Response to the Referee #2 comments for the manuscript "Correction of a lunar irradiance model for aerosol optical depth retrieval and comparison with star photometer" By Roberto Román et al. in AMTD

First, we are grateful for the effort of Referee #1 and her/his review in detail. Reviewer comments are in black font (RC), and author comments (AC) in red font.

Author's answer to Anonymous Referee #1

RC: The paper points out the importance of the accurate knowledge of the Moon extraterrestrial spectrum over a full moon cycle for nighttime AOD retrievals in lunar photometry. A large dataset of Langley extrapolated values at Cimel's photometer wavelengths, covering the spectral region 380 nm -1640 nm, has been retrieved under stable and low AOD conditions, leading to an empirical spectral correction factor (RCF) of the RIMO model with respect to MPA. The number of data points and the ideal conditions is expected to lead to a low uncertainty correction factor. The validation of the RCF, by AOD comparison of Cimel photometer against a star photometer gives convincing results always within the uncertainties of the two independent retrievals. I find this work very interesting as it leads to a very useful and practical correction that allows nighttime. AOD retrievals based on the lunar photometry, in anticipation of a traceable update of ROLO and RIMO models.

Comments

RC: 1. The correction methodology described in the paper in based on the assumption of linear behavior of the instrument with respect to the measured irradiance. The authors need to address this in the paper, to avoid any confusion between instrumental and RIMO correction.

AC: Referee comment is right, we assume that the instrument response is linear. This assumption was confirmed by the study of Taylor et al. (2018); hence, a sentence has been added in the new manuscript to indicate these issues:

"*It is important to remark that this AOD retrieval is based on the assumption of linear behaviour of the instrument with respect to the measured irradiance, but this assumption is reasonable as it was observed by Taylor et al. (2018), who found that nonlinearity can be considered negligible for the CE318-T instrument at Moon irradiance levels.*"

Taylor, S., Greenwell, C., and Woolliams, E.: D3: Lunar Photometer Calibration for Lunar Spectral Irradiance Measurements, Tech. rep.,http://calvalportal.ceos.org/documents/10136/703678/Lunar%2BIrradiance%2BD3%2B-%2BCalibration.pdf, 2018.

RC: 2. What is the spectral uncertainty of the correction? Figure 1 should include a panel demonstrating the uncertainty with respect to MPA as well as the relative RCF to a selected MPA

AC: The proposed RCF correction should only be used for the Cimel 318-T wavelengths: 340, 380, 440, 500, 675, 870, 940, 1020 and 1640 nm, but even the use of 340 and 380 nm is not recommended, as indicated in the conclusions. No wavelength interpolation of RCF should be applied to other wavelengths or spectral bands. It is mainly because the nature of RIMO. RIMO calculates the lunar reflectance at 32 wavelengths that are later interpolated to the CE318-T wavelengths. The accuracy of RIMO in the wavelengths within a spectral range defined by two consecutive RIMO wavelengths (of the 32 wavelengths) can be totally different in other spectral range.

Following the reviewer comment we have calculated the uncertainty on the a, b and c coefficients for the RCF calculation. Figure 1c panel has been modified including the uncertainty of the RCF but also Figure 1 has a new panel (Figure 1d) in the new manuscript version with the spectral variation of RCF for different MPA values. Figure 1c and 1d are shown in Figure R1. The next sentences have been added to discuss the obtained results.

"The uncertainty on RCF caused by the uncertainty on the coefficients is also shown in Figure 1c. This uncertainty increases with MPA and is in general low except for the UV channels. Figure 1d shows the RCF values as a function of the nominal wavelengths of the photometer channels and for a set of MPA values. The uncertainty of the RCF increases with MPA as observed in Figure 1c. About the variation of RCF with wavelength, it is similar for the different MPA values, being always larger for negative MPA values than for positive ones, except for 1020 channel. The RCF strongly decreases from 340 to 440 nm, while from 440 to 935 nm the variation is smoother, increasing from 440 to 675 nm and decreasing from 675 to 935 nm. This result could lead us to think that RCF can be calculated for other wavelengths by interpolation. However, the spectral variation of RCF is unknown and smooth or linear behaviour cannot be assumed. RIMO lunar reflectance values are calculated at 32 spectral bands which are interpolated to the other wavelengths, the accuracy of RIMO could drastically vary between two different RIMO bands. Therefore, the interpolation of RCF to other bands is not recommended or at least must be taken with care. The spectral uncertainty and accuracy of RCF is not known out of the CE318-T spectral bands."

