

1 **Report 5**

2 **Reply to Anonymous Referee #2**

3 We thank the reviewer for the constructive comments and thoughtful suggestions, which
4 are very helpful in improving our manuscript. We have carefully addressed all concerns
5 and revised the manuscript accordingly. A point-by-point response is presented below.

6 **General comments**

7 This study focuses on digging the potential of space-borne multi-angular polarimetric
8 sensors to simultaneously retrieve wavelength-dependent optical properties of atmospheric
9 aerosols and the Earth surface, namely the aerosol optical depth (AOD), single scattering
10 albedo (SSA) and directional hemispherical reflectance (DHR). The sensitivity study
11 highlights sensitivities of multi-angle intensity and polarimetric measurements to SSA at
12 different wavelengths and under different AOD loadings, leading to the demand of an
13 accuracy better than 5% for intensity and 0.01 for DOLP measurements, respectively to
14 retrieve SSA with 0.03 uncertainty. The study can contribute to the community by
15 providing aerosol and surface properties retrieved from DPC data, while I have some major
16 concerns related to the motivation, method, and validation of the study:

- 17 1. The motivations of this study are not well demonstrated. The potential and
18 limitations of multi-angular polarimetric observations for aerosol and surface
19 property retrievals has already been well demonstrated by numbers of previous
20 studies, for both POLDER and DPC measurements. The concept of the retrieval
21 method (optimal estimation) has been well established and the retrieval accuracies
22 of AOD, SSA and DHR don't show significant improvement compared with
23 existing algorithms, such as GRASP/PARASOL (Dubovik et al., AMT, 2011; Chen
24 et al., ESSD, 2020) and machine learning methods (Dong et al., TGRS, 2024). Thus,
25 the necessity of developing the retrieval algorithm is not convincing enough. While
26 the motivation of efficiently processing DPC data to generate global aerosol and

27 surface products may stand, it is somewhat regrettable that the retrieval
28 performance over the ocean is not strictly validated in this work.

29 We sincerely thank the reviewer for the constructive and insightful comments. We
30 appreciate the opportunity to further clarify the motivation and contribution of this study.

31 We fully agree that multi-angular polarimetric observations have demonstrated strong
32 capability for aerosol and surface property retrievals, and that optimal estimation is a well-
33 established inversion framework. We also acknowledge that the existing algorithms such
34 as GRASP (Chen et al., 2020; Dubovik et al., 2011) and RemoTAP (Hasekamp et al., 2011,
35 2024) have shown excellent performance in aerosol retrievals. The current limitation
36 mainly concerns SSA retrieval from DPC observations. Existing applications of GRASP-
37 or RemoTAP-type algorithms for DPC-based SSA retrieval have primarily been conducted
38 at regional scales. To our knowledge, global-scale SSA retrievals based on DPC
39 measurements using these numerical inversion frameworks have not yet been reported.
40 One of the main motivations of this study is therefore to generate global aerosol optical
41 products, particularly SSA, from DPC observations within a physically based inversion
42 framework.

43 Regarding machine learning (ML) approaches, we agree that recent methods have
44 demonstrated competitive performance (Dong et al., 2024). However, their robustness is
45 inherently influenced by the representativeness of the training dataset. In regions with
46 sparse AERONET coverage, the capability of ML-based retrievals may be limited (e.g.,
47 the anomalously high AOD values over South America in October 2019 reported by Dong
48 et al. (2024)). A physically based inversion framework provides an independent and
49 potentially more transferable solution for global applications.

50 Concerning validation over ocean regions, we agree that comprehensive validation is
51 important. However, AERONET-based validation over ocean is limited for several reasons.
52 First, aerosol optical depth over ocean is often relatively low, which makes SSA retrieval
53 from AERONET observations more uncertain and reduces the number of reliable SSA
54 records. Second, the spatial distribution of AERONET sites over oceanic and coastal
55 regions is sparse. Third, the DPC dataset available for this study covers only six months,

56 which further limits the number of collocated samples and prevents large-scale statistical
57 validation. To partially address these limitations, we have added comparisons between our
58 retrieval results and MODIS aerosol products over ocean regions in the revised manuscript.
59 Although such inter-comparisons cannot fully substitute for AERONET-based validation,
60 they provide useful consistency assessments at broader spatial scales.

