Authors' Response to Reviews of

BAYESIAN ATMOSPHERIC CORRECTION OVER LAND: SENTINEL-2/MSI AND LANDSAT 8/OLI

Feng Yin, Philip E Lewis, Jose L Gómez-Dans
Geoscientific Model Development, `https://doi.org/10.5194/egusphere-2022-170`

RC: ***Reviewers' Comment***, AR: Authors' Response, ☐ Manuscript Text

1. Reviewer #2

1.1. Concern #1

RC: ***Thanks for the authors' response and addressing for most of my concerns. I still could not follow how the spatial smoothness prior works.***

I am curious what is the spatial support in solving the Bayesian Equation (1). If there is no spatial smoothness, the Bayesian Equation can be solved at each Landsat/Setinel-2 pixel as neighbor Landsat/Setinel-2 pixels are independent. However, with spatial smoothness the Bayesian equation cannot be solved for each single pixel anymore, and a cluster of pixels will be put tougher so that D can be applied (I assume D matrix is applied on the water vapor and aerosol images). It looks like the authors choose to solve all Landsat/S2 pixels within a MODIS pixel together, i.e., D is applied all L8/S2 pixels within a MODIS pixel. In another word, the solution induced by the spatial smoothness is only applied within a MODIS pixel. The L8/S2 pixels coming from neighbor MODIS pixels are not constrained by the spatial smoothness even the two L8/S2 may be close to each other at the MODIS pixel boundaries (of course the neighbor MODIS pixels may very likely use the same prior as the prior is defined at 40 km resolution).

AR: We thank the reviewer for the insightful comments and suggestions. The spatial resolution for solving equation 1 is at Gc, which is also the spatial resolution used to define the D matrix. All the inputs to the solver have been processed to Gc, i.e. MODIS spatial resolution, and we solve the atmospheric parameters for the whole S2/L8 tile at grid Gc. Therefore, the D matrix is applied to the neighbouring MODIS pixels rather than the S2/L8 pixels within a MODIS pixel, as the S2/L8 TOA observations have been aggregated to Gc during the PSF modelling procedure.

We have added text in line 116-117 to clarify the spatial resolution of TOA observation (at Gc) after PSF modelling:

> The output through the ePSF modelling provide us with the TOA observations on grid G_c, i.e. MODIS grid.

AR: And in line 185-187 to clarify the spatial resolution of D matrix:

> The ~~matrix D is given as an example for~~ TOA reflectance observation, modelled TOA reflectance and prior information on the atmospheric parameters are processed to G_c through the procedures

> described above. Thus, the D matrix is also defined at G_c, i.e. 500 m to provide spatial constraint for the atmospheric parameters. For a variable length of n, the matrix D is given as

1.2. Minor points

RC: ***Line 80: "with an associated sub-40 km spatial correlation constraint" – But if my above statement is correct the spatial correlation is only on 500 m.***

AR: Yes, the spatial correlation is at 500 m and we have removed the sub-40 km and clarified the spatial constraint is for atmospheric parameters (AOT, TCWV) in line 81:

> Our approach uses *a priori* constraints in the form of a coarse resolution (500m) spectral BRDF dataset from MODIS (Schaaf and Wang, 2015) to provide *sample* land surface reflectance estimates, as well as a very coarse resolution (40 km) estimate of atmospheric composition from the CAMS near-real-time global assimilation and forecasting system (Morcrette et al., 2009; Benedetti et al., 2009), with an associated ~~sub-40 km~~ spatial correlation constraint for the atmospheric parameters.

RC: ***Table 2, Should X and Xb defined for L8/S2 resolution rather than MODIS resolution.***

AR: As clarified above, all the inputs to the solver are at Gc, MODIS resolution

RC: ***After Equation B3, "where n is the number of rows (columns) in the MODIS spatial grid Gc as the term is applied in the row (column) direction". This is where my interpretation coming from since n is the number of L8/S2 pixels in a MODIS grid Gc. It implies the D with n*n size is applied to all L8/S2 pixels in a MODIS grid.***

AR: The original text causes the confusion and the description has been changed in Line 587-588:

> where n is the number of rows (columns) ~~in the~~ of pixels within the S2/L8 spatial extent at the MODIS spatial grid G_c as the term is applied in the row (column) direction.

