Answers to Anonymous Referee #2, 29 Apr 2021

'Number of comments on amt-2020-521.'

We like to thank the reviewer for carefully examining our manuscript and for making many suggestions for improvements.

At this point we wish to make a general statement: In our manuscript we intent to present largely theoretical considerations about new ways to significantly (by two orders of magnitude) reduce volume and mass of spectrometers for environmental remote sensing applications. These considerations are based on first principles and we are glad that this is recognized by the reviewer. However, we neither intent to present a plan for actually realizing an array of spectrographs nor are our considerations restricted to satellite instruments.

Several of the reviewer's comments are aimed at very practical points (like the cabling, etc.), which of course will be of great important once (we hope soon) such an instrument is actually designed and manufactured. However, at the present stage, when the fundamental superiority of our approach is discussed these practical points tend to obstruct the grand view. We, therefore, answer to the points raised by the reviewer, but took the liberty to take up the majority of the technical issues raised in a general paragraph of the revised manuscript, but not in detail within other parts of the manuscript.

With this in mind we responded to all comments and suggestions (reproduced below in normal font) and – in most cases – made appropriate changes to the manuscript. Our responses are given in bold font below. Changes to the manuscript are given in red.

We are confident that we answered all questions and comments and that the revised version of the manuscript is considerably improved over the original version (in AMTD). We trust that the accordingly revised manuscript will be suitable for publication in AMT.

Reviewer's comment (here and throughout the rest of the document in normal font):
This is an interesting paper for exploring and discussing new possibilities to perform atmospheric trace gas measurements using satellite-based spectrographs that try to fundamentally improve on the concepts of predecessor instruments.

Answer: We like to thank the reviewer fort he positive assessment of our manuscript.

Traditionally, the sizing of predecessor instrument has been driven by user requirements on signal-to-noise and spectral resolution and sampling that are in some cases questionable when the resulting L2 data products are inspected afterwards.

Answer: Not quite clear what the reviewer is referring to.

The paper could benefit from a section of requirements in order to clarify which L2 data products are targeted with the optimised spectrometer design.

Answer: The requirements for an instrument based on our proposed design principles would be no different from the requirements for e.g. TROPOMI. We simply suggest a design that would accomplish the same with about one hundredth of the mass.

For example, from use perspective, the high spatial resolution of e.g. 1 km x 1 km in the spectral range 270-500 nm would 'only' benefit NO2 retrievals, for which a very limited spectral range (e.g. 420-450 nm) with high spectral resolution would be sufficient.

Answer: In our opinion from a high spatial resolution of e.g. 1 km x 1 km in the spectral range 270-500 nm not only the NO_2 retrievals would benefit, but also the retrieval of SO_2, BrO, IO, OClO, HCHO, O_4, glyoxal, and water vapour.

Changes to the manuscript: We add text clarify that point.

It is the combination of various requirements for various L2 products that are all given priority 1 that often drive the size and mass of these type of satellite UV-VIS-NIR-SWIR spectrometers.

Answer: See above

Properly accounting for polarisation has had a tendency in the past to increase instrument size (see also section 3.5).

Accepting the resulting errors from ignoring polarisation can be used to reduce the instrument size (and mass) considerably.

Answer: We agree with the reviewer regarding the question whether the polarisation measurement should be made or whether accepting the resulting errors from ignoring polarisation should not rather be used to reduce the instrument size (and mass).

Changes to the manuscript: We add text clarify that point.

In my view the paper could be further improved with some additional comparison information:

- Size comparison for predecessor instruments.
- Size comparison for 1D vs 2D predecessor instruments.

Answer: While we agree with the reviewer that more size comparisons may be interesting in principle we state that the aim of the manuscript is not the comparison of satellite instruments (that would be an interesting task in itself) but to propose a new approach to

spectroscopic instrumentation for environmental measurements – from satellite, other platforms, or from the ground. The size comparisons we are giving should be seen as examples fort he new possibilities.

Changes to the manuscript: We add text clarify this point.

Section 3.5 Further considerations

I don't share this statement:

"Obviously, for very small spectrometers the depolarizer will also be very small, thus adding negligibly to the volume and weight of the instrument."

Depolarizer plates work on the basis of spatial randomisation of the atmospheric polarization, which requires a certain minimal spatial size of the entrance aperture and depolarization plates. Has this been considered?

