GAIA-CLIM Report

Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring:

D2.7 Report summarizing the uncertainty estimates for the ECVs identified in Task 2.2

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1. Introduction

1.1. Project context

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

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

The primary goal of WP2 is to improve the metrological characterisation of a subset of high-quality non-satellite observational data products, which were chosen because the technique and data analysis were deemed to be mature enough for these Essential Climate Variable (ECV)/technique combinations to be likely candidates for data products of 'reference quality'. The outcome has been summarized in D2.8[1] and the measurement series have been characterized in such a way that the uncertainty information crucial for the inclusion of these measurements into the VO has been provided in a comprehensive and quantitatively evaluated way. These 'reference' measurements are then presented together with their uncertainty information and visualised in an easy to follow manner for the user of the VO. Here, reference quality has a specific meaning around traceability, uncertainty quantification, comparability, and representativeness as discussed in Thorne et al., 2017. In addition to those ECVs and measurement techniques studied and assessed within Task 2.1, the project uses GRUAN data which has its own rigorous uncertainty assessment independent of GAIA-CLIM.

[1] http://www.gaia-clim.eu/sites/www.gaia-clim.eu/files/document/d2.8.pdf

1.2. The changing role and context of Task 2.2

The role of Task 2.2 is to provide information on uncertainty quantification for baseline and comprehensive networks of relevance to GAIA-CLIM activities. Such quantification and understanding is necessary for such observations to be used appropriately within a GAIA-CLIM context.

Most aspects of the originally envisaged Task 2.2 work have been superseded by the C3S 311a Lot 3 activity under the Copernicus Climate Change Service. This activity, arising directly out of GAIA-CLIM, provides a more sustainable pathway to ultimately realise many of the original Task 2.2 aims in that it not only shall quantify such uncertainties, but provide access to the data and uncertainty information via the Climate Data Store(CDS). The work to date in Task 2.2 has been provided to this service and is in the process of being integrated.

In D2.4 (Progress report on the uncertainty estimates for the ECVs identified in Task 2.2), which was undertaken at an early stage of the project and prior to the instigation of C3S 311a Lot 3, we identified and explored several networks and ECV databases, which at the time were identified as being of potential interest for the VO:

1) GUAN/radiosondes for temperature and water vapour profiles.
2) MWRnet/microwave radiometers for temperature and water vapour profiles as well as total column-integrated water vapour content (TWVC) and total column-integrated liquid water content (TLWC).
3) SHADOZ/ozonesondes for ozone profiles.
4) GSN/surface meteorology for surface temperature.
5) AERONET/ aerosol optical depth measurements

Of these candidate series, only AERONET has been carried through to the final version of the VO. No additional series have arisen that were not foreseen in D2.4.

Given the above considerations, the final deliverable of Task 2.2 shall consider solely the AERONET network. Since the AERONET database was not included in any of the studies undertaken within Task 2.1, a description of the data product and its uncertainties based on the available literature is vital background information to be included into the VO and is hence undertaken as the final report of Task 2.2 herein.

1.3. AERONET as a Baseline network

The VO includes aerosol data arising from the 527 AERONET (AErosol RObotic NETwork) stations. The maturity assessment for AERONET, undertaken within WP1 of GAIA-CLIM in September 2016, classifies the network with 'baseline' status (see Table 1).

AERONET_PHOTONS

Metadata	Documentation	Uncertainty characterization	Public access, feedback and update	Usage	Sustainability	Software (optional)
Standards	Formal Description of Measurement Methodology	Traceability	Access	Research	Siting environment	Coding standards
Collection level	Formal Validation Report	Comparability	User feedback mechanism	Public and commercial exploitation	Scientific and expert support	Software documentation
File level	Formal Measurement Series User Guidance	Uncertainty Quantification	Updates to record		Programmatic support	Portability and numerical reproducability
		Routine Quality Management	Version control			Security
			Long term data preservation			
Legend						
1	2	3	4	5	6	Not applicable

Table 1: Maturity matrix assessing AERONET.

The maturity matrix approach assesses certain quantifiable aspects of typical measurement system maturity across the network for those ECVs and associated measurement systems that are relevant to GAIA-CLIM (Thorne et al., 2017). Typically, a reference-quality measurement program would score 5s and 6s against relevant criteria, a baseline capability 3s and 4s and a comprehensive capability 1s and 2s. While most entries for AERONET score 5-6 (e.g. all subcategories of the sustainability, usage and public access categories are of reference quality), some subcategories within the uncertainty characterization, documentation, and metadata of the AERONET maturity matrix score 3-4, which currently still labels the network with baseline status for the purposes of GAIA-CLIM.

Although not classified as a reference type network, the AERONET database is of critical importance for the VO since it provides continuous measurements of atmospheric aerosols, an important climate forcing agent with aerosol radiative forcing being one of the largest uncertainties in climate change studies. Aerosols are also highly variable, regionally and seasonally, and it is therefore vital to have a substantial and geographically representative network of stations (as can be seen for AERONET in Figure 1) available for the comparison of the ground-based data products with the satellite data in the VO. The AERONET data thus are a critical complement to the lidar aerosol data summarised in D2.8 and their accompanying Product Traceability and Uncertainty (PTU) documentation.

