims 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 encompasses the following tasks:

1. Defining and mapping existing non-satellite measurement capabilities;
2. Improving the metrological characterisation of a subset of non-satellite (reference) observational techniques;
3. Better accounting for co-location mismatches between satellite observations and non-satellite (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.

In each of these tasks, presently unfulfilled user needs ('gaps') are being identified.

Under its work package 6, the project performs an assessment of gaps in capabilities or knowledge relevant to the use of non-satellite data to characterise satellite measurements. This document summarises at an instance of time (May 2017 for this fourth version, v4, of the document) the outcome of this collection of gaps. It further describes the gap identification process, as well as the way these findings are presented and accessible to users, stakeholders, and actors. This GAIDv4 introduces the formulation of the gaps in a *SMART* fashion, i.e. specific or actionable, with a measurable outcome and clear relevance, with one or more remedies in given time bounds, and assigned to potential actors with an indicative cost estimate. It also provides the basis for a forthcoming, initial set of recommendations on potential gap remedies and improvements in capabilities. The final version (v5) of the GAID will then be produced in February 2018, supporting the delivery of a final set of recommendations to the Commission and other stakeholders arising from the project.

<u>The need for a non-satellite ECV monitoring capacity</u>

Europe has taken a leading role in the global Earth Observation constellation with the development of its own operational space infrastructure. This implies an increased need for assessment of and planning for observations from space. The growing European space infrastructure for climate monitoring builds upon the existing geostationary (*Meteosat*, since 1977) and low-earth orbit (*MetOp*, since 2006) operational monitoring capacity in space, supporting the operational meteorological and climate services. It is currently being extended with *Sentinels*, forming the Copernicus Space Segment (CSS). At time of writing in 2017, a first set of Sentinels is in orbit and several subsequent Sentinels are to be launched within the next 5-7 years. The long-term evolution of the CSS into its second generation during the next decade is currently under active development. In addition, ESA research satellites form an important component of Europe's space segment.

To maximise the return on investment in the European space infrastructure, a sustained and high quality characterisation capability, using both satellite and non-satellite data, is required. A multi-faceted approach is required for the production of sustained homogenized time series of Essential Climate Variables (ECVs) at both global and regional coverage. The activities should include non-satellite based ECV monitoring, intensive field campaigns, regular satellite-to-satellite comparisons as well as dedicated calibration payload missions.

At present, the ESA Climate Change Initiative (CCI) aims to strengthen the climate monitoring contribution of the past and present-day space segment for atmospheric composition. Its contributing projects cover several primary ECVs targeted by GAIA-CLIM, specifically ozone (O_3), Greenhouse Gases (GHGs) and aerosol, amongst many others. A follow-on project considering an expanded set of ECVs is shortly to begin. The EUMETSAT Satellite Application Facility (SAF) Networks further contribute to ECV monitoring. In particular, the Climate Monitoring SAF (CM SAF) provides climate data records of temperature and humidity, and the Atmospheric Composition SAF (AC SAF) provides climate data records of ozone, aerosols, and their precursors. Furthermore, the Copernicus Data Store (CDS) is being filled with a large set of long-term regional and global data records through dedicated Copernicus service contracts.

For climate monitoring, science, and applications, the need for long-term sustained (> 30 years) homogenized time series of known high quality constitutes a huge challenge, both on the observational sensors and the CSS. The satellite observations need to be calibrated and validated to standards that enable them to be used for climate services. This requires long-term sustained datasets from non-satellite platforms that need to be of high quality and sufficient quantity to robustly characterise satellite-sensor performance and radiative-transfer modelling, to provide confidence in the satellite observations. Currently, few, if any, of the non-satellite to satellite comparisons regularly undertaken provide fully traceable robust uncertainty estimates, taking into account uncertainty in both measurements and the inevitable additional variations owing to non-coincidence. Without such full traceability, ambiguity remains in any data comparison, and this ultimately limits the scientific value and utility for climate monitoring of both the satellite and non-satellite data records.

Gap assessment

Given the finite resources and time available, the GAIA-CLIM project has focussed upon a selected subset of atmospheric ECVs. These include temperature, water vapour (H_2O), ozone, carbon dioxide (CO_2), methane (CH_4), and aerosols. (Cf. Section 2.1 for an overview on the observations utilised within GAIA-CLIM.) For this set of ECVs, the GAID brings together the gaps in the availability of, and ability to utilize, truly reference quality traceable measurements in support of climate monitoring from satellites.

The key challenges regarding the gap assessment are:

(i) To ***identify*** the most important limitations of the non-satellite monitoring segment for characterising space-based measurements for climate monitoring focusing on unfulfilled user needs – the so-called '***gaps***';
(ii) To ***assess*** these gaps and to evaluate their user impact for climate services and research; and
(iii) To ***create*** a set of specific potential ***remedies*** to address the identified gaps

Because GAIA-CLIM is aiming to be application driven, the impact(s) of each of the gaps is – as much as possible – assessed from both a (end-) user perspective and a service and data provider perspective (e.g. Numerical Weather Prediction (NWP), Copernicus Climate Change Service (C3S), Copernicus Atmospheric Monitoring Service (CAMS)). Where possible, reference is made to the *Climate Monitoring Principles* as defined by the Global Climate Observing System (GCOS)[3].

For the atmospheric ECVs, a number of target user communities can be distinguished:

- Service providers (e.g. ECMWF for NWP, CAMS, and C3S)
- Users of ECV climate data records (e.g. for IPCC/WMO assessments)
- Users of reference observations

[3] GCOS Climate Monitoring Principles:
https://www.wmo.int/pages/prog/gcos/Documents/GCOS_Climate_Monitoring_Principles.pdf

- Users of baseline network observations
- Users of the planned 'Virtual Observatory'

In practice, there might be some overlap between these users.

The GAID is set up as a living document that has benefitted from broad stakeholder engagement and external input which is being solicited at various meetings and conferences and through a dedicated webpage[4] (cf. also Section 2.4 on outreach and dissemination activities). An on-line Catalogue of gaps[5] has been set up and maintained at the GAIA-CLIM website[6].

The purpose of the GAID is:

(i) To describe the process that has been followed to identify and assess the gaps;
(ii) To propose remedies per gap with potential actors;
(iii) To provide the latest status of the on-line catalogue of gaps; and
(iv) To provide an analysis of the list of gaps by taking cross-sections through the catalogue.

The remainder of this GAID document is structured as follows. In Section 2, the approach to the collection and identification of the gaps and remedies is given and we provide an overview of both past and further planned outreach activities in relation to the catalogue of gaps and this document. In Section 3, we present a set of cross-sections through the list of gaps and remedies. In Section 4, we summarize the current status of the GAID. The most recent version of the gap catalogue is presented in Annex I. Proposed remedies linked to potential actors are summarized in Annex II.

In this GAIDv4, a list of gaps is presented with only gap identifiers and short descriptions of the gap and the suggested remedies. The full gap descriptions together with their remedies following the gap assessment template (presented in Section 2.3) are provided in the on-line catalogue.

[4] GAID website: http://www.gaia-clim.eu/page/gaid
[5] online Catalogue of Gaps: http://www.gaia-clim.eu/page/gap-reference-list
[6] GAIA-CLIM website: http://www.gaia-clim.eu/

2 The Identification, Documentation and Management of Gaps

2.1 Primary ECVs and Contributing Instrumental Techniques

The primary ECVs addressed in GAIA-CLIM are temperature, water vapour, ozone, aerosols, and the well-mixed greenhouse gases CO_2 and CH_4. The gap analysis for precursor ECVs – CO, CH_2O, SO_2, NH_3, and NO_2, is covered by the sister EU FP7 project *Quality Assurance for ECVs'* (QA4ECV)[7]. Remaining ECVs are not presently assessed, but insights can be reached from a consideration of, e.g. the latest GCOS Implementation Plan[8]. Principal observations utilised within GAIA-CLIM are summarised in Table 2.1. A number of the gaps pertain directly to the entries in this table. The information content of Table 2.1 has been built partly on the mapping of non-satellite measurement capabilities and the assessment of geographical gaps that was performed within GAIA-CLIM under work package 1 (deliverables D1.6[9] and D1.7[10]).

Table 1 provides an overview of contributing surface networks and airborne observations per primary ECV addressed in GAIA-CLIM, split by altitude domain and network. The networks considered in GAIA-CLIM include:

- The Network for the Detection of Atmospheric Composition Change (NDACC),
- The GCOS Reference Upper-Air Network (GRUAN),
- The Total Carbon Column Observing Network (TCCON),
- The EUMETNET Aircraft Meteorological Data Relay Operational Service (E-AMDAR),
- The In-Service Aircraft for a Global Observing System (IAGOS),
- The Aerosol Robotic Network (AERONET),
- Aerosols, Clouds, and Trace gases Research InfraStructure / European Aerosol Research Lidar Network (ACTRIS/EARLINET),
- The NOAA Global Greenhouse Gas Reference Network (GGGRN),
- National Air Quality (AQ) networks.

Per network, the instrument platform or specific instrument techniques used are indicated in the table. The categories of observation include: surface in-situ, lidar, sun photometers, Fourier Transform InfraRed spectroscopy (FTIR), microwave radiometers (MWR), UV-visible (MAX) DOAS spectrometers, sondes, aircraft in-situ, balloon, and cryogenic frost point hygrometers (CFH).

***Table 2.1** Overview, per GAIA-CLIM primary ECV, of the contributions of surface networks and airborne observation programmes (incl. the applied instrumental techniques) to climate monitoring per atmospheric domain (PBL = planetary boundary layer; LT = lower troposphere < 6km; UT = upper troposphere > 6km; LS = lower stratosphere < 25 km; US+M = upper stratosphere + mesosphere > 25 km). Networks are denoted in italics, instrument techniques in plain text.*

[7] More information available on the QA4ECV website: http://www.qa4ecv.eu/
[8] GCOS Implementation Plan: https://library.wmo.int/opac/doc_num.php?explnum_id=3389
[9] D1.6 Report on data capabilities by ECV and by system of systems layer for ECVs measurable from space
[10] D1.7 Report on the collection of metadata from existing network and on the proposed protocol for a common metadata format

ECV per altitude domain	**Surface/PBL (< 1-2 km)**	**Total Column**	**LT (< 6km)**	**UT (> 6km)**	**LS (< 25 km)**	**US+M (> 25 km)**
T	*GRUAN* Surface in-situ, sondes, MWR	*Not applicable*	*GRUAN* Lidar, sondes *E-AMDAR, IAGOS* Aircraft in-situ	*GRUAN* Lidar, sondes, CFH *E-AMDAR, IAGOS* Aircraft in-situ	*GRUAN* Lidar, sondes, CFH	Lidar (NDACC, non-NDACC), sondes (up to 30-35 km)
H_2O	*GRUAN* Surface in-situ, sondes	*GRUAN* GNSS, sondes *NDACC* sondes, FTIR, MWR	*GRUAN* Lidar, sondes *NDACC* Lidar, sondes, FTIR, MWR *E-AMDAR, IAGOS* Aircraft in-situ	*GRUAN* Lidar, sondes *NDACC* Lidar, sondes, FTIR, MWR *E-AMDAR, IAGOS* Aircraft in-situ	*GRUAN* Lidar, sondes *NDACC* Lidar, sondes, FTIR, MWR *E-AMDAR, IAGOS* Aircraft in-situ	*Not available*
O_3	*NDACC* Surface in-situ, sondes, UV-visible, MAX-DOAS	*NDACC* Brewer-Dobson, UV-visible, MAX-DOAS, FTIR	*NDACC* Sondes, UV-visible, FTIR *IAGOS* Aircraft in-situ	*NDACC* Sondes, UV-visible, FTIR *IAGOS* Aircraft in-situ	*NDACC* Lidar, sondes, UV-visible, FTIR, MWR *IAGOS* Aircraft in-situ	*NDACC* Lidar, sondes (up to 30-35 km), UV-visible, FTIR, MWR
Aerosols	*AQ networks* Surface in-situ	*ACTRIS / Earlinet* Lidar *Aeronet* sunphotometer, MAX-DOAS	*ACTRIS / Earlinet* Lidar *NDACC* Lidar, MAX-DOAS	*ACTRIS / Earlinet* Lidar *NDACC* Lidar, sondes	*ACTRIS / Earlinet* Lidar *NDACC* Lidar, sondes	*Not available*
CO_2	*NOAA-GGGRN* Surface in-situ / flask	*TCCON* FTIR	*NDACC* FTIR	*NDACC* FTIR	*NDACC* FTIR	*Not available*
CH_4	*NOAA-GGGRN* Surface in-situ / flask	*TCCON* FTIR	*NDACC* FTIR	*NDACC* FTIR	*NDACC* FTIR	*Not available*

2.2 The Structure of Each Gap in the Online Catalogue

From GAID Version 3 onward, a common template has been provided to collect the input from the underlying GAIA-CLIM work packages. In this GAIDv4, the template has been updated, benefitting from external stakeholder review at the second user workshop[11]. This process has helped to populate the on-line catalogue with e.g. dropdown menus, and it has helped to harmonise the style in which especially the remedies to the gaps are formulated with specific actions assigned to potential actors, and with measurable outcomes of success.

