Atmospheric Measurement Techniques
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Interactive comment on "Cross-track Infrared Sounder (CrIS) satellite observations of tropospheric ammonia" By M. W. Shephard and K. E. Cady-Pereira

Anonymous Referee #2
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We would like to thank the Reviewer for their valuable comments and suggestions. Below we carefully answered all the Reviewer's comments. We also indicated where we modified the manuscript based on the comments.

This paper describes a retrieval procedure for ammonia in CrIS measurements. The details of the retrievals are described clearly and completely, employing both synthetic and real atmospheric spectra. I would recommend publication with minor changes.

The authors deduce a lower detection limit of 1 ppb, but there is no mention of what sort of geographic coverage that implies for the CrIS NH3 measurements. They define scenes with less than 1 ppb of NH3 as unpolluted, and in the real measurement example provided, NH3 was apparently below the detection limit for a small number of scenes, but this strongly polluted region is obviously not typical. I do not think a detailed discussion is required, but I thought it might be worthwhile to indicate whether their 1 ppb detection limit means 1) they would only be measuring a relatively small number of localized "hot spots" or 2) they anticipate observing a broad range of geolocations (and seasons) for which NH3 will exceed 1 ppb.

The short answer is that the detection limit of 1 ppbv is a typical peak profile value (generally at the surface), but in very ideal cases it can be smaller (for example Figure 5 in the 1<SNR>2 bin there are some (less than 10% of the profiles) with peak values of 0.6 ppbv that are detectable). Since these would be fairly rare, we decided to quote the median value in this 1<SNR>2 bin, which is ~1 ppbv.   We did include unpolluted scenes in order to span the range of possibilities when determining the lower detection limit.   In the real examples provided the ammonia values generally are at levels above the surface (~1-2km). Since the ammonia profile concentrations drop off very quickly with height, a more "unpolluted" profile with a surface value of 1 ppbv often has a much smaller value at the peak sensitivity of the aveaging kernel (i.e.850 mb).

To make this more apparent in the manuscript we added the following text and then included a spatial plot showing a range of values.

1) In the abstract we added "...a minimum detection limit of ~1 ppbv (peak profile value usually at the surface)"
2) We added in section 6.1.2 CrIS Minimum Dectection Threshold section, "Figure 4 contains scatter plots of individual peak profile NH_3 amounts, which as shown in Figure 2 are typically the surface value, as a function of the SNR under different thermal contrast (surface – atmosphere) conditions, and as a function of the retrieval information (DOFS)."
3) We also added the word "(surface)" everywhere after that in which the peak profile value is mentioned in section 6.1.2.
4) We also added to section 6.2.2 "Note, that since the QCL measurements are at the surface and the satellite measurements represent boundary layer values at ~1-2km where the ammonia concentrations are much reduced, the QCL observations are scaled by 1/6 for relative comparison purposes only. "
5) Modified it in the conclusions to, "It has a minimum NH_3 detection limit of ~ 1 ppbv (peak profile value typically at the surface). "
6) To provide a little more insight into the geographical distribution we have included a figure in the paper of ammonia amounts over California (Section 6.2.3). In this example we see a wide range of ammonia concentrations, from low levels in the mountains to elevated amounts in the valley.

