

Point-by-point response to the reviews and all relevant changes made in the manuscript

J. Michalsky (Referee #01)

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Received and published: 11 June 2018

“The authors main goal was to determine whether it was feasible to obtain a meaningful calibration of a sun radiometer in a less than optimal locale for performing Langley calibrations. Langley calibrations allow one to estimate the TOA response of a sun radiometer, but are best performed on a high mountain top above the boundary layer. To this end they compared aerosol optical depths obtain from an MFRSR with the CIMEL radiometer operated using the AERONET protocol. The CIMEL calibration is derived from comparison to instruments calibrated at Mauna Loa Observatory. The RMSE, which they define as a deviation from the AERONET results, was 0.025 and within the uncertainties of the two instruments. I find that the results of the paper are based on scientifically sound reasoning and should be acceptable for publication.”

Authors general comments: We are glad that the manuscript content was appreciated and we would like to thank the referee for the interesting points highlighted. We have tried to address the points raised. Below we provide answers to each of your comments.

Legend:

Q#<number> - Referee questions and suggestion

R#<number> - Authors reply and comments

Q#01:” Should the authors be so inclined, I am curious whether the results would change if some other estimate of V_o 's such at the median or the method used in Michalsky et al. (2001) had been used to obtain V_o 's.”

R#01: We used median to estimate V_o 's for both years 2012 and 2015 (Tables below). The results agree within ~1% for all wavelengths. In general, medians presented slightly lower values in 2012, except at 415 nm and higher values in 2015, except for 500 and 610 nm in 2012.

| Year 2012 | 415 nm | 500 nm | 610 nm | 670 nm |
|------------------|----------------------|-----------------------|-----------------------|-----------------------|
| Mean | 1.586 ±0.015 (1%) | 1,839±0.015 (0.8%) | 1.545±0.015 (0.7%) | 1.416±0.015 (0.7%) |
| Median | 1.586 | 1.829 | 1.537 | 1.405 |
| Median-Mean (%) | 0.001 (0.1%) | -0.010 (0.6%) | -0.008 (0.5%) | -0.011 (0.7%) |

| Year 2015 | 415 nm | 500 nm | 610 nm | 670 nm |
|------------------|-----------------------|-----------------------|-------------------|-----------------------|
| Mean | 1.579±0.017 (%1.1) | 1.870±0.015 (0.8%) | 1.572±0.011(0.7%) | 1.433±0.008 (0.6%) |
| Median | 1.582 | 1.890 | 1.592 | 1.443 |
| Median-Mean | 0.0035 (0.2%) | 0.020(1.1%) | 0.019(1.2%) | 0.010(0.7%) |

Q#02:” Could the authors explain why 2013 and 2014 data were not included?”

R#02: As we set the focus of the manuscript on the question whether it is possible to obtain accurate calibration constants derived from on site measurements applying the Langley plot method in Central Amazonia, we evaluated that two independent years would be adequate to support our findings concerning the question. That is the main reason why we present only 2012 and 2015. We selected 2012 and 2015 because of the temporal distance between them, which would allow us to detect a scenario of potential filter degradations. Now that we evaluated that consistent AOD retrievals, derived from local successful calibration constants, can be obtained, there is an ongoing study focusing on a multi-year analysis of AOD. We plan to include a broad discussion in terms of source contributions and atmospheric processes and also a time series of the calibration constant applied to obtain the correspondent MFRSR AOD values.

Q#03:” A plot of V_o 's might be helpful in demonstrating the stability of the Langley results in most of the filters with the 870-nm filter an exception. It would also perhaps demonstrate the lack of a seasonal dependence seen in other MFRSRs since the temperature of the central Amazon is rather stable throughout the year.”

R#03: A challenge that we faced in the attempt to evaluate the lack of a seasonal dependence is that during the wet season, when Amazon is too cloudy, we were not able to obtain a significant number of Langley plots, most of the Langley plots was obtained at the beginning and in the middle of the dry season.

Q#04:” There are a few grammatical and spelling errors, but none so egregious as to make the text misunderstood”

R#04: We went throughout the text and tried to identify and correct all remaining grammatical and spelling errors.

Anonymous Referee #2

Received and published: 5 August 2018

This article has as main goal of establishing and verifying an alternative setup for MFRSR calibration over the Amazonian basin. The need is clear: Amazonian atmosphere have to be continuously monitored and gaps (for example to send the instrument to a calibration facility) must be avoided. I think the authors achieved their objective with this work. Moreover, this article present a good example of comparison with the AERONET network, in terms of aerosol optical depth and Angström exponent. I find that the paper will be scientifically sound and it might be acceptable for publication after addressing the major points listed in my specific comments.

Authors general comments: We would like to thank the referee for his thoughtful revision and suggestions. We have tried to address all points raised, that certainly will improve our manuscript. Below we provide answers to each of your comments.

Legend:

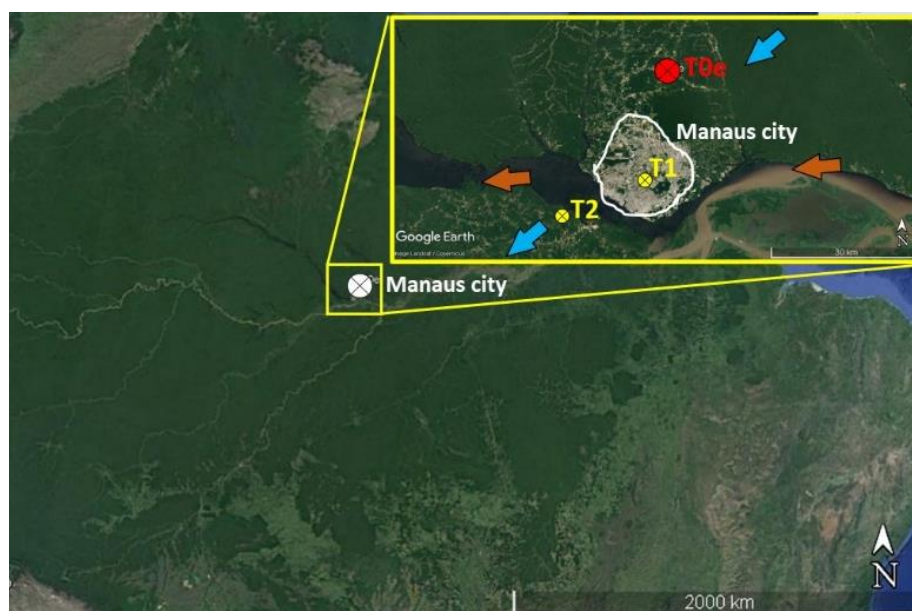
Q#<number> - Referee questions and suggestion

R#<number> - Authors reply and comments

Specific comments:

Q#01: Page 3, lines 12-14: For non-familiarized reader it would be more convenient to describe on Figure 1 the meaning of midst, upwind and downwind pollution plume. Is the plume generated inside Manaus city? Which kind of particles are mainly present?

R#01: Figure 1 was updated, we included more information: wind dominant direction during the dry (brown arrow) and wet (blue arrow) seasons. During the wet season (November – March) the dominant wind direction is from northeast and during the dry from east. We added examples of the GoAmazon sites to reference the downwind (T2), midst (T1) and upwind (T0e) position relative to the Manaus city, being the later site (T0e) the focus of the present study.



Regarding the composition of Manaus plume, nitrogen and sulphur oxides, submicron aerosol particles and soot are found in high concentrations (Kuhn et al., 2010), which is consistent with the nature of the major sources of air pollution from Manaus, vehicle fleet, power plants, and industrial activities. Sá et al. (2017) found that the submicron particles composition is dominated by organic material across measurement sites upwind and downwind of Manaus, independently of the levels of pollution. However, their study pointed out that, among the sites, the absolute mass concentrations varied significantly. Average concentrations downwind of Manaus were 100 % to 200 % higher than those upwind.

This description was included in the new version of the manuscript that is being prepared

Q#02: Page 8, lines 12-16: Ozone and dioxide nitrogen content was obtained from Sciamachy and OMI, but did you use a daily value, a monthly value or an average value over 2012-2015?

R#02: For both Ozone and NO₂ (O₃ = 267.6±5.8 Dobson Units, NO₂=0.076±0.012 Dobson Units) column content, we used average values over 2011 - 2015. This information was included in text.

Q#03: Page 9, line 2: How many individual Langley calibrations were performed over the period 2012-2015? Is this number robust enough? Only information on years 2012 and 2015 is included in the manuscript and supplement material.

R#03: As we set the focus of the manuscript on the question whether it is possible to obtain accurate calibration constants derived from on site measurements applying the Langley plot method in Central Amazonia, we evaluated that two independent years would be adequate to support our findings concerning the question. That is the main reason why we present only 2012 and 2015. We selected 2012 and 2015 because of the temporal distance between them, which would allow us to detect a scenario of potential filter degradations. Now that we evaluated that consistent AOD retrievals, derived from local successful calibration constants, can be obtained, there is an ongoing study focusing on a multi-year analysis of AOD. We plan to include a broad discussion in terms of source contributions and atmospheric processes and also a time series of the calibration constant applied to obtain the correspondent MFRSR AOD values.

Regarding the number of Langley calibrations (that varied from 14 to 22, depending on the year and wavelength channel), we think that those figures allow a consistent statistic for calibration constants. The numbers are similar to those of previous and reference studies on the Langley plot calibration, for instance, Schmid and Wehrli, 1995 (11 Langley plot cases) Michalsky et al., 2001 (20 Langley plot cases), Augustine et al., 2003 (18 Langley plot cases). Another important aspect to corroborate the quality of the Langley plots performed is that, in our study, we included more than 60 points per Langley plot, when 20 is suggested as a minimum to obtain good results from an individual Langley plot (Augustine et al., 2003).

Q#04: Page 9, lines 8-9: You wrote “ $\alpha\lambda_1, \lambda_2$ is a practical parameter to evaluate aerosol particles size”. This sentence is too general. What it can be inferred from the Angström exponent is the predominance of submicrometric or micrometric particles, but not the actual particle size. For that, information on particle size distribution (for instance) must be retrieved.

R#04: The reviewer point of view is correct. Therefore, we accepted and expanded the description of Ångström exponent as suggested.

Q#05: Page 9, line 21: please include also the reference Moran-Zuloaga et al. (2018) Moran-Zuloaga, D., Ditas, F., Walter, D., Saturno, J., Brito, J., Carbone, S., Chi, X., Hrabe de Angelis, I., Baars, H., Godoi, R. H. M., Heese, B., Holanda, B. A., Lavrić, J. V., Martin, S. T., Ming, J., Pöhlker, M. L., Ruckteschler, N., Su, H., Wang, Y., Wang, Q., Wang, Z., Weber, B., Wolff, S., Artaxo, P., Pöschl, U., Andreae, M. O., and Pöhlker, C.: Long-term study on coarse mode aerosols in the Amazon rain forest with the frequent intrusion of Saharan dust plumes, *Atmos. Chem. Phys.*, 18, 10055-10088, <https://doi.org/10.5194/acp-18-10055-2018>, 2018.

R#05: Suggestion accepted.

Q#06: Page 9, line 24: replace “aerosol optical depth” by “AOD” because you have already introduced the acronym. Check along the manuscript.

R#06: Suggestion accepted.

Q#07: Page 10, lines 5-6: Cloud screening is done based on the large standard deviations from the mean observed in some cases. However, it is necessary to quantify what you refer with “large standard deviations”.

R#07: The text was rewritten including the description of the threshold used to apply cloud screening:

“MFRSR AOD_λ at 1-minute rate was averaged within a 5-minute interval centered on AERONET retrieval. Large standard deviations from the mean AOD, i.e. higher than 0.08 (considering 4x AERONET AOD products nominal uncertainty, which is 0.02), were interpreted as cloud contamination in MFRSR, therefore excluded from the analysis.”

Q#08: Page 10, lines 8-9: replace the word “true” by “reference”. Page 12, Table 1 and Table 2: Following equation 1 the slope (after changing its sign) provides information on the daily average of AOD. All the values shown in Table 1 and Table 2, both referred to 500 nm, are in the range 0.20-0.30, what from my point of view are not low enough to be considered as clear atmosphere or values similar to those obtained at a mountain top (above the atmospheric boundary layer). In this sense, more discussion is needed.

R#08:

“True” replaced by “reference”

The slope represents the daily average of total atmospheric optical depth (including molecular OD + gaseous absorption OD + aerosols OD). Average molecular OD in central Amazonia at 500 nm is 0.14, and Ozone OD 0.01. So, the daily average AOD would be in the range of 0.05 - 0.15, which is the range typically observed in Amazonia background atmosphere (Schafer et al., 2008).

This analysis was included in the text to clarify.

Q#09: Page 14, line 2 (but also this is an overall comment): Only years 2012 and 2015 are analyzed in this paper? What about 2013 and 2014? Is there any reason for this lack of information?

R#09: Please, see the reply for the question **R#03**.

Q#10: Page 15, line 17: You attributed the few suspicious points to the presence of optically thin cirrus. This can be easily checked from lidar measurements. Do you have simultaneous lidar measurements to corroborate this?

Indeed, there was a Lidar operating at T0e site. Using the data from this Lidar, Gouveia et al. (2017) showed that cirrus clouds classified as subvisible (Optical Depth < 0.03) frequency in Central Amazonia can be as high as ~ 42%, while thin cirrus (0.03 < Optical depth < 0.3) ~38%. The presence of this subvisible and thin cirrus clouds may contaminate some AOD retrievals from MFRSR and Cimel.

