

Interactive comment on “Aerosol Optical Depth (AOD) retrieval using simultaneous GOES-East and GOES-West reflected radiances over the Western US” by H. Zhang et al.

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We thank reviewer #1 for the helpful comments and have made a lot of revisions on the manuscript following the suggestions.

Following are the response to the comments:

The manuscript provides a new retrieval approach for aerosol optical depth using geostationary satellites. The overlap of GOES-East and Goes-West is used to apply a hybrid retrieval for pixel where both satellites give radiance measurements at different geometry. The most significant improvement is the increased

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number of valid retrieval pixel based on the fact that geometries insensitive to AOD of one sensor are covered by the second sensor with different geometry. This method requires a precise estimation of surface BRDF and inter-calibration of both sensors. Both issues have been discussed in the manuscript. Results are compared to AERONET observations.

The approach of a hybrid AOD retrieval using two satellites is a very innovative idea potentially improving routine AOD retrievals and worth to be published. However, in my opinion the manuscript lacks of three issues which have to be reassessed in detail before publishing the manuscript. First the sensitivity of AOD retrieval to the geometry was misinterpreted. Second, a discussion on uncertainties in the retrieved AOD is missing. And the explanation of the retrieval algorithm has to be improved.

Below, I compiled a list of comments which have to be considered in a revised version of the paper. There might be some contradictory statements resulting from my misinterpretation of the text when first reading. I am sure the authors will know how to weight in such cases and how to improve the text to avoid misinterpretations by other readers.

1 Major comments

Sensitivitiy to AOD:

The whole argumentation why the retrieval is not sensitive to AOD for large scattering angles is wrong. The authors claim the anisotropic BRDF with higher reflectance in backscattering geometry (hot spot) causes the problems (e.g., p7957, 7 and p7952, 10 and p7964 24). This is only half the truth. As can be seen in Figure 7 surface reflectance does not change dramatically but the sensitivity does for scattering angles of about 90°. Lower scattering angles (forward scat-

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tering) gives higher sensitivity to AOD than high scattering angles (backscatter geometry). This is not due to surface BRDF. This is due to the shape of the scattering phase function of aerosol particles. You may use a Mie-tool and calculate the scattering phase function for your given aerosol size distribution. It comes out that the scattering phase function increases significantly for scattering angles below 90° . Especially for the fine fraction which is assumed to have twice the volume concentration than the coarse fraction and thus by far the strongest radiative impact. This sharp threshold of 90° perfectly fits to your calculation of Figure 7.

Due to the argumentation of the authors, the focus of the retrieval is to correctly estimate surface BRDF. Sure this is quite important, but scattering properties of aerosol are very important as well. Please revise the manuscript with regard to the significance of aerosol scattering. First a plot of the scattering phase function would help. Second it might be worth to check how sensitive the retrieval is to aerosol optical properties. Is a Henyey-Greenstein approximation used or Mie-calculations? What if the aerosol type is changed in the calculation of LUTs? Especially dust particles are mostly nonspherical and will show enhanced backscattering.

The phase function is plotted in the in the revised version, which is calculated using Mie theory. A paragraph is added in the introduction:

Another important reason for the high sensitivity of TOA reflectance to AOD in the forward direction is that the aerosol phase function is much larger in the low scattering angles. As shown in Fig. 3, the scattering phase function increases significantly for scattering angles below 100° , which coincides with the increase of the TOA reflectance sensitivity vs. AOD in the same scattering angles shown in Fig. 2.

The sensitivity of the AOD retrieval on aerosol model choice has been analyzed previously in Zhang et al., 2011, which shows an error of 25% in AOD retrieval can be

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resulted from uncertainty in aerosol model. This sentence was added in the paper.

Uncertainties:

A detailed discussion of retrieval uncertainties is missing.

We added a section (Sect. 5.2) on uncertainty.

The only validation is the comparison with AERONET data. But still this does not tell much about the uncertainties as the AERONET data may have uncertainties as well. Additionally this comparison is not presented well and summarized with "...results compare well to the AERONET AOD with correlation coefficients of 0.67-0.81 and the RMSEs of 0.06- 0.07." This is all relative. Correlation coefficients do not tell anything about an agreement only on correlation. Also an overestimation of factor 2 or 100 may have a correlation of 1.0. The RMSE is more meaningful. But here you have to consider the mean AOD values. RMSE of 0.06 for mean AOD of about 0.1 is a difference of more than 50%. This is not quite well in my opinion. In this regard, the discussion of Figure 8 and the regressions is not sufficient. As stated in one of the minor comments below, there seem to be systematic offsets,... which have to be discussed.

