Metrology for Aerosol oPtical Properties
(MAPP)

Deliverable 8

Good practices: a report on the requirements for SI-traceable calibrations of s from aerosol remote sensing monitoring networks.

P. Goloub

SFI DAVOS, AEMET, UV, CNR, UV , GSFC/NASA

Summary

This report describes the proposed requirements (protocol, procedures, laboratory infrastructure, resulting uncertainties) needed for SI-traceable calibrations of network s.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Content

1. Introduction

For several decades, the main aerosol networks providing AOD (such as AERONET, GAW-PFR, SKYNET, CARSNET, SONET,...) rely on a calibration strategy linking field (or network) s by direct comparisons to reference s at some specific locations (e.g GSFC, USA, OHP (CNRS, France), Valladolid, Spain, Davos (Switzerland). These reference s are in turn calibrated at high mountain stations (e.g Mauna Loa, Izana,..) using calibration procedures which are not traceable to the SI. This is justified by the fact that AOD is calculated from the instrument signal ratios and if the signals are measured or estimated absolute radiometric calibration coefficients cancel out. Some of these networks also are performing sky radiance measurements (e.g AERONET, SKYNET) which are combined with direct sun AOD to retrieve additional essential aerosol properties (ECV) such as size distribution and absorption. In this second group of networks, for example, AERONET conducted 30 years of SI traceable sky radiance calibration using integrating sphere source traceable to NIST/NPL. AERONET has demonstrated the importance of careful instrument maintenance and calibration within a large network. Such calibration efforts on a large scale however require long-term sustainability including simplification of calibration procedures, more accurate and precise procedures and SI traceable calibration.

The following sections describe (a) the requirements *for the reference* in terms of characterization and calibration, (b) the possible paths or routes to have SI traceable AOD for reference s, (c) the requirements to have SI traceable sky radiance (e.g spectral and angular downward atmospheric radiance) and (d) finally summarize the main requirements and recommendation for instrument calibration within a /radiometer network.

Instruments considered in this work are sun/sky/moon photometers measuring direct sun/moon attenuated irradiance and downward sky radiance from UV to MIR. This work is contributing to the ACTRIS aerosol remote sensing activity, in the framework of the French and Spanish components of the Center of Aerosol Remote Sensing (CARS) that operate the European branch of AERONET with the contribution of the Swiss component of CARS for traceability. This work is based on the contributions of different partners or associated partners of the MAPP project, including the GSFC/NASA in the USA.

2. Reference characterization and calibration

The reference s are the essential elements to transfer calibration to an entire network, possibly operating hundreds of s such as AERONET. As reference s are key instruments, they are selected following strict criteria, the main criteria being their stability. To ensure this stability, the use of 2 reference s simultaneously operated is mandatory. This stability is permanently controlled, first of all during their calibration phase at high altitude sites (Mauna Loa and Izana), and second, when they transfer their calibration to field instruments at specific sites, thus preserving the measurement traceability.

In the proposed strategy, it is therefore mandatory to characterize them in detail (radiometric temperature sensitivity, linearity response, filters functions, field of view and solid angle, spectral responsivity, dark current and its temperature sensitivity). Most of these characterizations are also mandatory for each field instrument, following defined procedures in laboratory or on site. The characterization of the field of view (and/or solid angle) is particularly important since it allows to link irradiance to radiance measurements. It has to be accurately measured (in lab or on site). Finally, the ultimate required characteristics are direct Sun (and Moon) calibration coefficients (both in terms of extraterrestrial irradiance & voltage) and radiance (both in terms of SI-traceable absolute radiance (W/m2/sr/um) and non-SI traceable normalized radiance (unitless)). In the MAPP project (WP 1), SFI DAVOS has measured precisely in the laboratory the FOV of the CNRS reference . The estimated uncertainty is ~0.3% (*see Task 1.3, Action 1.3.2, WP1).*

The main requirements for reference instruments characterization are given below

- Sensitivity of output bright signal to temperature,
- Sensitivity of output dark signal to temperature
- 4 quadrant alignment (instrument type specific)
- FOV / Ω (experimental laboratory procedure or in field-procedure)
- Sun/Moon gain (g), (instrument type specific)
- Signal linearity
- Filter transmission
- Spectral responsivity and irradiance calibration coefficients, s
- Extraterrestrial output voltage for direct sun observation, $V_{extraterrestrial}$
- Absolute radiance calibration coefficients, A

3. From standard to SI-traceable AOD

In a given channel, the instrument (e.g) measured quantity is voltage, V (DU, digital units), and is given by equation 1a and for narrow band filters can be simplified by eq. 1b:

$$V(\lambda_{band}) = \int_{\lambda_{start}}^{\lambda_{end}} s(\lambda)\cdot E(\lambda)d\lambda \quad (1a)$$

where E is the known light source irradiance $[\frac{W}{m^2\cdot\mu m}]$ *and* $s(\lambda) = f(S_{detector}(\lambda), T_{filter}(\lambda), T_{lens}(\lambda))$ is the spectral responsivity of the (also called the irradiance calibration coefficient $[DU\frac{m^2\cdot\mu m}{W}]$). T_{filter} is filter transmission function, T_{lens} is lens transmission function and $S_{detector}$ is the detector irradiance sensitivity $[DU\frac{m^2\cdot\mu m}{W}]$.