The gap collection template is provided here, together with the input as received for Gap G6.03 in *italics*, providing an example for the full content in the on-line catalogue.

[11] D6.6 Report from the 2nd User Workshop

Gap collection template used in version 4 of the GAID with worked example

Gap ID and Gap Title

G6.03 Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects

Gap Abstract

There are many non-satellite measurement systems that, in principle, could be used for the purposes of satellite characterisation on a sustained basis. Such measurements are metrologically well characterised and understood and target variables, which are measured or measurable from space. However, many of the measurement systems are discontinuous in time and their scheduling is made with no regard to satellite overpass times. This diminishes their value for satellite Cal/Val activities considerably. Better scheduling would increase their intrinsic value for satellite programs.

Part I Gap Description

(1) Primary Gap Type

Governance

(2) Secondary Gap Type(s)

Spatiotemporal coverage
Uncertainty in relation to comparator measures

(3) ECVs Impacted (GAIA-CLIM targeted ECVs only)

All

(4) User Categories / Application Areas Impacted

Operational services and service development
International (collaboration) frameworks
Climate research

(5) Non-satellite Instrument Techniques Involved

Radiosondes
Ozone sondes
Lidar
Other non-GAIA-CLIM target measurements

(6) Related gaps

G6.01 Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
To be addressed with G6.03 because the resolution to the current gap will be simpler if a more unified governance of non-satellite measurement networks is achieved and the data is provided from these networks in a more unified manner.

G6.06 Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite EO products and derived products
To be addressed with G6.03 because operationalising instruments that can be operated 24/7 removes the current gap for the instruments affected.

(7) Gap detailed description

For some non-satellite instruments there are geophysical limitations as to when measurements can be undertaken e.g. an FTIR requires direct line of sight to the sun or a MAX-DOAS can only measure at sunrise/sunset.

Other instruments can and do operate 24/7 and therefore shall always capture a co-location if the satellite passes overhead. For example both GNSS-PW and microwave radiometers in principle operate on a 24/7 basis.

But for many non-satellite measurement techniques it is for financial or logistical reasons that measurements are solely episodic. For example, radiosonde launches tend to be twice daily or at best four times daily at fixed times. Similarly, lidar operations may be made only when staff are available. These types of considerations effect very many non-satellite measurements, which could in principle be better targeted to support EO-sensor characterization by taking measurements much closer to satellite overpass time. This would reduce the co-location mismatch and thus the attendant mismatch uncertainties. Because funding for these observations typically is not concerned with satellite characterisation the current sampling strategy ends up being sub-optimal for satellite characterisation. Better aligning sampling strategies with times of satellite overpass, which are predictable in advance, would increase their utility to satellite Cal/Val activities.

(8) Operational space missions or instruments impacted

Independent of specific space mission or space instruments

(9) Validation aspects addressed

Representativity (spatial, temporal)
Calibration (relative, absolute)
Time series and trends
Radiance (Level 1 product)
Geophysical product (Level 2 and higher level products)

(10) Expected Gap Status after GAIA-CLIM

After GAIA-CLIM this gap is likely to remain

Part II Benefits to Resolution and Risks to Non-resolution

***Table 2.2** Summary of the benefits to gap resolution*

Identified benefit	User category / application area benefitted	Probability of benefit being realised	Impacts
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 services and service development Climate research	High	Better characterized satellite data will yield improved utilization in derived products including reanalyses products and resulting services
More robust funding support for ground-based observations continuity. Recognizing that ground-based products may have unique value in e.g. providing vertically resolved profiles	International (collaboration) frameworks Operational services and service development	Medium	Diversity of tools and data available to support service providers to develop bespoke products

Table 2.3 *Summary of the risks to non-resolution of the gap*

Identified risk	User category / application area at risk	Probability of occurrence if gap not remedied	Impacts
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	Operational services and service development Climate research	High	Reduced confidence in satellite measurements and products and services derived therefrom
Inability to use non-satellite segment to effectively bridge across any unplanned gap in spaceborne EO capabilities	Operational services and service development Climate research	Low / Medium	Reduced colocations reduces the opportunity to use the non-satellite series to bridge the effects of any gap and yield a homogeneous series. This reduces the value of the satellite record for monitoring long-term environmental changes
Reduction in perceived utility and value of measurements leading to reduction in funding	International (collaboration) frameworks	Low / Medium	Diversifying the usage base of the high-quality measurements increases their intrinsic value and helps support widespread adoption

Part III Gap Remedy/Remedies

Remedy Title: Optimization of scheduling to enhance capability for satellite Cal/Val activities

<u>(1) Primary gap remedy type</u>
Deployment

<u>(2) Secondary Gap Remedy Type(s)</u>
Governance

<u>(3) Specific Remedy Proposed</u>
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 in NRT for satellite characterisation if the full potential value of these measures is to be realised. 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 that optimise collection and dissemination of non-satellite data in support of the space-based observational segment.

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 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 missions from multiple agencies from multiple countries to maximise the scientific value of the Cal/Val exercise 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 taking new or additional measurements. The most obvious solution would be to instigate an international measurements support program which would administer and disperse funding support for sustained satellite Cal/Val from selected high-quality sites that optimise spending decisions and had as active stakeholders agencies, non-satellite data providers and end-users.

(4) Relevance

Better scheduling would increase the number of co-locations available for measurement systems that are discontinuous in time and increase the intrinsic value of the non-satellite observations for satellite Cal/Val.

(5) Measurable Outcome of Success

Increased number of high-quality non-satellite data co-locations with satellite measurements on a sustained basis

(6) Expected Viability for the Outcome of Success

High

(7) Scale of Work

Programmatic multi-year multi-institution

(8) Time Bound to Remedy

More than ten years

(9) Indicative Cost Estimate (investment)

Medium cost (<5 million)

(10) Indicative Cost Estimate (exploitation)

Yes, Annually recurring costs estimated about 5 million euro / year

(11) Potential Actors

EU Copernicus
EU Horizon 2020
WMO
ESA, Eumetsat, or other satellite agencies
Academia and individual research institutes
National Meteorological Services
National Measurement Institutes
National funding agencies
Industry and SMEs

2.3 Version Control of Individual Gaps and the GAID

As the GAID is a living document with several official versions being produced over the project lifetime, the following practices have been adopted to ensure the traceability and provenance of gaps between versions:

- Once identified, a gap is given a unique identifier associated with the most logical GAIA-CLIM work package from which the gap derives;
- A gap may have changed principal work package responsibility, but its unique identifier remains;
- A gap can be retired if felt by project participants either to be resolved or to be no longer relevant. If so, the gap identifier is also retired; and
- Gaps can be merged. In this case, the most appropriate initial identifier is retained and all other versions that were merged are retired.

All earlier versions of gaps can still be found in the preceding versions of the GAID. A total of 101 gaps have been identified since the start of the process. The reasons for earlier gap retirements are articulated e.g. in underlying deliverables such as D1.4[12], D2.2[13], D3.3[14], D4.3[15] and D5.2[16]. In some cases, a new more specific or more generic gap has been added in its place with a new identifier. For GAIDv3, a total number of 88 gaps had been identified and retained. During the first four months of 2017, these have been rationalised to a total of 43 gaps in GAIDv4 primarily through merging of sufficiently similar gaps to formulate more holistic gaps with one or more actionable remedies Table 2.4 provides a trace for the retired gaps since GAIDv3. Because gaps are not being renumbered during the course of the project, several identifier numbers do not appear in the GAIA-CLIM on-line catalogue of gaps and Annexes to this document.

Table 2.4 *Overview of retired gaps since GAIDv3. Note that the issues that are raised within some of the retired gaps have been maintained through a merge with gaps and their proposed remedies that have been retained in the catalogue of gaps (Annex I).*

Gap	Title	Change	Rationale
G1.02	Unknown suitability of measurement maturity assessment	Merged with G1.03	Made more coherent sense as a merged gap
G1.07	Need for a scientific approach to the assessment of gaps in the existing networks measuring ECVs	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.08	Evaluation of the effect of missing data or missing temporal coverage of fully traceable data provided by ground-based networks	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.09	Limited availability of quantitative CO profiles	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.11	Lack of understanding of traceable uncertainty estimates from baseline and comprehensive networks	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.12	Propagate uncertainty from well-characterized locations and parameters to other locations and parameters	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap

[12] D1.4 Review of and input to Gap Analysis and impacts document aspects relevant to WP1
[13] D2.2 Intermediate report on measurement uncertainty gap analysis
[14] D3.3 Review of and input to Gap Analysis and impacts document aspects relevant to WP3
[15] D4.3 Review of and input to Gap Analysis and impacts document aspects relevant to WP4
[16] D5.2 Review of and input to Gap Analysis and impacts document aspects relevant to WP5

G1.13	Uncoordinated lidar and microwave radiometer water vapour measurements	Removed	Too specific, redundant with gaps elsewhere
G1.14	Currently limited aircraft measurements in Eastern Europe	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.15	Northern Hemisphere bias in NDACC and PANDORA network sites distribution	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G2.01	Common lack of continuous operation of aerosol lidar measurements systems	Merged with G6.03 / G6.06	Specific case in point of the more generic gaps identified in WP6
G2.02	Lidar measurements missing vertical coverage in lowermost altitude range	Merged with G2.06	Aerosol lidar gaps combined into a more coherent single gap
G2.03	Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars	Merged with G2.06	Aerosol lidar gaps combined into a more coherent single gap
G2.04	Missing continued intercomparison of lidars with appropriate reference systems	Merged with G2.06	Aerosol lidar gaps combined into a more coherent single gap
G2.05	Lack of metrologically rigorous aerosol lidar error budget availability	Merged with G2.06	Aerosol lidar gaps combined into a more coherent single gap
G2.09	Continuous water vapour profiles from Raman lidars limited during daytime	Merged with G6.03/G6.06	Specific case in point of the more generic gaps identified in WP6
G2.14	Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals	Merged to form G2.36	Combination of MWR gaps into a more comprehensive gap
G2.15	Lack of unified tools for automated MWR data quality control	Merged to form G2.36	Combination of MWR gaps into a more comprehensive gap
G2.16	Missing agreement on calibration best practices and MWR instrument error characterization	Merged to form G2.36	Combination of MWR gaps into a more comprehensive gap
G2.17	Lack of a common effort in homogenization of MWR retrieval methods	Merged to form G2.36	Combination of MWR gaps into a more comprehensive gap
G2.19	Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a FTIR retrieval	Merged with G3.04	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.20	Lack of coordinated assessment of the spectroscopic uncertainties in infrared retrievals	Merged with G2.27	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.21	Current spectroscopic databases contain uncertainties specifically affecting TCCON retrievals of CH_4 and CO_2	Merged with G2.37	More generic spectroscopic gap required following user feedback
G2.24	Lack in in-situ calibration of CH_4 and CO_2 FTIR measurements	Merged with G2.23	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.28	Lack of understanding of the a priori profile shape for AMF calculations for zenith sky ozone retrievals	Merged with G2.27	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.29	Lack of knowledge of the vertical averaging kernels used for DOAS total column ozone retrievals	Merged with G2.27	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.32	Better characterization of the different MAXDOAS tropospheric ozone retrieval methods needed	Merged with G2.31	Combination of MAXDOAS related gaps into one gap to make a more coherent case
G2.33	Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements	Merged with G2.31	Combination of MAXDOAS related gaps into one gap to make a more coherent case
G2.35	TCCON sites with high/low albedo and hot spot monitoring	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G3.03	Missing generic and specific standards for co-location criteria in validation work	Merged with G3.02	Merged gaps felt to be more appropriate
G4.02	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to humidity	Merged with G4.01	Gaps were considered sufficiently similar to be better as a combined gap
G4.07	Error correlations for reference sonde (GRUAN) measurements	Merged with G5.09	The set of level-1 comparator tools were amalgamated to make a stronger case

G4.11	Geographical sampling of reference in-situ data	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G5.02	Access to and use of reference and satellite data provided in different data formats and structures (e.g. granularity of data) prevents easy exploitation	Merged with G1.06	All gaps to do with data access modalities combined and rationalised
G5.03	No common source for co-located data exists which prevents use of reference data to validate reference measurements to each other and to evaluate satellite data	Merged with G5.01	Combined gap felt to be more user relevant
G5.10	Characterisation of different types of uncertainty has not been systematically addressed per ECV preventing and potentially delaying inclusion of various instrument/ECV combinations into the Virtual Observatory	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G6.04	Mixed level of user experience with using uncertainty information	Removed	Insufficiently specific / actionable and overlapped with several other gaps
G6.05	Future support for GRUAN-processor	Merged with G5.09	The set of level-1 comparator tools were amalgamated to make a stronger case
G6.08	a) INSPIRE: Application of INSPIRE Implementing Rules to atmospheric and any other 3D/4D-data is not straightforward w.r.t. dimensionality, quality, etc. b) INSPIRE: Where do data of one Member State end up which acquired in another Member State and/or is derived from satellite?	Removed	INSPIRE is intergovernmental and it was felt to be outside the scope of GAIA-CLIM
G6.09	Observations in developing countries (Africa - Asia - S America)	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G6.10	An unlimited growth of data portals, metadata standards and formats might make data discovery and access increasingly difficult	Merged into G1.06	All gaps to do with data access modalities combined and rationalised
G6.11	The possible gradual loss of island radiosonde stations	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap

2.4 Dissemination and Outreach Activities in Relation to the GAID

Within GAIA-CLIM, a user survey has been undertaken (deliverable D6.1 'Report on results of user survey'), and two user workshops were held (October 2015 in Rome and November 2016 in Brussels, with associated reports under deliverables D6.3[17] and D6.6[18]). These activities provided important information on user needs, the formulation of gaps, as well as the information needed to develop and describe potential remedies as concrete actions assigned to potential actors with e.g. cost estimates and measurable outcome of success.