6.2.3   Spatial Distribution of NH₃ over California, USA.

To further demonstrate the capabilities of CrIS NH_3 observations, retrievals were performed over the state of California, USA on 13 June 2012 (Figure 11). This region was selected because it contains a range of NH_3 emissions with large spatial variability; there are very elevated NH_3 concentrations due to anthropogenic emissions from fertilizer applications and livestock waste, as well as unpolluted non-agricultural rural regions (i.e. mountainous regions). Note that this is not 28 January 2013 scene used in the comparisons above, as we wanted a scene with minimal cover over the entire state, and the 28 January 2013 had some clouds over this larger domain. The volume mixing ratio values in Figure 11 are from the peak sensitivity level of the CrIS retrieval, which ranges from 700 to 900 hPa. Ammonia volume mixing ratio values over the Central Valley, one of the world's most productive agriculture regions, and the Imperial Valley, which also has an economy based on agriculture, are elevated with values in the ~4-15 ppbv range at 909 hPa. In more rural non-agricultural regions the values are reduced to values below 2 ppbv at 909 hPa. Areas in white have ammonia signals so low that either no retrieval was performed or the retrieval had less than 0.1 DOFS. This example demonstrates CrIS' ability to monitor the daily spatial distribution of ammonia.
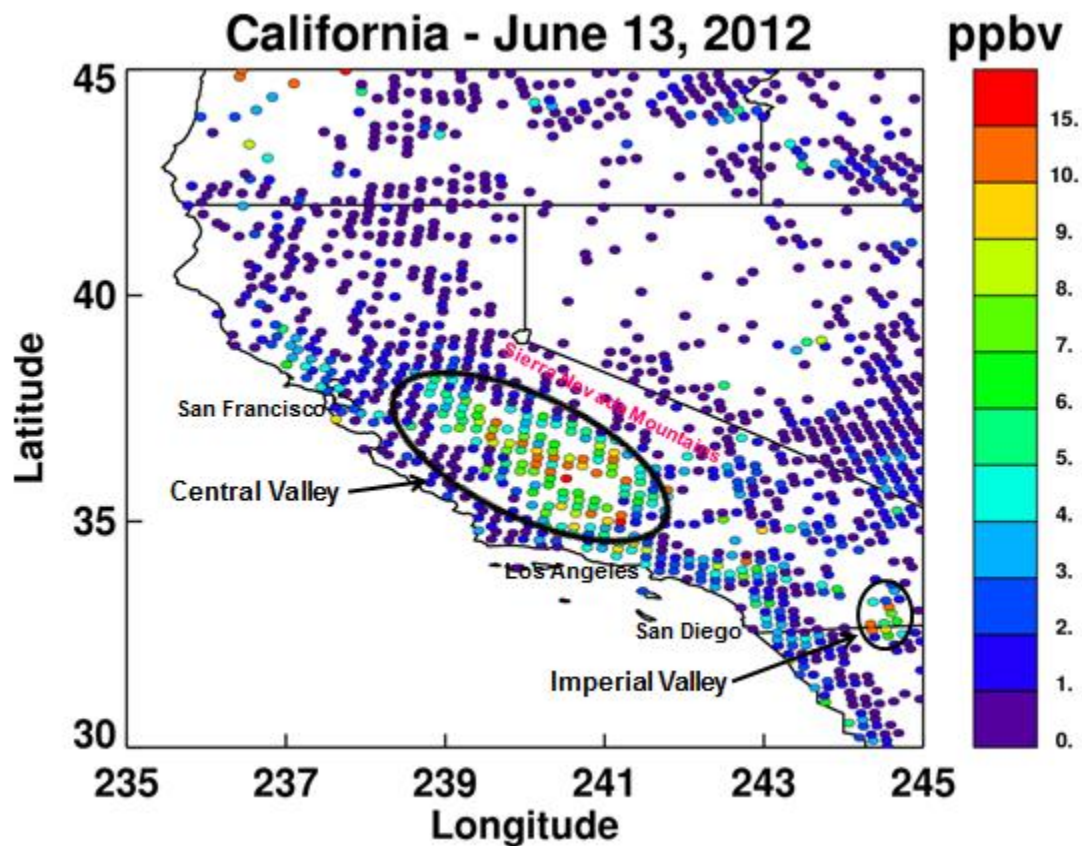
Figure 11. CrIS NH3 VMR retrievals over California, USA on 13 June 2012. Shown in the plot are the retrieved values at the 909 hPa (~1 km) retrieval level.