In this channel, the spectral responsivity can be written $s(\lambda) = s_n(\lambda)\cdot s_{max}$ where $s_n(\lambda)$ is the normalized responsivity and s_{max} the maximum value of the responsivity in this channel.

Within the narrow spectral band considered, the instrument sensitivity scaled irradiance received by the is given by eq. 1b:

$$E(\lambda_{band}) = \int_{\lambda_{start}}^{\lambda_{end}} E(\lambda) \bullet s_n(\lambda)d\lambda \quad (1b)$$

Hence, in this channel, the output voltage can be written as given by eq. 1c

$$V(\lambda_{band}) = s_{max}\cdot E\left(\lambda_{band}\right) \quad (1c)$$

This maximum responsivity coefficient, s_{max}, is the irradiance calibration coefficient for this channel. For the sake of simplicity, one will identify symbolicaly $s\ and\ s_{max}$ in the following.

Beer-Lambert-Bouguer attenuation law is used to derive AOD at a specific wavelength or similarly in the narrow spectral band :

$$E_{surface}(\lambda) = E_{extraterrestrial}(\lambda)\cdot exp(-\ TOD\cdot m) \quad (2)$$

Where TOD is total optical depth and is a sum of AOD (aerosol optical depth) and gas optical depth (molecular scattering and gas absorption, GOD). $E_{extraterrestrial}$ is the extraterrestrial solar irradiance, sometimes also called Top of Atmosphere irradiance (ToA), $E_{surface}$ is the solar irradiance measured at the Earth's surface (W/m2/µm), and m the air mass. For a narrow band filter-based sun , the irradiance is integrated over the filter transmission function (W/m^2).

The main challenge of AOD measurement at the Earth's surface is the estimation of the extraterrestrial irradiance since it requires instrument measurements outside Earth atmosphere (air mass = 0). However, if the were able to travel outside the atmosphere it would have the same irradiance calibration coefficient *s* at the surface as at the top of atmosphere (Eq 3).

$$ln\frac{E_{surface}}{E_{extraterrestrial}} = ln\frac{(V_{surface}/s)}{(V_{extraterrestrial}/s)} =-\ (AOD\ +\ GOD)\ \cdot m \quad (3)$$

where $V_{surface}$, $V_{extraterrestrial}$ are both instrument signals at surface and top of the atmosphere (ToA).

A well-established Bouguer-Langley extrapolation technique is used to estimate extraterrestrial signals (eq. 4) in clean conditions at high altitude sites (TOD is mostly constant and small). It consists in conducting a linear regression analysis from the instrument voltage measurements as a function of air mass (m) to determine the intercept (air mass (m) = 0)

$$ln(V_{surface}) = ln(V_{extraterrestrial}) - TOD\cdot m \quad (4)$$

This approach assures that $V_{extraterrestrial}$ is determined *only from the measurements* performed by the instrument and *does not depend on external data*.

For most narrowband s, spectral bands are chosen in spectral regions with small gas absorption, with the exception of water vapor channels at 940 nm.

a. Standard AOD determination (field calibration)

For example, in the AERONET network, AOD derivation is based on equation 5

$$ln\frac{V_{surface}}{V_{extraterrestrial}} =-\ (AOD\ +\ GOD)\ \cdot m\ \Rightarrow ln(V_{sur}) = ln(V_{ext}) - (AOD\ +\ GOD)\ \cdot m \quad (5)$$

The calibration (determination of $V_{extraterrestrial}$) is performed *in the field*, using the Langley extrapolation technique at a high-altitude clean site (Mauna Loa, Izana) to the air mass = 0 with the uncertainty ~ 0.3 % *(Toledano et al., 2018)*. Reference s are selected among the more stable s.

Therefore, a linear regression of a set of measurements $ln(V_{sur})$ vs m, from equation 5, would provide an ability to calculate AOD (considered small and constant) in a way that is mostly independent of the external to the instrument data (except for GOD if modified Langley method is used), and mostly depends on the accuracy of (i) the sun filter stability, (ii) the sun V measurements, (iii) of the determination of $V_{extraterrestrial}$.

In AERONET, as well as in similar networks, reference s are calibrated regularly (every ~3 months, *Holben et al., 1998*) at such clean high-altitude sites and this calibration is transferred to all field s (an additional transfer error of ~0.5 % has to be accounted for field s) when both are measuring at the same location (not high-altitude clean site) and making time and geometry synchronous observations of the same light source (e. g the sun, at Observatoire de Haute-de-Provence (OHP-CNRS), Valladolid (UVA) and Washington, D.C. (GSFC/NASA)).

b. SI-Traceable AOD preferred path (laboratory determination + Langley extrapolation) :

The preferred methodology to have SI-Traceable AOD is to calibrate the primary reference in irradiance (W/m^2). Metrology facilities (for example, PTB, NIST) are using dedicated and precise light sources (e.g. tunable laser with spectral uncertainties on the order of ~ 0.25-0.5%, or a simpler method using NIST calibrated 1000 W FEL source, see Grbner et al., 2023, AMTD).

