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Reply on RC2

Liviu Ivănescu et al.

Author comment on "Accuracy in starphotometry" by Liviu Ivănescu et al., Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2021-88-AC2, 2021

The referee's comments are presented in italic and our answers are written in plain text. **Modifications of the manuscript, if any, are written in plain bold text.**

In this paper "Accuracy in starphotometry", the authors present a detailed and comprehensive study of error sources for retrievals of the optical depth (OD) using the starphotometer technique. Based on this advanced quantification of errors impacts, the authors give some recommendations regarding maintenance, conditions of utilisation, calibration, observation techniques in order to reduce the uncertainties. A spectral aspect is discussed, that is very important for the starphotometry community: the pertinence of the existing catalogs of star magnitudes for the use of starphotometers, possible improvements and how to deal with all the discussed difficulties (choice of the resolution of the catalog; choice of the spectral channels that allow accurate inversions of the OD).

Despite some minor and very specific suggestions for improvements that I will explain in my comments, this is a well written paper, both considering the scientific quality (analyses, equations) and considering the quality of the English and the clarity of the text. Thus, I consider that this paper is an important contribution for enhancements in the use and for the accuracy of photometry techniques for OD retrievals. I recommend publication of this paper after some minor corrections.

We thank the referee for the in-depth reading, as well as for the insightful and generally positive feedback!

Comments:

- ***Observational error level of 1%***

In the abstract (Line 2), since the beginning of the introduction (Line 24 and after in Line 47) and during the whole article, you set the goal of the accuracy of this technique in "observational error level of 1%: a spectral optical depth (OD) error level of 0.01 level of". I have two comments/questions about that:

1) Please define what is the "OD": Is it "AOD" (Aerosol Optical Depth) or "COD" (Cloud Optical Depth) depending on what you want to retrieve, or is it the optical depth like considering the optical path interpretation (OD = ln(I/I0)), or is it the "TOD" (total optical depth: columnar optical depth): TOD = AOD + COD + tau_rayleigh + tau_gas + ... = ln(I/I0)/airmass?

"τ (total vertical optical depth") was defined on page 8, Line 169 of the submitted manuscript. We used τ and OD as synonyms (same definition in the Symbols and Acronyms list in Appendix D). **In order to clarify the slant-path versus columnar ambiguity, τ and OD were explicitly defined as "vertical (columnar) optical depth" in the Symbols and Acronyms list, as well as in the Introduction. Text (with footnotes) was also added to the Introduction to explicitly define (i) the scattering and absorption (extinction) components of any optical depth and (ii) our speciated optical depth acronyms.**

2) Explain briefly in introduction why you want a value of 0.01 as goal of this "observational error level". I suggest to look at WMO recommendation about the error on AOD (Aerosol Optical Depth), depending on the airmass (m): Delta_AOD must be < 0,005 +/- 0,001m (Formula can be found in Kazadzis, S., Kouremeti, et al. 2018, Results from the Fourth WMO Filter Radiometer Comparison for aerosol optical depth measurements. Atmos. Chem. Phys. (5), 3185–3201). From this formula of recommendation on AOD error, you can find out the most strict airmass condition, and compute the acceptable error on the OD that result of it.

The reasons behind our 0.01 goal were explained in Lines 23-25, page 1-2 of the submitted manuscript: we wished to limit the accuracy error to the 0.01 precision error inferred from Figure 4 of O'Neill et al., (2001). This is consistent with the WMO criteria for a high star with a typical airmass value of m=2 (inserted in the WMO expression of 0.005 + 0.01/m). It's also consistent with the satellite AOD retrieval requirements for climate energy budget analysis (Chylek, 2003). **In order to address this concern, we added a sentence detailing the last two 0.01 constraints immediately after the O'Neill et al. (2001) sentence in the Introduction.**

- ***About "C"***

You introduce the parameter C ("instrument specific calibration parameter") in Line 193 (in 3.3. Practical considerations). This is maybe the most important parameter for operational retrieval with a starphotometer. During the whole article, you assume that C is not star dependent: you use the same C for the two different stars in the TSM method for instance. This assumption (C is the same for two different stars) may be acceptable under some conditions that are mainly respected in the star photometry. One condition is that the channels are relatively narrow so that the convolution of the instrumental response function with the spectrum of the star magnitude is the same for the two stars that have different spectra of star magnitude. I think it is worth to give an information about below which value of bandwidth the assumption is valuable; cherry on the cake would be a quantification of the possible error that can result for a larger band or for different convolution of response function with star spectra (in case of big differences of star spectra inside the spectral band of the channel). This assumption should be remembered when you explain the basics of the TSM in equations (25) and (26) (Line 258 and 261, at the end of the paragraph 3.4.2). Again, you write this assumption without proof or discussion at line 286 (Beginning of Part 4): "the more convenient star-independent calibration in terms of C".