In the revised version, we added another criterion in the validation: expected error (EE) of $\pm(0.05 + 0.15\tau)$, which is adopted from MODIS AOD validation over land (Levy et al., 2010). The percentage of AOD retrievals falls within EE is more than 74% for the three sites, which is above that of MODIS AOD (68%). In this respect, the hybrid GOES AOD is as accurate as MODIS AOD. According to this criterion, the evaluation at low AOD is more focused on absolute values. For $\tau = 0.1$, the EE is ± 0.065 . Our RMSE of 0.06-0.07 is of similar magnitude.

Further, there are a lot of filters and screws in the algorithm which may affect the retrieved AOD. E.g. mean AOD in section 4.1, sensitivity quantity in 4.4. and several filters in 4.2. How does the choice of these thresholds affect the AOD?

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There might be some systematic biases due to the filters.

These are for the better AOD retrievals. The AOD retrieval accuracy will be lower if we relax those thresholds.

The average AOD is obtained from the retrieval in the geometries that TOA reflectance are most sensitive to the AOD variation. Therefore, the error of average AOD is small. We use low AOD days with $AOD < 0.3$ to retrieve surface BRDF to reduce the influence of AOD on surface BRDF retrieval. Such days have (1) high signal (surface) to noise (atmosphere) ratio; (2) low AOD variation; (3) small error from single aerosol model. If we increase the threshold of 0.3, we can have more influence of aerosol on surface BRDF retrieval and therefore larger errors in surface BRDF and AOD retrievals.

The filters in 4.2 are designed to remove outliers that caused by cloud/cloud shadow or high AOD variation contamination to the BRDF retrieval. The thresholds are based on observation of the data. We added in the revised paper the reasons for choosing such thresholds:

For threshold of (2) filter in Sect.4.2:

The value of the threshold is chosen through observation of surface reflectance variation from day to day. For a given observation time, the variation is usually observed to be about 10% or 20% and mostly below 0.03 or 30%. Therefore, variation larger than the threshold is most likely to be introduced by cloud, cloud shadow or large AOD variation and such data should be removed.

For threshold of (3) filter in Sect.4.2:

Similar to the previous one, the threshold is also chosen through the observation of the data: as shown in Fig. 2 and later in Fig. 11, the variation of surface reflectance in half hour is usually small and mostly less than 0.02 or 20%.

Using higher thresholds can introduce larger error from cloud/cloud shadow or AOD variation. Using lower thresholds can remove data points that are within normal varia-

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tion.

I know aerosol retrievals are difficult and I encourage your work. But this also means uncertainties have to be shown clearly even if they are high. In my point, it would be sufficient to estimate an uncertainty with respect to uncertainties in surface reflectance, aerosol scattering properties and radiance calibration of the sensors.

An uncertainty analysis is added (section 5.2).

Inter-calibration:

Similar to above, I appreciate the inter-calibration work but think it has to be discussed better as a wrong calibration will bias your AOD significantly. First, only one single point, Boulder, is used for the inter-calibration. How other locations behave?

Other locations should behave the same. The calibration coefficients are determined by the properties of the detectors but not by locations, since the same detectors are used to scan all the locations in the image.

Second, what does mean Boulder is located almost midway? The deviation from perfect midway may be the reason for the 5% difference.

Boulder is at 105.006°W and midway is 105°W . The difference is less than 1 km or 1 pixel of GOES channel 1 image. The difference should not be noticeable.

Third, why GOES-East is the reference sensor? GOES-West might measure the truth. Who is right West or East?

A paragraph is added to clarify this issue:

Here, the GOES-East (GOES-12) is assumed to be more accurate and the TOA reflectance of GOES-West (GOES-11) is corrected toward it. This is because GOES-12 is launched more than one year later than GOES-11 and GOES-12 also has longer

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period of star-based vicarious calibration sequence, i.e. GOES-12 has the sequence starting from 2003 while GOES-11 has the sequence starting from 2006 (NOAA GOES Calibration, 2011).