Answer: The reviewer gives no argument why the depolarizer should not be very small. In the following we will give a brief argument why our statement regarding the small (compared to the spectrometer+telescope) size of a polarisation scrambler is likely to be valid:
In order to estimate the size of a possible polarisation scrambler we have a look at the sketch of a depolarizer in Fig. 1. Across the combination of two wedged plates (shown in cross section) the polarisation changes from: Linear (e.g. vertical as shown in Fig. 1) - circular – linear (90^o twisted) – circular (opposite direction) – linear (vertical again). The required change of thickness Δd across the plate is given by $\Delta d = \lambda/\Delta n$, where Δn denotes the difference in the index of refraction for the ordinary ray and extraordinary ray, respectively. Typical values of Δn are around 0.01 (e.g. 0.009 for quartz). For λ=400nm a Δd of about 40μm would result. The polarisation scrambler would e.g. be mounted in front of the telescope. At a telescope diameter D_T of e.g. 12mm (see Table2, scaled 2-instrument) this would result in a wedge angle of $\alpha\approx0.003$ radian or about $\approx$0.2 degrees. In practice one might prefer not have only one cycle through the polarisation states, but rather e.g. 10 cycles, corresponding to an angle α of $\approx$2 degrees, (which is in fact close to the wedge angles of 0.6^o and 1.35^o given for the TROPOMI polarisation scrambler, as given in the "Algorithm theoretical basis document for the TROPOMI L01b data processor", document number S5P-KNMI-L01B-0009-SD, CI identification : CI-6480-ATBD, issue 8.0.0 of June 1, 2017). The plate could be 1-2mm thick. In summary, this small device would hardly contribute much to the total weight or volume of an individual spectrometer+telescope assembly. Regarding the comment of the reviewer that a "certain minimal spatial size of the entrance aperture and depolarization plates" is required, judging from the TROPOMI telescope size ($25mm^2$ area as stated in the "Algorithm theoretical basis document …", corresponding to a diameter <6mm) the scrambler diameter of the proposed 'scaled 2' instrument would be twice as large than that of TROPOMI.

Changes to the manuscript: We added a sentence stating that the size of a possible polarisation scrambler would be comparable to the device used in TROPOMI and its weight and volume would be small compared to the spectrometer+telescope units.

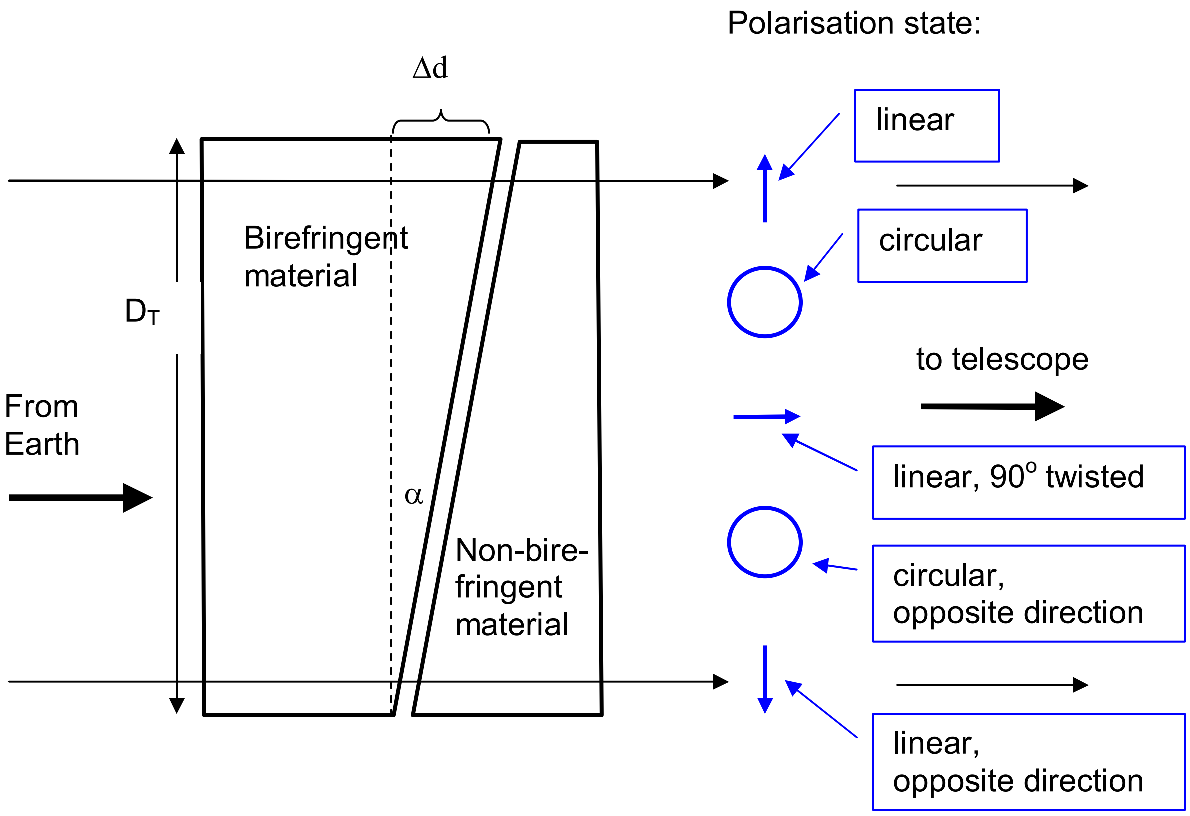

Fig. 1: Cross-section through a polarisation scrambler: Two wedges, the left made from birefringent material (e.g. crystalline quartz), the right from non-birefringent material (e.g. vitreous quartz) act to change and twist the polarisation state (shown in blue). The non-birefringent wedge is only needed for compensation. By superimposing many polarisation states the original degree of polarisation of the incoming radiation polarisation is (nearly) lost.