Therefore, we agree that a Lidar analysis would contribute to the discussion of the present manuscript, however, as it is in course a study focusing on the comparison of AOD in Central Amazonia from multiple platform (ex. Cimel, MFRSR, Satellite base sensors), in which

the Lidar information will be used, we evaluate that, while a Lidar data analysis would be interesting in the context of the present manuscript, its absence would not jeopardize the major results of this manuscript. So, in the ongoing study (focused on AOD variability) we will be able to explore in more details the role of seasonal and diurnal cycle of subvisible cirrus in AOD (as pointed out by Gouveia et al, 2017).

Q#11: Page 16, line 5: AERONET is not an instrument, replace by Sun-photometer or the AERONET Sun-photometer. The same in page 7, line 2.

R#11: Accepted

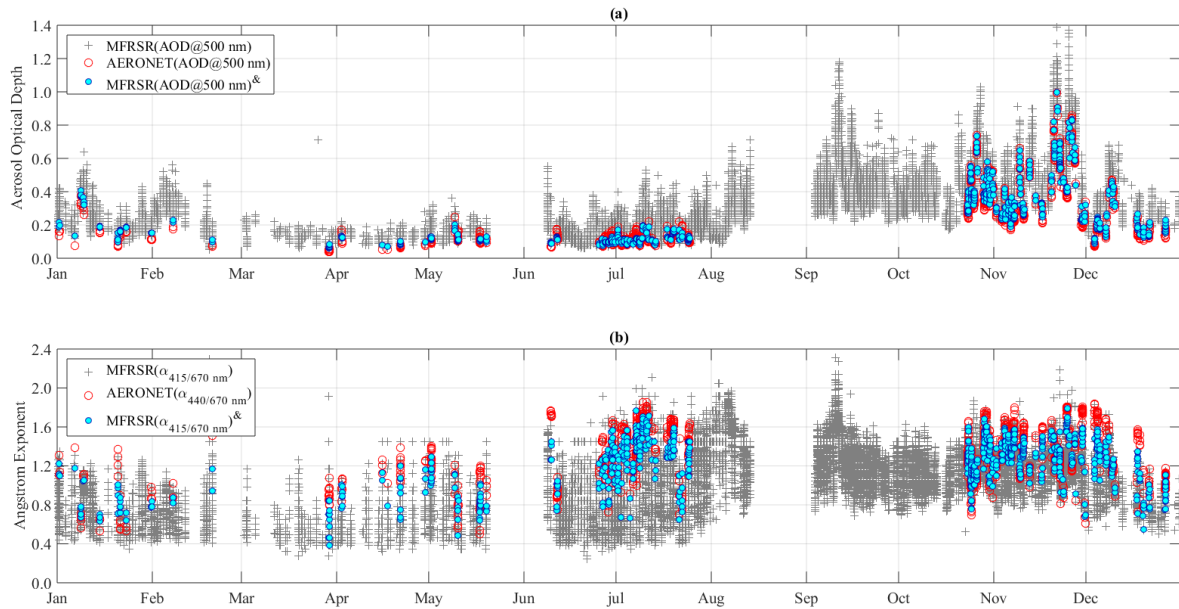
Q#12: Page 17, line 3: what about the results for 2013 and 2014? Page 17, figure 4: From this figure it seems that there is an overestimation of AOD from MFRSR respect to Cimel values, and underestimation of Angström Exponent values. Due to the different temporal resolutions I consider more convenient to present the temporal series of daily values or monthly values to check the overall coherence of both datasets. If monthly values are shown, the whole dataset (2012-2015) can be presented.

R#12: Regarding the results for 2013 and 2014, please, see **R#03**

To provide a consistent temporal series to compare AOD from both MFRSR and Cimel we updated the Figure 4 (pag 17) including coincident AOD and Ångström Exponent retrievals (Please, see figure below). In this scenario, it is not clear that there is a systematic overestimation of AOD from MFRSR with respect to Cimel. We would say that the MFRSR results are consistent with Cimel. Therefore, the apparent overestimation present in the Figure 4 is mainly related to MFRSR retrievals in scenarios when Cimel does not provide retrievals. In that case it is difficult to be conclusive about an eventual overestimation in MFRSR retrieval. It is recognized that AERONET AOD products are biased towards clear-sky conditions (Levy et al. 2010). Since cloudy conditions are likely to be related to distinct air mass conditions (humidity and particles composition) and, therefore, different aerosol conditions, MFRSR would be able to capture high frequency of aerosol scenario not captured by Cimel. MFRSR higher frequency retrieval, mainly during the wet season (this can be seen in Figure 4 itself), improves the number of retrievals in scattered and broken cloud conditions.

In other hand, cloudy conditions may influence MFRSR AOD retrieval accuracy via the diffuse/direct radiation partitioning and, consequently, on the direct-normal irradiance used to obtain AOD. These are interesting aspects; however, their discussion is out of the context of the present manuscript, but we plan to address in the mentioned manuscript being prepared focusing on AOD variability in central Amazonia from multiple-platform (ground based and space based).

In the present manuscript, to clarify the apparent overestimation of MFRSR AOD relative to Cimel and highlight that it is not present when coincident retrievals of both devices are compared, Figure 4 was updated including an additional plot comparing only coincident retrievals (see figure below).



Q#13: Page 18, figure 5: All wavelengths should be shown here. Also, explain the meaning of asterisk on the y-axis unit (interpolated values, I guess), and the meaning of red dotted line (1:1 line).

R#13: All MFRSR channels able to provide AOD retrieval are shown (415 nm, 500 nm, 610 nm and 670 nm), only the channel 870 nm is not presented, which was justified previously due to the difficulty to obtain a consistent calibration for this channel.

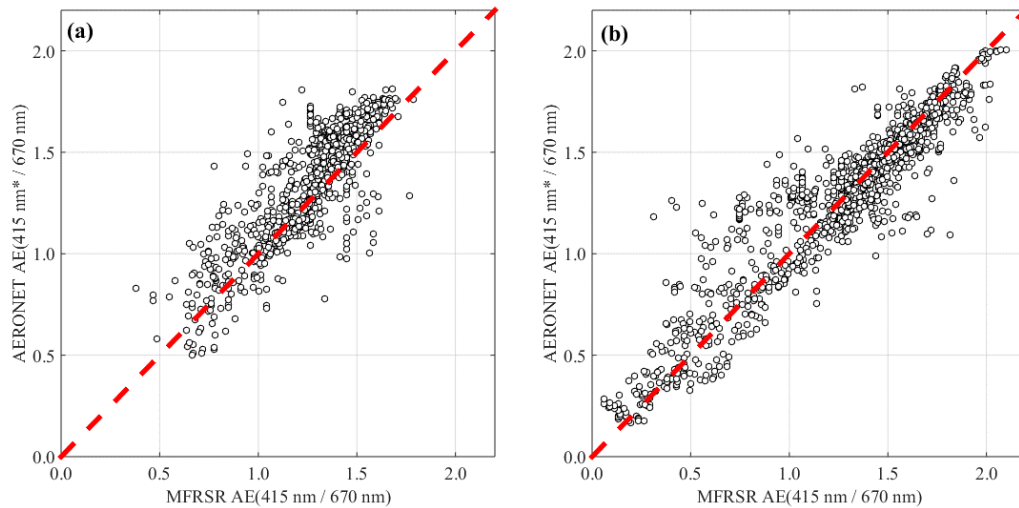
The asterisk indicates that the AOD at that particular channel (Cimel) was estimated using Ångström exponent, in that case to describe Cimel AOD. Red dashed line represents 1:1 line.

All these descriptions were included in the Figures 5 and 6 legends.

Q#14: Page 18, figure 6: The information from Figure 6 is summarized in Table 6. It would be nice if you replace figure 6 about AOD by the scatter plot of Ångström exponents.

R#14: We think that the referee is meaning Table 4.

Since the information presented in Table 4 (RMSE, Number of retrievals, R^2 and Bias) is already included in Figures 5 and 6 legends, instead of replacing 2015 AOD scatterplot by Ångström exponent scatterplot in Figure 6, we evaluated to replace the Table 4 by a new Figure (see below) showing the scatter plot of Ångström exponents considering the wavelengths 415 nm and 670 nm. 415 nm* indicates that the AOD used to obtain AE (415 nm*/670 nm) for Cimel was estimated using Ångström exponent. (a) – year 2012; (b) year 2015



Q#15: Page 19, Table 4: All wavelengths and years must be shown here. Other table 7 might contain the corresponding information for Angström exponent

R#15: As explained in **R#14**, Table 4 is duplicating results already described in Figures 5 and 6, so we replaced it to a scatter plot of Ångström Exponents (AE), therefore, we added information on AE without excluding any AOD information.

Q#16:Technical corrections:

Page 2, line 26: in “. . .the forest it is. . .” remove “it”.

Page 7, line 7: replace “. . .using leas-square. . .” by “. . .using least-square. . .”.

Page 15, line6: keep the same format along the paper (don't use I_(DN, λ)).

Page 15, line 22: replace “one minutes frequency” by “1-min frequency”.

Page 16, line 14: replace “sows and enhancement” by “shows an enhancement”.

Page 17, caption figure 4: replace “Depth” by “depth”.

Page 17, line 11: replace “For the 2015 years trends” by “The year 2015 trends”.

Page 19, Table 4, caption: replace “aerosol optical depth” by “AOD” and “optical depth”by “AOD”.

Page 19, line 7: replace “Do Central Amazonian pristine atmosphere provides” by “Does Central Amazonian pristine atmosphere provide”.

Page 19, line 9: “Amazônia” Please, in English not in Portuguese.

Page 19, line 18: replace “varied” by “varies”.

R#16: All recommended technical corrections listed below were accepted.

References

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Aerosol Optical Depth retrievals in Central Amazonia from a Multi-Filter Rotating Shadow-band Radiometer on-site calibrated

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Legend:

XXXXX - technical corrections and updates

XXXXX - Reference to inclusions based on referees' comments and questions

Comentado [NR1]:

Abstract

Extraterrestrial spectral response calibration of a Multi-Filter Rotating Shadow band Radiometer (MFRSR) under Amazonian Forest atmosphere pristine conditions using the Langley plot method was performed and evaluated. The MFRSR is installed in Central Amazonia as part of a long-term monitoring site, which was used in the context of the GoAmazon2014/5 Experiment. It has been operating continuously since 2011 without regular extraterrestrial calibration, preventing its application to accurate monitoring of aerosol particles. Once calibrated, the MFRSR measurements were applied to retrieve aerosol particles columnar optical properties, specifically Aerosol Optical Depth (AOD_{λ}) and Ångström Exponent (AE), which were evaluated against retrievals from a collocated CIMEL sunphotometer belonging to the AErosol RObotic NETwork (AERONET). Results obtained revealed that Amazonian pristine conditions are able to provide MFRSR extraterrestrial spectral response with relative uncertainty lower than 1.0% at visible channels. The worst estimate (air mass = 1) for absolute uncertainty in AOD_{λ} retrieval varied from ~ 0.02 to ~ 0.03 , depending on the assumption regarding uncertainty for MFRSR direct-normal irradiance measured at the surface. Obtained Root Mean Square Errors (RMSE ~ 0.025) from the evaluation of MFRSR retrievals against AERONET AOD_{λ} were, in general, lower than estimated MFRSR AOD_{λ} uncertainty, and close to the uncertainty of AERONET field sunphotometers (~ 0.02).

1 **1. Introduction**

2 Aerosol Optical Depth (AOD) is an important variable to characterize atmospheric particles
3 columnar abundance and is also fundamental to estimate their direct radiative forcing in the climate
4 system (Shaw, 1983, Kaufman et al., 2002, Menon, 2004, Satheesh and Srinivasan, 2005). Its relevance is
5 also growing in the context of air quality monitoring from satellite (Hoff and Christopher, 2009, van
6 Donkelaar et al., 2010, van Donkelaar et al., 2013). However, the so called Extraterrestrial Response
7 Calibration (ERC) of the radiometers designed to monitor AOD, for instance sun tracking and shadow-
8 band radiometers (Holben et al., 1998, Harrison and Michalsky, 1994), is a critical issue to the accuracy
9 of AOD retrievals (O'Neill et al., 2005, Sinyuk et al., 2012, di Sarra et al., 2015). Therefore, regular and
10 adequate calibration of sun-tracking and shadow-band radiometers dedicated to monitor AOD is vital
11 (Holben et al., 1998, Eck et al., 1999, Michalsky et al., 2001). The ERC consists in the estimation of the
12 solar energy that would be measured by the instrument at the top of the atmosphere (TOA) or in
13 hypothetical absence of the atmosphere. It remains one of the most critical calibrations to the accuracy of
14 AOD retrieval (Forgan, 1994; Michalsky et al., 2001, Eck et al., 1999; Chen et al., 2013). The classical
15 way to perform ERC is based on the Langley plot method, for which measurements on high mountain
16 tops under clean air and stable conditions are recommended (Shaw et al., 1976, Holben et al., 1998).
17 However, very often, regular trips to very high and clean mountain tops to perform ERC are not possible,
18 either due to the lack of resources or to avoid data collection interruption. Consequently, with the spread
19 of ground based AOD monitoring networks, on site calibration based on multiple Langley plots has been
20 successfully adopted elsewhere (Michalsky et al., 2001, Augustine et al., 2008, Rosario et al., 2008,
21 Mazzola et al., 2010, Michalsky et al., 2013).

