GAIA-CLIM Report / Deliverable D2.2

Gap Analysis for Integrated Atmospheric ECV Climate Monitoring:

Update for GAIA-CLIM Gaps Assessment and Impacts Document from WP2

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Document history

Version	Author(s) / Reviewers	Date	Changes
0	Peter Thorne, Michiel van Weele	13/05/16	Document template provision to all WP leads
0.1	Karin Kreher	22/06/16	Previously identified gaps reviewed and made SMART
0.2	Karin Kreher	29/06/16	Updates based upon feedback received
1.0	Karin Kreher	30/06/16	Final updates

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Executive Summary

This deliverable constitutes further input from WP2 (Measurement uncertainty quantification) to the drafting of the living Gaps Assessment and Impacts Document (GAID) of Task 6.2 (WP6), led by KNMI. The purpose of the GAID is to collate and document gaps directly relevant to the aims of the GAIA-CLIM project. The GAIA-CLIM project is concerned with increasing the utility, use and value of non-satellite observations to characterise satellite observations. Further project details are available at www.gaia-clim.eu.

This deliverable refers to the second official release of the GAID (D6.4) and builds upon the gaps identified therein. In addition, it arises any new gaps that have been identified in relation to the Work Package activities.

WP2 is concerned with the assessment and further development of reference quality measurement capabilities and uncertainty quantification. As part of this research, six instrument and ECV specific sets of measurements have been chosen, and in each case the aim is to either attain metrologically traceable measurements or to achieve substantial progress to that end. The steps foreseen include the production of traceability chains, the documentation as to how to take the measurements and process the data and peer-reviewed publications of the analyses. The existing gaps in the uncertainty assessment are also investigated and described. In addition, work is to be undertaken to understand and quantify uncertainty in measurements from several additional measurement techniques that are made in a more globally complete manner.

This deliverable further expands upon the gaps identified in the initial work package input, relevant gaps sourced externally, and new gaps that have been identified by participants. The gaps discussed herein are exclusively those related to the WP aims and remit (see prior paragraph). A key focus of the current iteration is to make the gaps and their remedies more SMART (Specific, Measurable, Actionable, Relevant and Timebound) with realistic cost estimates and assessments of the risk / cost of leaving the gap unremedied. In year 3 the GAID shall inform the development of a list of prioritised recommendations and this shift in emphasis is expected to help inform such an exercise.

1. Document rationale and broader context

The purpose of this document is to provide input to the Gaps Assessment and Impacts Document (GAID) of the GAIA-CLIM project arising from WP2. This WP is primarily concerned with quantifying the measurement uncertainty of a range of ground-based & sub-orbital reference instruments applicable to atmospheric ECVs that are, or could be used in the validation of satellite-based measurement of the same ECVs. The WP focus under Task 2.1 consists of six specific sub-tasks which are instrument and ECV specific. In each case, the aim is to either attain metrologically traceable measurements or achieve substantial progress to that end. Traceability chain models are designed within GAIA-CLIM consistent with what is done in other QA projects, such as QA4ECV and QA4EO, and applied in the H2020 sister project, FIDUCEO to ensure consistency of approach across the EO domain.

WP2 also looks across the various measurement techniques and measured quantities with the aim to establish the current state of the uncertainty propagation understanding and to review the robustness of the metrological aspects of this. One key challenge is to unify the approach taken by each of the contributors, providing a metrological framework into which the very diverse set of measurements can be brought. This unification leads to better inter-comparability between measurements of the same quantity (ECV) taken by very different techniques (e.g. ozone) but also allows common threads and steps to be identified. To this end, an initial 'Guide to Uncertainty in Measurement and its Nomenclature' summary document has been developed and used within WP2 (Task 2.3). The uncertainty assessment for the measurement capabilities will be added to the online tool for the visualization of existing measurements capabilities for each ECV (which is developed within WP1).

In addition, the WP shall undertake an assessment of the uncertainties in more globally complete measurements arising from baseline and comprehensive networks (see GAIA-CLIM deliverable D1.3). For these measurements best estimates of the uncertainties shall be derived based upon available evidence. However, these measurements shall not be fully traceable. This Task 2.2 activity has only just begun and so all current gaps arise from Tasks 2.1 and 2.3 in the current set of input gaps arising from this WP.

The GAID has now gone through 2 iterations. The first iteration was based upon a combination of the user survey and individual inputs from this and the four remaining underlying Work Packages. The second iteration built upon this by incorporating feedback from the first user workshop and additional informal input delivered from this and other Work Packages. The third version shall build upon the second by considering input arising from this current set of deliverables. That version shall be discussed at the second user workshop to be held in Brussels in November 2016 and the input received shall lead to a further iteration, which shall form the initial basis for a set of prioritised recommendations arising from Task 6.3.

Feedback from the science advisory panel, the first General Assembly, and the review pointed collectively to the need to evolve the GAID to go beyond characterising the gap to considering in more detail implications, potential SMART remedies, costs, and the benefits of resolving them. This then shall help allow external and internal users to more fully explore and appreciate the gaps identified prior to work by Task 6.3 to collate a set of prioritised recommendations.

2. Summary of gaps from GAID v2 relevant to the current WP

The gaps identified in GAID that shall be considered in further detail in Section 4 are summarised below. This is a direct subset of relevant entries from Table 2.2 of the version 2 release of the GAID. These gaps arose from either the initial Deliverable from this WP (D2.1) or from subsequent external input. All gaps are assigned an owner within GAIA-CLIM, even if they arose from an external source. Note that no text or update was forthcoming for Gap identifier G2.25. As a result although it is included in the table below it shall not be discussed in Section 4. Efforts will be made to update this gap by the FTIR task group and provide an update directly to KNMI as a supplement for incorporation in the GAID v3. Any such update shall be posted to the GAIA-CLIM website as a supplement to this deliverable. We have in addition adopted two gaps originally from WP1 that are felt to be more appropriate to be considered in WP2 (G1.10 and G1.11).

Gap Identifier	Gap Type	ECV(s)	Gap Short Description	Trace
G1.10	Uncertainty	H_2O, O_3, T, CO_2, CH_4, aerosols	Insufficiently traceable uncertainty estimates	D1.3 Immler et al., 2010
G1.11	Uncertainty	H_2O, O_3, T, CO_2, CH_4, aerosols	Traceable uncertainty estimates from baseline and comprehensive networks	D1.1, D1.4 Immler et al., 2010
G2.01	Coverage Governance	Aerosols	Common lack of continuous operation of aerosol lidar measurement systems	n/a
G2.02	Coverage	Aerosols	Lidar measurements missing vertical coverage in lowermost altitude range	D2.2, D2.4
G2.03	Comparator unc. Governance	Aerosols	Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars	n/a
G2.04	Uncertainty Governance	Aerosols	Missing continued intercomparison of lidars with appropriate reference systems	D2.2 Wandinger et al., 2015

G2.05	Uncertainty	Aerosols	Lack of metrologically rigorous aerosol lidar error budget availability	Earlinet
G2.06	Uncertainty Governance	Aerosols	Need for more multi-wavelength Raman lidars	D2.2 Veselovskii et al., 2012
G2.07	Uncertainty	Aerosols	Need for assimilation experiments using lidar measurements	D2.2 EU project website ACTRIS2: www.actris.eu
G2.08	Uncertainty	Aerosols	Reducing water vapour lidar calibration uncertainties using a common reference standard	D2.2
G2.09	Coverage	H_2O	Continuous water vapour profiles from Raman lidars limited during daytime	n/a
G2.10	Coverage	O_3	Tropospheric O_3 profile data from non-satellite measurement sources is limited	n/a
G2.11	Uncertainty	O_3	Lack of rigorous tropospheric O_3 lidar error budget availability	Leblanc et al., 2016a
G2.12	Uncertainty	T	Lack of rigorous temperature lidar error budget availability	Leblanc et al., 2016b
G2.13	Uncertainty	T, H_2O (+column), *liquid H_2O*	Missing microwave standards maintained by National/International Measurement Institutes	D2.1 Walker et al., 2011
G2.14	Uncertainty	T, H_2O (+column), *liquid H_2O*	Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals	D2.1 Rosenkranz, 2015
G2.15	Uncertainty Governance	T, H_2O (+column), *liquid H_2O*	Lack of unified tools for automated MWR data quality control	D2.1 EU Cost action TOPROF Report Löhnert & Maier, 2012
G2.16	Uncertainty Governance	T, H_2O (+column), *liquid H_2O*	Missing agreement on calibration best practices and MWR instrument error characterization	D2.1 EU Cost action TOPROF Report Löhnert & Maier, 2012
G2.17	Uncertainty Governance	T, H_2O (+column), *liquid H_2O*	Lack of a common effort in homogenization of MWR retrieval methods	D2.1 EU Cost action TOPROF Report

				Cimini et al., 2011
G2.18	Uncertainty	H_2O, O_3, CH_4	Better agreement needed on systematic versus random part of the uncertainty in FTIR measurements and how to evaluate each part	NORS_D4.3_UB.pdf
G2.19	Uncertainty	H_2O, O_3, CH_4	Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a FTIR retrieval	NORS_D4.2_DUG.pdf
G2.20	Uncertainty	H_2O, CH_4	Substantial spectroscopic uncertainties in FTIR H_2O and CH_4 products	Hase et al., 2012 Frankenberg et al., 2011
G2.21	Uncertainty	CO_2, CH_4	Current spectroscopic databases contain uncertainties specifically effecting TCCON retrievals of CH_4 and CO_2	Wunsch et al., 2011
G2.22	Uncertainty	O_3, CO_2, CH_4	FTIR cell measurements carried out to characterize ILS have their own uncertainties	Hase et al, 2012 Hase et al., 2013
G2.23	Uncertainty	CH_4	Possible SZA dependence in the FTIR CH_4 retrievals during polar vortex overpasses	n/a
G2.24	Uncertainty	CO_2, CH_4	Lack in in-situ calibration of CH_4 and CO_2 FTIR measurements	Wunsch et al., 2011
G2.25	Uncertainty	H_2O (column), O_3 (column), CH_4 (column)	TCCON calibration w.r.t. standards	n/a
G2.26	Uncertainty	O_3 (column)	Uncertainty in O_3 cross sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis	NORS_D4.3_UB.pdf NDACC_UVVIS-WG_O3settings_v2.pdf
G2.27	Uncertainty	O_3 (column)	Random uncertainty in total column O_3 retrieved by UV-vis spectroscopy dominated by instrumental imperfections impacting on the spectral fit calculations	NORS_D4.3_UB.pdf NDACC_UVVIS-WG_O3settings_v2.pdf
G2.28	Uncertainty	O_3 (column)	Uncertainty in *a priori* profile shape for AMF calculations for zenith sky O_3 retrievals	Hendrick et al., 2011
G2.29	Uncertainty	O_3 (column)	Uncertainty in the vertical averaging kernels used for DOAS total column O_3 retrievals	Eskes and Boersma, 2003

G2.30	Uncertainty	O_3 (column)	Lack of uncertainty quanification for Pandora O_3 measurements	Herman et al., 2015
G2.31	Uncertainty	O_3 (tropospheric column)	Lack of understanding of the information content of MAX-DOAS tropospheric O_3 measurements	D2.1; Liu et al., 2006 Irie et al, 2011 Gomez et al., 2014
G2.32	Uncertainty	O_3 (tropospheric column)	Better characterization of the different MAX-DOAS tropospheric O_3 retrieval methods needed	Same as for G2.31
G2.33	Uncertainty	O_3 (tropospheric column)	Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric O_3 measurements	D2.1; Liu et al., 2006 Irie et al, 2011
G2.34	Uncertainty	H_2O (column)	Uncertainties of ZTD for GNSS-PW, given by a 3rd party without full traceability	Ning, 2012

3. New gaps identified by WP participants to date

Subsequent to the first official input to the GAID (D2.1), substantial work has been undertaken upon the Work Package in the following respects:

- Traceability chains have been developed within WP2, Task 2.1, for several instrument/ECV combinations which are close to reference quality status or have now achieved that status.
- The measurement uncertainties for these specific instrument/ECV combinations have been investigated (ongoing) and the existing gaps in our knowledge of these actual measurements uncertainties have been reviewed.
- The best candidates of ground-based reference-type measurements to be added to the 'Virtual Observatory' have been identified and are listed in the Reference Observation Readiness (ROR) Table.

