Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2017-359-AC3, 2018

Atmospheric Measurement Techniques Discussions

Interactive comment on "Bayesian Dark Target Algorithm for MODIS AOD retrieval over land" *by* Antti Lipponen et al.

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Received and published: 23 January 2018

We thank the referee for the encouraging and constructive comments. Below we have included the referee's comments in boldface font and our replies below each of the comments.

General points

I am somewhat concerned by the way the approximation error (§3.3 and Ap-

pendix B) is computed. In §3.2 the authors state that the mean of the measurement noise PDF ($\mathbb{E}_n$) is assumed to be zero. However, it appears that this constraint is not applied when computing the approximation error mean ($\mathbb{E}_u$) from comparing MODIS TOA reflectance to values simulated from AERONET AODs. Is this correct? If it is, then this approach is making an implicit bias correction to the MODIS L1B reflectances, based on AERONET aerosol measurements and the retrieval's own forward model (plus the MCD43C surface reflectance) - this is fine as it stands, although it's clearly a bit of fudge. However, the authors then use the same AERONET measurements as validation data. It is thus not a huge surprise that they see a significant improvement in the bias against AERONET compared to the DT and Deep Blue products. Indeed, as the correction is computed separately for different regions (the same ones used in the validation?) and seasons, we might expect it to improve the correlation and RMS of global and yearly comparisons of AOD or FMF vs AERONET as well. If I am correct in my reading of how the approximation error is calculated and applied, then I would like to see the authors provide a comparison against AERONET where $\mathbb{E}_u$ is assumed to be zero. Otherwise, a clarification of how the approximation error is calculated is needed

In this study, the measurement noise is always assumed to be zero-mean. By measurement noise we mean the noise for example due to the instrument electronics. This has been clarified in the revised manuscript by changing: "...the random observation noise in MODIS observations is modelled by..." to "...the random observation noise in MODIS observations, for example due to measurement electronics in the instrument, is modelled by". In the computation of the approximation error statistics, we assume the measurement noise n to be small enough and set it to zero (but only in the construction of the statistics). This, however, does not mean that we would neglect the measurement noise in our retrieval but we model it and take it into account as random noise.

We have used an independent, older AERONET dataset for constructing the approximation error statistics (evaluation of retrievals was year 2015 and the approximation error statistics data from year 2014). We have added a sentence: "...AERONET data from 2014 (one year before the test year 2015). Also, as the approximation error statistics is generated using an independent AERONET dataset, the evaluation of the algorithm will not be using the same data and therefore not result in overoptimistic results that could be possible if same datasets would be used both for modeling and evaluation of the algorithm." to Section 4 to clarify the fact that the approximation error model was based on an independent set of measurements and therefore the comparisons we carry out are fair.

Some statistics for aerosol retrievals without the approximation error model are shown in Tables 2 and 3 of the manuscript.

The result resented in §5.2, that the retrieval performs best vs AERONET if the prior constraint of the spatial correlation of AOD and FMF are switched off, doesn't seem make sense without considering the above point, as you are then retrieving 6 parameters (four surface reflectances + AOD + FMF) from 4 measurements. Thus the results in tables 3 and 4 need further explanation.

In our text presented in §5.2, we have changed "Globally, the best correlation between the MODIS and AERONET retrievals is observed when the approximation error model is used and spatial correlation models are turned off. These results, however, should be interpreted very carefully as they only show the global statistics. In single retrieval cases, the spatial correlation models may even play more critical role than the approximation error model. As the aerosol properties usually have clear spatial correlation we would recommend using the spatial correlation models in the retrievals." to "Globally, the best correlation between the MODIS and AERONET retrievals is observed when the approximation error model is used and spatial correlation models are turned off.

This result was unexpected as the spatial correlation models were expected on average to improve the retrieval accuracy. The results show, however, that the use of spatial correlation models does not increase the accuracy of the retrievals on average. These results, however, should be interpreted very carefully as they only show the global average statistics. In single retrieval cases, the spatial correlation models may be helpful especially in some specific scenarios or, for example, if higher spatial resolution were used. Also, the spatial correlation model parameters may play a significant role in the accuracy of the retrievals. Due to differences in local meteorology and aerosol sources, regional models for the spatial correlation may be needed to reach the best possible accuracy of the algorithm. In this study, the correlation model parameters were not based on a thorough analysis of aerosol properties correlation structures, and only a global correlation model was used. As the aerosol properties usually have clear spatial correlation we would recommend using the spatial correlation models in the retrievals. "

I think that the fact that the best correlation, bias, fraction within EE_{DT} and RMS error all correspond to the configuration where spatial correlation is disabled, but approximation error is enabled, is simply due to the regional/seasonal bias correction against AERONET implicitly applied by the approximation error methodology. Again, there is nothing inherently wrong with doing such a correction, but you cannot then pretend that AERONET is an independent source of validation data.