22 During the last decades, Amazonia has been a stage for various intensive and mid to long term
23 atmospheric experiments (Avisar et al., 2002, Silva Dias et al., 2002, Andreae et al., 2004, Martin et al.,
24 2016), performing a large number of field measurements, and regularly including ground-based
25 monitoring of AOD. Given the inherent complex logistics that characterize field experiments in
26 Amazonia, regular trips to distant clean mountain tops, to perform ERC of AOD monitoring devices

1 operating inside the forest are a challenge, mainly for long-term sites. Unlike Aerosol RObotic NETwork
2 (AERONET) sunphotometers, which have a regular calibration logistic supported by NASA (Holben et
3 al., 1998), other ground-based devices for AOD monitoring operating inside the Amazonia have to find
4 alternative ways to provide regular calibration. Multi-Filter Rotating Shadow-band Radiometers
5 (MFRSR, Harrison and Michalsky, 1994) has been also deployed recurrently in the Amazon basin to
6 monitor spectral and broadband solar irradiance and AOD during specific seasons (Yamasoe and Rosario,
7 2009, Rosario et al., 2009, Yamasoe et al., 2014, Martin et al., 2016), and more recently focusing in mid
8 and long-term monitoring (Barbosa et al., 2014). An experimental site, located in central Amazonia, and
9 included in the context of the Observations and Modelling of the Green Ocean Amazon
10 (GoAmazon2014/5, Martin et al., 2016) under the reference of T0e, is operating since the year of 2011 a
11 MFRSR as part of a set of instruments to perform long term atmospheric monitoring of convection,
12 radiation, aerosols and cloud properties in Central Amazonia (Barbosa et al., 2014). GoAmazon
13 experimental sites range from time point zero (T0) upwind of pollution associated with Manaus city,
14 Brazil (Figure 1) to sites in the midst (T1) and downwind (T2, T3) of the pollution plume (Martin et al.,
15 2016). The MFRSR is being operated at the T0e site since 2011 without performing its ERC, which
16 prevent its application to retrieve AOD. In this context, the question that drives the focus of the present
17 study is: Does Central Amazonia pristine atmosphere conditions provide successful scenarios for
18 Extraterrestrial Response Calibration? Amazonia atmosphere under pristine conditions have been
19 denominated as Green Ocean due to its very low pollution concentration, comparable to remote ocean
20 areas (Robert et al., 2001, Andreae et al., 2004), which is a fundamental requirement to apply the Langley
21 plot method. To answer the question posed, the present paper describes and discusses methods and results
22 of an effort to calibrate, on site, the cited MFRSR. Its subsequent application to characterize the AOD
23 variability is evaluated against AOD retrievals from a collocated Cimel sunphotometer from AERONET
24 (Holben et al., 1998) also operated at the T0e site. The manuscript is organized as follow: **section 2**
25 describes the experimental site, a brief overview on MFRSR and Langley plot method and AOD retrieval
26 theory, **section 3** consists of results and discussion and final remarks are exposed in **section 4**.

1 **2. Experimental site, instruments, and methods**

2 **2.1 Experimental site T0e**

3 The T0e site has been operating continuously since February 2011 in Central Amazonia, up-wind from
4 Manaus city (59° 58' 12''W and 02° 53' 27''S, **Figure 1**), with a set of collocated atmospheric
5 monitoring instruments that include a MFRSR, a Cimel sunphotometer and a Raman lidar (Barbosa et al.,
6 2014). The site main goal is to provide long term characterization of diurnal and seasonal cycles of clouds
7 and convection and the interactions and feedback mechanisms between water vapour, clouds, radiation
8 and aerosol particles. It was incorporated as part of the GoAmazon 2014/15 experiment (Martin et al.,
9 2016) network sites, an international experiment designed to investigate the interactions that involve
10 Amazonia natural atmosphere conditions and the air pollution plume from Manaus city.



Comentado [NR2]: Updated based on Referee #02 – Question 01

11 **Figure 1-** T0e site location in Central Amazonia from a zoom in showing the site location upwind of the Manaus City. **During the wet season (December to May) the dominant wind direction is from northeast (blue arrow) and during the dry season (June to November) from east (brown arrow). GoAmazon 2014/15 experiment sites relative position to the Manaus city: T2 at downwind, T1 in the midst and T0e upwind of the city (Image source: Google Earth maps).**

12

1 The GoAmazon2014/5 sites were classified from time point zero (T0) upwind of the plume, to T1 in the
2 midst of the plume, to T2 just downwind of the Manaus, to T3 furthest downwind of Manaus (70 km).
3 Manaus city pollution plume composition includes nitrogen and sulphur oxides, and high concentrations
4 of submicron aerosol particles and soot (Kuhn et al., 2010), which is consistent with the nature of the
5 local major anthropogenic sources of air pollution, vehicle fleet, power plants, and industrial activities. Sá
6 et al. (2017) found that the submicron particles composition is dominated by organic material across the
7 sites upwind and downwind of Manaus, independently of the levels of pollution. However, their study
8 pointed out that, among the sites, the absolute mass concentrations of pollutants vary significantly.
9 Average concentrations downwind of Manaus are 100% to 200% higher than those upwind.

Comentado [NR3]: Included based on Referee #02 –
Question 01

10 In general, during the wet season, the atmosphere at T0e site is a clean reference, since its location
11 upwind of Manaus prevents the site of being strongly affected by the city pollution plume. Meanwhile,
12 during the dry season the atmospheric column at T0e, likewise large portion of the atmosphere across
13 central Amazonia, is influenced by smoke from biomass burning emissions that occur throughout the
14 Amazon basin.

16 2.2 Instruments

17 Multifilter Rotating Shadow-band Radiometer is designed to monitor global-horizontal, diffuse-
18 horizontal and direct-normal solar irradiances at narrow and broadband channels (Harrison et al., 1994). It
19 has been used worldwide to derive columnar aerosol optical properties (Harrison and Michalsky, 1994;
20 Alexandrov et al., 2002; Rosario et al., 2008, Michalsky et al., 2010, Mazzola et al., 2010, Michalsky and
21 LeBaron, 2013), water vapour (Michalsky et al., 1995, Alexandrov et al., 2009, Schneider et al., 2010)
22 and cloud optical properties (Min and Harrison, 1996, Wang and Min, 2008, Kassianov et al., 2011).
23 Direct-normal spectral irradiance ($I_{DN,\lambda}$) at the surface, needed to perform AOD retrievals, is obtained via
24 the difference between global-horizontal and diffuse-horizontal irradiances divided by the cosine of the
25 solar zenith angle (Harrison et al., 1994). Once MFRSR angular and spectral responses are properly

1 characterized and the automated shadow-band system adequately adjusted, accuracy in $I_{DN,\lambda}$ is expected
2 to be comparable to sunphotometers (Harrison et al., 1994). However, once in field, MFRSR filters
3 transmission may suffer degradation with time (Mychalsky et al., 2001, Michalsky and LeBaron, 2013),
4 which makes regular ERC critically necessary to keep the accuracy of AOD retrievals. The MFRSR of
5 the present study has been operating with sporadic interruptions at T0e providing irradiances
6 measurements at time interval of 1 minute at five narrow-band channels (415, 500, 610, 670 and 870 nm)
7 with half-bandwidth of 10 nm and able to permit AOD retrieval. Given the high cloud cover in central
8 Amazonia, the MFRSR high frequency measurements are crucial to improve the frequency of AOD
9 retrieval under cloudy sky and, therefore, minimizes the AERONET known bias toward clear-sky
10 condition (Levy et al., 2010).

12 2.3 Langley plot calibration and uncertainties

13 Langley plot calibration method is based on Lambert-Beer law (Shaw, 1983), which describes the
14 attenuation of a monochromatic beam propagating through a medium.

$$15 \quad I_{DN,\lambda} = f(d) I_{o,\lambda} e^{-m\tau_\lambda} \quad \text{eq. 1}$$

16 where, considering the full atmospheric column as a medium, $I_{DN,\lambda}$ is the direct solar spectral irradiance
17 at wavelength λ measured at the surface by the MFRSR, $I_{o,\lambda}$ is the solar spectral irradiance that would be
18 measured in the absence of the atmosphere at Earth-Sun mean distance (d_o), $f(d)$ is a correction factor
19 related to Earth-Sun distance variation (Iqbal, 1983), and m and τ_λ represent the atmosphere relative
20 optical air mass and total optical depth, respectively. Linearization of the equation 1 by applying the
21 natural logarithms to the both sides of the equation leads to a linear relation between m and $\ln(I_{DN,\lambda})$, on
22 which τ_λ and $\ln(f(d)I_{o,\lambda})$ represent, respectively, the angular and linear coefficients.

$$23 \quad \ln(I_{DN,\lambda}) = \ln(f(d)I_{o,\lambda}) - m\tau_\lambda \quad \text{eq. 2}$$

1 Knowing $\ln(I_{DN,\lambda})$ over a range of m , during which the atmosphere remained clean and stable, the least-
2 squares regression method can be applied to provide a linear fit formulation between both variables,
3 where the angular coefficient is the mean atmosphere optical depth, and the linear coefficient represents
4 the case of m equal to zero, a hypothetical absence of atmosphere, from which an estimation of the solar
5 extraterrestrial spectral irradiance ($I_{o,\lambda}$) can be made.

6 In the present study, the atmosphere relative optical air mass (m) was calculated as a function of
7 Solar Zenith Angle (SZA) based on the Kasten and Young (1989) and $\ln(I_{DN,\lambda})$ taken from MFRSR
8 direct-normal irradiance measurements for the years of 2012 and 2015. As we assumed that both, the
9 response variable, $\ln(I_{DN,\lambda})$, and the predictor variable, m , are subject to errors, it was applied the least
10 square regression treatment that consider errors in both adjusted variables (Irvin and Quickenden, 1983).
11 The errors in $\ln(I_{DN,\lambda})$ were obtained through error propagation theory considering Harrison et al. (1994)
12 estimate of uncertainty to MFRSR direct-normal irradiance ($\sigma_{I_{DN,\lambda}} = 2\%$). Regarding error in the
13 air mass (σ_m) we based on the study of Tomasi and Petkov (2014), which compared atmospheric air mass
14 results from Kasten and Young (1989) formulation against rigorous calculation and found differences
15 lower than 0.8%. Therefore, we assumed 0.8% as an estimate of uncertainty to the air mass calculated
16 using Kasten and Young (1989). Following previous studies suggestion (Mazzola et al., 2010 and
17 Alexandrov et al., 2004), to apply least square regression we adopted the air mass range from 2.0 to 5.0.
18 For air mass larger than 5.0, high solar energy incident angles, calibration may be affected by the
19 uncertainty of the MFRSR cosine angle correction and the shadow-band correction, meanwhile low
20 air masses, near 1.0, increase the probability of turbulent atmospheric conditions and, therefore, the
21 reduction of the optical depth stability (Chen et al., 2013).

22 The quality of the linear fit derived using least-square regression is highly dependent on optical
23 depth temporal stability, which is more likely to be observed under aerosol background conditions and
24 stable atmosphere. To obtain a set of linear fit able to provide high quality Langley plot calibration
25 samples, for both years 2012 and 2015, were selected only morning cases, to avoid the afternoon vigorous
26 convection, and only linear fit with correlation coefficients (R^2) higher than 0.990. This is the minimal

1 value usually obtained for calibration performed at high mountain top (Schmid and Wehrli, 1995). Also,
 2 considering Schafer et al. (1998) study on AOD climatology across the Amazon basin, only AOD values
 3 typical of background conditions were selected. For both years studied, 2012 and 2015, the MFRSR final
 4 extraterrestrial spectral response calibration ($\langle I_{o,\lambda} \rangle$) was estimated from the mean of the correspondent
 5 set of extraterrestrial response calibration ($I_{o,\lambda}$) obtained from individual Langley plot calibrations. The
 6 uncertainties of the derived final calibrations were estimated as the standard error of the mean ($\sigma_{\langle I_{o,\lambda} \rangle}$).
 7 Subsequently, the final calibrations results were applied to retrieve AOD_{λ} over the T0e site using the
 8 MFRSR.

10 **2.4 Aerosol Optical Depth (AOD_{λ}) inversion and uncertainty estimate**

11 From equation 2, the atmospheric total optical depth (τ_{λ}) can be separated as follow:

$$12 \quad \tau_{\lambda} = \tau_{m,\lambda} + AOD_{\lambda} + \tau_{g,\lambda} \quad \text{eq. 3}$$

13 Where $\tau_{m,\lambda}$, $\tau_{g,\lambda}$ represent, respectively, molecular scattering and gas absorption optical depths. All
 14 MFRSR channels are affected by molecular scattering, while gas absorption is highly selective, therefore
 15 affects specific channels. The most relevant influence of gas absorption on MFRSR channels is produced
 16 by ozone (O_3) at 610 and 670 nm channels and by nitrogen dioxide (NO_2) at 415 nm channel. Therefore,
 17 combination of the equation 3 and equation 2 leads to the AOD_{λ} retrieval equation

$$18 \quad AOD_{\lambda} = -\frac{1}{m} \ln \left[\frac{I_{DN,\lambda}}{f(d) \langle I_{o,\lambda} \rangle} \right] - \tau_{m,\lambda} - \frac{m_{O_3}}{m} \tau_{O_3,\lambda} - \tau_{NO_2,\lambda} \quad \text{eq. 4}$$

19 where $\tau_{m,\lambda}$ was calculated using the Kasten and Young (1989) formulation as a function of the
 20 climatological surface atmospheric pressure. Given its unique vertical distribution, ozone relative optical
 21 air mass (m_{O_3}) was estimated separately based on Staehelin et al. (1995). Ozone (O_3) and nitrogen
 22 dioxide (NO_2) absorption optical depths over T0e site were obtained considering their spectral cross
 23 section absorption and average column content ($O_3 = 267.6 \pm 5.8$ Dobson Units, $NO_2 = 0.076 \pm 0.012$
 24 Dobson Units) over the years between 2011 and 2015, taken from the SCanning Imaging Absorption

Comentado [NR4]: Updated based on Referee #02 – Question 02

1 spectroMeter for Atmospheric CHartography (SCIAMACHY, Bovensmann et al., 1999) and Ozone
 2 Monitoring Instrument (OMI, Levelt et al., 2006) products, respectively.