On a related note, in the IASI description the lower detection limit discussion was modified to include updated information from a very recent AMT paper. Added to the manuscript was the following, "Under conditions of elevated ammonia amounts and favourable thermal contrast, IASI has peak sensitivity to atmospheric ammonia in the boundary layer (Clarisse et al., 2010). Van Damme et al. (2014) using the IASI NH_3 Hyperspectral Range Index (HRI) retrieval method provides a minimum detection total column amount of ~1.7×10^{16} molec cm^{-2} under more favourable retrieval conditions (thermal contrast ~10 K), which is the most relevant quantity from the HRI retrieval. In a more recent overview HRI evaluation provided by Van Damme et al. (2015) they report these minimum detection total column values as the corresponding surface concentrations of 3.05 μg NH3/m^3 (thermal contrast of 10K) and 1.74 μg NH3/m (thermal contrast of 20 K), which for comparison purposes with CrIS (and TES) represents estimated minimum surface volume mixing ratio values of ~4.3 ppbv (thermal contrast of 10K) and ~2.4 ppbv (thermal contrast of 20K) (values extracted from supplemental figure R1 in Van Damme et al., 2015b) . These results are fairly consistent with earlier IASI NH3 an optimal estimation (which more similar to the CrIS) retrieval results by Clarisse et al., (2010) that more vaguely states that

under atmospheric states with large thermal contrasts the lower bound minimum detection threshold is a profile with a surface value of ~3 ppbv."

page 11393, line 5: There is a reference to Section 6.1.2, but that is the section we are in. I believe the reference should have been to Section 6.1.1.

You are correct. It was actual correct in my Word document, likely the cross-reference did not update properly before generating the pdf version. It is now correct.

page 11388, line 9 and line 11: You refer here to Section 3.3 showing the spectral region employed in the retrievals. I believe you intended to refer to Figure 1, not Section 3.3.

Yes, again it is correct in my Word document. Some of the cross-references must have got mixed-up on the submitted versions. "Figure 1" is the cross-reference here as noted.

page 11383, line 11: the acronym SNR is used here without defining it. However, the acronym is loosely (linking it to signal-to-noise instead of signal-to-noise ratio) defined later, on page 11385, line 12 and again (more properly this time) on page 11389, line 7 and once again on page 11393, line 5. Define the acronym only once, when it is first used.

The SNR on page 11383 refers to the specified radiometric SNR of the instrument itself, where 11389 the SNR is defined more as a scene derived SNR in terms of the ratio between the NH3 signal and the background. Nevertheless, they are both SNR and so the acronym should be stated only once on page 11383 where it is first used. This has been corrected in the manuscript as suggested by the Reviewer.

page 11385, line 20: the acronym RVMR is used without definition.

It is now defined in the manuscript as suggested.

In Section 2.1.2 (and elsewhere), the units ppbv are used, while in Section 2.1.3, ppb is used. It should be consistent. I believe the "v" is redundant when talking about a volume mixing ratio, which means ppb should be used rather than ppbv, but perhaps there is an accepted standard of usage that should be followed.

We agree that "v" is likely redundant if volume mixing ratio is already explicitly stated. However, in places where it is not spelled out it helps to separate it from mass mixing ratio. Thus, to be consistent we used ppbv everywhere in the text, even though we agree at times it is redundant as pointed out by the Reviewer.

page 11389, line 25: here you mention the TES averaging kernel, when you should probably be talking about the CrIS averaging kernel. The discussion is general, of course, not tied to a

particular instrument, but there is certainly no reason to be referring to the TES averaging kernel here.

We completely agree. Since this is a general discussion we change "TES" to "satellite".

page 11380, line 24... directly or indirectly impact air quality, should be...Directly or indirectly impacts air quality,

Corrected in manuscript as suggested.

page 11382, lines 20-21:...using IASI observations...should be...used IASI observations...

Corrected in manuscript as suggested.

page 11383, line 1: in order to development and evaluated a new...should be...in order to develop and evaluate a new...

Corrected in manuscript as suggested.

page 11383, lines 18-19:...with coincident TES satellite, Quantum Cascade-Laser...should be...with coincident TES satellite and Quantum Cascade-Laser...

