Author response to referee comment #1

December 8, 2020

We thank referee #1 for the time spent reading the manuscript and the productive and helpful comments. We have addressed the referee's comments on a point to point basis as below for consideration. All page and line numbers refer to the first version of the manuscript.

1 General comments

R1: *This is a well written paper. However, what this paper is currently missing in my opinion is visualization of the measured and processed data. Can you please add visualizations of actual measured data (both spectral and images) and results from each of the modeling steps? It would be interesting for readers to see how speckle patterns of that diffuser look and the pattern propagation to the final imaging plane. Can you also add some figures from the laser spectra used? Just as background information you could include in the introduction that sources like lasers produce temporal speckle and diffusers produce spatial speckle. Speckle pattern created by a diffuser can be averaged for example by rotating the diffuser during the measurement.*

Response: We will add figures illustrating the speckle patterns in the slit and detector plane. The width of the laser line is presented in Section 3. We will also add more detailed explanations and motivations regarding speckle effects and some mitigation principles.

R1: *This is slightly off from the focus on algorithm development itself, but very important what comes to the proper operation of the instrument. What are the criteria for the diffuser to reduce speckle effect and how does that affect overall performance of the instrument? Are there any tradeoffs?*

Response: Generally, the SFA will be lower the more independent speckle patterns per wavelength band a diffuser generates. For example, the NIR instrument used in this work would generate about 56 independent patterns ($M_{spectral}$) over a spectral range equal to the resolution λ_{res} at 776nm. This number is influenced by the sensitivity of the diffuser with respect to wavelength change. This sensitivity is significantly higher for transmission geometries, since it will yield a wider range of possible optical path differences. This effect also scales with the thickness of the diffuser. As far as our experience goes: a thicker diffuser also means less transmission and therefore less signal on the detector during calibration.

R1: *Maybe you could add reasoning why this specific glass volume diffuser was selected and refer to studies on some diffuser contamination and radiation tests? Contamination/degradation of the diffusers is to my understanding a major issue in satellite measurements. This is at least a problem at UV and visible and it has much larger effect than speckle. Since diffraction limit increases at longer wavelengths, at NIR and SWIR diffuser speckle is worse than at visible spectral range. You could mention this in the paper.*

Response: The specific diffuser material was chosen for the measurements since it was qualified for the Sentinel 5/UVNS (see Irizar et al. (2019)). We will mention this when describing the material in section 3.2. The impact of speckles generated by longer wavelengths can be seen in the smaller averaging factor $M_{spectral}$ of the SWIR band compared to the NIR. We will point this out during the discussion of the results.

2 Specific comments

Page1, row 22: R1: *"... spectrometers with fine spectral resolution and strict demands to radiometric accuracy..." You could specify these "strict demands" in the paper. At least stray light is usually a problem in imaging spectrometers.*

Response: We will clarify that diffuser speckles need to be considered as part of the radiometric accuracy error budget next to other contributors such as stray-light or polarization.

Page 1, row 29: R1: *"...end-to-end measurements by van Brug and Courrèges-Lacoste (2007) as well as models for different speckle averaging effects..." Can you explain in detail what end-to-end measurements were these and what existing speckle averaging methods are available (both hardware and software)?*

Response: We will add an explanation regarding the end-to-end measurements. The authors are convinced, that the effects of diffuser speckle can not be reliably characterized with representative end-to-end setups (which includes a full spectrometer, telescope optics, diffuser and light source). The suppression of the speckle effects is implicit to the design of the instrument. Therefore, if one were to measure speckle residuals with a certain setup, it can not be representative for an instrument that is supposed to have a neglectable residual speckle amplitude (SFA).

Page 5, Figure 2: R1: *Regarding the setup, please specify the type of optical* *fibers used between the tunable laser source and the fiber tab and between the fiber tab and the fiber output. You could say that since your spectral tuning range is narrow, you can use single mode fibers to transmit the laser beam and create uniform illumination. You could also show in a figure how spatially uniform the radiation output from the single mode fiber is before it hits the diffuser. Is there any spatial speckle created by the single mode fiber? You could mention that multimode fibers should not be used as they generate severe spatial speckle that can be worse than the diffuser speckle. The speckle pattern by the multimode fiber changes when the fiber bends only slightly. In addition, can you please draw Figure 2 so that it is easier to see which cables are optical fibers and which of them are electrical cables.*

Response: We will specify the exact fiber types used, include the result of spatial beam uniformity measurements at the diffuser plane, and add the referee's suggested comments regarding multi mode fibers. We will also correct Figure 2. The spatial uniformity measurements showed no apparent spatial speckles generated by the fibers, which we will mention as well.

Page 5, Figure 2: R1: *Please replace "Powermeter" with "Power meter".*

Response: Done.

Page 5, rows 109-111: R1: *Can you please give references to these data products?*

Response: Done.