3 In general, the accuracy of the AOD_{λ} inversion is dominated by the uncertainty in the
 4 extraterrestrial response calibration ($\langle I_{o,\lambda} \rangle$) and $I_{DN,\lambda}$ measurements (Michalsky et al., 2002,
 5 Alexandrov et al., 2007, Mazzola et al., 2010). Typically, uncertainties in both terms are at least one order
 6 of magnitude greater than the contributions of the other terms (Mazzola et al., 2010). Considering only
 7 the uncertainties in extraterrestrial response calibration ($\sigma_{\langle I_{o,\lambda} \rangle}$) and in $I_{DN,\lambda}$ measurement ($\sigma_{I_{DN,\lambda}}$), an
 8 estimate of uncertainty ($\sigma_{AOD_{\lambda}}$) of the retrieved AOD_{λ} can be evaluated as

$$9 \quad \sigma_{AOD_{\lambda}} = \sqrt{\left[\frac{1}{m} \frac{\sigma_{\langle I_{o,\lambda} \rangle}}{\langle I_{o,\lambda} \rangle} \right]^2 + \left[\frac{1}{m} \frac{\sigma_{I_{DN,\lambda}}}{I_{DN,\lambda}} \right]^2} \quad \text{eq. 5}$$

10 where $\sigma_{\langle I_{o,\lambda} \rangle}$, as described, is based on the standard error of the mean of multiple extraterrestrial
 11 responses obtained from a set of individual Langley plot calibration. Evaluation of the uncertainty in $I_{DN,\lambda}$
 12 is a challenge given its dependency on multiple factors, i.e., shadow-band adjustment, accuracy of the
 13 angular response and MFRSR positioning regarding misalignment and tilt (Harrison et al., 1994,
 14 Alexandrov et al., 2007). Harrison et al. (1994) estimated MFRSR $I_{DN,\lambda}$ typical uncertainty to vary
 15 between 2 and 3%. Alexandrov et al. (2007) achieved lower estimation, roughly 1.5% for all channels.
 16 Assuming Harrison et al. (1994) maximum uncertainty (3%), the final uncertainty in MFRSR AOD_{λ} , for
 17 all channels, was evaluated for the worst case scenario, i.e., for unit relative air mass ($m = 1$).

18 Additionally, considering AOD_{λ} at two spectral channels (λ_1, λ_2) as reference, the spectral
 19 dependence of AOD_{λ} was evaluated using Ångström exponent ($\alpha_{\lambda_1, \lambda_2}$), calculated using the following
 20 equation

$$21 \quad \alpha_{\lambda_1, \lambda_2} = - \frac{\ln[AOD_{\lambda_1}/AOD_{\lambda_2}]}{\ln(\lambda_1/\lambda_2)} \quad \text{eq. 6}$$

22 Due to its dependency on aerosol particle size distribution (Eck et al., 1999), $\alpha_{\lambda_1, \lambda_2}$ can be used as a
 23 qualitative indicator to evaluate the predominance of submicrometric (fine particles) or micrometric

1 aerosol particles (coarse mode) in the atmosphere. High values of $\alpha_{\lambda_1, \lambda_2}$, greater than 2.0, indicate
2 dominance of fine aerosol particles, while values lower than 1.0 are typically related to coarse aerosol
3 particles dominance (Eck et al., 1999). In central Amazonia, for regions upwind of Manaus urban area,
4 such as the T0e site, air masses rich in fine aerosol particles are typically associated with smoke transport
5 from biomass burning regions. Air masses dominated by coarse particles fraction are in general associated
6 with local and regional biogenic and soil particles (Artaxo et al., 1998). Eventually, under favourable
7 atmospheric circulation, air mass containing coarse dust particles transported from Sahara Desert may
8 also affect T0e site atmospheric column (Koren et al., 2006, Ben-Ami et al., 2010, Moran-Zuloaga et
9 al., 2018).

Comentado [NR5]: Updated based on Referee #02 –
Question 04

10 Retrievals of AOD_{λ} and $\alpha_{\lambda_1, \lambda_2}$ from MFRSR measurements were validated against AERONET
11 direct Sun products Level 2.0 retrieved by a Cimel sunphotometer also installed at T0e site. AERONET
12 provides AOD at seven wavelengths 340, 380, 440, 500, 670, 870 and 1020 nm, being three coincident
13 with MFRSR wavelengths, 500, 670 and 870 nm. In order to evaluate the MFRSR AOD_{λ} at the remaining
14 channels, 415 and 610 nm, the Ångström Exponent from AERONET was used to perform interpolation to
15 derive AOD_{λ} in those channels for the network. Specifically, for the comparison purpose, MFRSR AOD_{λ}
16 at 1 minute rate was averaged within a 5 minute interval centered on AERONET sun-photometer
17 retrieval, large standard deviations from the mean, i.e. higher than 0.08 (considering 4x AERONET field
18 sunphotometer AOD uncertainty, which is 0.02), were interpreted as cloud contamination in MFRSR,
19 therefore excluded from the analysis. Afterwards, MFRSR results were used to describe and analyse the
20 seasonal variability of columnar aerosol particles optical properties over T0e site.

Comentado [NR6]: Included based on Referee #02 –
Question 07

21 The statistical metrics used to compare MFRSR AOD (AOD_{MFR}) with AERONET sun-photometer AOD
22 (AOD_{Aer}), assuming the later as the reference, are the root mean square error (RMSE), a measure of
23 average deviation from the reference, and Bias, a measure of overall bias error or systematic error:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{AOD_{MFR,i} - AOD_{Aer,i}}{AOD_{Aer,i}} \right)^2} \quad eq.7$$

$$Bias = \frac{1}{N} \sum_{i=1}^N \frac{AOD_{MFR,i} - AOD_{Aer,i}}{AOD_{Aer,i}} \quad eq.8$$

3. Results

3.1 MFRSR Langley plot calibration and uncertainty

An example of the diurnal cycle of the spectral solar direct-normal irradiance measured (20 June 2012) by the MFRSR prone to a successful Langley plot is presented in **Figure 2**. In the morning period, before vigorous convection initiates, the direct-normal irradiance at all channels is characterized by a continuous increase. The suitability for a successful Langley plot is evidenced in the quality of the linear fit achieved, as can be confirmed in **Table 1** for the 500 nm channel. **Table 1** and **Table 2** present for the 500 nm channels, respectively, for the years 2012 and 2015, the obtained extraterrestrial response calibrations ($I_{o,\lambda}$) for each individual Langley plot that met the criteria defined, i.e. $R^2 \geq 0.990$ and background AOD. The tables with the results for the remaining channels (415, 610, 670 and 870 nm) are presented in the supplementary material. It is worth to mention that the slopes derived from Langley plot and presented in Tables 1 and 2 represent the daily average of total atmospheric optical depth (including molecular, gaseous absorption and aerosol optical depths). Mean molecular and ozone absorption optical depth in Central Amazonia at the visible spectrum are ~ 0.14 and ~ 0.01 , respectively. Therefore, assuming these typical values, the subtraction of ozone and molecular optical depth from the total atmospheric optical depth (slopes) would result in daily mean AOD values in the range of 0.05 - 0.15, which is typically observed in Amazonia background atmosphere (Schafer et al., 2008).

Comentado [NR7]: Included based on Referee #02 – Question 08

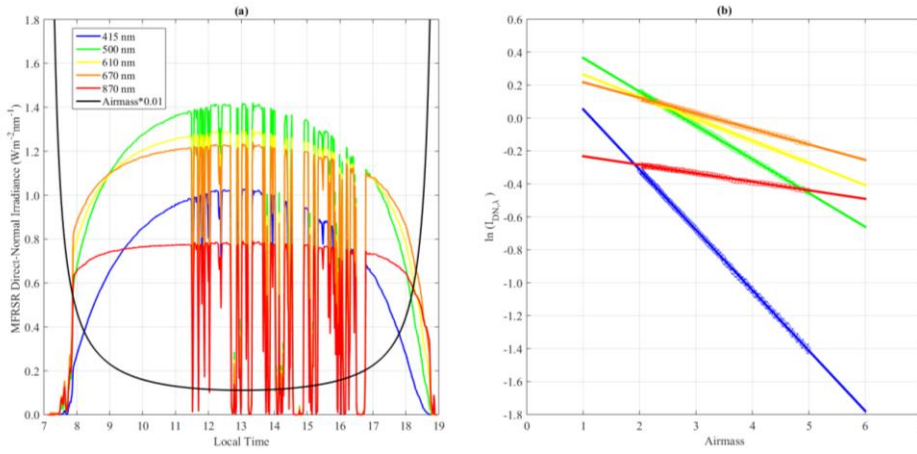


Figure 2 - (a) Diurnal cycle of air mass and direct-normal spectral solar irradiance measured by the MFRSR operating at the T0e site in Central Amazonia. (b) Example of Langley plot calibration applied to MFRSR spectral irradiance measurements taken under the clear sky period (08:00 to 11:00 Local Time) of the diurnal cycle shown in (a). (Day: 20 June 2012)

Table 1 – Individual extraterrestrial calibration results ($I_{0,500nm}$) applying Langley Plot technique to measurements of solar direct-normal irradiance at 500 nm from a MFRSR operating at T0e site in Central Amazonia for the year 2012. The individual uncertainty [$\sigma_{I_{0,\lambda}}$] used to obtain the relative error [$\sigma_{I_{0,\lambda}} (%)$] was estimated from the **intercept** and its respective uncertainty ($\sigma_{intercept}$) derived from the least square regression method.

| Date | slope | σ_{slope} | intercept | $\sigma_{intercept}$ | $I_{0,500nm}$ | $\sigma_{I_{0,\lambda}} (%)$ | R^2 | N |
|-----------|---------|------------------|-----------|----------------------|---------------|------------------------------|---------|----|
| 17-may-12 | -0.2426 | 0.0016 | 0.5709 | 0.0043 | 1.814 | 0.434 | -0.9992 | 63 |
| 16-jun-12 | -0.2450 | 0.0019 | 0.6058 | 0.0055 | 1.895 | 0.549 | -0.9939 | 64 |
| 17-jun-12 | -0.2237 | 0.0016 | 0.5560 | 0.0046 | 1.803 | 0.464 | -0.9990 | 61 |
| 20-jun-12 | -0.2117 | 0.0015 | 0.5846 | 0.0043 | 1.856 | 0.434 | -0.9992 | 64 |
| 21-jun-12 | -0.2261 | 0.0017 | 0.5722 | 0.0047 | 1.834 | 0.474 | -0.9996 | 65 |
| 22-jun-12 | -0.2265 | 0.0018 | 0.5362 | 0.0050 | 1.769 | 0.501 | -0.9995 | 71 |
| 25-jun-12 | -0.2585 | 0.0019 | 0.6461 | 0.0055 | 1.975 | 0.546 | -0.9992 | 78 |
| 3-jul-12 | -0.2493 | 0.0020 | 0.5848 | 0.0058 | 1.858 | 0.577 | -0.9978 | 61 |
| 4-jul-12 | -0.2436 | 0.0019 | 0.6060 | 0.0054 | 1.898 | 0.542 | -0.9998 | 63 |

| | | | | | | | | |
|-----------|---------|--------|--------|--------|-------|-------|---------|----|
| 8-jul-12 | -0.2430 | 0.0020 | 0.5668 | 0.0058 | 1.824 | 0.581 | -0.9996 | 64 |
| 11-jul-12 | -0.2420 | 0.0021 | 0.5456 | 0.0059 | 1.785 | 0.590 | -0.9995 | 62 |
| 1-aug-12 | -0.2616 | 0.0021 | 0.5843 | 0.0058 | 1.848 | 0.580 | -0.9997 | 64 |
| 2-aug-12 | -0.2401 | 0.0020 | 0.5221 | 0.0055 | 1.736 | 0.549 | -0.9920 | 62 |
| 3-aug-12 | -0.2775 | 0.0021 | 0.6313 | 0.0058 | 1.935 | 0.584 | -0.9912 | 65 |
| 4-aug-12 | -0.2359 | 0.0017 | 0.5751 | 0.0048 | 1.829 | 0.482 | -0.9991 | 62 |
| 6-aug-12 | -0.2880 | 0.0025 | 0.5561 | 0.0070 | 1.793 | 0.700 | -0.9987 | 63 |
| 21-dec-12 | -0.2658 | 0.0016 | 0.6294 | 0.0042 | 1.815 | 0.418 | -0.9996 | 63 |

1

2 **Table 2** – Individual extraterrestrial calibration results ($I_{0,500\text{nm}}$) applying Langley Plot technique to
3 measurements of solar direct-normal irradiance at 500 nm from a MFRSR operating at T0e site in Central
4 Amazônia for the year 2015. The individual uncertainty [$\sigma_{I_0\lambda}$] used to obtain the relative error [$\sigma_{I_0\lambda}(\%)$]
5 was estimated from the **intercept** and its respective uncertainty ($\sigma_{\text{intercept}}$) derived from the least square
6 regression method.