2. Characterisation of the AERONET database

2.1. Network and instrumentation

2.1.1. Network

AERONET is a global network of sun/sky radiometers that is monitoring Aerosol Optical Depth (AOD) and a limited subset of aerosol optical properties for AOD trend analysis, for optical properties characterization, and for the validation of satellite retrievals. The AERONET program[2] is a federation of ground-based remote sensing aerosol networks established by NASA and LOA-PHOTONS (CNRS) and has been greatly expanded by collaborators from various national agencies, institutes, universities, individual scientists, and partners. The program provides a long-term and readily accessible public domain database of aerosol optical, microphysical, and radiative properties for aerosol research and characterization and validation of satellite retrievals, and synergies with other databases. Cloud products are also available for a part of the network. At several stations, sun photometer measurements are co-located with Raman lidar measurements (which have been characterized via a PTU within Task 2.1, D2.8).

The network imposes standardization of instruments, calibration, data processing, and distribution. The measured radiances are automatically sent to the NASA – Goddard Space Flight Center (NASA-GSFC), where they are processed according to the standardized AERONET data analysis technique.

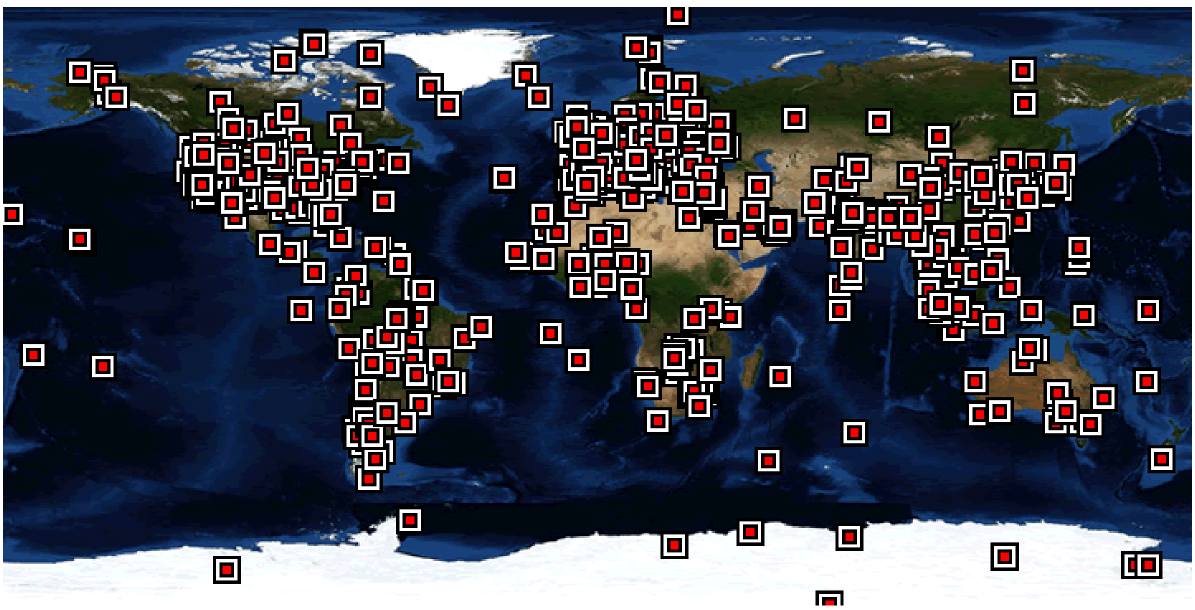

Figure 1: AERONET site information map

[2] https://aeronet.gsfc.nasa.gov/

AERONET provides globally distributed observations of spectral AOD, inversion products, and precipitable water in diverse aerosol regimes. Figure 1 shows all stations which are registered with the network; a total of 755 stations are listed on the AERONET website. All sites provide associated discovery metadata on their coordinates and elevation, a site description, details of the responsible PI and institution, and images of the instrument and its setup.

2.1.2. Instrumentation

The instruments are CIMEL CE318 multiband sun photometers that make measurements of spectral sun irradiance and sky radiances. There exist several versions of this instrument that are used throughout the network. The latest CE318-T model is also capable of making night-time measurements using spectral lunar irradiance (Barreto et al., 2016). The first night-time data are now routinely released through the AERONET website.

The system is fully automatic and powered using solar panels. As one example of many, Figure 2 shows a CIMEL sun photometer operated by GAIA-CLIM partner BIRA-IASB installed on the roof of their institute.


Figure 2: Both images show a CIMEL sun photometer installed on the roof at BIRA-IASB in Brussels (source: AERONET website).

Figure 3 annotates the instrument components of a CIMEL sun photometer in more detail. The instrument consists of the main stem containing the azimuth motor. On the top of the motor is an attached robot arm consisting of the zenith motor on one side and the sensor head on the other side. The sensor head is fitted with 25 cm collimators and attached to a 40 cm robot base which systematically points the sensor head at the sun, the sky and the moon according to a pre-programmed routine. Inside the sensor head, there are two silicon detectors, one for each of the collimators. A filter wheel is placed in between the collimator windows and the detectors, inside the sensor head. The wheel consists of eight narrowband interference filters (at 340, 380, 440, 500, 675, 870, 1020, and 1640 nm) mounted along the circumference. The two collimators have the same field of view (1.2 degree) but differ in the size of apertures. The larger aperture collimator is 10 times as large as the sun-viewing collimator and provides the necessary dynamic range to observe the sky. Three cables (a thick cable from the sensor head to the control box, and two battery power cables—one each to the motors) are attached to the instrument. The main stem is connected to a base plate consisting of mounting holes to ensure the instrument is mounted on a level surface. The CIMEL control unit, batteries, and Sutron satellite transmission equipment are usually deployed in a weatherproof plastic case.