In particular, for the individual subtasks of Task 2.1, the following activities have been undertaken:

- The lidar observation techniques for measuring aerosol, water vapour, ozone, and temperature have been reviewed, including additional material collected from related projects and networks (e.g., ACTRIS, ACTRIS-2, EARLINET, NDACC, ISSI-NDACC) to ascertain the existing gaps in forming a traceable chain defined according to the recommendation provided in the GAIA-CLIM Guidance note 'Guide to Uncertainty in Measurement and its Nomenclature'. **A similar review had been performed for all the other subtasks as well.**

- The relevant ECV product chains measured using lidar techniques have been developed incorporating feedback from discussions with NPL experts on aspects of uncertainty traceability. Initial ECV product chains using several lidar techniques have been provided according to the current state of our knowledge. They characterize the traceability chains for ozone, temperature, and aerosol-backscattering and aerosol-extinction coefficients measured using Differential absorption lidar (DIAL), Raman, and elastic lidar techniques respectively, and are based on the documents describing the quality-assurance procedures established within ISSI-NDACC and ACTRIS/EARLINET.
- Following and reporting on the development of microwave standards at metrology institutes. Scientists at the National Institute of Standard and Technology (NIST) have developed plans for establishing traceability for microwave remote-sensing measurements. The plan includes the theory necessary to link microwave remote sensing measurements to primary noise standards. It was documented in a NIST internal report (Randa, 2004). The current status is presented in a conference paper (Houtz et al., 2014). These activities are relevant for G2.14.
- Reviewing the literature for tackling the evaluation of microwave radiative transfer model uncertainties. A recently published paper (Brogniez et al., 2016) evaluates the forward model uncertainty near the 183 GHz absorption line. This paper will serve as a solid reference for evaluating the uncertainties in the 20-60 GHz range. These activities are relevant for G2.15.
- Reporting on the latest development assessing best practices for microwave radiometer (MWR) calibration and error characterization. In the frame of European COST action ES1303 (TOPROF), the MWR working group (WG3) made recommendations for standardized procedures for MWR calibration and error characterization. These activities are relevant to G2.16.
- Reporting on the latest development towards homogenization of MWR retrieval methods. In the frame of COST TOPROF, the WG3 is developing and testing network suitable retrieval methods. These activities are relevant to G2.17.
- FTIR traceability diagrams have been developed for TCCON and NDACC following the GAIA-CLIM Guidance note, "Guide to Uncertainty in Measurement and its Nomenclature" and the existing python uncertainty computation tools for the Optimal Estimation retrieval software tool SFIT4 have been adapted as required. This software package can now deal with full 2D covariance matrix inputs for the propagation of these retrieval parameter uncertainty matrices towards the target molecule. This is required to harmonize the uncertainty computations across the different retrieval software packages used within NDACC and TCCON.
- Based on the identified gaps and reviews of the measurement uncertainties, strategies have been developed on what needs to be done to achieve full traceability and hence reference quality status for DOAS and MAX-DOAS. Ozone data sets to be included in the 'Virtual Observatory' have been identified.
- For the GNSS water vapour subtask, the comparative analysis based on software documentation (Bernese and GAMIT/GLOBK) and related literature is very close to being finished. An outline of how to undertake collaborative experiments using the

same initial data have progressed and some of the necessary Perl-scripts for data management and analysis have been compiled (activity still in progress).

These activities, in addition to advancing the aims of the GAIA-CLIM project, have given cause to further reflect on potential gaps in our collective knowledge and capabilities. This has led to one additional gap being identified.

The new gap that the work package activities has identified is as follows:

G2.35. Lack of FTIR sites with high/low albedo and Carbon emissions hot spot monitoring

Gap Type: Uncertainty

Gap Short Description: So far, all TCCON sites are located in areas with good logistical support. Even sites like Ny-Aalesund or Ascension Island have a good infrastructure, although it is time consuming and expensive to go there for maintenance. However, sites located in regions with high or low albedo are missing. Since retrievals could be biased by the albedo, observations at such sites would help investigating the existing biases in the satellite retrievals.

Furthermore, future satellite missions will concentrate on hot spot sites, like large mega cities. A validation by ground-based instruments like within TCCON would require sites around the cities to detect the emission. This can be done by the mobile COCCON instruments, but TCCON instruments would have the advantage of, for example, long-term coverage or the detection of more trace gases.

In addition a possible gap relating to “**Higher and faster measurement frequency by automatic measurement and retrieval for FTIR**” was identified but has not been fully developed at this stage. As with gap G2.25 we shall make efforts to develop this gap further and transmit directly to KNMI, posting to the GAIA-CLIM website for provenance.

4. Detailed update on traces for the gaps arising from this Work Package for inclusion in the GAID

Within this section gaps that were detailed in Sections 2 and 3 are expanded to give a full trace of our current understanding of the gap, its impacts and its potential remedies. For those gaps identified in Section 2 we take as the starting point the corresponding text arising from the GAID (v2, Section 3) text and/or the initial deliverable text (D2.1) as we deem most appropriate. This is then expanded upon here in an attempt to better delineate the gap, its impacts, its potential remedies (including indicative costs and timelines) and the scientific impact of (non-)resolution. Gaps are ordered numerically and each given a specific subsection.

4.1 G1.10 Insufficiently traceable uncertainty estimates

Gap detailed description

Limited availability of traceable uncertainty estimates propagates to applications that use model or reanalysis fields. While a vast amount of data are available, the uncertainty of such data is - in a metrological sense - often only insufficiently specified, estimated or even unknown, which frequently limits the accuracy and thus the strict interpretation and use of atmospheric measurements. This concern has been raised also by the NMIs participating in atmospheric networks (e.g. METEOMET). In order to achieve progress it is critical to have data records that are stable over time, insensitive to the method of measurement, uniformly processed worldwide, and based on traceable references. This will allow us to establish the robust scientific basis for using such fields as a transfer standard in satellite dataset characterization and other activities, and for assessing the cost-effectiveness of potential observing system enhancements.

Benefits will be logical rigour, reduction in ambiguity and better communication. A more informed use of data generated might allow large improvement in the accuracy of climate data records and might also allow to use a few satellites as reference data for calibration of models and re-analysis systems but, at present, potential users have low knowledge about the relative qualities of alternative datasets.

Activities within GAIA-CLIM related to this gap

GAIA-CLIM WP2, starting from the Posited system of systems approach to observing system maturity arising from Task 1.1, will define reference quality measurement capabilities for instruments in reference quality networks and sub-orbital (sonde and airborne) measurement capabilities currently lacking full traceability.

Gap remedy(s)

Remedy

<u>Specific remedy proposed</u>

This gap requires improvements in the operational and research observing systems, addressed by GAIA-CLIM for several techniques (e.g. lidar, FTIR, microwave radiometer) in WP2, but also a better characterization of model-based & assimilation-based uncertainty, initiated by GAIA-CLIM in WP4.

Measurable outcome of success

Application of the GAIA-CLIM recommendations and its operational implementation in the networks will be the obvious measurable outcome of success.

Achievable outcomes

Technological / organizational viability: medium.

Indicative cost estimate: low (<1 million).

Relevance

GAIA-CLIM work will establish the premises to solve this gap, but will not be able to address it operationally because this is a task that each network must undertake by fully exploiting the recommendations provided within GAIA-CLIM WP2.

Timebound

A long term strategy, with a moderately low cost, is needed and likely more studies need to performed in future to improve the model performance through the data assimilation.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Limited or neutral improvement of assimilation-based measurements.	Medium	Not fully traceable products provide limited improvement in the characterization of model-based & assimilation-based uncertainties.

4.2 G1.11 Traceable uncertainty estimates from baseline and comprehensive networks

Gap detailed description

A baseline network provides a globally and regionally representative set of observations capable of capturing, at a minimum: global, hemispheric and continental-scale changes and variability. A comprehensive network provides observations at the detailed space and time scales required to fully describe the nature, variability and change of a specific climate variable, if analysed appropriately. As such, data provided by comprehensive networks but even more by baseline networks should be actively curated and retained. Datasets from baseline and comprehensive networks provide valuable spatio-temporal coverage, but often lack the metrological characteristics needed to facilitate traceable uncertainty estimates. It is therefore essential to identify the scope for baseline and comprehensive networks, leverage expertise from reference networks, including adopting elements of best practice from reference networks, and/or facilitating reprocessing that iteratively improves dataset quality.

Activities within GAIA-CLIM related to this gap

GAIA-CLIM WP1 and WP2 will work on this aspect.

Gap remedy(s)

Remedy

This gap cannot be entirely solved within GAIA-CLIM. Nevertheless, GAIA-CLIM deliverable D1.3 supports the designation of non-satellite observational capabilities into a structured system of systems architecture consisting of reference quality, baseline and comprehensive networks. In particular, baseline networks should:

1. periodically assess their measurements either against other instruments or by dual-measurements;
2. report representative uncertainties;
3. report metadata about changes in observing practices and instrumentation.

Comprehensive networks should do the same for at least the points 2 and 3.

Measurable outcome of success

International measurement programme and infrastructure to adhere to the criteria reported above.

Achievable outcomes

Classification of the networks as reference, baseline or comprehensive is now possible using the Maturity matrix assessment provided by GAIA-CLIM project.

Technological / organizational viability: medium. Best practice established in the frame of the reference networks may strongly support at least baseline network in filling this gaps; for comprehensive network situation organizational viability is low.

Indicative cost estimate: high (>5 million)/ medium (>1million), depending on the network size.

Relevance

GAIA-CLIM, through the work discussed in the deliverable D1.3, defines the role of the different networks representing the appropriate mechanism to assess the level of maturity of each network. This tool comes in support of the identification the networks' performances and help identifying where improvements are required.

This gap is strongly related with gap G1.10 because the transfer of knowledge and best practice from reference to baseline networks is the fundamental way to push forward baseline to report uncertainties, calibrate their instruments in traceable way and retain full metadata.

Timebound

The improvement of the operation of baseline networks is strongly dependent on the plans of international bodies and stakeholders.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Limited impact of the observations provided by baseline and comprehensive networks for climate studies and satellite cal/val.	High	Poor or lack of calibration procedure and data quality/traceability from baseline and comprehensive networks critically impact on all those applications requiring high quality measurements in time and space (i.e satellite cal/val).

4.03 G2.01 Common lack of continuous operation of aerosol lidar measurement systems

Gap detailed description

Lidar profiling of atmospheric aerosol and cloud layers has become increasingly important for climate research during recent decades. More recently, the aircraft safety strategies followed after the volcanic eruption hazards of Eyjafjallajökull and Grimsvötn (Pappalardo et al., 2014) have increased the need for height-resolved monitoring of the aerosol concentration on continental scales.

Most of the lidar measurements are not performed continuously (i.e. 24 hours/7 days a week). On the other hand, thousands of ceilometers and simple backscatter lidars are operating on a continuous basis all around the world, though the quality of their contribution to the characterization of aerosol impact on weather and climate as well as to satellite validation is limited compared to the more advanced multi-wavelength Raman lidar systems or HSRL. This is because of the strong assumptions needed to provide an estimate of the aerosol optical and microphysical properties. But, as a consequence of their complexity, higher-end lidar systems are quite expensive; thus their number is limited and many of them are operated by research institutes according to the local needs or to the protocols defined within research networks (e.g. EARLINET), or only occasionally during dedicated field campaigns. In principle, modern lidar instruments are capable of operating continuously, and several EARLINET stations can already provide continuous data. Continuous operation of aerosol lidars would dramatically increase the temporal coverage of lidar measurements for a continuous and sustained satellite validation program. Fully automated lidar systems would also decrease the high man-power costs involved in the operation of lidar systems, in particular during night-time measurements.

Activities within GAIA-CLIM related to this gap

This gap will not be addressed within GAIA-CLIM. Rather, GAIA-CLIM activities carried out in the context of WP2, and addressed to define the full traceable uncertainty for the lidar optical properties, will support the activities planned in other projects, like ACTRIS and TOPROF, aiming at the near real-time delivery of 24h/7 days aerosol lidar products.

Gap remedy(s)

Remedy #1

Specific remedy proposed

In the context of the H2020 ACTRIS-2 project (2015-2019), the ACTRIS network expertise will be used to facilitate developments of easy to implement and robust solutions for automated operation and remote control of lidar instruments at EARLINET stations. The optimization of instruments for long-lasting or continuous (unattended) operation will increase the number of systems working 24h/7-day to improve the temporal coverage of lidar data. The first and second reports of ACTRIS-2 (D2.5 and D2.7 from that project) related to technical upgrades and QA activities at EARLINET and Cloudnet stations, delivered in April 2016 and expected in April 2017 respectively, will provide an update about the number of operational systems and an estimate of the timescale and cost required to make an advanced aerosol lidar operational at any other station. GAIA-CLIM activity carried out within WP2 to define the full traceable uncertainty for the lidar optical properties will be combined with ACTRIS efforts towards the near real-time delivery of 24h/7-day aerosol products. Efforts towards automation will increase the number of systems working 24h/7-day and therefore increase the coverage.

Measurable outcome of success

The implementation of the ACTRIS aerosol near-real time products, assured by the agreement between the systematic validation of aerosol near-real time products with the well-established EARLINET Raman lidar products. The use of these products by modellers and the satellite community, as well as their use to monitor special events, is expected but over a longer time scale.

Achievable outcomes

Technological / organizational viability: medium. Technology has been already tested, but its implementation in the existing system requires a significant effort.

Indicative cost estimate: high (>5 million)/ medium (>1million). For an extended network lidar ACTRIS/EARLINET covering the European continent, a medium-high investment is required. An exact estimation depends on the extent of the required upgrades of the systems available at each candidate EARLINET station.

Relevance

The ACTRIS/EARLINET work described above will allow us to provide easy to implement and robust solutions for automated operation and remote control that will facilitate the optimization of instruments for long-lasting or unattended operation.

Timebound

First outcome by the end of the ACTRIS project (2019).

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Missing continuous availability of lidar measurements for satellite validation	High	Aerosol products for the satellite cal/val will not ensure the appropriate coverage and may require the use of additional ground-based lidars to assess satellite sensors' performances.
Missing continuous monitoring especially of atmospheric events (dust storms, volcanic eruptions, others).	High	Society and economy are strongly impacted by natural hazards; a mitigation of this impact requires continuous high resolution measurements in time and space.

4.04 G2.02 Lidar measurements missing vertical coverage in lowermost altitude range

Gap detailed description

Lidar profiling of atmospheric aerosol and cloud layers has become important for climate research during recent decades. Lidar systems have the technical limitation that they are limited in their coverage of the atmosphere close to the surface. The minimum altitude below which lidar can provide valid data depends on the particular configuration of the instrument and is in general different for each individual instrument even from a series-produced model as it is dependent on both, the optical design of the instrument, as well as the alignment of optical elements.

The blind area close to the ground can pose a problem in the case that the atmospheric constituent is abundant in this domain and forms a substantial part of the total atmospheric column. Therefore, in cases where a lidar profile is being used to estimate a total column observation (for instance the aerosol extinction profile in relation to a satellite derived total aerosol optical thickness), considerable biases can occur that serve to complicate the analysis.

Activities within GAIA-CLIM related to this gap

This gap will not be addressed within GAIA-CLIM. However, ongoing activities in other projects will be monitored and reported on.

