Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2017-437-AC2, 2018

Atmospheric Measurement Techniques Discussions

Interactive comment on "A highly miniaturized satellite payload based on a spatial heterodyne spectrometer for atmospheric temperature measurements in the mesosphere and lower thermosphere" *by* Martin Kaufmann et al.

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Received and published: 27 April 2018

Reply to the reviewers' comments: Reviewer #2

General

We thank the reviewer for carefully reading the manuscript and his/ her constructive and helpful comments and suggestions. They helped us to improve the paper in several

aspects. Before we consider them point by point, we like to make the following general remarks:

- The section about the instrument characterization was criticized by the reviewers and we restructured it.
- Further analysis of the spectral power estimation using subspace methods revealed some problems when dealing with interferograms with finite spectral resolution. For the figures shown in the first version of the manscript, infinite spectral resolution was assumed, which is not realistic. To handle finite spectral resultion with subspace methods, the number of spectral components has to be increased, but to develop concepts for further analysis of this kind of data is ongoing work not in the shape to be presented here. Therefore, all analyses and performance assessment in the second version of the manscript is based on conventional Fourier transformations.
- We corrected the value for the etendue of the instrument, which referred to the full circular aperture, but we use an inner rectangular for the later analysis, only. This reduces the orginal value of 0.014 cm^2 sr by about 1/3.
- some numbers (like the image size or spectral resolution) differed slightly across the document and were harmonized

Point by point response

1.: *The paragraph following equation 4 suggests that "the effective spectral resolution or bandpass is often limited by the detector resolution". Although the bandpass is limited by the detector resolution, as indicated by equation 5, the spectral resolution is not. The spectral resolution is independent of the detector resolution as it depends on* *two things: 1. The path difference provided by interferometer (as correctly captured in equation 4) and 2. any apodization functions applied to the interferogram.*

Reply: agreed, we changed the text accordingly.

2.: *The final paragraph of section 3 indicates that the design of the instrument was performed in a collimated configuration. I assume this to mean that only incident rays parallel to the optical axis were used during the optimization of the design. It would be useful to indicate the effect of converging ("focused") beams on the interferogram. Is there any reduction of contrast of the fringes, especially at the edges of the field where the path difference is largesft, due to the addition of the off-axis rays? Figure 6 and surrounding discussion suggest so.*

Reply: This text was misleading and we removed it. We designed and optimized the SHS using converging beams, but we were not able to calculate interferograms in this configuration at the time of the SHS design (not supported by raytracing software). This worked only for collimated light and therefore our first interferograms were calculated for collimated light only. However, in the meantime we control the raytracing software in such a way that we are able to calculate interferograms for the focused configuration as well, which we show later in the paper.

3.: *The description of the front optics in section 4 and table 1 indicate that the image of the limb formed on the grating plane is a circle of diameter 7 mm. If the image is circular, the highest and lowest altitude slices at the top and bottom of the image will suffer greatly reduced spectral resolution as they only sample a very small range of the interferometer aperture and only near zero difference. These altitudes will also have significantly reduced etendue due to their small spatial extent. To achieve uniform spectral resolution and etendue for each altitude slice the limb image on the grating and ultimately recorded at the detector should be rectangular as indicated in figure 4. It appears from Figure 5 that there is nothing in the entrance or exit optics that will result in a circular field and is reality limited by the grating or detector, both of which*

are presumably rectangular.

Reply: We agree, our wording was imprecise and not correct in all points. We changed the text in the following way: 'The front-optics consists of four lenses, which image an object at infinity onto a square with an edge length of 7 mm on the virtual image of the gratings. This corresponds to a theoretical spectral resolution of about 16,800. The maximum chief ray angle extent is about 1.9^o, such that a rectangular object with an angular extent of 1.3^o can be captured without vignetting.'

