Author replies are shown in blue
New text is shown in red

Anonymous Referee #1

The paper "Characterisation of spectroscopic properties of DOAS instruments using high-resolution solar spectra" by Thomas Wagner et al., presents a comprehensive investigation of spectroscopic properties of DOAS instruments using a Kurucz-fit approach applied to a long-term zenith-sky dataset from Kiruna, Sweden, spanning 30 years. The study investigates the impact of a detector change from a photodiode array to a CCD, demonstrates that the Ring effect leads to a systematic broadening of the retrieved ISRF, with a strong dependence on cloud conditions and seasonal changes in surface albedo. The authors provide also recommendations for the determination of the ISRF, intensity offsets and the wavelength dependence of the light throughput of the instrument. Continuous monitoring of the instrument properties is very important, particularly for long-term trend analyses, where instrumental effects can otherwise introduce biases.
The paper is well written, clearly structured and easy to follow, and its scientific content fits the scope of AMT. Below are my review, comments and remarks.

Many thanks for the positive assessment and helpful comments, which we all addressed as outlined below.

General comments:

(1) The authors state that the spectrometer of the instrument is maintained at 30±0.1°C (P.33, L.700). Nevertheless, could small temperature instabilities still contribute, at least partly, to the observed variability of retrieved instrumental parameters such as the FWHM? While the manuscript suggests that the dominant seasonal variability is driven by the Ring effect, an investigation of the diurnal variability of the retrieved instrument parameters during clear-sky days might help to assess the magnitude of (if any) remaining temperature-related contributions.
We can not exclude that there are small remaining temperature instabilities, but we found no obvious temperature deviations on a diurnal or seasonal basis. As suggested, we checked the diurnal variation of the FWHM on clear days, but found only a systematic dependence on the SZA, which is caused by the SZA-dependence of the Ring effect (see e.g. Fig. 5). Besides that, no further dependency of the FWHM was observed.
This information was added to section A1.

(2) Can the authors comment to what extent their main conclusions and recommendations apply to lower-latitude sites with weaker but still variable surface albedo and to other viewing geometries (e.g. MAX-DOAS)?

We added the following text as new point (e) to the conclusions:
‘e) Measurements at lower latitudes (without the presence of snow in winter) will be less affected by the seasonal changes of the Ring effect, but for measurements during twilight, the RSP at 90° SZA is still rather high (for a surface albedo of 0.05 it is about 0.075 for 350 nm and about 0.05 for 440 nm). Fortunately, for albedo values below about 0.1 the dependence of the RSP on surface albedo becomes almost negligible (changes are below about 0.002 at 320 nm, and below about 0.001 for wavelengths > 400 nm, see Fig. A6). For MAX-DOAS measurements, the situation is more complex than for zenith-sky observations, because the Ring effect depends not

only on SZA, but also on the elevation and relative azimuth angles as well as on the aerosol load (Wagner et al., 2009b). However, since MAX-DOAS measurements are usually analysed for smaller SZA ranges than zenith-sky observations, in general the strength of the Ring effect is weaker than for zenith-scattered light during twilight (see Fig. A6). Moreover, for MAX-DOAS measurements the focus is usually on trace gases located close to the surface (and thus typically below the last molecular scattering event), and their absorptions are hardly affected by the broadening due to rotational Raman scattering. Thus, to obtain the ISRF for the convolution of the trace gas cross sections the Raman scattering contribution should be subtracted from the measured spectrum before a KF is performed. Since for longer wavelengths, the strength of the Ring effect decreases, also a clear-sky zenith spectrum at low SZA might be selected for the Kurucz fit, for which the Ring effect is rather small.'

We also added a new figure showing the dependence of the RSP on SZA, surface albedo and aerosols (Fig. A6) to the appendix:

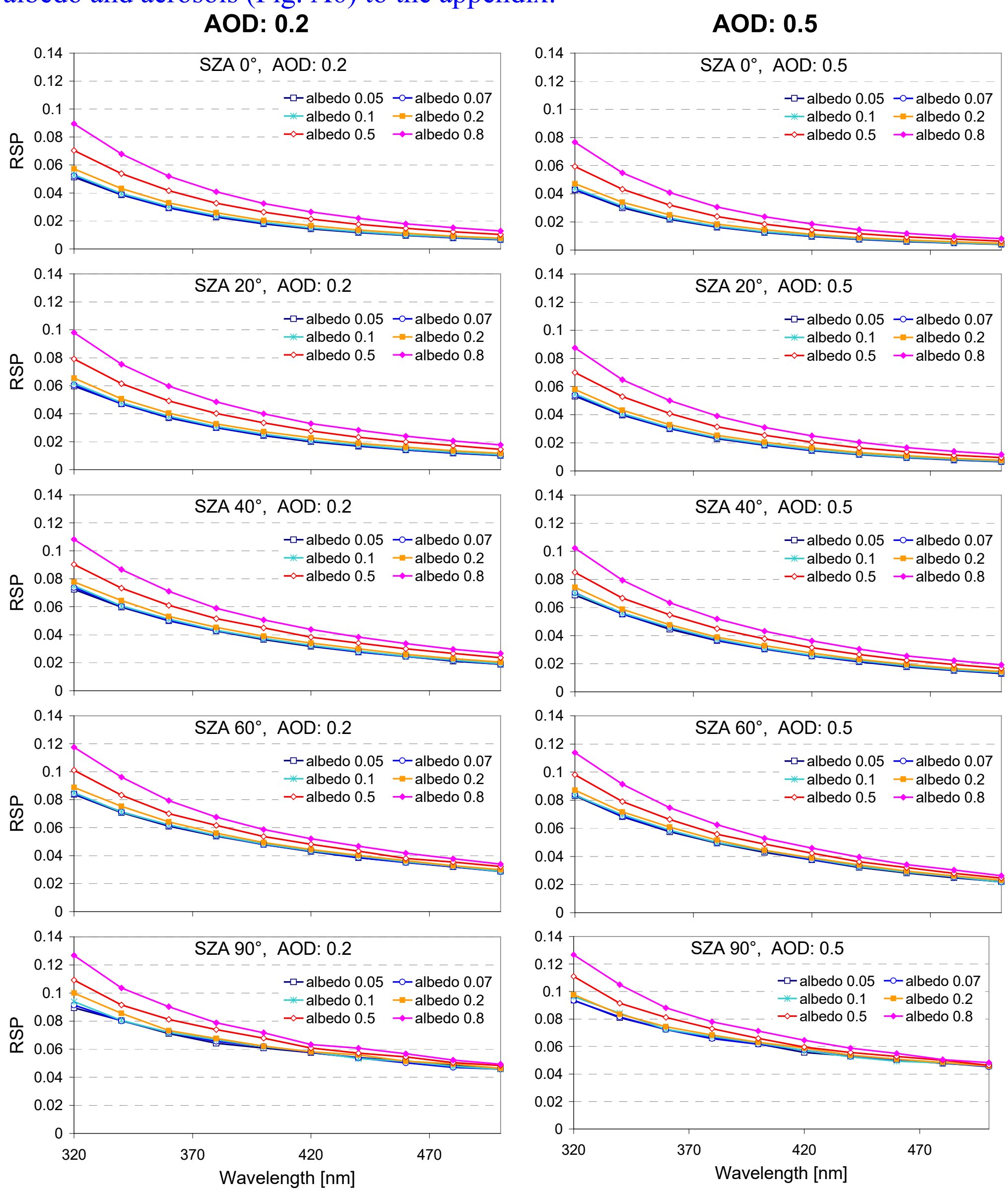

Fig. A6 Dependence of the RSP on wavelength for different surface albedos, SZA and aerosol loads derived from radiative transfer simulations with the radiative transfer model MCARTIM (Deutschmann et al., 2011). The aerosol profile is assumed as box-profile from the surface to 1 km. Single scattering albedo and asymmetry parameter are set to 0.95 and 0.68, respectively.

(3) In an ideal spectrometer the spectral line shape is determined by the grating, slit, and optics, while the detector merely samples the spectrum. The authors demonstrate that the older PDA detector is affected by the Fabry–Pérot etalon effect, which alters the sampled spectrum and influences the effective ISRF. Is this the only detector-related parameter that is different between the PDA and CCD sensor used in the study that may affect the ISRF?

The quantum efficiencies of both detectors are also different. However, the wavelength-dependencies of both detectors show no 'narrow'-band spectral features such as the Fabry–Pérot-etalon effect. Besides that, we see no further systematic differences. We added the potential effect of the wavelength-dependent quantum efficiency under point i) (old point h) in the conclusions.

(4) The authors conclude that, in order to obtain reasonable and spectrally consistent results of the ISRF FWHM, neither an intensity offset nor a Ring spectrum should be included in the KF. I think the authors should comment on whether this is expected to be an instrument-dependent conclusion and/or and if the same behavior is expected for different spectral regions (e.g. in the visible)

The following information was added to point c) in the conclusions:
'These conclusions are derived for our zenith-sky DOAS measurements in the UV spectral range. Further studies should be carried out for different instruments and wavelength ranges. Possibly, for instruments with higher spectral resolution, the effects of rotational Raman scattering and the width of the ISRF could be better separated.'

Specific comments:

P.3, L.71: The Fabry–Pérot etalon effect is first introduced at this point. While a short description of the effect is given in Sect. 4.2 (L.411-412), I think such a description is more appropriate here.
We added the following information to the text: 'The Fabry–Pérot etalon effect (Pérot and Fabry, 1899) is an interference effect (here between reflecting surfaces on top of the detector) and will be discussed in more detail in Sect. 4.2.'