Gap remedy(s)

The use of a tailored configuration of multiple receiving telescopes, each optimised to cover a specific altitude range in the atmosphere is a possible approach to minimise the problem.

In the H2020 ACTRIS-2 project (2015-2019), expertise will be used to facilitate developments of easy to implement new optical configurations at EARLINET stations. The first and second reports of ACTRIS-2 (D2.5 and D2.7) related to technical upgrades and QA activities at EARLINET and Cloudnet stations, delivered in April 2016 and expected April 2017 respectively, will provide an update on the implemented upgrades.

<u>Measurable outcome of success</u>

A measure of success is the reduction of the minimum altitude reported for a given lidar station.

<u>Achievable outcomes</u>

Technological viability: medium.

Indicative cost estimate: medium (>1million). If the technical implementation is limited to a single lidar channel the costs are modest per individual instrument. The number of channels that need to be involved in the expansion can be treated as a multiplicative factor. Also, no single instrument design is generally applicable, which adds another multiplicative factor to the design costs. For an extended network lidar ACTRIS/EARLINET covering the European continent, it requires a medium/high investment. An exact estimation depends on the upgrades of the system available at the single EARLINET station.

<u>Relevance</u>

The issue is relevant for ground-based lidar-observed species with high abundance close to the surface, and will become more important as more ground-based lidar observed ECVs will be used as reference observations.

Timebound

By the end of the ACTRIS project (April 2019), results on which is going to be the best solution to be implemented shall be available to the community.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Missing observations in blind region close to the surface.	High	Ground-based lidar products for the satellite cal/val will not fully cover the entire atmospheric column and uncertainties will remain for species with high abundance in the blind region.
Missing continuous monitoring especially of atmospheric events (dust storms, volcanic eruptions, others).	High	Society and economy are strongly impacted by natural hazards; a mitigation of this impact requires high resolution continuous measurements in time and space.

4.05 G2.03 Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars

Gap detailed description

Lidar profiling of atmospheric aerosols has become important for climate research during recent decades. Moreover, the synergy between lidar profiling and co-located total column aerosol properties provides additional insight into aerosol properties by using synergistic retrieval algorithms. For instance, using the synergy a distinction can be made between fine mode and coarse mode particles with height. This is important to understand radiative transfer in the atmosphere. In case a Raman lidar is collocated with a sunphotometer and/or a lunar photometer, even more additional parameters can be derived. Hence, to fully exploit the synergy between lidars and photometers, collocation between both types of instruments at the various sites is needed.

Activities within GAIA-CLIM related to this gap

This gap will not be addressed within GAIA-CLIM. However, ongoing activities in other projects will be monitored and reported on.

Gap remedy(s)

Installation of sun and/or lunar photometers with existing lidar systems is recommended. Placing lidars with existing sun and/or lunar photometers is often more difficult, since lidars are larger and more complex instruments that may have additional requirements related to the operating conditions of the laser.

Measurable outcome of success

More advanced aerosol information will become available when more lidars and sun and/or lunar photometers will be collocated.

Achievable outcomes

Organizational viability: medium.

Indicative cost estimate: medium (>1million). The actual cost of sun and/or lunar photometers is moderate.

Relevance

The issue is relevant for ground-based stations used for model validation and verification, as well as understanding satellite retrieval algorithms and observations. Such ground-based stations are typically multi-sensor inclined and can be motivated to install additional instrumentation.

Timebound

Ongoing

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Incomplete collocation between ground-based aerosol lidar and sun/lunar photometer	Medium	Missing height resolved aerosol microphysical information for radiative transfer calculations.

4.06 G2.04 Missing continued intercomparison of lidars with appropriate reference systems

Gap detailed description

Lidar profiling of atmospheric aerosol has become important for climate research during recent decades. Lidar systems cannot be independently calibrated. Therefore, the accuracy of aerosol lidar measurements can only be assured with internal instrumental quality checks, consistency of lidar observations with other instruments (e.g. total column aerosol observations), and through intercomparisons with lidar systems with a very well known and well documented behaviour – so called reference systems. Such reference systems and comparisons are scarce (because they are expensive due to the need for experienced crew and extensive documentation of the system) and intercomparisons have to be done by collocating the reference systems with one or more lidar systems under consideration, which is a very time consuming and costly procedure. Ideally, intercomparisons with reference lidar systems should be done regularly, but time and funding are insufficient to make this happen.

Activities within GAIA-CLIM related to this gap

This gap will not be addressed within GAIA-CLIM. However, ongoing activities in other projects will be monitored and reported on.

Gap remedy(s)

Internal quality checks and consistency with other observations must be made mandatory for established ground based aerosol lidar stations, as is done for ACTRIS/EARLINET in Europe and other networks (e.g. LALINET in South America). Furthermore, efforts should be put into sourcing funding for more regular intercomparisons with reference lidar systems. The overall recommendation is that each established ground based aerosol lidar station should be inter-compared with a reference lidar at least once during the early phases of operation of the ground based aerosol lidar station.

Measurable outcome of success

Number of intercomparisons of ground based aerosol lidars with reference systems.

Achievable outcomes

Organizational viability: low.

Indicative cost estimate: medium (>1million). Need for experienced crew, reference lidar systems, transportation, travel costs, and campaign and analysis time.

Relevance

The issue is highly relevant for any application that uses ground based aerosol lidar data as a reference.

Timebound

Ongoing

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**

Missing continued intercomparison with reference systems	High	Reduced level of traceability of ground-based aerosol lidar measurements which will have clear effects on their usefulness for aerosol transport modeller and air quality agencies, and on the monitoring of special events (e.g. volcanic eruptions, see Pappalardo et al., 2013 ACP), also leading to ambiguity in downstream applications such as satellite cal/val.

4.07 G2.05 Lack of metrologically rigorous aerosol lidar error budget availability

Gap detailed description

Lidar profiling of atmospheric aerosol has become important for climate research during recent decades. Lidar systems cannot be independently calibrated. Therefore, the accuracy of aerosol lidar measurements can only be assured with internal instrumental quality checks, consistency of lidar observations with other instruments (e.g. total column aerosol observations), and through intercomparisons with lidar systems with a very well known and well documented behaviour – so called reference systems (see G2.04). In order to establish a rigorous aerosol lidar error budget, instrumental influence, as well as influence from ancillary information and calibration issues will have to be taken into account.

Activities within GAIA-CLIM related to this gap

This gap will be addressed within GAIA-CLIM. Both a traceability chain and an error budget calculation scheme will be set up. This work is part of the GAIA-CLIM Tasks 2.1 and 2.2 with respective deliverables at months 21, 24, 33 and 34 and will be carried out by KNMI, CNR and NASA JPL.

Gap remedy(s)

A traceability chain will be set up and an error budget calculation scheme will be compiled. This will be achieved as part of Task 2.1 of GAIA-CLIM.

<u>Measurable outcome of success</u>

Established (published in peer reviewed journal) error budget calculation scheme supported by a measurement technical document detailing how these measurements should be undertaken.

Achievable outcomes

Organizational viability: high.

Indicative cost estimate: low. Lidar experts will review existing materials from open literature and other projects (e.g. ACTRIS/EARLINET and ISSI lidar project), and instigate a methodology for setting up the traceability and establishing the error budget calculations.

Relevance

The issue is highly relevant for any application that uses ground-based aerosol lidar data as a reference.

Timebound

GAIA-CLIM deliverables from WP2.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Lack of rigorous aerosol lidar error budget availability.	High	Reduced level of traceability of ground-based aerosol lidar measurements. Relevant for e.g. atmospheric radiation verification.

4.08 G2.06 Need for more multi-wavelength Raman lidars

Gap detailed description

Raman lidars or multi-wavelength Raman lidars are undoubtedly the backbone of an aerosol global measurement infrastructure as they can provide quantitative range-resolved aerosol optical and microphysical properties. Whereas the detection of aerosol layers and their vertical extent requires only simple single wavelength backscatter lidars, the derivation of extinction coefficient profiles and a series of intensive aerosol properties requires advanced lidar concepts such as high-spectral resolution lidars (HSRL, Shipley et al., 1983) or Raman lidars (Ansmann et al., 1992). The retrieval of aerosol microphysical properties and mass concentration requires at least a one-wavelength Raman lidar, but the error affecting these estimations can be dramatically reduced if a multi-wavelength lidar systems is used.

This shows the relevance of having a large number of multi-wavelength lidar systems at the global scale; the relevance is also related to their potential role as anchor reference station to study of the impact of aerosols on weather and climate and for satellite validation. The availability of multi-wavelength Raman lidar measurements also ensures that ground-based instruments can deliver wavelength conversion information for different aerosol and cloud types to relate the space-borne measurements performed by different satellite missions at different wavelengths (for example CALIPSO at 532 nm and the future EarthCARE mission at 355 nm).

Multi-wavelength Raman lidars could also 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 more dense global spatial coverage. In this process 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 an accurate aerosol study.

Activities within GAIA-CLIM related to this gap

Some activities pertinent to this will be addressed in Task 1.4 but the gap cannot be solved completely within the timeframe of GAIA-CLIM.

Gap remedy(s)

Remedy #1

Specific remedy proposed

The remedy is strongly related to the identification of the existing Raman lidar measuring aerosol properties at the global scale and then to the study of representativeness of each station in the characterization of aerosol variability in the different vertical atmospheric regions. This study will allow the identification of those climatic regions where multi-wavelength Raman lidars are required.

Measurable outcome of success

This is obviously related to the establishment of multi-wavelength Raman lidars in the region where a lack of lidar instruments is identified by a study of representativeness of the existing measurements of aerosol properties. This study allows a rationalization of the required investments.

Achievable outcomes

Task 1.4 of GAIA-CLIM will partly address this gap remedy. It will provide an estimation of the aerosol variability at the continental or at the global scale giving also recommendations for the optimal design of an aerosol lidar network. This study will allow us to identify on a scientifically sound basis the prescient gaps in the current observing systems of aerosol optical properties. This will also allow us to provide recommendations for the expansion of existing networks.

Technological: The technology to provide a robust, compact and affordable solution already exists and has been launched on the market by a few companies; decreasing the current costs and improving the performance of these systems, while taking advantage of the expertise of the existing lidar networks and of their calibration facilities, this development should not represent a big technological challenge.

Organizational viability: medium. Several institutions are investing in lidar systems and the available budget may cover the purchase or the implementation of multi-wavelength Raman lidars.

Indicative cost estimate: high (>5 million)/ medium (>1million). This gap's resolution also depends upon the funding plans of scientific institutions, agencies and Met Services who are encouraging the development of ceilometer/simple lidar networks but tend to neglect the need for a few reference Raman lidars. Costs are also strongly dependent upon the development of new robust low-cost solution available on the commercial market.

Relevance

On the basis of Task 1.4 activities, recommendations on the improvements of the existing global lidar network to characterize aerosol optical and microphysical properties will be 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.

Timebound

Recommendations will be provided in the deliverable D1.9 expected in December 2017.

Low-cost commercial solutions may increase the number of Raman systems deployed at the global scale over the next 5-10 years. Future work will be addressed to assess this commercial solution using the WP2 work on the measurement traceability and the activities carried out at the ACTRIS-2 calibration centre.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Lower spatial coverage for satellite validation using Raman lidar measurements.	Medium	There is a continuously increasing demand for aerosol products for different applications (climate, weather, satellite, air quality, solar applications, agriculture, health), but quantitative measurements can only be provided by Raman lidar systems, the spatial coverage of which is also essential for the calibration

		of baseline observations (i.e. ceilometers).
Need for the harmonization of aerosol satellite measurements performed at different wavelengths.	High	Over the coming decades, the number of aerosol satellite missions will increase and this requires the establishment of databases containing the conversion factors to allow a physically consistent use of measurements performed at different wavelengths, as described in Pappalardo et al., 2010. The risk is to have not harmonized CDRs that cannot effectively contribute to interpretations of global climate change.

4.09 G2.07 Need for assimilation experiments using lidar measurements

Gap detailed description

Uncertainties associated with aerosol emissions, both in terms of their intensity and distribution pattern, atmospheric processes, and optical properties, represent a significant part of the uncertainty associated with the quantification of the impact of aerosols on climate and air quality in regional and global models. Data assimilation techniques are implemented to decrease these uncertainties, constraining models with available information from observations. Data assimilation is possible with horizontally sparse vertically dense data. In particular, lidar data can be effectively assimilated to greatly improve model skills.

The use of ground-based lidar data allows us to anchor the bias correction for satellite lidar data using a variational bias correction scheme, in line with the growing interest by the global NWP community in using high-accuracy data from ground-based networks to constrain satellite data biases.

Aerosol lidar data can also 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. Ground-based lidar networks can instead provide quantitative measurements of aerosol backscatter and extinction coefficients. However, a limited number of aerosol lidar data assimilation experiments have been performed, preventing us from assessing the effective impact of assimilating continuous satellite lidar data and wether the current state of the lidar technology fulfils the modellers needs.

Activities within GAIA-CLIM related to this gap

GAIA-CLIM has no specific activities to help addressing this gap.

Gap remedy(s)

Remedy #1

Specific remedy proposed

ACTRIS-2 activities (ACTRIS-2 WP12) will develop a new solution for lidar data assimilation. In particular, the available lidar Near-Real time (NRT) data will be used for routine evaluation of operational models, while quality-checked (QC) and added-value (higher level data) products generated within ACTRIS networking activities will be used for the retrospective assessments of model simulations (reanalysis/reforecasts). The potential of ground-based measurements of ACTRIS-2 aerosol parameters for improvements in the regional prediction of aerosol distributions will also be explored through pilot studies addressing extreme events of public relevance, like volcanic eruptions, mineral dust storms and biomass burning events. Building on the growing interest from the global NWP community in using high accuracy data from ground-based networks to constrain satellite data biases, ACTRIS-2 will also test the use of ground-based lidar data to anchor the bias correction for satellite lidar data, using a variational bias correction scheme. The activity will overlap with the current challenges like those related to the observation density, the observation biases, and the need of models to be able to capture realistic correlations in the vertical for global forecasts.