And finally, at P7951, 9: a precision of 1% of the sensors is mentioned. This does not fit to the factor of 0.95 obtained in the inter-calibration. This has to be discussed.

It has been changed to "The radiance calibration between detectors on the same satellite imager has less than 1% difference."

Due to this high uncertainty of 5% I suggest to investigate how this will bias the retrieved AOD.

A paragraph is added for this:

As will be shown in Sect. 6, the GOES sensors have a calibration error about 5%, which can introduce uncertainty in AOD retrieval. However, since the surface reflectance is also retrieved from the same GOES measurements, the AOD error can be partially compensated. For example, an over-estimate of TOA reflectance can also introduce an over-estimate in surface reflectance and therefore the over-estimate of AOD can be reduced. In this case, an over-estimate (under-estimate) of TOA reflectance of 5% can introduce an over-estimate (under-estimate) of surface reflectance of 8%, which will be shown in Sect. 6. Simulations were performed by perturbing TOA reflectance by 5% and surface reflectance by 8% correspondingly for different geometries, surface reflectance, and AOD. AOD was retrieved using the perturbed inputs and compared with the original AOD. The results show that the uncertainty from calibration is about 3% for low AOD (< 0.3), and about 10% for high AOD (~ 1.0).

Description of retrieval algorithm:

It is quite hard to understand the retrieval algorithm when first time reading. This can be improved by little restructuring. Here are some suggestion which

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came into my mind when reading. First I suggest to add a brief road map before starting to describe the algorithm in detail. Here you can motivate why the single steps 4.1, 4.2,.. have to be taken.

Added in the introduction: *The algorithm first makes an estimate of average daily AOD from GOES-MAIAC retrievals with best quality. Surface BRDF shape is updated using the timeseries of TOA reflectance and average daily AOD on the day with low daily AOD. The updated BRDF shape is used as a reference in the following day retrieval. AOD and surface reflectance are then retrieved simultaneously using two satellites measurements at the same time.*

and in the beginning of Sect. 4:

As already introduced in the sect. 1, several steps are taken in the algorithm for each pixel: (1) Daily average AOD is estimated for each pixel using GOES-MAIAC AOD retrieval algorithm with best quality. Low daily AOD days are selected for BRDF update. (2) A time series of surface reflectance is retrieved using the daily average AOD and TOA reflectance for one to three consecutive low AOD days. (3) This surface reflectance time series then used to retrieve surface BRDF. In low AOD days, surface reflectance can be retrieved more accurately, since they tend to have high signal to noise ratio and less interference of AOD model choice. Further more, low AOD days also have less AOD temporal variability and average daily AOD can be used without much potential errors. (4) The surface BRDF shape is used as a reference for the following day surface reflectance and AOD retrieval at each observation time. In this step, surface reflectance is assumed to be different from the previous day but has same BRDF shape. Because of two TOA reflectance measurements from the satellites, both surface reflectance and AOD can be retrieved at the same time. This can potentially improve AOD retrieval accuracy in period when surface reflectance changes rapidly from one day to another.

One example is section 4.1 the part explaining the sensitivity study (p 7956, 8-

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24). It was not introduced or motivated why now AERONET data is analyzed and a clear day AOD threshold is justified. This does not fit into the reading fluency as I expected a complete description of the algorithm first. Such a sensitivity study may be conducted after the description of the whole algorithm or in advance by defining clear sky conditions.

This part was moved to the uncertainty section (sect. 5.2)

Also section 4.4. come without introduction of the problem.

Added at the beginning of Sect. 4.4:

As mentioned before, the surface reflectance is found to be changing from day to day with a magnitude about 10% to 20%. Therefore, the current surface BRDF is not assumed to be the same as the one retrieved in the last step, but is assumed proportional to the one updated in the previous step instead: ...

A road map in advance and a short introduction, motivation of each step of the algorithm description would help a lot.

Some comments resulting from my misunderstanding of the algorithm may follow in the minor comments. Please consider these comments to improve the description of the algorithm.

Reflectance or reflectivity, surface or TOA:

The use of reflectivity properties is not consistent throughout the manuscript. Mostly reflectance is used but not at P7956, where surface reflectivity is discussed. Please stick to one, reflectivity or reflectance, unless there is a physical difference in between. Then exactly define what is meant with both quantities.

