# EGUSPHERE-2025-1353

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# Response to the reviewers

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## Reviewer 3

*The paper presents a sensitivity study for the retrieval of AOD using FCI. The topic is important for the new sensor; however, the overall structure of the paper is difficult to follow. The authors divide the study into several sections based on different settings, channels, and methods, but the logic behind the sensitivity study is not clearly articulated. The authors are encouraged to reconsider the organization of the paper. For instance, the one-channel retrieval could be presented as a subsection alongside the two-channel retrieval, clearly indicating the added value of including more channels. Similarly, the distinction between the idealized cases and real-world cases should be better structured, with a clear conclusion on how ignoring real-world conditions affects retrieval accuracy.*

We thank the reviewer for the valuable comments and the time spent reviewing our work. We have attentively considered all the raised issues and have produced a revised version of the manuscript addressing most of them. Please find below our replies to the comments and questions from the reviewer (shown in italics). The line numbers given in our answers correspond to the revised manuscript, with the "track changes" mode on.

Regarding clarity, the manuscript has been restructured and shortened to make it more easy to follow. This was achieved by removing some parts of the initial manuscript (e.g., Figure 1, Sect. 4.3.1, equations in Appendix B) and moving some others to the appendices (e.g., Sect. 2.3, Sect. 4.1 and Sect 4.2). Also, many parts of the manuscript have been revised to improve the clarity of the goals that we pursue, the purpose of experiments and the main assumptions (e.g., the end of the introduction, Sect. 2.1 and the beginning of Sect. 3 and Sect. 4). Moreover, we have renamed sections 3 and 4 to "Retrieval of AOD from single channels" and "Joint retrieval of AOD and FMF using two channels" because the important distinction between the sections is that we retrieve AOD in one, and AOD+FMF in the second, and not that we use one channel or multiple ones. With all this, we believe that the revised manuscript enables to catch the main messages more easily now, while keeping the essential information.

Finally, the connection of the present work with real world conditions has been clarified in the article. In addition to the discussion in Sect. 3.2.1 and Sect. 3.2.2, we have added a new paragraph in the "Conclusions" section: see L493 "It must be noted that the retrieval accuracies observed in this study may be degraded when processing real FCI data, mainly due to differences between the optical properties of the aerosol models used for inversion and those of the real world aerosols observed by FCI (e.g., showing a large variability of mixtures in the case of desert dust and biomass burning particles). In the near future, the inversion methods used in this work will be tested with actual FCI data and real world limitations will be determined. For example, the consistency of the hybrid model used for FMF/AOD inversion with respect to the natural variability of smoke and dust particles will be assessed. Furthermore, the use of daily averages of retrieved AOD and FMF to constraint the second inversion of the two-step method will have to be circumvented if we are to meet near real time constraints."

*Some more specific comments are listed below:*

- *P155–P160: The radiative transfer model used for the simulations is critical. More detailed information about the strengths and limitations of the aerosol and surface simulations within the model is needed. For example, is the two-layer assumption sufficiently accurate? What are the potential impacts of the aerosol vertical distribution on the results?* We chose the DOAD radiative transfer model for our FCI data simulation due to its well-known high accuracy in remote sensing applications. DOAD consists in combining successive reflections, back and forth, of the transmission of the radiance through two layers to model multiple scattering (Lenoble, 1993), while taking into account light polarization (i.e., the geometrical orientation of the radiation waves oscillations) (de Haan et al., 1987). DOAD limitations include the use of a plane-parallel assumption, which is not correct for extreme geometries, and a low processing speed. We now describe DOAD in more detail with the following text that has been added to the revised manuscript (L124: "Simulations are made with the accurate doubling-adding (DOAD) radiative transfer model (de Haan, 1987), which models multiple scattering by combining successive reflections, back and forth, of the transmission of the radiance through two layers (Lenoble, 1993), while taking into account light polarization.". In our simulations, DOAD was run considering a standard atmosphere made of 30 layers, with aerosols being present in a few layers near the surface only. The mention of "two layers" in the original manuscript referred to the way DOAD solves the radiative transfer equation (and in particular the multiple scattering) between two "given" adjacent layers. For further understanding, the reviewer can take a look to the figure below (Fig. 1). It must be noted, however, that atmospheric vertical distribution is not very important in our simulation of FCI top-of-layer (TOL) reflectance because gases are not taken into account, and therefore the vertically-dependent gas-aerosol coupling is excluded from our simulations. This makes the potential impact of aerosol vertical distribution in our study very low. We remind the reviewer that the simulation of TOL reflectance (i.e., including aerosol and surface contribution, but excluding gas effects) and not TOA reflectance was made for the sake of simplicity and so that we could concentrate on aerosol-surface decoupling (i.e., the essential issue in aerosol remote sensing; see L127 "Synthetic data are simulated without including atmospheric gases for the sake of simplicity and to focus on the retrieval of aerosol properties"). Correction of FCI observations for gas contribution is being currently addressed in our team and will be published in a separate publication.