The results of the user survey indicate a clear need for user education and capacity building on how satellite and non-satellite data can be used in conjunction for scientific and practical applications. Also, the user needs for functional match-up facilities were clear. Another important gap that was clearly revealed in the survey was related to user familiarity with, and use of, uncertainties in non-satellite (reference) observations. These inputs have been taken on board in the list of gaps.

The first user workshop in Rome provided specific operational user needs, e.g. for the CAMS operational validation. Also, a set of specific gaps related to GHG monitoring were identified and taken on board in the list of gaps. Inputs to the identified gaps were further derived informally through a bottom up approach, put forward by individual scientists within the project, and from external sources, such as GCOS Climate Monitoring Principles and (target) requirements, the ESA

[17] D6.3 Summary of first workshop with external users
[18] D6.6 Report from the 2nd User Workshop

Climate Change Initiative (CCI), EUMETSAT Satellite Application Facilities (SAF), and the Copernicus services. Input from external parties continues to be invited through the GAID website. A designated e-mail address[19], and a specific template for gap reporting is provided at the website.

Inevitably, the materials that are brought together in the GAID have a bias towards those gaps and ECVs that are considered important by GAIA-CLIM project participants. Further user feedback collected during the final year of GAIA-CLIM will be important in refining the GAID and ensuring its usefulness to the broader scientific and policymaker communities, as well as space agencies and international organisations and funding bodies.

For the different GAID versions, a range of outreach activities has been undertaken:

- GAID Version 1.0 was presented at the first GAIA-CLIM user workshop on 6 October 2015 in Rome, Italy.
- GAID Version 2.0 was presented at the GCOS conference *Global Climate Observation: the Road to the Future*, 2-4 March 2016, Amsterdam, The Netherlands, and at the European Space Solutions (ESS 2016) Conference, 30 May - 3 June 2016, The Hague, The Netherlands.
- GAID Version 3.0 was presented at the ConnectinGEO workshop on 'Gaps in EO and its prioritization', 10-11 October 2016 in Laxenburg, Austria and at the second GAIA-CLIM user workshop, 21-23 November 2015 in Brussels, Belgium.

Upon completion of the present GAIDv4, we will begin immediately with the prioritization exercise and the production of a recommendations document. Such that, in the remainder of the project lifetime, GAIA-CLIM will concentrate upon user engagement on the GAID process and the production of a resulting set of prioritized recommendations. User engagement shall be achieved through a series of visits to key stakeholders through the summer and autumn of 2017. These visits shall discuss the gaps process and attendant prioritisation exercise, as well as the 'Virtual Observatory' facility.

The final version (v5) of the GAID will be produced in February 2018.

[19] Email address for GAID feedback: gaid@gaia-clim.eu

3 Gaps Analysis

3.1 Cross-sections through the Catalogue

Gaps in the catalogue are enumerated such that the first number denotes the work package from which it arose. Cross-sections through other dimensions, such as gap type and the instrument technique used for validation of observations, provide support to further analysis of the identified gaps and to find e.g. any similarities, complementarities and/or inconsistencies. Note that some of the 43 gaps in total might appear multiple times by taking such cross-sections, e.g. a gap may pertain to technical, educational and governance issues, so when split by category, it would appear three times. The cross-sections are selected inclusively rather than exclusively to get the complete overview.

3.2 Gaps per Primary Gap Type

Seven generic gap types have been distinguished in the GAIA-CLIM gap identification process:

- ***Gaps in Spatiotemporal Coverage of Validation Observations of ECVs***: gaps in geographical and/or temporal coverage, i.e. a lack of measurements of the ECVs
- ***Gaps in the Coverage of the Vertical Domain and/or in Vertical Resolution***: either limitations in the altitude range covered or not resolving the vertical column sufficiently
- ***Gaps in the Measurement Uncertainty***: incomplete knowledge of the uncertainty budget, including calibration and e.g. spectroscopic uncertainties, i.e. all uncertainties intrinsic to one measurement
- ***Gaps in the Comparator Uncertainty***: uncertainties relating to comparator measures, i.e. uncertainties related to comparisons between (types of) measurements which have different attributes individually
- ***Technical gaps***: the more specific user needs related to data dissemination, specific missing tools, formats, etc.
- ***Parameter gaps***: missing parameter knowledge, missing metadata and auxiliary information related to the measurement of an ECV
- ***Governance gaps***: user needs related to network governance, data policies and data access, as well as gaps in QA/QC methodologies, traceability, documentation and education/training

Each of the identified gaps is being associated with one generic primary gap type, complemented by one or more secondary gap types in cases where the gap is cross-cutting. In the following tables only the primary gap type is used to sort the gaps.

3.2.1 Gaps in Spatiotemporal Coverage of Validation Observations of ECVs

Gaps in coverage typically correspond to user needs related to missing non-satellite (reference) observations. Gaps in coverage could be either temporal (i.e. insufficient time sampling) or geographical (i.e. missing network locations). Gaps in either the vertical coverage and/or vertical resolution are categorized separately. Gaps in spatiotemporal coverage, which have been identified within GAIA-CLIM, are:

Table 3.1 *Gaps in the spatiotemporal coverage of validation observations of ECVs*

G1.04	Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs in atmospheric, ocean and land domains
G2.06	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
G6.02	Geographically dispersed observational assets reduce their utility for satellite Cal/Val
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products

3.2.2 Gaps in the Vertical Domain and/or in Vertical Resolution

The gaps in the vertical domain and resolution specifically refer to user needs on (better-resolved) vertical profile observations for the ECVs, mostly extending on existing observations at the surface or lower atmosphere, or total column observations, but also e.g. through aircraft observations. Gaps related to the vertical domain or vertical resolution that have been identified within GAIA-CLIM are:

Table 3.2 *Gaps in the Vertical Domain and/or in Vertical Resolution.*

G2.24	Lack of calibrated in-situ vertical profiles of CH_4, CO_2 and CO for improving the accuracy of FTIR column and profile measurements of CH_4, CO_2 and CO
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere

3.2.3 Gaps in Knowledge of the Uncertainty Budget and Calibration

The gaps in relation to the uncertainty budget and calibration refer to the missing knowledge on the (reference) quality of a single observation or a certain type of observation, relating to its traceability and comparability that limit its scientific utility and value. The gaps in knowledge of the uncertainty budget and calibration, which have been identified within GAIA-CLIM, are:

Table 3.3 *Gaps in Knowledge of the Uncertainty Budget and Calibration*

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
G2.07	Lack of uptake of lidar measurements in data assimilation
G2.08	Lack of a metrological rigorous approach for ensuring continuous 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 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 part of the uncertainty in FTIR measurements and how to evaluate each part
G2.22	FTIR cell measurements carried out to characterize ILS 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, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30	Incomplete uncertainty quantification for Pandora ozone measurements
G2.31	Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements

G2.34	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G2.37	Poorly quantified uncertainties in spectroscopic information
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
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

3.2.4 Gaps in Knowledge of the Uncertainty in Relation to Comparator Measures

Uncertainty gaps in relation to comparator measures typically include validation uncertainties, such as uncertainties on representativeness, uncertainties due to co-location mismatches and due to differences in spatiotemporal sampling and smoothing, and in other specific observation attributes. These comparator uncertainties exclude the uncertainties related to a single observation. The uncertainty gaps in relation to comparator measures, which have been identified within GAIA-CLIM, are:

Table 3.4 *Gaps in Knowledge of the Uncertainty in Relation to Comparator Measures*

G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity

3.2.5 Technical Gaps

Technical gaps might include e.g. specific missing tools, data portal technicalities, instrument technology limitations etc. The technical gaps, which have been identified within GAIA-CLIM, are:

Table 3.5 *Technical Gaps*

G1.05	Lack of integrated user tools showing all the existing observing capabilities for measuring ECVs with respect to satellite spatial coverage
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
G5.06	Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G5.09	Need to propagate various reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable robust characterisation of satellite FCDRs

3.2.6 Parameter Gaps

Parameter gaps are a separate generic category. These gaps include user needs related to parameters (or reported observations) that are missing with respect to ECV monitoring and which would have value on their own and/or as auxiliary data to the ECV monitoring. For example, users typically wish to have a temperature vertical profile provided with the sonde ozone profile. As another example: modellers might need additional parameters with the observed ECVs to verify their models, e.g., parameters related to the Brewer-Dobson Circulation, convective mixing, etc. The parameter gaps that have been identified within GAIA-CLIM are:

Table 3.6 *Parameter Gaps.*

G1.03	Lack of internationally recognised framework for assessment of fundamental observation capabilities

3.2.7 Governance Gaps

Governance gaps include user needs related to network and data policies, including data provision, open access, etc.

Table 3.7 *Governance Gaps*

G5.11	Non-operational provision of reference measurement data and some (L2) satellite products may prevent use in Copernicus operational product monitoring
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.07	Distinct data policies across different networks harm the use of complementary data from different networks
G6.12	Under-capacity of workforce to exploit satellite data and satellite characterisation

3.3 Gaps per Instrument Technique and the Primary Calibration and Validation Aspects involved

3.3.1 Gaps identified per Instrument Technique

In this section, we include the gaps, which are specific for only one, or maybe two, instrument techniques. There are, of course, many gaps, which do not relate just to one or two techniques specifically, and are more of general nature. Such more generally applicable gaps are not repeated in these cross-sections of gaps separated per instrument technique. The instrument techniques considered include:

- Lidar
- FTIR
- UV-visible
- Radiosondes
- Ozone sondes
- MWR
- GNSS-IPW

UV-visible instrument techniques involve UV-visible zenith DOAS, UV-visible MAX-DOAS and Pandora observations. Note that some gaps are not listed in this section because these gaps do not specifically apply to a single instrument technique or are independent of the technique involved.