Changed to reflectance.

Further, sometimes "surface" or "TOA" is used together with reflectance but again not consistently. At some occasions "surface" or "TOA" is missing and it

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is not clear if the authors refer to the surface or TOA reflectance. This makes an understanding of the algorithm unnecessary difficult. Please add "surface" or "TOA" always even if it is repeated again and again.

Changed.

Figures

The labelling of most figures (4, 8, 9, 10, 11) is too small and has to be enlarged.

Changed. However, in the scatter plot (Fig. 7 in the revised version), we don't have enough space for enlarge the fonts much.

2 Minor comments

P7946, 17: What UCSP stands for?

Added:

UCSB (University of California Santa Barbara)

P7946, 21: "coincidences with AERONET" is too specific for the abstract and coincidence is not the right word implying, that AOD also matches. Better write: "For single observation areas the number of valid AOD data increases..."

Changed.

P7947, 22: SEVIRI provides also a rapid scan service with 5 min temporal resolution for a smaller area of Europe.

Added:

...and it also provides a rapid scan service with 5 minutes temporal resolution for a smaller area of Europe (EUMETSAT, 2013).

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P7948, Fig. 1: There is no need to show both morning and afternoon. Only one sketch is sufficient. The definition of the geometry does not change at noon. The sensitivity to surface reflectance is illustrated in Fig. 7.

Removed the afternoon sketch.

Instead of two sketches better show the scattering angle for both satellites and selected spots at the surface (image center, mid and high latitudes, in and outside the overlap region) over an entire day. Similar to Fig. 7c. This plot can be used to discuss the threshold of extreme viewing geometries of the mentioned prior work better.

Added.

Further, symbols are too small. One single sketch can be printed larger. This would help to identify the symbols as well. For (a): the two arcs for Φ_w and Φ_e look like one. I first thought Φ_w is the entire arc. Please separate.

Changed.

P7949, 3: Are there any references discussing and quantifying the rapid change of surface reflectance. It would be helpful to read the numbers here again and get a feeling for this issue.

We did the analysis in Zhang et al., 2011. The following text is added:

For example, a change of surface reflectance from 0.11 to 0.14 in a 28-day period was observed at 16:45UTC at GSFC site in the fall (Zhang et al., 2011).

P7949, 4: Do not forget to mention snow.

Added.

P7950, 1-8: The part starting with "It is found... the BRDF shape." should be removed from the introduction. It already summarizes findings which will be

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shown later. At this point the statements are not convincing as the sensitivities have not been shown yet. This part can easily be converted into a road map of the retrieval algorithm.

Removed.

A brief description of the algorithm is added here.

P7950, 22: "be" change to "are"

Changed.

P7951, 9: 1% precision does not fit to the factor of 0.95 obtained in the inter-calibration. This has to be discussed.

The text has been changed. It is 1% difference between detectors of single satellite.

P7951, 5: Are both pairs of satellites used in this study? If yes, change "should" to "are". Otherwise it should be mentioned, that this study only uses 11 and 12.

Added "In this study, GOES-11 and GOES-12 data are used."

P7951, 9: I do not understand what is meant with an exponential change of calibration over time and how this can be allowed. Please specify this argument.

The text is changed to "... the sensor calibration changes exponentially over time due to the degradation of the sensor sensitivity."

P7952, 1: Explain where this reference image comes from? Is it also from GOES or from a different sensor?

Text changed to:

The incoming images are compared with a predefined reference image, which is built by regridding the average of 2.1 μm band isotropic component of MODIS BRDF data on GOES grids, at locations with high contrast using correlation analysis.

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P7953, 24: add "... BRDF kernels fiso, fvol, fgeo, respectively." This would help to understand what is done here.

Changed.

P7953, 26: remove "of"

Changed.

P7954, 12: Why BRDF is now assumed to be lambertain? Didn't you just convince the reader, that BRDF is very important for aerosol retrieval? I don't understand. Do you have two retrieval steps? First retrieving BRDF with RT simulations considering BRDF and a second step for the AOD implementing the retrieved BRDF as lambertain value into the simulations? If so, then clearly explain this: "The reflectance in the viewing geometry is used and assumed to be the lambertain value for the AOD LUT." That's right?