Once this primary reference is calibrated at NMI (PTB or at any other similar metrology facility), irradiance calibration coefficients (s coefficient in eq. 1c) are determined. $V_{extraterrestrial}$ determination can be accurately done by the Langley extrapolation method at the clean high-altitude location.

$$ln\frac{(V_{surface}/s)}{(V_{extraterrestrial}/s)} = ln\frac{E_{surface}}{E_{extraterrestrial}} =-\ (AOD\ +\ GOD)\cdot m \qquad (6)$$

By using the irradiance calibration coefficients and the measured and extrapolated voltages, both $E_{surface}$ and $E_{extraterrestrial}$ are expressed in SI units for the *primary irradiance reference* and are transferred to the rest of the field s (with an additional error ~0.5%).

In this case the calculated AOD remains consistent with the historical AERONET procedure and depends on filter stability, V measurements and determination of $V_{extraterrestrial}$

c. SI-Traceable AOD alternate path (laboratory determination + use of external extraterrestrial solar irradiance spectrum) :

The alternate path is to calibrate a secondary CIMEL reference in irradiance (W/m2). Once this secondary reference is calibrated at PTB (or at any other similar metrology facility), the irradiance calibration coefficients, s, are known in each narrow spectral band.

In case of pure SI irradiance traceability without direct determination of the instrument $V_{extraterrestrial}$, AOD calculation needs external data, the $E_{Extraterrestrial}$ solar spectrum, measured by various sensors onboard satellites *(e.g TSIS-1, Kouremeti et al., 2022)*, with a given uncertainty UE_{solar} that can reach ~1% in some spectral bands, as well as $s_n(\lambda)$.

$$ln\frac{E_{surface}^{photometer}}{\int_{\lambda_{start}}^{\lambda_{end}} E_{extraterrestrial}^{satellite}(\lambda).\, s_n(\lambda)d\lambda} = -\,(AOD\,+\,GOD)\,\cdot m \quad (7)$$

Therefore, inverting equation 7 provides an ability to calculate AOD in a way that always considers physical quantities expressed in the SI unit system, but depends on

1. the optics (e.g. filter) and detector stability,
2. the accuracy of the V measurements, $V_{surface}$
3. the accuracy of the extra-terrestrial solar irradiance measurements by satellite sensors,
4. the accuracy of irradiance calibration coefficient measurements, s, using metrology facilities, since $E_{surface}^{photometer} = V_{surface}/s$
5. the spectral responsivity measurements,

This suggests that the *preferred* method has smaller uncertainty on the AOD than the *alternate* method (error in estimation of $V_{extra\ terrestrial}$ < combined error in extra-terrestrial solar irradiance measurements by satellite sensors, irradiance calibration coefficient measurements using metrology facilities and filter transmission function measurements).

d. SI-Traceable AOD by comparison to GAW-PFR (AOD SI-Traceable reference)

As there are already GAW-PFR s co-located with the AERONET reference s in operation at European (ACTRIS) and US (NASA) calibration centers, a last and simple methodology could consist in operating, aside from a non SI-traceable AERONET reference , a PFR having an AOD SI-Traceable calibration. Systematic comparison of both AOD records showing differences systematically below the GAW limit (0.005+0.01/m) during the 3 month operation will certify the quality of AOD data and provide AOD traceability to SI, at least daytime, at the moment.

e. SI-Traceability of nighttime AOD

This topic is specifically addressed in WP2, Task 2.3, and associated actions, however, in this subsection, we tentatively propose a set of equations yielding nighttime AOD. The main difficulty here is the knowledge of the moon's extraterrestrial irradiance, which changes with time due to moon illumination, tilt angle, distance etc. ROLO lunar model provides estimates of lunar irradiance as a function of time.
Since for some s (e.g CIMEL CE318T), the optical path used for day and night measurement is the same, differing only in their electronic gain, we present equations both for day and night observations.

$$V_{extraterrestrial}^{Sun} = s_{Sun}\, E_{extraterrestrial}^{Sun} \quad (8)$$

$$V_{extraterrestrial}^{Moon} = s_{Moon}\, E_{extraterrestrial}^{Moon} \quad (9)$$

Technically, lunar and solar acquisition modes differ in their signal amplifications, such that

$$g = s_{Moon} / s_{Sun} \quad (10)$$

For example, for AERONET, this gain is equal to 4096 and is very accurately and precisely determined in the laboratory. Hence the moon calibration coefficient, s_{Moon}, is

$$s_{Moon} = g \cdot s_{Sun} = g \frac{V^{Sun}_{extraterrestrial}}{E^{Sun}_{extraterrestrial}} \quad (11)$$

