Point-by-point response to the reviews, a list of all relevant changes made in the manuscript of "A simple method for retrieval of dust aerosol optical depth with polarized reflectance over oceans" by Wenbo Sun et al.

Response to Referee 1

General comments: The current passive satellite instruments can only measure the total intensity of solar radiation, which couldn't detect the optically super-thin cirrus clouds due to the uncertainty in surface reflection. This manuscript proposes a novel and robust algorithm of using passive polarimeter and can detect the super-thin clouds and dust aerosols. The optical depth of dust aerosols in the neighborhood of the backscatter angle can be also retrieved by using the degree of polarization of reflected light, regardless of the reflecting surface conditions. This novel method is expected to be used in the planned NASA-Korea CubeSat mission for detecting the super-thin clouds and dust aerosol over midlatitude and tropical oceans. Overall, I think the idea and algorithm proposed by this manuscript are innovative and the English writing is fine, and I recommend this manuscript is appropriate for publishing after minor revision.

The authors thank this reviewer for the helpful comments. The manuscript was revised following the comments rigorously.

Minor comments: 1. Page 2, lines 81-83: "In the modeling, we assume the dust particles are nonspherical debris aggregates with a refractive index of 1.4 + 0.01i (Zubko >et al. 2006; 2009; 2013)" Please explain briefly the reason of the refractive index (1.4 + 0.01i) of dust particles assumed in the model, whether the selection of different refractive index will affect the modeling results.

Since dust refractive index has uncertainty due to different components and moisture, we chose this representative refractive index just for demonstration of the idea of the method, this will affect the modeling result a little bit (especially when imaginary part is very big), but not affect any conclusions in the paper.

2. Page 2, lines 79-81: "Also shown in the figure are results from 12 days of PARASOL level-1 reflectance and level-2 ocean aerosol and clouds data (Deschamps et al. 1994; Buriez et al. 1997; Tanre et al. 2011) across May to August of 2006." Page 3, Figure 1, line 107: "12 days of PARASOL data in May-August, 2018 are used for this study." The date of PARASOL data used in this manuscript should be the same. Please check it.

This is a typo, "2018" should be "2006". We corrected it.

Response to Referee 2

The paper "A simple method for retrieval of dust aerosol optical depth with polarized reflectance over oceans" is aimed at the development of the technique to retrieve dust aerosol optical depth using spaceborne observations. Unfortunately I can not recommend this paper for publication. Actually the authors do not describe their technique to solve the inverse problem in *the paper. They also do not show the validation results. They a state that there is no robust method for remote sensing of aerosols based on polarized radiation measurements. This is not true (please, see the papers by Dubovik, Hasekamp, Herman, etc.).*

The authors thank this reviewer for the helpful comments and followed the reviewer's comments to correct the manuscript rigorously.

Actually the authors do not describe their technique to solve the inverse problem in the paper. They also do not show the validation results.

Our Fig. 1 has clearly showed that dust aerosol OD can be simply retrieved using the DOP in the neighborhood of backscatter angle. PARASOL data in the same figure validated the results. However, for a detailed algorithm, we are planning a full article after our instrument's data are obtained. This short letter has no intention to report full technical algorithm, but a simple idea.

They a state that there is no robust method for remote sensing of aerosols based on polarized radiation measurements. This is not true (please, see the papers by Dubovik, Hasekamp, Herman, etc.).

To follow this comment, we changed our statement to "However, the retrieval method of remote sensing of aerosols based on polarized radiation measurement is still in progress (Dubovik et al. 2019)." And cited:

Dubovik, O., Li, Z., Mishchenko, M. I., Tanré, D., Karol, Y., Bojkov, B., Cairns, B., Diner, D. J., Espinosa, W. R., Goloub, P., Gu, X., Hasekamp, O., Hong, J., Hou, W., Knobelspiesse, K. D., Landgraf, J., Li, L., Litvinov, P., Liu, Y., Lopatin, A., Marbach, T., Maring, H., Martins, V., Meijer, Y., Milinevsky, G., Mukai, S., Parol, F., Qiao, Y., Remer, L., Rietjens, J., Sano, I., Stammes, P., Stamnes, S., Sun, X., Tabary, P., Travis, L. D., Waquet, F., Xu, F., Yan, C., and Yin, D.: Polarimetric remote sensing of atmospheric aerosols: instruments, methodologies, results, and perspectives, J. Quant. Spectrosc. Radiat. Transfer 224, 474-511, doi:10.1016/j.jqsrt.2018.11.024, 2019.

