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Comment on amt-2021-15

Bernd Sierk (Referee)

Referee comment on "Slit homogenizer introduced performance gain analysis based on the Sentinel-5/UVNS spectrometer" by Timon Hummel et al., Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2021-15-RC2, 2021

General comments:

The manuscript addresses an important instrument effect and potentially significant error source in the context of the upcoming Sentinel-5 mission, a space-borne multiple-band push-broom imaging spectrometer to be launched in 2023 in the frame of the Copernicus programme. It has been shown that for atmospheric chemistry missions applying DOAS or optimal estimation retrieval schemes, accurate knowledge of the Instrument Spectral Response Function (ISRF) is of paramount importance. This is in particular the case for when operating at spectral bands with deep absorption bands in the near- and shortwave infrared (NIR, SWIR). Scene-dependent ISRF distortion isa significant, and potentially critical error source in next-generation push-broom imaging spectrometers. Depending on the spectral and spatial resolution of the mission, ISRF knowledge typically ranks among the most critical figures-of-merit, together with straylight performance and signal-to-noise ration. Previous missions have suffered from ISRF instability originating from non-uniform entrance slit illumination over Earth scenes with cloud-contamination or large albedo contrast. In order to mitigate such effects, a novel type of entrance slit has been developed, based on parallel mirrors separated by the slit width in spectral direction. The purpose of this device, referred to as a slit homogeniser (SH) aims at equalising radiometric non-uniformity at the entrance and providing a uniform slit image at the exit. Sentinel-5 is the first space mission embarking this type of entrance slit, and although its performance has been analysed in previous studies (Caron et al. 2019, duly quoted), some aspects of these devices have not been explored yet.

The present manuscript addresses such a "secondary effect", which however may turn out to be of primary importance if the theoretical results reported were supported by experimental evidence (which is however not provided in this work). The analysis focuses on the impact of non-uniform pupil illumination, originating from far-field interference patterns (due to the use of the SH device), in combination with several types of aberration in the spectrometer optics. Scene-dependent pupil non-uniformity is shown to be a consequence of the use of mirror-based SH. For perfect, aberration-free collimator and imaging optics, this pupil-non-uniformity would not significantly affect the spectral performance of the instrument. However, inevitable aberrations of the optical system lead to a scene-dependent weighting of the components of the spectrometer's point-spread function (PSF). The PSF, in turn, is a contributor to the Instrument Spectral Response Function (ISRF) as a convolution kernel of the near-field slit image (and detector pixel). The scene-dependent variation of the PSF is thus causes a similar impact on the ISRF as a non-uniform slit image, the error source of "classical slit" spectrometers intended to be mitigated by the SH device.

It is understood that pupil inhomogeneity is introduced by far-field interference originating from wave propagation within the mirror-based SH (creating multiple coherent sources), and would not occur with a classical slit. The far-field non-uniformities are also independent from the achieved near-field homogenisation, and are not a consequence of "remaining" inhomogeneities. This should be stated more clearly in the text (both, if this understanding is correct and if not).

The presented work is important and timely, as performance aspects following from it have not been accounted for in previous analyses. Given the importance of the upcoming Sentinel-5 mission for the atmospheric chemistry community, as well as the potential impact on similar future space missions, the topic is also highly relevant for scientific users. The paper is generally well written, although the explanation of the methodology can be improved in terms of clarity (as pointed out in the detailed comments). The equations are derived from standard optical theory (which is duly cited) and appear correct, although the use of coordinates in the presented equations is not always clear (same symbols are used for different planes in the instrument).

Despite of the relevant scope and importance of the addressed topic, the manuscript suffers from shortcomings, which affect the relevance of the obtained (partially alarming) results, as well as the validity of some conclusions. These limitations are delailed in the below, and generally can be summarised by the following main points:

1.) Limitation of the analysis to a single wavelength in a single band, which is insufficient to draw far-reaching conclusions on the performance of wide-bandwidth multiple-spectrometer instruments

2.) Limitation to four artificial input scenes, none of which representing a realistic in-flight scenario (even though one is referred to as "representative Earth scene")

3.) Unclear, somewhat arbitrary assumptions on imaging aberration, which partly invalidates the applicability of the results to the instrument under investigation (Sentinel-5)

4.) Lack of exploitation of the obtained results (no comparison with classical slit, no flow-down of the results to Level-2 performance, missing interpretation in terms of implications for design improvements)

5.) Invalid conclusions about other missions, which use different SH technology, and based on inadequate comparison of mission requirements

In my view, none of the above listed shortcomings is a blocking point for publication of the paper, provided each of them is properly addressed in a revised version of the manuscript. In the following, the above criticism will be explained in more detail, including suggestions for addressing them.