Coming back to the computation of the AOD, using the general Beer-Lambert law,

$$E^{Moon}_{surface} = E^{Moon}_{extraterrestrial} \cdot exp(-\ TOD \cdot m) \quad (12)$$

and combining eq. 8, 9, 10, 11, one can obtain an expression for TOD (and AOD) derived from the moon scattered irradiance measurements in terms of direct sun irradiance:

$$\frac{V^{Moon}_{surface}}{s_{Moon} \cdot E^{Moon}_{extraterrestrial}} = \frac{1}{g} \cdot \frac{V^{Moon}_{surface}}{V^{Sun}_{extraterrestrial}} \cdot \frac{E^{Sun}_{extraterrestrial}}{E^{Moon}_{extraterrestrial}} = exp(-\ TOD \cdot m) \quad (13)$$

$E^{Moon}_{extraterrestrial}$ is given by ROLO model with U= 2 % (SI)

$E^{Sun}_{extraterrestrial}$ is also SI traceable (U~1%)

See Deliverable 3, for more details on this part.

f. Summary of requirements and good practices

1. Irradiance calibration cannot be performed for each individual field included in a network. Therefore, transfer of calibration from SI-traceable reference AOD to field will provide the traceability of the produced AOD with field to SI. The standard procedure to transfer calibration is applied in the field (specific calibration platforms, e. g OHP, GSFC, Valladolid, etc) where both reference and field s are, for a short time, in operation side to side. In this configuration, the targeted stable light source is the sun.
2. **Therefore, only the reference s have to be SI traceable for AOD.**
3. Two reference s simultaneously operated are mandatory for each network or sub-network for internal stability control (ratio of output voltages of the 2 co-located reference s must be less than 1 % variation over 1 continuous month of measurement (2% for UV channels).
4. Procedure 1 : operate a PFR providing a SI-traceable AOD aside from the 2 reference s.
5. Procedures 2 (preferred) and 3 (alternate) : both procedures require that the reference s are calibrated in irradiance in the laboratory with respect to primary calibrated source.

Selection of procedure 1, 2 or 3 depends on the network capacity.

4. SI-traceable sky radiance : standard and new strategies

Networks such as AERONET, CARSNET or SONET are calibrating s in radiance following similar protocols, e.g using an SI traceable integrating sphere source (traceable to a primary NIST/NPL source).

Similar to the AOD case, ***we consider here only the reference*** *absolute radiance calibration following the SI-traceable methodology for aerosol property inversion (e.g. single scattering albedo, size distribution).*

In a given narrow band channel, the instrument measured quantity is also voltage V (DU), and is linked to the incoming absolute radiance, L(λ_{band}), similarly to eq. 1c:

$$V(\lambda_{band})=A(\lambda_{band}).L(\lambda_{band}) \quad (14)$$

with A being the absolute radiance calibration coefficient (DU / (W/m2/sr/um)) within this narrow band.

While there are some individual network nuances in their calibration transfer approach (use of traveling reference instruments to link sub-networks, etc), the philosophy is the same for all of them. This approach we call the standard procedure. However, although being traceable to SI, there are limitations and complexity in such a procedure. These limitations increase the uncertainty of aerosol properties retrieved from the inversion procedure. In addition, this approach is time consuming and labor/cost intensive. Therefore, it potentially limits network growth to a larger scale. This section intends to present new requirements/procedures to overcome these limitations, to reduce the operational complexity, and also to reduce the time needed for calibrating a .

a. Standard procedure for absolute radiance calibration within aerosol observing networks

The standard absolute radiance calibration is by nature SI traceable since it is performed using the integrating sphere source, regularly re-calibrated against a primary integrating sphere source to be SI traceable and to be consistent within the entire network. Once this procedure is applied A(λ) coefficients are known for all field instruments, and, then, equation (14) yields L(λ) in each individual spectral band. The uncertainty on L is mainly controlled by the uncertainty of the integrating sphere source (~1 to 3 %).
It is important to remember here that in aerosol retrievals such as those performed by AERONET, both AOD and radiance are inverted together. However, absolute radiance has to be normalized to the extraterrestrial solar irradiance before being inverted. This normalization introduces additional error (~1%), thus increasing the uncertainty on the retrieved aerosols properties (WP3, Task 3.2).

We present some alternative calibration strategies to the currently used "standard" procedure. These strategies are being evaluated and if their uncertainties are lower or comparable to the standard procedure they potentially can be applied across networks.

b. Proposed alternative strategies for absolute radiance calibration

We propose two strategies to simplify the calibration procedure, to improve its accuracy and to provide SI-traceable calibration. These approaches fully benefit from one sun/sky-characteristic that has not yet been considered operationally, at least in the AERONET network. Sun irradiance and sky radiance are measured using the same optical elements defining their field of view and are linked by the instrument field of view (FOV) or, more precisely by its solid viewing angle, Ω. Several studies (Nakajima, 1996; Li et al., 2008; Uchiyama et al., 2018) and dedicated laboratory measurements *(Task 1.3, Action 1.3.2, WP1)* have shown that Ω can be determined precisely enough (0.3%) to transfer irradiance (or $V_{extraterrestrial}$) calibration to radiance calibration. In-field determination of the FOV or solid angle obtained with 2D-sun scan is under study by GSFC/NASA partners and very preliminary results are given in the annex b.