61 2. The retrieval algorithm is not clearly illustrated. The retrieval algorithm is based on
62 the optimal estimation which is a well-established inversion concept, while many
63 aspects are still ambiguous: what are the exact definitions of the utilized
64 measurements and the parameters to retrieve? Are all the spectral, angular, intensity
65 and polarimetric measurements from DPC used? How are the a priori values and
66 covariance matrix determined? How is the optimization procedure realised
67 (iteration step, convergent criteria, initial points, etc.)?

68 Thank you for this comment. We agree that the retrieval algorithm should be described
69 more clearly within the optimal estimation framework. In the revised manuscript, we have
70 added explicit definitions of both the measurement vector and the state vector, clarified
71 which spectral, polarimetric, and angular DPC observations are used, and explained how
72 the measurement errors and a priori constraints are prescribed. We have also added two
73 tables (Tables 2 and 3) in the manuscript to summarize these information. Table 2
74 summarizes the usage of DPC measurements and their corresponding error specifications,
75 and Table 3 summarizes the prescribed a priori values and associated uncertainties for
76 aerosol and surface parameters.

77 In particular, we have clarified that the measurement vector \mathbf{y} is constructed from
78 calibrated scalar reflectance at 443, 490, 565, and 670 nm together with DOLP at 490 and
79 670 nm, collected from multiple viewing angles (L167-168):

80 *The measurement vector, \mathbf{y} , is constructed with calibrated scalar reflectance at 443,*
81 *490, 565, and 670, as well as DOLP at 490 and 670 nm from several angles.*

82 Since the number of available viewing angles varies among pixels, we have further
83 clarified the angular treatment by excluding pixels with fewer than 9 angles and using a
84 fixed set of 9 viewing angles for all remaining pixels (L171-173):

85 *Pixels with fewer than 9 viewing angles, which are primarily located near the scan*
86 *edges, were therefore excluded. For the remaining pixels, observations from the*
87 *first 9 viewing angles were used in the retrieval to maintain a fixed number of*
88 *viewing angles for all pixels.*

89 We have also specified that the measurement error covariance matrix is determined based
90 on the official pre-launch calibration uncertainties (L175-178):

91 *Although previous studies have suggested that observational errors of DPC*
92 *increased after launch (Qie et al., 2021; Zhu et al., 2022), the magnitude of this*
93 *increase has not been quantitatively characterized. Therefore, this study adopts the*
94 *official pre-launch laboratory calibration errors, namely 5 % radiance errors and*
95 *0.02 DOLP errors (Li et al., 2018), as the observational errors used to construct*
96 *the measurement error covariance matrix.*

97 In addition, the definition of the state vector \mathbf{x} and the retrieved parameters have been made
98 explicit in L180-189:

99 *The state vector, \mathbf{x} , is composed of aerosol and surface parameters. Particularly,*
100 *for land surfaces, the state vector \mathbf{x} consists of AOD ($\tau(\lambda)$), SSA ($\omega(\lambda)$), kernel*
101 *intensity parameters of RTLS model ($K(\lambda)$, k_{vol} , and k_{geo} in Eq. 2), and the scale*
102 *factor of BPDF-NDVI model (C in Eq. 8)...For water surfaces, only $\tau(\lambda)$ and $\omega(\lambda)$*
103 *are retrieved as components of the state vector \mathbf{x} , and the New Cox-Munk model is*
104 *implemented to compute the surface reflectance (Spurr, 2006). The wavelength-*
105 *dependent parameters, $\tau(\lambda)$, $\omega(\lambda)$, and $K(\lambda)$, are retrieved at 443, 490, 565, and*
106 *670 nm, corresponding to the wavelengths at which DPC observations are used to*
107 *construct the measurement vector.*

108 The description of a priori values and their error covariance matrices has been clarified in
109 L189-192:

110 *For AOD and SSA, the a priori state vector and its associated error covariance*
111 *matrix are prescribed as fixed values, derived from the mean and variance of*

112 *AERONET measurements. The a priori estimates of surface properties are also*
113 *fixed, with their errors defined by the corresponding ranges of variability.*

114 Finally, we have stated that the cost function minimization is implemented through an
115 iterative Gauss–Newton approach (L201-202):

116 *The algorithm minimizes the cost function defined in Eq. 4 using an iterative*
117 *Gauss–Newton method to obtain the final retrieval results.*

118 We believe these revisions resolve the ambiguities noted by the reviewer and provide a
119 clearer and more reproducible description of the retrieval algorithm, including the
120 measurements utilized, parameters retrieved, error characterization, a priori constraints,
121 and optimization strategy.