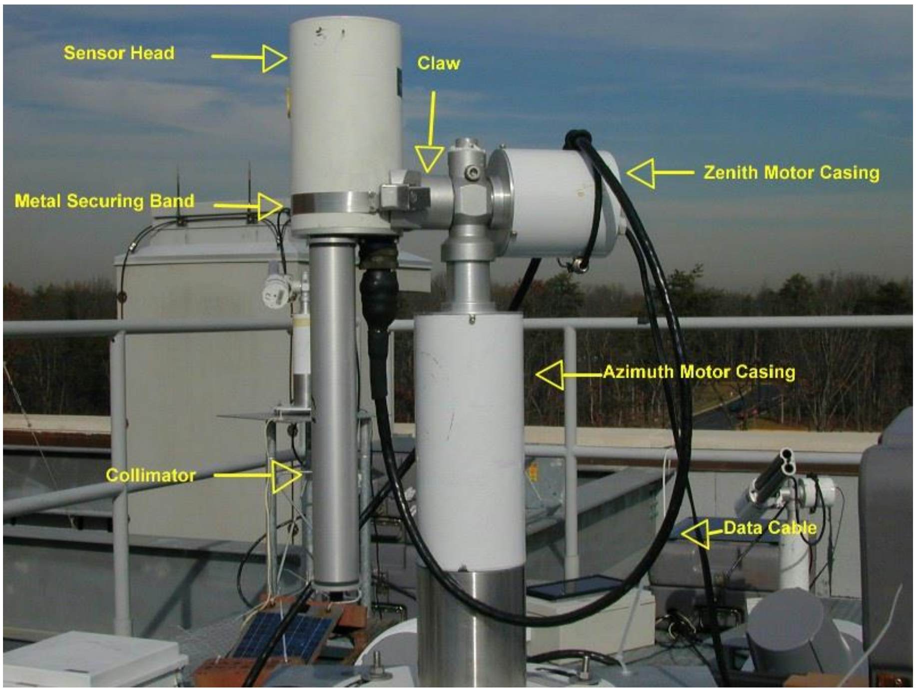

Figure 3: Picture showing a CIMEL sun photometer with sensor head and data cables attached (Source: AERONET website).

2.2. Measurement procedure

The sun photometers are operated in a fully automated manner and are making two basic measurements using either direct sun or sky light as a light source. The direct sun measurements are made in eight spectral bands using interference filters at wavelengths of 340, 380, 440, 500, 670, 870, 940 and 1020 nm. The filters are located in a filter wheel which is rotated by a direct drive stepping motor (see also Section 2.1.2). The 940 nm channel is used for the determination of total column water abundances.

A pre-programmed sequence of measurements is taken automatically without operator assistance. The instrument measures direct solar irradiance by first pointing the collimator toward the approximate position of the sun (provided it is aligned properly) based on a built-in program that takes into account the time of the year and the coordinates of the location. A four-quadrant detector then positions the sun at the centre of the fields of view of the collimators by using a feedback control loop. The filter wheel rotates in front of the detector to obtain a measurement sequence. A sequence takes about 10 seconds. In order to discriminate against the presence of thin cirrus clouds, which may be non-uniform, three measurement sequences are performed (called a triplet), lasting about 35 seconds. During the data analysis procedure, the measured voltages are compared to eliminate non-uniform scenes.

Direct solar irradiance data are obtained for all the filters every 0.25 (or 0.5, depending on the station) air mass[3] intervals above an optical air mass of 2 (which corresponds to a solar zenith angle (SZA) > 60^o) and every 15 minutes otherwise (SZA </= 60^o). The time variation of clouds is usually greater than that of aerosols causing an observable variation in the triplets that can be used to screen clouds in many cases. Additionally, the 15-minute measurement interval allows a longer temporal frequency check for cloud contamination. The optical depth is then calculated from the spectral extinction of direct beam radiation at each wavelength based on the Beer-Bouguer Law. The attenuation due to Rayleigh scatter, and absorption by ozone, and gaseous pollutants is estimated and removed to isolate the AOD.

In addition to the direct solar irradiance measurements that are made with a field of view of 1.2 degrees, the CIMEL instruments also measure the sky radiance in four spectral bands (440, 670, 870 and 1020 nm) along the solar principal plane up to nine times a day and along the solar almucantar up to six times a day. The solar principal plane sky measurements are obtained by scanning the sky in a plane containing the sun and the instrument. Almucantar sky radiance measurements are obtained by scanning the sky at the current solar zenith angle but different azimuth angles to obtain the angular variation of skylight in the four filters. Data are taken more frequently near the sun since the intensity varies rapidly in the solar aureole. This approach is used to acquire aureole and sky radiances observations through a large range of scattering angles from the sun through a constant aerosol profile to retrieve size distribution, phase function and aerosol optical depth. The sky radiance measurements are inverted by radiative transfer routines (e.g. Dubovik and King, 2000) to derive aerosol size distribution and phase function.

