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Title: The Langley Ratio method, a new approach for transferring photometer calibration from direct sun measurements

Response to Referee#3

The authors appreciate the overall positive response of the Referee #3 and we would like to thank for his/her constructive comments. In the following, the Referee suggestions (in bold) are in detail addressed (the author's responses are provided below in blue colour).

The authors present a new method for transferring calibration from a reference photometer, using a synergetic approach when master and field instruments have different spectral bands. This new method, so called Langley Ratio method, was first applied between a PFR and a CE318-TS photometer, because these two photometers have different optics, sun-tracking systems and spectral bands. The campaign and validation at Izaña Observatory (IZO) and Valladolid showed the very low relative differences and standard deviations in the calibration constant transferred in Izaña from PFR to Cimel, up to 0.29 % and 0.46 %. This is really a satisfactory result, and the following studies vitrificated that the Langley Ratio method is a robust and suitable tool for transferring calibrations, detecting and correcting possible instrumental issues.

In summary, the paper is well-written and logically organized. I think it provided a useful way to conduct the calibration of sun photometer in a more efficient pattern, which is important thing for the observation network all over the world. So, I recommend this paper to be published in AMT after revision**, but I still have some question that the authors should take into consideration as below:**

1, Line 49. I think it is unnecessary to emphasize the Valladolid site is not a part of GAW.

We agree with this comment. This information will be deleted from the manuscript.

2, Line 66. The authors should explain more about "SI", as we don't know what is the "SI".

We missed the acronym definition. SI is for International System of Units. We will add this information in the text.

3, Line 70. I think the LR method is useful for the sun photometers in different/same spectral bands. However, the sentence here implies it just for the different spectral bands. The authors should check this.

Line 70 states that "In this paper, we present a new methodology specifically designed to be applied when the calibration transference is carried out between two photometers with different spectral bands in terms of central wavelength (λ_c) or Full-Width-at-Half-Maximum (FWHM)." The authors think that LR method is a hybrid calibration technique (between the Langley plot reference method and the faster and less accurate

Ratio cross-calibration method) suitable for transferring the calibration between instruments with different spectral bands. In the case of the calibration transference between instrument with similar spectral bands and coincident measurements LR method converges to the Ratio cross-calibration method.

4, Line 90. I think a table should be more useful here, to highlight the different spectral bands of device in this paper. So that to avoid much too long title in your Figures, repeating the bands.

We agree with this referee's comment, which coincides with the Referee's 2 comment #6. We will add two tables, one for section 2.1 and another one for section 2.2 describing the CE318-T and the PFR photometers:

Table 1: Main features of the CE318-TS and CE318-TV12-OC sun photometers used in this study.

	CE318-TS	CE318-TV12-OC
Type of instrument	Standard version, Reference instrument in AERONET	Reference instrument in AERONET-OC (Ocean Color)
Type of observation	Automatic sun–sky tracking	Automatic sun–sky–sea tracking
Available standard channels	340, 380, 440, 500, 675 nm, 870, 1020, 1640 nm	400, 412.5, 442.5, 490, 510, 560, 620, 665, 779, 865, 937, and 1020 nm
FWHM	2 nm (340 nm), 4 nm (380 nm), 10 nm (VIS-NIR), 25 nm (1640 nm)	10 nm

Table 2: Main features of the CE318-TS and the GAW-PFR sun photometers used in this study

	CE318-TS	PFR
Type of instrument	Standard version, Reference instrument in AERONET	Standard version, Reference instrument in GAW-PFR
Type of observation	Automatic sun–sky tracking	Automatic continuous direct sun irradiance
Available standard channels	340, 380, 440, 500, 675 nm, 870, 1020, 1640 nm	368, 412, 500, 862 nm
FWHM	2 nm (340 nm), 4 nm (380 nm), 10 nm (VIS-NIR), 25 nm (1640 nm)	5 nm
FOV	1.3º	2.5º
Sun tracker	Robot specifically designed by CIMEL and controlled in conjunction with the radiometer	Any sun tracker with a resolution of at least 0.08º

5, Line 108. Maybe "every 15 minutes (in default)" is more accurate. This is an adjustable option in control box of CE318.