Specific comments:

1.) While the methodology and the developed model seem adequate to analyze the impact of using a one-dimensional slit homogeniser, the present analysis is rather limited, and should be extended to come to more meaningful results w.r.t Sentinel-5 and potentially other space missions. The single analysed wavelength is in the NIR band of Sentinel-5, but Fig. 2 shows the SWIR-3 spectrum (with CO, CH_4 and H_2O absorption). The SWIR-3 is likely the most critical band in terms of the impact on retrieved products (e.g. CH_4 and CO column densities). This is due to the deep absorption structures and the relatively high spectral resolution (although the O_2 A-band in the NIR may also be critical). It is therefore recommended to extend the analysis at least to the SWIR-3 band at 2.3 µm (and ideally also SWIR-1 at 1.6µm). The mathematical model should still be valid for these spectral ranges, and the results would give an impression on the wavelength-dependency of pupil inhomogeneity and its impact on the ISRF. At minimum, please explain why the analysis was not performed for the SWIR-3 band plotted in Fig. 2. In this case it is suggested to replace the plot by the NIR.

Another important extension of the analysis would the application to other wavelengths within the chosen band. The main impact of ISRF distortion (or knowledge error) is due to its variation within the spectral band used for the retrieval of the targeted molecular species. The results for one wavelength (or spectral channel) at 760nm reported here give no insight in intra-band variability. However, ISRF knowledge is required over the entire spectral range. Please discuss the expected variation of the results with wavelength. Do they only differ in terms of the contrast, which is lower in deep absorption lines ? Do the errors in the figure-of-merit (shape, FWHM, and centroid position) scale linearly with contrast ?

2.) The S5-ESA-scene used in this study, on which the compliance statement for Sentinel-5 is based on, remains obscure, in the sense that its origins and generation remain unclear. Although it is referred to as "representative Earth scene", the very low contrast plotted in figure 5 does not appear realistic for a ground-scene with considerable contrast. The instrument is likely to frequently see much higher contrast in orbit, e.g. when flying over cloud fields (bright in the NIR) or water bodies (dark in the SWIR). It is suspected that the authors picked one wavelength (in the continuum of the NIR band) of

an artificial contrast scene from the S5 requirement documents, and convolved a bright-dark step transition with the motion boxcar of the ALT spatial sample (please confirm or not). This is however not flight-representative, as such artificial reference scenes are typically designed to specify straylight performance, not to define a representative geophysical scenario.
In order to demonstrate its relevance to expected Sentinel-5 performance, the authors shall clarify the origin and processing of the "S5-ESA-scene". What are the geophysical assumptions behind the scene ? Was it convolved to account for "motion smear" over the ALT spatial sampling distance? It is also recommended to extend the analysis to more than just one (basically flat) convolved transition, in stating compliance of the mission. The method would even allow to explore the maximum contrast transition, which would still lead to compliant ISRF knowledge requirements for the Sentinel-5 instrument. This would represent a relevant performance prediction for Sentinel-5, and greatly enhance the scope of the conclusions.

The three other scenes considered (25%,50%, and 75% ALT slit illuminated) are also artificial (even impossible to be observed in flight). However they could serve the purpose of highlighting the criticality of pupil inhomogeneity for on-ground calibration. The authors should comment on the implications of their results for the on-ground ISRF characterization, which typically prescribes measurements with partially illuminated slit widths. At any rate, instantaneous transitions are impossible be observed by any push-broom instrument with finite FoV and integration time. Therefore they cannot be claimed to be representative for so-called "high-contrast missions" (which is not a defined category anyway).