The measurements are then stored in memory in the CIMEL control box and at predetermined times, the instrument PC collects the data from the control box and transmits them via the

[3] For a plane-parallel atmosphere, the optical air mass or air mass factor (m) is simply determined by the solar zenith angle θ: $m = 1/\cos(\theta)$.

internet to the AERONET processing facility (for further details, see Section 2.4). Although the measurements are made continuously under all cloud conditions, the data is subsequently screened for impacts of clouds and only cloud-free data sets are considered.

2.3. Calibration and uncertainties

Direct sun and radiance sphere calibration values are measured at distributed calibration sites. The NASA GSFC calibration facility manages direct solar calibrations and radiance sphere calibrations. In addition, NASA GSFC is responsible for maintaining "reference" instruments that meet high operating standards and determining the apparent extra-terrestrial constants at Mauna Loa Observatory in Hawaii. Other distributed calibration sites include direct sun measurements in Izana, Spain and radiance sphere measurements in Lille, France (PHOTONS), El Arenosillo, Spain (RIMA), and Canberra, Australia (CSIRO).

Instruments located initially at a calibration facility are considered in "pre-deployment" status. Pre-deployment direct sun and radiance calibration data values are obtained at the calibration facility. The instrument is considered as "field-deployed" once the instrument leaves the calibration facility. After a determined measurement period, the instrument is returned from its measurement location to a calibration facility. At this stage, "post-field deployment" calibration direct sun and radiance values are measured and applied to the data. Some window cleaning or filter maintenance may be necessary. After the lab maintenance, the instruments are considered in a "pre-deployment" status again.

Note that field-deployed instruments should normally collect data for a period of 6 to 12 months. Data collected after 12 months may be susceptible to environmental conditions (e.g., spider webs or dust), which may jeopardize the post-calibration values necessary for raising data to the highest quality. This means that the instruments need to be sent to a calibration site at least on an annual basis.

Any changes in the calibration coefficients are documented, and the calibration event and the method is documented as part of the database at AERONET. The calibration coefficients are linearly interpolated between pre- and post-deployment calibrations. Large changes in calibration coefficients between pre- and post-deployment will result in larger uncertainties in the derived measurements. If the AERONET analyst considers the change as too large, the data will not be processed to the quality assured Level 2 (see Section 2.5 for description of the AERONET data levels).

2.3.1. Direct sun calibration and resulting uncertainty

Calibration refers here to the determination of the calibration coefficients needed to convert the instrument output digital number (DN) to a desired output, in this case aerosol AOD, precipitable water (cm), and radiance ($W/m^2/sr/um$). As mentioned previously, field instruments are generally returned to the GSFC for intercomparison with reference instruments approximately every 6 to 12 months in order to maintain accurate calibration. The GSFC reference CIMEL instruments are calibrated using the Langley technique at the Mauna Loa Observatory (MLO) in Hawaii on a frequent basis.

The Langley plot is a logarithm of the DN taken during these times plotted against the optical air mass between a range of 5 and 2 (which corresponds to measurements taken at a SZAs between 60^o and approximately 80^o), where the intercept is the calibration coefficient (zero air mass DN) and the slope is the optical depth. Langley plots from MLO have been made to determine the spectral 'extraterrestrial' voltage for these instruments since 1994. The observatory's high altitude and isolation from most local and regional sources of aerosols provides a very stable irradiance regime in the mornings, and is thus ideally suited for calibration purposes.

AERONET reference instruments (4 to 5 CIMELs) are typically recalibrated at MLO every 3-5 months using the Langley plot technique. The zero air mass voltages (V_o, instrument voltage for direct normal solar flux extrapolated to the top of the atmosphere (Shaw, 1983)) are inferred with an uncertainty of approximately 0.2 to 0.5% for the MLO calibrated reference instruments (Holben et al., 1998). Therefore, the uncertainty in AOD due to the uncertainty in zero air mass voltages (computed as the standard deviation/mean of the V_o values from MLO) for the reference instruments is better than 0.002 to 0.005.

The sun photometers at sites other than GSFC are inter-calibrated against a MLO calibrated AERONET reference instrument both before deployment in the field and post- deployment. A linear rate of change in time of the zero air mass voltages is then assumed in the processing of the data from field sites. Further analysis suggests that this results in an uncertainty of approximately 0.01 - 0.02 in AOD due to calibration uncertainty for the field instruments (which is wavelength dependent with the higher uncertainties in the UV; Eck et al. (1999)). Schmid et al. (1999) compared AOD values derived from 4 different solar radiometers (including an AERONET sun-sky radiometer) in a field experiment and found that the AOD values from 380 to 1020 nm agreed to within 0.015 (rms). For wavelengths >400 nm the AERONET AOD uncertainty is approximately 0.01-0.015 when using the Level 2 data (this includes both pre- and post- deployment calibrations).

2.3.2. Radiance calibration and resulting uncertainty

For the sky radiance measurements, calibration is performed at the NASA Goddard Calibration Facility using a calibrated integrating sphere with an uncertainty of +/- 5%. For the 940 nm channel that includes water absorption, calibration is performed using a variant of the modified Langley method. With respect to the long-term stability of the calibration coefficients, the optical interference filters are the limiting factors. On average, there has been a decrease from 1 to up to 10% per year. Therefore, instruments are calibrated on a 6- to 12-month rotation and filters are changed when needed.

