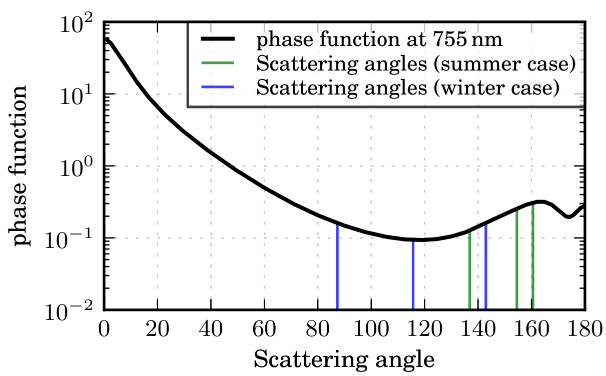
Response to Rev #3 (review comments in red, response in black)

This is a clearly written, well-focused paper on an important topic, namely the potential of detailed aerosol retrieval to support accurate CO_2 and CH_4 retrievals from NIR-SWIR spectrometry. Although earlier sensitivity studies have been published on aerosol retrievals from the O_2 A-band, this study demonstrates the advantage of multidirectional sensors for both aerosol and CO_2-CH_4 retrievals as compared to single view sensors. Also the study of the DOF dependence on FWHM and SNR is very useful (Figs. 5-6). The study is relevant for future GHG missions like OCO-2, but also for aerosol missions like 3MI.

Many thanks for this very positive overall feedback and the thorough and thoughtful review. We highly appreciate this effort in helping us improve the manuscript substantially!

At some places in the paper (like Sect. 3.2) a more physical explanation of the sensitivities found would be in place. Why are certain aerosol microphysical parameters better retrievable with multiple directions than other parameters? This must be due to the phase function effect. But this should hold also for particle size. Furthermore, some of the results shown in Fig. 2 seem counter-intuitive (see below).

We expanded on this aspect by adding:
"*In general, especially aerosol parameters which alter the phase function (see figure \ref{fig:phase}) will be retrieved with higher accuracy as the potentially dominant single-scattering contribution is sampled at various angles.*"
and also include (as requested by rev 2) a figure of the phase function. Figure 2 had some issues, which we solved (scaling of O_2 A-band Jacobian was wrong for the AOD!).



Specific comments

The comments below are mainly aimed at clarification, referencing, and improvement of presentation. When these comments are taken into account, the paper can be accepted.

Abstract:

p. 2858, l. 11: here - and in the Introduction - POLDER should be mentioned first, since POLDER was earlier than MISR in aerosol remote sensing with multiple viewing directions; and POLDER has more aerosol retrieval capabilities than MISR: more viewing angles, O2 A-band channel, and polarization capability.

Added POLDER in the abstract and put it first in the introduction.

Introduction:

- Missing reference on aerosol retrieval from the O2 A-band and sensitivity studies relevant to CO2: Boesche et al.: Aerosol influence on polarization and intensity in nearinfrared O2 and CO2 absorption bands observed from space, J. Quant. Spectrosc. Rad. Transfer, 110, 223–239, doi:10.1016/j.jqsrt.2008.09.019, 2009.

added

- Missing reference on the importance of multi-directionality for cloud geometric thickness retrieval from the O2 A-band: Ferlay, et al. 2010: Toward New Inferences about Cloud Structures from Multidirectional Measurements in the Oxygen A Band: Middle-of-Cloud Pressure and Cloud Geometrical Thickness from POLDER-3/PARASOL. J. Appl. Meteor. Climatol., 49, 2492–2507. doi: C11622ttp://dx.doi.org/10.1175/2010JAMC2550.1

added

- It should be noted that inclusion of polarization in the multidirectional measurements could also lead to more information on the aerosols, especially on the particle size.

Added: "*Polarization can provide further information especially on particle size but here we focus solely on the benefits of information from resolved absorption spectra.*"

Please give a reference of a POLDER paper using this information.

Added

- How many viewing directions will OCO-2 have ? (p. 2860, l. 4-5). Are the three viewing direction of Fig. 1 typical for OCO-2 ? Does the information content increase linearly with the number of viewing directions? This point occurs also later in the paper (in Sect. 2 an "arbitrary number" of viewing directions is mentioned).