The following sections describe these two approaches for absolute radiance calibration of the reference s. We also present a new methodology to transfer directly the radiance calibration from reference to any field .

i) Irradiance-to-radiance calibration transfer

As the calibration coefficients, s, have been measured (see section 3), solar irradiance at the top of the atmosphere can be computed via eq. 15, once $V_{Extraterrestrial}$ has been determined,

$$E_{Extraterrestrial} = V_{Extraterrestrial}/s \tag{15}$$

Combination of eq. 15 and eq. 14, yields, for the absolute radiance calibration coefficient (eq. 10),

$$A_{Absolute}^{Photometer} = \Omega. V_{Extraterrestrial}/E_{Extraterrestrial} \tag{16}$$

Uncertainty on $V_{extraterrestrial}$ is, *for a reference instrument*, ~0.3 %, uncertainty on Ω is ~ 0.3% *(Task 1.3, Action 1.3.2)* and the uncertainty on $E_{Extraterrestrial}$ can reach ~1% at some wavelength *(Groëbner et al., 2023*), hence the combined uncertainty on the absolute radiance is ~1.1 %.

ii) $V_{Extraterrestrial}$-to- radiance calibration transfer

This variant method is calibrating directly into normalized radiance (hence without introducing, as previously or as with an integrating sphere source, error coming from the uncertainty on the solar extraterrestrial irradiance). Indeed, converting absolute radiance to normalized radiance from eq. 16, yields

$$A_{Normalized}^{Photometer} = \Omega. V_{Extraterrestrial}/\ \pi \tag{17}$$

Clearly, in this approach, the combined uncertainty is lower and is, now, *for a reference* , ~0.4-0.5 %, about half the uncertainty of the previous case. Thus, performing routine standard radiance calibration and new procedures will provide SI-traceable absolute radiance calibration.

In the last sub-section, we will present a new procedure to simplify the transfer of radiance calibration from reference to field .

iii) Transfer of radiance calibration to field

A direct transfer can be performed, similarly to $V_{Extraterrestrial}$ transfer for AOD calibration, when both reference and field instruments are targeting the same light source at the same time and in a synchronous way.

In this new procedure, still in the experimental and evaluation phase in the AERONET network, the light source is the downward atmospheric radiance (‘Sky’). Downward angular and spectral atmospheric radiances can be written as $L_{reference}$ =(1/$A_{sky,\ reference}$). f(atmosphere, geometry) and L_{field}=(1/$A_{sky,\ field}$). f(atmosphere, geometry) respectively for reference and field .

Hence, as the atmosphere is the same and as pointing and synchronization are accurate between reference and all field s, one can derive

$$A_{sky,\ field} = A_{sky,\ ref} \cdot L_{ref}\ (geometry) / L_{field}\ (geometry) \tag{18}$$

The same ratio is expected at each viewing angle. This approach is SI traceable but normalization to solar irradiance introduces additional errors on L.

This method has been tested in AERONET (details are not given here), as a provisional strategy, and the first comparisons, that are validating this new approach, shows that the difference with the standard calibration is lower than 0.4 % from 440 to 1020 nm, 0.9 % at 1640 nm and ~1% at 380 nm (*results presented at the AERONET workshop, May 2023, communication J. Shafer, NASA*). The great advantage of this method is that it can be performed under the same conditions as the $V_{Extraterrestrial}$ calibration transfer (e.g at calibration OHP-CNRS, UVA, GSFC platforms). Preliminary results are given in the annex a.

Three scenarii can be considered :

- *Scenario 1: reference s are calibrated using an integrating sphere source (standard approach, with uncertainty on radiance 1-3 %). Normalization to solar irradiance before going to inversion introduces ~1 % or more uncertainty on L, etc. This approach is SI-traceable.*

- *Scenario 2 : reference s once calibrated in irradiance can be calibrated in radiance using irradiance-to-radiance method (uncertainty is ~1 %). This approach is SI-traceable and applicable from UV to MIR channels.*

- *Scenario 3: reference s are calibrated in radiance using $V_{Extraterrestrial}$-to-radiance method which yields directly normalized radiance calibration. This option reduces the final uncertainty on radiance (~0.4 -0.5 %) and inversion results, but it is not fully SI-traceable, but applicable from UV to MIR channels.*

At this point, one can recommend systematically applying the 3 scenarii, ***but for reference only***. On one hand, this approach benefits from the gain of accuracy brought by dealing directly with normalized radiance instead of absolute radiance. On the other hand, we are gaining the SI-traceability due to absolute radiance calibration brought by the use of SI traceable integrating sphere or by applying irradiance-to-radiance calibration transfer procedure.

c. Summary of requirements and good practices

1. By analogy to $V_{extraterrestrial}$ calibration transfer on the sun, we recommend to directly transfer radiance calibration from reference to field s. It will be done at the same time as $V_{extraterrestrial}$ transfer from the same reference .
2. Reference s are AOD SI-traceable (see section 3).
3. Reference s have to be calibrated in absolute radiance (SI-Traceable)
4. Combination of 1+2+3 together provides full SI-traceability for field s.
5. Uncertainty can be reduced by transferring normalized radiance calibration from reference to field (variant of 1).
6. Combination of 1+2+3+5 yields SI traceable field and benefits from the reduced uncertainty on normalized radiance

5. Good practices : summary

Regarding AOD SI-traceability, the simultaneous operation of an SI traceable AOD PFR and a reference appears to be the simplest solution (scenario A and B (figure 1)). However, PFR requests very regular cleaning (much more than a CIMEL or PREDE) and their wavelengths are different (annex c). These are limitations.