Table 3.8 *Gaps related to Lidar*

G2.06	Poor spatial coverage of high-quality multi-wavelength lidar systems capable of characterising aerosols
G2.07	Lack of uptake of lidar measurements in data assimilation
G2.08	Lack of a metrological rigorous approach for ensuring continuous long-term water vapour measurements from Raman lidars in the troposphere and UT/LS
G2.10 (also UV-visible)	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.12	Lack of rigorous temperature lidar error budget availability limits utility for applications such as satellite characterisation

Table 3.9 *Gaps related to FTIR*

G2.18	Better agreement needed on systematic and random part of the uncertainty in FTIR measurements and how to evaluate each part
G2.22	FTIR cell measurements carried out to characterize ILS have their own uncertainties
G2.24	Lack of calibrated in-situ vertical profiles of CH_4, CO_2 and CO for improving the accuracy of FTIR column and profile measurements of CH_4, CO_2 and CO

Table 3.10 *Gaps related to UV-visible*

G2.10 (also lidar)	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
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, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30	Incomplete uncertainty quantification for Pandora ozone measurements
G2.31	Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements

Table 3.11 *Gaps related to Radiosondes*

G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere

Table 3.12 *Gaps related to Ozone Sondes*

G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions

Table 3.13 *Gaps related to MWR*

G2.13	Missing microwave standards maintained by National/International Measurement Institutes
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
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

Table 3.14 *Gaps related to GNSS-IPW*

G2.34	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software

3.3.2 Gaps grouped along Primary Calibration and Validation Aspects addressed

The following, potentially partly overlapping, calibration and validation (Cal/Val) aspects have been identified:

- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Spectroscopy
- Time series and trends
- Radiance (level 1 products)
- Geophysical, gridded and/or assimilated products (product levels 2,3,4)
- Other aspects (auxiliary parameters, timeliness, education on validation aspects)

The Cal/Val aspects addressed by a gap could involve one or more aspects. Here, the primary Cal/Val aspect of the gap has been selected. The cross-sections addressed are as follows:

Table 3.15 *Gaps related to representativity (spatial/temporal)*

G1.03	Lack of internationally recognised 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 in atmospheric, ocean and land domains
G1.05	Lack of integrated user tools showing all the existing observing capabilities for measuring ECVs with respect to satellite spatial coverage
G1.06	Currently heterogeneous metadata standards negatively impact data discoverability and usability
G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.34	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and 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
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
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
G5.06	Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.02	Geographically dispersed observational assets reduce their utility for satellite Cal/Val
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.07	Distinct data policies across different networks harm the use of complementary data from different networks

Table 3.16 *Gaps related to calibration*

G1.03	Lack of internationally recognised framework for assessment of fundamental observation capabilities
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
G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.13	Missing microwave standards maintained by National/International Measurement Institutes
G2.26	Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.34	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and 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
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
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
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.02	Geographically dispersed observational assets reduce their utility for satellite Cal/Val
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products
G6.07	Distinct data policies across different networks harm the use of complementary data from different networks

Table 3.17 *Gaps related to spectroscopy*

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
G2.13	Missing microwave standards maintained by National/International Measurement Institutes
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, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G2.37	Poorly quantified uncertainties in spectroscopic information
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and 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
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G5.09	Need to propagate various reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable robust characterisation of satellite FCDRs
G6.07	Distinct data policies across different networks harm the use of complementary data from different networks

Table 3.18 *Gaps related to time series and trends*

G1.06	Currently heterogeneous metadata standards negatively impact data discoverability and usability
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	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
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.12	Lack of rigorous temperature lidar error budget availability limits utility for applications such as satellite characterisation
G2.13	Missing microwave standards maintained by National/International Measurement Institutes
G2.26	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, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30	Incomplete uncertainty quantification for Pandora ozone measurements
G2.31	Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements
G2.34	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and 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
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
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products
G6.07	Distinct data policies across different networks harm the use of complementary data from different networks

Table 3.19 *Gaps related to radiance (level 1 products)*

G1.06	Currently heterogeneous metadata standards negatively impact data discoverability and usability
G2.13	Missing microwave standards maintained by National/International Measurement Institutes
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and 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
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
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
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere
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
G5.06	Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations

	for atmospheric ECV validation systems
G5.09	Need to propagate various reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable robust characterisation of satellite FCDRs
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.02	Geographically dispersed observational assets reduce their utility for satellite Cal/Val
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products
G6.07	Distinct data policies across different networks harm the use of complementary data from different networks

Table 3.20 *Gaps related to geophysical, gridded and/or assimilated products (product levels 2,3,4)*

G1.06	Currently heterogeneous metadata standards negatively impact data discoverability and usability
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
G2.07	Lack of uptake of lidar measurements in data assimilation
G2.08	Lack of a metrological rigorous approach for ensuring continuous long-term water vapour measurements from Raman lidars in the troposphere and UT/LS
G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.13	Missing microwave standards maintained by National/International Measurement Institutes
G2.18	Better agreement needed on systematic and random part of the uncertainty in FTIR measurements and how to evaluate each part
G2.22	FTIR cell measurements carried out to characterize ILS have their own uncertainties
G2.24	Lack of calibrated in-situ vertical profiles of CH_4, CO_2 and CO for improving the accuracy of FTIR column and profile measurements of CH_4, CO_2 and CO
G2.27	Lack of understanding of random uncertainties, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30	Incomplete uncertainty quantification for Pandora ozone measurements
G2.31	Incomplete 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
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and 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
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
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere
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
G5.06	Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products
G6.07	Distinct data policies across different networks harm the use of complementary data from different networks

Table 3.21 *Gaps primarily related to other Cal/Val aspects: auxiliary parameters, timeliness and education on validation aspects*

Auxiliary parameters	
G2.12	Lack of rigorous temperature lidar error budget availability limits utility for applications such as satellite characterisation
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and 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
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
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
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.02	Geographically dispersed observational assets reduce their utility for satellite Cal/Val
G6.07	Distinct data policies across different networks harm the use of complementary data from different networks
Timeliness	
G5.11	Non-operational provision of reference measurement data and some (L2) satellite products may prevent use in Copernicus operational product monitoring
Education on validation aspects	
G6.12	Under-capacity of workforce to exploit satellite data and satellite characterisation

3.4 Remedies: Types of Actions along with their Cost Estimates and Potential Actors

3.4.1 Remedies sorted by Primary Remedy Types

Six types of remedies are distinguished. A remedy type is the proposed type of action in response to the identified user need(s). In total, six different types of action have been distinguished. The remedy types along which the proposed remedies sorted include:

- Technical work,
- Laboratory work,
- Scientific research,
- (Instrument) Deployment,
- Governance, and
- Education/Training

Technical work, laboratory work and scientific research are more or less self-explaining proposed types of activity. Deployment is mostly related to the implementation of new or improved instrumentation. Governance type of remedies would address user needs related to coordination, funding, data policies (dissemination, free access), clarification of methodologies, missing traceability, and missing documentation. Educational activities could involve specific user training.

A proposed remedy might involve different types of activities. The primary proposed activity has been used to categorize the remedies. Secondary types of the proposed remedies have been identified as well and these are provided, and can be further selected, through the on-line catalogue of gaps. However, in the following tables only the primary remedy type is used to sort the gaps.

For some of the gaps, multiple remedies have been proposed and therefore the remedies are numbered as Rx. Here, (R1) is used for the first remedy proposed, (R2) for a second remedy to the same gap, etc. Within the set of multiple remedies for one gap, there is no priority, i.e., the second (R2) and third remedy (R3), etc., are on equal footing with the first remedy listed (R1).

***Table 3.22** Remedies involving technical work*

G1.05(R1)	Mapping tools to match satellite and non-satellite observations
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.13(R1)	Development and testing of MWR standards and secondary standards
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.22(R1)	Regular cell measurements and ILS retrievals are to be performed in a consistent manner
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G4.01(R1)	Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G4.12(R1)	Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.09(R1)	Implement a forward radiative transfer capability into the Virtual Observatory
G5.09(R2)	Improved characterisation of error covariances in GRUAN measurements
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis

***Table 3.23** Remedies involving laboratory work*

G2.08(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterisation

***Table 3.24** Remedies involving scientific work*

G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Steps to better realise benefits of a system of systems approach to observing strategies
G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G2.34(R1)	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software
G2.37(R1)	Establish traceability of spectroscopic properties of Essential Climate Variables
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.

G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables

Table 3.25 *Remedies involving (instrument) deployment*

G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G1.10(R4)	Instigation and propagation of high quality reference network research infrastructures in data sparse regions
G2.06(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G5.01(R1)	Successful implementation of the Copernicus activity C3S 311a Lot3 leading to consistent provision via the CDS
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM VO facility
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities

Table 3.26 *Remedies involving governance*

G1.04(R1)	Extension and continuous update of the GAIA-CLIM review of existing geographical gaps for non-satellite observations
G1.06(R1)	Design and implementation of Unified Meta Data Format
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R1)	Short-term cross-network governance steps
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.07(R1)	Coordination at European level to harmonise data and licence policies by extending the use of existing technical standards

Table 3.27 *Remedies involving education/training*

G1.03(R1)	Further deployments and refinements of the GAIA-CLIM approach
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

3.4.2 Cost Estimates of the Proposed Remedies (Costs on Investment)

The provided cost estimates are rough estimates, based upon the scope of the work proposed and the likely timeline to completion. However, these provide a useful first indication of the scale of the proposed remedy. Costs are differentiated between investment, i.e. initial costs, and operational, i.e. (annual) recurring costs.

Table 3.28 *Proposed Remedies with Low (< 1M Euro) Cost Estimates (Costs on Investment)*

G1.03 (R1)	Further deployments and refinements of the GAIA-CLIM approach
G1.05(R1)	Mapping tools to match satellite and non-satellite observations
G1.06(R1)	Design and implementation of Unified Meta Data Format
G2.08(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterisation
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.22(R1)	Regular cell measurements and ILS retrievals are to be performed in a consistent manner
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G2.34(R1)	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.01(R1)	Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.12(R1)	Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val
G6.01(R1)	Short-term cross-network governance steps
G6.07(R1)	Coordination at European level to harmonise data and licence policies by extending the use of existing technical standards
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs

Table 3.29 *Proposed Remedies with Low-Medium (1-5M Euro) Cost Estimates (Costs on Investment)*

G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G1.04(R1)	Extension and continuous update of the GAIA-CLIM review of existing geographical gaps for non-satellite observations
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Steps to better realise benefits of a system of systems approach to observing strategies
G2.06(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars
G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.13(R1)	Development and testing of MWR standards and secondary standards
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G2.37(R1)	Establish traceability of spectroscopic properties of Essential Climate Variables
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and

	ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G5.01(R1)	Successful implementation of the Copernicus activity C3S 311a Lot3 leading to consistent provision via the CDS
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM VO facility
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.09(R1)	Implement a forward radiative transfer capability into the Virtual Observatory
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table 3.30 *Proposed Remedies with Medium-High (5-10M Euro) Cost Estimates (Costs on Investment)*

G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects

Table 3.31 *Proposed Remedies with High (>10M Euro) Cost Estimates (Costs on Investment)*

G1.10(R4)	Instigation and propagation of high quality reference network research infrastructures in data sparse regions
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products

3.4.3 Cost Estimates of the Proposed Remedies (Annual Recurring Costs)

For a subset of the gap remedies, there are ongoing repeating costs associated with operations and upkeep following instigation. In those cases, and based upon the scale of the remedy, an indicative estimate of the annual recurring costs has been provided.

Table 3.32 *Proposed Remedies with Low-Medium (<100k Euro/yr) Cost Estimates (Annual Recurring Costs)*

G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G5.01(R1)	Successful implementation of the Copernicus activity C3S 311a Lot3 leading to consistent provision via the CDS

Table 3.33 *Proposed Remedies with Medium-High (100-500k Euro/yr) Cost Estimates (Annual Recurring Costs)*

G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM VO facility

Table 3.34 *Proposed Remedies with High (>500k Euro/yr) Cost Estimates (Annual Recurring Costs)*

G1.10(R4)	Instigation and propagation of high quality reference network research infrastructures in data sparse regions
G2.06(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities

Table 3.35 *Proposed Remedies with identified though unspecified annual Recurring Costs*

G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G5.09(R2)	Improved characterisation of error covariances in GRUAN measurements
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation
G6.07(R1)	Coordination at European level to harmonise data and licence policies by extending the use of existing technical standards
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

4 Conclusions

The GAID is a living document. Each iteration has benefitted from internal and external stakeholder engagement, and over time, it has become progressively more complete and consistent. Gap identification numbers have been maintained between versions for backward traceability.

The gaps assessment exercise is limited in scope to consider solely gaps identified as relevant to the GAIA-CLIM project aims. Thus, the GAIA-CLIM catalogue has a focus on the availability of, and ability to utilize non-satellite (reference) observations in support of the long-term sustained space-borne and non-satellite monitoring of a set of ECVs. Inevitably, the materials that are brought together in the GAID have a bias towards those gaps and ECVs that are considered important by GAIA-CLIM project participants.

Several possible ways to filter the gaps have been developed and implemented for the first time in this fourth release (GAIDv4). The gap assessment along cross-sections aims to help guide users and potential stakeholders through the catalogue. The cross-sections also aid the gap definition process by identifying relationships between gaps or their remedies, by flagging of complementarities or inconsistencies between gaps that might originate from different communities, and by finding potentially missing gap elements.

There is, however, an often-ignored issue in such gap analyses as undertaken here, which users should be cognisant of. Gap analyses are quite rightly designed to identify, assess and address deficiencies. They are not designed to highlight existing capabilities. In the real world, there is only a finite resource of expertise and resource to fulfil user needs. In this context, there is a risk of proverbially 'robbing Peter to pay Paul' in that addressing a gap is achieved via removal of resource from elsewhere, which in turn then raises a new gap. That is not to say that efficiencies cannot be realised, but rather, that the consequences of reallocating resources to address a perceived gap need to be carefully considered

This GAIDv4 provides a snapshot of the gaps status as per May 2017. These gaps are represented online together with a set of actionable suggested remedies. The on-line catalogue provides the full content of the materials that have been brought together and is available from http://www.gaia-clim.eu/page/gap-reference-list.

A total number of 43 gaps has been identified and maintained in GAIDv4 after an important consolidation process in which project partners were tasked to review the collected set of gaps and harmonize the suggested remedies. For some of the gaps, a set of several distinct remedies is being proposed, reflecting different types of remedies that can be addressed by different potential actors.

In GAIDv4, a set of cross-sections of the gaps is presented, firstly by grouping the gaps into a set of generic gap types. Further cross-sections are then presented per instrument technique, along the validation and calibration aspects involved. For the remedies, the cross-sections provide an overview per remedy type and cost estimate.

