EGUSPHERE-2025-1353

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Response to the reviewers

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June 5, 2025

Reviewer 2

This manuscript explores the additional information content gained from the new channels for the Flexible Combined Imager (FCI) on the Meteosat Third Generation-Imager compared to its predecessor, the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on the Meteosat Second Generation platform. It uses synthetic top of layer reflectances generated using a combination of aerosol models using known exact atmospheric and solar and sensor geometric parameters as well as surface reflectance data derived from monthly GRASP/POLDER surface reflectance data which have been curve fit to the satellite spectral bands and then calculated at 15-minute intervals for two challenging case study regions, one in a desert dust event and another in a biomass burning event. An information content analysis is performed on retrievals for both AOD-only (to compare FCI with SERVIR) and AOD+Fine Mode Fraction (to highlight the potential for FCI to further characterize aerosol properties with the new channels).

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. The manuscript has been restructured and significantly revised to improve its clarity and completeness, and it has also been shortened (as suggested by other reviewers) but keeping the essential information. 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.

General Comments:

The topic itself is incredibly relevant and the scientific community can stand to gain a lot from it, but I feel that this manuscript is not finished in terms of characterizing the uncertainties and utilizing them in their sensitivity analyses for retrievals using the different channels, particularly over the course of the diel cycle and at different AOD concentrations. The assumptions of constant error covariance matrices for both the input satellite observations as well as the a priori inputs to the aerosol models seems overly simplistic, and I worry about their impacts on the final results, especially as these are very complex aerosol case studies. I'd like to see if both the final retrievals and the sensitivity analysis significantly changes due to a dynamically-varying uncertainty at the very least for:

- *the trace gas correction as a function of solar and sensor angles,*
- *the polynomial fit function to interpolate the GRASP/POLDER spectra to the FCI channels,*
- *a systemic bias due to the magnitude of the AOD retrieval itself as an a priori,*
- *the instrument uncertainty itself as a function of wavelength (5% for the VIS and 10% for the NIR), and*
- *a spectrally-invariant BRDF shape as a function of solar angle*

While we agree that the definition of appropriate covariance matrices is important for accurate inversion in optimal estimation, we honestly think that the additional work suggested by the reviewer is out of the scope of the present manuscript. Our study focuses on the potential of the new FCI for aerosol remote sensing, which is addressed by comprehensive analyses of (i) the information content of new measuring channels and (ii) their performances for AOD and FMF retrieval in comparison to SEVIRI's. To achieve this goal, we have used inversion methods that were satisfactorily used in previous works to process real SEVIRI data for AOD retrieval (Ceamanos et al., 2023; Georgeot et al. 2024). The choice of using existing methods (including their setup in terms of covariance matrices) was made to focus the present manuscript on the FCI potential assessment, since the development (and validation!) of new inversion methods is a topic in itself that deserves fully-dedicated works in our opinion. Despite assuming constant error covariance matrices in AOD retrieval, the selected inversion methods were comprehensively validated in the previously cited past works by successful comparisons of the SEVIRI-obtained AOD retrievals with reference data, including AERONET measurements and state-of-the-art satellite products. For example, Ceamanos et al, 2023 analyzed around 400,000 AOD retrievals over the whole SEVIRI field of view to find a very good agreement with AERONET (i.e., MBE=0.010, RMSE=0.093, R=0.800), comparable to that found for the state-of-the-art product GRASP/POLDER (see Fig. 13 in Ceamanos et al., 2023). For us, this is proof enough that the selected inversion methods, which make assumptions of constant covariance matrices, can allow us to achieve the main goal of the present manuscript (i.e. the assessment of FCI potential for aerosol remote sensing). This is now clearly mentioned in the new text starting at L214. While we agree that dynamically-varying uncertainties could benefit aerosol inversion in some situations, the accurate calibration of the covariance matrices according to all parameters suggested by the reviewer would require extensive experiments that do not fit in the present manuscript and therefore should be addressed in a separate study.

It is also worth noting that gas correction was not carried out in our study, as FCI data were simulated in top-of-layer (TOL) reflectance units (i.e., including aerosol and surface contribution, but excluding gas effects) for the sake of simplicity (see L127: "Synthetic data are simulated without including atmospheric gases for the sake of simplicity and to focus on the retrieval of aerosol properties. This choice results in the simulation of top of aerosol layer (TOL) reflectance, resulting from the contributions from aerosols and the surface only. "). Correction of FCI observations for gas contribution is being currently addressed in our team and will be published in a separate publication.

As for the surface reflectance used in the synthetic data simulation, the main goal was to consider the natural variation of surface reflectance in GEO observations coming from the combination of the surface BRDF and the changing solar geometry during the day (every 15 min in our study). This was made possible by estimating for each selected station 15-min surface reflectance from real SEVIRI VIS06 observations, which was then satisfactorily validated as presented in the appendices (e.g., see Table A1). It must be noted that GRASP/POLDER data were only used in a second time to derive the spectral ratios used to "scale" the SEVIRI-derived 15-min surface reflectance spectrally (as indicated now in L594), 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 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. In fact, residual uncertainties are not important in the data inversion, as the final surface reflectance (including those uncertainties) is considered to be the "true surface" in our synthetic observations. The same goes for the spectrally-invariant BRDF shape, which we assume to be a valid assumption to simulate our synthetic data. Similar to the GRASP/POLDER spectral scaling, this assumption with respect to "the real world" does not affect the inversion results in our study as the resulting surface reflectance becomes the true surface in "the synthetic data world". We added a line on our confidence on the surface reflectance used in the data simulation in L601: "Despite these assumptions, the realism of surface reflectance obtained with the presented approach is judged to be high overall".