- *Using only two scenarios to represent real-world conditions is insufficient, particularly for assessing anthropogenic contributions. Additional cases representing various anthropogenic aerosol types are recommended.* We agree that knowing the FCI performances for "typical" aerosol conditions (e.g., continental aerosols with an anthropogenic influence) is also important, but we preferred to conduct our study on more extreme and therefore more retrieval-challenging aerosol conditions for which the previous SEVIRI instrument showed limitations. While Ceamanos et al. (2023) and Georgeot et al. (2024) showed a good agreement of SEVIRI AOD retrievals with reference data in regions with standard anthropogenic-influenced aerosol conditions (e.g., Europe, or South America when fire smoke is not present), they found much greater errors in bright surface regions such as Northwest Africa (corresponding to case study 1 in the present work) and in some areas of Southwest Africa due to aerosol-unfavorable geostationary satellite geometry (corresponding to case study 2). Naturally, AOD retrieval over more "aerosol-standard" regions (i.e., with an already acceptable AOD information content from SEVIRI) will improve with FCI thanks to the general increase in AOD sensitivity made possible by this new sensor. Finally, we agree that anthropogenic particles can also be found in extreme aerosol conditions such as in the case of very high pollution. Nonetheless, we decided to focus on dust and smoke events only for the sake of brevity (the manuscript is already quite long as it was noted by other reviewers) and because these events (i) are more frequent in the Meteosat's field of view (contrary to Himawari's, with frequent high pollution conditions in big cities such as Beijing) and (ii) are related to more challenging retrieval configurations (i.e., bright surfaces in the north African case study 1 and unfavorable geometry in south African case study 2). The following sentences on this subject has been included in Sect. 2.2 (L141): "These two case studies are chosen because of the high occurrence of desert dust and wildfire smoke events in the Meteosat's field of view and the SEVIRI retrieval limitations observed in these cases. Other challenging aerosol scenarios, such as heavy pollution episodes, have not been taken into account here for the sake of brevity and because they are less frequent in the Meteosat's field of view than in that of other geostationary missions