As explained above, the AERONET data used to construct the approximation error model was from an independent dataset (different year) than the AERONET data used for algorithm evaluation.

Furthermore, tables 3 and 4 show that applying the correlation constraints don't actually improve the results vs AERONET, even if the approximation error is dis-

abled. This would seem to imply that the correlation constraints aren't improving the retrievals at all. I would be surprised if it turned out that these constraints don't actually improve the retrieval in many cases, but I feel that a concrete example is needed, rather than the vague assurances given at the end of §5.2.

We cannot say that the correlation constraints are not improving the retrievals at all. There may be cases in which the correlation helps and there may be cases in which the correlation makes the retrievals worse. On the other hand, it seems that the use of the spatial correlation model does not make the retrieval accuracy significantly worse. Also as it is clear that aerosol properties have spatial correlation structures we decided to include this possibility in our algorithm. It could be, for example, that in higher-resolution retrievals the correlation constraints would be more helpful. Also, we have not carefully analyzed the optimal correlation model parameters but just selected some reasonable values for the correlation models and the retrievals could be improved if more realistic correlation models were used. As this manuscript is mainly an algorithm description, we leave the further analysis of the spatial correlation models to future research. As stated above, we have modified the text in the manuscript to make it more clear that here the spatial correlation model did not seem to be the key factor in improved AOD retrievals.

Also, am I right in thinking that if both the approximation and spatial correlation errors are switched off, the retrieval effectively assumes the prior surface reflectance values from the MCD43C product are correct (i.e. the retrieval doesn't move from the a priori values)?

The optimization algorithm is based on gradient information and therefore it depends on the sensitivity of our posterior distribution which variables are optimized in the retrieval. If both the approximation error model and spatial correlations are switched off, it does not mean that the retrieval algorihm would assume the prior surface reflectance values

as correct but optimizes them similarly as AOD and FMF. Of course, in this case there are more unknowns than observations and therefore the solution in general may not be unique. In this case, the retrieved values also may depend on the initial point selected for iteration. In our case, we always select the most likely values according to our prior models as initial points for iteration.

I agree with the point made in an earlier comment by Dr Sayer regarding the name of the algorithm. Clearly, given that the processing done by the authors shares the cloud-clearing, look-up tables (and thus aerosol models) etc as the DT algorithm, it would seem fair enough to call the resulting product as the Bayesian Dark Target product, but the retrieval algorithm itself could be described as opposite in approach to the NASA DT algorithm, as BDT does away with both the independent pixel and spectrally correlated surface reflectance assumptions which form the basis of the DT (and Deep Blue) approaches (while introducing its own assumptions about spatial correlations in aerosol properties). My feeling is that the authors are in danger of "under selling" the algorithm, as, without going through the details of the algorithm, it could appear to just be DT with pixel-by-pixel uncertainty estimates.

Based on Dr Sayer's and referees' comments, we have changed the name of the algorithm to Bayesian Aerosol Retrieval (BAR) algorithm and revised the manuscript accordingly.

In a similar fashion, I'd like to see the authors move away from the (in my opinion misleading) use of the term fine-mode fraction to describe the fraction of the AOD due to the fine mode. Perhaps "fine mode AOD fraction" is a better term? At the very least, the definition of what is actually meant by FMF needs to be stated up-front.

The fine mode AOD fraction may also be misleading because in Dark Target and our algorithm the fine mode fraction is actually the fraction of top-of-atmosphere reflectance due to fine aerosol part of the model. We define the FMF as the ‘fine aerosol model weighting’ in our manuscript. Furthermore, we added the following sentence to Section 2: "It should be noted that in DT algorithm, the FMF is actually the weighting coefficient for the TOA reflectances due to fine aerosol model, and do not necessary represent the true concentration fraction of the fine-mode aerosol."

Finally, though I appreciate that adding in an additional product into their validation would be a bit much, the authors don’t seem to be aware of the MAIAC MODIS product, which (as Dr Sayer noted) in some ways has more in common with their approach than DT.

We have now mentioned the MAIAC algorithm with references to doi:10.1029/2010JD014985 and doi:10.1029/2010JD014986 in the introduction.