The other acceptable option is to calibrate the 2 reference s in irradiance requesting a regular calibration to the National Metrology Institutes. This approach was proposed in section 3b and summarized in scenario C (figure 1). However, this calibration has to be rigorously organized/scheduled and efficient since the network service cannot be interrupted. It must be done within the components of the existing networks which calibrate and operate reference s (Europe, USA, Asia) and linked.

Once these reference s are SI traceable for AOD, any field s calibrated against them will be traceable to SI. Of course, there will be an increase of uncertainty due to the transfer but no other way is manageable for a network of hundreds of s. In addition, the stability control enabled by the systematic simultaneous operation of 2 reference s is crucial to preserve the traceability chain. This quality control is being continuously performed and recorded both at the high and low altitude calibration centers.

Reference s being fully characterized, especially their solid angle, can be accurately calibrated in radiance (absolute or normalized). Scenarii to be applied in parallel to reference s are summarized on figure 1.Finally, recent results have shown that a direct transfer from reference sky calibration can be transferred accurately to any field , in a traceable way. This opens a new era of simplification. These are the basic requirements to provide SI traceable calibration for networks of sun/sky/moon s, such as AERONET operating a worldwide network in cooperation with the ACTRIS Infrastructure.

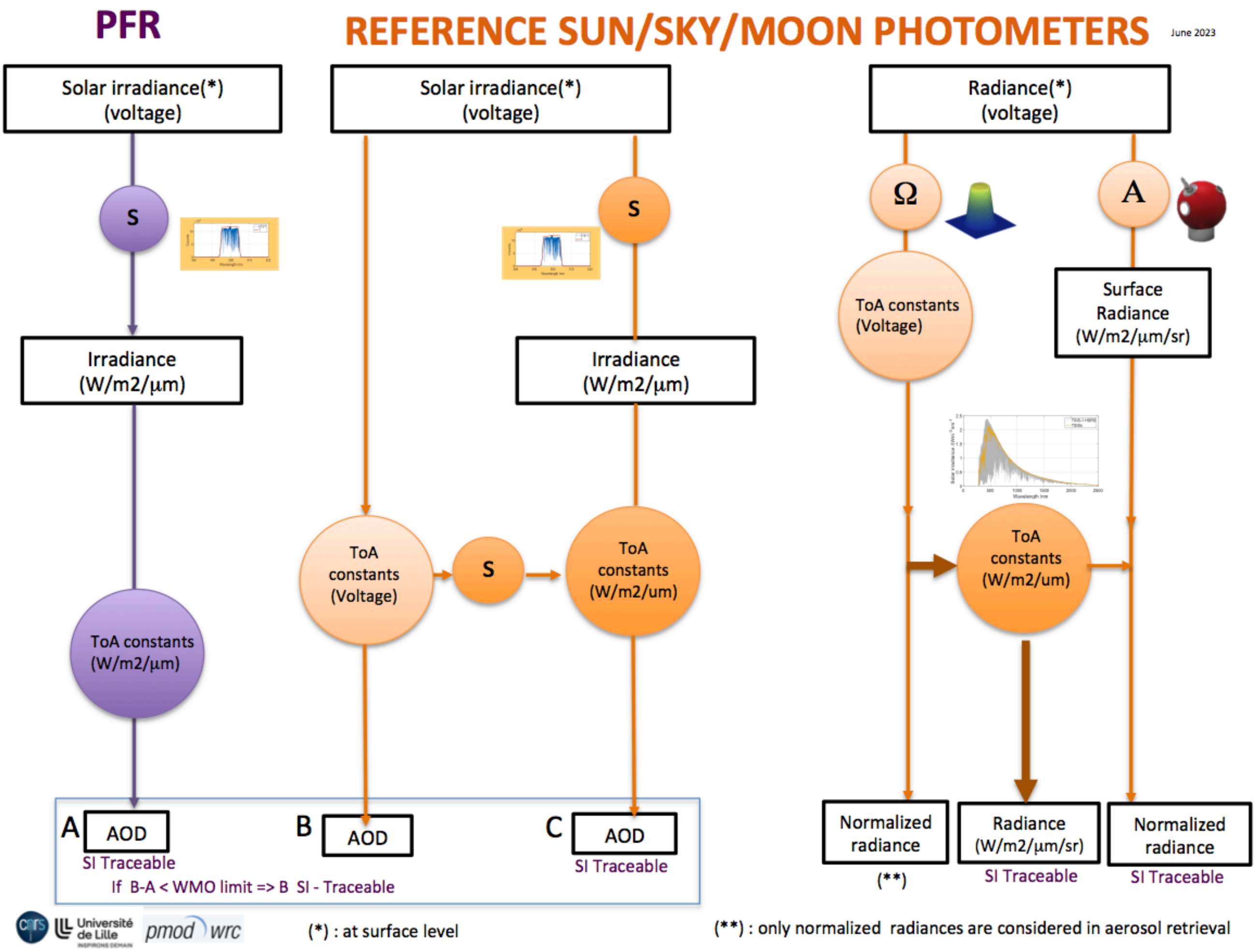

Figure 1: Possible routes to SI traceable networks. PFR channels are 368, 412, 500 and 862 nm. s operating in the other networks (AERONET, SKYNET, …) have different wavelengths. ToA stands for Top of Atmosphere, meaning extraterrestrial signals / radiometric quantities. Scenarii A-C can be applied for moon observation.