Finally, we did not consider the currently known channel-dependent FCI uncertainties (as this reviewer mentioned, 5% for the VIS and 10% for the NIR) because these values were not known when the study was carried out. Instead, we used the expected SNR values (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 spectral change in SNR was not accounted in the definition of the inversion uncertainties for simplicity, but also because it was considered to be weak (n.b., SNR only differs for channel VIS06). As explained in L214 (and L262, L343), the observation error is set for all channels to 0.0001, which roughly corresponds to an uncertainty of 3% (and therefore a SNR of 30). A new line was included in the revised manuscript on this point (L214: "For example, the value of S_ϵ 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.")

This might be outside the scope of this manuscript as it stands, but while I do really like the evaluation of the information content changes for extreme aerosol events like desert dust and biomass burning, I was left wanting to see it also in the context of more "typical" retrievals like standard atmospheres over land and/or ocean to give a larger perspective on how much more information content we can gain from FCI in a more global context.

We agree that knowing the FCI performances for "typical" aerosol conditions 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 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.

The following sentence on this subject has been included in the "Conclusions" section (L480): "It is 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."

Specific Comments:

- *Line 84 (and throughout the manuscript): I think it might be better to call the channels by their center wavelengths (e.g. "FCI 444 nm channel") throughout the text, or at the very least have a table with the center bands and the FWHM (but I'd much prefer having it in the text to avoid the reader having to keep referencing it).* We have added a new table in the introduction specifying the names of the spectral channels of FCI and SEVIRI, as well as the characteristics relevant in our study (see Table 1).
- *Figure 1: This figure by itself seems like it could be removed for brevity, especially as the FCI data were still pre-operational. More attention then could be devoted to Figure 2 to highlight the FCI additions.* The figure has been removed as suggested.
- *Figure 2: Could we change the SEVIRI bands to grey (or something slightly different from the gridlines) and the FCI to blue to highlight them as the newer wavelengths? Also, the "Sand" color and the "Desert Dust" color are blending to my eyes (especially with the right legend overlaid so closely to the desert dust line). Could this be swapped to another color, and the spectral reflectance lines given a different weight or dotted/dash style to discriminate them better?* The figure was modified according to the reviewer's suggestion, and vertical grid lines were removed for more clarity. *This figure could also be partnered with a table going over the wavelength comparisons between FCI and SEVIRI (showing channel names, band centers, FWHM, etc).* We thank the reviewer for this idea. As suggested, we have added a new table in the introduction (see Table 1).
- *Section 3.1: This section might be better titled "Information Content Analysis" since it primarily analyzes the DFS which isn't quite the same as the uncertainties of the retrievals.* We have renamed the section "Information Content Analysis".
- *Line 225: I wonder if this is an oversimplification to be set as constants when it could vary spatially and temporally depending on the input models (such as the polynomial fit uncertainty*

for the spectra, or the uncertainty from trace gases especially at high angles, the biases in retrievals due to AOD magnitude, etc). How would the impacts from these affect the information content retrievals performed here? Please refer to our previous first answer to this point above.

- *Table 2: Instead of simply calling it case study 1 and 2, for clarity it might be better to call it dust and biomass burning.* After some thinking, we have preferred to keep calling them "case study 1" and "case study 2". In our opinion, using "desert dust" and "biomass burning" would create confusion with the aerosol models that we used in our work, which are named the same.

- *Figure 4: All three orange-red markers as well as the light green markers are very difficult to distinguish here.* We have modified the markers colors in the two sub-figures to make them more visible. We also checked that markers are easily distinguished in the black-and-white version of the figure.

- *Line 338: Would a systemic bias in TOL reflectance from this influence the final results?* Here we meant that we choose to omit the dependence of equations on lambda for the sake of simplicity (i.e., to simplify the writing of the equations to come). However, the spectral dependence of all variables was taken into account in all the experiments of our study.

- *Line 464: What were the values for these? Are they based on the Georgeot et al 2024 paper?* Values are Sa=(0.2, 0 & 0, 0.5) and Sy=(0.0001, 0.00052884 & 0.00052884, 0.0001). The variance for TOL reflectance in channels VIS04 and NIR22 was chosen accordingly to Georgeot et al., 2024. The covariance values for TOL reflectance in VIS04 and NIR22 were calculated by using the synthetic data set and computing the covariance between these two channels. We have added explanations in the revised manuscript on this point (L343 "The measurement covariance matrix S_ϵ is 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) are obtained from the whole synthetic data set by calculating the covariance between the TOL reflectance of these two channels. As for the a priori covariance matrix, it is 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)."