We agree with the referee comment, we will change to "every five minutes (this is the default value in the last firmware version, but it can be adjusted between 2 and 15 minutes)"

6, Line 195. The variable in equation 2 is undefined, please check.

We agree with the referee comment (assuming that the referee refers to equation 3 not 2), which also coincides with Referee's 2 comment #11. We have changed the text from line 188 as follows:

Due to the scarcity of locations with Langley conditions, the typically high costs associated with shipping equipment to such remote areas, and the extended time required to conduct this calibration, alternative methods have been developed (Soufflet et al. 1992; Schmid et al. 1998; Holben et al. 1998; Fargion et al. 2001). Specifically, transferring calibration from a Langley-calibrated reference instrument ($V_{0,\lambda}^{M}$), referred to as the "master," to uncalibrated instruments ($V_{0,\lambda}^{F}$), known as "field" instruments, conducted in more accessible facilities offers a practical solution for calibrating multiple instruments simultaneously. In this regard, AERONET applies the method exposed by Fargion et al. 2001, where the calibration of the field instrument, $V_{0,\lambda}^{F}$, is determined by calculating the ratio between equation 1 applied to the field instrument and equation 1 applied to the master instrument for measurements that are both coincident in time and within the same spectral band. Consequently, this ratio can be expressed in terms of quasi-coincident ratios between raw direct sun measurements from the master (V_{λ}^{M}) and the field instrument (V_{λ}^{F}) as follows:

$$V_{0,\lambda}^{F} = \frac{V_{\lambda}^{F}}{V_{\lambda}^{M}} \cdot V_{0,\lambda}^{M},$$

7, Line 416. In conclusion part, the authors should give us some advice that the shortage of LR ratio method, or the un-suitable case, to avoid the calibration uncertainty.

As stated in Section 4, where the method LR is described, $\Delta\tau$ is the critical term in the LR formulation. The validity of the LR method relies on the fact that $\Delta\tau$ is assumed to be constant. Despite being less sensitive to atmospheric variations than the standard Langley method, this assumption can be compromised in cases of high atmospheric extinction and high variability in aerosol concentration and size, leading to significant changes in $\tau_{\lambda,a}$ and Ångström exponent (AE).

To properly address this question, we have decided to conduct a sensitivity study of V_0 obtained with the LR method concerning the variability in AOD and AE. To do this, we have modified the sensitivity study of $\Delta\tau_a$ concerning AOD and AE, which was conducted to respond to a question from the Referee 1. The details of this study are presented below.

First, we created a set of synthetic measurements by applying the Bouguer-Lambert-Beer equation (equation 1 of the preprint article) for a range of τ values, both for the master photometer with CWL λ_M and for the field photometer with CWL λ_F. To generate this set of synthetic measurements, we assumed that the contribution from Rayleigh scattering and gas absorption remains constant, while the contribution due to aerosols varies. Thus, for the master aerosol contribution, we considered a range of AOD values ($\tau_{\lambda_M,a}$) randomly distributed in a normal distribution characterized by their mean and standard deviation. For the field instrument, the AOD was calculated from the master instrument using the Ångström law, that is:

$$\tau_{\lambda_F,a} = \tau_{\lambda_M,a}\left(\frac{\lambda_F}{\lambda_M}\right)^{-\alpha} \quad (1)$$

where α is the Ångström exponent. In this case, we have also considered a range of α values randomly distributed in a normal distribution characterized by their mean and standard deviation.

Once these synthetic voltages were generated, we calculated $V_{0,F}$ from $V_{0,M}$ after applying the LR method (see equation 5 of the preprint article). We performed 1000 evaluations of Equation 5 for each set of random values (every set has 10 values, the minimum number of data used for a LR calibration), denoted by $< \tau_{\lambda_M,a} >, \sigma(\tau_{\lambda_M,a}), < \alpha >$ and $\sigma(\alpha)$. Subsequently, we calculated the standard deviation of $V_{0,F}$ obtained from the 1000 evaluations.

The range of values we considered included five values for $< \tau_{\lambda_M,a} >$ (0.02, 0.05, 0.1, 0.25 and 0.5), four values for $< \alpha >$ (0.1,0.5,1.0 and 2.0), 100 values for $\sigma(\tau_{\lambda_M,a})$ (ranging from 1 to 20% relative to the average) and 100 values for $\sigma(\alpha)$ (ranging from 1 to 50% relative to the average). These values are consistent with the actual measurements obtained in Valladolid and IZO stations. The analysis has been focused on the CWL pair at 675/500 nm. The results are presented in Figure 1.

