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Atmospheric Measurement Techniques
Discussions
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Interactive comment on "Sensitivity of remotely-sensed trace gas concentrations to polarisation" *by* D. M. O'Brien et al.

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We thank the reviewer for his constructive and helpful comments. A revised manuscript is attached as a supplement showing the responses to the reviewer's comments marked in blue.

Comment 1

Section 2: Would it be worth mentioning that quantities are wavelength dependent?

Reply 1

At the end of the opening paragraph of Section 2, we have added the following sentence.

> All quantities in the polarisation model depend on wavelength, but the dependence is not shown explicitly in order to simplify the notation.

Comment 2

Section 3: The calibration procedure puts the scan mirrors in their exact nadir position. Would it not be necessary to separately calibrate radiometric response and polarization properties for the relevant range of off-nadir angles?

Reply 2

We agree. In the discussion paper we assumed that the reflection coefficients and phase shifts associated with the scan mirrors would be characterised pre-flight as functions of wavelength and angle of incidence, but we omitted to say so. After line 9 on page 8785 of the discussion paper, we have added the following sentence.

> The reflection coefficients $r_{||}$ and $r_{\perp}$ and the phase shift ϕ are functions of wavelength and the angle of incidence, which must be characterised during radiometric and polarimetric calibration.

Comment 3

P8795: It would be good to elaborate a bit more on the radiative transfer algorithm used (or to provide the relevant references).

Reply 3

The radiative transfer code has been described by us in earlier work, some of which was released as a technical report for the Cooperative Institute for Research in the Atmosphere at Colorado State Univerity, and therefore might not be readily accessible. Therefore, we have added the following paragraph after line 14 on page 8795.

> The Stokes vector $\boldsymbol{S}$ was computed using a three-step approach: calculate the exact contribution to $\boldsymbol{S}$ from first-order scattering (1OS); calculate the multiply scattered radiance I at the top of the atmosphere (I_{ms}); calculate the contributions from second-order scattering to Q and U, as well as the polarisation corrections from second-order scattering to I (2OS). By combining the results of these calculations, the Stokes vector at the top of the atmosphere can be estimated reasonably accurately for nearly clear scenes (Natraj and Spurr, 2007). The 1OS and 2OS terms used code developed by Natraj and Spurr (2007). Calculation of the first-order component of I used the TMS correction of Nakajima and Tanaka (1988), and all three first-order scattering terms include the direct beam scattered from the surface. The multiply scattered intensity term I_{ms} is calculated using the successive orders of interaction (SOI) radiative transfer model (Heidinger et al., 2006) with slight updates for the infrared. The SOI model employs the delta-M phase function truncation technique of Wiscombe (1977). The SOI model is both fast and accurate (O'Dell et al., 2006). Lastly, the techniques of

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> low-streams interpolation (LSI) developed by O'Dell (2010) was used to compute the Stokes vector on a 0.01 cm^{-1} spectral grid; high accuracy, but widely spaced, radiances were interpolated to the fine spectral grid using a two-stream solver of the radiative transfer equation.

Comment 4

P8795: Section 6 describes the differences between simulated measurement and retrieval algorithm which are in particular the (polarization relevant) surface reflection and particle scattering properties. Bullet 1 at P8795,L21 seems to indicate that absorption coefficients are also different between simulation and retrieval. Is this true? This would induce errors that could mask the polarization effects to be isolated here.

Reply 4

We interpolated the absorption coefficients from tabulations on fixed pressure and temperature grids. Because the meteorology can differ between the forward and inverse calculations, the corresponding absorption coefficients also can differ. However, we expect these differences to be small. Much more important for an instrument in flight will be the differences between the absorption line parameters from laboratory measurements and those of the real world. Those differences might mask polarisation effects, as the reviewer suggests. However, they are beyond the scope of this paper.

Comment 5

P8795: I agree that noisy simulations could dilute conclusions on polarization-induced errors. Therefore, the authors choose to run noiseless simulations. In principle, linear retrieval theory could be used to a posteriori subtract the noise error using the *contribution function matrix and the actual noise realization in the spectra (known for simulations), see e.g. Butz et al., Remote Sensing of Environment, 2012. Subtracting noise errors a posteriori would have the advantage that the retrieval faces the real challenge. Noiseless simulations could, for example, result in overly optimistic convergence behavior. This is, however, a minor point and does not need to be evaluated for the current simulations.*

Reply 5

We appreciate the reviewer's suggestion of an alterantive method for subtracting the instrument noise error. Because the total error is likely to be dominated by model errors, rather than numerical retrieval errors, the differences should be small. However, in future work we will try adopting the method he suggests.