This review article reports the current status of polarization retrieval algorithms.

Other changes

We also changed the presentation VZA angle range of Fig. 1 to make the figure more symmetric. (No data are changed).

We inserted an Acknowledgment at end of the paper.

Formatted: Font: 16 pt, Bold

Formatted: Font: 16 pt, Bold

Formatted: Font: 12 pt, Bold

Formatted: Normal, Left

Formatted: Font: Bold

Formatted: Font: 12 pt, Bold

A simple method for retrieval of dust aerosol optical depth with polarized reflectance over oceans

Wenbo Sun[1,3,*], Yongxiang Hu[2], Rosemary R. Baize[2], Gorden Videen[3,4], Sungsoo S. Kim[3], Young-Jun Choi[5], Kyungin Kang[6], Chae Kyung Sim[3], Minsup Jeong[5], Ali Omar2, Snorre A. Stamnes[2], and Evgenij Zubko[3]

[1]Science Systems and Applications Inc, Hampton, VA 23666, USA
[2]NASA Langley Research Center, Hampton, VA 23681, USA
[3]Kyung Hee University, Yongin-shi, Kyungki-do 17104, Korea
[4]US Army Research Lab, Adelphi Maryland 20783, USA
[5]Korea Astronomy and Space Science Institute, Yuseong-gu, Daejeon 34055, Korea
[6]Korea Advanced Institute of Science and Technology, Daejeon 34141, Korea
[*]Enterprise Parkway, Hampton, VA 23681, USA. Email: wenbo.sun-1@nasa.gov

Abstract. Our previous study shows that the angle of linear polarization (AOLP) of solar radiation that is scattered from clouds at near-backscatter angles can be used to detect super-thin cirrus clouds over oceans. Such clouds are too thin to be sensed using any current passive satellite instruments that only measure light's total intensity, because of the uncertainty in surface reflection. In this report, we show that with a method similar to the super-thin clouds detection algorithm, dust aerosols may also be detected and differentiated from clouds. We also show that the degree of polarization of reflected light can be used for retrieving the optical depth of dust aerosols in the neighborhood of the backscatter angle, regardless of the reflecting surface conditions. This is a simple and robust algorithm, which could be used to survey dust aerosols over midlatitude and tropical oceans.
Key words: Polarized reflectance; degree of polarization; dust aerosol; retrieval; remote sensing.

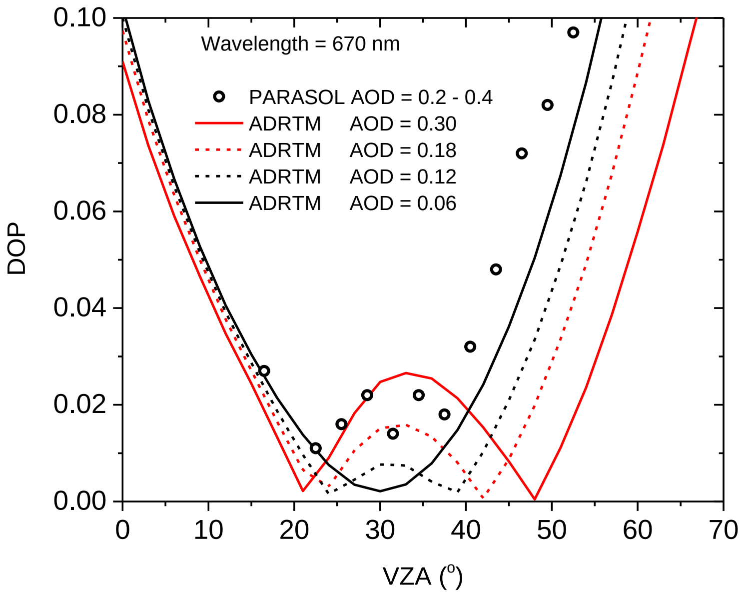
A NASA-Korea CubeSat mission is currently under preparation by NASA Langley Research Center, the Korea Astronomy and Space Science Institute (KASI), and Kyung Hee University of Korea. We plan to use polarimeters on two CubeSats to detect the super-thin clouds over global oceans and dust aerosols over oceans and land around the Korean peninsula. The polarimeters will be developed by KASI, that are modified versions of the Polarimetric Camera (PolCam) developed by KASI for the Korea Pathfinder Lunar Orbiter (KPLO). This planned polarimeter-on-CubeSat mission will measure the polarization features of scattered light from clouds and aerosols to identify the super-thin clouds and dust aerosols over oceans and retrieve their optical depth.