The uncertainty of the sky radiance data is more difficult to ascertain since these only constitute single observations and no absolute self-calibration procedure is yet implemented between the sphere calibrations. Based on the sphere calibration, the uncertainty in the sky radiance at the time of calibration is also approximately +/-5% for all four channels at the time of calibration. Since the scattering aerosol optical depth is directly related to the aureole brightness, the uncertainty is largely a function of the sky calibration. In summary, sky retrievals can have uncertainties of +/-5%[4]. The sky absolute uncertainties decrease with longer wavelengths.

2.3.3. Uncertainty due to aerosol forward scattering

In their study, Sinyuk et al.[5] have evaluated the uncertainty in AOD, estimated from 1.2° FOV sun photometer observations, due to the aerosol forward scattering effect. The analysis was performed using radiative transfer modeling employing both a Junge aerosol size distribution (ASD) and ASDs based on AERONET aerosol retrievals. Using the Junge ASD in radiative transfer modeling resulted in considerable overestimates of modeled AOD uncdertainty as compared to more realistic AERONET based ASDs which were used in subsequent analyses. The analysis found that 99.53% of the AERONET AOD data have 440 nm uncertainties due to FOV effects much lower than the AERONET AOD estimated uncertainty of 0.01 and are hence negligible.

Only approximately 0.47% of the AERONET Level 1.5 and Level 2 data (see Section 2.5 for description of the AERONET data levels) corresponding mostly to dust aerosol with high AOD and low solar elevations have AOD uncertainties larger than 0.01. Sinyuk et al. also showed that observations with extreme reductions in direct solar irradiance and potentially large AOD uncertainties do not contribute to Level 1.5 and Level 2 AOD due to low sun photometer digital counts that are below the AERONET processing threshold. Potentially AOD retrievals

[4] https://aeronet.gsfc.nasa.gov/valdesaire/val.html
[5] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140008327.pdf

with FOV uncertainties larger than 0.01 and the signal level above the digital counts threshold can be flagged as diffuse light contaminated. These AOD retrievals could be corrected using radiative transfer modeling for a set of representative ASDs.

2.3.4. Summary of quantified uncertainties

AERONET imposes standardization of instruments, calibration, and data processing and distribution[6]. The influence of various instrumental, calibration practices, atmospheric and methodological factors affecting the uncertainty of optical depth determination requires their minimization (see for example Shaw, 1976, Reagan et al., 1986 and Russel et al., 1993).

Instrumental uncertainties due to electro-optical precision and systematic uncertainties due to FOV effects are considered negligible for all practical purposes for a properly operated instrument. The variability of the atmosphere is characterized by the variability of the triplet optical thicknesses which may at times be cloud contaminated. This uncertainty is computed, can be used as a screening tool, and may be retrieved from the AERONET data base[7]. Additionally, the uncertainty due to calibration is tracked with time dependent data and may also be retrieved from the data base.

For the direct sun measurements, calibration of the field instruments is performed by a transfer of calibration from reference CIMELs, which are calibrated by the Langley plot technique at MLO (Hawaii). Typically, the total uncertainty in AOD (aerosol optical depth) from a newly calibrated field instrument under cloud free conditions is < ±0.01 for wavelengths > 440 nm and < ±0.02 for shorter wavelengths (e.g. Eck et al., 1999). The uncertainty of the sky radiance data is more difficult to ascertain and they have an uncertainty of typically +/-5%.

For both solar pointing and sky radiance the uncertainties increase in field conditions, and with respect to the long-term stability of the calibration coefficients, the optical interference filters are the main limiting factors. On average, a decrease from 0 to approx. 5% per year is expected, depending largely on material deposition on the optics. In the absence of a more nuanced approach the uncertainties are assumed to scale linearly between calibrations, although this clearly shall not always be a good approximation.

Baretto et al. (2016) undertook a quantitative estimation of the latest CIMEL model CE318-T AOD uncertainties by means of error propagation theory during daytime. They found that the AOD uncertainties for Langley-calibrated instruments were similar to the expected values for other reference instruments, ranging from 0.002 to 0.009, and 0.015 for field instruments.

[6] e.g. http://aeronet.gsfc.nasa.gov/new_web/PDF/AERONETcriteria_final1.pdf
[7] https://aeronet.gsfc.nasa.gov/valdesaire/val.html

2.4. Data processing

The data processing for the AERONET data product is divided into 4 steps.

Step 1. Data Collection

All CIMEL sun photometers (SPs) are separated into 3 main groups:

1. SP connected to Data Collection Platforms (DCPs),
2. SP connected to a PC that can go online,
3. SP not connected to the internet.

Group 1 sends the data automatically to 4 satellites: GOES East, GOES West, Meteosat and GMS using a DCP. Data are transferred from satellites to an AERONET processing server via several receiving stations.

Group 2 automatically uploads the data to a PC using CIMEL's program. The PC can be set up to submit the data to the processing server either automatically (usually every day) or the data can be submitted manually.

Group 3 needs to be periodically visited and data has to be collected and submitted manually.

The data collection technique deployed has no effect upon the resulting uncertainty of the measured series, although Group 3 transmission, obviously, makes real-time diagnosis of data issues impossible so may increase the risk of substantial periods with grossly incorrect (unusable) data.