In Annex I, the list of gaps with potential remedies is provided as a copy of the information in the on-line catalogue of gaps. Gap title and abstract are provided together with the remedy title and its relevance. For the full description of the gaps and their proposed (set of) remedies, please visit the on-line catalogue of gaps at: http://www.gaia-clim.eu/page/gap-reference-list.

In Annex II, the proposed remedies are assigned to potential actors.

Further user feedback collected during the final year of GAIA-CLIM will be important in refining the GAID and ensuring its usefulness to the broader scientific and policymaker communities, as well as space agencies and international organisations and funding bodies.

Annex I GAIA-CLIM Catalogue of Gaps

In this annex, we list the catalogue of identified gaps per work package through their gap title, short gap description, proposed remedy or remedies, and the relevance of the remedy. The on-line GAIA CLIM Catalogue of Gaps (http://www.gaia-clim.eu/page/gap-reference-list) provides a full description of each of the identified gaps, including their trace, and a full description of the proposed remedies, together with a description of the required activities. All entries of the gap and remedy template in Section 2.3 are made available through the on-line catalogue, which is being maintained and updated throughout the project.

The excerpt of the catalogue as provided in this Annex I summarises the content per the 16th of May 2017. Note that gaps have retained their identification number Gx.xx throughout the consolidation process of the GAIA-CLIM project (Section 2.4). Therefore, a non-continuous gap numbering appears in the catalogue. Retired gaps numbers since GAIDv3 are listed in Table 2 (Section 2.3).

Table A1.1 *GAIA-CLIM Catalogue of Gaps (per 16th of May 2017). The web address of the on-line version of the Catalogue of Gaps is:* http://www.gaia-clim.eu/page/gap-reference-list

G1.03	**Lack of internationally recognised framework for assessment of fundamental observation capabilities** There currently exists no universally recognised approach to assessing quantifiable fundamental measurement quality (maturity) of available observing networks. Although absolute measurement quality cannot be assured, fundamental properties of the measurement system that build confidence in its appropriateness and metrological verity can be assessed. The lack of an agreed international framework for such an assignment leads to heterogeneity in approaches to choices of suitable measurement series for any given application and this has knock-on effects for downstream applications. Suggested Remedy or Remedies and main relevance ***(R1) Further deployments and refinements of the GAIA-CLIM approach*** *The application of the GAIA-CLIM approach to other cases shall lead to improvements in the guidance and approach and enable greater buy-in from a more diverse range of stakeholders.* ***(R2) Adoption of measurement systems approach and assessment by international bodies*** *The adoption of an international programmatic effort to assess measurement capabilities would directly address the gap and ensure broad buy-in.*
G1.04	**Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs in atmospheric, ocean and land domains** While a comprehensive review of space-based missions and needs has been put together within official documents of the international community, in contrast the mapping of current non-satellite observing capabilities is piecemeal and poorly documented. Extensive reviews have been provided by WMO, GEOSS, GCOS, but they are limited to those networks and ECVs relevant for their institutional mission, and often disagree with one another in regards to the perceived adequacy of the current capabilities and the required innovations. Suggested Remedy or Remedies and main relevance ***(R1) Extension and continuous update of the GAIA-CLIM review of existing non-satellite observations*** *The C3S-BARON Copernicus project will facilitate the access to rich discovery metadata and support the reduction of the fragmentation already experienced in the metadata sets available worldwide for a large number of networks.*
G1.05	**Lack of integrated user tools showing all the existing observing capabilities for measuring ECVs with respect to satellite spatial coverage** The necessary user tools to be able to fully visualize all the sub-orbital observing capabilities for measuring

	ECVs at the global scale with respect to spatial coverage of space-based sensors have never been provided in the past by international bodies and agencies. Several tools have been implemented for specific networks of the global observing system, but all of them have been designed on the basis of very specific needs, using different criteria/functionalities, and typically including just one ECV and only one or a small subset of the networks at the global scale. This lack of integrated user tools inhibits the uptake of non-satellite measurements to characterize satellite observations. Suggested Remedy or Remedies and main relevance ***(R1) Mapping tools to match satellite and non-satellite observations*** *The GAIA-CLIM 3D mapping software is a flexible open-source solution to visualize and quickly identify geographical gaps and a good starting point for any scientific assessment. It offers opportunities to support the development of downstream services.*
G1.06	**Currently heterogeneous metadata standards negatively impact data discoverability and usability** Metadata is an increasingly central tool in the current research environment, enabling large-scale, distributed management of resources. Recent years have seen a growth in interaction between previously relatively isolated communities, driven by a need for cross-domain collaboration and exchange of data and products. However, metadata standards have not been able to meet the needs of interoperability between independent standardization communities. Observations without metadata are of very limited use. Several efforts have been undertaken to improve the harmonization of metadata across the networks and international programs, but currently this is still not sufficient. Suggested Remedy or Remedies and main relevance ***(R1) Design and implementation of Unified Meta Data Format (UMDF)*** *The proposed remedy will help to aid discoverability and interoperability of holdings and avoid the repetition of work for format conversions and conversions of data. The UMDF will also allow preserving the richness of the original metadata. The proposed UMDF is a significant attempt to improve the metadata harmonization at the international level and represents an important step forward towards the harmonization of metadata and data standards and formats in the weather and climate communities. Its benefit may be expected to be large and affecting many (primarily expert) data users.*
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** Limited availability of traceable uncertainty estimates limits the direct applicability of the majority of existent data to high-quality applications such as satellite data characterisation, model validation and reanalyses. While a vast amount of data is available, the uncertainty of such data is - in a metrological sense - often only insufficiently specified, estimated, or even unknown. What reference quality measurements exist tends to be geographically concentrated. In order to achieve progress it is critical to have sufficient coverage of reference quality data records that are stable over time, across the various methods of measurement, uniformly processed worldwide, and based on traceable references. 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. It is also essential to identify the scope for baseline and comprehensive networks to leverage expertise from reference networks, including adopting elements of best practice from reference networks, and/or facilitating reprocessing that iteratively improves dataset quality. Suggested Remedy or Remedies and main relevance ***(R1) Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques*** *Directly addresses the paucity of reference quality instrumentation by developing improved metrological understanding for a broad range of instrumentation that is either currently in the field or could be deployed.* ***(R2) Steps to better realise benefits of a system of systems approach to observing strategies*** *Better propagating information across observing networks increases the value of all measurement programs to a range of applications, including satellite characterisation.* ***(R3) Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data*** *A more robust scientific basis to assessing the impacts of current gaps would greatly aid decision makers in deciding how and where to expand reference network capabilities.*

	(R4) Instigation and propagation of high quality reference network research infrastructures in data sparse regions *There is a current paucity of high-quality reference network observational infrastructures in many areas of the globe for reasons of logistics, skills, geopolitics, and funding (amongst others).*
G2.06	**Poor spatial coverage of high-quality multi-wavelength lidar systems capable of characterising aerosols** Raman lidars or multi-wavelength Raman lidars are undoubtedly an integral component of an aerosol global measurement infrastructure as they can provide quantitative range-resolved aerosol optical and microphysical properties. It is very important to carefully assess the value of the retrieval of advanced lidar systems and to study if the coverage of the existing networks at the global scale is sufficient to carry out adequate satellite retrieval characterisation. The availability of a larger number of multi-wavelength Raman lidar measurements will strengthen the global observing system for the upcoming research satellite Cal/Val and ensures a critical contribution to distinguish natural and anthropogenic aerosols from satellite data. Multi-wavelength Raman lidars could be considered to be the future backbone of a larger network incorporating simpler lidar instruments and/or ceilometers, and so be able to have a denser global spatial coverage. Suggested Remedy or Remedies and main relevance ***(R1) Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars*** *On the basis of GAIA-CLIM activities (Task 1.4), recommendations on the improvements of the existing global lidar network to characterize aerosol optical and microphysical properties are provided. However, a complete remedy for this gap is strongly related to the strategies of the international research institutions, which are at present the key players in the deployment and the operation of Raman lidar measurements.*
G2.07	**Lack of uptake of lidar measurements in data assimilation** Aerosol lidar data can potentially be used to constrain uncertain model processes in global aerosol-climate models. Satellite-borne lidar data can be effectively assimilated to improve model skills but, at the current stage, aerosol lidar data assimilation experiments are mainly limited to the assimilation of attenuated backscatter, which is a non-quantitative optical property of aerosol. There is much additional valuable data that could be utilised to improve data assimilation. Such improved data assimilation may allow broader inferences about satellite quality as being developed in GAIA-CLIM for temperature and humidity. Suggested Remedy or Remedies and main relevance ***(R1) Extension of the GAIA-CLIM data assimilation approach to aerosol lidars*** *The described remedy via the ACTRIS-2 project shows a promising perspective to start addressing these gaps, and to foster further long-term data assimilation experiments, also given the upcoming satellite missions with a lidar technique on-board including the ESA missions ADM-Aeolus and EarthCARE.*
G2.08	**Lack of a metrological rigorous approach for ensuring continuous long-term water vapour measurements from Raman lidars in the troposphere and UT/LS** One of the paramount needs for developing a long-term data set for monitoring atmospheric water vapour using lidar techniques is represented by the calibration of Raman lidar water vapour profiles using reference calibration lamps, tools traceable to NMIs standards. Another critical issue to ensure continuous water vapour Raman lidar measurement is due to the weakness of the Raman backscattering from water vapour molecules. During daytime, a few water vapour Raman lidars have already proven to be able to measure water vapour up to 3-4 km above ground level, but this work is compromised as only a few of them are operated on a continuous basis. Technological improvement or the effective integration with other techniques shall be extensively pursued. Suggested Remedy or Remedies and main relevance ***(R1) Further deployments and refinements of the GAIA-CLIM approach to metrological characterisation*** *For water vapour lidar calibration, the proposed remedy will dramatically improve the traceability of water vapour Raman lidar measurements and data consistency at the global scale, and will help to manage any change in the system. The synergetic approach to improve water vapour measurement continuity is at present the only chance to improve daytime water vapour profiling capabilities.*
G2.10	**Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions**

	Tropospheric ozone has an impact on air quality and acts as a greenhouse gas and therefore plays a role in public and environmental health, as well as climate change, linking the two subjects. Establishing processes and trends in tropospheric ozone, in particular in the free troposphere, above the mixed layer and below the stratosphere, is difficult due to a lack of data. Also, ozone soundings using balloon borne samplers are too scarce to capture the relatively high spatial and temporal variability in the troposphere. Contrary to stratospheric ozone, passive satellite observations have limited access to information about tropospheric ozone. However, new sensors on the next generation of satellite measurements shall have better tropospheric sensing capabilities, and shall require validation. Suggested Remedy or Remedies and main relevance ***(R1) Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone*** *An increase in data on tropospheric ozone is expected from various space-borne platforms with increased capabilities, such as TES and TROPOMI and the instruments proposed for Sentinel 4 and 5. However, a reinforcement of the ground based observational capacity is also required to validate these space borne observations and establish high-quality time series. The issue is relevant to understand the links between air pollution and climate change. Satellite data will likely not suffice to fill the gap.*
G2.11	**Lack of rigorous tropospheric ozone lidar error budget availability** Tropospheric ozone has an impact on air quality and acts as a greenhouse gas and therefore plays a role in public and environmental health, as well as climate change, linking the two subjects. In order to establish tropospheric ozone trends, more high-quality and high-frequency observations are needed (see G.2.10) and a rigorous error budget is required. Measurements of tropospheric ozone by means of the Differential Absorption Lidar (DIAL) Technique are close to reference quality and may meet this need if development of traceable products can be realised. Suggested Remedy or Remedies and main relevance ***(R1) Create and disseminate a fully traceable reference quality DIAL lidar product*** *The issue is highly relevant for any application that uses ground based tropospheric ozone lidar data as a reference. In particular to understand the tropospheric ozone budget and the reduction of the uncertainties in estimation of the resulting radiative forcing.*
G2.12	**Lack of rigorous temperature lidar error budget availability limits utility for applications such as satellite characterisation** Temperature lidars provide important information for trend detection in the middle atmosphere (connected to trends in the ozone layer). These are measured using lidar systems that often also measure the ozone layer. The lidar technique to measure temperature is sensitive to the presence of aerosol, which is an important contribution to the error budget. In addition, lidar techniques exist to measure temperature profiles in the troposphere using the pure-rotational Raman technique that can be used in the presence of aerosol. For temperature measurements in the presence of aerosols using the pure rotational Raman lidar technique a rigorous error budget needs to be established to improve their utility for applications such as satellite characterisation. Suggested Remedy or Remedies and main relevance ***(R1) Create a fully traceable reference quality temperature lidar product*** *The issue is highly relevant for any application that uses ground based temperature lidar data as input or reference. In particular, to detect temperature trends in the middle atmosphere and aerosol-cloud-humidity interactions.*
G2.13	**Missing microwave standards maintained by National/International Measurement Institutes** The traceability of ground-based microwave radiometer (MWR) estimates and their uncertainty requires the traceability of MWR calibration to SI standards. Currently, no SI standard is available for MWR at any national/international measurement institute. Thus, SI-traceability of ECVs from MWR is currently not feasible. However, at least one national measurement institute is currently developing SI standards for MWR. It is expected that SI-traceable standards for MWR will be available in the next few years. This will then allow the standard transfer to MWR manufacturer and user communities. Suggested Remedy or Remedies and main relevance ***(R1) Development and testing of MWR standards and secondary standards*** *The remedy will make microwave standards available at least at one measurement institute (NIST). GAIA-CLIM*