Comment 6

Section 7: While the histograms clearly illustrate that, statistically, polarization effects have a small impact on geoCARB's retrieval performance, it could be worthwhile to investigate whether badly performing cases correlate with viewing and solar angles or polarization/scattering/reflection properties of the atmosphere and surface.

Reply 6

In this preliminary study our aim was simply to determine whether careful pre-flight calibration might allow errors caused by polarisation to be corrected. The conclusion appears to be so, because other systematic errors dominate the total error. As we say in the conclusion, if these other sources of error can be reduced, then the polarisation issue might need to be reconsidered. If geoCARB proceeds to a Phase A study, then

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further analysis of the residual polarisation errors as the reviewer suggests would be appropriate.

Comment 7

P8799,L24: Why are XCH4 and XCO less reliant on the O2A-band than XCO2?

Reply 7

We will remove the offending sentence, which was offered only as a possibility. The sentence before states that the “impact on retrieved X_{CH_4} and X_{CO} is smaller, for reasons presently unknown, but is still significant.” We leave this as an open question to be investigated during the Phase A study for geoCARB.

Comment 8

Figures 4 and 6: At first glance, it is somewhat misleading that the upper panels show spectral ranges beyond the ones in use while the lower panels focus on the actually used ones.

Reply 8

For the O_2 A-band and the CO_2 weak band, we had measured efficiencies for the grating. We thought it useful to show the wider spectral range to emphasise the significant variations in efficiency that occur with real gratings. In the CO_2 strong band and the CO band, all we had available were theoretical predictions of grating efficiency for the proposed instrument bands.

Comment 9

Figure 5: Define relation between datasets and right-hand/left-hand axes.

Reply 9

Good point! We have amended the figure caption to read as follows.

> Angle η_0 (right-hand scale) between the reference planes for polarisation used by the radiative transfer code and the geoCARB instrument, shown as a function of latitude along the frames through Agra, Wuhan and Alice Springs. Also plotted are $\cos 2\eta_0$ and $\sin 2\eta_0$ (left-hand scale), which are essentially the Stokes coefficients for the simplified model of the instrument (hence the left-hand label).

Comment 10

Figure 9: It could be interesting to also show the degree of polarization for the bands other than the O2A-band. Could it be true that polarization effects are smaller in the 2.3 micron CH4, CO window than in the CO2 windows and therefore, XCH4 and XCO are less affected by polarization effects?

Reply 10

Fig. 1 in this reply shows the degree of polarisation in the geoCARB bands for the ensemble of soundings with cloud enabled. The degree of polarisation is largest in the O_2 A-band, principally due to the contribution from molecular scattering. In the CO_2 weak band, the CO_2 strong band and the CH_4 and CO band the mean degrees of polarisation are approximately 0.057, 0.077 and 0.075. In each case the high frequency variations associated with the molecular absorption spectra appear as relatively small signals superimposed on spectrally flat offsets. Because these plots are difficult to interpret, we have kept the original plot showing only the O_2 A-band. We reiterate that the purpose of the plot in the manuscript is simply to indicate the range expected for the degree of polarisation in spectra at the top of the atmosphere.

Comment 11

Figure 10: I presume that the column-average mole fractions are calculated by dividing the retrieved total column CO2, CH4, and CO concentrations by the retrieved (surface pressure derived) O2 column. So, XCO2, XCH4, XCO errors include both sources, erroneous total column retrievals of the actual species and erroneous surface pressure retrievals. What are the individual contributions?

Reply 11

Unfortunately we do not have to hand the data needed to answer the reviewer's question in the present paper, and therefore must defer the issue until a Phase A study. Since the present paper indicates that polarisation errors will be secondary, deferment is reasonable. However, we recognise that such information will become important later. For example, if polarisation errors turn out to be largest in the O_2 A-band, then extra care should be given to the calibration (radiometric and polarimetric) of the O_2 A-band. Knowing this in advance from a Phase A study would assist the instrument engineers.

Comment 12

Figure 11: Should albedo slope have units of 1/wavelength? Does the cloud of lower-than-true albedo slope (right panel) correlate with geophysical parameters?

Reply 12

The units of albedo slope are ‘per wavenumber’ or $(\mathrm{cm}^{-1})^{-1}$, which equates to cm. We have added the units to figure 11.

Again the reviewer poses an interesting question. Due to constraints on both time and space, the matter will be deferred until Phase A.