Our previous works (Sun et al. 2014; 2015) show that distinct features exist in the angle of linear polarization (AOLP) of solar radiation that is scattered from clouds at near-backscatter angles. At these angles the dominant electric field from clear-sky oceans is nearly parallel to the Earth surface. However, when clouds are present, this electric field can rotate significantly away from the parallel direction. Our modeling results suggest that this polarization feature can be used to detect super-thin cirrus clouds having an optical depth of only ~0.06 and super-thin liquid water clouds having an optical depth of only ~0.01. Such clouds are too thin to be sensed using any current passive satellite instruments that only measure light's total intensity, because of the uncertainty in surface reflection.

Similar to super-thin clouds, aerosols such as dust particles also affect surface remote sensing and global climate significantly. The optically thin aerosols are also very difficult to detect even over a dark surface condition such as oceans. In optical remote sensing of aerosols, how to distinguish between surface and atmospheric contributions to the TOA reflectance keeps on a problem. Because of aerosols' small optical thickness, the uncertain effect of ocean surface reflection to the light cannot be well quantified when using total reflectance as a measurement to the aerosols, even with multiple angles and wavelengths in measurements (Dubovik et al. 2019). Several methods are proposed to separate the atmospheric and the surface contributions (e.g., Kaufman et al. 1997), but no ideal method is reported to date. The use of the degree of polarization of the radiance is thought to have great potential for aerosol retrieval (Herman et al., 1997). However, ~~no robust method for remote sensing of aerosols based on polarized radiation measurement is reported to date~~ the retrieval method of remote sensing of aerosols based on polarized radiation measurement is still in progress (Dubovik et al. 2019). Based on our modeling results, we will propose a novel method of using passive polarimetric instruments to detect dust aerosols over oceans in this paper.

Unpolarized solar radiation can be polarized by surface reflections as well as by scattering from atmospheric molecules and particles. When sunlight propagates through a clear atmosphere and is scattered back toward the Sun, the resulting signal is nearly unpolarized when the solar zenith angle (SZA) is less than ~40^o (Sun and Lukashin, 2013). By considering a longer solar wavelength, such as 670 nm, the contribution of molecular scattering is small. Unlike total radiance (*I*), the degree of polarization (DOP) and angle of linear polarization (AOLP) of the reflected sunlight are insensitive to surface roughness and absorption by atmospheric water vapor and other gases (Sun and Lukashin, 2013). This insensitivity makes the polarization measurement robust for different environmental conditions, even when the detected components are within the lower layers of the atmosphere. For example, super-thin water clouds close to the surface of the Earth that cannot be detected using 1.38µm radiance can be identified by the polarization properties of light backscattered from them. Method for using AOLP feature to detect super-thin clouds is reported in Sun et al. (2014). The method for using polarized reflectance to retrieve the optical depth of super-thin clouds is reported in Sun et al. (2015). Sun et al. (2015) reports that the optical depth of super-thin clouds can be retrieved at near-backscatter angles without the effect of background reflection.

Our studies show that the polarization of backscattered light can also be applied to aerosol remote sensing. Figure 1 shows the modeled DOP of reflected sunlight at 670 nm from dust aerosols over oceans. Also shown in this figure are results from 12 days of PARASOL level-1 reflectance and level-2 ocean aerosol and clouds data (Deschamps et al. 1994; Buriez et al. 1997; Tanre et al. 2011) across May to August of 2006. In the modeling, we assume the dust particles are nonspherical debris aggregates with a refractive index of 1.4 + 0.01i (Zubko et al. 2006; 2009; 2013). The aerosols are within a 1-km layer over ocean surface. The aerosol size distribution and single-scattering property calculation follow those reported in Sun et al. (2013). The PARASOL measurements obtained over Atlantic Ocean area (0^oN -35^oN and 0^oW -60^oW) are used to capture Sahara dust over oceans. Only those data with an AOD = 0.2 – 0.4 from the PARASOL OC2 dataset are used for comparison with the modeled results. We can see that the modeled DOP of reflected light is a strong function of dust AOD. At the near-backscatter viewing angles, DOP of reflected light monotonically increases with the AOD. This means that when using a polarimeter at these observation angles, AOD can be retrieved from the DOP of the backscattered light. The PARASOL data well prove the modeled results at the near-backscatter angles. However, significant difference is found at other viewing angles, with unknown reasons. Figure 2 shows the AOLP of the reflected light from the ADRTM (left panel, AOD = 0.3) and the PARASOL (right panel, AOD = 0.2 – 0.4). We can see that at near-backscatter angles, AOLPs from the model and satellite data are significantly different. The PARASOL results have a glory pattern at near-backscatter angles that indicates transparent cloud particles such as water droplets or ice crystals (Sun et al. 2014; 2015). This means the PARASOL OC2 aerosol product has clouds contamination. Thus, the aerosol properties in the PARASOL OC2 may not be very reliable for this case.