122 3. The analysis of the algorithmic accuracy and comparison with other studies are not
123 adequate neither based on simulated data nor based on real measurements. The
124 retrieval from simulated data assumes absolutely accurate measurements fully
125 represented by the radiative transfer model, while it does not assess the influence
126 of measurement noise on the retrieval results. There is also lack of comparison with
127 other multi-angle polarimetric inversion algorithms based on simulated data (e.g.,
128 the work by Dubovik et al., (AMT, 2011)) to evaluate the advantages and
129 disadvantages of the retrieval algorithm proposed in this work. Furthermore, when
130 applying to real DPC measurements, there is only a small part (L312-313)
131 mentioning the comparability of SSA correlation coefficient with one study based
132 on DPC data (Fang et al., RS, 2022). If the development of DPC retrieval products
133 is one of the main motivations of this study, more comprehensive comparison of
134 the DPC retrieval accuracy with others studies, such as those you mentioned in
135 Introduction (L47-54), is probably necessary.

136 Thank you for this detailed comment. We have revised the manuscript to strengthen the
137 evaluation of retrieval accuracy for both simulated and real DPC data, and to add more
138 comparisons with existing studies. For the simulated-data evaluation, we perform retrievals
139 for two simulation settings generated with the same forward model and geometry: a noise-
140 free dataset and a dataset with Gaussian noise added representing the DPC laboratory

141 calibration uncertainties (5% error in I and 0.02 error in DOLP). By comparing the two
142 retrieval results against the known “true” inputs, we explicitly quantify how measurement
143 noise affects the retrieved parameters, rather than assuming perfectly accurate observations.
144 Particularly, after adding noise, the SSA retrieval performance degrades rapidly: the
145 correlation coefficient decreases from above 0.6 (noise-free case) to below 0.4 (noisy case),
146 indicating that SSA is highly sensitive to measurement uncertainty. We also examined the
147 simulated-data results reported by Dubovik et al. (2011), but their results are presented in
148 a substantially different form and under different evaluation settings, which makes a direct,
149 metric-by-metric comparison difficult.

150 For the application to real DPC measurements, we note that reported SSA retrieval results
151 from DPC/Gaofen-5 remain limited. In addition to Fang et al. (2022), we added a
152 comparison with the SSA results reported by Dong et al. (2024). The SSA retrievals
153 reported by Jin et al. (2024) mentioned in the Introduction are based on DPC-2/ GaoFen-
154 5(02) measurements, which differ from the instrument configuration used here and cover
155 a different time period, which have been clarified in the revised manuscript. We also
156 acknowledge that discrepancies across studies may arise from differences in calibration
157 and error assumptions, screening, collocation, surface constraints, and aerosol model
158 settings.

159 Overall, these revisions aim to provide a clearer and more quantitative assessment of
160 algorithmic accuracy, the role of measurement noise, and the relative performance of our
161 approach compared with existing studies.

162

163 According to these concerns, more adequate illustration of the motivation and a more
164 comprehensive discussion section might be needed in order to be qualified in the
165 publication in AMT. In addition, there are several statements not true or at least not
166 rigorous enough in the main text. Please see the following comments for more details.

167 **Specific comments**

- 168 1. L54-56: What do you mean by “lack physical interpretability”? A method is
169 considered as effective as long as its accuracy is sufficiently validated, isn't it?