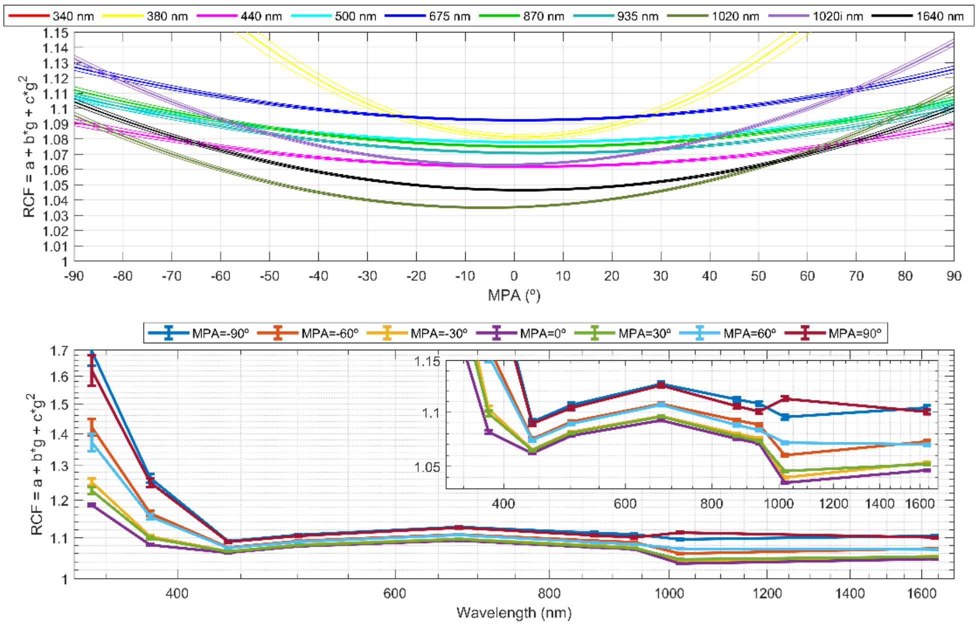

Figure R1: a) Fitted RCF and ± its propagated uncertainty vs. MPA for different wavelengths (340 nm values are not shown because they are out of the axis limits). b) Fitted RCF and ± its propagated uncertainty (error bars) against the nominal wavelength of each CE318-T channel, for different MPA values.

RC: 3. Has the RCF been applied to other photometers/spectroradiometers?

AC: The RCF has been applied to other Cimel CE318-T photometers and it works good even at different locations (see González et al., 2020). But this correction has not been applied to other photometer models or spectroradiometers yet. To test how much dependent on the instrument the proposed correction is, we encourage other researchers to validate this method with other instruments. However, we know the RCF was developed only for the CE318-T spectral bands and therefore the extrapolation of RCF to other spectral wavelengths is not recommended. For other instruments the full methodology should be applied in order to retrieve new RCF for their specific spectral bands.

The last sentence of the paper has been modified as follows:

"*Moreover, additional studies using different Moon photometer/spectroradiometer models or using alternative and independent night-time instrumentation, like lidar or star photometers, are highly recommended to characterize the AOD uncertainty, the accuracy of the proposed method and the feasibility of its use with other instrumentation.*"

RC: 4. How the degradation of the reference Cimel is accounted for? Are the daytime calibrations used between the night observation?

AC: The calibration coefficient of each channel is time interpolated between the previous (pre-) and later (post-) AERONET standard calibration for daytime (solar observations for AOD). This interpolated coefficient is transferred to the night-time calibration by the Gain method. Hence the degradation of the instrument is considered by the temporal interpolation between the pre- and post-deployment calibrations.

RC: 5. The stability of the atmospheric aerosol load has been well described, however what is maximum difference between the afternoon and next morning AOD to retrieve the correction factor? Is there any dependency of the RCF to the slope of the linear fit?