Measurable outcome of success

Lidar data used in data assimilation techniques for appropriate model-based activities will provide a measurable outcome of success as will a few deliverable within the ACTRIS-2 project:

- D13.4 Initial report on assimilation activities expect on March 2017.
- D13.5 Report on value of measurements in the reduction in global model expect on April 2018.
- D13.7 Final report on combined measurement/model activities expect on April 2019.

Achievable outcomes

Technological/organizational viability: high. The current infrastructure already used by the ACTRIS-2 partners to assimilate CALIPSO lidar data allows for the possibility to extend their OSSE to the assimilation of other optical properties using ground-based lidar data (e.g. EARLINET). This excludes any technological challenge to remedying the reported gap.

Indicative cost estimate: low (<1 million). Costs for future operational aerosol lidar data assimilation cannot be estimated at the current stage.

Relevance

The described remedy via the ACTRIS-2 project shows a promising perspective to start addressing these gaps, and to foster further long-term project and data assimilation experiments, also given the upcoming satellite missions with a lidar instrument on-board (i.e. ADM-Aeolus, EarthCARE).

Timebound

ACTRIS-2 deliverables relevant to this gap are expected within the period from March 2017 to April 2019. This activity should continue over subsequent years with an effort that will be quantified by the Met Services.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Lack of skill in bias correction for satellite lidar data using a variational bias correction scheme.	High	Assimilation of satellite lidar data will continue to bias the model output instead of improving the forecast skills.
Larger uncertainty if aerosol lidar data are not used to constrain uncertain model processes in global aerosol-climate models.	High	Uncertainties associated with aerosol emissions impacts on climate and air quality simulations in regional and global models.

4.10 G2.08 Reducing water vapour lidar calibration uncertainties using a common reference standard

Gap detailed description

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 that vary randomly around some mean value (often addressed as a calibration constant that depends only on the instrument setup) and does not involve step jumps of unknown magnitude. These step jumps in calibration increase the time required to detect atmospheric trends, which is already typically measured in decades (Weatherhead et. al., 1998; Boers and Meijgaard, 2009). For this reason, it is important to carefully examine any calibration technique developed for ensuring stable and long-term calibrations. Absolute and relative, but also hybrid calibration methods have been developed. More recently, reference calibration lamps, tools traceable to NMIs standards, have proven to be robust for absolute calibration of water vapour Raman lidar to reduce systematic uncertainties and may represent a common reference for all the available systems.

Activities within GAIA-CLIM related to this gap

GAIA-CLIM will partially address this gap as part of WP2.

Gap remedy(s)

Remedy #1

<u>Specific remedy proposed</u>

GAIA-CLIM WP2 deals with this technique in cooperation with ACTRIS-2 WP2. At a few stations a comparison among different methods (absolute and relative) will be investigated in order to provide a set of specific recommendations for the solutions (including how to implement in a systematic way), and about the uncertainties these solutions may imply with regard to the monitoring of water vapour in the whole troposphere and in the UT/LS.

<u>Measurable outcome of success</u>

Success would be, for example, if long term comparisons between Raman lidar water vapour measurements and another traceable reference measurement technique (e.g. GRUAN radiosondes) illustrated a reduction in the lidar calibration uncertainty using absolute techniques. Evidence of this potential improvement has been reported in the literature, but comparisons and validation over longer time period have not yet been reported.

<u>Achievable outcomes</u>

Implementation of the best calibration standard identified within GAIA-CLIM WP2 in GRUAN and NDACC.

Technological / organizational viability: high.

Indicative cost estimate: low (<1 million). The cost of this lamp and of their operational use on a systematic basis is limited and affordable (less than 10k Euros per year), and therefore its implementation and use on a large scale is sustainable.

<u>Relevance</u>

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.

<u>Timebound</u>

This is not clear yet. The time frame depends on the adoption of the approach and effort required by the networks to operate Raman lidars for measuring water vapour.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Lack of harmonization between water vapour Raman lidar collected at the global scale.	High	Inhomogeneities affecting water CDR in the troposphere and stratosphere to detect a signal of climate change.
Bias in the intercomparison or in the retrieval of the site atmospheric state best estimate.	Medium	Biased site atmospheric state best estimate; partially compensated by potential sensor intercalibration.
Bias affecting datasets used for satellite validation.	Medium	Misinterpretation of satellite CDRs assuming the ground-based measurement of water vapour lidar as the reference; partially compensated using satellite intercalibration based on GPS-RO.

4.11 G2.09 Continuous water vapour profiles from Raman lidars limited during daytime

Gap detailed description

Raman lidars have been shown to provide high-resolution measurements in several experiments, but these measurements are typically restricted to night-time only, as Raman scattering is a weak physical process and the high solar background radiation during the day tends to mask these signals. 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. Only DIAL systems can do better, but they do worse in the UT/LS. Most of the water vapour Raman lidar systems are not operated during daytime and this generates a discontinuity in the water vapour monitoring in the troposphere in a climatological sense.

The use of commercial systems, Raman lidar or DIAL, designed to operate on a continuous basis, can improve the gap but with moderate to high costs, though their performance needs to be carefully assessed in advance.

Synergy with other techniques, like passive microwave radiometry, provides an alternative solution to obtaining a profile of atmospheric water vapour during daytime over the entire investigated atmospheric column: this could partially address this gap but this synergetic solution requires the elaboration of new and more accurate algorithms to fully exploit the potential of the combined datasets.

Activities within GAIA-CLIM related to this gap

GAIA-CLIM does not have any specific activity to address this gap.

Gap remedy(s)

Remedy #1

Specific remedy proposed

The ACTRIS-2 and HD(CP)² projects are working on this aspect and before April 2017 both should provide results and the assessment of the real performances of this synergetic solution. Technological improvements of lidar techniques for measuring water vapour are also expected but over the mid and long term.

Measurable outcome of success

Successful comparison with other ground-based measurement techniques (e.g. radiosondes) showing the capability of lidar - microwave radiometer synergy during daytime operations. Technological improvements to the current lidar technology must be validated against radiosoundings as well.

Achievable outcomes

Retrieval algorithms exploiting the synergy between lidar and microwave radiometer are under elaboration to improve daytime water vapour profiling capabilities.

Technological / organizational viability: high/medium.

Indicative cost estimate: low (<1 million). The cost of technological improvements in the Raman lidar or DIAL systems to improve daytime performance in the troposphere must be quantified once implemented or available on the market.

Relevance

The proposed remedy is the only chance at the moment to improve daytime water vapour profiling capabilities.

Timebound

Synergetic retrieval shall be available by end of ACTRIS project (2019).

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high

		quality services to science / industry / society
Missing monitoring of water vapour such that it is measured only during night time conditions.	Medium	Diurnal water vapour variability in the troposphere will rely on radiosoundings only; temporal resolution of available data for OSSE and satellite validation will be limited.
Lower performances of the algorithm retrieving the site atmospheric state best estimate.	Medium	Lower vertical and temporal resolution of the lidar profiling used to retrieve the site atmospheric state best estimate.

4.12 G2.10 Tropospheric O_3 profile data from non-satellite measurement sources is limited

Gap detailed description

Tropospheric O_3 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 O_3, in particular in the free troposphere, above the mixed layer and below the stratosphere, is difficult due to lack of data. Contrary to stratospheric O_3, passive satellite observations have limited access to information about tropospheric O_3. Also, ozone soundings using balloon borne samplers are too scarce to capture the relatively high spatial and temporal variability in the troposphere.

Activities within GAIA-CLIM related to this gap

This gap will not be addressed within GAIA-CLIM. However, ongoing activities in other projects will be monitored and reported on.

Gap remedy(s)

An increase in data on tropospheric O_3 is expected from various space-borne platforms with increased capabilities, such as TES and TROPOMI. However, a reinforcement of the ground-based observational capacity is also required to validate the space-borne observations and establish high-quality time series. An increase in the number of O_3 balloon borne soundings is not likely due to the high costs involved (material and personnel). There is a potential for tropospheric O_3 lidars (using the differential absorption lidar technique) to fill this gap. In the US a network of tropospheric O_3 lidars has been established (TOLNET). Similar initiatives could be pursued in Europe, where a latent tropospheric ozone lidar network could be revived. In Europe, such a network might become part of ACTRIS, which deals with short-lived greenhouse agents.

Measurable outcome of success

A measure of success is the increase in the number of available tropospheric ozone profiles.

Achievable outcomes

Technological viability: low.

Indicative cost estimate: high (>5million). Installation of new tropospheric ozone lidar systems, or refurbishment in a small network would be a fairly large undertaking.

Relevance

The issue is relevant to understanding the links between air pollution and climate change. Satellite data will likely not suffice to fill the gap.

Timebound

Ongoing.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Tropospheric O_3 profile data is limited and limits applicability to range of activities including tropospheric ozone validation from satellites.	High	Remaining gap in appropriate data sources to optimally use new satellite data and to understand processes in the troposphere related to the linkage between air pollution and climate change.

4.13 G2.11 Lack of rigorous tropospheric O_3 lidar error budget availability

Gap detailed description

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 trends, more observations are needed (see G.2.10) and a rigorous error budget is needed.

Activities within GAIA-CLIM related to this gap

This gap will be addressed within GAIA-CLIM. A traceability chain and an error budget calculation scheme will be set up. This work is part of GAIA-CLIM Task 2.1 and 2.2 and will be carried out by the task members (KNMI, CNR and NASA JPL).

Gap remedy(s)

A traceability chain will be set up and an error budget calculation scheme will be compiled.

Measurable outcome of success

Established (published in peer reviewed journal) error budget calculation scheme.

Achievable outcomes

Organizational viability: high.

Indicative cost estimate: low. Lidar experts will review existing material from open literature and other projects (e.g. ACTRIS/EARLINET and ISSI lidar project), the methodology required for setting up the traceability and establishing the error budget calculations.

Relevance

The issue is highly relevant for any application that uses ground-based tropospheric O_3 lidar data as a reference. In particular to understand the tropospheric O_3 budget and the reduction of the uncertainties in estimation of the resulting radiative forcing.

Timebound

GAIA-CLIM deliverables from WP2.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Lack of rigorous tropospheric O_3 lidar error budget availability.	High	Reduced level of traceability of tropospheric ozone lidar measurements leading to ambiguity in downstream applications such as satellite cal/val.

4.14 G2.12 Lack of rigorous temperature lidar error budget availability

Gap detailed description

Temperature lidars provide important information for trend detection in the middle atmosphere (connected to trends in the ozone layer). These are detected using lidar systems that often also measure the O_3 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 both techniques a rigorous error budget needs to be established.

Activities within GAIA-CLIM related to this gap

This gap will be addressed within GAIA-CLIM. A traceability chain will be set up and an error budget calculation scheme will be set up.

Gap remedy(s)

A traceability chain will be set up and an error budget calculation scheme will be compiled that assures metrological traceability.

Measurable outcome of success

Established (published in peer reviewed journal) error budget calculation scheme, published measurement guidance and traceability chain.

Achievable outcomes

Organizational viability: high.

Indicative cost estimate: low. Lidar experts will review existing materials from open literature and other projects (e.g. ACTRIS/EARLINET and ISSI lidar project), establish a methodology for setting up the traceability and establishing the error budget calculations.

Relevance

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.

Timebound

GAIA-CLIM deliverables from WP2.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Lack of rigorous temperature lidar error budget availability.	High	Reduced level of traceability of temperature lidar measurements leading to ambiguity in subsequent applications such as satellite cal/val.

4.15 G2.13 Missing microwave standards maintained by National/International Measurement Institutes

Gap detailed description

The traceability of the microwave radiometer (MWR) estimates and their uncertainty requires the traceability of MWR calibration to SI standards. This implies the use of certified black-body (BB) targets and temperature sensors (measuring the target physical temperature). Commercial BB targets have reached a mature state, but their characterization is usually limited. Despite this, many realizations of microwave brightness temperature standards exist in the form of heated or cooled calibration targets, although none are currently maintained as a standard by a national/international metrology institute (Walker, 2011). Thus, despite the efforts for fully characterizing the MWR absolute calibration, the traceability of any ECVs from MWR to national/international standards is currently not feasible. However, the development is ongoing (Houtz et al., 2014). This gap shall be addressed by national/international metrology institutes, and thus cannot be addressed within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

The role of GAIA-CLIM is to follow and report the technological developments at national/international metrology institutes and to inform MWR users and manufacturers about these developments.

Gap remedy(s)

Remedy #1

<u>Specific remedy proposed</u>

Metrology applicable to microwave remote sensing radiometry is currently under development at national/international measurement institutes (e.g. National Institute for Standards and Technology, USA). These efforts include the development of a standard radiometer and standard high-emissivity black body (BB) targets. It is expected that SI-traceable calibration for BB targets and transfer standards in the form of calibrated BB targets will be available at NIST in the next few years. The current status is presented in a conference paper (Houtz et al., 2014). Typical achievable uncertainties for the standard radiometer developed at NIST are on the order of 1 K in the frequency range 10 to 50 GHz. A standard BB target is also under development. The uncertainty in the BB Tb is around 0.1 K (1-sigma), covering the frequency range from 10 to 200 GHz. NIST plans to be able to calibrate other BB targets against their standards, which could then be used as transfer standards.

<u>Measurable outcome of success</u>

The successful outcome is to make MWR users and manufacturers aware of the above developments. The effective characterization of existing and/or new MWR against microwave standards would be an additional measure of success, which is subject to the availability of the transfer standards before the end of GAIA-CLIM.

