

Responses to reviewers: “The GHGSat-D imaging spectrometer”

We thank the reviewers for their comments and suggestions, which we address below. Reviewer comments are in *italics* and our responses are in normal font style.

Anonymous Referee #2

- 1) *P2, L25: “...which limits their detection sensitivity.” Can you state any more quantitatively what the detection limit of these coarse spectral resolution instruments might be? Even providing a range would be helpful to the non-expert (like me).*

Since the detection sensitivity not only depends on the spectral resolution, but on the specific spectral band and quantities such as the per-pixel signal level and absence of unwanted signal as well, it is hard to state a general quantitative relationship. Therefore, we have deleted this part of the sentence.

- 2) *P7, L21: It’s becoming “standard” in our community to use the “Geoff Toon” solar transmittance spectrum. Mainly because everything thinks Geoff is incredibly careful and pays more attention to detail than anyone else. In any case, typically the best residuals are yielded when you use this linelist. It may not matter much for your application, but just FYI. (https://mark4sun.jpl.nasa.gov/toon/solar/solar_spectrum.html, I recommend 2016, diskintegrated spectrum). You have to multiply by the solar continuum yourself.*

We switched to Geoff Toon’s solar transmittance in the past few months ago and have noticed an improvement in retrieval quality. We thank the reviewer for the suggestion.

- 3) *P8, L25: I do not understand why it is so computationally expensive. Your forward model is literally $F_{\text{sun}}(\lambda) * \mu_0 * \text{Albedo}(\lambda) / \pi * \exp(-m * \tau(\lambda))$, where m is the airmass factor. Nearly all the work is done in calculating $\tau(\lambda)$: $\tau(\lambda) = \tau_{\text{ch4}}(\lambda) + \tau_{\text{h2o}}(\lambda)$ $\tau_{\text{ch4}}(\lambda) = \sum_{i=1..N_{\text{layers}}} \{ \sigma_{\text{ch4}}(i, \lambda) * u_{\text{ch4}}(i) \}$ $\tau_{\text{h2o}}(\lambda) = \sum_{i=1..N_{\text{layers}}} \{ \sigma_{\text{h2o}}(i, \lambda) * u_{\text{h2o}}(i) \}$ The σ ’s can be calculated once for the whole scene (unless you’re retrieving surface pressure or temperature, which I do not think you are).*

The computational expense results from the evaluation of the instrument + atmospheric model rather than just the atmospheric model itself. In particular, our instrument model contains an integral which is slow to compute.

- 4) *P9, L5: Is retrieving d analogous to retrieving the wavelength shift and stretch for a standard GOSAT-type retrieval? If so, say so.*

We are not as familiar with GOSAT retrievals as the reviewer, but replacing a retrieval of d with the wavelength equivalent would require not only a shift and stretch, but also a nonlinear component to account for the cosine dependence of the FP transmission mode position on the camera. The benefit of retrieving the FP gap spacing d is that we are able to monitor this physical quantity over time to determine any mechanical or thermal drift.

- 5) *P9, Sect 4.5: It is hard to tell what you are doing without more information – could you please include a table that lists your state vector parameters, the source of your prior information or the prior values themselves, and the prior uncertainty you assume?*

As per Referee #1's comment (2), we have revised the manuscript to include information about what the atmospheric state parameters are. We have also revised the manuscript in Section 4.5 to mention that we currently set the prior variances large enough that the state parameter estimate is entirely determined by the data.

Also, do you assume any spatial pixel-to-pixel correlations in your prior covariance matrix?

We do not assume any spatial pixel-to-pixel correlations in the prior covariance matrix.

Do you retrieve a scale factor for CH₄, CH₄ in the boundary layer only, or a full profile in some way? Etc. {It looks like you retrieve "VCD". But do you spread this equally in the vertical? Ie, you might have sensitivity to HOW you retrieve CH₄. What if you put it all in the boundary layer? Because the gas absorption cross section is different down there, I expect it will affect your results in a small way.}

We have revised the manuscript to include the fact that the molecular components of the Jacobian are calculated assuming an enhancement in the lowest atmospheric layer only.

Also, I'm surprised you can use AIRS. Plus AIRS will die someday. And all the decent NWP models assimilate it anyway. Why not just use GEOS5 or ECMWF model output?

We thank the reviewer for this suggestion. We will investigate incorporating these data sources.

Additionally, where does your prior surface pressure and temperature profile come from?

We state in Section 4.2 that we use the US_Standard pressure and temperature profile.

Do you assume a fixed surface elevation across the field of view, or do you use a high-res DEM to get the surface elevation for each pixel, and a hypsometric adjustment to determine the prior surface pressure of each pixel? You don't say anything about if you can do this over complex topography or not.

Yes, we assume a fixed surface elevation across the field of view. Given the GHGSat-D error levels, we are only sensitive to elevation changes of approximately >1km.

Finally, can you say how many iterations this takes typically, and how long the retrieval takes for one full scene of data (on however many CPUs you typically use).

We have revised the manuscript and included this information in Section 4.3.

Same paragraph – do you have any way to test for and remove bad pixels? You could also attempt to include a stray light parameter or two in your forward model. You'd probably have the information content to solve for it.

We do test and remove bad pixels, as noted in Section 4.6. We thank the reviewer for the suggestion to try and retrieve stray light in our retrieval.

- 6) *P12, L10: I'm really surprised by this 6.5% theoretical (noise-drive) error. This is something like 120 ppb of methane. TROPOMI has errors more on the order of 10 ppb. And your number assumes PERFECT knowledge of temperature, water vapor, surface albedo, surface pressure, spectroscopy, instrument, etc. Literally everything but the instrument noise, which isn't bad; you list radiance SNR = 200 at these conditions. I have a feeling that if I wrote my own simple Beer's law forward model in wavelength space, and put an SNR of 200 per channel, using your spectral resolving power, I'd get a posterior uncertainty of less than 1%. What am I missing? In other words, can you say why this noise-driven uncertainty is so large compared to what a grating instrument with a similar SNR and spectral resolution would achieve?*

The difference between a grating instrument and our FP instrument is that we have multiple FP modes contributing to the signal at a given camera pixel, which can reduce the fractional absorption and hence methane sensitivity if not properly optimized, as is the case in GHGSat-D. In the recently launched GHGSat-C1, the FP spectroscopic configuration has been chosen such that shot-noise limited posterior error is indeed less than 1%.