Step 2. Preprocessing

After being collected in the processing server, the data are converted to the unified format and the server generates reports about each instrument and DCP (if relevant). The reports are posted on the website and also sent to the parties responsible for each instrument's maintenance. The converted SP data are placed in the database. Data are also copied to a backup system and cloned on several other workstations.

Step 3. Processing

The processing consists of several sequential algorithms applied to the raw data:

1. Aerosol Optical Depth (AOD) retrieval.
2. AOD cloud screening.
3. Sky Radiance data (Almucantars and Principal Planes) inversion.

As algorithm 3 is very processor intensive and time consuming it is used simultaneously on several smaller workstations, each of which has a fully functional clone of the central database.

Step 4. Assurance and Reprocessing

Quality control is provided by AERONET during processing and retrieval of the geophysical quantities. Once these data sets are manually inspected, they can then be upgraded to Level 2 (quality assured data product, see Section 2.5).

2.5. Data availability and coverage

As previously discussed, the sun photometer measurements of the direct (collimated) solar radiation provide information to calculate the columnar AOD. The AOD can then be used to compute columnar water vapor (precipitable water) and estimate the aerosol size using the Angstrom parameter relationship. Three data versions (Versions 1 and 2, and since 5 January 2018 also Version 3) and three quality levels (Levels 1.0, 1.5, 2.0) exist for each product. While Levels 1.0 and 1.5 are provided in near real-time, until the adoption of Version 3 (see below) the 12-month or longer delay (due to final calibration and manual inspection) ensures that the highest quality data can be found in the Level 2.0 data products.

Description of the three quality levels for Version 2:

- Level 1.0: Minor corrections, selective high AOD restoration applied to all levels.
- Level 1.5: Improved cloud clearing, high air mass data included, and automatic data quality assurance applied.
- Level 2.0: Manual QA replaced by automatic QA.

Changes in Version 3 as compared to Version 2:

- Level 1.0: Minor difference, captures fine mode aerosol plumes at very high AOD. Latency of ~30 minutes or less from the time data are received for processing.
- Level 1.5: Latency of 30 minutes or less from the time data are received for processing. Less cloud contamination, fewer instrumental anomalies, and more accurate data. Because the cloud clearing is improved and a series of automatic quality assurance algorithms are further removing compromised data, the Level 1.5 may be close to Level 2.0 in the absence of large inter-periodic-calibration point jumps.

AERONET's recommendation is that Level 1.5 should provide good data for near real time operational comparisons, such as for satellite and model validation and for model assimilation. All Level 1.5 products are reprocessed multiple times within the first several weeks to utilize the most recent and best ancillary inputs that originate from satellites, radiative transfer models and reanalysis models for both AOD and inversion products. The Level 1.5 products may or may not change during the first six weeks after data collection and/or after a post field calibration is applied prior to Level 2.

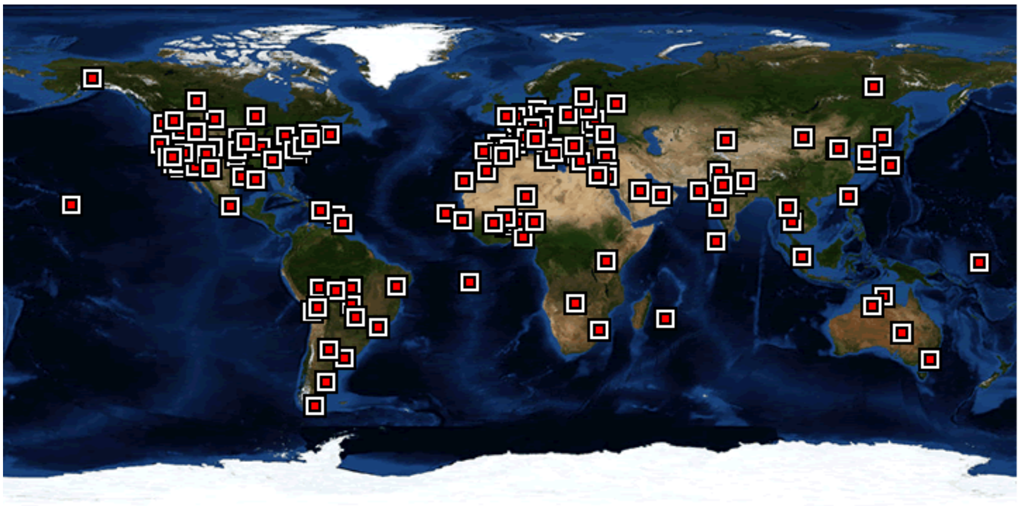

Figure 4: AERONET sites with Version 3 Direct Sun Algorithm, Level 2.0 data sets > 5 years, automatically cloud cleared and quality assured with pre-field and post-field calibration applied.