170 Thank you for this comment. We agree that a method can be considered effective if its
171 accuracy is sufficiently validated. In this context, our intention was not to question the
172 effectiveness of machine learning approaches, but to highlight some commonly discussed
173 characteristics of data-driven methods. Many machine learning approaches rely primarily
174 on training data and do not explicitly represent the underlying physical mechanisms. As a
175 result, their performance may depend on the availability and representativeness of training
176 samples, and may degrade in regions or conditions where training data are limited. For
177 example, Dong et al. (2024) used AERONET observations as training samples, which may
178 limit the performance in regions with sparse ground-based measurements (e.g., the
179 anomalously high AOD values over South America in October 2019).

180 We have revised the manuscript to clarify this point and to avoid overstating the limitation
181 of machine learning approaches:

182 *Although machine learning approaches have demonstrated strong performance,*
183 *they are typically data-driven and rely on the availability of representative training*
184 *samples, without explicitly modeling the underlying physical mechanisms. As a*
185 *result, their performance may decrease in regions or conditions with limited*
186 *observations.*

187 2. [L57-58: It is recommended to insert a short paragraph at the end of the Introduction](#)
188 [to briefly describe the structure of the manuscript as well as the main contents of](#)
189 [each section.](#)

190 We thank the reviewer for this helpful suggestion. We have added a short paragraph at the
191 end of the Introduction to outline the structure of the manuscript and to briefly summarize
192 the main content of each section.

193 *The remainder of this paper is organized as follows. Sect. 2 describes the data,*
194 *methods, and experiments conducted in this study. Sect. 3 presents the main results,*
195 *including sensitivity experiments, validation using simulated data and DPC*
196 *observations, and regional and global maps of the retrieved parameters. Sect. 4*
197 *discusses the results and concludes the paper.*

198 3. L84-87: The phase matrix is an important microphysical property which depends
199 on aerosol size, shape and refractive index, and which in turn influences aerosol
200 SSA which is the core retrieval parameter throughout this study. Thus, rather than
201 simply referring to other studies, you need further sensitivity studies to justify the
202 statement of “relatively minor influence of aerosol phase matrices on the inversion”.

203 Thank you for the comment. We have added additional sensitivity experiments in Sect. 3.1
204 to quantify the impact of the aerosol phase matrix on the simulated TOA I and DOLP.
205 Specifically, we conducted forward simulations using several aerosol models listed in
206 Table 4 (which represent different phase matrices). The results indicate that the changes in
207 both I and DOLP caused by different phase matrices are much smaller than those caused
208 by other parameters such as AOD and SSA. This is consistent with the studies cited in
209 L84–87.

210 4. L136-137: What are the exact retrieval parameters that compose the state vector?
211 The AOD, SSA, and three RTLS parameters? At which wavelengths?

212 Thank you for this comment. This point is addressed in detail in our response to the General
213 Comments #2 regarding the retrieval algorithm description. Briefly, the state vector \mathbf{x}
214 consists of aerosol and surface parameters, including AOD ($\tau(\lambda)$), SSA ($\omega(\lambda)$), kernel
215 intensity parameters of RTLS model ($K(\lambda)$, k_{vol} , and k_{geo} in Eq. 2), and the scale factor
216 of BPDF-NDVI model (C in Eq. 8), with wavelength-dependent parameters retrieved at
217 443, 490, 565, and 670 nm. The complete definition of the state vector and the
218 corresponding wavelengths is provided in the revised manuscript and summarized in Table
219 3.

220 5. L156-158: Do you mean the x_0 and S_a in Eq. (4) and Eq. (5) are derived from the
221 statistics of multi-year datasets? If so, then:

- 222 • Which datasets (i.e., which climate models, or observations) do you use? By “multi-
223 year”, what are the exact time periods? And what are the rules for data screening?
- 224 • On a yearly and global scale, how do you take into account the variability of aerosol
225 and surface properties and ensure no systematic bias is introduced by the a priori
226 constraints?

- 227 • Please specify the “fixed constants” of \mathbf{x}_0 and \mathbf{S}_a .
- 228 • And if not, please explain the way of determining the a priori constraints in more
- 229 details.

230 Thank you for this comment. The a priori state vector \mathbf{x}_0 and the associated covariance
231 matrix \mathbf{S}_a in Eqs. 4 and 5 are prescribed as fixed values in this study, and are not
232 dynamically adjusted for individual pixels or acquisition times. They are not derived from
233 spatially or temporally varying multi-year climatological datasets.

