Reply to Anonymous Referee #1

We thank the reviewer for their helpful and constructive comments. Please find our answers (black text) to the comments (blue text) in-line below. Respective changes are indicated in the revised manuscript in blue and are stated here in addition when a reviewer comment lead to a modification of the manuscript along with the updated line number, where necessary.

This paper describes the aerosol optical depth retrieval candidate algorithm for the EarthCARE mission. The method described in the paper shows quite some limitations, mostly on the limited number considered valid for retrieval purposes. The results presented should be further discussed and the algorithm should be better placed in a broader context, highlighting its unique features, pros and cons, compared to other existing algorithms. Overall, the paper could be strongly improved with more precise explanation and much more elaborated discussions.

Thank you for your comment.

While we fully understand that an elaborated assessment of algorithm pros, cons and unique features are typically highlighted and compared in publications of novel algorithms, this publication is intended to serve as an introduction to the operational M-AOT product. Hence, the algorithm is introduced as a means to understand limitations this product has, not as a novel algorithm itself.

We rephrased the following statement in the beginning of the introduction for clarification and in order to avoid confusion, we might have introduced before:
“The presented algorithm and its accompanied product provide conventional imager aerosol information within the retrieval chain (Eisinger et al., 2022)”
to →
“The operational imager aerosol product, that is introduced here, provides aerosol information based on passive measurements alone within the Level 2 retrieval chain (Eisinger et al., 2022), using a conventional passive aerosol retrieval algorithm approach. Both, product and algorithm, are [...]” (L25-28)

Further we added a dependent clause in the last paragraph of the introduction:
“The operational Level 2 M-AOT algorithm […] is introduced [...] in order to highlight the aerosol product characteristics [...]” (L71)

Additionally, we think a point we missed to make right in the beginning of our manuscript are the constraints the operational M-AOT algorithm and consequently also the official Level-2 product, also called M-AOT, are exposed to due to the nature of the instrument and the operational requirements of the ESA ground segment. Hence, we added the following statement in the introduction for clarification:
“While M-AOT has been developed to operationally enable users interested in aerosol properties from EarthCARE to assess the horizontal aerosol loading, it is subject to many constraints due to the design of MSI itself, e.g. number and placement of spectral channels, small swath width, no polarization or multi-angle capabilities, as well as due to operational, near-real-time algorithm requirements imposed by the ground segment. Both, instrument design and computational constraints, prevent more elaborate retrieval attempts using for instance multi-temporal approaches, as used for e.g. SEVIRI and PROBA-V (Luffarelli and Govaerts, 2019). The usage of real-time a priori updates of made assumptions in the

M-AOT algorithm, e.g. about land surface characteristics or the aerosol composition, is not possible due to operational environment definitions. Further, in order to provide the product in near-real-time along with other Level 2 products, there are strict run-time requirements and processing hardware assignments in place." (L61-69)

We additionally added the purpose of MSI in the discussion section of the manuscript once again to remind the reader of what was already stated in the introduction:
"Nonetheless, it could be demonstrated that the M-AOT product is capable of serving its purpose of offering a horizontal context by providing columnar aerosol loading information." (L462-463) after stating the strict limitations (L458-461).

We hope that these modifications are sufficient for the purpose of a product introduction publication now. Further, we think that statements about MSI, using e.g. "conventional", "heritage" or "limited" instrument, should be enough information for a the reader or potential user of the product. Further, we think that placing M-AOT in a broader context of passive imager retrievals, highlighting pros and cons could potentially end up in a review paper on passive aerosol retrievals due to MSI's limitations. However, this is clearly not the scope of this publication.

General comments

- The verification of a retrieval algorithm against simulated data is expected to represent the best possible retrieval performances, as all the assumptions are the same both in forward and inverse modelling and as the true state of the scene is known, which is never the case from actual observations. Therefore I am a bit puzzled to see such low correlation against the simulated test data set. Either there is something wrong in the construction of this exercise, or there is something I am missing.

