Response to Review of Referee #3

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First of all, we would like to thank the anonymous referee for his/her valuable comments, which have helped to improve the manuscript. In the revised manuscript, we have tried to accommodate the suggested changes. All comments and recommendations are copied here as underlined texts.

The use of the fisheye lens is attractive because it gives the possibility to measure the sky brightness at all azimuthes and VZAs by taking one image. But this technique is very sensitive to the quality of the flat field and to the presence of a stray light. The authors use the ratio of measurements acquired at two different VZAs, i.e. the measured light intensity from the different parts if the image. This means that the uncertainties due to the flat field problem should be important.

Answer:

As the referee pointed out the quality of flat field is important. We have added the description about the quality of flat field in more detail including its uncertainties in page 212, line 27 as:

"In this study, we assumed there is no error induced from the quality of flat field, because we used a spirit level to confirm that horizontal axis of a photograph is to be parallel to the horizon. Uncertainty of the spirit is approximately 0.8 degree that may lead to small uncertainties of VZA and RAA estimation only in the pixels far from the image center. The pixels used in the aerosol retrieval were distributed around the image center, which made the uncertainties of VZA and RAA negligible."

Authors take the vignetting into account, but it is impossible to remove the vignetting effect absolutely perfectly. Uncertainties caused by this effect should be discussed.

Answer:

The vignetting effect is indeed difficult to be removed perfectly. We have added the more detailed description about the vignetting effect and an experiment for correcting the effect (page 197, line 9) as follows:

"The vignetting characteristics of the fisheye lens have been investigated by Saito et al. (2015). We tried to eliminate the effects of vignetting from the image digital counts by an experiment using integrated sphere and Halogen light source that enables to generate homogeneous light. In the experiment, the intensity of integrated light at an edge is usually lower by 1% than that at the center so that the vignetting correction parameter has such biases near the edge of photographs, which does not significantly influence the aerosol retrievals. Therefore, we assume that the vignetting effect is totally eliminated for our purposes." The most important problem which was not addressed in the paper is a stray light. The twilight sky brightness is highly nonuniform, with very bright segment near the horizon and the dark sky in the zenith area. When we take an image using fisheye lens any light scattered in the optics can cause the stray light in the darker part of the image. The stray light will affect both the normalized green channel measurements and the color ratios. The stray light problem should be investigated.

Answer:

A stray light from a bright part might affect on the digital counts in the dark part of the twilight sky. We have investigated the order of magnitude of a stray light effect on the digital counts. Accordingly we have added the followings in the manuscript (page 197, line 17).

"In order to use a digital camera with fisheye lens as a measurement instrument, we should comprehend the characteristics of fisheye lens. A stray light, which may affect the camera digital counts, is caused by multi-reflected light among the lenses and reflection on near-Lambertian surface, namely a plastic part installed in the equipped lens. The dynamic range of twilight sky brightness is large, and bright light might cause a stray light in dark part of the photograph. We have experimentally investigated the order of magnitude of a stray light effect on digital counts in twilight photographs. It was found that the stray light effect provided small biases, which became significantly smaller towered to larger angle from a bright light: approximately 1%, 0.1% and below 0.05% at angle of 1°, 5° and >15°, respectively, from the light source. The stray light effect is smaller than the CMOS noise. Thus, the stray light effects are neglected in this study."

Nothing has been told about the dark current. If it was not extracted it could become a significant source of uncertainty.

Answer:

We have added the following sentences (page 206, line 5):

"The dark current also leads negligible bias in digital counts in the twilight photographs used in this study: less than 0.5% (0.1%) for the camera signal corresponding to the twilight sky at VZA of 60° (88°)."

Nothing was told about the distortion corrections. The distortion can introduce uncertainties in the VZA and azimuth estimations.

Answer:

We appreciate the reviewer's comment. Our bibliographical survey about the lens distortion effect has been summarized and added in page 197, line 17 as follows:

"The distortion of a fisheye lens may lead to uncertainties in VZAs and RAAs estimation. Currently, several researchers investigated and showed that the recent lenses for consumers had very slight distortion, leading that a difference between ideal and distorted optical path was within a pixel (Schneider et al. 2009; Shahriar et al. 2006). Robaza et al. (2010) showed that the distortion effect for a Nikkor fisheye lens was considered negligible. For this reason, we assumed the lens distortion did not influence our results."