234 For aerosol parameters, the a priori values and variances of AOD and SSA are derived from
235 the mean and variance of AERONET measurements over a six-month period. The standard
236 AERONET Level 2.0 quality-control criteria except for the AOD threshold are applied
237 during data screening. For surface parameters, the a priori values are not derived from
238 observational datasets. Instead, they are prescribed as fixed values summarized in Table 3,
239 and the corresponding a priori uncertainties are defined as half of the physically plausible
240 parameter ranges. This approach is intended to constrain the retrieval within realistic
241 bounds without imposing observational climatology on surface properties.

242 The use of fixed a priori values in this study is intended to provide a controlled and
243 consistent configuration for evaluating the algorithm’s inherent retrieval capability. Under
244 this setting, the fitting performance is not dominated by the choice of initial conditions, but
245 is primarily determined by the information content of the multi-angle and polarimetric DPC
246 measurements. We note that multi-year averages from climate models or other
247 observational products could be incorporated in future applications to further improve
248 retrieval performance, but this is beyond the scope of the present algorithm assessment.

249 The values of \mathbf{x}_0 and the diagonal elements of \mathbf{S}_a used for aerosol and surface parameters
250 have been listed in Table 3 of the revised manuscript. Further details on the retrieval
251 configuration are provided in our response to the General Comments.

- 252 6. Section 3.1: The authors are encouraged to reduce the discussions on some already-
- 253 known phenomena and focus on key features related to the retrieval accuracy, so
- 254 that the section can be more refined. For example, the authors may simplify the
- 255 narrative about the relationship between SSA and TOA radiance, the influence of

256 AOD loading on SSA sensitivity... instead, incline more to the angular and
257 wavelength variations of the SSA sensitivity and how do they influence the
258 selections of viewing geometry and measurement bands.

259 Thank you for the suggestion. We have rewritten Sect. 3.1 to make the discussion more
260 concise and more directly linked to retrieval accuracy. In the revised text, we shortened the
261 narrative on well-established qualitative relationships (e.g., the general dependence of
262 TOA radiance on SSA and the effect of AOD loading on SSA sensitivity) and focused
263 instead on the angular and spectral characteristics of SSA sensitivity. In addition, we added
264 new sensitivity experiments and briefly compared the impacts of different parameters on I
265 and DOLP.

266 7. L219: As we can see from Figure 2, ΔI for different wavelengths does not approach
267 zero at 180° scattering angle.

268 We thank the reviewer for this careful observation. The reviewer is correct that ΔI does not
269 reach zero at a scattering angle of 180° . Our original statement was intended to describe
270 the general decreasing trend of ΔI as the scattering angle increases toward 180° , rather than
271 implying that ΔI becomes exactly zero at that angle. We have revised the manuscript in
272 L257 to clarify:

273 *Overall, as the scattering angle increases, ΔI gradually decreases, indicating*
274 *reduced sensitivity to SSA.*

275 8. Figures 2-4: What is the SSA value used for producing these figures? Is the value
276 wavelength-dependent? Why is this value chosen and considered representative?

277 Thank you for this important comment. The SSA used in producing Figures 2-4 is
278 wavelength-dependent, as SSA generally varies with wavelength. To clarify its
279 representativeness and assess its impact, we have conducted additional sensitivity
280 experiments with SSA values ranging from 0.7 to 1.0, covering most SSA values in the
281 actual atmosphere. The detailed experimental settings are summarized in Table 4 The
282 analysis helps evaluate the influence of SSA assumptions on the results and support the
283 robustness of the conclusions.

284 9. L226-228: Why does this sign reversal happen?

285 Thanks for the comment. A plausible explanation is that the wavelength dependence of the
286 relative contributions from Rayleigh scattering, aerosol scattering, and surface reflection
287 leads to a sign change in Δ DOLP. As wavelength increases, Rayleigh scattering (and its
288 polarized contribution) decreases rapidly, so the TOA polarized signal becomes dominated
289 by aerosol and surface. Around certain scattering angles, the aerosol-scattering
290 contribution and the surface-related contribution (including atmospheric transmission of
291 surface-reflected light) can be comparable and partially cancel. An SSA increase enhances
292 aerosol scattering and modifies the balance between these terms. For smaller scattering
293 angles the aerosol term tends to dominate, giving a positive Δ DOLP, whereas for larger
294 scattering angles the surface-related term becomes relatively more important, and the same
295 SSA perturbation can reduce DOLP, resulting in a sign reversal.