Achievable outcomes

Technological / organizational viability: medium. The technological development is ongoing. The transfer to existing MWR instruments brings organizational challenges.

Indicative cost estimate: high (>5 million).

Relevance

The remedy will make microwave standards available at least at one metrology institute (NIST), and thus it should be able to address the gap entirely. The availability of microwave standards will also help in addressing another identified gaps concerning MWR, specifically G2.16. In fact, the effective use of microwave standards may provide a solid benchmark for characterizing calibration and instrument uncertainties of different MWR instruments.

Timebound

2 to 5 years.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
No SI-traceability possible for MWR.	High	Difficult to reconcile long time series of MWR observations.

4.16 G2.14 Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals

Gap detailed description

Most common MWR retrieval methods are based on the theory of radiative transfer through the atmospheric medium. Thus, uncertainties in modelling the absorption/emission of microwave (MW) radiation by atmospheric gases and hydrometeors affect all the retrieval methods based on simulated MW radiances. Only retrieval methods based on historical datasets of MWR observations and simultaneous atmospheric soundings are not affected by absorption model uncertainties. Currently, the information on MW absorption model uncertainties are dispersed and not easily accessible. Most operational MWR operate in the 20-60 GHz range, where relevant absorption comes from water vapour, oxygen, and liquid water. A variety of models are available which combine the absorption of water vapour, oxygen, and liquid water, as well as other minor contributions. Absorption model uncertainties are currently estimated from the output difference of different models, while a more rigorous estimate is lacking. The intention is to address this gap within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

A review of the state-of-the-art of MW absorption models and the associated uncertainty is planned and has already started. The absorption model uncertainties need to be propagated through radiative transfer and inverse operator to estimate the total uncertainties affecting the retrieval methods.

Gap remedy(s)

Remedy #1

Specific remedy proposed

Modifications of absorption models are continuously proposed within the open literature based on laboratory data and MWR field observations. In addition, there have been some recent advances in this area, specially related to liquid water absorption, which are yet to be published. To fill this gap, and thus estimate the total uncertainties affecting the MWR retrievals, the following activities are needed: (i) a review of the state-of-the-art and the associated uncertainty of MW absorption models; (ii) propagation of absorption model uncertainties through radiative transfer and inverse operator.

Measurable outcome of success

The successful outcome is to produce rigorous estimates of MW forward model uncertainties in the 20-60 GHz band. An additional measure of success would be the usage of the estimated uncertainties in the retrieval methods exploited by the MWR user community.

Achievable outcomes

Technological / organizational viability: medium. The literature review has been started including several recently published papers on this topic. The review of the rigorous approach may highlight scientific challenges that shall be tentatively addressed within GAIA-CLIM.

Indicative cost estimate: low (<1 million).

Relevance

The remedy will make estimates of MW forward model uncertainties available for the MWR user community. The availability of these uncertainties will also help in addressing another identified gap concerning MWR, specifically G2.16. In fact, the effective use of MW forward model uncertainties will provide better characterization of MWR temperature and humidity retrieval uncertainties.

Timebound

2 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high

		quality services to science / industry / society
Lack of rigorous estimate for MW forward model uncertainty.	High	Lack of rigorous estimate of MWR-derived products uncertainty.

4.17 G2.15 Lack of unified tools for automated MWR data quality control

Gap detailed description

Quality control (QC) procedures are fundamental for providing users with tools for judging and eventually screening MWR data and products. Most operational MWRs apply QC procedures that are developed by either the MWR manufacturer or by the operators based on their experience. There are different levels of QC procedures, going from sanity checks of the system electronics, to monitoring the presence of rain/dew on the instrument window, to Radio Frequency Interference detection, to monitoring calibration against independent reference measurements (usually by radiosondes). The nature of the QC procedures varies, as these may be applicable to all instruments or conversely be instrument and/or site specific. Therefore, there is currently a lack of harmonization and automation of MWR QC procedures. This impacts on the quantity and quality of the data delivered, as poor QC may result in either delivery of faulty data, or screening out of good data. This gap shall be addressed at both manufacturer and network levels. An attempt is currently being carried out within the EU COST action TOPROF. Progress will be reported within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

The activities within GAIA-CLIM are to follow the developments at TOPROF and report to GAIA-CLIM as well as MWR users/manufacturers.

Gap remedy(s)

Remedy #1

Specific remedy proposed

MWR QC procedures shall be harmonized and automated to the maximum extent possible. In the framework of the EU COST Action TOPROF, the Working Group on Microwave Radiometers (WG3) is actively addressing this issue by interacting with manufacturers and proposing ways for QC automation. The leader of GAIA-CLIM Task 2.1.2 is co-chairing the TOPROF WG3. The results of these activities will be followed and reported within the GAIA-CLIM project as suggestions to users and manufacturers.

Measurable outcome of success

A successful outcome is the transmission of TOPROF findings to MWR manufacturers and users. An additional measure of success is the effective usage of the proposed QC procedures by MWR manufacturers and users.

Achievable outcomes

Technological / organizational viability: medium. Activities are ongoing, both at manufacturer and research levels. The transfer to MWR network management highlights yet to be resolved organizational challenges.

Indicative cost estimate: low (<1 million).

Relevance

The remedy will foster the application of improved QC procedures by MWR manufacturers and users. Better QC will reduce the effect of suspicious data and faulty calibration. This also helps in addressing G2.16, as better QC leads to more solid characterization of MWR temperature and humidity retrieval uncertainties.

Timebound

2 years.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Inspection by eye is recommended to detect suspicious data and faulty calibration.	High	Additional personnel costs, prone to human error, reduced homogeneity across the network impacts downstream applications.

4.18 G2.16 Missing agreement on calibration best practices and MWR instrument error characterization

Gap detailed description

Common procedures are applied by the operators to perform MWR calibration and instrument error characterization. Currently, these procedures are for the most part provided by the manufacturers, and thus they are often instrument specific. Therefore, there is currently a lack of standardization in calibration procedures and uncertainty characterization. This in turn impacts negatively on the harmonization of products provided by a heterogeneous MWR network. This gap shall be addressed at both manufacturer and network levels. An attempt is currently being carried out within the EU COST action TOPROF. Progress will be reported on within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

The activities within GAIA-CLIM are to follow the developments at TOPROF and report to GAIA-CLIM as well as MWR users/manufacturers. The currently available practices for MWR calibration and uncertainty characterization have been reviewed by the EU COST Action TOPROF Working Group on Microwave Radiometers (WG3). A first report is now available, including recommendations for calibration and uncertainty characterization. Manufacturers are also proposing new developments to make the calibration process easier. Further activities will be followed and reported within the GAIA-CLIM project.

Gap remedy(s)

Remedy #1

Specific remedy proposed

The currently available practices for MWR calibration and error characterization shall be reviewed. From these, the best practices should be defined and reported, and the documentation shall be made available to operators and users. This task is currently tackled within the EU COST Action TOPROF by the Working Group on Microwave Radiometers (WG3).

Measurable outcome of success

A successful outcome is the dissemination of TOPROF findings to MWR manufacturers and users. An additional measure of success is the effective usage of the proposed calibration and uncertainty characterization procedures by MWR manufacturers and users.

Achievable outcomes

Technological / organizational viability: high. First reports are available and the cooperation with manufacturers is established. The transfer to MWR network management provides some organizational challenges.

Indicative cost estimate: low (<1 million).

Relevance

The remedy will foster the application of standardized calibration and uncertainty characterization procedures by MWR manufacturers and users.

Timebound

1 year.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
MWR instrument reliability varying throughout a network.	High	Lack of network-harmonised MWR products which reduces their utility to applications requiring cross-network harmonised

		values such as satellite cal/val.

4.19 G2.17 Lack of a common effort in homogenization of MWR retrieval methods

Gap detailed description

Different retrieval methods are applied by different MWR manufacturers, operators, and users. Common retrieval methods include, but are not limited to, multivariate regression, neural networks and optimal estimation. This situation holds true for heterogeneous networks, such as those currently establishing in Europe. The uncertainty of MWR retrievals depends partially on the retrieval methods used, and the documentation and versioning of different methods are not usually easily accessible. Information on retrieval uncertainty is often completely missing. The traceability of software documentation and versioning is also not guaranteed. This impacts negatively on the harmonization of products provided by an heterogeneous MWR network. This gap shall be addressed at the network level. An attempt is currently being carried out within the EU COST action TOPROF. Progress will be reported on within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

The activities within GAIA-CLIM are to follow the developments at TOPROF and report to GAIA-CLIM as well as MWR users/manufacturers. Network-suitable retrieval methods are currently under development within TOPROF WG3. These activities will be followed and reported within the GAIA-CLIM project.

Gap remedy(s)

Remedy #1

Specific remedy proposed

The different types and flavors of the retrieval methods currently exploited shall be reviewed and reported. A common retrieval method is recommended for MWR belonging to a network. This task is currently tackled within the TOPROF WG3. A software package for a common retrieval method is expected within the next 2 years. The results of these activities will be followed and reported within the GAIA-CLIM project as recommendations for MWR network management.

Measurable outcome of success

A successful outcome is the dissemination of the availability of a network-suitable retrieval method to MWR manufacturers and users. An additional measure of success is the effective usage of the proposed network-suitable retrieval method in a MWR network such as the one currently establishing in Europe.

Achievable outcomes

Technological / organizational viability: high. The development is ongoing. The transfer to MWR network management faces some significant organizational challenges.

Indicative cost estimate: medium (>1million).

Relevance

The remedy will foster the use of a common network-suitable retrieval method. This will harmonise the MWR network products. This also helps to address G2.16, as better product harmonization leads to more solid characterization of uncertainties.

Timebound

2 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Quality of MWR products varying throughout a network.	High	Lack of network-harmonised MWR products leading to challenges for applications that require a harmonised network of measurements such as satellite cal/val.

4.20 G2.18 Better agreement needed on systematic versus random part of the uncertainty in FTIR measurements and how to evaluate each part

Gap detailed description

There is no clear agreement yet on what is the systematic part of the uncertainty, and on what the random part of the uncertainty in FTIR measurements is, and how to evaluate each part. Random and systematic uncertainty sources are defined differently for the two main retrieval software distributions within the FTIR NDACC working group (PROFFIT and SFIT). To harmonize the uncertainty computation, a recipe should be developed as to how a random and systematic uncertainty should be determined for each of the leading uncertainty contributions in the target retrieval uncertainty budget. The distinction between systematic and random uncertainties is important for determining accuracy and precision, e.g. when comparing to satellite data, and uncertainty of an average of data.

Activities within GAIA-CLIM related to this gap

The uncertainty calculation routines of the SFIT4 retrieval software package has been adapted so that the uncertainty budgets between both PROFFIT and SFIT4 are comparable.

Gap remedy(s)

Remedy #1

Specific remedy proposed

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.

Measurable outcome of success

Comparable and consistent errors for all different sites.

Achievable outcomes

Technological / organizational viability: high. The development is currently ongoing.

Indicative cost estimate: medium (>1million).

Relevance

The agreement on the input data for the uncertainty calculations will assure that the error estimations are comparable between different sites.

Timebound

We are now working on reprocessing FTIR CO for QA4ECV, 3 years.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Incomparable uncertainty budgets for different sites within NDACC.	High, it occurs right now	Difficulty of a network-wide and consistent data usage by downstream applications that require network homogeneity.

4.21 G2.19 Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a FTIR retrieval

Gap detailed description

The line of sight (LOS) is an important "first order" characterization of the horizontal averaging for FTIR measurements. Tools exist to calculate the line of sight for individual FTIR measurements. The UVVIS GEOMS templates have introduced variables and can be transferred to the FTIR GEOMS template to store the LOS information. This is planned for the next FTIR GEOMS template update. Comparisons cannot yet account fully for the representativeness of the data, even though the LOS is used in such a comparison. To further characterize the horizontal averaging, a more detailed study of the 3D kernels should be issued.

Activities within GAIA-CLIM related to this gap

This gap is not addressed within GAIA-CLIM.

Gap remedy(s)

Remedy #1

Enhance the existing retrieval software packages so that the forward model allows non-uniform atmospheric states.

<u>Measurable outcome of success</u>

Updated retrieval software packages along with horizontal averaging kernels.

<u>Achievable outcomes</u>

Technological / organizational viability: medium.

Indicative cost estimate: medium (<1million).

<u>Relevance</u>

Horizontal averaging and off site location of the probed airmasses is important for validation activities.

<u>Timebound</u>

5 years.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Non-optimal validation results for gases and sites	High	Ambiguity in interpretation of the observed measurements, particularly

with strong spatial gradients.		in the presence of strong gradients in the measured parameters.

4.22 G2.20 Substantial spectroscopic uncertainties in FTIR H_2O and CH_4 products

Gap detailed description

The current spectroscopic databases contain too large uncertainties to model correctly the spectral windows used for H_2O and CH_4 retrievals. Meanwhile, the FTIR instruments (ground- and space-based high resolution spectrometers) are of such high quality that they cannot only reveal inconsistencies between the parameters of different lines but also of insufficient line shape parameterisations (Voigt line shape, speed dependent Voigt line shape, etc.). This gap causes an increase the uncertainty on the delivered H_2O and CH_4 products retrieved from high resolution and high quality measurements.

Activities within GAIA-CLIM related to this gap

This gap is not addressed within GAIA-CLIM.

Gap remedy(s)

Remedy #1

Specific remedy proposed

Perform and analyse spectroscopic experiments in the laboratory in the spectral bands used for ground-based and satellite retrievals. Use the high quality atmospheric spectra for indentifying uncertainties in the parameterisation of the line shape and for constraining the uncertainties of the line parameters.

Measurable outcome of success

Updated spectroscopic databases that have better demonstrated quality and following this, an improvement in the uncertainty budget of the FTIR H_2O and CH_4 products.