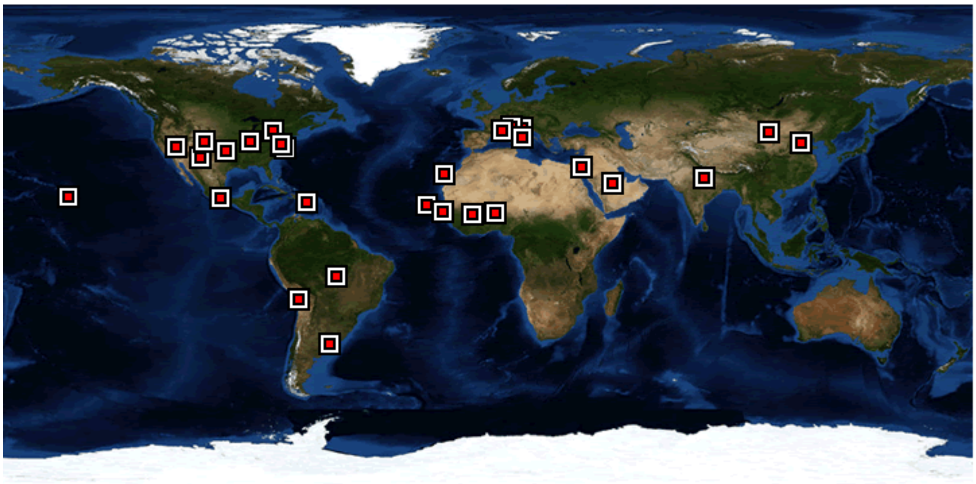

Figure 5: AERONET sites with Version 3 Direct Sun Algorithm, Level 2.0 data sets > 10 years, automatically cloud cleared and quality assured with pre-field and post-field calibration applied.

In the GAIA-CLIM VO, Level 2.0 AODs from 527 AERONET stations are currently included and plotted against ENVISAT AATSR AOD measured at 550 nm. A total of 30086 collocations are available within the VO. The satellite data set covers the time period for 2002-2012 while many AERONET stations, however, cover only much shorter time periods with 316 out of the 527 stations having fewer than 50 available co-locations and 256 fewer than 25 available co-locations, while the top 10 sites have between 295 and 336 co-located observations. While Figure 1 shows an overview of all available AERONET sites, Figure 4 shows the sites where the Level 2.0 AOD data sets are available for more than 5 years and Figure 5 for more than 10 years.

2.6. Validation via intercomparison studies

AERONET data has been used in a wide range of intercomparison studies (e.g. Schafer et al., 2014, Cheymol et al., 2009, Mazzola et al., 2011, Kim et al., 2008, Glantz et al., 2014, Nyeki et al., 2013, Friess et al., 2016, Piters, 2012, Shinozuka et al. 2011, McArthur et al., 2003). A couple of examples of these studies are discussed in more detail below.

Kim et al. (2008) discuss comparisons of aerosol optical depths (AODs) determined from several types of sun photometers operating side by side as part of four different networks (GAW PFR, AERONET, SKYNET, and NOAA/ESRL aerosol monitoring programs). The comparisons were made at 6 different stations to evaluate the different types of current state-of-the-art instruments under different aerosol loading conditions. A comparison between AERONET CIMEL and GAW PFR at a high altitude calibration site, Mauna Loa, shows an excellent agreement with 0.001 uncertainty for 500 nm AOD. AODs obtained from direct sun-pointing instruments are within 0.01 uncertainty, though these results are similar to or slightly larger than those given in previous short-term intensive studies. These results suggest that well-maintained networks of direct sun-pointing instruments developed by different companies/institutions can provide quality-assured AOD data across the globe to the aerosol-climate research community.

Cheymol et al. (2009) present an intercomparison between AOD measured by CIMEL sun photometer at 340 nm and 440 nm (shifted to 320 nm using Angström's law) and AOD retrieved from Brewer ozone measurements at 320 nm. The sun photometer data were taken from the AERONET database and the comparison was performed for 7 stations for time periods between 1 to 7 years. Cheymol et al. found that for the 4 instruments which were truly co-located the correlation coefficients were 0.82 and above, while for the other 3 instruments (distance of 12-16 km) the correlation was lower. Uncertainties were only provided for the AODs retrieved from the Brewer measurements.

Nyeki et al. (2013) summarize the results of AOD intercomparison campaigns conducted at eight EUSAAR (EUropean Super-sites for Atmospheric Aerosol Research) sites during the 2008–2011 period. A PFR (Precision Filter Radiometer) travelling standard from the GAW-PFR network was run alongside the existing CIMEL sun photometers located at the 8 stations from the PHOTONS/AERONET network. Basic statistical analysis of coincident measurements at $\lambda = 500$ and 862 nm illustrated good agreement. The CIMEL-PFR difference of all campaigns was in the range -0.009 – 0.007 at $\lambda = 500$ nm and -0.002 – 0.006 at $\lambda = 862$ nm. However, when WMO criteria for traceability were applied only one wavelength at three stations was traceable. Other stations were close to being traceable but had slight issues with window cleanliness and calibration.

Nyeki et al. also emphasized that a lower limit exists beyond which the AOD difference becomes increasingly difficult to minimize. In a previous AOD intercomparison study

(McArthur et al., 2003) of CIMEL and PFR sun photometers, it was demonstrated that only a marginal improvement in AOD uncertainty at the 0.005 level could be obtained through advances in the following areas: i) solar pointing precision, ii) more accurate determination of Rayleigh, ozone, etc. contributions to optical depth, and iii) better instrument characterization including calibration. Nyeki et al. suggest that apart from improvements in these areas, the improved cleanliness of sun photometer windows and standardization of cloud-screening algorithms would lead to better traceability.