Errors related to bandwidth size were indeed found to be negligible in section 6.1 (Heterochromaticity) of the submitted manuscript. The errors related to the convolution of the instrumental response function with the star spectrum were presented in section 4 (Spectrophotometric catalog (M_0) accuracy). This response also addresses the reviewers "the more convenient star-independent calibration in terms of C" comment. **Section 4 of the revised manuscript was divided into four subsections in order to better underscore its key elements[1].** We consider that the spectrophotometric catalog errors (including the mismatch error) are a major limitation to improving the OD measurement accuracy. For this reason, as the referee also noted, C cannot be simply retrieved from equation (25), at least not from a single pair of stars. **Significant revisions were made to Subsection 3.4.2 (TSM) in order to address the issues raised above(particularly in terms of better detailing the different options available for retrieving accurate C and τ values in the face of M_0 errors).**

- ***Forward scattering error***

Question about Figure 14 and the discussion about it at the end of paragraph 6.3: you consider delta_tau/tau as the important parameter and you look [at] the forward parameter part. Is it only a formula that is plotted on the figure, or are there the results of a real irradiances computation with a radiative transfer code? A proper radiative transfer simulation would have the benefit to consider not only single scattering, but also multi-scattering and scattering between the different layers.

We thank the referee to point out that this aspect is worth mentioning it. Figure 14 is based on equation (36): a purely single scattering result which is an entirely appropriate approximation for the cirrus type crystals which can significantly decrease their measured OD. **As we point out in a footnote of the revised manuscript, multiple scattering plays no significant role in the forward scattering error in the case of starphotometers.**

- ***Table summarizing all sources of errors***

Before 8.2 (recommendations): Here it would be welcome to have a table that summarizes all sources of errors that have been quantified above, with the values of the possible errors considering different way of dealing with the instrument (calibration often or rare, weather conditions, elevation of the stars, etc...).

We thank the referee for this good idea! **Such a table was created and inserted at the beginning of the Starphotometry recommendations section.**

- ***Appendix D: Symbols and acronyms***

Please make two tables: one for the symbols used in equations (tau, omega, f, etc...), and one for the acronyms, and please sort both of them in alphabetical order!

We thank the referee for this good idea! **It was implemented accordingly.**

- ***Minor comments/typos***

Line 28: "Sunphotometry, and to some extend moonphotometry, are much more mature technology" -> Moonphotometry (after 2013) is less mature than starphotometry (beginning of the 90ies)

While having its particular issues and challenges, moonphotometry is much closely related to sunphotometry, and is able to inherit several of its advantages. In order to address this issue, we replaced that sentence with **"Sunphotometry, and to a certain extent moonphotometry, are much more mature technologies"**.

*Line 298: Typo: "shorcomings" -> *shortcomings.* **It was corrected accordingly.**

Line 584: Problems are mentioned above 1000 nm, what is not a big issue considering the range of the SPST starphotometers.

The SPST starphotometers have the ability to go beyond 1100 nm (see Figure 26), but the sensitivity is very low and this may only be possible with a cold star such as Procyon.

However, one can work with most stars up to about 1050 nm. The range beyond 1000 nm is useful for anchoring coarse mode OD calculations (especially in the case of cloud particles) and to make a better base-line estimations for water vapor retrieval.

Line 774: You give the value of tau_NO2 for 400 nm, please give also the value at 500nm, since the order of magnitude of this parameter is better known at this wavelength (standard of the community).

Based on the cross-section spectrum of Burrows (1998), the 500 nm τ_{NO2} value is a factor of 3 smaller than the value at 400 nm. A summertime 500 nm τ_{NO2} value at Eureka would then be 0.001 while a wintertime value is expected to be even smaller. However, at low latitudes, it may be as high as τ_{NO2}=0.01 at 500 nm. **In order to address this concern, in the 8.2 Starphotometry recommendations subsection, we replaced** "(i.e. up to 0.03 OD at 400 nm)" by "(i.e. up to 0.03 OD at 400 nm**, or 0.01 OD at 500 nm**)".

Table 2, Channel 15: "almost WMO lambda" is truer than "WMO lambda" (20 nm shift).
Corrected accordingly.

Table 12, Channel 17: 936 nm is also an AERONET standard (935 nm is used by AERONET, but only for the PWV retrieval, not for the AOD, thus if you want to compare starphotometer and AERONET for WV, this channel is the most important one).
Addressed accordingly (in the table and in the corresponding description list).

*Line 947 (Appendix A1): "at the Lindenberg observatory in Germany" -> *at the Deutscher Wetterdienst (DWD) Meteorological Observatory of Lindenberg (Germany).*
Text was corrected.

Line 1065 (Appendix D: Acronyms): SPST = Schulz and Partner STarphotometer (or "Schulz and Partner STernphotometer" in German). **Text was added.**

Line 1072 (Appendix D: Acronyms): FOV = "Field Of View". **It was modified accordingly.**

Footnotes
[1] with "Bandwidth mismatch error" being one of those subsection

References
All references not found below can be found in the references section of the revised paper.

Burrows, J.P., A. Dehn, B. Deters, S. Himmelmann, A. Richter, S. Voigt, J. Orphal Atmospheric remote-sensing reference data from GOME: Part 1. Temperature dependent absorption cross-sections of NO2 in the 231–794 nm range, J. Quant. Spectrosc. Rad. Transfer, 60, pp. 1025-1031, 1998.