Achievable outcomes

Technological / organizational viability: high.

Indicative cost estimate: medium (<1million).

Relevance

If the spectroscopic databases could be updated and improved accordingly to model correctly the spectral windows used for H_2O and CH_4 retrievals, this would demonstrably improve the data quality of the delivered H_2O and CH_4 products retrieved from otherwise high quality measurements.

Timebound

3 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Errors on the retrieved product. These errors will increase the higher the quality of the measured spectra.	It occurs right now and will become even more important in the future.	Erroneous data products leading to incorrect inferences by users and limiting applicability for downstream applications.

4.23 G2.21 Current spectroscopic databases contain uncertainties specifically effecting TCCON retrievals of CH_4 and CO_2

Gap detailed description

The shape of the calculated absorption depends on the spectroscopic data and the line shape model used. Both, the spectroscopic data and the line shape model, have a direct impact on the retrieved dry mole fractions of CH_4 and CO_2.

In the TCCON retrieval, isolated lines are assumed and the Voigt line shape, which is a convolution of a Gaussian (Doppler broadening) and a Lorentzian (pressure broadening), is used. The reason for the TCCON retrieval using the very basic Voigt line shape is that the spectroscopic databases provide almost all data needed for the calculation (not provided are the temperature dependence of the shift, self-broadening and H_2O broadening). The calculation of the shapes of isolated lines should include speed dependence and Dicke narrowing, but the spectroscopic databases do not provide any data in this regard. Hence, instead of isolated lines the line shape model should include line mixing, but also for this problem HITRAN does not provide the relevant data. A further refinement of the retrieval would be to add the calculation of speed dependent and Dicke narrowed line mixing profiles.

Spectroscopic uncertainties are present in all spectral windows used for the TCCON retrieval and, more specifically, spectroscopic uncertainties are known to increase co-retrieved O_2, which serves as an internal standard to calculate XCO_2 (CO_2/O_2) and XCH_4, (CH_4/O_2), thus increasing the uncertainty of the CO_2 and CH_4 products.

Activities within GAIA-CLIM related to this gap

This gap is not addressed within GAIA-CLIM.

Gap remedy(s)

Remedy #1

Specific remedy proposed

So far TCCON uses a scaling factor to account for the uncertainties. Since the scaling factor has been found to be the same and constant over time for all sites, this approach works well. However, for higher precision laboratory measurements as well as better line shape, models are required to consider this.

Measurable outcome of success

Retrieval of averaged mixing ratios without applying a scaling factor as well as spectral fit residuals at the noise level (without systematic features).

Achievable outcomes

In TCCON the O_2 volume mixing ratio can be regarded as constant in the atmosphere and therefore retrieved O_2 columns divided by pressure could be used as an internal standard to check the network consistency that is if the retrieval is sufficiently precise.

Relevance

Since the use of the current scaling factor allows to retrieve correct values for CO_2 and CH_4, the relevance is limited.

Timebound

We expect that within the next five years better spectroscopic data will be available. Scientists working on the line shape models include J.M. Hartmann, H. Tran (L.I.S.A., Paris) and G. Toon (NASA-JPL).

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Direct impact on the retrieved CH_4 and CO_2 products.	High	FTIR data products not of as high quality as required compromising satellite cal/val.

4.24 G2.22 FTIR cell measurements carried out to characterize ILS have their own uncertainties

Gap detailed description

Cell measurements carried out to characterize FTIR instrument line shape (ILS) 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. For instance, in order to have ILS sensitivity for fine spectral signatures we need very low pressure cells. If the pressure is too high, the cell spectra will not contain information about the ILS at large optical path difference, which is important to understand the fine spectral signatures. This problem is reported by the averaging kernel of the ILS retrieval. Inaccurate knowledge of the ILS leads to larger uncertainties on the retrieved concentrations (XCH_4, XCO_2).

Activities within GAIA-CLIM related to this gap

This gap is not remedied within GAIA-CLIM.

Gap remedy(s)

Remedy #1

Specific remedy proposed

This can be remedied by requiring that for each ILS retrieval, the averaging kernels are also reported.

Measurable outcome of success

Detailed description of the ILS uncertainties and its influence on the retrieved targets.

Achievable outcomes

Technological / organizational viability: high.

Indicative cost estimate: medium (<1million).

Relevance

The reported uncertainty budgets will be more accurate.

Timebound

2 years

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society

Underestimation of the uncertainty on the retrieval targets.	high	Inappropriate confidence assigned to the measurement series leading to erroneous conclusions in downstream applications.

4.25 G2.23 Possible SZA dependence in the FTIR CH_4 retrievals during polar vortex overpasses

Gap detailed description

Possible SZA (solar zenith angle) dependence in the retrieval during of CH_4 measured by polar vortex overpasses may influence CH_4 retrievals. During polar vortex overpasses, stratospheric profiles of CH_4 are expected to differ from those measured outside the polar vortex. This may influence some measurements at high latitudes in winter. Applying more accurate winter time *a priori* profiles would reduce residuals in the retrieval. Currently there is a lack of accurate CH_4 profile measurements under wintertime conditions.

Activities within GAIA-CLIM related to this gap

We propose to investigate the effect of profile shape changes on CH_4 retrievals measured with FTIR instruments. New measurement techniques have become available recently, such as AirCore (Karion et al., 2010; Paul et al., 2016) which provide the potential for analysis of samples collected in-situ. For example, in Sodankylä it is possible to sample stratospheric air using AirCore at the site of TCCON FTIR measurements (although there will be some spatial mismatch owing to balloon drift). Thus the effect of vortex variability can be estimated based on both FTIR and AirCore measurements.

Gap remedy(s)

Remedy #1

Specific remedy proposed

Use AirCore measurements to understand SZA dependence effects. Currently there is limited availability of these AirCore data. However, new measurements will become available during the project. For example, Lindenberg has initiated a series of AirCore launches. There are also ongoing activities to increase the usability and decrease the costs of AirCore measurements, thus allowing more sites to participate in future.

Measurable outcome of success

The measurements will contribute to the analysis, development and verification of the next version of the FTIR retrieval.

Achievable outcomes

Technological / organizational viability: medium / low. The development is ongoing. The transfer to network management provides some organizational challenges.

Indicative cost estimate: medium (>1million)/ low (<1 million).

Relevance

The remedy will contribute to improve the network wide retrieval method. This will also help to address G2.24, by providing more information on accurate profiles in both, the stratosphere and troposphere.

Timebound

2 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Quality of some FTIR products varying throughout the network.	Medium /low	Lack of network-harmonised products will lead to ambiguity in interpretation and to a reduced value in applications including satellite characterisation.

4.26 G2.24 Lack in in-situ calibration of CH_4 and CO_2 FTIR measurements

Gap detailed description

In-situ calibration of CH_4 and CO_2 can be performed by aircraft overpasses equipped with in-situ instruments. Such campaigns have been undertaken in the past at many sites, for example as part of IMECC. However, new flight campaigns in Europe are currently not planned and the flights cover only altitude up to about 12 km. Hence the AirCore technique is of great interest to many stations. Total gas column measured by an AirCore sampling system is directly related to the World Meteorological Organization in situ trace gas measurement scales. Therefore the measured AirCore data can be used to contribute to the FTIR calibration (Wunch et al., 2010) and will also provide in-situ data for a more regular validation of ground-based FTIR measurements.

Since Aircore data cover the altitude range up to 30 km, they complement the aircraft campaigns in a very suitable way. Furthermore, the station-to-station bias, which is already quite small, will be further reduced by performing new validation exercises. Understanding and minimizing the bias is essential when studying fluxes from e.g. hot spot regions.

Activities within GAIA-CLIM related to this gap

We propose to perform new AirCore measurements. The AirCore balloon measurements have the benefit of reaching much higher vertical altitudes (up to 30-35 km), compared to the aircraft measurements. In addition, year-round measurements by AirCore are possible. The

AirCore method that we propose to use here is a 100 m long coiled sampling tube, with a volume of ≈ 1400 ml (Paul et al., 2016). The sampling tube is filled during the payload descent and is automatically closed within a short time lag after the landing. The profile analysis can be performed within 2-3 hours after the landing of the payload. Gas analysis can be performed by a Cavity Ring-Down Spectrometer. Within GAIA-CLIM we will be using existing AirCore measurements and also the new AirCore measurements that become available during the project. FTIR data from the AirCore site is obtained simultaneously with the AirCore measurements. The goal is to cover all seasons so that any seasonal differences can be investigated. In addition, we will obtain a larger distribution of measured values due to the existence of a seasonal cycle. The need to perform further aircraft validation flights in combination with these AirCore measurements will be forwarded to the EU, ESA and the national agencies.

Gap remedy(s)

Remedy #1

Specific remedy proposed

Analyse new AirCore measurements. Currently there is a limited availability of AirCore measurements. However, new measurements are envisaged to become available during the project. There are also ongoing activities to simplify and reduce the cost of making AirCore measurements, thus allowing more sites to participate. The EU, ESA or national agencies should consider arranging dedicated aircraft campaigns for validation purposes in combination with Aircore launches.

Measurable outcome of success

The study would contribute to the next, improved version of the FTIR retrievals and to the assessment of the seasonal cycle. It would also lead to an increased number of AirCore measurements.

Achievable outcomes

Technological / organizational viability: High/medium**.** The development is ongoing. The transfer to network management presents some organizational challenges.

Indicative cost estimate: High (>5 million)/medium (>1million). This gap has more general nature compared to the prior gap (G2.23) which requires the use of a much larger data sets and hence is leading to an increase in the costs.

Relevance

The remedy will contribute to the network wide retrieval method. This also helps to address G2.23, by providing more information on accurate profiles in the stratosphere and troposphere.

Timebound

2 years

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
New data to be used to verify the network wide in situ calibration.	High/Medium	An impact on the traceability to standards.

4.27 G2.26 Uncertainty in O_3 cross sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis

Gap detailed description

The uncertainty in the O_3 absorption cross sections is one of the main systematic error sources in the remote sensing of atmospheric O_3 using UV-visible spectroscopy techniques. Even though the uncertainty can be considered as a systematic error source, the actual error depends on atmospheric temperature, and thus it can be considered as a *pseudo-random* error, as mentioned in the deliverable D4.3 'Uncertainty Budget' of the EC FP7 project NORS (see http://nors.aeronomie.be/projectdir/PDF/NORS_D4.3_UB.pdf). Presently the uncertainty in total column O_3 due to uncertainty in absorption cross sections is assumed to be around one to a few percent (WMO GAW report 218, NORS_D4.3_UB.pdf). In general, when the uncertainties related to O_3 cross sections and their temperature dependencies are well characterized, this effect can be included in the error budget of O_3 observations.

The recent WMO IGACO-O3/UV activity ACSO (Absorption Cross Sections of O_3 , http://igaco-o3.fmi.fi/ACSO/), performed a thorough evaluation of the existing cross sections and their impact on ground-based and satellite O_3 retrievals. In particular cross sections studied were Bass and Paur (1985), Brion, Daumont Malicet (1995) and Serdyuchenko et al. (2014). The outcome of the ACSO study was that the latest Serdyuchenko et al. cross sections are recommended to be used for ground-based Brewer and Dobson instruments. However, these cross sections were not recommended to be used for satellite retrievals due to deficiency in the signal-to-noise ratio close to 300nm. From the perspective of satellite validation, it would be beneficial if the same cross-sections were used by both satellites and ground-based instruments. However, if different absorption cross sections are used in the satellite validation, it is important to understand what type of differences they cause in the validation. Related to GAIA-CLIM, it is to be noted that neither Pandora nor any other DOAS or MAX-DOAS instruments were included in the ACSO study.

The uncertainties in the O_3 absorption cross sections are partially addressed in the GAIA-CLIM project.

Activities within GAIA-CLIM related to this gap

A literature study leading to a summary of the findings including a recommendation of how this should be applied with regard to DOAS, MAX-DOAS and Pandora instruments is planned.

Gap remedy(s)

Remedy #1

Specific remedy proposed

It would certainly be beneficial to study what impact the differences in the O_3 cross sections recommended for Dobson and Brewer instruments and the ones used for satellite retrievals have on the retrieved O_3 amount when applied within the DOAS data analysis. This will be predominantly a literature study but will also include consultation with the Brewer and Dobson community.

Measurable outcome of success

If the difference in the end product (total column O_3) is quantifiable with regard to which of the different O_3 cross sections have been used within the retrieval, then this can be applied to better compare the O_3 data measured by satellites with ground-based data sets while both satellite and ground-based observations still use their preferred O_3 cross sections for the data analysis.

Achievable outcomes

Technological / organizational viability: medium.

Indicative cost estimate: medium (>1million)/ low (<1 million). While the cost estimate for a basic sensitivity study would be low, the cost estimate for applying more sophisticated measures such as funding new lab measurements would see the cost estimate rise to medium.

Relevance

The study suggested here will help to understand the uncertainties caused by different sets of O_3 cross sections used within the data analysis and how this impacts on the overall measurement uncertainty, and therefore directly addresses this gap.

Timebound

2 years.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Higher uncertainty and/or bias in O_3 data sets due to differences in the O_3 cross sections used in the analysis.	High	Less reliable comparisons between O_3 satellite and ground-based DOAS/MAX-DOAS/Pandora data sets.

4.28 G2.27 Random uncertainty in total column O_3 retrieved by UV-vis spectroscopy dominated by instrumental imperfections impacting on the spectral fit calculations

Gap detailed description

The uncertainties in the O_3 slant columns retrieved with the standard DOAS data analysis fitting procedures are to a large part caused by (1) instrumental imperfections such as detector noise, resolution change, etaloning (a fault that develops in thin charge-coupled devices when they behave as etalons) and other non-linearities of the detector, stray-light, and polarisation effects, as well as (2) by issues introduced within the analysis routine such as uncertainties in the Ring effect, unknown absorbers, and the wavelengths dependency of the AMF (air mass factor). Such uncertainties are mostly random in nature and therefore can be estimated statistically from the least-squares fit procedure.