3.) For the propagation of the non-uniform pupil illumination pattern to the focal plane, aberration theory is used, describing the various types aberration with Zernike polynomials. While this is an adequate approach, the derivation of Zernike coefficients appears odd. It is claimed that the aberration components of the Sentinel-5 instrument are unknown, which seems surprising given the long history of design and development work (starting 2010). Instead, two aberration types are presented (spherical and comatic), without further explanation why they are selected to represent the instrument. The coefficients are derived by fitting the width of the PSF to the expected Gaussian (from optical analysis), implying that only one type of aberration is present and accounts for the entire PSF width. While this approach may be useful to qualitatively indicate the criticality of different types aberration, it does not appear representative for the Sentinel-5 instrument (as implied by the manuscript title). The strong dependence on the shape of the PSF, which seems to govern the wide range of ISRF errors, raises the question if the results can be used to predict the ISRF performance for a (more realistic) combination of the investigated aberrations. Do the ISRF-shape errors for spherical and comatic errors (reported in tables 1-3) add up linearly or RSS in systems with both aberrations ?
The authors shall...
1a) perform analysis with the estimated aberrations of the Sentinel-5 instrument (NIR and SWIR bands), or
1b) justify more clearly why such estimate of Sentinel-5 (in the NIR band) cannot be made.
2) in case of 1a) perform various analysis with cases of mixed aberration to explore the how different aberration components add up
3) if possible, extend the analysis to other types of aberration

4.) The final results are presented in three tables, in which the three figures-of-merit (shape distortion, FWHM and spectral barycentre position) are listed for three assumed aberration scenarios and four selected scenes. The interpretation is limited to commenting on the values listed therein, reporting the expected higher values for higher contrast, the difference between the three aberration cases, and the large values for the CAL-scenes. The latter are found to be are alarmingly high, but no conclusions are drawn for the instrument under investigation. It is merely stated that the performance is compliant for the "S5-ESA-scene", which is not surprising as it features very low contrast. The reader is left clueless about the real performance for higher contrast scenes, or complex albedo variation which the instrument will be exposed to in flight. In fact, it is not even clear if the use of a SH brings any advantage over using a classical entrance slit. It would be important to clarify if the performance gain by homogenisation of the near-field is completely or only partially lost by the induced far-field non-uniformity.

No plots of the distorted ISRFs are provided, which would be instructive for the prediction of the impact on retrieved products. It would be interesting to see, how the different types of aberration affect the ISRF for the various scenes (e.g. extension of the wings or skewing the shape). While the changes are probably too subtle to be seen in the ISRF, it should not be difficult to include difference plots w.r.t. the homogeneous reference for some (extreme) cases.
It should even be possible to flow down the obtained ISRF distortions to the Level-2 products. This is not easy in absence of a Level-2 processor (or end-to-end simulator), but could be approximated by using so-called gain vectors, which are part of the Sentinel-5 requirement definition. It would also be insightful to present the radiometric errors arising from the distorted ISRFs, at least for the extreme cases (largest and lowest). For this, the monochromatic reference spectrum would be convolved with the obtained (distorted) ISRFs and the difference plotted as a fraction of the true radiance (homogeneous, aberration-free case).
The manuscript also falls short on providing implications of the results, and recommendations for design improvements. Can the pupil non-uniformity from SH be limited by design or is it an unchangeable "fact-of-life" ? Does it depend on the number of reflections and can be mitigated by extending of SH along the optical axis? How important is the slit width and the focal lengths of the telescope and collimator ? Can the results be used to guide the optical design of the collimator and imager optics, e.g. regarding the types of aberration ?

5.) Two main conclusions drawn by the authors are poorly justified:

Conclusion 1): Quote: "A representative scene of the Sentinel-5/UVNS instrument has a rather weak contrast and therefore the instrument fulfils the ISRF specifications in order to meet the Level-2 performance requirements of the mission. In contrast to this, future missions like CO2M have to be compliant with higher contrast scenes with almost a sharp transition from dark to bright slit illuminations."