References

Heidinger, A. K., O’Dell, C., Bennartz, R., and Greenwald, T.: The successive-order-of-interaction radiative transfer model: Part I: Model development, J. Appl. Meteorol. Clim., 45, 1388–1402, doi:10.1175/JAM2387.1, 2006.

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Natraj, V. and Spurr, R. J. D.: A fast linearized pseudo-spherical two orders of scattering model to account for polarization in vertically inhomogeneous scattering-absorbing media, J. Quant. Spectrosc. Radiat. Transfer, 107, 263–293, doi:10.1016/j.jqsrt.2007.02.011, 2007.

O’Dell, C., Heidinger, A. K., Greenwald, T., Bauer, P., and Bennartz, R.: The successive-order-of-interaction radiative transfer model: Part II: Model performance and applications, J. Appl. Meteorol. Clim., 45, 1403–1413, doi:10.1175/JAM2409.1, 2006.

O’Dell, C. W.: Acceleration of multiple-scattering, hyperspectral radiative transfer calculations via low-streams interpolation, J. Geophys. Res., 115, D10 206, doi:10.1029/2009JD012803, 2010.

Wiscombe, W. J.: The delta-M method: rapid yet accurate radiative flux calculations for strongly asymmetric phase functions, J. Atmos. Sci., 34, 1408–1422, doi:10.1016/0021-9991(77)90031-6, 1977.

Please also note the supplement to this comment:
http://www.atmos-meas-tech-discuss.net/8/C3297/2015/amtd-8-C3297-2015-supplement.pdf

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Interactive comment on Atmos. Meas. Tech. Discuss., 8, 8779, 2015.

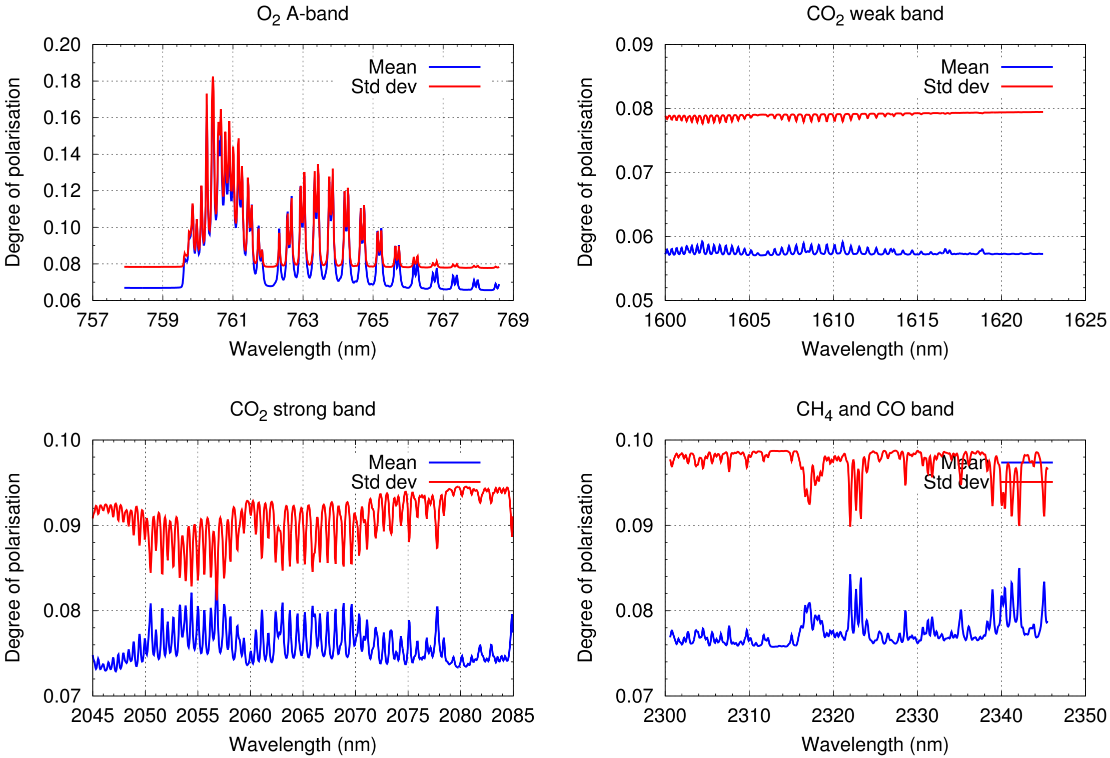

Fig. 1. Mean (blue) and standard deviation (red) of the degree of polarisation simulated at the top of the atmosphere in the geoCARB bands. The ensemble of soundings has cloud enabled.