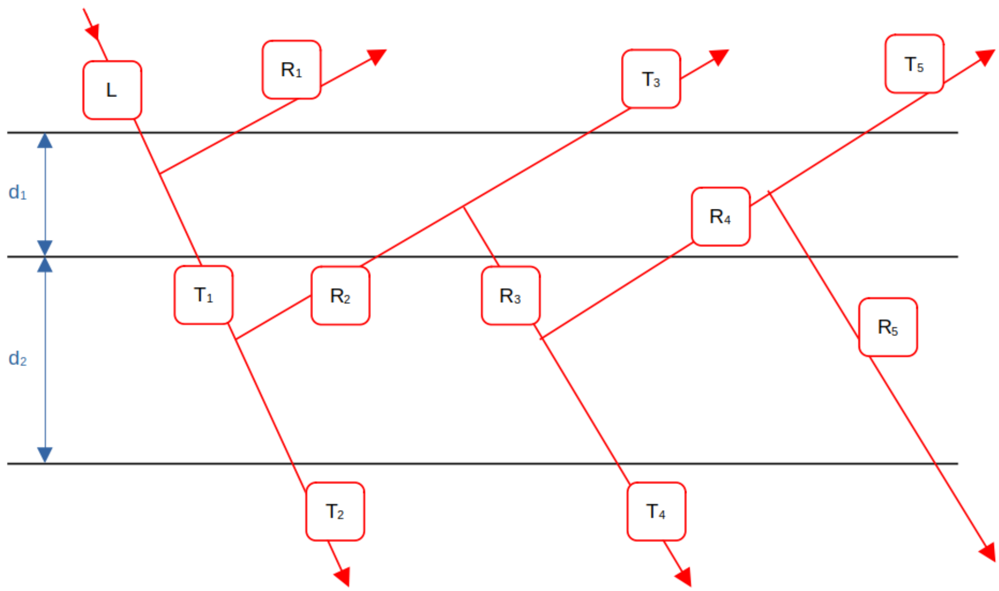


Figure 1: Principle of DOAD: We consider two layers of width d1 and d2. When the incident beam L crosses the first layer, part of it will be reflected and leave the layer (see R1 in the scheme) and part of it will be transmitted to the second layer. Then, the transmitted beam T1 will either be transmitted fully through the layer and leave the medium (T2), or will be reflected and therefore come into the first layer again (R3 ). In this first layer, the beam will either be reflected or transmitted, and so on. Basically, the part of the beam that changes direction is the reflected one, and the part that stays in the same direction is the transmitted one. In order to perform this method, we need to know the reflectance and transmission functions of the two layers.

(e.g., Himawari covering the big and often heavily polluted cities of East Asia)". Finally, the "Conclusions" section now reads (L480): "It is also worth noting that the FCI performances for AOD retrieval in less extreme and therefore less retrieval-challenging aerosol conditions than the ones considered in the selected case studies (e.g., anthropogenically influenced continental aerosols) are also expected to improve with respect to SEVIRI's."

- *Clarification is needed on how the AERONET-based aerosol models from MAIAC are implemented in the simulations. Specifically, which parameters are used as inputs? Models 6 and 7 are mentioned—are these fixed models, or are they updated using real-time AERONET data?* The MAIAC/MODIS C6 desert dust and biomass burning models (respectively, models 6 and 7) are introduced now in Appendix A1. These models are defined in Lyapustin et al. (2018) through their microphysical properties (i.e., particle size distribution, refractive index, sphericity). Mie and T-matrix codes included in the MOPSMAP software were used to calculate the optical properties (e.g., scattering phase function, single scattering albedo) of spherical smoke and non-spherical dust particles, respectively. The following sentence appears now in the revised manuscript (see L538): "Calculations are done taking into account the FCI spectral responses, and using a Mie code for spherical smoke particles in model 7 and a T-matrix code for non-spherical dust particles in model 6.". Finally, some clarification on the dynamism of these models was also added as it follows (see L534): "MAIAC aerosol models were built based on AERONET measurements that were fitted to by an AOD-dynamic bi-modal aerosol distribution. This means that size distribution, and therefore aerosol optical properties, vary with AOD, but remain constant with time.".

- *Regarding surface reflectance, the authors state that POLDER products were used and fitted to the FCI wavelengths. A thorough validation of this fitting procedure is necessary. Why not use a well-established BRDF model for the simulation instead?* As explained in Appendix A2, we use highly realistic surface reflectance that naturally varies every 15 minutes due to the combination of BRDF effects and the GEO-typical diurnally changing solar geometry. This was made possible by estimating for each selected station the corresponding 15-min surface reflectance from real SEVIRI VIS06 observations. This was preferred to the fitting of a surface BRDF model, which will show differences with real BRDF as most well-established models are semi-empirical. GRASP/POLDER data were only used in a second time to derive the spectral ratios that are used to "scale" the SEVIRI-derived 15-min surface reflectance spectrally, from the SEVIRI VIS06 channel to each of the considered FCI channels. The goal here was to obtain a realistic spectral variation of surface reflectance (which is proved to be essential in aerosol satellite retrieval in our work). Therefore, the potential residual uncertainties coming from the GRASP/POLDER-based polynomial fit are not relevant as long as the resulting spectral surface reflectance captures well the natural spectral variation, which is proved to be the case. The final surface reflectance (including any residual uncertainty) is considered to be the "true surface" in our synthetic observations, and therefore cannot affect the inversion results obtained in our study. Finally, the synthetic data (and indirectly the considered surface reflectance) were satisfactorily validated as presented in the appendices (e.g., see Table A1 and Fig. A3). We added the following lines on this topic in the revised manuscript (see L594 and L601): "It is worth noting that GRASP/POLDER data are only used to spectrally scale the SEVIRI-derived 15-min surface reflectance to impose a realistic spectral variation in synthetic data" and "Despite these assumptions, the realism of surface reflectance obtained with the presented approach is judged to be high overall".