Both parts of the above conclusion...
a) There is no criticality for Sentinel-5 as it will only see low contrast
b) CO2M will experience large errors, because it will see much larger contrast
...cannot be justified by the presented analysis:

a) The low-contrast scene for Sentinel-5 (no source and details given) is likely from the system requirement document (please confirm). Such reference scenes are often specified to constrain individual error sources (e,g, straylight), but do not necessarily represent realistic geophysical scenarios. It appears certain that a Sentinel-5 measurement in the SWIR band near water bodies (coast lines or lakes), with an instantaneous field-view of ~2.5 km smeared over 7.5 km will yield much larger effective contrast than the scene referred to as "S5-ESA-scene".

b) CO2M is not a "high-contrast mission" as opposed to Sentinel-5. All nadir-looking push-broom spectrometers look at the same Earth scenes, and the effective scene contrast observed over the integration time depends on the ratio of the slit projection and the ALT sampling distance. This ratio is comparable for bot, S5 and CO2M, and therefore the "smearing" of the contrast will be similar (not a sharp transition as claimed). The formulation of requirements by means of contrast scenes is often driven by straylight requirements, which may be more stringent for CO2M (due to deeper absorption structures in the SWIR-2 around 2.0 µm). However, such contrast scenes cannot be regarded as "representative Earth scenes". In case of CO2M the specified scenes exhibit an extreme albedo contrast (~factor of 8) that is only observed over coast lines (and then mitigated by motion smear). The authors should refrain from performance prediction based on the interpretation of requirement documents, especially for missions out of the scope of this investigation (see below).

Conclusion 2): Quote: "The application of the slit homogenizer for missions with high contrast scenes (CO2M) will impose strong variations in the spectrograph pupil and will result in large errors in the ISRF and hence significantly degrades the accuracy in the retrieval of the atmospheric composition and therefore the mission product."

This speculative statement is most likely false for the following reasons (on top of the ones given above):
a) The presented model for ISRF distortions is based on waveguide propagation along a mirror-based SH. Such a device is not foreseen for CO2M, where a fibre based slit will be employed instead. The model developed in this paper is not valid for light propagation in multimode fibres. In fact, measurements of transfer functions with such a fibre based, two-dimensional slit homogeniser (2DSH) have not shown interference patterns as shown in Fig. 3b. (see S.Amann et al., Characterization of fiber-based slit homogenizer devices in the NIR and SWIR, Proceedings Volume 11180, International Conference on Space Optics — ICSO 2018; 111806C (2019) https://doi.org/10.1117/12.2536147
b) Scene-dependent far-field effects from scene non-uniformity are also expected for fibre slits, but are typically less pronounced and can be mitigated by adjusting the fibre length (see G. Avila, "FRD and scrambling properties of recent non-circular fibres," Proc. SPIE 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 84469L (24 September 2012); doi: 10.1117/12.927447). They are related to the fibre modes and are expected to show lower frequency variations than the ones found in this study. They can also be mitigated by fibre bending.

It is understood that the authors seek to underline the importance of their results by pointing out the relevance to other missions. While this is legitimate, CO2M is not an appropriate mission for comparison. I am aware of only one other mission considering the implementation of a mirror-based SH: The Geostationary Carbon Cycle Observatory (GeoCarb), which is not quoted in the manuscript. Its step-and stare slit-scan strategy is likely to be more critical regarding the discussed effects than Sentinel-5, because of the absence of motion smear.

Unless the authors can justify the validity of their propagation model for rectangular multi-mode fibres, it is suggested to remove speculative statements about CO2M's in-orbit ISRF stability performance. Instead it is proposed to make reference to GeoCarb (and make the team aware of a potential error source not yet considered), e.g.:
- B.Moore, “The GeoCarb Mission,” in 14th International Workshop on Greenhouse Gas Measurements from Space, (2018)
- J. Nivitanont et al: Characterizing the Effects of Inhomogeneous Scene Illumination on the Retrieval of Greenhouse Gases from a Geostationary Platform. Poster presented at the 4th International Workshop on Greenhouse Gas Measurements from Space, (2018)

Finally, I propose to add a conclusion that is currently missing: Both, the transfer function shown in Fig. 3b, as well as the pupil intensity distributions in Fig. 6 should be accessible to measurement employing an appropriate test bench. It is assumed that the two SH devices in Sentinel-5 are now mature enough to be tested (btw. please note the existence of two different such slits in the manuscript). Far-field measurements with these devices could be used to verify the derived model, and to quantify the ISRF errors expected from measured pupil intensity variation. If the authors agree, I suggest to include such proposal and give indications on how to implement an appropriate measurement.