296 10. Figure 8 (a) and Figure 9 (a):

- 297 • What are the grids of latitude and longitude of these panels? Does the geolocation
298 exactly match with (b) and (c)?
- 299 • The figures are not labeled with lowercase letters.

300 Thank you for reminding. For Fig. 8, the spatial domain of panel (a) covers 16°E–24°E and
301 5°S–9°S. For Fig. 9, the spatial domain of panel (a) covers 20°W–4°W and 16°N–25°N.
302 The geolocation of panel (a) exactly matches that of panels (b) and (c) in both figures. We
303 have added this information to the corresponding figure captions, and added lowercase
304 letters (a), (b), and (c) to Figs. 8 and 9 in the revised manuscript.

305 11. L325-328: It would be interesting to compare the retrieved AOD with the
306 corresponding MODIS product, which adds more insights on the retrieval
307 performance when the algorithm is applied to DPC data. The same comment for
308 the following dust event.

309 Thank you for this helpful suggestion. We have added VIIRS AOD maps in the Supplement.
310 Comparisons between the retrieved AOD and the corresponding VIIRS AOD product for
311 both the biomass burning and dust events have also been conducted. The results show that

312 the spatial patterns of VIIRS AOD are highly consistent with our retrievals, demonstrating
313 good agreement in the overall distribution characteristics.

314 12. L334: Please refer to the last comment.

315 Thank you for the suggestion. As mentioned above, comparisons between the retrieved
316 AOD and the corresponding VIIRS AOD product for the dust event have also been added
317 in the manuscript.

318 13. L340-341: Looking at Figure 9, there is an obvious contrast in retrieved SSA
319 between the region (21-23°N, 16-17°W) and the region (19-20°N, 17-19°W), while
320 from the true color picture, the aerosols in these regions seem to be in the same type
321 (mineral dust). What's the reason for such a contrast in SSA? Is it an artifact of the
322 algorithm?

323 Thank you for this insightful comment. The apparent contrast in retrieved SSA between
324 the two regions is likely related to differences in cross-track viewing geometry rather than
325 changes in aerosol type. The two regions are located in different cross-track scan positions,
326 which may introduce discontinuities in viewing geometry and associated retrieval
327 sensitivities. Consistently, the retrieved AOD over the region (19–20°N, 17–19°W) is also
328 relatively lower, suggesting that the SSA contrast is coupled with changes in aerosol
329 loading and retrieval constraints.

330 14. L352-355: The global patterns retrieved here may not be quite comparable with the
331 MODIS, OMI and POLDER products from the cited studies due to the differences
332 in measurement period and wavelength. The comparison with the study of Dong et
333 al. (TGRS, 2024) seems to bring more insights since the retrievals are from the
334 same DPC measurements. Why don't the authors present the retrievals at 670 nm,
335 just the same wavelength showed by Dong et al. (2024), for a more straightforward
336 comparison?

337 Thank you for this insightful comment. We have added the global retrieval results at 565
338 nm and 670 nm in the Supplement, and compared our results with MODIS and Dong et al.
339 (2024) in the manuscript. Overall, the patterns of AOD, SSA, and DHR retrieved in this

340 study are consistent with those reported by Dong et al. (2024), demonstrating similar global
341 distribution characteristics. At the same time, some differences are observed. For example,
342 Dong et al. (2024) reported anomalously high AOD values over South America in October
343 2019, whereas both our results and the MODIS AOD show relatively low values in that
344 region. These comparisons and discussions have been incorporated into the revised
345 manuscript to provide a more rigorous evaluation.

346 15. L325: "... composed of..." → be composed of

347 Thanks for reminding. We have revised the expression in the manuscript.

348 Reference

349 Chen, C., Dubovik, O., Fuertes, D., Litvinov, P., Lapyonok, T., Lopatin, A., et al. (2020).
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363 directional polarimetric camera. *Remote Sensing*, 14(18), 4571.

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