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Interactive comment on “Assessment of nocturnal Aerosol Optical Depth from lunar photometry at Izaña high mountain Observatory” *by* África Barreto et al.

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We thank the reviewer #2 for the positive and constructive comments. Listed below are our responses to the eight different discussion points.

» C1 As stated above, the Introduction is rather long compared to the other sections of the paper. A possible solution may be to split up the introduction into a more concise version and a second section containing background information and references. In my view this will add to the readability of the paper

According to the referee’s comment we have reduced the introduction in order to improve the readability of the paper. This is the new introduction:

“Aerosols can significantly influence the climate in several ways: through aerosol-radiation and aerosol-cloud-precipitation interactions (Foster et al., 2007, IPCC 2013). This fact has motivated notable efforts in atmospheric sciences envisaged to increase the understanding of the role played by aerosols in the global climate balance.

Aerosol optical depth (AOD) is a valuable parameter accounting for aerosol load in the atmosphere because it is a measure of the extinction of the solar beam by absorption and scattering processes caused by aerosols. Sun photometry provides useful information to retrieve columnar aerosol optical and microphysical properties with an excellent spatial coverage but with the lack of vertical resolution (Holben et al., 1998, Eck et al., 1999, Holben et al., 2001, Eck et al., 2009, 2010). A good example of the spatial extent of Sun photometry techniques is the widespread ground-based AErosol RObotic NETwork (AERONET) (Holben et al., 1998) and its federated networks, including hundreds of stations globally distributed. However, aerosols at night-time have been studied to a much lesser extent (Barreto et al, 2013a,b, Baibakov et al., 2015). There is a growing interest in studying the diurnal dynamics and evolution of atmospheric aerosols (Pérez-Ramírez et al., 2012a), as well as understanding the nucleating role of aerosols and their net radiative effects (Baibakov et al., 2015). Therefore, new technological developments try to fill the night-period gaps in AOD time series. As Baibakov et al. (2015) pointed out, star and Moon photometry have arisen as plausible solutions to this problem. Star photometer technique (Leitener et al., 1995, Pérez-Ramírez et al., 2015, Baibakov et al., 2015) has been revealed as a useful tool to infer aerosol information during night-period. However, infrastructure and logistic constraints still represent an important limitation for the operational use of stellar measurements, especially for global networks such as AERONET. Alternatively, Moon photometry is a technique that can be implemented more easily, and at a lower cost, in an operational way (Barreto et al., 2016). Nevertheless, Moon photometry technique is still affected by notable limitations. Despite the Moon is our nearest celestial neighbor, our knowledge about its spectral irradiance is far from being as precise as the spectra from the Sun or bright stars like Vega (Cramer et al., 2013). The main important obstacle in Moon photometry is the fact that the Moon is a variable reflector of sunlight and, as a result, it is a highly variable source of visible light (Miller et al, 2012).

Pioneering works in lunar photometry were developed by Esposito et al. (1998), Berkoff et al. (2011) and Barreto et al. (2013a,b). Recently, Barreto et al. (2016) presented the new photometer CE318-T which combines the features of the extensively used by the Cimel Sun photometer, standard model in AERONET network, with the lunar photometer prototype previously presented in (Barreto et al, 2013a,b). The higher precision of this new instrument compared to the previous versions of Sun and Moon photometers and its ability to monitor atmospheric aerosols in a diurnal cycle, have made it a suitable instrument to replace the CE318-AERONET reference instrument.

As many authors have stated (Berkoff et al., 2011, Barreto et al, 2013a,b, Barreto et al., 2016), a precise Moon irradiance model is mandatory in Moon photometry to take the continuous change of Moon's brightness over the cycle into account. In this respect, RObotic Lunar Observatory (ROLO) model, developed by Kieffer and Stone (2005), is the most careful radiometric study on the Moon's brightness to date (Cramer et al., 2013). The ROLO model has recently emerged as a unique tool for Moon photometry (Berkoff et al., 2011, Barreto et al, 2013a,b, Barreto et al., 2016), and is an essential part of the calibration process. Although this model provides precise information about the change of Moon's irradiance with the phase angle (g) and lunar librations, small systematic effects have been found in this model. Lacherade et al. (2013) and Viticchié et al. (2013) found a small phase angle dependence of the ROLO calibration using the Pleiades Orbital Lunar Observations (POLO) and Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) solar bands. Cramer et al. (2013) developed a novel apparatus to accurately measure the lunar spectral irradiance with the aim of estimating these systematic effects in the ROLO model. Barreto et al. (2016) used the CE318-T and the ROLO model to retrieve AOD at day and night-time in Izaña, a high altitude observatory located at Tenerife (The Canary Islands, Spain). These authors observed an important dependence of the AOD uncertainty with phase angle and also a faint nocturnal cycle in AOD, indicating a possible dependence of AOD uncertainty on the Moon's zenith (θ) and phase angles. As these authors stated, the reason for these discrepancies remain unclear, although it is likely to be due to a sum of causes, such as inaccurate instrument calibration, possible systematic errors in the ROLO model, and uncertainties in night-time AOD calculation.

This work is based on all of the previous results to improve the AOD retrieval at night-time by selecting a set of clean and stable night-time conditions at Izaña in which day-time AOD data could be considered a good proxy for nocturnal AOD. Clean and stable conditions of days used in this study have been ensured using AERONET daytime data at the station and Micropulse lidar version 3 (MPL-3) atmospheric vertical profiles extracted from a nearby coastal station. The main aim of this study is to identify the errors sources, thereby trying to fix experimentally some of the problems currently affecting Moon photometry.