Technical corrections / Editorial comments

p. 1; >> "The spectral accuracy" is not well defined so far.

l. 3-5: << "As the ISRF is the direct link between the forward radiative transfer model"

>> add: ", used to retrieve the atmospheric state..."

l. 14: << "By homogenizing the slit illumination, the SH moreover strongly modifies the spectrograph pupil as a function of the input 15 scene"
>> insert "illumination" after "pupil"

l. 16: "type" -> "type"

l. 19 << "As in most space based 20 imaging spectrometer"
>> is too general, e.g. imaging FTS (e.g. IASI) are not affected (no slit)

Also indicate the difference to scanning spectrometers, like SCIAMACHY

l. 20: "spectrometer" -> "spectrometers"

"gets imaged" -> "is imaged" (is the purpose)

l. 21: delete "eventually"

l. 22: "gets convoluted" -> "is convolved"
better: "The limited spectral resolving power of the instrument arising from diffraction and aberration is decribe by a convolution of the slit image with the spectrometer and detector point spread functions (PDF).

l. 24: " The resulting intensity pattern on the FPA in the spectral direction is called the instrument spectral response function (ISRF)."
-> This is not a universal definition. According to ESA definition, this is the ISMF (Instrument Spectral Measured Response), which is not measurable continuously, but sampled by the detector pixels. ESA defined ISRF for each detector pixel as a continuous function of wavelength, defined as the individual pixel's response at a given wavelength. In absence of aberrations, this ISRF is a mirror of the ISMF (inverted on the spectral scale), but in reality this is not the case. For definitions please refer to : Caron, J., Sierk, B., Bézy, J.L., Löscher, A., and Meijer, Y., The CarbonSat candidate mission: Radiometric and spectral performances over spatially heterogeneous scenes, Proceedings of the International Conference on Space Optics (ICSO), Tenerife, Spain, 2014

It is also suggested that the authors read and (if found appropriate) cite the following reference, which highlights the issue of inhomogeneous slit illumination for a relevant airborne instrument:
Gerilowski, K., Tretner, A., Krings, T., Buchwitz, M., Bertagnolio, P. P., Belemezov, F., Erzinger, J., Burrows, J. P., and Bovensmann, H.: MAMAP – a new spectrometer system for column-averaged methane and carbon dioxide observations from aircraft: instrument description and performance analysis, Atmos. Meas. Tech., 4, 215–243, https://doi.org/10.5194

l. 28: << "Figure 2 depicts a representative Top- of-Atmosphere spectrum"
>> Be more specific, indicate the albedo and SZA.

<< "in the SWIR wavelength band" -> "for the Sentinel-5 SWIR-3 spectrometer, used for retrieval of CH_4 and CO"
>> The plotted spectral band is one out of 2 SWIR bands of the Sentinel-5 mission, and other missions have yet different band definitions.

l. 29: "entering a space-borne instrument" -> "incident on a space-borne instrument's entrance aperture"
"high-resolution" -> "monochromatic" or "unconvolved"

l. 30: "for every monochromatic stimulus"
Not clear what is meant by this. It seems to refer to the incident spectrum as a continuum of monochromatic stimuli. Better replace by "for any given wavelength"

l. 31 "Whenever the ISRF shape deviates from the on-ground characterized shape..."
while the ISRF has been introduced as a mathematical convolution kernel, on-ground characterisation is mentioned "by the way" in a side sentence. It should be mentioned in the text that the ISRF is a wavelength- and field-of-view dependent instrument characteristic (varying with wavelength and ACT field position), and is determined by on-ground characterisation prior to launch.