Specific points

P1L1: Suggest you reword to “...(BDT) algorithm for the retrieval of aerosol optical depth over land from MOderate Resolution...”

Reworded as suggested.

P1L18: Reword to “...particles may be hazardous to human health when inhaled...”

Corrected as suggested.

P1L21: Add a comma after “predictions”.

Corrected as suggested.

P2L4: I’d describe DT as the primary operational algorithm used to retrieval aerosol, not just “an algorithm”.

Was changed to: “The primary operational algorithm to retrieve aerosol properties, such as the aerosol optical depth (AOD), is the Dark Target (DT)...”

P2L7: Reword to “...DT algorithm is the brightening effect, whereby an increased amount of aerosol over dark...”

Changed as suggested.

P2L19: Remove “for example”.

Removed.

P2L24-L27: The sentences describing the Deep Blue algorithm don’t scan well at all.

The sentences were changed to: “DB is used for over land aerosol retrievals and it was developed especially for retrievals over bright-reflecting surface. The capability of retrieving aerosol properties over bright-reflecting surfaces is useful, for example, in retrieving dust properties over deserts. Regardless of the bright-reflecting surface capabilities, DB does not carry out retrievals over snow or ice.”

P2L34: Please provide a reference/justification for the statement that taking advantage of spatial correlations in aerosol properties can improve retrieval results. I note that your own results (Section 5.2, Tables 3 and 4) don't actual support this statement (although I'd be surprised if it wasn't true!)

We agree that the statement may have been too strong. We have changed "Often, however, aerosol properties have strong spatial correlations. Taking advantage of the spatial correlations of aerosol properties in the retrieval can, in many cases, improve the accuracy of the retrieved parameters." to "Often, however, aerosol properties have strong spatial correlations (Anderson et al, 2003). Modeling and taking advantage of the spatial correlation structures of aerosol properties in the retrieval may therefore, in some cases, improve the accuracy of the retrieved parameters."

P4L8: Why did you choose the listed bands in particular? Was just because these were the ones for which look-up tables were available?

The reason for selecting the listed bands in particular was that the lookup-tables were already easily available for these bands. The algorithm is not restricted to these bands only and the use of all possible data is expected to improve the retrieval accuracy. The downside of using more bands, however, would be increased computational costs. We consider retrievals with more bands as a topic for future research.

P4L21: As with the other referee, Dr Povey, I am also confused by the $\tau = log(\tilde{\tau} + 1)$. I understand retrieving AOD in log space (not only do you avoid the problem of negative AODs, but the observed distribution of AODs is much closer to log-normal than normal), but where does the "+1" come from? Also, as Dr Povey notes, $log(\tau + 1)$ is defined for $\tau > -1$, and thus doesn't prevent negative optical-depth values as you state in the text.

In our optimization solution, we constrain the values of $\log(x+1)$ to non-negative values that guarantees us with non-negative AOD retrievals. As we retrieve $\log(\tau + 1)$, the prior model is written for the same quantity as well. If we retrieved $\log(\tau)$ instead, it would mean that for really small AOD values we would have really small $\log(\tau)$ values (approaching to $-\infty$ when AOD approaches 0). This in turn would require the use of really high variances (or standard deviations) for the $\log(\tau)$ to allow for higher AOD values to be retrieved. To avoid this problem of small numbers and high variances in the prior models, we decided to retrieve $\log(1 + \tau)$ instead of $\log(\tau)$. To make this clear, we added a sentence: "In practice, these constraints are implemented in the optimization algorithm." to the manuscript.

P4L22: The retrieval using log reflectance is also new to me. Can you elaborate on why this was chosen? In particular, doesn't this complicate the use of the estimates of the measurement noise of the MODIS reflectances? And, again the "+1" needs explaining.

The use of log-scale reflectances were selected based on a test where we compared the AOD retrievals with and without log-scale. The use of log-scale resulted in slightly better retrieval accuracy so we decided to use it. In this setting, the measurement noise (+1) is normal-distributed in log-scale (lognormal distributio). This means that it is slightly more probable that the true reflectance is higher than the observed reflectance than it would be lower than the observed reflectance. As the reflectances in AOD retrievals are generally quite small this seems to be more realistic assumption and results in slightly improved retrievals. The "+1" was used for the same reason as for the AOD, please see the reply regarding the use of $\log(\tau + 1)$.

P4L25: Please explicitly define the symbols used for expected value vectors and covariance matrices here.

Definitions added.

P5L6: Eq (2) needs reformatting so that it fits within the margins.