One and the same exposure time 8 sec was used for all measurements (page 197 line 8). The twilight sky brightness changes significantly from SZA 90° to SZA 96°. Is the CCD dynamic range large enough to register the maximal and minimal brightness? At least one plot with the exponential data and the appropriate measurement uncertainties should be presented. When the measurements were carried out at the VZA=88° the signal in the blue and the green channels should be quite low. It is necessary to show that the signal is still above the level of noise.

Answer:

In the previous manuscript, a description about the exposure time for twilight photographic observations was missing. We used the same exposure time 8 sec only in the CMF estimation experiment (page 197 line 8). Different exposure times were used for twilight photographic observations. We have added the following sentences in page 197, line 17:

"For photographic observations in the twilight, exposure times are optimized to sky brightness levels, which make the digital counts on the pixel used for the retrievals in a dynamic range of the camera. For example, we used the exposure time of 1/2048, 1/512 and 1/4 sec in the SZAs of 90°, 93° and 96°, respectively in clean atmospheric conditions."

The calibration factor is considered as independent of the wavelength. This should be discussed.

Answer:

It is our definition of the calibration factor that is independent of wavelength. Wavelength dependence is included in the CMFs. We have changed the sentences (page 197, line 18) accordingly, as follows:

"where I_k is channel-averaged spectral radiance, weighted by the camera spectral response of the channel k. The parameter c is the absolute calibration factor that can be defined as independent of wavelength, because the wavelength-dependence of CMOS detector is considered in the CMFs."

The real and the imaginary parts of the refractive index (page 204, line 25) as well as the coarse-fine particle volume ratio (page 199, line 20) were taken the same for the troposphere and the stratosphere. They are essentially different.

Answer:

We thank the reviewer for this comment. Our sensitivity tests indicate that the twilight sky color and brightness are not very sensitive to refractive indices of aerosol. The retrieved coarse-fine particle volume ratio represents that of tropospheric aerosol because contribution of variation in the stratospheric aerosol properties is small. We have added a discussion on error induced by this assumption in page 205, line 20 as:

"Aerosol optical properties, such as the refractive indices and the coarse-fine particle volume ratio, are assumed to be vertically homogenous through the entire atmosphere from the stratosphere to the troposphere. In general, aerosol optical properties in the troposphere and the stratosphere are essentially different. Most of stratospheric aerosol is sulfate or sulfuric acid, while that of tropospheric aerosol is highly variable. However, aerosol amount in the troposphere is dominant compared to that in the stratosphere, under the present, normal conditions. The retrieved optical property, namely coarse-fine particle volume ratio, is representative as tropospheric one. Furthermore, the twilight sky color and brightness are not very sensitive to the refractive indices of aerosol according to a sensitivity test, suggesting that the assumption of constant refractive indices leads to insignificant uncertainties. "

The authors presented the sensitivity tests (section 3.2) to show that the color ratios and the normalized green channel are sensitive to the stratospheric and tropospheric optical depths. Instead of this they should show that the proposed measurements (page 202, line 13–14) with the associated uncertainties contain enough information to retrieve the stratospheric and tropospheric optical depth and the coarse/fine fraction aerosol ratio. They should show the appropriate averaging kernels to demonstrate that it is possible to separate the stratospheric and tropospheric aerosol optical depths. The spectral halthwidths of the channels are quite large (80-100 nm). This should reduce the altitude resolution and bring uncertainties to the stratospheric optical depth determination. The state vector should be also reconsidered. Is it worth to try to retrieve the coarse/fine particle volume? The retrieval result does not show good correlation with the skyradiometer results (Fig. 9c). The coarse/fine particle volume ratio cannot be the same for the boundary layer, the troposphere and the stratosphere. To avoid too many parameters to retrieve it is better to use climatological values. Aerosol profiles were not retrieved in this study.