  While we fully agree, that the verification of the retrieval algorithm using simulated test data should represent the best possible retrieval performance, it should be kept in mind here that the simulated test data and the M-AOT algorithm do not use the same forward models. As this was not clearly stated before, we added an additional statement for clarification in L332-336:
  "Even though, input assumptions are tried to be used as consistently as possible, it should be kept in mind that the L1c forward model is not the same as the M-AOT forward model. Hence, no perfect agreement should be expected for this kind of verification. In particular, the surface spectrum over land surfaces is quite different in the respective forward models. While M-AOT uses the parameterization described in sec. 2.3.5, the surface description used for the test scene creation is based on Vidot and Borbás (2014)."
  We omit a full list of differences here, since this would be out of scope of this work. Nonetheless, we agree that the addition of the cause for the biggest discrepancies over land surfaces, should be added and hence did so.

- The selection of valid pixels is mentioned in several part of the manuscript, yet it remains confusing. To summarise, the algorithm only processes open ocean water and dark vegetation, is this correct? If so, it should made it clear in the paper. Sometimes you refer to "relatively bright" or similar statement that are not very conclusive.

You are correct with your assumption: only ocean and dark vegetation. We removed “relatively” and “very” bright or dark wherever it was unnecessarily used.

Also, in Table 1 the values you chose for the surface reflectance in the NIR are quite low, I assume this is because dry vegetation is also excluded from the processing. If this is not the case, you should include larger value of surface reflectance.
Again, you are correct with your assumption. Dry vegetation is excluded. We modified the first sentence in sec. 2.3.4 “Aerosol optical thickness retrieval over vegetated land surfaces” to explicitly exclude dry vegetation. (see L245).
Additionally, we are sorry to have introduced confusion by accidentally having switched the superscript descriptions of 1 and 2 in Table 1, which is corrected now. In particular: 1: for VIS, SWIR-1 and SWIR-2, 2: for NIR only

Also, in what quantity is the latter expressed? BRF, BHR, ecc.. Please clarify.
When we state surface reflectance, we are considering a Lambertian reflector. This is already stated in sec. 2.3.1 Forward model. In addition, we further clarify the usage of bi-hemispherical reflectance in sec. 2.3.4 now. This update is also related to a minor comment or yours below.

- State vector: it is not clear what does the algorithm actually retrieve: the AOT at 550 nm (as stated at L163) or the AOT at 670 nm and (over water) at 865 nm, as suggested from the abstract and introduction? I seem to understand that the retrieved quantity is the AOT at 550nm, it should therefore be made clear that the AOT at 670 and 865 nm is derived from 550 nm based on your (quite strict) aerosol composition assumptions).
  We added:
  “Hence, AOT will need to be extrapolated to 670 nm and 865 nm using strict assumptions about the underlying aerosol composition.” (L177)

- I think that there is a bit of confusion between absolute accuracy and RMSE, which is dependent on the magnitude of the quantity you’re measuring. The RMSE can largely increase with the AOT range, it should not be taken as a reference for absolute accuracy purposes.
  We added a clarification and your warning in the updated manuscript:
  ”It should be noted that the term absolute accuracy as used in the formal mission requirements inherits some ambiguity. Added on top, the RMSE, which is used as a measure for it here, includes both systematic and random errors and is dependent on the magnitude of AOT itself in the comparisons. Nonetheless, keeping this in mind, this terminology will be used from now on in this study as an initial and rough accuracy assessment before launch.” (L355-359)
  Additionally, we also state other quality measures in the verification sections.

- The impact of your assumptions should be better assessed, e.g. lambertian surfaces, fixed atmospheric composition, etc.
  We decided to not do a full assessment of the assumptions since this would be out scope and decided to rather list them throughout the manuscript. However, an elaborated assessment of the respective assumptions should rather be done based on real world EarthCARE MSI data.

Minor comments

- L4 670 nm over ocean and valid land pixels, and at 865nm over ocean.
  Thank you, done.

- L36 It has been applied, for instance, to MODIS
  Thank you. Updated.

- L40 The algorithm from Luffarelli and Govaerts is not satellite dependent. In the very same paper you refer to it is applied to PROBA-V as well. Please correct.
  We added both applications of the Luffarelli and Govaerts algorithm explicitly in L65, where it fits better in the logical structure of our text.

- L52 Please update the reference to Govaerts and Luffarelli, 2018
  Updated. Now, Using the Govaerts and Luffarelli, 2018 instead of the Govaerts et al., 2010.