| Date | slope | σ_{slope} | intercept | $\sigma_{\text{intercept}}$ | $I_{0,500\text{ nm}}$ | $\sigma_{I_0\lambda}(\%)$ | R^2 | N |
|------------------|---------|-------------------------|-----------|-----------------------------|-----------------------|---------------------------|---------|----|
| 19-feb-15 | -0.2045 | 0.0014 | 0.5723 | 0.0041 | 1.734 | 0.412 | -0.9959 | 62 |
| 27-mar-15 | -0.2335 | 0.0015 | 0.5957 | 0.0039 | 1.809 | 0.395 | -0.9941 | 69 |
| 4-jun-15 | -0.2787 | 0.0021 | 0.6436 | 0.0058 | 1.963 | 0.583 | -0.9923 | 68 |
| 24-jun-15 | -0.1900 | 0.0013 | 0.5545 | 0.0039 | 1.802 | 0.394 | -0.9996 | 63 |
| 1-jul-15 | -0.2301 | 0.0016 | 0.6247 | 0.0048 | 1.933 | 0.478 | -0.9989 | 62 |
| 2-jul-15 | -0.2039 | 0.0015 | 0.5530 | 0.0043 | 1.800 | 0.433 | -0.9995 | 62 |
| 6-jul-15 | -0.2397 | 0.0019 | 0.6022 | 0.0054 | 1.890 | 0.542 | -0.9979 | 61 |
| 10-jul-15 | -0.2513 | 0.0019 | 0.6256 | 0.0055 | 1.934 | 0.546 | -0.9988 | 61 |
| 11-jul-15 | -0.2487 | 0.0019 | 0.6169 | 0.0056 | 1.917 | 0.556 | -0.9996 | 61 |
| 12-jul-15 | -0.2634 | 0.0022 | 0.5949 | 0.0063 | 1.876 | 0.634 | -0.9993 | 61 |
| 15-jul-15 | -0.2896 | 0.0026 | 0.6070 | 0.0074 | 1.898 | 0.745 | -0.9994 | 61 |
| 28-jul-15 | -0.2606 | 0.0020 | 0.6344 | 0.0056 | 1.945 | 0.555 | -0.9982 | 62 |
| 29-jul-15 | -0.2496 | 0.0021 | 0.5611 | 0.0059 | 1.807 | 0.585 | -0.9901 | 62 |
| 30-jul-15 | -0.2406 | 0.0018 | 0.5912 | 0.0051 | 1.862 | 0.510 | -0.9964 | 62 |
| 1-aug-15 | -0.2500 | 0.0019 | 0.6162 | 0.0054 | 1.908 | 0.536 | -0.9954 | 62 |
| 2-aug-15 | -0.2907 | 0.0024 | 0.6385 | 0.0066 | 1.950 | 0.657 | -0.9983 | 62 |

| | | | | | | | | |
|-----------------|---------|--------|--------|--------|-------|-------|---------|----|
| 7-aug-15 | -0.2535 | 0.0018 | 0.6151 | 0.0051 | 1.902 | 0.508 | -0.9997 | 64 |
| 23-aug-15 | -0.2652 | 0.0018 | 0.6047 | 0.0048 | 1.870 | 0.482 | -0.9987 | 69 |
| 5-sep-15 | -0.2623 | 0.0018 | 0.5373 | 0.0044 | 1.737 | 0.438 | -0.9983 | 74 |
| 9-sep-15 | -0.2411 | 0.0014 | 0.6266 | 0.0038 | 1.895 | 0.376 | -0.9996 | 75 |
| 22-sep-15 | -0.2825 | 0.0018 | 0.5998 | 0.0045 | 1.831 | 0.454 | -0.9992 | 75 |

1

2 The final extraterrestrial response estimations $\langle I_{o,\lambda} \rangle$, for both years and all channels, based on average
3 of all individual Langley plot calibration, are presented in **Table 3** along with the standard error from the
4 mean as the uncertainty ($\sigma_{\langle I_{o,\lambda} \rangle}$), sample number (N) and the relative difference between calibration
5 estimated for 2012 and 2015. The relative uncertainties among the channels varied from 0.7% (870 nm)
6 to 1.0% (415 nm) in 2012, and from 0.4% (870 nm) to 1.0% (415 nm) in 2015, which are surprisingly
7 satisfactory for conditions diverse from those recommended (clean top mountain). Regarding the relative
8 difference (-0.4%) between calibration constant derived for the two years, the difference for the channel
9 415 nm is not statistically significant, suggesting that between 2012 and 2015 the correspondent
10 transmission filter did not suffer relevant degradation. Meanwhile, a drift of 4.8 % was observed for the
11 870 nm channel, an indication of the lower stability of its transmission filter. The remaining channels
12 (500, 613, 670 nm) calibrations constant, opposite to the 870 nm channel, presented positive trend
13 between 2012 and 2015 calibrations. However, given the values of the uncertainty ($\sigma_{\langle I_{o,\lambda} \rangle}$) in their
14 calibration constants, we are not able to attest that 500, 613 and 670 nm channels have statistically
15 suffered degradation.

16 **Table 3** – MFRSR final extraterrestrial calibrations estimates $\langle I_{o,\lambda} \rangle$ for the years 2012 and 2015 averaging
17 results of individual Langley plot calibration from Table 1, Table 2 and tables in the supplementary material. The
18 uncertainty estimation ($\sigma_{\langle I_{o,\lambda} \rangle}$) is based on the correspondent standard error of the average.

| Channels | Year 2012 | | | Year 2015 | | | Difference (%) |
|----------|-----------|---------------------------------|--|-----------|---------------------------------|--|--|
| | N | $\langle I_{o,\lambda} \rangle$ | $\sigma_{\langle I_{o,\lambda} \rangle}$ | N | $\langle I_{o,\lambda} \rangle$ | $\sigma_{\langle I_{o,\lambda} \rangle}$ | $\Delta \langle I_{o,\lambda} \rangle$ (2012-2015) |
| 415 nm | 21 | 1.586 | 0.015 (1.0 %) | 22 | 1.579 | 0.017 (1.0%) | -0.4 |

| | | | | | | | |
|--------|----|-------|---------------|----|-------|--------------|------|
| 500 nm | 17 | 1.839 | 0.015 (0.8 %) | 21 | 1.870 | 0.015 (0.8%) | +1.7 |
| 613 nm | 14 | 1.545 | 0.010 (0.7%) | 17 | 1.572 | 0.011 (0.7%) | +1.8 |
| 670 nm | 15 | 1.416 | 0.010 (0.7%) | 18 | 1.433 | 0.008 (0.6%) | +1.2 |
| 870 nm | 15 | 0,842 | 0.008 (0.9%) | 20 | 0.802 | 0.003 (0.4%) | -4.8 |

1

2 Considering the estimate uncertainties in the extraterrestrial calibration constant (0.4% -1.0%),
3 and the Harrison et al. (1994) maximum uncertainty (3%) for MFRSR $I_{DN,\lambda}$ measurements, accordingly
4 to the error propagation analysis (equation 6), the worst estimative (i.e., for unit airmass) for our absolute
5 uncertainty in AOD_{λ} is ~ 0.03 , which is comparable with uncertainty of AOD_{λ} retrieved from AERONET
6 field sunphotometers measurements (~ 0.02 , Eck et al., 1999). However, if a lower uncertainty in $I_{DN,\lambda}$ is
7 assumed, for instance 1.5% (as suggested by Alexandrov et al., 2007), that would reduce MFRSR AOD_{λ}
8 uncertainty from ~ 0.03 to ~ 0.02 .

9 In general, perfect linear Langley plots are associated with stable **AOD**, however it is possible that
10 not all nearly linear Langley plots are able to provide correct calibration. Airmass assumption, mainly
11 regarding aerosol particles airmass (Schmid and Wehrli, 1995), instruments induced artefact, the shadow-
12 band system alignment (Chen et al., 2013), may contribute to error in calibration. These influences are all
13 challenge to estimate. Therefore, taking the mean of a set of individual Langley plot calibration as the
14 best estimate for the final calibration constant, along with the comparison of the AOD results with
15 AERONET sunphotometer retrievals should provide a good reference to evaluate the quality of the
16 calibration constant obtained. The results obtained for RMSEs derived from the comparison between
17 MFRSR retrievals and AERONET sunphotometer AOD are lower than the estimated uncertainty for
18 MFRSR AOD_{λ} retrievals (i.e., $\sim 0.02 - 0.03$, depending on the **$I_{DN,\lambda}$ uncertainty** assumed, 1.5 or 3 %) and
19 just above the maximum uncertainty for AERONET field instrument (~ 0.02), demonstrating that, in spite
20 of eventual error associated with assumption made during the Langley plot application, the final derived
21 constants are able to provide reliable AOD retrievals.

1 **3.2 Aerosol Optical Depth (AOD_{λ}) inversion and uncertainty estimate**

2 Once determined the MFRSR channels final extraterrestrial response calibration, direct-normal
3 irradiance measurements taken along 2012 and 2015 were applied to retrieve AOD_{λ} and to calculate
4 Ångström Exponent. **Figure 3** illustrates, for a specific day (22 November 2012), results of cloud
5 screening and a comparison between the diurnal variability of AOD_{λ} from MFRSR and **AERONET**
6 **sunphotometer**. The cloud screening criteria captured the majority of contaminated measurements, but
7 few suspicious remaining points are likely related to optically thin cirrus. A more conservative algorithm
8 would remove a significant amount of cloud free cases, as seems to be the case for AERONET
9 sunphotometer retrievals. The intercomparison showed the consistency of MFRSR retrievals regarding
10 AOD_{λ} diurnal variability. It is worth to emphasize the higher frequency of MFRSR retrieval during the
11 afternoon when compared with AERONET product. This is a critical aspect regarding the representativity
12 of AOD_{λ} diurnal variation in regions marked by strong diurnal cycle of convection and cloud cover such
13 as Central Amazonia. The MFRSR **l-min frequency** is expected to improve the statistic of AOD under
14 cloudy conditions, since AERONET sunphotometer current statistics are recognized to be biased toward
15 cloudless sky conditions (Levy et al., 2010).

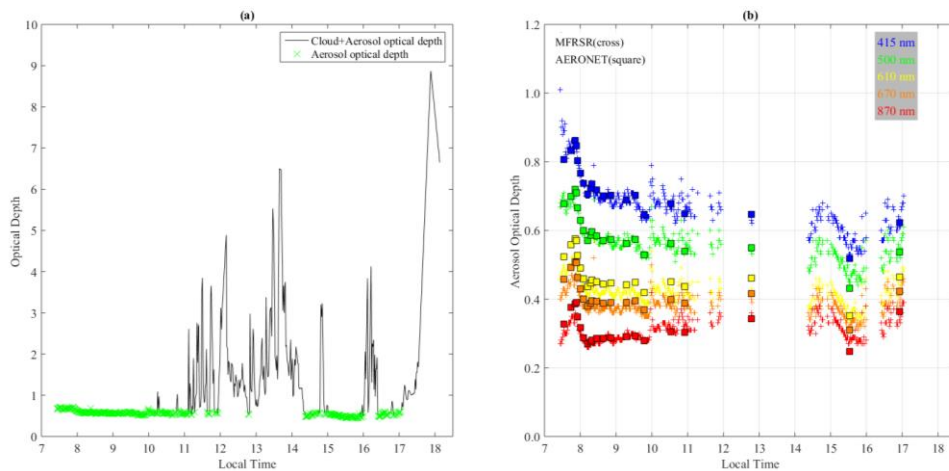
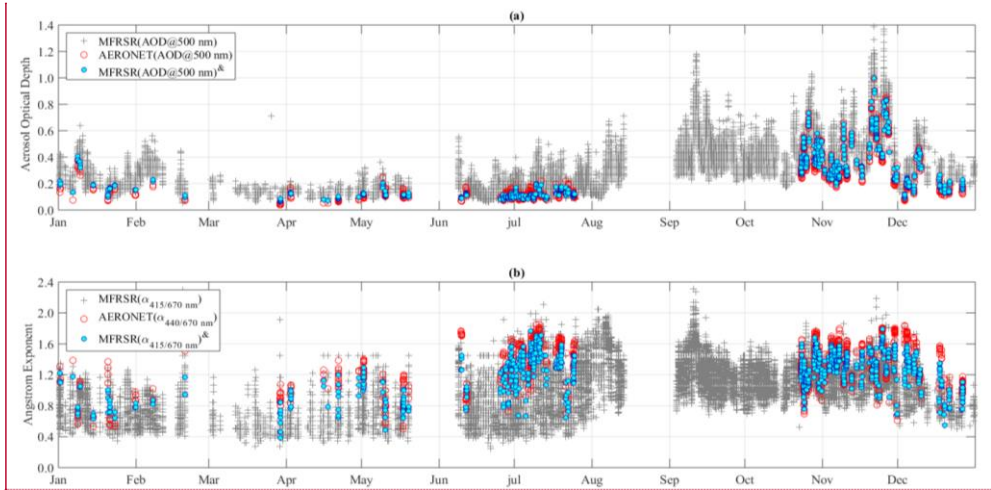


Figure 3 - (a) Example of the cloud screening applied to the MFRSR aerosol optical depth retrievals (22 November 2012). (b) Cloud screened diurnal cycle of multichannel aerosol optical depth from MFRSR compared with AOD retrievals from AERONET Level 2.0 product.

A comparison focusing on seasonal variability was also performed. **Figure 4** presents the 2012 seasonal variability of $AOD_{500\text{ nm}}$ and $\alpha_{415,670\text{ nm}}$ over T0e site as seen by MFRSR (based on 1 min time resolution) and AERONET sunphotometer. When all MFRSR instantaneous retrievals are analysed against AERONET sunphotometer AOD there is an apparent overestimation of AOD and underestimation of Ångström Exponent (AE). However, when analysing only coincident retrievals in time of both MFRSR and AERONET sunphotometer, the AOD and most of AE results are consistent. Therefore, the apparent higher AOD retrievals and low AE seen in MFRSR results are related to period during which AERONET AOD product does not provide retrieval. MFRSR retrievals were able to represent consistently the major seasonal features. From March to June, central Amazonia presents its lowest $AOD_{500\text{ nm}}$ levels, ranging from ~ 0.05 to ~ 0.20 . In a completely opposite scenario, during the biomass burning season (August to November), $AOD_{500\text{ nm}}$ hardly goes down below 0.20 and values above 0.50 are quite frequent. During the transition periods, from background conditions to biomass burning (June to July) and from biomass burning to background (December to February), $AOD_{500\text{ nm}}$ values oscillated between typical background

Comentado [NR8]: Included based on Referee #02 – Question 12

1 and biomass burning season. Considering that the enhancement of AOD_{λ} during the biomass burning
 2 season across central Amazonia is dominated by increase in small particles (Eck et al., 1999, Rosario,
 3 2011), $\alpha_{415,670\text{ nm}}$ variability (Figure 4) is consistent with the AOD_{500} discussion, i. e., as the aerosol
 4 loading increases from July to the biomass burning months (Aug-Sep-Oct-Nov), $\alpha_{415,670\text{ nm}}$ also shows
 5 an enhancement. Ångström Exponents ranging from 0.4 to 0.8, which are dominant under background
 6 conditions, became rare throughout the biomass burning season and intermittent during the transition
 7 periods, a feature consistently described by MFRSR and AERONET sunphotometer. Similar results, for
 8 both AOD_{500} and $\alpha_{415,670\text{ nm}}$ were observed regarding the year 2015 (not shown here).