Equation reformatted.

P6 (§3.1.1 and 3.1.2): I don't agree with your approach in presenting the Prior models and their covariance matrices in particular. For a start, the values for σ^2_{nugget} make up a small fraction of the total variance (3rd sig. fig. for AOD and 2nd sig. fig. for FMF) and thus are largely irrelevant. Furthermore, I think it be clearer if you were define a correlation matrix and variance matrix separately, which are then combined to give you your covariance. The off-diagonal elements of a covariance matrix are combination of the variance of the variables concerned (where an increased value corresponds to a less tight constraint) and correlation between them (where a increased value implies a tighter constraint).

We highly appreciate your opinion about the presentation of the covariance matrices. This form of presentation, however, is similar to the ones we have seen in the literature (for example the reference we have used doi:10.1029/2009JD013765). To make it easier for the readers to compare our model with others from the literature we would like to leave the presentation of the covariance matrices as it is now. **P6L16-18: The**

authors need to acknowledge that an inherent weakness of their scheme, and the use of a spatial correlation constraint in particular, is that it will always result in the smoothing of sharp features in the aerosol field (such as smoke plumes). There is no way you will be able to "correctly" retrieve the AOD of a near-source aerosol plume when assuming a correlation in aerosol AOD and FMF over 50 km.

The sentence was changed from "This selection was made to let the neighbouring pixels have relatively high spatial correlation but on the other hand to allow for certain features such as smoke plumes to be retrieved correctly and not be smoothed out." to "This selection was made to let the neighbouring pixels have relatively high spatial correlation but on the other hand to allow for certain features such as smoke plumes to be retrieved as well as possible and not be smoothed out too much."

The use of this type of spatial prior information does not necessarily mean that the retrieved AOD distribution is always very smooth but it means that there is a high probability for the AOD distribution to be smooth. In this type of prior model, AOD distributions with rapid changes, for example due to smoke plume, still have a non-zero probability. In cases where the observations really strongly suggest that there are rapid changes in AOD it is possible that these rapid changes are seen in the retrieved distributions as well.

P7L14: Please provide some reasoning behind the choice of the blue sky albedo, and the 0.5 weighting coefficient in particular.

The blue sky albedo (with weight of 0.5) was selected based on initial tests in which it resulted in the best retrieval results. In the tests, we carried out retrievals with white-sky, black-sky, and blue-sky (weight 0.5) albedos for a small amount of granules and compared the results. The differeces between the surface albedos were small but the blue-sky was the best performing one so we selected it to be used in the algorithm. We added the following sentences to the surface reflectance prior model section of the manuscript: "This selection to use the blue sky albedo was done based on a test in which we carried out retrievals with white-sky, black-sky, and blue-sky albedo based prior models. The differences between the different surface albedo types were small but the blue-sky albedo resulted in the best results when compared with the collocated

AERONET AOD values."

P7L29: I know Eq (5) is fairly ubiquitous in aerosol and cloud remote sensing, but a reference for its derivation would be nice.

References to Chandrasekhar Radiative Transfer (1960) and doi:10.1109/TGRS.1986.289617 were added.

P8L11: How are the look-up tables corrected for surface elevation? Is this an additional parameter in the table?

The same approach as in the Dark Target algorithm is used for correcting for the surface elevation. In this approach, the lookup-tables are directly corrected for and therefore no additional variables for the tables are not needed. The method is based on adjustment of the Rayleigh optical depth at different surface elevations. For more information on the surface elevation method see for example: MODIS Dark Target ATBD or Fraser, R. H., Ferrare, R. A., Kaufman, Y. J., Mattoo, S. (1989). Algorithm for Atmospheric Corrections of Aircraft and Satellite Imagery. NASA Technical Memorandum 100751. Greenbelt, MD USA, NASA Goddard Space Flight Center.

P9L8-9: Change to "We model the approximation error u as spatially, but not spectrally, uncorrelated, meaning the correlations between MODIS bands are taken into account".

Corrected as suggested.

P9L10: Delete the "the" before "spatial and season variations", Also, place a

comma after "Similarly".

Corrected as suggested.

P9L19: Remove "the" before "± 30".

Removed.

P9L25: Change to "In order to evaluate the near real time..."

Changed.

P10L14: Remove "the" before "DB retrievals".

"the" removed.