l. 32 "..., which serves as a basis for the applied retrieval algorithms."
-> "...from which the Level-2 products are retrieved". (measurements are the input to, not the basis of an algorithm).
Since the paper mainly addresses the Sentinel-5 mission and the SWIR bands, the retrieved Level-2 products shall be mentioned (CH_4, CO columns).

l. 33: "The along track motion of the satellite accounting for the spectral direction of the spectrometer serves as an averaging and smearing effect of the scene"
"The along track motion of the satellite during the integration times results in a temporal averaging of the ISRF variation, which reduces the impact of scene heterogeneity."
Also mention here that the impact of albedo variations depends on the ratio of the instantaneous field-of-view (IFOV) and the sampling distance in ALT. Please indicate these numbers for Senyinel-5 (FoV=2.5km, ALT SSD = 7.5km).

l. 36: "are less vulnerable to contrast in the Earth scene"
-> Indicate the reason: The effect depends on the ratio of spatial sampling distance (in this sentence "scan area"), and the instantaneous field of view (see comment above)

l. 36: "In contrary," -> in contrast

l. 37: "...define a set of stringent requirements on the inflight knowledge and stability of the ISRF."
>> add the reasone before: "...high resolution hyperspectral imaging spectrometers with IFOV comparable to the sampling distance (or scan area) are more strongly affected and therefore define..."

l. 38: "will introduce biases in the Level-2 data"
add "and pseudo-random noise" after "biases", which is actually the main impact over an ensemble of measurements.

l. 39: "For the 2017 launched Sentinel-5 Precursor (S5P) satellite..."
-> "For Sentinel-5 Precursor (S5P) satellite, launched in 2017,", and add reference for mission description, e.g.
J. P. Veefkindet al., TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications, Remote Sensing
of Environment, Volume 120, p. 70-83 (2012)

p. 3; Figure 2:
>> Suggested to plot the monochromatic TOA spectral radiance and the convolved, simulated measurements should be plotted here as well.

>> Briefly explain the origin of the spectral structure, indicating the absorption features by CH_4, CO, and H_2O.

>> It would be instructive to include an over-plot of a spectrum with distorted ISRF for a realistic scene contrast, and to include a difference plot w.r.t. the homogeneous case

l. 43: "NoeÌ□l et al. (2012) quantify the retrieval error for the Sentinel-4 UVN imaging spectrometer for the tropospheric O_3, NO_2, SO_2 and HCHO."
>> Indicate that Sentinel-4 is not yet launched (adding "upcoming") and that these results are based on simulations, not real measurements (in contrast to the TropOMI results quoted before). Also introduce the not yet defined acronym "UVN".

l 45: "They propose a software correction algorithm which is based on a wavelength calibration scheme individually to all Earthshine radiance spectra"
- add comma in -> "algorithm, which..."
- add "applied" and replace "Earthshine" by "Earth" (even though used in the reference)->
"...individually applied to all Earth radiance spectra..."

l. 49,50: "...to mitigate the effect of non-uniform scenes."
add "in along-track direction", as the S5's SH only homogenises in ALT.
It shall be mentioned, that non-uniform scenes in ACT direction also result in ISRF distortion in presence of smile distortion in the image plane. This is e.g. explained in the already quoted Caron et al. 2014 (see reference above).

l. 51: move "in the along track direction (ALT) of the satellite flight motion" after "Earth radiance"

l. 53: "...mirrors is of b = 240 μm (NIR)," -> replace "of" by "has dimensions of"
Proposed: "The two parallel rectangular mirrors composing the entrance slit have a distance of b = 240 μm (NIR), side lengths of 65 mm in ACT and a length of 9.6 mm along the optical axis".

l. 54: "gets scrambled" -> "is scrambled by multiple reflections"

l. 55: "For a realistic reference Earth scene of the Sentinel-5/UVNS mission"
>> Please indicate the specifics of the scene (albedo image or artificial contrast) ?

l. 56: "the total in orbit ISRF shape error budget is < 2 %, the relative Full width half Maximum (FWHM) error < 1 % and the centroid error in the NIR 0.02 nm"
>> Although hidden in the word "budget" state more clearly that these are requirements, not resulting performances.