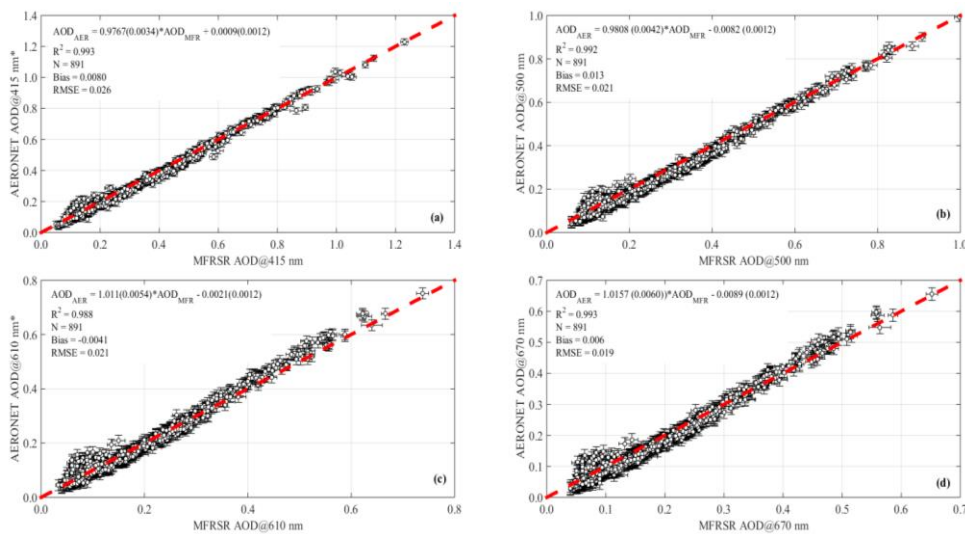
Comentado [NR9]: Updated based on Referee #02 – Question 12

9 **Figure 4** – Seasonal variability of (a) Aerosol Optical Depth and (b) Ångström exponent (AE) at the
 visible spectrum region in Central Amazonia for the year 2012. MFRSR ($AOD@500\text{ nm}$) represents
 MFRSR instantaneous AOD retrieval at 1 min rate; MFRSR ($AOD@500\text{ nm}$)[&] represents only MFRSR
 AOD retrieved collocated in time with AERONET sunphotometer AOD retrieval (AERONET
 ($AOD@500\text{ nm}$)). MFRSR ($\alpha_{415,670\text{ nm}}$) represents MFRSR instantaneous AE at 1 min rate; MFRSR
 ($\alpha_{415,670\text{ nm}}$)[&] represents only MFRSR AE retrieved collocated in time with AERONET sunphotometer
 AE retrieval (AERONET ($\alpha_{440,670\text{ nm}}$)).

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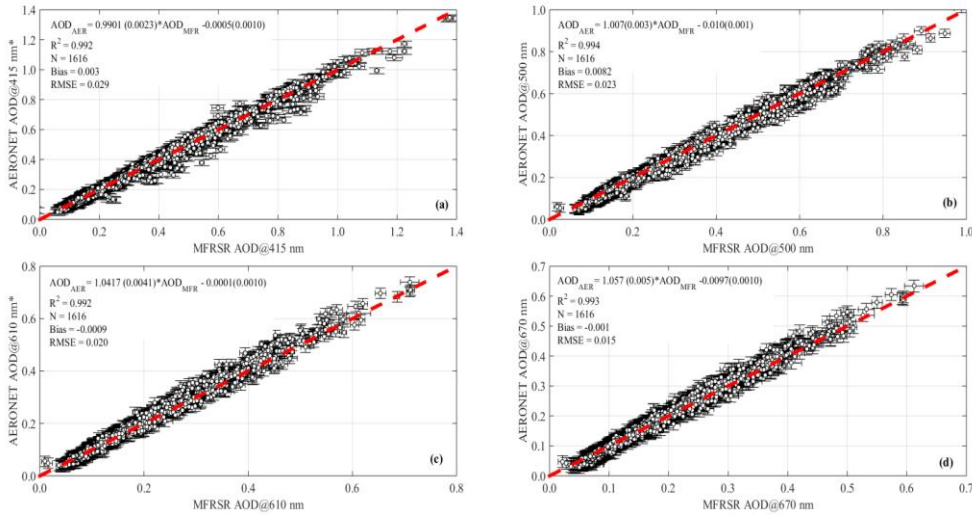
11 **Figures 5** and **6** show scatter plots and statistic metrics (Bias, RMSE and correlation coefficient)
 12 comparing MFRSR and AERONET sunphotometer retrievals for 2012 and 2015, respectively. In general,

1 there is a good agreement between both AOD_{λ} retrievals. However, non-negligible trends are seen,
 2 especially for 2012, and in particular for the lower and higher AOD edges. For low AOD_{λ} values, a
 3 systematic underestimation by MFRSR is observed for all channels, while for high AOD_{λ} , the longer
 4 wavelength channels (610 and 670 nm) tend to underestimate AOD. The year 2015 trends are less
 5 evident, mainly for the low aerosol loading when compared with 2012. Nevertheless, overall, the statistics
 6 metrics used to evaluate MFRSR retrievals performance against AERONET sunphotometer suggest that,
 7 when is not possible to perform high top mountain calibration, the extraterrestrial response calibration
 8 performed at Central Amazonia has reliability to support consistent retrievals of AOD. The obtained
 9 RMSEs are lower than the estimated uncertainty for MFRSR AOD_{λ} retrievals (i.e., $\sim 0.02 - 0.03$,
 10 depending on the $I_{DN,\lambda}$ uncertainty assumed) and slightly above the maximum uncertainty for AERONET
 11 field instrument (~ 0.02).



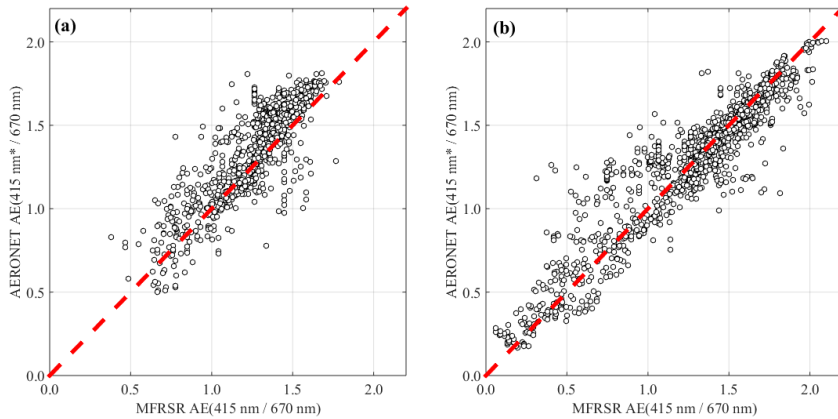
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Figure 5 - Spectral AOD retrieval from the on-site calibrated MFRSR as a function of AOD from AERONET direct Sun product level 2.0 for the year 2012. The asterisk (*) indicates that the AOD at that wavelength was estimated using Ångström Exponent and the red dashed line represents the 1:1 line.



1 **Figure 6** - Spectral AOD retrieval from the on-site calibrated MFRSR as a function of AOD from
 2 AERONET direct Sun product level 2.0 for the year 2015. **The asterisk (*) indicates that the AOD at that**
 3 **wavelength was estimated using Ångström exponent and the red dashed line represents 1:1 line.**

4 **Figure 7** compares Ångström Exponents derived using AOD retrieved from AERONET sunphotometer
 5 and MFRSR measurements, although comparisons are not as good as that observed for AOD, MFRSR
 6 results provides consistent range of Ångström Exponent in respect to the AERONET results.



7 **Figure 7** – Ångström Exponent (AE) for visible spectrum derived using AOD at 415 nm and 670 nm
 8 from the on-site calibrated MFRSR as a function of AE derived from AOD at 415 nm* and 670 nm
 9 corresponding to the AERONET direct Sun product level 2.0 for the years (a) 2012 and (b) 2015. The

Comentado [NR10]: Included based on Referee #02 – Question 14

Comentado [NR11]: Included based on Referee #02 – Question 14

1 asterisk (*) indicates that AERONET AOD at 415 nm was estimated using AE since this channel is not
2 present in network sunphotometers. The red dashed line represents 1:1 line.

3 4. Conclusions

4 Does Central Amazonian pristine atmosphere provide successful extraterrestrial response calibration
5 based on Langley plot method? This question emerged from the challenge to maintain regular calibration
6 of a MFRSR dedicated to long-term retrieval of columnar aerosol optical properties in central Amazon.
7 To answer the question, the MFRSR was calibrated on site using the Langley plot method for two distinct
8 years, 2012 and 2015, and subsequently applied to retrieve aerosol columnar optical properties, i.e., AOD
9 and Ångström Exponent (AE). Retrievals were evaluated against direct sun inversion products (Level 2.0)
10 from a collocated Cimel sunphotometer belonging to AERONET. Results obtained show that on site
11 calibration using Langley plot, under Amazonian pristine conditions, is able to provide extraterrestrial
12 response with relative uncertainties varying from ~0.4 to ~1.0 % at MFRSR visible channels. The worst
13 estimative (airmass = 1) for absolute uncertainty in retrieved AOD_{λ} can vary from ~0.03 to ~0.02,
14 depending on the assumption regarding the uncertainty assumed for MFRSR direct-normal irradiance
15 measured at the surface ($I_{DN,\lambda}$), which in the literature varies from 1.5% to 3.0%. All Root Mean Square
16 Error (RMSE), obtained from the comparison of MFRSR retrievals against AERONET sunphotometer
17 AOD_{λ} for coincident channels (500 and 670 nm), were lower (< 0.025) than the estimated MFRSR AOD_{λ}
18 uncertainties and close to AERONET field sunphotometers (~ 0.02). Under the point of view of the
19 question posed, these results suggest that on site calibration in central Amazonia pristine conditions is
20 able to provide consistent retrieval of AOD_{λ} . Another relevant aspect of the results provided by the
21 MFRSR, due to its high measurement frequency (one minute), is the improvement of the statistics of
22 AOD under cloudy conditions, which is critical for Amazonia. AERONET sunphotometer current
23 statistics are expected to be biased to cloudless sky conditions, which are dominant during the morning
24 period and dry season.

1 **Competing interests.** The authors declare that there are no competing interests.

2 **Acknowledgements.** The authors would like to EMBRAPA, INPA, and the LBA Central office for
3 logistical support. Special thanks to Marcelo Rossi, Victor Souza, and Jocivaldo Souza at EMBRAPA,
4 and to Ruth Araujo, Roberta Souza, Bruno Takeshi, and Glauber Cirino from LBA. Henrique Barbosa
5 acknowledges the financial support from FAPESP Research Program on Global Climate Change under
6 research grants 2008/58100-1, 2012/16100-1, 2013/50510-5, and 2013/05014-0. Theotonio Pauliquevis
7 acknowledges the financial support from CNPq research grant 458017/2013-2. Boris Barja acknowledges
8 the financial support of CAPES project A016_2013 on the program Science without Frontiers and the
9 SAVERNET project.