Section 3.6 How to combine the signal of a large number of spectrographs?

This chapter is a bit an oversimplification of a post-processing issue to combine the data of the various spectrometers that may become problematic in terms of efforts and processing power.

Answer: Clearly, there will be some software development needed, however it is about e.g. shifting/stretching spectra to match each other, well known principles (see e.g. Platt and Stutz 2008)

Changes to the manuscript: We add text to clarify that point.

Section 3.7 How to manufacture arrays of (micro) spectrographs?

This is a bit of an oversimplification, because the issue is not so much the manufacturing costs, but more the space qualification and documentation costs.

Answer: It is likely that some development will be needed. However, it is unclear whether space qualification and documentation of a large number of identical (and rather simple) spectrographs is more effort than that of a single (relatively complicated) spectrograph.

Changes to the manuscript: We add a sentence to make that point.

Section 4.1 is not fully understood, because here the authors start to use two competing objectives without making clear (to the opinion of the reviewer) how these are combined:

1. Using multiple small spectrographs to each observe a different ground pixel, whereas an instrument such as TROPOMI observes all ground pixels simultaneously.
2. Using multiple small spectrographs to each observe the same ground pixel, in order to improve signal and signal to noise using multiple similar small spectrographs instead of one bigger one.

For example, in table 2, the TROPOMI type has 576 ground pixels per spectrograph, whereas the 'Scaled 1' has 6 ground pixels per spectrograph.

Hence to cover the same spatial range and resolution on the ground the 'Scaled 1' needs 576/6=96 spectrographs.

The number of spectrographs difference is 100, which thus covers only for the above spatial range/resolution per spectrograph, not for signal / signal-to-noise.

Answer: In section 4.1 we explain that there could be one spectrograph per viewing direction or several („one or more“). These two approaches are not competing, they are just options in case the light throughput of a single, scaled down spectrograph is not sufficient then several spectrographs (with their own telescope each) could observe the same ground pixel.

Changes to the manuscript: We add text clarify that particular option.

Using mechanical scanners, as mentioned earlier in the section, doesn't comply with the simplicity and small design of the downscaled spectrographs.

Answer: This is a misunderstanding, in line 33 of page 15 (which is the only point in this section where we mention a scanner) we refer to scanners being used by existing, conventional instruments (e.g. the GOME-series). We do not suggest to use mechanical scanners.

Changes to the manuscript: We add text clarify that point.

I find the conclusion section 5.2 somewhat biased and not considering all advantages and disadvantages equally, and to some extent also comparing different things. See also the above comments.

Answer: Obviously our summary is trying to list the strong points, but we also point out some problems at the end of the summary. In order to come to a more balanced presentation we added text to list more possible hurdles to the implementation as given by both reviewers.

Changes to the manuscript: We added text to list more possible hurdles to the implementation as given by both reviewers.

I am not convinced that at the same spatial resolution and range, same spectral resolution and range and the same user / L2 requirements the option of the array of identical downscaled spectrographs presents a significant mass volume advantage. I find this aspect is not conclusively demonstrated in the preceding sections and I encourage the authors to improve this demonstration, including the aspects also mentioned here, e.g. by clearly separating the aspects of number of ground pixels per spectrograph and signal/signal-to-noise per spectrograph.

Answer: We are somewhat surprised by this conclusion of the reviewer, since we demonstrate the advantage of arrays of small spectrographs at length in section 3. The further questions regarding the possible confusion of one or several spectrographs (+telescope) observing the same ground pixel were answered above (question to section 4.1).

I also recommend that clear recommendations for the downscaled spectrographs for spectral range/resolution and the use of two-dimensional detector arrays vs. the use of mechanical scanners are given, because the use of scanners in small spectrographs is not an option and the use of two-dimensional arrays complicates the optics (as pointed out in the paper).

Answer: We do not recommend mechanical scanners (see answer to the mechanical scanner issue, above. Whether mechanical scanners in conjunction with miniaturized spectrographs make sense may be a target of future investigations.

Changes to the manuscript: None, since the point was taken up above.

In addition, operating a fleet of small satellites with small spectrographs is an expensive undertaking. Which operational institution (or company) is supposed to do this and at what cost?

Answer: We think that this is a question that goes beyond the scope of the manuscript. Whether a fleet of small satellites (how many?) would really be more expensive than a large single satellite is to be found out. Clearly, the idea of Cubesat and similar micro

satellites is to make them cheap. Regarding the question who could finance and operate such a fleet: We presently see a surge of private space activities. Thus it is possible (and even likely) that these NGOs will be interested in Earth observation in the near future.

Changes to the manuscript: None, since the point is beyond the scope of the manuscript.

That having been said, the paper contains a number of interesting and valuable design points that certainly deserve further discussion. To guide that discussion better I recommend to account for the above suggestions and questions.

Answer: We like to thank the reviewer for the positive comment and for pointing out unclear points in our manuscript. Of course we tried to do our best to answer all questions and to improve the text. We trust that our answers to the reviewer's questions are satisfactory.