AC: There is no threshold for the maximum AOD difference between afternoon and next morning, but for stable and pristine selection we are demanding that the AOD at 500 nm must be below 0.025. Hence, indirectly there are a maximum difference between the afternoon and next morning AOD at 500 nm of 0.025. The dependence of RCF on the slope (AOD variation rate during nights) has not be studied. However previous studies about Izaña (Toledano et al. 2018) indicate no systematic diurnal cycle of the aerosol at the site. Therefore, we are confident about the absence of systematic effects that could bias our results.

RC: 6. Apart from the comparison of the corrected AOD to the star photometer it would be very interesting to add in figures 2,3,4 the uncorrected AOD retrievals, so the reader can visualize the improvement.

AC: The same analysis for the uncorrected AOD has been done. The main problem is the cloud-screening application, since these uncorrected AOD results in Angström Exponent values out of the cloud-screening limits and a lot of cloud-free measurements are rejected. Anyway, the same Moon-Star comparison with uncorrected AOD has been done choosing the data labelled as cloud-free by the RCF-corrected AOD. The next figures (R2, R3, R4 and R5) show the results. It is true that the reader can see how the uncorrected AOD fits worse, underestimating the star AOD (around -0.05) which is more evident as MPA increases. However, the reader knows that because the AOD differences regarding a reference AOD are shown in Figure 1a at Izaña. Moreover, the addition of the uncorrected data to the panels makes them more confusing due to the high number of data points and information. We know that it is important to remark the improvement, but in this case, we assume that the uncorrected data is not useful for AOD calculation and hence we prefer to focus the comparison on the analysis of the proposed method.

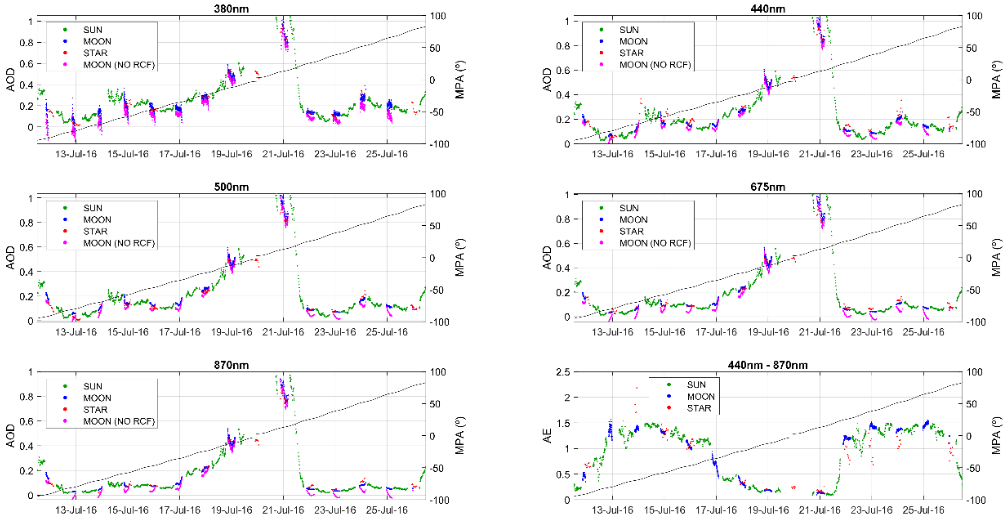

Figure R2: Aerosol optical depth (AOD) values from Sun, Moon (with and without RCF correction) and star photometer at Granada (Spain) from the first to third Moon quarter in July 2016. Bottom panel at right shows the Angström Exponent (AE) calculated with the wavelengths of 440, 500 and 675 and 870 nm (436, 500, 670 and 880 nm for star photometer). Moon phase angle (MPA) is represented with a black line in each panel.