Corrected in manuscript as suggested.

page 11384, line 9:...a across...should be...a cross...

Actually, it should be "CrIS is an across track…" The manuscript was modified.

page 11392, line 26:...where full atmospheric state...should be...where the full atmospheric state...

Corrected in manuscript as suggested.

page 11392, lines 27-28:...on average the peak sensitive in the vertical region from ~850-750 hPa...should presumably be something like...on average the peak sensitivity occurs in the range ~850-750 hPa...There appears to be some confusion about the sensitivity peak in the article. Here you give the range 850-750 hPa. This agrees with the value 800 hPa mentioned in the abstract, but on page 11396 and in the caption of Figure 9, you state a value of 900 hPa, which does not fall in that range. On page 11397, you give a range of 900-750 hPa. Perhaps this could be made more consistent.

Yes, we see the Reviewer's point and we need to make this more consistent. In summary what was provided in the text is:

1. On page 11392 we referred to the 850-750 hPa mainly from Figure 3 where the 750-850 bin show the most sensitivity. Then next bin is 850-950 hPa, which includes less sensitive retrievals below 900 hPa so we cannot say much about the 900 hPa range from this Figure. Thus, here we could just state that the most sensitivity was in the 850-750 hPa bin, or also refer to Figure 2 and state that on average the main sensitivity is in the 900-750 hPa region.
2. On page 11396 it is referring to the central valley example, which are more ideal and not "typical" or "average" NH3 conditions, thus here having averaging kernels down to 900 hPa would seem reasonable.
3. In the Figure 9 caption, values at 900 hPa were chosen as it was the level where most of both CrIS and TES showed there peak sensitivity (again more ideal and not typical conditions for NH3 retrievals).
4. In the conclusions we did not state whether or not it was typical or average and just state that its peak sensitivity is in the ranges from 900-750 hPa.

We modified the manuscript to provide more description of each situation in order to better relate the reported vertical sensitivities through-out the paper more closely. We modified the text as follows:

For (1) we changed the sentence to: "The sum of the rows of the averaging kernels in Figure 2 show that the peak sensitivity generally ranges from ~900-700 hPa, with the summary statistics in Figure 3 showing that the ~850-750 hPa (~1.5 to 2.5 km) bin (on average) has the greatest peak vertical sensitive for these simulated cases that span a large range of atmospheric states.

For (2) and (3) we modified the sentence to : "The peak vertical sensitivity for the satellite retrievals under these more ideal retrieval conditions is around 1-km (900 hPa), with CrIS sometimes having its peak sensitivity as high as ~2.5 km (750 hPa). "

For (4) in the conclusions we modified the sentence to: "The peak CrIS sensitivity to NH_3 is in the "boundary layer" as it is mostly sensitive in the range from 900-750 hPa (~1.0 - 2.5 km) depending on the atmospheric conditions. "

We also change the abstract to: "…sensitive to ammonia in the boundary layer with peak vertical sensitivity typically around ~850-750 hPa (~1.5 to 2.5 km), which can dip down close to the surface (~900 hPa) under ideal conditions,…"

page 11393, line 12:...contains a scatter plots of...should be...contains scatter plots of...

Corrected in manuscript as suggested.

page 11397, line 3:...and range from 900-750 hPa...should be...and ranges from 900-750 hPa...

Modified the sentence.

page 11397, line 4:...information content with most 1 piece...should be...information content with at most 1 piece...

Corrected in manuscript as suggested.

Caption to Figure 1: an acronym (TOA) is used here that is not defined in the text.

Defined in caption as suggested by Reviewer.

One addition change to the paper is we added in the standard deviation to the summary statistics from the simulations as this is a statistic metric that more people can relate to, also it is good to compare against the estimated CrIS errors that come out of the optimal estimation retrieval method. "...with a standard deviation of ~±20% (ranging from ±12% to ±30% over the vertical profile)."