4.: *- The final paragraph in section 4 suggests that a simulation using focused light indicates a reduction of fringe contrast near the edges of the image where the path difference is large. It would be helpful to indicate by how much the contrast is reduced. A plot of intensity vs pixel for a slice through the image shown in figure 6 which shows the fringe reduction would quantify this statement.*

Reply: Agreed, we added a 1d plot of the interferogram and the following text: 'The detection plane was placed between the focal planes for the on axis and the 0.65^o off axis light source points as a compromise, and closer to the latter one to enhance the visibility on the edges of the interferogram. Nevertheless, the visibility reduction is about 1/3 towards the edges. Interestingly, the highest visibility is achieved by placing the detector plane outside both focal planes in a plane which is near the on axis focal point. The suspected reason is that the shape of the focal spots, which are blurred by aberrations resulting in a reduction of visibility, becomes more compact if the detector plane is positioned slightly out of the on axis focus, yielding to higher contrast (Figure 7).'

5.: *The discussion section 5 of the effect of dark current on the measurement is confusing and on its surface appears to be wrong. It is stated that the dark current at 20 deg C is a factor of 2.4 larger than the maximum atmospheric nighttime signal it does not significantly affect the signal because the multiplex noise is a factor of 5 – 10 larger. I don't believe this is the case with the spatially sampled interferogram obtained with*

SHS. From a noise perspective signal and dark generated electrons are equivalent so if the total number of photons detected in the signal is less than the total dark signal (either on a pixel by pixel or entire detector basis) the noise from the dark signal will dominate. As the authors point out, cooling the detector can reduce the dark signal. It would seem from the discussion that if the dark noise were to be made comparable to the maximum signal, the detector should be cooled to about 10 deg C.

Reply: agreed, our wording was not correct and referred to the signal of a single emission line. We give the expected photon flux per pixel earlier in the chapter (40 ph/s, not given explicitely in the previous version) and changed the statement related to the significance of the dark current in the following way: 'At 20°C, the dark current is at least a factor of 5 lower than the atmospheric signal in the emission layer maximum and therefore not a dominant source of random noise at these altitudes. This becomes more critical at other altitudes and for higher detector temperatures.'

6.: *The discussion in section 6.2 on image and phase distortion correction was confusing. I agree in principle that by measuring the fringe pattern at all wavelengths in the passband of the instrument, corrections for exit optics induced image distortion, which displaces each image point by a fixed distance on the detector, and interferometer induced phase distortion, which changes the phase of a fringe by a fixed amount can be obtained. Note that phase distortion shifts the location of, say, a peak of a fringe by more pixels at low spatial frequency than at high spatial frequency while image distortion would shift a peak by the same number of pixels independent of the frequency of the fringe. That said, it is unclear from the discussion how this will be accomplished in practice. Reference is made to fitting a linear or higher order polynomial correction term to each row, however it is not clear what would be fit: phase?, visibility?, brightness? something else? More discussion here would be helpful.*

Reply: agreed, we have re-written the entire chapter.

7.: *Figure 7 and surrounding discussion suggests that an improvement of factor of 2 in*

noise performance over conventional FFT methods can be achieved by utilizing a-priori information in the fitting process. There isn't enough information in the manuscript to evaluate this technique, however, reference is made to a manuscript in preparation describing the technique and its application to SHS. I look forward to reading this manuscript.

Reply: section removed, see general remark.

8.: *Both the abstract and conclusions suggest that the instrument can deliver a 1-2 K temperature precision for a one-minute nightglow observation and a few seconds during the day. I would have liked to have seen more support for this statement in the manuscript. Has it?*

Reply: We added the following text: 'The required signal-to-noise ratio to achieve a given temperature precison was determined by Monte-Carlo simulations: First, a simulated spectrum with the optical resolving power of 16,800 was calculated. This spectrum was inverse Fourier-transformed and white noise was added. In the next step, the spectral power in the various frequencies was estimated by applying a Fourier-transformation using a windowing function. The resulting spectra were then used to retrieve an atmospheric temperature profile and some other instrumential parameters, such as the spectral resolution of the data. Considering the intensity of the A-band signal of the nightglow layer maximum and the detector performance, the expected signal-to-noise ratio for a vertical resolution of 1.5 km and an integration time of 60 s will be 10-20 in the nightglow maximum, resulting in a retrieved temperature precision of 1–2 K.'

9.: *Technical Corrections: - The figure 4 caption indicates that the figure will be updated. There are two missing "C"s to indicate degrees Centigrade in the text immediately following figure 4.*

Reply: agreed, this was a pdf problem in the final document, corrected