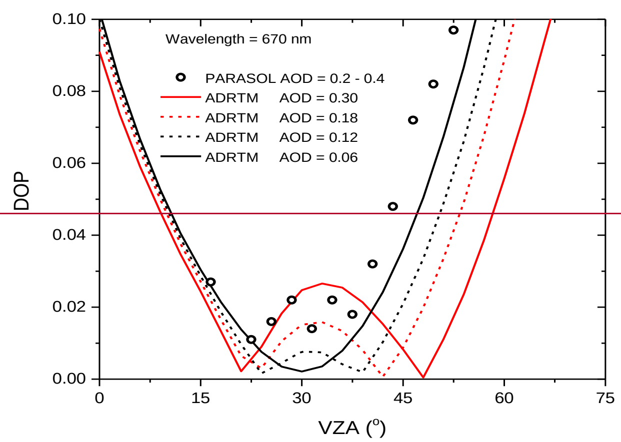


Figure 1. At near-backscatter angles [For this case, it is at viewing zenith angle (VZA) = ~20-40º, and relative azimuth angle (RAZ) = ~170-180º], the DOP of light from dust monotonically increases with the AOD of dust aerosols. In this modeling, the adding-doubling radiative transfer model (ADRTM) developed in Sun and Lukashin (2013) is used. The wavelength is 670 nm, the

solar zenith angle (SZA) is 30°, and wind speed over ocean surface is 7.5 m/s. Also shown in this figure are the PARASOL measurements obtained over Atlantic Ocean area (0°N -35°N and 0°W - 60°W) that has Sahara dust. 12 days of PARASOL data in May-August, 2006018 are used for this study. The results are for a RAZ of 177°.

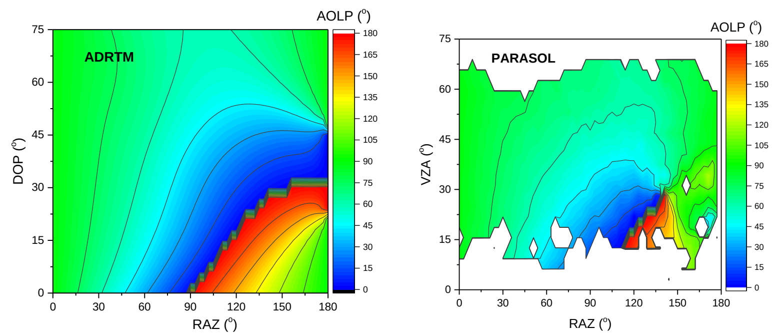


Figure 2. Same as in Fig. 1, but for the AOLP of the reflected light from the ADRTM (left panel, AOD = 0.3) and the PARASOL (right panel, AOD = 0.2 – 0.4).

In summary, our modeling results show that the DOP of scattered sunlight can be used to detect aerosols. Figure 2 also shows that the AOLP of scattered light from nonspherical dust particles are very different from that of light scattered by clouds as reported in Sun et al. (2014; 2015). This can be used to differentiate aerosols from clouds, regardless of the ocean surface conditions. This is a simple and robust algorithm, which could be used to survey dust aerosols over midlatitude and tropical oceans, as planned by the NASA-Korea CubeSat mission for the detection of super-thin clouds/aerosols.

Acknowledgment

This work was supported by NASA Langley Research Center's "Lidar Data Analysis and Theory" project. Wenbo Sun thanks Patricia Lucker of Science Systems and Applications, Inc (SSAI) for the management help during this work.