	aims at monitoring and effectively communicating the progress to MWR manufacturers and users, in order to promote the uptake of certified targets.
G2.18	**Better agreement needed on systematic and random part of the uncertainty in FTIR measurements and how to evaluate each part** There is no clear agreement yet within the FTIR community on the distinction and characterisation of the random and systematic parts of the uncertainty in FTIR measurements. As a consequence, no common approach is available on how to evaluate each part. Suggested Remedy or Remedies and main relevance ***(R1) Improved traceability of uncertainties in FTIR measurements*** *Comparison and tuning of the uncertainty modules of the retrieval software packages. Write down a manual of how to estimate the uncertainties for all parameters that are part of the forward model in the retrieval software packages.*
G2.22	**FTIR cell measurements carried out to characterize ILS have their own uncertainties** For the retrieval of information about the vertical distribution of target species from FTIR spectra, it is important to know the FTIR instrument line shape (ILS). Therefore, regular cell measurements are carried out to characterize the ILS. However these cell measurements have their own uncertainties: an ILS retrieval comes along with an uncertainty and an averaging kernel. In particular the averaging kernel for an ILS retrieval is often not adequately considered. Inaccurate knowledge of the ILS mainly affects the retrieved vertical profile (e.g. for water vapour and ozone profile retrievals) but also leads to larger uncertainties on the retrieved column-averaged concentrations of CH_4 and CO_2 (XCH4, XCO2). In other words, the uncertainties on the ILS retrieved from cell measurements will propagate to the total uncertainty budget of the retrieved species. Suggested Remedy or Remedies and main relevance ***(R1) Regular cell measurements and ILS retrievals are to be performed in a consistent manner*** *Improved traceability of uncertainties is a core objective of GAIA-CLIM. Traceable ILS uncertainty will allow a traceable estimation of the FTIR product uncertainty due to ILS uncertainties.*
G2.24	**Lack of calibrated in-situ vertical profiles of CH_4, CO_2 and CO for improving the accuracy of FTIR column and profile measurements of CH_4, CO_2 and CO** This gap addresses the need for in-situ vertical profiles of CO2, CH4 and CO that cover the troposphere up to the lower stratosphere and that are calibrated to accepted standards, e.g., the WMO standards. These profiles are needed for calibrating FTIR total column measurements of CO, CO2 and CH4, and also for providing a priori vertical profiles for the FTIR data retrieval, especially under polar vortex conditions and high solar zenith angle (SZA). Today, the AirCore technique can provide the required profiles, up to the altitude of 30 km, therefore the uncertainty of total column estimates is reduced, compared to aircraft in situ profile measurements. However, the technique is not yet completely operational, it cannot be used everywhere, and there aren't yet enough AirCore data available to demonstrate that their use as a priori profiles improves the accuracy of the FTIR measurements under polar vortex conditions. The urgency of filling the gap is dictated by the current and planned satellite missions, which have the capability to measure greenhouse gases from space (e.g. IASI, GOSAT, OCO-2, Tansat, S5P, GOSAT-2, Merlin, MicroCarb, OCO-3, Sentinel-5). Suggested Remedy or Remedies and main relevance ***(R1) Use of AirCore data to contribute to the FTIR calibration*** *The remedy will contribute to the network wide, more cost-effective calibration tool. This also helps to address the gap, by providing more information on accurate profiles in the stratosphere and troposphere.*
G2.26	**Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis** The uncertainty in the ozone absorption cross-sections is one of the main systematic error sources in the remote sensing of atmospheric ozone using UV-visible spectroscopy techniques. Even though the uncertainty can be considered as a systematic error source, the actual error depends on atmospheric temperature. Presently the uncertainty in total column ozone due to uncertainty in absorption cross-sections is assumed to be around one to a few per cent. If the same cross-sections are used in satellite observations and ground based observations, one source for non-consistency can be excluded from the comparison. In addition, when the uncertainties related to ozone cross-sections and their temperature dependencies are well characterized,

	this effect can be included in the error budget of ozone observations. It may be possible that this also improves the retrieval itself. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Improved understanding of the effects of differences in ozone cross-sections*** *Starting from the results achieved within the ACSO study the study suggested here will help to better understand the uncertainties caused by different sets of ozone cross-sections used within the data analysis and how this impacts on the overall measurement uncertainty.*
G2.27	**Lack of understanding of random uncertainties, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy** The uncertainties in the ozone slant columns retrieved with DOAS data analysis fitting procedures are predominantly caused by instrumental imperfections and by issues introduced within the analysis routines. Such uncertainties are often random and therefore can be estimated statistically from e.g. the least-squares fit procedure. However, the fitting uncertainties derived from such analysis typically result in unrealistically small uncertainties and can lead to an underestimate by up to a factor of two. Further uncertainties are introduced during the calculation of air mass factors (AMFs), which are required to convert the measured ozone slant columns into vertical columns. The AMF uncertainties are dominated by errors in *a priori* profile shape effects with ozone and pressure/temperature *a priori* profiles being key input parameters for the AMF calculations. For further interpretation of the total column observations, averaging kernel information as part of the retrieval product plays an important role. However, currently vertical averaging kernels are only approximations of the real 3D averaging kernel and cannot fully account for the representativeness of the data. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error*** *This remedy is specific for measurements using UV-visible spectroscopic measurement techniques and it will address the existing gap by providing a better understanding on what causes the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random uncertainty.* ***(R2) Improve climatological databases of a priori ozone profiles*** *Improving the climatological databases of a priori ozone profiles will improve the accuracy of the a priori data used within the respective RT model to calculate the AMFs and hence to improve the overall accuracy of the measured total ozone column retrieved from zenith sky UV-visible measurements.* ***(R3) Standardize AMF calculation methods and databases of a-priori information used in AMF calculations*** *Standardized AMFs will improve the overall accuracy of the measured total ozone column retrieved from zenith sky UV-visible measurements.* ***(R4) Standardized AMFs will improve the overall accuracy of the measured total ozone column retrieved from zenith sky UV-visible measurements.*** *Many research groups are not setup to run their retrieval code coupled with a chemistry-transport model and so it is essential to have a less computationally demanding approach, which can then be used much more widely. Hence it is vital to understand how the uncertainties increase using the method based on the look-up tables and how representative the vertical averaging kernel climatology is of real measurement conditions.*
G2.30	**Incomplete uncertainty quantification for Pandora ozone measurements** Pandora is a relatively new UV-visible instrument for measuring total ozone and also ozone profiles in a similar way as MAX-DOAS instruments. So far only a few studies exist which describe measurement uncertainties or measurement validation. As a relatively cheap and automatic instrument there is a potential that a network of Pandora instruments would have a substantial role in the satellite validation in e future. A metrologically rigorous uncertainty quantification for the Pandora instrument is therefore needed. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Steps towards reference quality measurement program for Pandora measurements*** *Given that the Pandora instruments will form the backbone of a new measurement network (PANDONIA) run in close collaboration with NDACC, any better understanding of and reduction in the measurement uncertainties will contribute to the homogenisation of the ozone data products available within these networks.*

G2.31	**Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements** Retrieving tropospheric ozone from passive remote sensing observations is difficult because almost 90% of the total column ozone resides in the stratosphere. Pioneering studies have demonstrated that information on tropospheric ozone can be extracted using the so-called MAX-DOAS (Multi-Axis Differential Optical Absorption Spectroscopy) technique. The information content of such measurements, however, remains to be thoroughly explored. Furthermore, within these studies, different experimental retrieval methods have been applied and more research is needed to better characterize the different possible approaches for tropospheric ozone retrieval. In addition to the lack of understanding of the information content and consensus on retrieval approaches, the lack of uncertainty characterization of tropospheric ozone measurements from MAX-DOAS instruments restrains the potential for the assessment of network capabilities and the usage of these data for satellite and model validation purpose. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone*** *A better characterisation of the information content and uncertainty budget of MAX-DOAS tropospheric ozone retrievals will improve the usability of MAX-DOAS observations for model and satellite validation studies.* ***(R2) Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS*** *The better characterisation of the MAXDOAS tropospheric ozone retrieval is fully aligned with the requirements of providing traceable and harmonized tropospheric ozone vertical columns and profiles for satellite and model validation.*
G2.34	**Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software** The Zenith Total Delay (ZTD) uncertainty is a dominant component in the Global Navigation Satellite Systems Integrated Precipitable Water (GNSS-IPW) total uncertainty budget. If not handled properly, it may drastically affect the GNSS-IPW uncertainty estimate. It is essential to understand possible software-dependent peculiarities and to find recommendations while using uncertainty estimates obtained by different data processing software packages for undertaking GRUAN-type uncertainty analysis. The goal is to investigate at least two geodetic software packages using the same GNSS-data processing method, comparing the uncertainty definition and uncertainty handling, leading to potentially large differences in the uncertainty estimates. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Comparison of at least two geodetic software packages*** *The proposed remedy will help to better define GRUAN GNSS-IPW uncertainties, starting from the level reached thus far, with data processing and uncertainty estimation.*
G2.36	**Lack of traceable uncertainties in MWR measurements and retrievals** Ground-based microwave radiometry (MWR) provides continuous and unattended retrievals of atmospheric temperature and humidity profiles, as well as of vertically-integrated total column water vapour (TCWV) and total cloud liquid water (TCLW). Despite the significant scientific advancements allowed by MWR observations over the last forty years, current operational MWR retrievals are still lacking a traceable uncertainty estimate. The characterization of the total uncertainty budget for MWR retrievals requires quantification of the contributions from the instrument hardware (including absolute calibration) and the retrieval method (including the radiative transfer model). These contributions have been quantified in open literature, but they often refer to one particular instrument and/or environmental condition, and thus shall not be generalized. A systematic approach that dynamically evaluates the total uncertainty budget of MWR, i.e., as a function of instrument/environment conditions, at network level is lacking. Initiatives for mitigating this gap are being undertaken in Europe as well as in the United States. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Adoption of multidisciplinary review approach and further implementation by international bodies*** *Once addressed, traceable MWR observations and retrievals will be available together with the estimate of the time-dependent uncertainty uniformly across the network. The remedy will foster the application of standardized calibration and uncertainty characterization procedures by MWR manufacturers and users, the use of a common network-suitable retrieval method, the consideration of MW forward model uncertainties in MWR retrievals and the application of improved QC procedures by MWR manufacturers and users.*

G2.37	**Poorly quantified uncertainties in spectroscopic information** Molecular spectroscopy provides the primary link between radiance and atmospheric gas composition. Full knowledge of the spectroscopic properties of a 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 – and a series of related gaps have been identified. However, there would be a clear benefit in a top-level spectroscopic coordination activity that identified and disseminated common issues and solutions, and developed a harmonised process for dealing with spectroscopic uncertainties and establishing spectroscopic traceability. Suggested Remedy or Remedies and main relevance ***(R1) Establish traceability of spectroscopic properties of Essential Climate Variables*** *The proposed coordination activity is required to ensure a harmonised approach to addressing specific gaps in spectroscopic knowledge. This will lead to the efficient development of an improved understanding of spectroscopic uncertainties and a unified methodology in establishing traceability in spectroscopic measurements.*
G3.01	**Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location** For many ECVs, the atmospheric field is known to vary in space and time at the scale of the individual measurements, and at the scale of the co-locations between multiple measurements in the context of validation work. However, the exact amplitude and patterns of these variations are often unknown on smaller scales. Consequently, it is impossible to estimate the resulting uncertainties, which nevertheless ought to be taken into account when using the measurements and/or interpreting the comparisons. This gap thus concerns the need for a better quantification of atmospheric spatiotemporal variability at the small scales of single measurements and co-locations. Suggested Remedy or Remedies and main relevance ***(R1) Improved high-resolution modelling to quantify mismatch effects*** *If successful, this remedy would largely close the gap, and it would facilitate remedies for most other gaps related to comparator uncertainties through the use of OSSEs (Observing System Simulation Experiments) based on these model fields.* ***(R2) Use of statistical analysis techniques based upon available and targeted additional observations*** *This remedy concerns the statistical analysis of existing and future satellite and non-satellite high-resolution data sets, which allows us to separate the contribution of atmospheric variability from the total uncertainty budget of a data comparison, e.g. using so-called 'structure functions' or heteroskedastic functional regression. Within the geographical and temporal coverage of the data set, these methods produce an estimate of the variability (or auto-correlation) of the field.*
G3.02	**Missing standards for, and evaluation of, co-location criteria** The impact of a particular choice of co-location criterion is only rarely explored in the atmospheric validation literature. However, without some quantification of the impact of the co-location criterion that was adopted, it is virtually impossible to assess the contribution of natural variability to the total error budget of the comparisons. As such, this gap impacts significantly the potential interpretation of the comparison result in terms of data quality. Some in-depth studies do exist, but testing multiple criteria, or using criteria based on the latest results of such exploratory work, is far from common practice. This gap thus concerns the need for more awareness among validation teams, for more detailed studies comparing the (dis-)advantages of various co-location criteria, and for community-agreed standards on co-location criteria that are broadly adopted in the context of operational services. Suggested Remedy or Remedies and main relevance ***(R1) Systematic quantification of the impacts of different co-location criteria*** *These studies and the proposed associated governance support target this gap directly. They will provide stakeholders with a traceable, authoritative reference on which to base their validation requirements and protocols regarding co-location criteria. It will also facilitate meta-analysis of different validation studies without the need to take into account differences in results due to differences in the impact of co-location mismatch on the results.*