- *In the Gaussian noise section, is the wavelength-dependent behavior of noise considered? If so, what are the impacts of this dependence?* Indeed, we used wavelength-dependent SNR values (i.e., 25 for channels VIS04, VIS05 and NIR22 and 30 for channel VIS06 according to Holmlund et al. 2021) to define the Gaussian noise that was added to the synthetic data. This is explained in "Step 3" of Appendix A1 (see L559), and also in a new Table 1 that we included to improve the description of FCI channels. However, the relatively weak spectral change in SNR (n.b., SNR only differs for channel VIS06) does not result in a relevant impact on the synthetic data, nor their inversion, the main reason being that SNR is high for all channels.

- *Degrees of Freedom for Signal (DFS) is a useful theoretical metric for understanding information content, but I strongly recommend that the authors also evaluate retrieval uncertainty by comparison with real measurements—for example, comparing simulated and observed surface reflectance, TOA reflectance, and retrieved AOD.* The evaluations suggested by the reviewer already exist. First, synthetic data are validated in Appendix A3, in which the simulated time series of satellite TOL (and not TOA) reflectance is compared with real SEVIRI observations for all selected stations. The good agreement (mean RMSE of 0.016 and mean bias of 0.002) as it is shown in Table A1 and Fig. A3 proves not only the high quality of synthetic data, but also the realism of the inputs used for simulation (e.g., the surface reflectance). The direct validation of surface reflectance is not possible since there is not ground measurements of bi-directional reflectance at the selected stations, but in our opinion the indirect validation based on the successful evaluation of the FCI synthetic data is proof enough. Note that ground measurements would have been used in the simulations if they existed. Second, retrieved AOD (and FMF) is extensively validated (in Sect. 3.2, Sect. 4.2.2 and Sect. 4.3.2) through a comparison with the input AOD (and FMF, respectively), which in our case comes from AERONET measurements. It is important to remind here that our study was conducted based on synthetic data, mainly because in this way all the analyses made in our work can be precisely validated using the known inputs used for data simulation. For example, this helped us to know which individual FCI channel contains the highest AOD information content (through the DFS analyses) and which enables the most accurate retrievals. This would have not been possible with real FCI observations (which by the way were not available at the time of writing this manuscript) for which most parameters such as surface reflectance would have been unknown (or known with a certain degree of accuracy at best). The importance of synthetic data is reminded in the revised manuscript in L130 ("The choice to use synthetic data is made to precisely evaluate the retrieval performances with FCI, which would not be possible with real satellite observations for which many parameters are unknown.").

- *P218: How are the observation and prior covariance matrices incorporated into the DFS calculation? This needs further clarification.* The values of the observation and prior covariance matrices used to compute DFS are given at the beginning of Sect. 3.1: "We calculate DFS following Eq. 2 for each station included in the FCI-like synthetic data setting Sa to 0.05 and $S_\epsilon$ to 0.0001 according to Georgeot et al. (2024), who found these values to provide accurate AOD retrievals from SEVIRI observations based on comprehensive experiments.". In fact, Georgeot et al. (2024) and Ceamanos et al. (2023) proved these values to be appropriate for AOD retrieval from Meteosat data based on the good results obtained after extensively processing real SEVIRI observations. We now explain the choice of these values in L215 for example: "For example, the value of $S_\epsilon$ was set to encompass the uncertainty of the SEVIRI channel VIS06 (equal to 3% according to Luffarelli et al. (2019)) and other errors operating in the inversion process".

- *The sensitivity study sections are largely qualitative. A more comprehensive and quantitative analysis is strongly recommended.* First, please note that we have renamed the original Sect. 3.1 and Sect. 4.3 (now Sect. 4.1) in which DFS are used to "Information Content Analysis" according to the suggestion of another reviewer. Second, we honestly believe that our DFS-based analyses are largely quantitative since we not only provide mean and case study-dependent statistics (e.g., see Table 3), but we also zoom in on the scores obtained for selected stations (e.g., Fig. 3 and Fig. 6). While we agree that conclusions drawn based on the DFS-based analysis only give a first idea of the FCI potential (indeed, DFS calculation is theoretical and may therefore be not 100% conclusive; is this what the reviewer meant when talking about "qualitative results"?), they are later confirmed by results obtained in subsequent sections, in which synthetic data are inverted and results are comprehensively and quantitatively assessed with the reference input data (see Sect. 3.2, Sect. 4.2.2 and Sect. 4.3.2). We added some clarification on this in the revised manuscript (see L211: "The goal of this step is to get a first idea of which channels contain the most information on aerosols and, in particular, on AOD, before processing the synthetic data for inversion", and L339: "to get a first idea of the FCI potential before processing the synthetic data for FMF/AOD inversion")