However, the fitting uncertainties derived from the least-squares analysis typically result in unrealistically small uncertainties and can lead to an underestimate of the measurement uncertainty by up to a factor of two. Results from intercomparison exercises (e.g. Van Roozendael et al., 1998, Vandaele et al., 2005, Roscoe et al., 2010) show that state-of-the-art instruments hardly ever agree to better than a few percent, even when standardised analysis procedures are used. This indicates that the actual accuracy in the O_3 slant columns is at least to some degree limited by uncontrolled instrumental and/or analysis factors.

Activities within GAIA-CLIM related to this gap

This gap is addressed within GAIA-CLIM and the planned activities are described below.

Gap remedy(s)

Remedy #1

<u>Specific remedy proposed</u>

The proposed action is to improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error. This will be done, firstly, by evaluating all literature studies and other documentation available on this topic and, secondly, by using the upcoming intercomparison campaign at Cabauw, the Netherlands, in September 2016 to provide more state-of-the-art data for further investigation specifically tailored to this issue.

<u>Measurable outcome of success</u>

The success will be measured by how much we can improve our understanding of the difference between a realistic uncertainty estimate versus the uncertainty provided by the data analysis fitting routines.

<u>Achievable outcomes</u>

Technological / organizational viability: medium.

Indicative cost estimate: low (<1 million).

Relevance

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.

Timebound

It will take approximately 1 year to develop and apply the suggested remedy on some test data.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
A distinct difference remains between realistic uncertainty estimates and the uncertainty calculated by the fitting routines, leading to undue confidence in reported data values.	Medium-high	Higher and poorly quantified uncertainty in data products (such as O_3) measured with the DOAS technique leading to reduced utility in applications.

4.29 G2.28 Uncertainty in *a priori* profile shape for AMF calculations for zenith sky O_3 retrievals

Gap detailed description

AMFs are required to convert the measured O_3 slant columns into vertical columns with O_3 and pressure/temperature *a priori* profiles being key input parameters for the AMF calculations. AMF uncertainties for zenith-sky twilight O_3 retrievals are dominated by errors on *a priori* profile shape effects. There is a lack of an adequate database of tropospheric O_3 in particular and in regions where tropospheric or stratospheric O_3 contents deviate from the climatological values, uncertainties of several percent can be introduced in total column O_3 retrievals. Apart from uncertainties in the O_3 *a priori* profiles, further sources of uncertainty are based on uncertainties in the aerosol and cloud information used. There is also a lack of harmonization of the AMF calculation methods, which can introduce inconsistencies between the data sets measured at different locations within e.g. the NDACC network.

This gap is to be partially addressed within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

In-depth uncertainty analysis of the AMF calculations.

Gap remedy(s)

Two remedies are listed.

Remedy #1

Specific remedy proposed

Improve climatological databases of *a priori* O_3 profiles, with particular emphasis on tropospheric O_3. Test the quality/suitability of the databases of O_3 profiles through a comparison with ozonesonde profiles at a selection of stations.

Measurable outcome of success

If we can show that the updated and improved O_3 database, when used as *a priori* for the O_3 AMF calculations, leads to a smaller uncertainty in the calculation of O_3 AMFs then we know that we have succeeded.

Achievable outcomes

Technological / organizational viability: medium. Differences between AMFs are causing the largest discrepancies between the NDACC O_3 datasets and to reduce these discrepancies, the use of standardized and further improved O_3 *a priori* data that account for the latitudinal and seasonal dependencies of the O_3 vertical profile will make a substantial contribution.

Indicative cost estimate: low (<1 million)

Relevance

Improving the climatological databases of *a priori* O_3 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 O_3 column retrieved from zenith sky UV-visible measurements.

Timebound

Marked improvement and results expected within the GAIA-CLIM time period.

Remedy #2

Specific remedy proposed

Standardize AMF calculation methods and databases of *a-priori* information used in AMF calculations.

Differences between AMFs can cause discernible discrepancies between the O_3 data sets. For example, some NDACC UV-visible groups use their own individual DOAS settings and O_3 AMFs calculated with different RTMs and sets of O_3, pressure and temperature profiles as input data, and with or without latitudinal and seasonal variations. The objective of the recommendations formulated by the NDACC UV-visible WG previously was thus to reduce these discrepancies through the use of standardized DOAS settings and O_3 AMF look-up tables that account for the latitudinal and seasonal dependencies of the O_3 vertical profile (see Hendrick et al., 2011). These tables will be reviewed and updated within GAIA-CLIM and promoted to be used to homogenise the O_3 total column data measured at different locations.

Measurable outcome of success

Determine the difference between standardized AMFs and individually calculated ones and, in turn, the difference in the calculated vertical O_3 columns. If the standardized AMF lead to smaller uncertainties in the total column O_3 datasets we know that the remedy was successful.

Achievable outcomes

Technological / organizational viability: medium.

Indicative cost estimate: low (<1 million).

Relevance

Standardized AMFs will improve the overall accuracy of the measured total O_3 column retrieved from zenith sky UV-visible measurements.

Timebound

1-2 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
AMFs used by different groups are not standardized.	Medium-high	O_3 measurements provided by different groups are not homogenized and will likely show some unknown bias from site to site or group to group.

4.30 G2.29 Uncertainty in the vertical averaging kernels used for DOAS total column O_3 retrievals

Gap detailed description

Within the NDACC UV-vis working group, look-up tables of total column O_3 averaging kernels have been developed based on the Eskes and Boersma (2003) approach, i.e. the averaging kernel of a layer i can be approximated by the ratio of the box airmass factor of this layer i and the total airmass factor calculated from an O_3 profile climatology. The availability of averaging kernel information as part of the total column retrieval product is important for the interpretation of the observations, and for applications like chemical data assimilation and detailed satellite validation studies. However, vertical averaging kernels (when provided based on a climatology) are only approximations of the real 3D averaging kernel of a retrieval and cannot fully account for the representativeness of the data.

Activities within GAIA-CLIM related to this gap

This gap is not addressed within GAIA-CLIM.

Gap remedy(s)

Remedy #1

Specific remedy proposed

An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables described above is needed and a comparison with averaging kernels derived using a direct coupling of the retrieval with the output of a chemistry-transport model, in which the *a priori* profile used in the air-mass factor calculation is replaced by a more realistic model-derived time and space dependent profile.

Measurable outcome of success

Including 3D averaging kernels for zenith-sky UV-visible O_3 measurements in satellite and model validation studies should improve the agreement between the different data sets, especially for UV-visible stations located in winter/spring at the edge of the polar vortex where the spatial and temporal gradients of the O_3 field can be very large.

Achievable outcomes

Technological / organizational viability: medium.

Indicative cost estimate: medium (>1million) - low (<1 million).

Relevance

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.

Timebound

2-3 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high

		quality services to science / industry / society
Vertical averaging kernel climatology not representative of real measurement conditions.	Medium-high	The smoothing of model and/or satellite data using vertical averaging kernel climatology can introduce bias in the validation studies.

4.31 G2.30 Lack of uncertainty quantification for Pandora O_3 measurements

Gap detailed description

Pandora is a relatively new UV-VIS instrument for measuring total O_3 and also O_3 profiles in a similar way as MAX-DOAS instruments. So far only a few studies exist which describe measurement uncertainties or measurement validation (see e.g. Herman et al. 2015, Tzortziou et al, 2012). This yields low confidence that the measurement uncertainties are currently either fully documented or rigorously quantified. For example, systematic uncertainty in Pandora direct-sun measurements are limited by temperature effects not corrected in current operational baselines. The neglect of temperature effects (related to the O_3 spectroscopy in the Huggins bands) leads to seasonally dependent systematic biases, of various amplitudes depending on the latitude of the site. This gap is partially addressed within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

A literature review will be written on the uncertainties related to total ozone retrievals using the Pandora instrument. Based on this and additional information obtained during the CINDI-2 campaign and analysis of Pandora O_3 observations at Helsinki, preliminary studies related to selected types of uncertainties will be done. We expect that the outcomes of the CINDI-2 campaign in September 2016 will provide input for this gap (http://www.tropomi.eu/science/cindi-2). Several Pandora instruments as well as MAX-DOAS instruments will participate in the campaign. Exercises and studies performed during this campaign will provide the community with relevant datasets and information about how to proceed most effectively.

Gap remedy(s)

Remedy #1

<u>Specific remedy proposed</u>

A literature review undertaken in consultation with the Pandora community will provide a better quantification of the measurement uncertainties. This literature review will be supported by findings from the CINDI-2 campaign and Pandora/Helsinki analysis, taking into account the limited funding available within GAIA-CLIM for this effort.

Measurable outcome of success

To reduce the total uncertainty of the final O_3 data product and to understand the uncertainty budget.

Achievable outcomes

Technological / organizational viability: medium.

Indicative cost estimate: low (<1 million).

Relevance

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 O_3 data products available within these networks.

Timebound

The gap will not be fully solved within the GAIA-CLIM project timeframe.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Potential systematic errors may limit satellite validation if not taken into account in the validation.	Relevance varies depending on the geographical positions if the effect is not taken into account in the satellite validation.	Potential source of systematic errors that are correlated in time and space.

4.32 G2.31 Lack of understanding of the information content of MAX-DOAS tropospheric O_3 measurements

Gap detailed description

Retrieving tropospheric O_3 from passive remote sensing observations is difficult because almost 90% of the total column O_3 resides in the stratosphere. However, it has been shown that information on tropospheric O_3 can be extracted from multi-angular observations of the sunlight scattered by the atmosphere, using the so-called MAX-DOAS technique or similarly designed instruments (see e.g. Irie et al., 2011; Liu et al., 2006; Gomez et al., 2014). Although these pioneering studies have demonstrated the feasibility of tropospheric O_3 measurements from UV-Visible absorption measurements in both the Huggins (Irie et al., 2011) and Chappuis bands (Gomez et al., 2014), the information content of such measurements remains to be explored in depth in terms of altitude range, dependency on measurement geometry (in particular the number of viewing angles being sampled), dependency on atmospheric visibility (i.e. aerosol content), solar geometry, horizontal representativeness, etc.

This current lack of knowledge of the information content of MAX-DOAS tropospheric O_3 measurements limits the assessment of the usability of the technique for large scale O_3 monitoring. This gap is partially addressed within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

This gap is partially addressed within GAIA-CLIM – however, due to the limited available funding, we envisage to inform the wider community about the gap and to contribute towards resolving the gap, but we will not be able to remedy the situation solely within GAIA-CLIM.

Gap remedy(s)

Remedy #1

Specific remedy proposed

More studies are needed to investigate the potential of the MAX-DOAS remote-sensing technique for tropospheric O_3 measurements. In particular, the information content of measurements must be analyzed in different spectral ranges (covering both Huggins and Chappuis O_3 absorption bands) and a broad range of observation geometries and atmospheric conditions. These issues will be addressed during the CINDI-2 MAX-DOAS intercomparison campaign which will be held in September 2016 in Cabauw (the Netherlands).

Measurable outcome of success

One measure of success would be the greater availability of more accurate tropospheric O_3 data based on MAX-DOAS measurements e.g. within NDACC.

Achievable outcomes

Technological / organizational viability: medium.

Indicative cost estimate: medium (>1million).

Relevance

If the information content can be better defined, and thus provide us with a clearer picture of, for example, the vertical profile and altitude range of the measurements, then this will lead to better usability of the MAX-DOAS measurements made globally.

Timebound

To develop and test this remedy will take about 2-3 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Ability to retrieve tropospheric O_3 vertical profiles/column densities from MAX-DOAS observations not assessed/investigated.	High	Satellite and model tropospheric O_3 validation studies will not benefit from these potentially highly-relevant (global coverage; measurement frequency: every 20 minutes during daytime) correlative data sets.

4.33 G2.32 Better characterization of the different MAX-DOAS tropospheric O_3 retrieval methods needed

Gap detailed description

The potential of MAX-DOAS and similarly designed instruments to measure tropospheric O_3 have only been demonstrated in a limited number of pioneering investigations. In these studies, experimental retrieval methods have been applied which are based on Optimal Estimation (OE) schemes (Liu et al., 2006; Irie et al., 2011) or on more simple approaches such as the modified geometrical approximation used in Gomez et al. (2014) to infer free-tropospheric O_3 concentration from a high-altitude site. More work is necessary to better characterize the different possible approaches to tropospheric O_3 retrievals from multi-axis scattered light measurements in both UV and visible wavelengths ranges.

Similar to the lack of information content analysis (see G2.31), the lack of consensus on retrieval methods limits the assessment of the usability of the technique for large scale O_3 monitoring. This gap is partially addressed within GAIA-CLIM.

Activities within GAIA-CLIM related to this gap

To address this gap we will undertake an investigation of the different retrieval approaches suitable to measure tropospheric O_3 from MAXDOAS-type instruments and provide an overview of the state-of-the-art understanding of the different methods.

Gap remedy(s)

Remedy #1

Specific remedy proposed

More in-depth studies are needed to investigate the different retrieval methods. Ideally this should be conducted in a coordinated way, e.g. as part of an instrument intercomparison experiment such as the CINDI campaign (Piters et al., 2012). A suitable combination would be to first develop possible strategies within GAIA-CLIM and then to test these as part of the upcoming CINDI2 intercomparison campaign during September 2016. With most of the active MAX-DOAS research groups involved, this campaign will provide an ideal opportunity for a retrieval technique study for tropospheric O_3 MAX-DOAS observations.

Measurable outcome of success

A measure of success would be if we can provide in-depth characterisations of the different retrieval methods and their advantages and disadvantages for the retrieval of tropospheric O_3 from MAX-DOAS measurements.