In Figure 1, the variability of $V_{0,F}$ is represented on a color map, showing the standard deviation of $V_{0,F}$ relative to the Average ($\sigma(V_{0,F})/\langle V_{0,F}\rangle$), plotted against the standard deviations of $\tau_{\lambda_M,a}$ and α relative to their averages ($\sigma(\tau_{\lambda_M,a})/< \tau_{\lambda_M,a} >$ and $\sigma(\alpha)/\langle\alpha\rangle$) for various average values of $\tau_{\lambda_M,a}$ and α ($< \tau_{\lambda_M,a} >$ and $\langle\alpha\rangle$), resulting in a total of 20 subfigures. Panels from left to right correspond to increasing $\langle\alpha\rangle$ values, and panels from up to down correspond with increasing $< \tau_{\lambda_M,a} >$. The variability in $V_{0,F}$ ($\sigma(V_{0,F})/\langle V_{0,F}\rangle$) is displayed on a logarithmic color scale, where bluer shades indicate lower variability and redder shades indicate higher variability.

In the first place, as expected, the results depicted in the figure show that an increase in any of the different parameters ($< \tau_{\lambda_M,a} >, \sigma(\tau_{\lambda_M,a}), < \alpha >$ and $\sigma(\alpha)$) leads to an increase in the variability of $V_{0,F}$. For clean conditions ($< \tau_{\lambda_M,a} > <=0.02$), the variability of $V_{0,F}$ remains below 1% (except for $< \alpha >= 2$ and $\sigma(\alpha)/\langle\alpha\rangle$ higher that 30%). For very low values of $\langle\alpha\rangle$ (<=0.1) and $< \tau_{\lambda_M,a} >$ (<=0.1), $\sigma(V_{0,F})/\langle V_{0,F}\rangle$ remains below 1%, regardless of the variability in $\tau_{\lambda_M,a}$ and α (within the study range). For high values of $\langle\alpha\rangle$ (>= 1) and $< \tau_{\lambda_M,a} >$ (>= 0.25), $\sigma(V_{0,F})/\langle V_{0,F}\rangle$ is almost always greater than 1% (except in unrealistic cases where the variability in $\tau_{\lambda_M,a}$ and α is extremely low). For the rest of the intermediate cases, $\sigma(V_{0,F})/\langle V_{0,F}\rangle$ would generally have values below 10%, reaching lower $\sigma(V_{0,F})/\langle V_{0,F}\rangle$ values (below 5%) depending on the variability in $\tau_{\lambda_M,a}$

and α. In general, it can be stated that the method should not be applied when $< \tau_{\lambda_M,a} >$ >= 0.25 and ⟨α⟩ >= 1.

This information will be included in the supplementary material in the manuscript.

Taking into account this information, we will include the following paragraph in Line 416-419:

“In conclusion, this hybrid calibration technique between the Langley plot reference method and the faster and less accurate Ratio cross-calibration method appears to be a suitable technique for transferring the calibration between instruments with different spectral bands. However, despite being less sensitive to aerosol variations compared to the standard Langley calibration method, the validity of LR relies on the assumption of moderate to low aerosol loads and a moderate to low Ångström exponent during the calibration period, making it unsuitable for cases where $\tau_{a,500} \geq 0.25$ and $\alpha \geq 1.0$.”