Yes. Changed as suggested.

P7955, 8: Instead of "view geometries away from the backscattering direction" use "low scattering angles". This is easier to understand and the reader has not to transform the geometry into scattering angle in mind.

Changed.

P7955, 17: "clear day". What do you mean with clear day? Usually it is called clear pixel as the entire scene of GOES will never be completely clear sky. After further reading I understood, that a single pixel has to be clear sky for the whole day so that BRDF can be obtained for different scattering angles. You should add the word "pixel" somewhere in your explanation. Further one might ask, why an AOD retrieval is used to screen for clear sky? You already applied a cloud mask.

We mean the day with low average AOD, i.e. $AOD^{av} < 0.3$. To make it clear, we changed "clear day" to "low AOD day". The low AOD days are used for surface BRDF

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retrieval because: In low AOD days, surface reflectance can be retrieved more accurately, since they tend to have high signal to noise ratio and less interference of AOD model choice. Further more, low AOD days also have less AOD temporal variability and average daily AOD can be used without much potential errors.

P7955, 21: What the 80km horizontal scale stands for? Probable, aerosol variability? Please justify.

Changed to "horizontal scale of aerosol variability". This is the conclusion from Anderson et. al., 2003.

P7955, 23: Wording. Simplify: "This step requires a sensitivity of retrieved AOD to the assumed surface reflectance."

Changed.

P7956, 1: Figure 4 is discussed twice in the text. During the first occasion it is not clear where the dashed lines come from and how the sensitivity threshold is defined?

The discussion on this figure in Sect. 4.1 is removed.

P7956, 2: Is TOA reflectance measured or simulated. In the figure caption it is written that TOA reflectance was simulated.

The discussion on this figure in Sect. 4.1 is removed.

P7956, 10: Space is missing after "Here, "

Changed.

P7956, 20: Justify the value of 0.05. Standard deviation?

From the analysis of AERONET data, the standard deviation of AOD during a day is usually smaller than 0.05 if AOD^{av} is less than 0.3. Therefore, we assume the variation of AOD is 0.05 for retrieving surface BRDF.

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P7956, 23, Fig. 6: You did plot only $AOD^{av} < 0.3$. So you can not judge if this threshold is appropriate. What about $AOD=0.4$. Do the differences increase for higher AOD? To show this, Fig. 6 has to be expanded and to be discussed why 0.3 is the threshold.

When average AOD is larger than 0.3, it usually means that a pollution episode or dust storm occurs. The variation of the AOD is large, usually larger than 0.05. Therefore, we cannot use the assumption the over-estimate or under-estimate to be 0.05. Besides, for large AOD, the choice of aerosol model can have more effect the surface BRDF retrieval. Therefore, we use the threshold of 0.3. Actually, we don't lose much if we choose the threshold to be 0.3 instead of 0.4 since most of the days are low AOD days. In our multi-year statistics (2001-2008) of the three AERONET sites used, 3374 days (three sites total) have average AOD less than 0.3 but only 27 days have average AOD between 0.3 and 0.4. Of those 27 days, 18 days have daily AOD standard deviation greater than 0.05.

In Fig. 6 only overestimations of AOD are assumed. What about underestimations? Do they show the same differences? Further, Fig. 6 applies a single fixed surface reflectivity of 0.1. What if the reference surface reflectivity is changed from 0.1 to 0.2? How your criterion will change? Or is it robust enough to account for all possible surface reflectivities?

We did the similar analysis for underestimation and changed surface reflectance. The magnitude of errors are the same. Therefore, it is robust.

P7957, 3-10: These geometry related issues should be discussed earlier, because you already talked a lot about that before.

It is moved to the introduction section.

P7957, 13: The sensitivity parameter is later (P7959, 25) defined different.

We removed this one here. The criterion is satisfied automatically if the scattering

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angle is less than 100° .

P7957, 21: remove "also"

Changed.

P7957, 25: change "one-three" to "one to three"

Changed.

P7957, 25: change to " are required to ... of the entire image."

Changed.

P7959, 4 and 8: add equation numbers

Changed.

P7959, 4: It is a bit unfortunate that a is defined here and not earlier when Fig. 4 is discussed the first time.

Fig.4 was moved after this.