References

1. Buriez, J. C., Vanbauce, C., Parol, F., Goloub, P., Herman, M., Bonnel, B., Fouquart, Y., Couvert, P., and Sèze, G.: Cloud detection and derivation of cloud properties from POLDER, Int. J. Remote Sens., 18, 2785–2813, 1997.
2. Deschamps, P. Y., Breon, F.-M., Leroy, M., Podaire, A., Bricaud, A., Buriez, J.-C., and Sèze, G.: The POLDER mission: Instrument characteristics and scientific objectives, IEEE Trans. Geosci. Rem. Sens., 32, 598-615, 1994.
2.3. Dubovik, O., Li, Z., Mishchenko, M. I., Tanré, D., Karol, Y., Bojkov, B., Cairns, B., Diner, D. J., Espinosa, W. R., Goloub, P., Gu, X., Hasekamp, O., Hong, J., Hou, W.,

Knobelspiesse, K. D., Landgraf, J., Li, L., Litvinov, P., Liu, Y., Lopatin, A., Marbach, T., Maring, H., Martins, V., Meijer, Y., Milinevsky, G., Mukai, S., Parol, F., Qiao, Y., Remer, L., Rietjens, J., Sano, I., Stammes, P., Stamnes, S., Sun, X., Tabary, P., Travis, L. D., Waquet, F., Xu, F., Yan, C., and Yin, D.: Polarimetric remote sensing of atmospheric aerosols: instruments, methodologies, results, and perspectives, J. Quant. Spectrosc. Radiat. Transfer 224, 474-511, doi:10.1016/j.jqsrt.2018.11.024, 2019.

~~3.~~4. Herman, M., Deuze, J. L., Devaux, C., Goluob, P., Breon, F. M., and Tanre, D.: Remote sensing of aerosols over land surfaces including polarization measurements and application to polder measurements, J. Geophys. Res., 102, 17,039-17,050, 1997.

~~4.~~5. Kaufman, Y. J., Wald, A. E., Remer, L. A., Gao, B. C., Li, R. R., and Flynn, L.: The modis 2.1 μm channel correlation with visible reflectances for use in remote sensing of aerosol. IEEE Trans. Geosci. Remote Sens., 350, 1286-1298, 1997.

~~5.~~6. Sun, W., and Lukashin, C.: Modeling polarized solar radiation from ocean-atmosphere system for CLARREO inter-calibration applications, Atmos. Chem. Phys., 13, 10303-10324, https://doi.org/10.5194/acp-13-10303-2103, 2013.

~~6.~~7. Sun, W., Videen, G., and Mishchenko, M. I.: Detecting super-thin clouds with polarized sunlight, Geophy. Res. Lett., 41, 688-693, https://doi.org/10.1002/2013GL058840, 2014.

~~7.~~8. Sun, W., Baize, R. R., Videen, G., Hu, Y., and Fu, Q.: A method to retrieve super-thin cloud optical depth over ocean background with polarized sunlight, Atmos. Chem. Phys., 15, 11909-11918, https://doi.org/10.5194/acp-15-11909-2015, 2015.

~~8.~~9. Tanre, D., Breon, F.-M., Deuze, J. L., Dubovik, O., Ducos, F., Francois, P., Goloub, P., Herman, M., Lifermann, A., and Waquet, F.: Remote sensing of aerosols by using polarized, directional and spectral measurements within the A-train: The PARASOL mission, Atmos. Measur. Tech., 4, 1383-1395, https://doi.org/10.5194/amt-4-1383-2011, 2011.

~~9.~~10. Zubko, E., Shkuratov, Y., Kiselev, N. N., and Videen, G.: DDA simulations of light scattering by small irregular particles with various structure, J. Quant. Spectrosc. Radiat. Trans., 101, 416–434, 2006.

~~10.~~11. Zubko, E., Kimura, H., Shkuratov, Y., Muinonen, K., Yamamoto, T., Okamoto, H., and Videen, G.: Effect of absorption on light scattering by agglomerated debris particles, J. Quant. Spectrosc. Radiat. Trans., 110, 1741–1749, 2009.

~~11.~~12. Zubko, E., Muinonen, K., Munoz, O., Nousiainen, T., Shkuratov, Y. Sun, W., and Videen, G.: Light scattering by feldspar particles: Comparison of model agglomerate debris particles with laboratory samples, J. Quant. Spectrosc. Radiat. Trans., 131, 175-187, 2013.