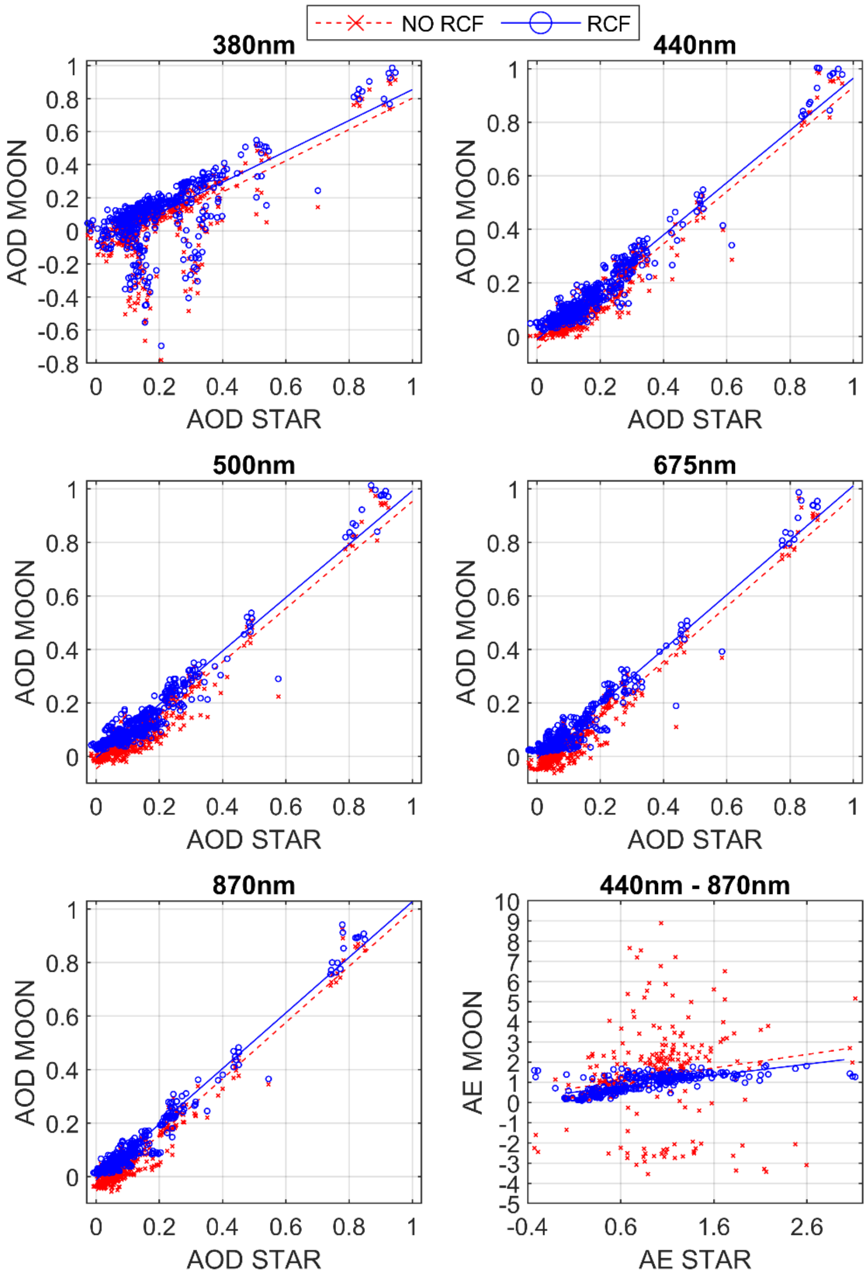

Figure R3: Aerosol optical depth (AOD) and Angström Exponent (AE) from Moon photometer with and without RCF correction versus the AOD from star photometer for 2016-2017 period and for different wavelengths. Linear fits are also represented for each wavelength.