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Supplementary material

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3 **Table A.1** – Individual extraterrestrial calibration results ($I_{0,415 \text{ nm}}$) applying Langley Plot technique to
4 measurements of solar direct-normal irradiance at 415 nm from a MFRSR operating at T0e site in Central
5 Amazônia for the year 2012. The individual uncertainty [$\sigma_{I_{0,\lambda}}$] used to obtain the relative error [$\sigma_{I_{0,\lambda}}$
6 (%)] was estimated from the **intercept** and its respective uncertainty ($\sigma_{\text{intercept}}$) derived from the least
7 square regression method.

| <i>Date</i> | <i>slope</i> | σ_{slope} | <i>intercept</i> | $\sigma_{\text{intercept}}$ | $I_{0,415 \text{ nm}}$ | $\sigma_{I_{0,\lambda}}(\%)$ | R^2 | N |
|-------------|--------------|-------------------------|------------------|-----------------------------|------------------------|------------------------------|---------|-----|
| 20-feb-12 | -0.3702 | 0.0048 | 0.378 | 0.014 | 1.429 | 1.38 | -0.9902 | 63 |
| 22-apr-12 | -0.4534 | 0.0050 | 0.457 | 0.014 | 1.600 | 1.36 | -0.9968 | 73 |
| 17-may-12 | -0.4083 | 0.0048 | 0.422 | 0.013 | 1.564 | 1.34 | -0.9999 | 71 |
| 16-jun-12 | -0.4217 | 0.0055 | 0.482 | 0.016 | 1.674 | 1.62 | -0.9965 | 65 |
| 17-jun-12 | -0.3959 | 0.0053 | 0.409 | 0.016 | 1.556 | 1.56 | -0.9998 | 65 |
| 19-jun-12 | -0.3816 | 0.0052 | 0.385 | 0.015 | 1.520 | 1.54 | -0.9919 | 64 |
| 20-jun-12 | -0.3783 | 0.0049 | 0.445 | 0.014 | 1.615 | 1.43 | -0.9999 | 64 |
| 21-jun-12 | -0.3895 | 0.0052 | 0.422 | 0.015 | 1.578 | 1.54 | -0.9999 | 64 |
| 22-jun-12 | -0.3970 | 0.0055 | 0.397 | 0.016 | 1.539 | 1.63 | -0.9988 | 64 |
| 25-jun-12 | -0.4321 | 0.0056 | 0.510 | 0.017 | 1.724 | 1.66 | -0.9998 | 63 |
| 03-jul-12 | -0.4302 | 0.0060 | 0.438 | 0.018 | 1.604 | 1.82 | -0.9961 | 62 |
| 04-jul-12 | -0.4261 | 0.0058 | 0.477 | 0.017 | 1.668 | 1.74 | -0.9996 | 62 |
| 08-jul-12 | -0.4282 | 0.0062 | 0.432 | 0.019 | 1.594 | 1.87 | -0.9990 | 61 |
| 11-jul-12 | -0.4253 | 0.0063 | 0.395 | 0.019 | 1.536 | 1.91 | -0.9995 | 61 |
| 24-jul-12 | -0.4298 | 0.0060 | 0.442 | 0.018 | 1.606 | 1.78 | -0.9951 | 61 |
| 01-aug-12 | -0.4491 | 0.0062 | 0.438 | 0.018 | 1.597 | 1.84 | -0.9997 | 62 |
| 02-aug-12 | -0.4271 | 0.0061 | 0.367 | 0.018 | 1.486 | 1.80 | -0.9996 | 63 |
| 03-aug-12 | -0.4712 | 0.0062 | 0.493 | 0.018 | 1.685 | 1.81 | -0.9993 | 63 |
| 04-aug-12 | -0.4157 | 0.0056 | 0.422 | 0.016 | 1.570 | 1.63 | -0.9999 | 63 |
| 21-dec-12 | -0.4402 | 0.0045 | 0.484 | 0.012 | 1.569 | 1.22 | -0.9998 | 78 |

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1 **Table A.2** – Individual extraterrestrial calibration results ($I_{0.610\text{nm}}$) applying Langley Plot technique to
 2 measurements of solar direct-normal irradiance at 610 nm from a MFRSR operating at T0e site in Central
 3 Amazônia for the year 2012. The individual uncertainty [$\sigma_{I_0\lambda}$] used to obtain the relative error [$\sigma_{I_0\lambda}$
 4 (%)] was estimated from the **intercept** and its respective uncertainty ($\sigma_{\text{intercept}}$) derived from the least
 5 square regression method.

| <i>Date</i> | <i>slope</i> | σ_{slope} | <i>intercept</i> | $\sigma_{\text{intercept}}$ | $I_{0.610\text{ nm}}$ | $\sigma_{I_0\lambda}(\%)$ | R^2 | N |
|-------------|--------------|-------------------------|------------------|-----------------------------|-----------------------|---------------------------|---------|-----|
| 17-may-12 | -0.1688 | 0.0011 | 0.4038 | 0.0030 | 1.5351 | 0.3008 | -0.9994 | 71 |
| 17-jun-12 | -0.1456 | 0.0010 | 0.3882 | 0.0029 | 1.5248 | 0.2932 | -0.9996 | 65 |
| 20-jun-12 | -0.1395 | 0.0010 | 0.4107 | 0.0029 | 1.5601 | 0.2860 | -0.9997 | 64 |
| 21-jun-12 | -0.1554 | 0.0011 | 0.4067 | 0.0032 | 1.5540 | 0.3196 | -0.9996 | 64 |
| 25-jun-12 | -0.1752 | 0.0013 | 0.4567 | 0.0036 | 1.6341 | 0.3637 | -0.9994 | 63 |
| 04-jul-12 | -0.1575 | 0.0012 | 0.4220 | 0.0034 | 1.5786 | 0.3382 | -0.9991 | 62 |
| 08-jul-12 | -0.1566 | 0.0012 | 0.3946 | 0.0036 | 1.5356 | 0.3550 | -0.9975 | 61 |
| 11-jul-12 | -0.1555 | 0.0012 | 0.3820 | 0.0035 | 1.5159 | 0.3518 | -0.9990 | 61 |
| 01-aug-12 | -0.1680 | 0.0013 | 0.4045 | 0.0035 | 1.5435 | 0.3501 | -0.9989 | 62 |
| 02-aug-12 | -0.1512 | 0.0011 | 0.3617 | 0.0032 | 1.4784 | 0.3208 | -0.9992 | 63 |
| 03-aug-12 | -0.1749 | 0.0012 | 0.4351 | 0.0035 | 1.5904 | 0.3492 | -0.9987 | 63 |
| 04-aug-12 | -0.1493 | 0.0010 | 0.4017 | 0.0029 | 1.5378 | 0.2948 | -0.9994 | 63 |
| 06-aug-12 | -0.1814 | 0.0015 | 0.3830 | 0.0040 | 1.5081 | 0.4010 | -0.9980 | 64 |
| 21-dec-12 | -0.1846 | 0.0011 | 0.4626 | 0.0029 | 1.5365 | 0.2890 | -0.9989 | 78 |

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1 **Table A.3** – Individual extraterrestrial calibration results ($I_{0.670\text{nm}}$) applying Langley Plot technique to
 2 measurements of solar direct-normal irradiance at 670 nm from a MFRSR operating at T0e site in Central
 3 Amazônia for the year 2012. The individual uncertainty [$\sigma_{I_0\lambda}$] used to obtain the relative error [$\sigma_{I_0\lambda}$
 4 (%)] was estimated from the **intercept** and its respective uncertainty ($\sigma_{\text{intercept}}$) derived from the least
 5 square regression method.

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| <i>Date</i> | <i>slope</i> | σ_{slope} | <i>intercept</i> | $\sigma_{\text{intercept}}$ | $I_{0.670\text{ nm}}$ | $\sigma_{I_0\lambda}(\%)$ | R^2 | N |
|-------------|--------------|-------------------------|------------------|-----------------------------|-----------------------|---------------------------|---------|-----|
| 17-may-12 | -0.1264 | 0.0008 | 0.3109 | 0.0022 | 1.3989 | 0.2245 | -0.9991 | 71 |
| 17-jun-12 | -0.1022 | 0.0007 | 0.2996 | 0.0021 | 1.3955 | 0.2070 | -0.9995 | 65 |
| 20-jun-12 | -0.0983 | 0.0007 | 0.3213 | 0.0021 | 1.4266 | 0.2099 | -0.9994 | 64 |
| 21-jun-12 | -0.1133 | 0.0008 | 0.3171 | 0.0023 | 1.4208 | 0.2303 | -0.9994 | 64 |
| 25-jun-12 | -0.1280 | 0.0009 | 0.3579 | 0.0026 | 1.4804 | 0.2633 | -0.9993 | 63 |
| 04-jul-12 | -0.1118 | 0.0008 | 0.3290 | 0.0024 | 1.4384 | 0.2389 | -0.9987 | 62 |
| 08-jul-12 | -0.1104 | 0.0008 | 0.3059 | 0.0024 | 1.4052 | 0.2443 | -0.9958 | 61 |
| 11-jul-12 | -0.1093 | 0.0008 | 0.2959 | 0.0024 | 1.3908 | 0.2367 | -0.9986 | 61 |
| 01-aug-12 | -0.1192 | 0.0008 | 0.3137 | 0.0024 | 1.4095 | 0.2405 | -0.9986 | 62 |
| 02-aug-12 | -0.1049 | 0.0007 | 0.2791 | 0.0021 | 1.3612 | 0.2136 | -0.9992 | 63 |
| 03-aug-12 | -0.1221 | 0.0008 | 0.3357 | 0.0024 | 1.4400 | 0.2406 | -0.9981 | 63 |
| 04-aug-12 | -0.1025 | 0.0007 | 0.3110 | 0.0021 | 1.4043 | 0.2072 | -0.9991 | 63 |
| 05-aug-12 | -0.1573 | 0.0012 | 0.3753 | 0.0032 | 1.4971 | 0.3228 | -0.9936 | 63 |
| 06-aug-12 | -0.1260 | 0.0009 | 0.2863 | 0.0026 | 1.3692 | 0.2614 | -0.9958 | 64 |
| 21-dec-12 | -0.1380 | 0.0008 | 0.3686 | 0.0022 | 1.3988 | 0.2182 | -0.9979 | 78 |

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1 **Table A.4** – Individual extraterrestrial calibration results ($I_{0.870\text{nm}}$) applying Langley Plot technique to
 2 measurements of solar direct-normal irradiance at 870 nm from a MFRSR operating at T0e site in Central
 3 Amazônia for the year 2012. The individual uncertainty [$\sigma_{I_0\lambda}$] used to obtain the relative error [$\sigma_{I_0\lambda}$
 4 (%)] was estimated from the **intercept** and its respective uncertainty ($\sigma_{\text{intercept}}$) derived from the least
 5 square regression method.

| <i>Date</i> | <i>slope</i> | σ_{slope} | <i>intercept</i> | $\sigma_{\text{intercept}}$ | $I_{0.870\text{ nm}}$ | $\sigma_{I_0\lambda}(\%)$ | R^2 | <i>N</i> |
|-------------|--------------|-------------------------|------------------|-----------------------------|-----------------------|---------------------------|---------|----------|
| 21-jun-12 | -0.0697 | 0.0022 | -0.1695 | 0.0069 | 0.8734 | 0.6889 | -0.9991 | 64 |
| 25-jun-12 | -0.0758 | 0.0022 | -0.1466 | 0.0070 | 0.8939 | 0.6981 | -0.9990 | 63 |
| 17-jun-12 | -0.0549 | 0.0019 | -0.1882 | 0.0062 | 0.8568 | 0.6234 | -0.9989 | 65 |
| 04-jul-12 | -0.0609 | 0.0021 | -0.1750 | 0.0067 | 0.8689 | 0.6724 | -0.9982 | 62 |
| 11-jul-12 | -0.0574 | 0.0022 | -0.2010 | 0.0071 | 0.8462 | 0.7086 | -0.9981 | 61 |
| 20-jun-12 | -0.0548 | 0.0019 | -0.1719 | 0.0061 | 0.8712 | 0.6092 | -0.9981 | 64 |
| 01-aug-12 | -0.0607 | 0.0023 | -0.2257 | 0.0074 | 0.8219 | 0.7372 | -0.9977 | 62 |
| 03-aug-12 | -0.0577 | 0.0021 | -0.2184 | 0.0069 | 0.8274 | 0.6878 | -0.9977 | 63 |
| 17-may-12 | -0.0846 | 0.0022 | -0.1685 | 0.0066 | 0.8661 | 0.6614 | -0.9976 | 71 |
| 02-aug-12 | -0.0523 | 0.0022 | -0.2436 | 0.0070 | 0.8071 | 0.7041 | -0.9975 | 63 |
| 21-dec-12 | -0.0845 | 0.0020 | -0.1808 | 0.0060 | 0.8075 | 0.6016 | -0.9960 | 78 |
| 04-aug-12 | -0.0480 | 0.0021 | -0.2328 | 0.0066 | 0.8153 | 0.6583 | -0.9959 | 63 |
| 07-aug-12 | -0.1091 | 0.0030 | -0.2187 | 0.0095 | 0.8260 | 0.9477 | -0.9955 | 64 |
| 08-jul-12 | -0.0609 | 0.0022 | -0.1850 | 0.0071 | 0.8601 | 0.7077 | -0.9935 | 61 |
| 06-aug-12 | -0.0579 | 0.0023 | -0.2594 | 0.0074 | 0.7933 | 0.7404 | -0.9928 | 64 |

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1 **Table A.5** – Individual extraterrestrial calibration results ($I_{0.415\text{nm}}$) applying Langley Plot technique to
 2 measurements of solar direct-normal irradiance at 415 nm from a MFRSR operating at T0e site in Central
 3 Amazônia for the year 2015. The individual uncertainty [$\sigma_{I_0\lambda}$] used to obtain the relative error [$\sigma_{I_0\lambda}$
 4 (%)] was estimated from the **intercept** and its respective uncertainty ($\sigma_{\text{intercept}}$) derived from the least
 5 square regression method.