RC: ***Line 855, "expressed in 6 and controlled by allowing for gradual changes in atmospheric parameters in X over the whole of Gc". This is also where my interpretation coming from since the parameters X over Gc has gradual changes and consequently X should be defined at L8/S2 resolution (Gm).***

AR: The preposition 'in' has caused the confusion for the reviewer, and we have changed Line 820-823:

> Within SIAC, the broad scale (40 km) variations of atmospheric parameters are estimated from CAMS. But there are often finer-scale features that may impact our interpretation of surface reflectance, and we wish to be able to resolve these. To this end, we assume an effective resolution of G_c (500 m) for atmospheric parameters, with the ~~sub-40 km~~ smoothness constraint expressed in Eq. 6and controlled by γ~~allowing~~. This spatial constraint allows for gradual changes ~~in atmospheric parameters in~~ in atmospheric parameters X ~~over the whole~~ at the spatial resolution of G_c over the S2/L8 image spatial extent. The values in X that we solve for in SIAC are controlled by a weighting of the location and information content of samples in Y and assumed uncertainty of the *a priori* constraint that is, in essence, blurred over G_c. The degree of smoothing imposed, and so the resultant ~~(sub-40 km)~~ correlation length of the derived atmospheric parameters, is mainly controlled by γ. Its squared inverse,

> $1/\gamma^2$, a measure of roughness, can also be phrased as the expectation that there is no change at a scale of 500 m (Lewis et al., 2012).

RC: ***If I am wrong, please find a place to clarify, better in 2.2 and 2.4 both.***

AR: Clarification have been made in section 2.2 and 2.4 stated above.

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1. Reviewer #3

1.1. Major Concern #1

RC: ***The manuscript of Feng Yin proposes a method for atmospheric correction for radiometers with a typical spatial resolution of few tenths of meters relying on prior information determined at much lower spatial resolution (few hundredths of meters). The proposed method relies on a Bayesian approach. Though the title of the manuscript "BAYESIAN ATMOSPHERIC CORRECTION OVER LAND: SENTINEL-2/MSI AND LANDSAT 8/OLI" is very appealing, this research work misses delivering the expected Analysis Ready Data outcome, essentially due to several unjustified assumptions and approximations. As stated in the abstract, mitigating the impact of atmospheric effects on optical remote sensing data is critical for monitoring intrinsic land processes. In the context of delivering Analysis Ready Data, intrinsic land processes mean that no additional variables are needed to analyse the delivered surface reflectance. Despite the apparent complexity of the proposed SIAC Bayesian approach, the delivered geophysical variable, namely the bottom of atmosphere Bidirectional Reflectance Factor (factor and not function as stated in line 29) is erroneously presented as Analysis Ready Data. It still depends on the actual state of the atmosphere! [...] Unfortunately, I would not recommend the publication of this manuscript as long as it relies on erroneous assumptions.***

AR: We want to thank the reviewer for his/her time, but we note that this is only a very partial review of the manuscript. As a general comment, the reviewer claims that higher order effects need to be accounted for in order to produce a useful Analysis Ready Data (ARD) product. We note that this is not a requirement of the CEOS ARD for Land (CARD4L) (CEOS, 2021b). The assumption of a Lambertian surface is made in most of the atmospheric correction schemes that take part on the Atmospheric Intercomparison Exercise (ACIX) (Doxani et al., 2018, 2022), and a number of surface reflectance products adopting this assumption are accepted as CEOS assessed ARD products (CEOS, 2021a). We have also quoted the last sentence, which we think is inappropriate: we have made an assumption that is commonly used, and have tried to quantify its impact. This does not make it "erroneous"

1.2. Major concern #2

RC: ***In line 60, it is written "We wish to estimate the probability distribution function (PDF) of BOA spectral BRF, R with illumination and viewing vectors Ω_s, Ω_v respectively". The Bidirectional Reflectance Factor is indeed an intrinsic property of the surface that depends on Ω_s, Ω_v The BRF should be estimated at the surface to achieve this objective, removing all possible atmospheric effects as written in line 94. In line 120 Equation (3), it is however assumed that the surface reflectance rb represents a "Lambertian reflectance" which is equivalent to assuming that the sky radiation is perfectly diffuse which is true only when the sky***

is overcast. rb is however estimated with Equation (4) which provides the BRF for the Ω_s, Ω_v geometry. It is therefore not a Lambertian Equivalent Reflectance as assumed in Equation 3. The relationship between rb expressed in Equations (3) and (4) is thus inconsistent. Assuming that rb in Equation (3) can be estimated with Equation (4) is strictly correct for the direct contribution only. It is inconsistent with the definition of the terms representing the total (direct and diffuse) downwelling and upwelling atmospheric transmittance. Consequently, the retrieved surface reflectance still depends on the actual atmospheric state (diffuse contribution). Hence, as long as this issue is not properly solved, the proposed approach will not work for the delivery of Analysis Ready Data. It is a major flaw in the proposed approach that should be corrected, and they are elegant ways to do so!