- L55 “where possible” is very vague. Please be more clear: “on valid land pixels”, “on dark vegetated surfaces”
  Rephrased: “over dark vegetated land pixel”. (L57-58)

- L79 Add reference to the DEM model used.
  Updated.

- L134 Explain why the method to describe water bodies is not suitable for coastal water. I assume it is because a fix value of chlorophyll content is considered?
  Added an additional sentence for clarification:
  ”This means, only a clear water spectrum is assumed for LUT simulations since there is operationally no real-time information available about e.g. chlorophyll content or colored dissolved organic matter or sediment.” (L146-148)

- L143 […] the AOT, the aerosol scattering phase function […]
  Thank you. Updated.

- L170 make sure you use the same symbols as in Eq. 8
  Thank you. Fixed.

- L171 Therefore, the state vector […]
  Updated.

- L175 justify the value of 0.03 and 0.001. Do they come from a certain number of tests, from literature, …?
  Added:
  “These two values are based on pre-launch testing of the algorithm. Nonetheless, they might be modified based on commissioning phase algorithm testing.” (L188-191)

- L242 surface reflectance in terms of? Albedo?
  Yes. We further clarified by adding "[…] the surface reflectance, in terms of spectral bi-hemispherical reflectance or albedo, [...]" (L258), which is also related to one of your general comments above.

- L254 You should mention the issue of the radiative coupling between surface and atmosphere
  Added:
  "Hence, the TOA signal is not dominated by atmospheric scattering processes as over ocean outside of sun glint, but rather represents a strongly coupled surface-atmosphere signal." (L272-274)

- L254 more complex than
  Thank you. Adjusted.

- L267 "empirically found". How? What is the accuracy?
  We added a clarification. Reading:
  "This formula has been empirically chosen in such a way, that MODIS band 7 black sky albedo can be used to reasonable reproduce the expected black sky albedo at band 1, 2 and 6. The correlation between parameterized and actual black sky albedo is above 0.9 for band 1 and 6 and above 0.7 for band 2. The corresponding average root mean squared error is below 0.02 (band 1 and 6) and 0.04 (band 2)." (~L293-296)

- Eq. 21 make sure to define all symbols
  Updated.

- Figure 3: the scatterplots show values close to 0.15 which are not really visible in the images. Also there is a cloud of points in figure 3 f) and 3 g) where the M-AOT strongly underestimate AOT between 0.05 and 0.1. Do you have a possible explanation for this?
  Updated the figure to a higher resolution and added the following clarification:
  "The bulk of the aerosol loading is to be expected in the range 0.06-0.1 for the Halifax scene. This is also color-coded in the respective comparison figures e-g). Nonetheless, occasionally, values exceeding this range are also available here although scattered, mostly close to cloud edges and consequently hard to spot in subfigures a) and c)." (L350-L353)
  "Strong underestimations in AOT over ocean between 0.05 and 0.1 are present close to cloud edges according to Fig. 3b, d, f, g). This is caused by a wrong aerosol composition assumption following the approach of sec. 2.3.3 in such complex regions, where, contrary to the assumptions used, in reality, a sharp transition of optical properties occurs." (L361-364)

- L325 "Explained variance"??
  Added clarification:
  "The explained variance, in terms of the squared correlation in percent, is [...]" (L359)

- Table 3 Here you suddenly mention “all simulated scenes”. You should mention in the text that more scenes were simulated and refer to the annex.
  Added sentence after introduction of the test scenes referring to the appendix.
  “Nonetheless, results for all simulated test scene cases will be summarized at the end of this subsection and corresponding figures can be found in appendix A.“ (L326-327)

- L357 Missing reference
  Thank you. Updated.

- L376 “more sophisticated” More than what?
  Updated. “than M-AOT applied to MODIS” (L414)

- L381 transferred = extrapolated?
  Exactly, updated.

- L387 The correlation for that scene is 0.97 and 0.99 over ocean and still reaches 0.87 […]
  Restated for clarification.
  “The correlation regarding AOT in that scene is 0.97 (670 nm) and 0.99 (865 nm) over ocean and reaches 0.87 (670 nm) over land, [...]” (L425-426)

- L422 “relatively bright” - please avoid this kind of statement and be precise
  Thank you. Removed “relatively” from the sentence.