This is somewhat tricky to answer. In principle, OCO-2 will provide measurements of the target spot every 1/3s while it overflies the target. This will results in almost continuous (>1000) angle coverage. However, the satellite may, on purpose, "jitter" a little and not keep staring at the exact same spot (providing some sampling). OCO-2 will definitely provide more angles than we could possibly use in a combined retrieval as ours (esp. as we invert already about 2500 spectral points per angle; if we had 1000 angles, our measurement vector would be of length 2.500.000). Choosing 3 angles was a rather arbitrary choice (based on an instrument concept currently under review) and we have yet to investigate the change in DOF as a function of amount of viewing angles. This will certainly be a topic of future research but currently beyond the scope of this work. Hence, we are afraid that we cannot yet answer your question regarding the information content increase as a function of # of viewing angles.

Sect. 2 p. 2861, l. 14: its > their, wavelengths > wavelength

Changed (thanks)

p. 2862, l. 15: reflectance > surface reflectance

Changed

Eq. 7: what kind of surface is represented by this equation?

The formula represents both soil and vegetation surfaces, or a mixture.
The parameters for the kernels chosen here represent a mixture of soil and vegetation.
We explained this more clearly and added the following reference:
Litvinov, P., O. Hasekamp, and B. Cairns, 2011: Models for surface reflection of radiance and polarized radiance: Comparison with airborne multi-angle photopolarimetric measurements and implications for modeling top-of-atmosphere measurements. Remote Sens. Environ., 115, 781-792, doi:10.1016/j.rse.2010.11.005.

Eq. 7: please explain the symbols representing angular quantities; show these quantities also in Fig. 1 and Table 2.

theta_s is solar zenith angle
theta_v is viewing zenith angle
phi is relative azimuth angle

l. 21: 1995).

Changed

l. 24: Lambertian

Changed

p. 2863, l. 15: are the aerosol refractive indices at the 3 or 2 bands allowed to vary independently from each other? Or is there some spectral relationship imposed on the refractive indices at the different spectral bands? Please note the large spectral distance of the 3 bands, which would make an assumption on a spectral relationship problematic.

So far, we didn't retrieve them independently. This would even enhance the benefits of the multi-angle mode as more angular information per band will be available. However, we would like to keep the study focused on fewer aspects for now and thus won't include this aspect.

l. 15: real-and > real- and

Changed

l. 17: column > column density

Changed

l. 26: what kind of surface does Lamont have? What is the typical albedo?

Typical surface albedos used in our study are listed in Table 1 (The scaling value). It would be 0.276, 0.216, and 0.1 for the three bands (O2, weak, strong). This is a typical vegetation spectrum. Added this to the table legend:
"*BRDF scaling factors per band are roughly equivalent to the Lambertian albedos observed over Lamont*."

p. 2864, l.2: Please mention that since the three viewing directions were chosen in the principal plane (0 – 180 deg relative azimuth) the information content of the three different viewing directions is maximized. In general, the information content of three viewing directions outside the principle plane will be less.

The simulations were actually not performed in the principal plane but an almost realistic scenario using solar azimuth angles typical for a GOSAT summer and winter case. The 0 and 180 degree azimuth are wrt to North, not relative to the sun. This is also one reason why the DOF in winter and summer changes (closer to the principal plane in winter, where the solar azimuth is about 200 degrees (i.e. multi-angle mode is "only" 20 degrees off from the principal plane).

l. 3: scattering angles > solar and viewing geometries. The scattering angle is a specific angle, namely the angle between the direction of incident sunlight and the direction of scattered light towards the sensor. This should also be corrected in Table 2. Please clearly introduce angles in Fig. 1.

We chose a different convention, basically showing 180-scattering angle. Corrected now (and also displayed in the phase function figure).

Sect. 3

p. 2866, l. 7: aerosols > aerosol

Changed (thanks)

p. 2867, l. 11: introduce here the abbreviation DOF

Done

l. 19: line-shapes

Changed (embarrassing, thanks).

p. 2868, l. 15: and/or

Changed

Sect. 4

p. 2870, l. 8: a priori > a priori value

Changed

l. 9: N should be in italics

Changed

l. 15: satellite > satellites

Changed (thanks for spotting all those very embarrassing typos!).

Tables and figures

Table 1: header: a prior > a priori

Changed, thanks

1-sigma: looks like a subtraction: 1 – sigma. Please adapt, e.g. 1sigma; same holds for text and captions.

Will remove the dash and say 1\,σ

Please specify together with the aerosol column density also the relevant aerosol optical thickness (AOT), since that is a more commonly used quantity for aerosol amount.