G3.04	**Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties** This gap concerns the need for a more detailed assessment of the actual spatiotemporal smoothing and sampling properties of both satellite-based EO measurements and ground-based in-situ or remote-sensing measurements. Indeed, EO measurements are most often associated with single locations, or at best pixel footprints, while in fact the actual measurement sensitivity covers a larger spatiotemporal extent, due for instance to the radiative transfer determining the measured quantities, or the actual measurement geometry (choice of line-of-sight, trajectory of a weather balloon, etc.). In an inhomogeneous and variable atmosphere, this leads to additional errors and uncertainties that are not part of the reported measurement uncertainties, but still need to be quantified, in particular when performing comparisons with other types of measurements, with different smoothing and sampling characteristics. For several ECVs and measurement techniques, significant work is needed to (1) determine/model the actual spatiotemporal smoothing and sampling properties, and (2) quantify the resulting uncertainties on the measurements of the variable atmosphere. Suggested Remedy or Remedies and main relevance ***(R1) Comprehensive modelling studies of measurement process*** *The remedy will provide a description for every instrument and measurement type of the full 4-D measurement sensitivity, and the errors and uncertainties resulting from the assumption that a measurement can be associated with a nominal geo-location and time.*
G3.05	**Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements** Level-3 data are, by definition, constructed by averaging level-2 data over certain space-time intervals, so as to arrive at a (regularly) gridded product. However, the (global) sampling pattern of the sounder(s) that produced the original L2 data is never perfectly uniform, nor are revisit times short enough to guarantee dense temporal sampling of e.g. a monthly mean at high horizontal resolution. Consequently, the averages may deviate from the true average field that would be obtained if complete spatiotemporal coverage were possible. These so-called representativeness errors are only rarely investigated, and almost never provided with a product, in spite of their importance in interpreting the data. Suggested Remedy or Remedies and main relevance ***(R1) Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques*** *Studies are required quantifying the representativeness of averages, e.g. by model-based simulations of averages based on either the limited real sampling or on an ideal, complete sampling.*
G3.06	**Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences** A validation exercise is meant to check the consistency between two datasets within their reported uncertainties. As such, the uncertainty budget of the comparison is crucial. Besides the measurement uncertainties on both data sets, the comparison is affected by uncertainties in harmonization manipulations (e.g. unit conversions requiring auxiliary data) and co-location mismatch, i.e. differences in sampling and smoothing. In particular, the latter term is hard to quantify and often missing in validation work, resulting in incomplete uncertainty budgets and improper consistency checks. Suggested Remedy or Remedies and main relevance ***(R1) Use of observing system simulation experiments*** *The remedy concerns Observing System Simulation Experiments (OSSEs). The aim is to calculate the error due to spatiotemporal mismatch for each comparison pair, and to derive the mismatch uncertainties from these, so that they can be added to the measurement uncertainties to derive the full uncertainty budget.* ***(R2) Statistical estimation of typical co-location mismatch effects*** *Employ statistical modelling on the differences, for instance with a heteroskedastic functional regression approach. Efforts are required to generalise the GAIA-CLIM approach and tools to enable broader exploitation.*
G4.01	**Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity** Numerical Weather Prediction (NWP) models are already routinely used in the validation and

	characterisation of Earth Observation (EO) data. However, a lack of robust uncertainties associated with NWP model fields and related top-of-atmosphere (TOA) radiances prevent the use of these data for a complete and comprehensive validation of satellite EO data, including an assessment of absolute radiometric errors in new satellite instruments. Agencies and instrument teams, as well as key climate users, are sometimes slow (or reluctant) to react to the findings of NWP-based analyses of satellite data, due to the current lack of traceable uncertainties. Suggested Remedy or Remedies and main relevance ***(R1) Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties*** *The software will be open-source and will enable users (by which we mean reasonably knowledgeable users) to compare NWP fields from both ECMWF and Met Office (in the first instance) with GRUAN data. This will include a comparison of temperature and humidity, as well as TOA brightness temperatures for all sensors supported by the (publically available) RTTOV radiative transfer model.*
G4.08	**Estimates of uncertainties in ocean surface microwave radiative transfer** Several passive microwave missions (operating in the 1-200 GHz range) make measurements in spectral regions where the atmosphere is sufficiently transmissive that the surface contributes significantly to measured radiances. The accuracy of retrievals of atmospheric temperature and humidity over ocean is therefore dependent on the accuracy of ocean surface microwave radiative transfer. Similarly, the accuracy of modelled radiances using Numerical Weather Prediction (NWP) models is limited, in some applications, by this uncertainty in the modelled surface contribution. The dominant source of uncertainty for ocean surface microwave radiative transfer is expected to be ocean emissivity estimates. Suggested Remedy or Remedies and main relevance ***(R1) Intercomparison of existing surface emissivity models*** *An intercomparison exercise is a useful step towards a full validation of emissivity models. In many cases, such an intercomparison yields useful insights into the mechanisms, processes and parameterisations that give rise to biases.* ***(R2) The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz*** *It is proposed to use traceably calibrated radiometers in field campaigns. As well as in airborne campaigns, it would be useful to use this type of radiometer in laboratory experiments using wave tanks and field campaigns with radiometers mounted on oil rigs. A combination of different techniques should lead to more robust estimates of the uncertainties in the emissivity models.*
G4.09	**Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer** There is a lack of traceable uncertainties associated with the contribution of land surface microwave radiative transfer to Top of the Atmosphere (TOA) brightness temperatures for microwave imaging and sounding instruments. The land surface emission exhibits significant spatial and temporal variability, particularly in snow and ice-covered regions. There are a number of sources of uncertainty in the approaches currently used to estimate the land surface contribution, including the emissivity and skin temperature prior, ineffective cloud and precipitation screening and errors introduced by the simplification of the radiative transfer equation for practical computations. Solving this gap will require a combination of different approaches, including the use of experimental campaigns, which are useful to validate the overall contribution of the land surface. Suggested Remedy or Remedies and main relevance ***(R1) The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based)*** *It is proposed to use traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based). Such campaigns can be used to validate both the (combined) emissivity and skin temperature estimates calculated from window channels observations for temperature and humidity sounders, and emissivity models.* ***(R2) Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables*** *There is a need to establish traceable uncertainties for NWP fields and radiances calculated from them.*

G4.10	**Incomplete estimates of uncertainties in land surface infrared emissivity atlases** Land surface emissivity atlases in the infrared region (3-17 µm) are required for the validation of infrared satellite sounding measurements over land. Work is underway, outside of the GAIA-CLIM project, to develop dynamic atlases of spectral emissivity in this part of the spectrum, based on measurements from polar-orbiting hyper-spectral infrared observations and using a rapidly updating Kalman Filter. However, these new dynamic atlases need to be validated to ensure the estimates have robust uncertainties associated with them. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Provision of validated land surface infrared emissivity atlases*** *There is a need to establish a comprehensive set of dynamic land surface infrared emissivity atlases. The resulting improved infrared emissivity atlases should be made openly available in usable formats and broadly advertised.*
G4.12	**Lack of reference quality data for temperature in the upper stratosphere and mesosphere** The GCOS Reference Upper Air Network (GRUAN) provides reference in-situ data for temperature and humidity with traceable estimates of uncertainty. This network can be used to validate NWP short-range forecasts for temperature and humidity to reference standards (see gap G4.08). The NWP temperature and humidity forecasts can then be used to perform satellite Cal/Val of new instruments, with improved knowledge of the associated uncertainties. However, there are very few GRUAN data above 40 hPa and none above 5hPa. We therefore identify a gap in reference-quality observations in the upper stratosphere and mesosphere, which particularly affects the calibration/validation of microwave and infrared temperature sounding channels at these heights, particularly AMSU-A channels 12 – 14, ATMS channels 13 – 15, CrIS channels at 667.500 cm-1, 668.125 cm-1, and 668.750 cm-1, IASI channels at 648.500 - 669.750 cm-1 and AIRS channel numbers 54 - 83. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val*** *The solution proposed here addresses the lack of reference observations for temperature at atmospheric heights 40 – 5hPa. This is important for the calibration/validation of stratospheric temperature sounding channels. An additional benefit would be increased global coverage of reference temperature-sensitive observations.*
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** Presently, access to high-quality reference network data and satellite 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 that lack interoperability (see Gap 1.06). 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 and data read/write routines and fully understand and adhere to a broad range of data policies. This is a substantial impediment to their effective usage to applications such as the GAIA-CLIM Virtual Observatory or other, similar, application areas. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Successful implementation of the Copernicus activity C3S 311a Lot3 leading to consistent provision via the CDS*** *The remedy would provide single point of access to harmonised data products served under a common data model. Note that rapid access, e.g. for satellite validation in the commissioning phase is not being addressed through this remedy (see also G6.07).* ***(R2) Operationalisation and extension of the GAIA-CLIM VO facility*** *An operational and extended virtual observatory facility would provide unified access to non-satellite reference quality measurements and specific co-located data under its purview via the Copernicus CDS.*
G5.06	**Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary** Climate research and services have an increasing need to consider a large amount of observational data and

	model outputs at the same time. Because the data volumes provided by satellite observations and ensemble model runs have increased to levels that prevent easy download to local compute environments there is an enhanced need for tools that provide functionality for data extraction, analysis and visualisation. Reference measurements are needed to provide evidence for the quality of satellite observations and models but the aforementioned tools to exploit the potential of reference measurements are currently only rudimentary. This in particular includes tools to analyse and display uncertainty of comparison results due to differences caused by in space and time mismatches of data used in comparisons. Suggested Remedy or Remedies and main relevance ***(R1) Operationalisation of a satellite – non-satellite matchups facility with appropriate discovery and user tools*** *The GAIA-CLIM Virtual Observatory could serve as a tool for the Evaluation and Quality Control pillar of the C3S if being made operational after the end of the project. Such implementation would represent an important step towards an easily accessible comparison tool that considers all kinds of uncertainty relevant for data comparisons.*
G5.07	**Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems** Recently established Quality Assurance and validation guidelines and systems are not sufficiently well recognized or understood in the global community, where validation purposes, methodologies and results can differ significantly from one report to another. Harmonized practices should now be advertised and applied more universally across the community to avoid (1) missing quality indicators, (2) incoherent results between different validation exercises, and (3) unreliable results or additional methodological uncertainties due to sub-optimal data manipulations. Moreover, there is room for further improvement in validation methodologies, taking advantage of the ever-increasing breadth of measurement, modelling, and data analysis techniques. Suggested Remedy or Remedies and main relevance ***(R1) Propagation and adoption of metrological best practices in sustained validation activities*** *The integrated concept of the proposed remedy (including research, technical developments, education and governance) ensures that the gap is broadly addressed. For optimal acceptance by the scientific community and the major stakeholders, the composition of the expert teams is key.*
G5.09	**Need to propagate various reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable robust characterisation of satellite FCDRs** Presently the evaluation of the quality of Fundamental Climate Data Records (FCDR) (observations at radiance level that serve as key inputs for model-based reanalyses and retrievals of GCOS ECVs) is based mainly on isolated activities by individual research groups. Given the importance of FCDRs for all downstream data records, there is an important and evolving requirement to improve the assessment of FCDRs by utilising non-satellite reference measurements and model fields, among other means, for validation. The utilisation of non-satellite reference measurements for this purpose requires the use of observation operators (often in the form of radiative transfer models) to transfer the reference measurements into the measurement space of the satellite instrument. 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 FCDRs. Suggested Remedy or Remedies and main relevance ***(R1) Implement a forward radiative transfer capability into the Virtual Observatory*** *Implementing the proposed remedy would help to satisfy a clear user need expressed by the GAIA-CLIM User Survey. The remedy present an important step forward towards the validation of Fundamental Climate Data Records that can be evaluated for many instruments using non satellite reference measurements available within the GAIA-CLIM VO.* ***(R2) Improved characterisation of error covariances in GRUAN measurements*** *Uncertainty covariance information needs to be made available and used appropriately within applications that convert from geophysical profile data to TOA radiances. The solution proposed is fully aligned with the requirement to establish traceable uncertainties for NWP fields and radiances calculated from them.*
G5.11	**Non-operational provision of reference measurement data and some (L2) satellite products may prevent use in Copernicus operational product monitoring**