P7959, 8: Here again the road map is missing. I thought after obtaining the new BRDF you are fine and do not have to think about BRDF again. Why not simply the new updated BRDF is used not caring about the change from the last day. Or do you want to account for short changes in surface BRDF/reflectance again?

Yes, we do want to account for short changes in surface reflectance. Here, we only assume BRDF shape is unchanged but not the absolute values.

P7961, 4: Is there any explanation for the improvement at Boulder and not for the other sites? Check potential differences, geometry, surface BRDF,...

We looked at the difference in surface BRDF and gave an possible explanation in line 410-426.

P7973, Fig. 4: This figure is hard to understand from the description in the text

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and my comments might be wrong. Take this as a motivation to improve your explanation. First, isn't it better to switch a and AOD, abscissa and ordinate? Later you define the slope like that and the quantity searched for is AOD. The quantity causing differences is a.

Changed.

Second, what are the dashed lines? Where do they come from? How did you define the sensitivity threshold?

The dashed lines represent $S = -2$. If S is below 0 and larger than -2, the AOD retrieval is less sensitive to surface reflectance errors, i.e. TOA reflectance is sensitive to AOD variation. Otherwise AOD retrieval is sensitive to surface reflectance error, i.e. TOA reflectance is more sensitive to surface reflectance variation. The value -2 is chosen empirically to give good retrieval.

Third, when I do understand right, for $a = 1.0$ the correct AOD is retrieved because surface reflectance did not change. For GOES EAST this would be something like 0.15. Why for GOES-West a never has a value of 1?

The surface reflectance do change. In this simulation, $a = 0.9$, at which GOES-East and GOES-West cross each other, and the solution for τ is 0.2.

Further in the text P7959, 16: I would have thought it its vice versa and 4a is the problem. In 4b both sensors yield the same a and τ . This is OK.

The solution of (a, τ) is where the two curves cross each other. In Fig 4b, the location of the cross point can have a big move if there is a small shift of a curve due to some error in the satellite data. It is even possible that the two curves do not cross at all due to the errors, in which case we do not have a solution.

But in 4a both sensors give different a and τ . There should be only one real solution, one pair of a and τ . But in 4a GOES-East and -West give different pairs.

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They are different everywhere else except at the cross point, which defines the unique solution.

P7973, Fig. 4 caption line 2: Line 2 "where a represents" Here "a" is the quantity a. Use italic letters for symbols. Otherwise it is hard to distinguish from text. Especially "a".

Changed.

P7976, Fig 7: For the upper panels add labels "GOES-west" and "GOES-east".

Changed.

P7976, Fig 7: I suggest to rearrange the panels to facilitate an easy comparison of what is interesting. e.g. scattering angle vs. TOA reflectance and scattering angle vs. surface reflectance. (a) and (b) are fine. (c) and (d) scattering angle and surface reflectance should be merged with one panel for GOES-west and one panel for GOES-east. The GOES-west plot should be positioned below the west TOA reflectance. Same holds for GOES-east. This will help a lot to interpret the figure.

Changed. We also correct an error in scattering angle calculation. Therefore, the scattering angles are a little different from the original paper.

P7977, Fig 8: A description of the regression lines is missing in the caption.

Added.

P7977, Fig 8: How the linear regressions were calculated.

Least-square fit.

By eye I would assume completely different slopes. E.g., panel (h) most data is in a box between 0-0.1 AOD(AERONET) and 0-0.2 AOD(GOES). The slope should be much steeper.

C3756

Large AOD values should contribute more to the slope and small AOD values should contribute more to the intercept. In this case, the AOD larger than 0.2 should have more contribution to the slope.

Here and also in other panels, AOD(AERONET) seem to have a lower threshold at about 0.05. This does not come out in the regression equations. Why? This differences should be discussed in the text.

The threshold of 0.05 only appears in UCSB. The other two sites have much smaller ones, i.e. about 0.01-0.02. There are some small biases on the retrievals at small AOD, which makes the intercepts above 0. This is probably due to the cloud contamination. This point was added in the text.

P7978, Fig 9: This plot does not tell much. You may add some more information to interpret potential relations. E.g., mean AOD, scattering angle,...

Added.

P7979, Fig 10: Labels use GOES-11 and 12 here. Better use GOES-East and -West as before in the manuscript.

Changed.