- *Section 3.2.1: In the ideal case, why does such a large retrieval error occur? The authors briefly mention potential sources such as noise and the inversion method, but this requires more detailed investigation and explanation.* Please note that the "Ideal Conditions" section title was misleading, and has been therefore modified to simply "Results" (see Sect. 3.2.1). Indeed, while input data are perfectly known in these experiments, data inversion is not made in ideal conditions since it can be impacted by several error sources. The main error source comes from the biases of the simplified radiative transfer model used for inversion (i.e., MSA, compatible with operational constraints), which is not the same than the one used for data simulation (i.e., DOAD, operational processing incompatible). The increase of MSA biases with AOD (see Fig. B1 in Appendix B) results in an increasingly large retrieval error on days with higher AOD (see June 23, 24 and 25 in Fig. 4a). Furthermore, inversion uncertainty can also come from the additive Gaussian noise and the Levenberg-Marquardt method, which may fail in finding a solution in some challenging inversion cases. All the existing biases can have an impact on the inverted AOD quality, with the magnitude of this impact potentially varying during the day because of the also diurnally varying AOD information content in GEO satellite observations. This variation comes from the diurnal change in solar geometry, which results in a diurnally varying aerosol scattering (peaking when SZA is high, and therefore scattering angle is low; eg. at the beginning and end of the day over regions along the 0° meridian) and an also diurnally varying surface reflectance (peaking when SZA is low, and therefore scattering angle is high; eg. around local noon along the 0° meridian, see TOL reflectance curves in Fig. 3a). As a result, AOD retrieval becomes more biased at noon over Saada for example (see the higher biases in the first four days of Fig. 4a, at noon). Additional explanations have been now included in L274 ("These uncertainties can result in retrieved AOD errors, which can vary in magnitude (e.g., due to the increase of MSA bias with AOD; see Fig. B1) and according to the time of day (i.e., because AOD information content varies during the day due to the also diurnally varying solar geometry in geostationary observations).").

- *Why is a one-channel retrieval necessary given that the sensor has multiple channels? Will both one-channel and two-channel retrievals be used in practice when the satellite becomes operational?* We agree with the reviewer that aerosol remote sensing can benefit from multi-channel retrieval. However, the goal of Sect. 3 is to quantify the retrieval potential of each channel separately, so that the obtained results can be used in developing future aerosol retrieval algorithms for FCI data. The following text was included at the beginning of Sect. 3 (L201): "In this section, we analyze each channel separately due to two main reasons. First, previous works performed AOD retrieval from SEVIRI data using the channel VIS06 only (Ceamanos et al. (2023a), Georgeot et al. (2024)), and therefore the results obtained in this section can help to assess how much FCI can improve AOD estimation using a similar single-channel algorithm. Second, knowing the sensitivity to AOD of each channel can help identifying the most appropriate to be used in multi-channel retrieval algorithms, which have proved to benefit aerosol remote sensing (Lyapustin et al. (2018), Limbacher et al. (2024))". It must be noted that the results obtained in Sect. 3 helped us to select channels VIS04 and NIR22 for the AOD/FMF retrieval described in Sect. 4.

- *All similar comments regarding Section 3 also apply to Section 4.* Further explanations have been included in Section 4 according to the reviewer's comments on Section 3 wherever they applied. For instance, the beginning of Sect. 4 has been clarified, the previous Sect. 4.1 and 4.2 have been moved to Appendix, and Sect. 4.3.1 has been removed for the sake of brevity and clarity. Also, we have renamed the previously named "Sensitivity Study" section 4.1 as "Information Content Analysis", which is much clearer in our opinion. We have also given the values of the covariance matrices used for calculating DFS in this section (see L343: "The measurement covariance matrix $S_\epsilon$ was set as follows: $S_\epsilon = \begin{pmatrix} 0.0001 & 0.00052884 \\ 0.00052884 & 0.0001 \end{pmatrix}$. The variance (0.0001) for channels VIS04 and NIR22 was chosen accordingly to Sect. 3. The covariance values (0.00052884) were calculated by using the whole synthetic dataset and calculating the covariance between the TOL reflectance of these two channels. As for the a priori covariance matrix, it was set to $\begin{pmatrix} 0.2 & 0.0 \\ 0.0 & 0.5 \end{pmatrix}$ following a similar empirical approach as in Georgeot et al. (2024)."