l. 61: " We present an end-to-end model of the Sentinel-5/UVNS NIR channel (760 nm)."
Please justify why the model (resp. its application) is restricted to the NIR band. Also replace, or add equivalent plots of the NIR band, as for SWIR in Fig. 2.

l. 63: "consequently implies a scene dependency in the optical PSF"
"implies" -> "results in"

l. 65: "spectrograph pupil intensity distribution" -> "intensity distribution across the spectrograph pupil"

l. 76: "contains details" -> "describes"

l. 78: "The second part focusses on the novel modelling technique of the spectrograph optics."
Not understood. Is "novel modelling technique" referring to the previous sentences, or is it announcing a new technique to be established in the paper ? In the latter case, better write: "In the second part a novel modelling technique of the spectrograph optics is introduced".

l. 87: Please mention that equation 2 follows from equation 1 with the simplifying assumption of a square entrance pupil. This is currently hidden in a side remark on line 92.
Clarify the calculated quantity U Ì□ (electrical field?), currently referred to as "the Airy disk"

>> Please clarify if this propagation model has been verified against measurements of the SH transfer function.

Caption of Fig. 3 "...highly dependent on interference effects" -> "are strongly affected by interference effects, resulting in a complex illumination pattern at the slit exit".
You should mention that this is not a new finding, but a known characteristic of such SH device, and that the interference pattern, although not uniform, already represents an improvement over no scrambling in a classical slit.

l. 121: ". Independent of the applied scene in ACT, the telescope pupil is retrieved again at the spectrograph pupil despite a magnification factor and a truncation of the electric field at the SH entrance plane, which leads to a slight broadening and small intensity variations with a high frequency in angular space (Berlich and Harnisch, 2017)."
>> split in 2 sentences

Figure 4.: Indicate in the caption the astigmatism of the collimator, which is adjusted to the slit length.

l. 134: "...spectrograph pupil will be altered with respect to the telescope pupil"
The manuscript frequently refers to "altering" telescope and spectrograph pupils, although these are optical-geometric terms that do not depend on the illumination. For better correctness it should be rephrased in terms of "pupil illumination "

l. 134: "A general case for the connection between slit exit plane and spectrograph pupil plane is considered by Goodman (2005, p. 104)"
The coordinates in Eq. 5 seems to be for the slit exit and spectrograph pupil, respectively, which differs from Eq. 2-3, where x,y, denote coordinates in the telescope pupil and u,v those in the slit exit. Please clarify the coordinates or use indices to indicate the difference.

l. 139: "where k is the wavevector of the incoming wave, λ is the wavelength and f is the focal length of the lens"
Quantities already defined above.

l. 144, Eq. 6: Is it necessary or convenient to keep 2pi and lambda in the argument of the field distribution ?

l. 145: By ending the section with an uncommented equation, the reader is left with the question what is the conclusion so far (or the purpose of the calculation). It should be noted that this is an intermediate result, which will be further propagated and refined in the following (for collimator astigmatism).

l. 162: " straight forward" -> "straightforward"

l. 175: " Further, we model the dispersive element as a 1D binary phase diffraction grating."
>> Indicate if this choice is relevant to the actual Sentinel-5 instrument.
An image of the binary grating structure would be useful here (also for explaining the quantities used in the text).

l. 191: "...representative Earth scene for the Sentinel-5/UVNS instrument provided by ESA (S5-ESA-scene)..."
The "scenes" referred to here need to be further described. Is it the artificial contrast scene (bright and dark reference spectrum)? In that case they should not be called "representative Earth scene", but a step transition scene with contrast factr representative for the mission requirements.

l. 194: "Fig. 5 shows the top of atmosphere (ToA) radiance level given by a realistic Earth scene for the Sentinel-5/UVNS instrument."
This is likely showing the contrast for one wavelength (supposedly spectral continuum level), which can vary significantly across the spectrum (zero in case of saturation). Please clarify in the text.

l. 195: "Due to smearing of the satellite’s movement, this scene has a significantly lower contrast than the calibration scenes"
>> Indicate this by plotting the convolution of the contrast with a boxcar function of the motion smear, which would show the contrast the instrument sees during integration time.

l. 196-200:
The remark about the CO2M seems misplaced here, and should be moved to the discussion of the results (if maintained at all). It seems incorrect to equate a "calibration scene" with stationary contrast in the slit with a "representative scene of another instrument (especially with a different type of SH, see below). While it is true that non-homogeneous scenes are more critical for CO2M, there will also be smoothing by morion smear, and a sharp transition cannot be observed. This is different from step-and-stare instruments (e.g. GeoCarb), which could be mentioned here.