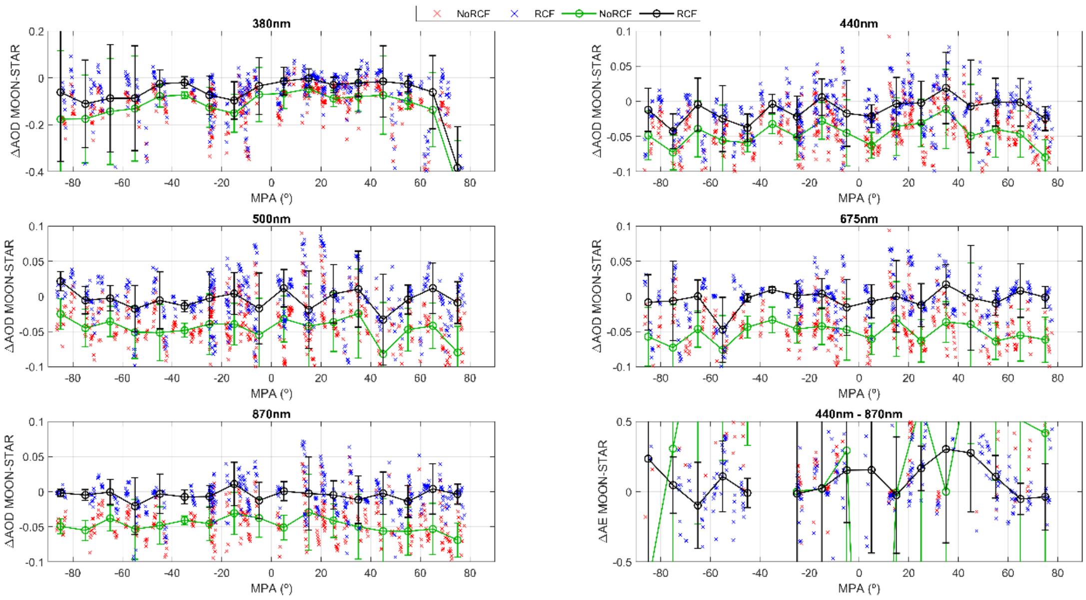

Figure R4: Aerosol optical depth (AOD) differences between the Moon and star photometers as a function of Moon phase angle (MPA) for different wavelengths. Bottom-right panel shows these differences for Angström Exponent (AE) in the 440-870 nm range. Black circles represent the median of all differences in a ±5º MPA interval, while error bars indicate ± standard deviation of the data in the same interval.

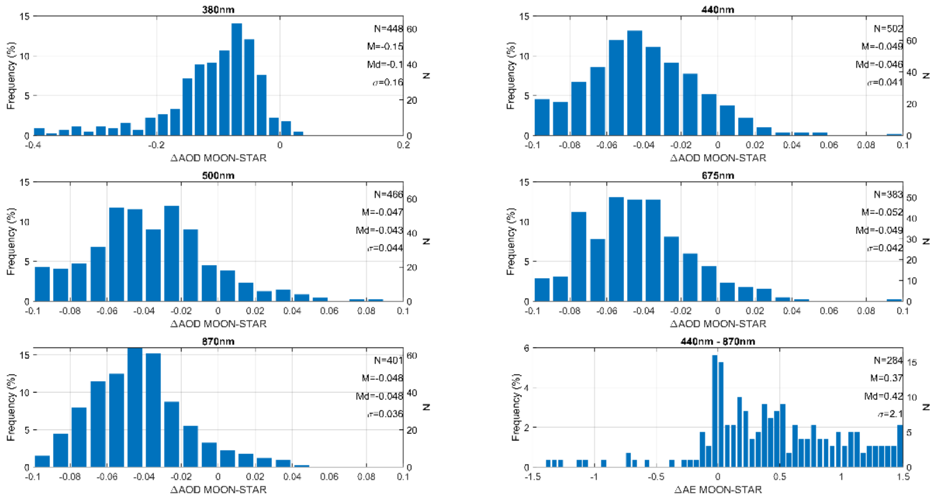

Figure R5: Frequency of the aerosol optical depth (AOD) differences between the Moon (without RCF correction) and star photometers for different wavelengths. Bottom-right panel shows the frequency of these differences for the Angström Exponent (AE) in the 440-870 nm range.

RC: 7. A spectral RCF version of the Figure 1c for selected MPA would be helpful.

AC: See the answer to the second referee comment.

RC: 8. Why the could-flagging is wavelength dependent? Given the noise of 380 nm why the cloud flag from next measured wavelength is not used?

AC: The development of a robust cloud-screening for AOD at night-time is out of the scope of this paper, as it is explained in the manuscript. As a first step, we translated the cloud-screening for daytime AOD (based on AERONET criteria) to the night-time.