Added tau for each band in Table 1

What type of surface is represented by these surface parameters?

This is a typical albedo distribution observed over Lamont (vegetation). BRDF parameters represent a mix of vegetation and soil (realistic for a large footprint as GOSATs). Also added a reference (Litvinov) and text in the manuscript.

Table 2: Please specify all relevant angles: solar zenith angle, viewing zenith angle,r6elative azimuth angle, and scattering angle. Now the term scattering angle is incorrectly used for viewing zenith angle. For satellite observations, scattering angles are mostly > 90 deg. Show the relevant angles also in Fig. 1.

We didn't confuse scattering angle with viewing angle but just had a different convention (basically showed 180-scatteringAngle). We added the following to the table caption
"*Azimuth angles for the fore and aft satellite viewing are 180 $^\circ$ and 0 $^\circ$, respectively (i.e. straight south and north-looking). Satellites viewing angles for those off-nadir geometries are always 30 $^\circ$.*"

Fig. 1: show all angle definitions here. Here "viewing angle" should be corrected into "viewing zenith angle". What does the white-blue box mean? What does "scan" mean?

Unfortunately, my graphical capabilities are somewhat limited, making this a hard task (especially if 3D drawings are necessary, I tried my best). We added the explanation of the satellite azimuth angles in the caption and modified the figure as follows:

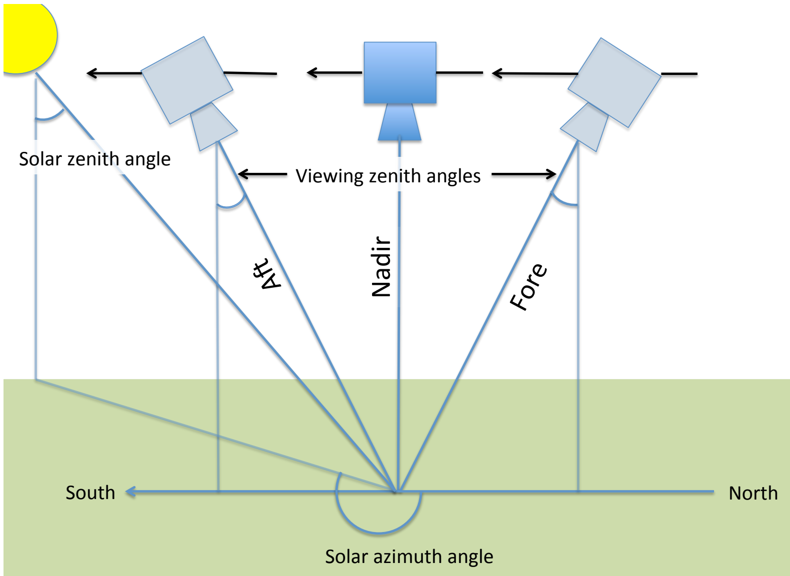


Fig. 2: Why is the sensitivity (Jacobian) of the O2 A-band to aerosol height so small? The values are around 10e−7 . This looks very unrealistic. How can it be that the CO2 band Jacobian for aerosol height is even larger than the O2 A-band Jacobian ?

Good catch! It turns out that this was indeed a bug in the plotting script, omitting the Jacobian scaling from meters to kilometers (i.e. the O2 derivative was in units of meters, the others in km). We fixed that.

Please explain the quantity along the y-axis. What is the unit? Or is it a normalized radiance? Is it a reflectance?

It is reflectance, will make this clear in the figure caption.

Fig. 2: how do the Jacobians look like for the SZA=20 deg case? Please add that figure, since the other figures are shown for both the large and small SZA cases.

Initially, we refrained from showing the 20 degree case because it is a large figure and mostly just illustrative (to get an intuition as to why the information content his higher from a more physical point of view). Looking at it more closely, there are some differences in the 20-degree case, so we included it in the manuscript. We will leave it up to the reader to fully interpret the differences in the plots.

In order to avoid confusion with the terms "high sun" and "low sun", please change in the figure captions and text: high solar zenith angle > large solar zenith angle low solar zenith angle > small solar zenith angle

Changed throughout the text.

Fig. 3: what is the a priori value of AOT at 760 nm?

0.1, see Table 1 (we now specify AOD at all wavelengths)

Figs. 5-6: please give the SZA in the caption.

Done