P.4, Fig. 1: What do IRF 1 and IRF 2 represent? The small hut on the roof and the room inside the institute, respectively?
Yes, correct. We added this information to the figure caption.

P.5, L.117-120: Can the authors comment on how the KF performs at lower SZAs? Are similar results expected?
We added the following information at the end of the paragraph (directly before Sect. 3.1): 'For smaller SZA, similar results of the KF are obtained, but the derived FWHM is usually (for clear days) smaller, because the strength of the Ring decreases with decreasing SZA (see also Sect. 3.3).'

P.5, L.137-138: Is an ozone absorption cross section included in the fit as stated in L.110? Please clarify
We made clear (in the second sentence of Sect. 3) that for all cases an ozone absorption cross section was included.

P.7, L.154-157: Can the authors comment on why doesn't the inclusion of a Ring

spectrum and/or of an intensity offset improve the results, especially in the UV range? Is this an instrument-dependent observation?
With respect to the first question, we added the following information at the end of Sect. 3.2: 'This finding is further explored and discussed in the following 2 sections.'
With respect to the second question, we added the following text to point c) in the conclusions (see also our reply to point 4 above): 'These conclusions are derived for our zenith-sky DOAS measurements in the UV spectral range. Further studies should be carried out for different instruments and wavelength ranges. Possibly, for instruments with higher spectral resolution, the effects of rotational Raman scattering and the width of the ISRF could be better separated.'

P.8, Fig. 3b: Are there any missing data in panel b) between 2003 and 2007? Or is this due to a visualization reason?
Many thanks for this hint! The data were lost during combining the time series of the individual years. The missing data were now added.

P.13, Fig. 5: The simulated RSP (panel a) should either become differential RSP, relative to 80 deg. SZA, or for the measured RSPs (panels b and c) the ylabels should be dRSP
We changed the labels in panels b and c to 'dRSP'

P. 20, L.309-400: Are there any lamp measurements to confirm the increase of the FWHM?
Unfortunately, no atomic line lamp measurements during that period are available. During the next visit at the measurement site (hopefully in 2026), atomic line lamp measurements) will be performed.

Technical corrections:

P.3, L.61: "ist" -> "is"
corrected

P.4, L.104: "ERS" -> "ESR"
corrected

P.4, L.109: "software QDOAS" -> "QDOAS software"
corrected

P.6, L.149: "Finally, also the effect…". -> "Finally, the effect…"
corrected

P.7, L.160: "Mio spectra" -> "million spectra"
corrected

P.8, Fig. 3 caption: Color assignments are wrong. They should probably be magenta, cyan, orange and black. Please revise. Same applies for Fig. 14 and Fig. A4
The figure caption of Fig. 14 was corrected. For Fig. 3 and Fig. A4, the color assignments in the figure captions were removed.

P.9, L.206: "prpared" -> "prepared"
corrected

P.9, L.207: "teh" -> "the"

corrected

P.9, L.216-217: “According to Wikipedia (2025), snow cover generally lasts from late September to mid-May”. This sentence may be omitted since afterwards, the snow depth is given in Fig. 4a
the sentence was deleted

P.10, Table 1 caption: “Also shown are the settings from Alliwell et al., (2002)” -> “The settings from Alliwell et al., (2002) are also shown/included”
corrected

P.11, Fig. 4: The x label names (month names) should be given in English. Same applies for Fig. 13. Also in panel d, the marker color of the legend for 341-348 nm is wrong
corrected

P.12, L.241: “Kuruzc” -> “Kurucz”
corrected

P.12, L.252: “…are shown (black dots)” -> “filled markers”?
corrected

P.12, L.253: “Fig, 5a” -> “Fig. 5a”
corrected

P.12, L.255 “(blue dots)” -> “(small dots/markers)”?
corrected

P.15, Fig. 7: A ylabel should be given
corrected

P.15, Fig. 7 caption and in all other places: “ISFR” -> “ISRF”
corrected

P.16, L.311-312: “the better choice” -> “the best choice” or “a better choice”
corrected

P.16, L.315: the word “however” is not necessary
corrected

P.16, Table 2 caption and in all other places: “super Gaussian” -> “super-Gaussian”
corrected

P. 20, L.408 “charateristics” -> “characteristics”
corrected

P. 21, L. 437: “Appendix 3” -> “Appendix A3”
corrected

P. 33, L.698 and 700: “spectromter” -> “spectrometer”
corrected

P. 33, Fig. A1 caption: Either include a) and b) texts in the two panels or replace with

“left”-“right”. Also replace “the visible spectrometer” with “the spectrometer operating in the visible range” or something similar.
corrected

P. 41, L.797: “of scattered” is a duplicate
corrected