AR: Errors caused by higher order effects, such as BRDF coupling, only become dominant when there is high aerosol loading, large sun/view zenith angle and strong surface anisotropy. To account for those higher order effects in the atmospheric correction, knowledge on the surface BRDF is required, which is not available for medium resolution (10 m - 60 m) data. This is also likely to be the reason why most of the current methods assume a Lambertian surface. One option we have explored and will present in future work is to consider the coupling at a coarser spatial resolution from the ancillary MODIS data, but that is difficult to validate with the data we present in this paper. We stress again that the CARD4L, we aiming to produce, does not specify the requirements on the correction higher order effects. However, the reviewer rejected our paper with his subjective view on the ARD and ignored the community agreed standards.

To further clarify the potential errors caused by the Lambertian assumption, we have added some quantification of the likely uncertainties introduced by this assumption based on the literature in Section 2.2 as follows:

> We assume a Lambertian surface in the atmospheric correction process. The relative errors caused by this Lambertian assumption on the surface reflectance is 3-12% in the visible bands and 0.7–5.0% in the near-infrared bands. Its effect on the NDVI analysis is around 1% and less than 1% for albedo (Franch et al., 2013), which is within 5% accuracy requirement on albedo by the Global Climate Observing System (GCOS) (GCOS, 2019). This Lambertian assumption is also widely used to produce the surface reflectance for MODIS (Franch et al., 2013), Landsat (Vermote et al., 2016) and S2 (ESA, 2021), where the Landsat and S2 surface reflectance products have been accepted as the CEOS assessed ARD products (CEOS, 2021a).

1.3. Minor points

RC: ***In lines 19 and 20, R defines a correlation coefficient.***

AR: R has been changed to correlation in the abstract. Thanks.

> SIAC is demonstrated for a set of global S2 and L8 images covering AERONET and RadCalNet sites. AOT retrievals show a very high correlation to AERONET estimates (~~R~~ correlation coefficient around 0.86, RMSE of 0.07 for both sensors), although with a small bias in AOT. TCWV is accurately retrieved from both sensors ~~($R > 0.96$, $RMSE < 0.32$ g/cm^2)~~(correlation coefficient over 0.96, $RMSE < 0.32$ g/cm^2). Comparisons with *in situ* surface reflectance measurements from the RadCalNet network show that SIAC provides accurate estimates of surface reflectance across the entire spectrum, with $RMSE$ mismatches with the reference data between 0.01 and 0.02 in units of reflectance, for both S2 and L8. For near-simultaneous S2 and L8 acquisitions, there is a very tight relationship (~~$R > 0.95$~~ correlation coefficient over 0.95 for all common bands) between surface reflectance from both sensors, with negligible biases. Uncertainty estimates are assessed through

> discrepancy analysis and found to provide viable estimates for AOT and TCWV. For surface reflectance, they give conservative estimates of uncertainty, suggesting that a lower estimate of TOA reflectance uncertainty might be appropriate.

RC: ***In Table 1, the symbol r is not defined.***

AR: Added definition in the table caption:

> Threshold uncertainty specifications for Aerosol Optical Thickness (AOT), total column of water vapour (TCWV) and BOA BRF (r) used in this paper.

RC: ***In Table 2, R is defined as R N(r,Cr) as the a posteriori PDF of the BRF but the symbols r and Cr are not defined.***
In Table 2, Rb is defined as Rb (rb,Cb) as the a priori PDF of the BRF but the symbols rb and Cb are not defined

AR: Clarification on C has been added to the Table caption:

> Main symbols used in the paper. C_* represents the covariance matrix part of the PDF for parameter $*$.

RC: ***In line 200, r is defined as the mean surface reflectance.***

AR: Yes, r is the mean surface reflectance estimate under Lambertian assumption

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