- *Line 500: A 50x multiplier seems very arbitrary. What would different Sa values do for final retrievals?* This value was selected empirically after carrying out several experiments testing different values of Sa, which sets the weight given to the prior value used for FMF. Lower (higher) Sa values were found to constrain too much (not enough) the retrieved FMF, and resulted in less accurate retrieved AOD time series for example.

- *Line 585: Could you add a bit more detail about this correction in the text here? Just enough to cover how it's done for the full diurnal timeframe.* The following sentence was included in L578 "More precisely, satellite radiance was corrected for gas absorption and Rayleigh scattering considering a US Standard 62 atmosphere adjusted by model analyses of surface pressure, total column water vapor and total column ozone.". *As they use SMAC to correct for molecular effects, what are the minimum and maximum ranges of solar and sensor angles for these stations? How are the increased uncertainties here at sunrise and sunset accounted for in the sensitivity analysis?* Details on the gas correction made with SMAC can be found in Ceamanos et al. 2021 and 2023, which mention for example that "The accuracy of SMAC is within 2%–3%, if slope effects are mild, and high viewing and solar angles are avoided.". As for geometry, SMAC is found to be accurate for zenith angles up to 60-70° when the considered plane-parallel assumption is valid. For the selected stations, view zenith angle is always below this threshold, but solar zenith angle goes beyond each time we are close to sunrise or sunset. SMAC limitations in this case could result in an inferior quality of the SEVIRI-retrieved surface reflectance at the beginning and end of the day (see Fig. A2b), which after using it in the data simulation could degrade the realism of the synthetic data at these times of the day. However, it must be noted that these potential inaccuracies not only should affect a few data points, but also should not directly affect the inversion results since the SEVIRI-derived surface reflectance is the "true" surface reflectance in the synthetic data. Indeed, surface-related inversion errors are avoided since the same SEVIRI-derived surface reflectance is used for inversion. Only the potentially degraded realism of synthetic data close to sunrise and sunset could impact our analyses conclusions, as it is now mentioned in the manuscript (see new sentence in L602: "We note the sole potential exception of high zenith angles for which the quality of the gas correction applied in step 1 may be impacted by the considered plane-parallel assumption."). Finally, it is worth noting one more time that the present study has not been carried out with TOA data but gas-free TOL simulations, and therefore the impact of SMAC biases on the found FCI performances is not relevant here.

- *Also, there are two Ceamanos et al 2023, so there might need to be an "a" and "b" discriminant depending on how this journal does it.* We thank the reviewer for spotting this issue, which we have corrected.

- *Line 595: Is there any random or systemic uncertainty that needs to be accounted for using this polynomial fit, in particular for the FCI 510nm and FCI 640/SEVIRI 635 channels, and, if so, how is it being accounted for? From Figure A1 it seems like there might be some systemic biases being introduced here.* The goal in our study is to simulate realistic FCI synthetic data, and that includes using surface reflectance as realistic as possible in the simulation. We honestly believe that the followed approach (described in Appendix A2) allows us to reach this goal. In particular, we use state-of-the-art satellite-derived data to spectrally extrapolate the 15-min surface reflectance obtained from SEVIRI VIS06 to the new FCI channels. While some uncertainty may be introduced by this approach (e.g., the polynomial fitting), we believe that the resulting surface reflectance is of high realism, and in particular its spectral dependence. Note in Fig. A2a that FCI points were obtained using the GRASP/POLDER spectral ratios only, and therefore are not expected to follow the fitting curve exactly. Again, it is important to note that the resulting surface reflectance becomes the "truth" in the synthetic data simulation and posterior inversion, and therefore residual biases such as the ones commented by the reviewer cannot easily impact the drawn conclusions. We added the following line on this topic in the revised manuscript (see L594): "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.".

- *Line 602-603: How bad of an assumption would a spectrally invariant BRDF shape be? Is there a quick thought or reference you can put in here to give an estimate on how it might impact the retrieval capabilities, particularly at larger angles?* Please refer to our previous answer, which also applies here. A spectrally invariant BRDF shape is considered to provide realistic enough FCI synthetic observations, and the same assumption is made in inversion. See new sentence in L601 mentioning this point.

- *Line 625: For clarification, this was used to estimate the surface reflectance in Figure A1b?* Yes. Please note that this figure (now Fig. A2b) has been updated, as the previous one corresponded to a wrong instrument channel.

- *639: view of both solar and viewing zenith angles for the mu terms?* You are right, but please note that this appendix was removed for brevity as suggested by other reviewers. Readers are now referred to Ceamanos et al, 2023 for details on the MSA RTM equations.

- *Line 660: To me, Figure C2 looks to have a pretty similar error, if not more in some day/variable combinations, as C1. Could these be better visualized as a scatter plot or a Tukey mean-difference plot?* Please note that the main visual differences between Fig. D1 and Fig. D2 (in the revised manuscript) happen for the "b" plots corresponding to Mongu Inn station, notably for the retrieved AOD time series. Table 6 confirms the better results of FLOTSAM in comparison to MSA (with respectively 4 and 1 "best" scores when they are both compared to the reference DOAD)