Achievable outcomes

Technological / organizational viability: medium.

Indicative cost estimate: medium (>1million).

Relevance

The characterisation would then provide the necessary information for the scientific community to make a better informed decision on which retrieval approach to choose and to aim at increased homogenisation of tropospheric O_3 data provided by different research groups.

Timebound

To develop this remedy will take approximately 2 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Existing methods for the retrieval of tropospheric O_3 from MAX-DOAS	High	Satellite and model tropospheric O_3 validation studies will not benefit from

observations not assessed and possibilities for further improvements/new methods not investigated.		these potentially highly-relevant (global coverage; measurement frequency: every 20 minutes during daytime) correlative data sets.

4.34 G2.33 Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric O_3 measurements

Gap detailed description

Although several studies have demonstrated the potential of multi-angular UV-Visible scattered light measurements of the MAX-DOAS and Pandora types to measure tropospheric O_3, the analysis of uncertainties and the validation of the resulting measurements has generally been limited in scope. As a result, a comprehensive error budget and validation of tropospheric O_3 retrieval from MAX-DOAS and Pandora measurements is currently lacking. Like for other MAX-DOAS measurements, the main uncertainties for O_3 are related to the estimation of the effective photon light path, which is dependent on the aerosol content and optical properties. In addition, for O_3, the interference with the strong O_3 absorption taking place higher up in the atmosphere is potentially a significant source of systematic bias.

In addition to the lack of information content (G2.31) and consensus on retrieval approaches (G2.32), the lack of uncertainty characterization and validation of tropospheric O_3 measurements from MAX-DOAS and Pandora instruments analysis limits the potential for network capabilities assessment.

Activities within GAIA-CLIM related to this gap

Assessment of both random and systematic uncertainties based on a literature review and on current findings of other projects such as NORS and FRM4DOAS.

Gap remedy(s)

Remedy #1

Specific remedy proposed

More studies addressing the characterization of uncertainties in tropospheric O_3 measurements from MAX-DOAS type of instruments are necessary. This should include an assessment of both random and systematic uncertainties and validation with reference independent observations, which can be provided by ozonesonde data and/or in-situ surface O_3 instruments. The CINDI-2 intercomparison campaign will be an ideal opportunity to support such an assessment.

Measurable outcome of success

A measure of success would be to provide a realistic traceability chain for tropospheric O_3 measured with MAX-DOAS type instruments.

Achievable outcomes

Technological / organizational viability: medium.

Indicative cost estimate: medium (>1million).

Relevance

An accurate understanding of the uncertainties in the MAX-DOAS measurements is an important prerequisite for developing strategies to further reduce the measurement uncertainty and for the validation of the MAX-DOAS data using other independent measurement techniques.

Timebound

To develop this remedy will take approximately 2 years.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
MAX-DOAS retrieval uncertainties of tropospheric O_3 not estimated in a robust and consistent manner.	Medium-high	An incomplete assessment of the error budget on tropospheric O_3 retrievals from MAX-DOAS observations will lead to a lack of robustness in the satellite and model validation studies which would use these measurements as correlative data.

4.35 G2.34 Uncertainties of ZTD for GNSS-PW, given by a 3rd party without full traceability

Gap detailed description

The Zenith Total Delay uncertainty is a key component of the total uncertainty in GNSS-PW measurements (Ning et al., 2016). If it is not handled in a proper way, it may drastically affect the GNSS-IPW uncertainty estimate. Fixing it equal to 4mm is just a compromise, excluding outliers from longer time series.

When discussing GRUAN GNSS-IPW uncertainties, we only discuss data analysis using Precise Point Positioning (PPP) in the EPOS software package. While suggesting GRUAN GNSS-IPW uncertainties should be implemented by other data analysis centres, we talk about implementing the GNSS-IPW uncertainty analysis method as described by T. Ning et al. (AMT, 2016) in different software (i.e. not EPOS, solely used by GFZ and GRUAN data analysis). This task is not trivial; for example, the orbital error components described by J. Dousa (GPS Solutions, 2010) and used by T. Ning *et al* in AMT 2015 are not delivered for end users like ZTDs from IGS (or simply obtainable from standard software for GNSS-data analysis).

Preliminary analysis has been made (and is still in progress) on documentation and related articles published by the developers of Bernese and GAMIT/GLOBK software. ZTD uncertainty is known as a main contributor to the GNSS-IPW uncertainty budget. Therefore, it is essential to understand and to find recommendations when 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 (often remarkably) different numeric values of uncertainty estimates.

Activities within GAIA-CLIM related to this gap

It has been discussed and agreed that within the GAIA-CLIM time-frame we'll concentrate solely on GRUAN GNSS-PW uncertainty assessment. This restricts the 'Virtual Observatory' user to GRUAN GNSS-PW data only, but provides a possibility to describe the traceability chain and uncertainty estimation in a consistent way, compared to all other instruments within this project and GAID.

Comparing the results offered by different parties and processed with different software (or, even while processed with the same software, but by a different operator using different initial settings) is not as straightforward as it could be expected.

Gap remedy(s)

The gap remedy actions will continue with definitions of "GRUAN GNSS-PW uncertainties" at the level GFZ has reached with their data processing and uncertainty estimation thus far as described in Ning et al. (2016).

Remedy #1

Specific remedy proposed

Task 2.1.6 aims to clarify the nature of ZTD formal error estimation, having focus on the data analyst's freedom in giving different initial constraints for GNSS data processing. TUT and MO continue with collaborative experiments, using the same set of sites in experimental network (sites chosen from COST Action BENCHMARK test), using different software and different experimental setups. The results give a possibility for a comparative study – how much the results may differ from different experiments and what will be the average formal error differences from different software. Using E-GVAP sites gives us a possibility to compare our results with results from processing the same sites by many other data analysis centres.

The main goal for the next steps is making analysis of experimental results illustrating the data processing and uncertainty assessment chain with suggestions on how to guarantee the maximum transparency of the full process. The results will be published in the peer-reviewed literature.

Achievable outcomes

The first outcome will be making GRUAN GNSS-PW with transparent uncertainty analysis usable for the 'Virtual Observatory'. It cannot be expressed in euros, but additionally it should help to make decisions for selecting and extending the 'Virtual Observatory' database with verified and usable non-GRUAN GNSS-data available worldwide (potentially processed with alternative software and data processing strategies compared to GFZ). In the future there could be a relatively dense global dataset for GNSS-PW data usable for the 'Virtual Observatory'.

Technological / organizational viability: high.

Indicative cost estimate: medium (>1million)/low (<1 million).

Relevance

This remedy (Remedy #1) should be sufficient for G2.34 and is not relevant to any other gaps defined.

Timebound

The task should be mostly completed by the end of 2016, beginning of 2017.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
GNSS-PW data cannot be used in GAIA-CLIM for the calibration and validation of satellite products.	Medium-high	GNSS-PW has an important role also in calibration/validation of radiosondes (and other instruments capable of measuring IPW). Therefore it is important that the uncertainty budget is handled in a way which is consistent with all other instruments.

4.36 G2.35 Sites with high/low albedo and hot spot monitoring

Gap detailed description

So far, all TCCON sites are located in areas with good logistical support. Even sites like Ny-Aalesund or Ascension Island have a good infrastructure, although its time consuming and expensive to go there for maintenance. However, sites located in regions with high or low albedo are missing. Since retrievals could be biased by the albedo, observations at such sites would help investigating the existing biases in the satellite retrievals.

Furthermore, future satellite missions will concentrate on hot spot sites, like large mega cities. A validation by ground-based instruments like within TCCON would require sites around the cities to detect the emission. This can be done by the mobile COCCON instruments, but TCCON instruments would have the advantage of for example long term coverage or the detection of more trace gases.

Activities within GAIA-CLIM related to this gap

This gap is not addressed within GAIA-CLIM.

Gap remedy(s)

Remedy #1

<u>Specific remedy proposed</u>

Identify suitable sites in geographical areas with high and low albedo. Establish contacts with scientists, or other appropriate partners.

<u>Measurable outcome of success</u>

New TCCON sites in target areas

<u>Achievable outcomes</u>

Atmospheric data from regions needed for satellite validation purposes

Technological / organizational viability: high.

Indicative cost estimate: medium (<1million).

<u>Relevance</u>

High

<u>Timebound</u>

The set-up of new TCCON sites depend on the financial support by EU, ESA, NASA, or other sources. We currently expect no new site in such areas within the next five years.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high**

		quality services to science / industry / society
Lack of column CO_2 and CH_4 measurements in areas required for satellite validation	High	Low confidence in the true satellite quality in areas of high / low albedo and in areas of high emissions leading to reduced utility for emissions monitoring applications and lower confidence in changes in regional abundances.

5. Summary

A primary goal of WP2 is the development and the advance of the reference quality status of a range of selected ECV/instrument combinations, such as ozone profiles measured with lidar, just to name one specific example. These techniques range from lidar, FTIR, UV-visible spectroscopy to GNSS and microwave radiometry, and many of the data streams are made available under the umbrella of networks such as GRUAN, NDACC, and TCCON. The key ECVs investigated within WP2 are ozone, water vapour, aerosol, methane, carbon dioxide and temperature. Each of the chosen combinations were lacking in some aspects of their measurement uncertainty quantification and/or in full traceability. WP2 is investigating and identifying these gaps in our understanding, and summarizing the most essential areas where further development is needed within this WP2 deliverable (D2.2) which is then, in turn, incorporated in the next version of the GAID. This report includes some gaps which already have been partially addressed, or will be addressed, within GAIA-CLIM. Some gaps will also be addressed in collaboration with the wider scientific community while other gaps will have to be left to be addressed within future projects.

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Glossary

ACSO	Absorption Cross Sections of O_3
ACTRIS	European Research Infrastructure for the observation of Aerosols, Clouds, and Trace gases
ACTRIS-2	Consolidates and improves services offered within FP7 funded Integrated Infrastructures Initiative ACTRIS (http://actris2.nilu.no/Projects/ACTRIS2IAinH2020(20152019).aspx)
ADM-Aeolus	Atmospheric Dynamics Mission Aeolus
AMF	Air Mass Factor
BB	Black Body
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CDR	Climate Data Record
CLOUDNET	Network of stations for the continuous evaluation of cloud and aerosol profiles in operational NWP model (http://www.cloud-net.org/)
COCCON	Collaborative Carbon Column Observing Network
COST TOPROF	European Cooperation in Science and Technology (COST) Towards Operational ground based profiling with ceilometers, doppler lidards and MWR for improving weather forecast (http://www.toprof.imaa.cnr.it/index.php)
DIAL	DIfferential Absorption Lidar
DOAS	Differential Optical Absorption Spectroscopy
EARLINET	European Aerosol Research Lidar Network (https://www.earlinet.org/index.php?id=earlinet_homepage)
EarthCARE	ESA Earth Explorer Mission for Global Observation of Clouds, Aerosols and Radiation (http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/EarthCARE/Overview2)

ECV	Essential Climate Variable
E-GVAP	EUMETNET GNSS network for Water Vapour Programme (http://egvap.dmi.dk/)
EUMETNET	The Network of European Meteorological Services (http://www.eumetnet.eu/)
FIDUCEO	Fidelity and Uncertainty in Climate Records from Earth Observations (http://www.fiduceo.eu/)
FTIR	Fourier Transform Infrared Spectroscopy
FRM4DOAS	Fiducial Reference Measurements for Ground-Based DOAS Air-Quality Observations
GAID	Gaps Assessment and Impacts Document
GRUAN	GCOS Reference Upper-Air Network
GNSS-PW	Global Navigation Satellite System - Precipitable Water
GNSS-IPW	Global Navigation Satellite System – Integrated Precipitable Water
GPS-RO	Global Positioning System - Radio Occultation
HD(CP)²	High Definition Clouds and Precipitation for Climate Prediction (http://www.hdcp2.eu/index.php?id=mission)
HSRL	High Spectral Resolution Lidar
IMECC	Infrastructure for Measurement of the European Carbon Cycle
ILS	Instrument Line Shape
ISSI	International Space Science Institute
LOS	Line Of Sight
LS	Lower Stratosphere
MAX-DOAS	Multi Axis Differential Optical Absorption Spectroscopy
METEOMET	Metrology for Meteorology
MO	Met Office UK
MWR	Microwave Radiometer
NDACC	Network for the Detection of Atmospheric Composition Change
NIST	National Institute of Standard and Technology

NMI	National Measurement Institute
NORS	Network of Remote Sensing Ground-Based Observations in support of the Copernicus Atmospheric Service
NRT	Near Real Time
NWP	Numerical Weather Prediction
OE	Optimal Estimation
OSSE	Observing System Simulation Experiments
PANDORA	Pandora Spectrometer System for Measuring Trace Gas column amounts
PPP	Precise Point Positioning
QA	Quality Assurance
QA4ECV	Quality Assurance for Essential Climate Variable (http://www.qa4ecv.eu/)
QA4EO	Quality Assurance Framework for Earth Observation (http://qa4eo.org/)
QC	Quality Control
RTM	Radiative Transfer Model
SFIT	Spectral Data Analysis Model
SZA	Solar Zenith Angle
TES	Tropospheric Emission Spectrometer
TCCON	Total Carbon Column Observing Network (http://www.tccon.caltech.edu/)
TOPROF	Towards Operational Ground Based Profiling with Ceilometers, Doppler lidars and Microwave Radiometers for improving weather forecasts (http://www.toprof.imaa.cnr.it/)
TOLNet	Tropospheric Ozone Lidar Network
TROPOMI	TROPOspheric Monitoring Instrument
UT	Upper Troposphere
UVVIS GEOMS	Ultraviolet–visible spectroscopy, Generic Earth Observation Metadata Standard
WG	Working Group
ZTD	Zenith Total Delay