To investigate the performance requirements for AOD in polar regions which are much more stringent than those usually encountered in established sun photometer networks, two intercomparison campaigns were held during spring 2006 at Ny-Ålesund (Svalbard) and autumn 2008 at Izaña (Tenerife) within the framework of the IPY POLAR-AOD project (Mazzola et al., 2011). Various research institutes routinely employing different sun photometer models at Arctic and Antarctic stations participated in the intercomparisons which were also aimed at investigating the comparability of data from different archive centers.

Hence, a common algorithm was used for data analysis with the aim of minimizing a large part of the discrepancies affecting previous studies. During the Ny-Ålesund campaign, spectral values of AOD derived from measurements taken with different instruments were found to agree, presenting at both 500 nm and 870 nm wavelengths average values of root mean square difference (RMSD) and standard deviation of the difference (SDD) equal to 0.003. Correspondingly, the mean bias difference (MBD) varied mainly between -0.003 and +0.003 at 500 nm, and between -0.004 and +0.003 at 870 nm. During the Izaña campaign, which was also intended as an intercalibration opportunity, RMSD and SDD values were estimated to be equal to 0.002 for both channels on average, with MBD ranging between -0.004 and +0.004 at 500 nm and between -0.002 and +0.003 at 870 nm. The results of this study by Mazzola et al. confirm that sun photometry is a valid technique for aerosol monitoring in the pristine atmospheric turbidity conditions usually observed at high latitudes.

Omar et al. (2013) compare the AOD retrieved from backscatter measurements of the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite with coincident AERONET measurements over a 4 year period (2006 - 2010). Overpass coincidence criteria of ±120 min and within a 40 km radius are satisfied at least once at 149 globally distributed AERONET sites. Most data pairs (> 80%) use AERONET measurements acquired within ±30 min of the overpass.

Omar et al. examined the differences in AOD estimates between CALIOP and AERONET for various aerosol, environmental, and geographic conditions. The results show CALIOP AODs are lower than AERONET AODs especially at low optical depths as measured by AERONET (500 nm AOD < 0.1). Furthermore, the median relative AOD difference between the two measurements is 25% of the AERONET AOD for AOD > 0.1. Differences in AOD between CALIOP and AERONET are possibly due to cloud contamination, scene inhomogeneity, instrument view angle differences, CALIOP retrieval uncertainties, and detection limits. Omar et al. also find that CALIPSO and AERONET do not agree on the cloudiness of scenes. Of the scenes that meet the above coincidence criteria, CALIPSO finds clouds in more than 45% of the coincident atmospheric columns AERONET classifies as clear.

Based on their study, Omar et al. suggest the following recommendations for a high fidelity daytime AOD comparison between CALIOP (or similar space-based backscatter lidar) and AERONET (or similar ground-based sun photometer): (1) cloud cleared data using the lidar cloud mask, (2) only use high confidence retrievals, (3) homogeneous scenes determined by examining adjacent columns, and (4) fairly level surface around the AERONET station to ensure lidar column and sun photometer column are of the same depth. Upcoming refinements to CALIOP algorithms will yield improved estimates of AOD, and data possibly contaminated by cirrus clouds may be removed in a later version of AERONET products using an improved cloud screening algorithm. Both of these refinements should lead to improvements in the correlation between the two measurements.

3. Conclusions

AERONET provides globally distributed observations of spectral AOD, inversion products, and precipitable water in diverse aerosol regimes, and as such is of great interest for inclusion into the GAIA-CLIM VO. Since AERONET imposes a clear standardization of instrumentation using low maintenance radiometers, a fully automated measurement protocol, prescribed calibration, real time data reception, and centralised processing, such a network has great potential to fully develop the procedures to support long-term observations of AODs, which are fully traceable with well characterized uncertainties. Given that a new version (Version 3) of the AERONET data has just been released, a full re-assessment of its maturity status would be an appropriate next step.

A major goal for AERONET would be to provide data products, which include a fully traceable uncertainty estimation for the AOD measurements and for the other aerosol and water products released at NASA-GSFC. We would strongly encourage the AERONET network to consider undertaking the analysis steps of a traceability chain and PTU documentation as undertaken for a number of instruments under Task 2.1. In particular, such an exercise may serve to highlight hitherto unrecognized effects and sharpen the quantification of those effects already recognized.

One ongoing challenge, however, still lies with the diligence of the owners and operators of the AERONET sun photometers, and with the uncertainty in AOD being strongly determined by the requirement of regular (once or twice yearly) calibrations, it is vital that this is adhered to. If it is, then the typical total quantified uncertainty in AOD from a newly calibrated field instrument under cloud free conditions is $<\pm 0.01$ for wavelengths >440 nm and $<\pm 0.02$ for shorter wavelengths. These uncertainty estimates are based on studies by Eck et al. (1999). We also note that the GSFC integrating sphere uncertainty is quoted as ±5%, with the instrument retrieved sky radiance also quoted as ±5%, suggesting there is no significant expansion of uncertainties from the reference artefact to the individual instrument product uncertainty and any effect of aging or any environmental degradation. With the caveat that these uncertainties may be incomplete owing to the lack of a full traceability diagram and PTU documentation that would permit a strict metrological verification, WP2 recommends the use of these AERONET data in the VO.

4. References

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