Section 2 describes the experiment site, instruments and methods used in this study. A description of the methodology developed to improve nocturnal AOD measurements and the corresponding validation performed at Izaña, as well as in other complementary stations, is presented in section 3. Finally conclusions are shown in section 4."

» C2 - In Sections 2 and 3 the two methods for calibration are mentioned; the "common Langley technique" and the "Lunar-Langley technique". Although well-informed readers are familiar with the two techniques I suggest to spend a few more words on the techniques and its limitations, in particular the "every-night requirement" for the common technique (including an explanation).

Information about the common Langley and the Lunar Langley as well as their limitations has been included in the text as follows: Pag. 5, line 24: "$\ldots AOD_V 2.html$). The calibration κ_λ is calculated by means the Lunar-Langley method developed by Barreto

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et al. (2013a). The main equations involved in this method are the Eq. 2, derived from the Beer-Lambert-Bouguer Law (the basis of the Langley calibration technique described by many authors in sunphotometry -Shaw, 1976, 1983, Holben, 1998; among others-) and the Eq. 3 (the basis of the Lunar-Langley calibration technique), which defines the calibration constant as the ratio of V_0 to I_0.

$ln(V_\lambda) = ln(V_{0,\lambda}) - m(\theta)\cdot\tau_\lambda$ (2)

$V_{0,\lambda}$=$I_{0,\lambda}\cdot\kappa_\lambda$ (3)”

Pag. 6, line 11: “Nocturnal measurements were performed by means of a master CE318-T installed at Izaña station. This instrument has been calibrated following the Lunar-Langley calibration method (Barreto et al., 2013a) previously described. This is a new absolute calibration technique, specifically developed for lunar photometry, which avoids the determination of one different calibration coefficient every night required by the common Langley technique (Shaw, 1976, 1983). It is important to emphasize the moon’s illumination variation inherent to the lunar cycle, which means the V0 and I0 terms in Eq. 3 are continuously changing, even during the $\sim$ 2 hour observation time period required to perform the Langley calibration. Even if we discard the I0 variation during the Langley period, the extraterrestrial voltages V_0 should be determined every day, which is not plausible considering the restrictive requirements in terms of atmospheric stability and cloudiness of this calibration technique. In spite the simplicity of the Lunar-Langley technique, its accuracy relies on the uncertainty involved in the ROLO model.”

» C3 Section 3.1: it is stated that stable AOD conditions are selected using ancillary vertical information from an MPL-3 lidar. Although Fig. 1 is useful I suggest to give some more information on what exactly is meant by "stable" and how stable periods are selected (is there a quantitative criterion?). The interpolation method to get nighttime AOD from daytime values is a crucial aspect in the paper, so the background of how to select stable data deserves more attention/explanation.

We have verified the stable AOD conditions with MPL-3 lidar aerosol backscattering information, and using an AOD stability criterion in the 1-h average AERONET AOD of two consecutive days at 870 nm. Doing so, the night is considered stable if the average of the AOD difference between two consecutive days is about 0.005. This information will be included in the final manuscript.

» C4 An interesting and good aspect of the work is that the AOD correction has been applied to three other stations in different aerosol climates. The question that arises is: is the correction (the coefficients presented in Table 1 fully instrument-independent? Since the correction is wavelength-dependent, the assumption that the parameterization can be applied to other instruments seems to rely on comparable spectral characteristics (in particular the filters) of the reference instrument and the instruments to which the correction is applied. I suggest the authors spend a few words on explaining why the correction can safely (?) be applied to the Carpentras, Dakar and Lille instruments, and on the possible introduction of extra uncertainty.

Our results showed that the correction can be applied to any other instrument and location. However, we will include in the text the following information: Pag. 11, line 3: “This evaluation analysis in different stations seems to corroborate the applicability of this correction procedure to other instruments and sites. However, it is fair to admit this correction has been performed by means of an unique instrument, with certain optical interference filters. The difference in the filter responses as well as the degradation of optical filters with time are the limiting factors. They could add an extra uncertainty depending on the different band responses between instruments. Further studies will be focused on the estimation of this extra uncertainty.”

» C5 The title of Section 3.5 is not entirely correct since the method is not really validated. The authors have applied their correction method to AOD retrievals at the three sites but a real validation has not been performed. I suggest changing the title into something more appropriate ("Impact of correction. . ." or something equivalent).

We agree with this comment. We will replace the current title by “Evaluation of the AOD empirical correction at other sites: Carpentras, Dakar and Lille”.

» C6 Section 3.4 (line 19): Lille is considered to be affected by "relatively clean conditions". I think that this cannot be stated in general considering the highly polluted environment the site is located in. The AOD may be not particularly high during the selected period but "clean conditions" is maybe a bit too optimistic

We agree. We will replace “clean” by “relatively low AOD conditions”.

» C7 Table 1: R-squared: the value –0.71 seems to be incorrect.

We have corrected this mistake.

» C8 Although Fig. 8 can be understood, it is not very easy to distinguish between the asterisks and the circles. It maybe an idea to present AOD differences instead of absolute values in order to avoid unclearness. If this is not desirable, the authors may think of another way to make the figure more clear.

AOD differences don’t show whether the correction actually improves the AOD retrievals, so we consider AOD absolute values the best way to confirm the correction presented in this work functions adequately. However, we have improved this figure to make it clearer to the reader. We have enlarged the figure and we have also decreased the frequency of points in the case of Carpentras site.

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