The used cloud-screening is not wavelength dependent. When the algorithm detects clouds then all the wavelengths are removed for the particular observation. The cloud-screening main criteria employ temporal variation thresholds at different time scales, using the infrared channels and 500nm. The low signal at 380 nm can result in bad AOD data in this channel even if the sky conditions (as indicated by the other wavelengths) were cloud free.

We may in the future introduce additional quality-assurance criteria within the screening algorithm, in order to reject channels without realistic AOD data even in the absence of clouds (for instance due to noisy signal or defective filter, etc).

Technical comments/suggestions

RC: Line 2: that is very relevant in polar areas Important, interesting, high value

AC: "Relevant" has been replaced by "important".

RC: Line 14: that provides the expected AOD values provides AOD closer to the expected values

AC: Done.

RC: Line 87: located below the Izaña's level. located below Izaña's level /altitude

AC: "level" has been replaced by "altitude".

RC: Line 121: same detectors as the Sun

AC: The sentence has been changed by:

"*Sky radiance at solar aureole and direct Moon irradiance are measured with the same detectors used to measure direct solar irradiance, but with an electronic amplification factor (gain) of 128 and 4096, respectively.*"

Line 125: the photometers used in this paper belong to AERONET, being the #933 a reference photometer used at Izaña data Used for Izaña data / operated at Izaña What is the measurement period?

AC: "used" has been replaced by "operated". The period is not added in this part since it is always the same photometer used for Izaña data, while for UGR we need to discern between three different photometers which is important in the Moon-Star comparison because some differences could be caused by the photometer. The measurement period chosen for the #933 photometer at Izaña is mentioned in Section 3.3: from June 2014 to March 2018.

RC: Line 165: makes that the knowledge of the absolute extraterrestrial irradiance is not needed in the AOD calculation, because an equivalent Noncompulsory
AC: we have reformulated the paragraph:

"*A main advantage of Sun photometry is that the measured irradiance is directly emitted by the Sun and then, the solar irradiance reaching the top of atmosphere (extraterrestrial irradiance) does not significantly change, at least along one day. The Earth-Sun distance is the main factor modulating this irradiance, causing variations about ±3% along the year. Following the Beer-Bouguer-Lambert law, the extraterrestrial signal of the instrument (rather than irradiance in physical units) is needed for AOD calculation. This can be obtained by the Langley plot method (Shaw, 1976, 1983), in which direct Sun irradiance is observed at different solar elevations in order to extrapolate the top-of-the-atmosphere signal of the instrument. Side by side comparison with a reference instrument is the common practice in AERONET for calibration transfer in field instruments (Holben et al., 1998; Toledano et al., 2018; Giles et al., 2019; González et al., 2020).*"

RC: Line 167: calibration transfer
AC: Done.

Line 170: this fact points out the need of knowledge of the extraterrestrial lunar irradiance for Moon photometry purposes this fact points out the need of knowledge of the extraterrestrial lunar irradiance, and especially the variation with respect to the MPA, for Langley based Moon photometry purposes
AC: the text has been changed as:

"*However, the Moon is not a self-illuminating body. It reflects solar radiation with exceptional stability (Kieffer and Stone, 2005). Due to the changing positioning of Sun, Moon and Earth, lunar irradiance at the top of the Earth's atmosphere significantly changes with the Moon Phase Angle (MPA), even along one single night. This fact points out the need of accurate knowledge of the extraterrestrial lunar irradiance for Moon photometry purposes. In this framework, AOD from lunar irradiance observations can be calculated following the Beer-Bouguer-Lambert law, as follows (Barreto et al., 2013)*"

RC: Line 360: appreciated in Figure 3 since they are out of axis limits, and they are not cloud-screened since the used criteria does not reject Seen
AC: This sentence has been changed to:
"*These values are not cloud-screened because the removal of negative AOD values is not included in the screening algorithm. These negative values are the main cause of the shifted linear fit shown in Figure 3 for 380 nm. This plot, however, shows that there are many data points of AOD (380 nnm) close to the 1:1 line.*"