6. Annex: recent results on new calibration procedures

a. Direct transfer sky calibration

A prototype of this approach has been implemented in the AERONET processing system in Spring 2023. A set of 10 CE318T have been calibrated using the NASA integrated sphere. Two reference s also calibrated in absolute have been used to transfer their radiance calibration to these 10 field s, at the same time as they were transferring their $V_{extraterrestrial}$ calibration for the standard AOD calibration. After 8 days of "*calibration quality data*" (low and stable AOD) at GSFC, first comparisons were made. Difference between laboratory sphere calibration and direct transfer calibration is presented on figure A.1 and shows a very good consistency (< 1% for most of the channel, for the first results).

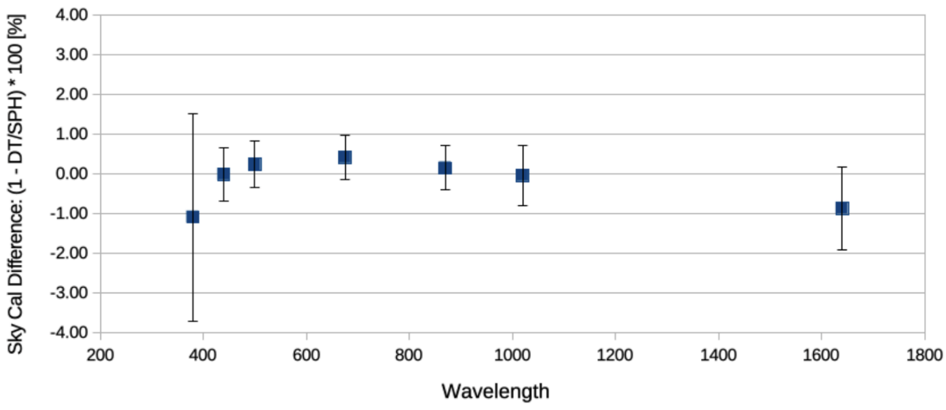

Figure A.1: Difference between Directly transferred and sphere calibration (preliminary results, NASA/GSFC, J. Shafer, April 2023).

b. 2D- sun scan method (on-field)

The 2D-sun scan method (Nakajima, 1996; Torre et al., 2013) was applied to the CIMEL sun to determine its FOV. It corresponds to several days and various solar zenith angles. The preliminary results tend to indicate that FOV and Ω measurements are very repeatable within 0.5%. Some results are presented on figure A.2.

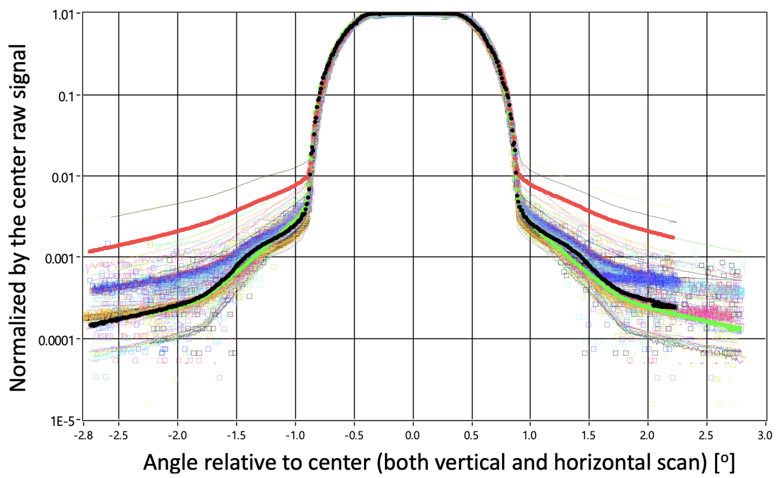

Figure A.2 : Accumulation of 2-D scans (80 measurements at various solar zenith angles and days and all wavelengths, AOD varying from 0.07 to 0.7 at 550 nm). The corresponding FOV is (1.211+/-0.01)°, corresponding to a Solid angle=3.802 10^{-3}sr. (Preliminary results, source : E. Lind, NASA/GSFC, April 2023).