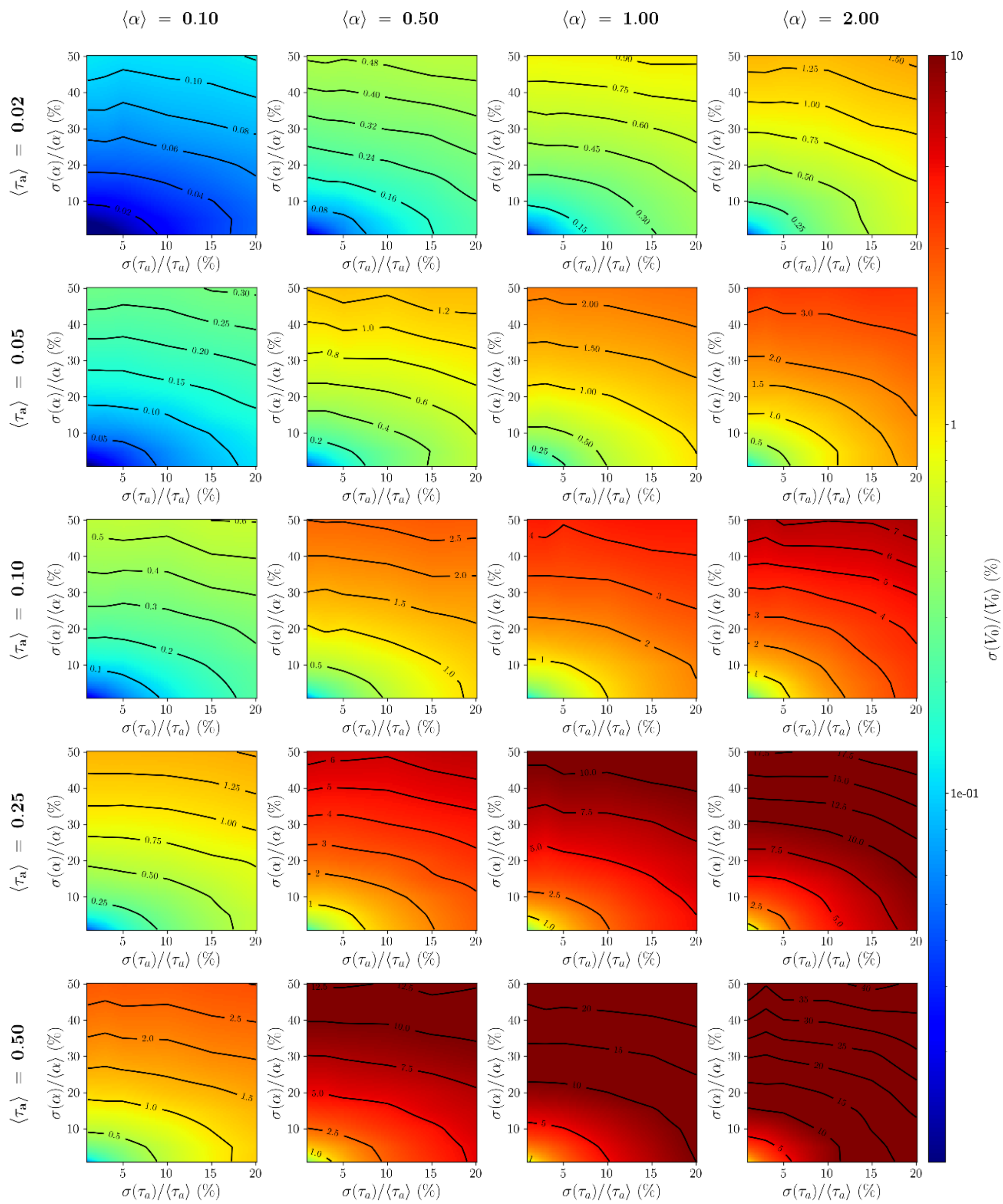

Figure 1: Colormaps representing $V_{0,F}$ variability as $\sigma(V_{0,F})/\langle V_{0,F}\rangle$ as a function of the standard deviations of τ_a and α relative to their averages ($\sigma(\tau_{\lambda M,a})/<\tau_{\lambda M,a}>$ and $\sigma(\alpha)/\langle\alpha\rangle$) for a set of average values of $\tau_{\lambda M,a}$ and α ($\langle\alpha\rangle$ = 0.1, 0.5, 1.0, and 2.0) and ($<\tau_{\lambda M,a}>$ = 0.02, 0.05, 0.1, 0.25, and 0.5) for the 675/500 CWL pair. Panels from left to right correspond to increasing $\langle\alpha\rangle$ values, and panels from top to bottom correspond to increasing $<\tau_{\lambda M,a}>$ values. $\sigma(V_{0,F})/\langle V_{0,F}\rangle$ is displayed on a logarithmic color scale, where bluer shades indicate lower variability, and redder shades indicate higher variability.