Page 5, row 110: R1: *Please replace "... CO2, Aerosols, or the O2 absorption..." with "... CO_2, aerosols, or the O_2 absorption ..."*

Response: Done.

Page 6, rows 117-118: R1: *"For the NIR the laser source has a center wavelength of 780 nm and a nominal linewidth of 300 kHz." Can you give the nominal linewidth in wavelengths?*

Response: Done.

Page 6, rows 125-126: R1: *"The SWIR laser source center wavelength is 1550 nm, with single mode output of nominal 150 kHz linewidth." Can you give the nominal linewidth in wavelengths?*

Response: Done.

Page 6, row 129: R1: *Please define a speckle oversampling ratio*

Response: We will provide an explanation without this confusing term. It states how many detector pixel the speckle correlation areas are being sampled with.

Page 6, row 162: R1: *Please define* f_m.
Response: We will change this part slightly to be more understandable, also introducing the symbol Δf correctly.

Page 7, row 167: R1: *You have an error in the spatial offset equation.... How does correcting this affect the results?*

Response: The symbol "Δf" was used incorrect at some instances, which led to the misleading expression for Δb. It will be corrected accordingly.

Page 8, row 172: R1: *Please present exact equation for the path length probability density function* $p(l)$.

Response: We will use a direct analytic expression for $F(\Delta f)$ given by Zhu et al. (1991), which lead to similar results. However, this way one does not need to detour of calculating $p(l)$ first and taking the Fourier transform after. Also this expression gives direct access to the angular correlation function, too, which is interesting for estimations of angular contributions in the future. For the interested reader see Patterson et al. (1989), where an expression for $p(l)$ is derived explicitly.

Page 8, row 178: R1: *There is one extra parenthesis, please replace* $\Delta b(\Delta f))$ *with* $\Delta b(\Delta f)$.

Response: We will use the symbol "Δb" without the explicit frequency dependence.

Page 8, row 180: R1: *There is a typing error in Equation (10), the integrals' limits should be* $\int_{-\infty}^{\infty}$ *instead of* $\int_{\infty}^{\infty}$.

Response: Done.

Page 8, row 181: R1: *"...*$P(h)$ *is the aperture function of the imaging system ...". Please present the exact equation for* $P(h)$.

Response: We will give an example for a circular aperture now.

Page 10, row 225: R1: *"Therefore, the resultant speckle correlation function at the detector* $\mu_{det}\,(\Delta a, \Delta b)$ *is a convolution of ...". Please present* $\mu_{det}\,(\Delta a, \Delta b)$ *as an equation.*

Response: We will present an equation.

Page 10, row 250: R1: *"We assume, that detector noise is averaged in this step" Can you please add what the noise properties of the detector are (e.g. in* $V/\sqrt{Hz}$*) and what integration times were used?*

Response: We will present a complete rework regarding the uncertainties for the averaging factors and the SFA.

Page 10, Subsection 4.4 Predicted SFA: R1: *Since this subsection includes only one sentence, to me it makes more sense to remove this subsection 4.4 and move the equation to the beginning of Section 4, right after Eq. (7). There you could also define* $M_{polarization}$*,* $M_{spectral}$*, and* $M_{detector}$ *and link these symbols to the steps 1, 2, and 3.*

Response: Done.

Page 11, Table 2: R1: *Based on the values of* $M_{polarization}$*,* $M_{spectral}$*, and* $M_{detector}$*, the SFA on the first row of Table 2 should be 0.0039 (not 0.0040). Can you please give SFAs in percents in Table 2?*

Response: We will include an error analysis and also fixed a minor inconsistency in our spectrometer propagation, which caused some systematic deviations in the measured averaging factors, especially for the NIR band.

Page 11, row 254: R1: *"It is also dependent on detector noise, which explains slightly higher averaging factors than predicted." Can you predict noise properties of the detector used and add them to the calculations?*

Response: We will rework the discussion of uncertainties.

Results section: R1: *How much diffuser speckle contributes to the overall measurement uncertainty?*

Response: The relative spectral radiometric accuracy (RSRA) budget of ESA's CO2M mission is 0.5% for all bands (see Meijer et al.). However, the SFA results presented in this work should not be directly compared to this budget, since it does not account for angular averaging effects. The SFA including those effects can be two orders of magnitude lower.

3 References

Zhu, J. X., Pine, D. J., and Weitz, D. A.: Internal reflection of diffusive light in random media, Phys. Rev. A, 44, 3948–3959, https://doi.org/10.1103/PhysRevA.44.3948, https://link.aps.org/doi/10.1103/PhysRevA.44.3948, 1991.

Patterson, M. S., Chance, B., andWilson, B. C.: Time resolved reflectance and transmittance for the noninvasive measurement of tissue optical properties, Appl. Opt., 28, 2331–2336, https://doi.org/10.1364/AO.28.002331, http://ao.osa.org/abstract.cfm?URI=ao-28-12-2331, 1989.

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