| <i>Date</i> | <i>slope</i> | σ_{slope} | <i>intercept</i> | $\sigma_{\text{intercept}}$ | $I_{0.415\text{ nm}}$ | $\sigma_{I_0\lambda}$ (%) | R^2 | <i>N</i> |
|-------------|--------------|-------------------------|------------------|-----------------------------|-----------------------|------------------------------|---------|----------|
| 19-feb-15 | -0.3732 | 0.0048 | 0.4156 | 0.0137 | 1.482 | 1.37 | -0.9991 | 62 |
| 27-mar-15 | -0.4088 | 0.0046 | 0.4331 | 0.0126 | 1.537 | 1.26 | -0.9989 | 69 |
| 07-apr-15 | -0.4877 | 0.0054 | 0.5114 | 0.0147 | 1.673 | 1.47 | -0.9985 | 71 |
| 04-jun-15 | -0.4702 | 0.0058 | 0.5161 | 0.0168 | 1.728 | 1.68 | -0.9970 | 68 |
| 24-jun-15 | -0.3492 | 0.0048 | 0.3686 | 0.0142 | 1.496 | 1.42 | -0.9998 | 63 |
| 01-jul-15 | -0.3973 | 0.0054 | 0.4447 | 0.0161 | 1.615 | 1.61 | -0.9995 | 62 |
| 02-jul-15 | -0.3674 | 0.0052 | 0.3627 | 0.0158 | 1.488 | 1.58 | -0.9999 | 62 |
| 06-jul-15 | -0.4053 | 0.0058 | 0.4322 | 0.0173 | 1.595 | 1.73 | -0.9992 | 61 |
| 10-jul-15 | -0.4335 | 0.0060 | 0.4700 | 0.0181 | 1.656 | 1.81 | -0.9995 | 61 |
| 11-jul-15 | -0.4288 | 0.0060 | 0.4639 | 0.0180 | 1.645 | 1.80 | -0.9999 | 61 |
| 12-jul-15 | -0.4461 | 0.0064 | 0.4460 | 0.0194 | 1.616 | 1.94 | -0.9998 | 61 |
| 20-jul-15 | -0.3916 | 0.0057 | 0.3756 | 0.0173 | 1.504 | 1.73 | -0.9898 | 61 |
| 28-jul-15 | -0.4503 | 0.0060 | 0.4921 | 0.0178 | 1.687 | 1.78 | -0.9995 | 62 |
| 29-jul-15 | -0.4352 | 0.0061 | 0.4298 | 0.0181 | 1.585 | 1.81 | -0.9968 | 62 |
| 30-jul-15 | -0.4181 | 0.0058 | 0.4204 | 0.0171 | 1.570 | 1.71 | -0.9987 | 62 |
| 01-aug-15 | -0.4394 | 0.0059 | 0.4727 | 0.0175 | 1.653 | 1.75 | -0.9982 | 62 |
| 07-aug-15 | -0.4309 | 0.0055 | 0.4584 | 0.0161 | 1.626 | 1.61 | -0.9999 | 64 |
| 23-aug-15 | -0.4409 | 0.0053 | 0.4282 | 0.0148 | 1.567 | 1.48 | -0.9993 | 69 |
| 05-sep-15 | -0.4386 | 0.0053 | 0.3290 | 0.0141 | 1.410 | 1.41 | -0.9994 | 74 |
| 09-sep-15 | -0.4114 | 0.0042 | 0.4448 | 0.0111 | 1.580 | 1.11 | -0.9998 | 75 |
| 10-sep-15 | -0.4993 | 0.0058 | 0.3722 | 0.0154 | 1.468 | 1.54 | -0.9983 | 76 |
| 22-sep-15 | -0.4809 | 0.0053 | 0.4357 | 0.0140 | 1.554 | 1.40 | -0.9997 | 75 |

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1 **Table A.6** – Individual extraterrestrial calibration results ($I_{0.610\text{ nm}}$) applying Langley Plot technique to
2 measurements of solar direct-normal irradiance at 610 nm from a MFRSR operating at T0e site in Central
3 Amazônia for the year 2015. The individual uncertainty [$\sigma_{I_0,\lambda}$] used to obtain the relative error [$\sigma_{I_0,\lambda}$
4 (%)] was estimated from the **intercept** and its respective uncertainty ($\sigma_{\text{intercept}}$) derived from the least
5 square regression method.

| <i>Date</i> | <i>slope</i> | σ_{slope} | <i>intercept</i> | $\sigma_{\text{intercept}}$ | $I_{0.610\text{ nm}}$ | $\sigma_{I_0,\lambda}$ (%) | R^2 | <i>N</i> |
|-------------|--------------|-------------------------|------------------|-----------------------------|-----------------------|-------------------------------|---------|----------|
| 19-feb-15 | -0.1317 | 0.0009 | 0.3922 | 0.0027 | 1.448 | 0.271 | -0.9912 | 62 |
| 24-jun-15 | -0.1242 | 0.0008 | 0.3946 | 0.0026 | 1.536 | 0.263 | -0.9989 | 63 |
| 01-jul-15 | -0.1519 | 0.0010 | 0.4458 | 0.0031 | 1.617 | 0.315 | -0.9982 | 62 |
| 02-jul-15 | -0.1328 | 0.0009 | 0.3949 | 0.0028 | 1.537 | 0.280 | -0.9994 | 62 |
| 06-jul-15 | -0.1682 | 0.0013 | 0.4376 | 0.0037 | 1.603 | 0.374 | -0.9979 | 61 |
| 10-jul-15 | -0.1661 | 0.0012 | 0.4380 | 0.0035 | 1.604 | 0.351 | -0.9980 | 61 |
| 11-jul-15 | -0.1664 | 0.0012 | 0.4306 | 0.0036 | 1.592 | 0.362 | -0.9995 | 61 |
| 12-jul-15 | -0.1826 | 0.0015 | 0.4223 | 0.0043 | 1.578 | 0.429 | -0.9995 | 61 |
| 28-jul-15 | -0.1708 | 0.0012 | 0.4391 | 0.0035 | 1.600 | 0.354 | -0.9964 | 62 |
| 30-jul-15 | -0.1625 | 0.0012 | 0.4226 | 0.0033 | 1.573 | 0.334 | -0.9931 | 62 |
| 01-aug-15 | -0.1694 | 0.0012 | 0.4432 | 0.0035 | 1.605 | 0.351 | -0.9924 | 62 |
| 02-aug-15 | -0.1930 | 0.0015 | 0.4536 | 0.0041 | 1.621 | 0.409 | -0.9976 | 62 |
| 07-aug-15 | -0.1751 | 0.0012 | 0.4378 | 0.0034 | 1.593 | 0.343 | -0.9994 | 64 |
| 23-aug-15 | -0.1827 | 0.0012 | 0.4352 | 0.0032 | 1.579 | 0.323 | -0.9987 | 69 |
| 05-sep-15 | -0.1792 | 0.0012 | 0.3892 | 0.0029 | 1.498 | 0.290 | -0.9979 | 74 |
| 09-sep-15 | -0.1666 | 0.0010 | 0.4602 | 0.0026 | 1.604 | 0.264 | -0.9993 | 75 |
| 22-sep-15 | -0.1910 | 0.0012 | 0.4303 | 0.0030 | 1.546 | 0.299 | -0.9991 | 75 |

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1 **Table A.7** – Individual extraterrestrial calibration results ($I_{0.670\text{nm}}$) applying Langley Plot technique to
 2 measurements of solar direct-normal irradiance at 670 nm from a MFRSR operating at T0e site in Central
 3 Amazônia for the year 2015. The individual uncertainty [$\sigma_{I_0.\lambda}$] used to obtain the relative error [$\sigma_{I_0.\lambda}$
 4 (%)] was estimated from the **intercept** and its respective uncertainty ($\sigma_{\text{intercept}}$) derived from the least
 5 square regression method.

| <i>Date</i> | <i>slope</i> | σ_{slope} | <i>intercept</i> | $\sigma_{\text{intercept}}$ | $I_{0.670\text{ nm}}$ | $\sigma_{I_0.\lambda}$ (%) | R^2 | <i>N</i> |
|-------------|--------------|-------------------------|------------------|-----------------------------|-----------------------|-------------------------------|---------|----------|
| 24-jun-15 | -0.0857 | 0.0006 | 0.3032 | 0.0019 | 1.4014 | 0.1937 | -0.9978 | 63 |
| 01-jul-15 | -0.1101 | 0.0007 | 0.3515 | 0.0023 | 1.4712 | 0.2346 | -0.9972 | 62 |
| 02-jul-15 | -0.0925 | 0.0006 | 0.3058 | 0.0020 | 1.4054 | 0.2035 | -0.9992 | 62 |
| 06-jul-15 | -0.1262 | 0.0009 | 0.3430 | 0.0028 | 1.4587 | 0.2777 | -0.9966 | 61 |
| 10-jul-15 | -0.1193 | 0.0008 | 0.3349 | 0.0025 | 1.4464 | 0.2492 | -0.9971 | 61 |
| 11-jul-15 | -0.1218 | 0.0009 | 0.3329 | 0.0026 | 1.4435 | 0.2607 | -0.9995 | 61 |
| 12-jul-15 | -0.1348 | 0.0011 | 0.3190 | 0.0031 | 1.4234 | 0.3108 | -0.9992 | 61 |
| 15-jul-15 | -0.1539 | 0.0013 | 0.3316 | 0.0039 | 1.4409 | 0.3860 | -0.9987 | 61 |
| 28-jul-15 | -0.1228 | 0.0009 | 0.3356 | 0.0025 | 1.4428 | 0.2533 | -0.9947 | 62 |
| 02-aug-15 | -0.1436 | 0.0010 | 0.3555 | 0.0029 | 1.4697 | 0.2931 | -0.9966 | 62 |
| 07-aug-15 | -0.1295 | 0.0009 | 0.3401 | 0.0025 | 1.4448 | 0.2508 | -0.9992 | 64 |
| 08-aug-15 | -0.1639 | 0.0013 | 0.3615 | 0.0034 | 1.4756 | 0.3435 | -0.9990 | 64 |
| 10-aug-15 | -0.1734 | 0.0015 | 0.3402 | 0.0041 | 1.4434 | 0.4096 | -0.9997 | 64 |
| 23-aug-15 | -0.1379 | 0.0009 | 0.3415 | 0.0024 | 1.4373 | 0.2419 | -0.9983 | 69 |
| 24-aug-15 | -0.1618 | 0.0014 | 0.2831 | 0.0036 | 1.3552 | 0.3605 | -0.9981 | 69 |
| 05-sep-15 | -0.1334 | 0.0008 | 0.3008 | 0.0021 | 1.3710 | 0.2134 | -0.9972 | 74 |
| 09-sep-15 | -0.1227 | 0.0007 | 0.3635 | 0.0020 | 1.4564 | 0.2012 | -0.9987 | 75 |
| 22-sep-15 | -0.1407 | 0.0009 | 0.3318 | 0.0022 | 1.4006 | 0.2190 | -0.9987 | 75 |

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1 **Table A.8** – Individual extraterrestrial calibration results ($I_{o,870nm}$) applying Langley Plot technique to
2 measurements of solar direct-normal irradiance at 870 nm from a MFRSR operating at T0e site in Central
3 Amazônia for the year 2015. The individual uncertainty [$\sigma_{I_o,\lambda}$] used to obtain the relative error [$\sigma_{I_o,\lambda}$
4 (%)] was estimated from the **intercept** and its respective uncertainty ($\sigma_{intercept}$) derived from the least
5 square regression method.

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| <i>Date</i> | <i>slope</i> | σ_{slope} | <i>intercept</i> | $\sigma_{intercept}$ | $I_{o,870\ nm}$ | $\sigma_{I_o,\lambda}$ (%) | R^2 | <i>N</i> |
|-------------|--------------|------------------|------------------|----------------------|-----------------|-------------------------------|---------|----------|
| 24-jun-15 | -0.0400 | 0.0022 | -0.2766 | 0.0071 | 0.7848 | 0.7127 | -0.9905 | 63 |
| 02-jul-15 | -0.0427 | 0.0022 | -0.2725 | 0.0073 | 0.7883 | 0.7319 | -0.9926 | 62 |
| 06-jul-15 | -0.0787 | 0.0028 | -0.2246 | 0.0089 | 0.8269 | 0.8900 | -0.9970 | 61 |
| 10-jul-15 | -0.0624 | 0.0025 | -0.2554 | 0.0083 | 0.8015 | 0.8325 | -0.9955 | 61 |
| 11-jul-15 | -0.0675 | 0.0026 | -0.2503 | 0.0086 | 0.8056 | 0.8573 | -0.9988 | 61 |
| 12-jul-15 | -0.0788 | 0.0029 | -0.2584 | 0.0094 | 0.7990 | 0.9402 | -0.9992 | 61 |
| 15-jul-15 | -0.0910 | 0.0031 | -0.2462 | 0.0099 | 0.8085 | 0.9921 | -0.9941 | 61 |
| 28-jul-15 | -0.0642 | 0.0025 | -0.2525 | 0.0080 | 0.8013 | 0.8028 | -0.9911 | 62 |
| 02-aug-15 | -0.0789 | 0.0027 | -0.2350 | 0.0085 | 0.8143 | 0.8550 | -0.9908 | 62 |
| 07-aug-15 | -0.0730 | 0.0025 | -0.2428 | 0.0079 | 0.8066 | 0.7936 | -0.9984 | 64 |
| 08-aug-15 | -0.0963 | 0.0028 | -0.2252 | 0.0089 | 0.8207 | 0.8909 | -0.9981 | 64 |
| 10-aug-15 | -0.1048 | 0.0031 | -0.2374 | 0.0096 | 0.8101 | 0.9618 | -0.9992 | 64 |
| 12-aug-15 | -0.1131 | 0.0032 | -0.2505 | 0.0100 | 0.7989 | 0.9961 | -0.9963 | 65 |
| 23-aug-15 | -0.0810 | 0.0024 | -0.2353 | 0.0074 | 0.8074 | 0.7358 | -0.9958 | 69 |
| 24-aug-15 | -0.0937 | 0.0028 | -0.2684 | 0.0085 | 0.7807 | 0.8459 | -0.9962 | 69 |
| 05-sep-15 | -0.0775 | 0.0023 | -0.2590 | 0.0068 | 0.7832 | 0.6835 | -0.9967 | 74 |
| 09-sep-15 | -0.0695 | 0.0020 | -0.2176 | 0.0058 | 0.8145 | 0.5786 | -0.9958 | 75 |
| 22-sep-15 | -0.0796 | 0.0022 | -0.2417 | 0.0065 | 0.7893 | 0.6504 | -0.9976 | 75 |
| 23-sep-15 | -0.1127 | 0.0026 | -0.2062 | 0.0075 | 0.8174 | 0.7452 | -0.9982 | 75 |
| 24-sep-15 | -0.1109 | 0.0028 | -0.2627 | 0.0081 | 0.7721 | 0.8102 | -0.9962 | 75 |

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