The next step will be to start routine sun scans in 2D every hour to continue the analysis and draw final conclusions and take operational decisions.

c. entral wavelength for the main networks

PFR : 368, 412, 500, 862 nm

CIMEL : 340, 380, 440, 500, 675, 870, 935, 1020, 1640 nm

PREDE : 340, 380, , 500, 670, 870, 940, 1020, 1640, 2200 nm

References

1. Barreto, A., et al., Evaluation of night-time aerosols measurements and lunar irradiance models in the frame of the first multi-instrument nocturnal intercomparison campaign. Atmospheric Environment, 2019. 202: p. 190-211
2. Goloub, P et al., AERONET operational activities in the frame of the Center for Aerosol Remote Sensing, ACTRIS workshop, Prague, October, 2022.
3. Giles, D. M., Sinyuk, A., Sorokin, M. G., Schafer, J. S., Smirnov, A., Slutsker, I., Eck, T. F., Holben, B. N., Lewis, J. R., Campbell, J. R., Welton, E. J., Korkin, S. V., and Lyapustin, A. I. (2019): Advancements in the Aerosol Robotic Network (AERONET) Version 3 database – automated near-real-time quality control algorithm with improved cloud screening for Sun photometer aerosol optical depth (AOD) measurements, Atmos. Meas. Tech., **12**, 169-209, https://doi.org/10.5194/amt-12-169-2019.
4. Gröbner, J., Kouremeti, N., Hülsen, G., Zuber, R., Ribnitzky, M., Nevas, S., Sperfeld, P., Schwind, K., Schneider, P., Kazadzis, S., Barreto, A., Gardiner, T., Mottungan, K., Medland, D., and Coleman, M.: Spectral Aerosol Optical Depth from Traceable Spectral Solar Irradiance Measurements to the SI, Atmos. Meas. Tech. Discuss. [preprint], https://doi.org/10.5194/amt-2023-105, in review, 2023.
5. Holben, B.N., et al., AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization. Remote Sensing of Environment, 1998. 66(1): p. 1-16.
6. Kouremeti, N., Nevas, S., Kazadzis, S., Gröbner, J., Schneider, P., and K. M. Schwind, SI-traceable solar irradiance measurements for aerosol optical depth retrieval, Metrologia 59, 044001, https://doi.org/10.1088/1681-7575/ac6cbb, 2022.
7. Kazadzis S., N. Kouremeti, H. Diémoz, J. Gröbner, B. W. Forgan, M. Campanelli, V. Estellés, K. Lantz, J. Michalsky, T. Carlund, E. Cuevas, C. Toledano, R. Becker, S. Nyeki, P. G. Kosmopoulos, V. Tatsiankou, L. Vuilleumier, F. M. Denn, N. Ohkawara, Osamu Ijima, P. Goloub, P. I. Raptis, M. Milner, K. Behrens, A. Barreto, G. Martucci, E. Hall, J. Wendell, B. E. Fabbri, and C. Wehrli, Results from the Fourth WMO Filter Radiometer Comparison for aerosol optical depth measurements, Atmos. Chem. Phys., 18, 3185–3201, https://doi.org/10.5194/acp-18-3185-2018, 2018
8. Li, Z., Blarel, L., Podvin, T., Goloub, P., Buis, J.-P. & Morel, J.-P. (2008). Transferring the calibration of direct solar irradiance to diffuse-sky radiance measurements for CIMEL Sun-sky radiometers. *Appl. Opt.*, 47(10), 1368-1377. 10.1364/AO.47.001368
9. Nakajima, T., Tonna, G., Rao, R., Kaufman, Y., and Holben, B.: Use of sky brightness measurements from ground for remote sensing of particulate polydispersions, Appl. Opt., 35, 2672–2686, 1996.
10. Schmid B., C. Wehrli, "Comparison of Sun photometer calibration by use of the Langley technique and the standard lamp," Appl. Opt. **34**, 4500-4512 (1995), https://opg.optica.org/ao/abstract.cfm?URI=ao-34-21-4500
11. Toledano, C., González, R., Fuertes, D., Cuevas, E., Eck, T. F., Kazadzis, S., Kouremeti, N., Gröbner, J., Goloub, P., Blarel, L., Román, R., Barreto, Á., Berjón, A., Holben, B. N., and Cachorro, V. E.: Assessment of Sun photometer Langley calibration at the high-elevation sites Mauna Loa and Izaña, Atmos. Chem. Phys., 18, 14555-14567, https://doi.org/10.5194/acp-18-14555-2018, 2018.
12. Torres, B., Toledano, C., Berjón, A., Fuertes, D., Molina, V., Gonzalez, R., Canini, M., Cachorro, V. E., Goloub, P., Podvin, T., Blarel, L., Dubovik, O., Bennouna, Y., and de Frutos, A. M.: Measurements on pointing error and field of view of Cimel-318 Sun photometers in the scope of AERONET, Atmos. Meas. Tech., 6, 2207–2220, https://doi.org/10.5194/amt-6-2207-2013, 2013.

13. Uchiyama, A., Matsunaga, T., and Yamazaki, A.: The instrument constant of sky radiometers (POM-02) – Part 2: Solid view angle, Atmos. Meas. Tech., 11, 5389–5402, https://doi.org/10.5194/amt-11-5389-2018, 2018.