	Copernicus Services including the Climate Change Service provide information in close to real time using global and regional reanalysis outputs as well as satellite L2 products. These outputs are not always consistent with their own climatology because input data are not produced with the same quality at real time as they are in elaborated climate data records. The availability of so called Climate Data Record Interim products would remedy this problem by producing products with as high as possible consistency with the climatology being based on automated satellite inter-calibration and careful quality control. This type of data records is emerging from operational satellite agencies but lacks optimal means for validation due to unavailability of many non-satellite reference measurements in close to real time. Suggested Remedy or Remedies and main relevance ***(R1) Operationalise processing and delivery for non-satellite reference measurements and satellite CDR Interim L2 products*** *The remedy would significantly increase the use of non-satellite reference data in Copernicus Services. The operational character of quality control and delivery mechanism for such data and their subsequent operational use would potentially lead to a funding of measurement systems from operational sources that would sustain the measurement systems and associated data services rather long term. This could be realised in conjunction with the already emerging generation of CDR Interim L2 products that need reliable reference measurement for their validation, which may increase the chance for funding.*
G6.01	**Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions** Current governance of high-quality measurement programs is highly fractured. Numerous networks exist at national, regional and global levels that have been set up and funded under a variety of governance models. This fractured management of observational capabilities can lead to, amongst others: redundancies; spatiotemporal gaps; varied data formats; varied data processing choices, and fractured provision of data. The gap thus contributes to many other more specific gaps identified in the GAIA-CLIM GAID process. Suggested Remedy or Remedies and main relevance ***(R1) Short-term cross-network governance steps*** *The remedy would lead to improved cross collaboration and understanding between networks of potential synergies and serve to improve the visibility of activities between synergistic groups.* ***(R2) Longer-term rationalisation of observational network governance*** *The remedy would make it easier for funding and research communities to interact with the high-quality measurement networks.*
G6.02	**Geographically dispersed observational assets reduce their utility for satellite Cal/Val** As a result of fractured governance along with historical funding decisions, observation systems, which may, in principle, be synergistic, are not presently sufficiently geographically co-located in order to realise the benefits. For example, a twice-daily radiosonde program is undertaken 100 km from a facility with lidars and an FTIR. This dispersion of observational capabilities substantially reduces their overall value to the user community for uses including, but not limited to, satellite instrument characterisation. Suggested Remedy or Remedies and main relevance ***(R1) Reviews of capabilities leading to action plans for rationalisation*** *The remedy would lead to rationalisation of observing capabilities to selected super-sites where justified.*
G6.03	**Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects** There are many non-satellite measurement systems that, in principle, could be used for the purposes of satellite characterisation on a sustained basis. Such measurements are metrologically well characterised and understood and target variables, which are measured or measurable from space. However, many of the measurement systems are discontinuous in time and their scheduling is made with no regard to satellite overpass times. This diminishes their value for satellite Cal/Val activities considerably. Better scheduling would increase their intrinsic value for satellite programs. Suggested Remedy or Remedies and main relevance ***(R1) Optimization of scheduling to enhance capability for satellite Cal/Val activities*** *Better scheduling would increase the number of co-locations available for measurement systems that are discontinuous in time and increase the intrinsic value of the non-satellite observations for satellite Cal/Val.*

G6.06	**Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 and derived higher level products** Many sub-orbital reference measurements have the potential to be operated on a sustained and continuous basis, thereby maximising opportunities for the validation of satellite-based measurements, as well as higher level data products derived from them. For various reasons - including scientific, technical, operational, organisational and financial reasons - this potential has not been fully realised to date as many reference observations are obtained only intermittently. This gap sets out the general and overarching case for '*operationalising*' key reference measurements. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis*** *Remedy 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 of the asset.*
G6.07	**Different data policies in different networks harm the use of complementary data from different networks** Most networks have grown bottom-up and each one has established its own specific data policy. The consequence hereof is that portals providing access to data from several networks, or users who combine data from different networks in a study or application, must deal with different data policies. This makes the combined use of complementary data quite tedious, also requiring for the user to be familiar with the different data policies used in order to fully conversant with the stated policies. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Coordination at European level to harmonise data and licence policies by extending the use of existing technical standards*** *The remedy of adopting an open data policy means that once the data are submitted to the data archive/data centre, they are public for all users, including commercial users; This facilitates and stimulates the use of the data and stimulates the (combined) use of complementary data from different networks, hence a larger cost-effectiveness of the networks. To make this option acceptable for the data providers, the latter should get credit for their data. The funding organisations must be made aware of the use of the data, as an encouragement to sustain the data acquisition. Harmonisation of data policies, facilitates the data access in data portals and for data users – stimulating the (combined) use of complementary data from different networks, hence a more beneficial use of the networks data.*
G6.12	**Under-capacity of workforce to exploit satellite data and satellite characterisation** While it is necessary to address technical and organisational gaps that reduce the availability, effectiveness and quality of satellite characterisation data, doing so is moot unless there is a sufficient capacity to develop and deliver products and services to the marketplace. There is a shortage of skilled workforce from the development and deployment of high-quality non-satellite instrumentation, through its processing to its exploitation to provide high-quality data products making use of both satellite and non-satellite data. 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 that can fully exploit the substantive investment in space-based and non-space based observational assets and deliver the envisaged step-change in capabilities and services. <u>Suggested Remedy or Remedies and main relevance</u> ***(R1) Undergraduate, masters and doctoral training programs in Copernicus-relevant programs*** *The exploitation of Copernicus data and services requires the training of a competent workforce of data providers, analysts, managers and service provision experts.* ***(R2) Instigate formal qualification of competency in provision of Copernicus services*** *Ensure that users can be confident of competency of service provider to deliver relevant information services.*

Annex II Proposed Remedies per Potential Actor(s)

In order to facilitate the use of the catalogue of gaps by stakeholders and potential actors, this Annex provides additional tables listing the proposed remedies per potential actor. Note that many of the proposed remedies have been assigned to (many) more than one potential actor and, therefore, each of the remedies might appear multiple times in the tables below.

The potential actors that have been distinguished include:

- Copernicus Programme
- EU Horizon 2020 Programme
- Space Agencies
- WMO
- National Funding Programmes
- Academia and Individual Research Institutes
- National Meteorological Services
- National Measurement Institutes
- SMEs and Industry

Table A2.1 *Remedies proposed for the Copernicus Programme*

G1.03(R1)	Further deployments and refinements of the GAIA-CLIM approach
G1.04(R1)	Extension and continuous update of the GAIA-CLIM review of existing geographical gaps for non-satellite observations
G1.05(R1)	Mapping tools to match satellite and non-satellite observations
G1.06(R1)	Design and implementation of Unified Meta Data Format
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Steps to better realise benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G2.34(R1)	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations

G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G5.01(R1)	Successful implementation of the Copernicus activity C3S 311a Lot3 leading to consistent provision via the CDS
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM VO facility
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.09(R1)	Implement a forward radiative transfer capability into the Virtual Observatory
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R1)	Short-term cross-network governance steps
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table A2.2 *Remedies proposed for the EU Horizon 2020 Programme*

G1.03(R1)	Further deployments and refinements of the GAIA-CLIM approach
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Steps to better realise benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.34(R1)	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G2.37(R1)	Establish traceability of spectroscopic properties of Essential Climate Variables
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.01(R1)	Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties
G4.12(R1)	Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val

G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.09(R1)	Implement a forward radiative transfer capability into the Virtual Observatory
G5.09(R2)	Improved characterisation of error covariances in GRUAN measurements

Table A2.3 *Remedies proposed for Space Agencies*

G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G1.05(R1)	Mapping tools to match satellite and non-satellite observations
G1.06(R1)	Design and implementation of Unified Meta Data Format
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Steps to better realise benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.06(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM VO facility
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.09(R1)	Implement a forward radiative transfer capability into the Virtual Observatory
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R1)	Short-term cross-network governance steps
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation

G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table A2.4 *Remedies proposed for WMO*

G1.03(R1)	Further deployments and refinements of the GAIA-CLIM approach
G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G1.04(R1)	Extension and continuous update of the GAIA-CLIM review of existing geographical gaps for non-satellite observations
G1.05(R1)	Mapping tools to match satellite and non-satellite observations
G1.06(R1)	Design and implementation of Unified Meta Data Format
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Steps to better realise benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G6.01(R1)	Short-term cross-network governance steps
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis

Table A2.5 *Remedies proposed for National Funding Programmes*

G1.04(R1)	Extension and continuous update of the GAIA-CLIM review of existing geographical gaps for non-satellite observations
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Steps to better realise benefits of a system of systems approach to observing strategies
G2.06(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations

G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.07(R1)	Coordination at European level to harmonise data and licence policies by extending the use of existing technical standards
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table A2.6 *Remedies proposed for Academia and Individual Research Institutes*

G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Steps to better realise benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.06(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars
G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.08(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterisation
G2.13(R1)	Development and testing of MWR standards and secondary standards
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.22(R1)	Regular cell measurements and ILS retrievals are to be performed in a consistent manner
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-

	based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table A2.7 *Remedies proposed for National Meteorological Services*

G1.04(R1)	Extension and continuous update of the GAIA-CLIM review of existing geographical gaps for non-satellite observations
G1.06(R1)	Design and implementation of Unified Meta Data Format
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.01(R1)	Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G4.12(R1)	Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val
G5.09(R2)	Improved characterisation of error covariances in GRUAN measurements
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table A2.8 *Remedies proposed for National Measurement Institutes*

G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.08(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterisation
G2.13(R1)	Development and testing of MWR standards and secondary standards
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities

G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.07(R1)	Coordination at European level to harmonise data and licence policies by extending the use of existing technical standards
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table A2.9 *Remedies proposed for SMEs and Industry*

G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.08(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterisation
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis

List of Acronyms

ACSO	Absorption Cross Section of Ozone (IGACO activity)
AQ	Air Quality
AMF	Air Mass Factor
C3S	Copernicus Climate Change Service
Cal/Val	Calibration and Validation
CAMS	Copernicus Atmospheric Monitoring Service
CCI	Climate Change Initiative (ESA)
CDR	Climate Data Record
CDS	Copernicus Data Store
CEOS	Committee on Earth Observation Satellites
CFH	Cryogenic Frost point Hygrometer
DIAL	Differential Absorption Lidar
DOAS	Differential Optical Absorption Spectroscopy
E-AMDAR	Eumetnet Aircraft Meteorological Data Relay
EARLINET	European Aerosol Research Lidar Network
EARTHCARE	Earth Clouds, Aerosols and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
ESA	European Space Agency
EUMETNET	European Meteorological Network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FTIR	Fourier Transform InfraRed spectroscopy
GAIA-CLIM	Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring
GAID	Gaps Assessment and Impacts Document
GCOS	Global Climate Observing System
GEOMS	Generic Earth Observation Metadata Standard
GEOSS	Global Earth Observation System of Systems
GHG	Green House Gas
GNSS-IPW	Global Navigation Satellite Systems Integrated Precipitable Water
GRUAN	GCOS Reference Upper-Air Network
IAGOS	In-service Aircraft for a Global Observing System
IGACO	Integrated Global Atmospheric Chemistry Observations
ILS	Instrument Line Shape
IR	Infrared radiation
LIDAR	LIght Detection And Ranging
LOS	Line Of Sight

LS	Lower Stratosphere
LSM	Land Surface Models
LT	Lower Troposphere
MAX-DOAS	Multi-Axis Differential Optical Absorption Spectroscopy
MWR	Microwave Radiometry
NDACC	Network for the Detection of Atmospheric Composition Change
NMI	National Metrological Institute
NMS	National Meteorological Service
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
QA/QC	Quality Assurance / Quality Control
QA4ECV	Quality Assurance for Essential Climate Variables
SZA	Solar Zenith Angle
TCCON	Total Carbon Column Observing Network
TCWV	Total Column Water Vapour
TCLW	Total Cloud Liquid Water
TOA	Top of Atmosphere
US+M	Upper Stratosphere and Mesosphere
UT	Upper Troposphere
UT/LS	Upper Troposphere / Lower Stratosphere
UV	Ultraviolet
VO	Virtual Observatory
WMO	World Meteorological Organization
WP	Work Package
ZTD	Zenith Total Delay