Fig. 5: It is still unclear, how the relatively flat "S5-ESA-scene" was derivedn(origin and processing, e.g. convolution with motion smear, assumption of slit projection, etc.). Please clarify.

l. 201: "Figure 6 depicts the pupil intensity distribution in the NIR (760 nm) for the applied test scenes"
>> Indicate that these are simulations based on the equations derived before.

l. 202: remove "is happening" -> "due to the absence of interaction, i.e. reflection, with the SH"

l. 204: "retrieved" -> "preserved"; "Contrary" -> "In contrast"

l. 215: "We know from ray tracing simulation predictions the PSF size on the FPA of the Sentinel-5/UVNS NIR channel, which in a simplified model is given by the standard deviation of a normal distribution.As the actual aberrations present in the system are yet unknown,..."
-> It is hard to believe that the aberrations for the Sentinel-5 instrument are completely unknown at this point (so far into the project).The PSF usually depends on field position (and wavelength), and should be well characterised by the optical analysis. It is understood that the use of Gaussians is convenient for the mathematical analysis, but it would be good to verify the results are robust against more representative PSF.

Eq. 14:
- Explain that (u,v) are now the coordinates at the focal plane
- The intensity I_theta is the square of the absolute value of U_FPA, which has no dependence on theta in Eq. 14. Please clarify why it appears as a function of theta in Eq. 15. It might be good to write here the one-dimensional equation for I(theta, nu), as it represents the final result for the ISRF distortion.

It is not clear how the aberrations to demonstrate the impact of inhomogeneous pupil illumination were selected (randomly, analysis or for convenience) ? It should be possible to make realistic estimates on the aberrations present in the Sentinel-5 instrument. This would enhance the credibility of the results regarding ISRF impact.

l. 262: "result" -> "results"

l. 264: << "As a direct comparison of the difference 265 between an ISRF calculated with a PSF disturbed by aberrations and a PSF given as a pure normal distribution is problematic, we rather compare the errors relative to a homogeneous scene."
>> Please explain in more detail why it is "problematic". It was stated above that assuming a Gaussian PSF would "neglect the non uniformity in the pupil and the spectrometer aberrations."

Table 1-3:
- It is not clear why the errors are so large for the Gaussian PSF case. If the ISRF distortion originates from scene-dependent weighting aberrations, then this case should not yield large errors.
- Please indicate in the text how these results compare with the requirement for ISRF knowledge.
- Please plot the distorted ISRFs corresponding to the results in the table (at least the extreme ones)
- It is suggested to also include plots showing radiometric errors resulting from such distortions

>> Does the result, which predicts large ISRF knowledge errors from the "calibration scenes", have any implications on the on-ground calibration of the instrument? Please elaborate.

l. 277: "gets significantly higher" -> "becomes significantly higher"

l. 279: "...comes only by..." -> "...comes only from..."

l. 285: "A scene dependency of the spectrograph pupil will lead to similar ISRF distortion as due to non-uniform slit illuminations"
>> This could, but was not shown here. The authors should provide calculations for ISRF distortions for a classical slit, in order to compare and support this claim.

l. 281: "We also conclude, that for the Sentinel-5/UVNS instrument the impact of this effect is of second-order and doesn't degrade the performance of the SH significantly."
This conclusion should be restricted to the reference scene used, not the Sentinel-5/UVNS instrument. Independent on the requirement formulation, the instrument might be exposed to larger contrast than used in this study.

l. 328: Duplication in reference:
Goodman, J. W.: Introduction to Fourier optics, Introduction to Fourier optics, 3rd ed., by JW Goodman. Englewood, CO: Roberts & Co. Publishers, 2005, 1, 2005.