Answer:

As the referee suggests, we have investigated whether enough information is obtained from measurement to retrieve the three elements or not, investigating the averaging kernel. Figure A1 shows the averaging kernels in typical cases. Although the retrieved coarse-fine particle volume ratio does not have good correlation with skyradiometer results, the measurements have enough information to retrieve it, so that we do retrieve it in the present algorithm. We have added a discussion in the section 4 (page 207 line 21) as follows:

"In addition, the averaging kernel,

 $\mathbf{A} = \left[\mathbf{K}^T \mathbf{S}_{\mathbf{y}}^{\mathbf{\cdot}\mathbf{l}} \mathbf{K} + \mathbf{S}_{\mathbf{a}}^{\mathbf{\cdot}\mathbf{l}} \right]^{-1} \mathbf{K}^T \mathbf{S}_{\mathbf{y}}^{\mathbf{\cdot}\mathbf{l}} \mathbf{K} , \qquad (15)$

shows a sensitivity of retrievals to the true states, demonstrating whether the measurement with associate uncertainties contains enough information to retrieve the state vector or not (Rodgers, 2000). The diagonal elements of the averaging kernel are 0.94, 0.96 and 0.97 (0.99, 0.51 and 0.95) corresponding to tropospheric AOT, stratospheric AOT and coarse-fine particle volume ratio under the atmospheric condition whose tropospheric AOT is 0.1 (0.3), while the non-diagonal elements are relatively significantly small (below 0.05) except for the sensitivity of coarse-fine particle volume ratio on the true stratospheric AOT state (around 0.4) under large tropospheric AOT condition. Furthermore, The degree of freedom for signal (DOFS) given by trace of the A shows above 2.5 under the general atmospheric conditions. Therefore, it is reasonable to retrieve

the three state variables under clean atmospheric condition and at least tropospheric and stratospheric AOTs when AOT is large."



Figure A1 averaging kernels (Not shown in the manuscript)

Answer:

As the referee suggests we have added a figure of a priori aerosol vertical profile and description in page 199 line 8 as follows:

"Figure 3 shows a priori aerosol vertical profile."

Furthermore, the description about discussion of the uncertainty caused by this assumption has been added in Section 4.2 page 205, line 12 as follows:

"In general, aerosol vertical profiles are highly variable in the troposphere. The amount and vertical profile in the boundary layer varied according to atmospheric condition, and that in upper troposphere are also variable as typically seen in dust transport events. Considering their variability, we determined the possible ranges of the shape and scale parameters in the forward-model-error analysis."

In the chapter 3.1 some assumption about the aerosol extinction profile were made. It is desirable to include a figure where the used aerosol profile will be shown and to discuss what uncertainties can bring this a priory aerosol profile.



The term "chromaticity" is not correct. Better to use the term "color ratio".

Answer:

This has been corrected as suggested.

List: page 197, line21; page 200, line 3, 6, 21, 26; page 201, line 5; page 205, line 14, 21; page 206, line 13; captions in Figs. 3–5.

"was sensitive to twilight sky" (p. 193 line 24) should be "..twilight sky brightness" or "twilight sky intensity".

Answer:

This has been corrected as: "twilight sky brightness".

The measurement vector is determined only in Conclusions (p.211, line 14). It should be done earlier.

Following the suggestion, we add the follow sentences in page 202, line 3 as follows: "A measurement vector y is derived from twilight photographs taken with SZA of 90–96°. The color ratios (R/G, B/G) and the normalized brightness (G_n) around solar direction (the VZA of 60–88° and the RAA of 0–30°) were used in the elements of the measurement vector."

Instead of this, the description of the measurement vector in conclusion has been shortened (page 211, line 14) as:

"The measurement vector was set to be the normalized brightness and the color ratio around the solar direction derived from camera RAW data in RGB channels.".

Figs 3,4,5 and 9 are too small.

We made the font size of the axis labels and annotations larger. We believe it helps the readers.



Figure. 3



Figure 4.



Are the units in Figs 6–7 percents?

Answer:

Figs 6–7 denote RMS error for color ratios and normalized brightness, whose units are not percent but dimensionless, absolute values. To avoid misunderstandings, we have added the description "(**absolute values**)" in captions of Figs. 6–7.

The authors propose to use the twilight measurements during the polar night (e.g. page 194, line 20). They should speak about the polar twilight because there is no twilight during the polar night. Before to claim that such observations can be useful in the polar regions it is necessary to show at which latitude and how long time the solar zenith angle varies in the desirable range.

Answer:

According to the suggestions, we have corrected "the polar night" to "the polar twilight" in page 194, line 20. In addition, we have changed the description from page 212, line 29 to page 213, line as follows:

"Particularly in polar region in winter, aerosol measurements are very limited, and the proposed twilight photometry method should be helpful to increase the availability of aerosol measurements."