P11L13: The use of "oversmoothed" here irks me somewhat. For a start, how does one define what is "oversmoothed"? I feel the authors should be up-front and acknowledge that there is some evidence in Fig. 3 that their algorithm is smoothing the AOD field to a certain degree - in particular, I am looking at the thin smoke plume slightly above the smoother, wider area of smoke in the middle of the image. There is a clear linear feature in both the true-colour and DT images, which largely absent from the BDT results.

Thank you for the remark. We have changed the sentence: "Regardless of the spatial correlation model used for AOD in BAR, the plume is not oversmoothed and shows similar details as the DT retrieval." to "The use of spatial correlation model for AOD in

BAR can be seen as slight smoothing of the plume details when compared to the DT retrieval."

P11L14-17: The authors present some circumstantial arguments to suggest that the BDT FMF in Fig. 3 is superior to that provided by DT, and I agree that some of the features present in the DT results are almost certainly artefacts. However, due to the spatial constraints applied to the BDT algorithm, it is always going to produce a more pleasing looking, smoothly varying field than an independent pixel approach like DT. This doesn't mean that we can conclude that, for the scene in question, we can say which product is quantitatively more accurately. Again, some acknowledgement of the fact that some real features might be smoothed-out in the BDT product should be included.

The following sentence was added to the manuscript: "It should be noted, however, that the spatial correlation model for FMF may in some cases result in too smooth FMF fields that are unrealistic, for example in cases of smoke plumes, reducing the accuracy of the retrievals in these cases."

P12L2: Insert a comma after "algorithms".

Comma inserted.

P12L4: Insert a comma after "Figure 4".

Comma inserted.

P12L8: Change to "...was carried out, based on the DT algorithm QA flag, which

is designed to discard ..."

Changed.

P13L6: Change to "Visual inspection shows the BDT retrievals..."

Changed.

P21L28: I have never heard of anyone trying to use spatial correlation constraints on the surface land reflectance. This doesn't seem to make sense as the land surface is generally pretty anisotropic at all spatial scales. Do the authors mean spectral correlation instead?

We do mean spatial correlation. It is possible to write a suitable spatial correlation model for the land surface. It would not necessary be a correlation model implying smoothly varying surface but, for example, the anisotropic nature of the surface could be encoded into the model. As stated in the manuscript, this is a topic for future research.

P22L1: I don't believe the claim that the signal-to-noise ratio of MODIS reflectances is too low to allow accurate aerosol retrievals. The reasons that aerosol products have usually been done on a courser spatial scale than native instrument resolution are all to do with dealing with residual cloud contamination and surface anisotropy (and reducing product size and computational cost).

We agree with you in signal-to-noise ratio issue. We have changed the future research item text to "High-resolution retrievals. In high-resolution pixel-by-pixel retrievals, the anisotropic and non-smooth surface reflectance, and residual cloud contamination are major sources of uncertainties and may lead to poor retrieval accuracy. BDT takes into account the spatial correlations of aerosol properties and this may make the algorithm more tolerant to higher uncertainties. Therefore, the use of BDT would especially improve the high-resolution (3 km) aerosol retrievals."

P22L4: Due to the inclusion of the AERONET based approximation error term, the scheme already has a kind of data-fusion with AERONET!

We rather think it is more an aerosol model calibration than data-fusion as the approximation error model is constructed using independent, older AERONET dataset. But you are correct, if the AERONET data used in the approximation error model were collocated in time with the MODIS retrievals it could be thought of a simple data-fusion with AERONET.

P21/P22: I have an additional thought for future development of the algorithm: Is there any reason the approach couldn't be applied over the ocean?

There are no restrictions to use the algorithm over ocean as long as there is some information about the surface. Especially over ocean there could be clear benefits of using spatial correlation model for the surface reflectance. In Dark Target over Ocean algorithm, the ocean surface reflectance depends on the wind speed. A similar surface model could also be used with our retrieval algorithm as well (Dark Target surface reflectance as prior mean, for example). We thank the referee for this idea and have listed the over ocean retrieval as a topic of future work in the conclusions.

P22L21: Remove one of the instances of "statistical".

Removed.

P22L25: Consistency of symbol for TOA reflectance.

By ρ^{TOA} we denote the simulated TOA reflectances and by $\rho^{\mathrm{TOA,MODIS}}$ the true MODIS observed TOA reflectances. We have clarified this by changing "...given the observed TOA reflectances..." to "...given the true MODIS instrument observed TOA reflectances..."

P23L4-5: Insert commas after "unknown" and "ρ^{TOA} is fixed".

Commas added.

P24L2: Reformat equation to fit.

Equation reformated.

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2017-359, 2017.