

Interactive comment on “Development and characterization of the CU ground MAX-DOAS instrument: lowering RMS noise and first measurements of BrO, IO, and CHOCHO near Pensacola, FL” by S. Coburn et al.

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Dear referee # 2, thank you for taking the time to review our paper and for your helpful comments. Detailed below are our answers.

General Comments: The authors present a new developed MAX-DOAS instrument for the detection of trace gases in the boundary layer with very high sensitivity due to very low achievable RMS values in the residual spectrum. The manuscript is well structured and clearly written. Appropriate figures are shown. The authors present an analysis of

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arising unwanted spectral structures for MAX(or passive)-DOAS measurements if an insufficient temperature stabilisation is realised. This theoretic investigation is so far the first one I know performed in such detail. The temperature instability would increase the RMS in the residual spectrum and thus the measurement error and detection limit. The authors conclude that the main reason for remaining structures in the RMS arise from temperature fluctuations. These structures are minimised in the presented instrument by a two stage temperature stabilisation of the spectrometer. Other existing MAX-DOAS instruments use only a one stage temperature stabilisation. A mayor part of the manuscript is to describe and demonstrate the good performance of the instrument. The application to field measurements is shortly shown for observations near Pensacola, FL. However the instrument characterisation is incomplete to convince the reader of the better performance in comparison to existing ones.

- We would like to note that this is not a theoretical study, as that all calculations and conclusions are based on empirical data. - We did not intend for a major conclusion to be that remaining structures in the RMS are always due to temperature fluctuations, but that this is merely one of several potential contributors (including non-linear effects) that, depending on measurement conditions and instrument set-up, can explain the observed RMS limitations. The text will be updated to make sure that this is more clearly communicated. -We did not intend to claim that the instrument presented here performs better than other state-of-the-art instruments, but rather that it is certainly comparable. The main focus of this paper was to provide an in depth study on factors currently limiting state-of-the-art DOAS hardware.

Throughout the manuscript typically the best achieved values which are shown in the figures are written in the text and not the typical or average values. This misleads the reader. If comparing the average achieved RMS values plotted in the figures, they are in the same range as other very good MAX-DOAS instruments (Table 1). Additionally the noise test is only based on elevation angles of 25° (vs. 80°), but typical MAX-DOAS observations use mainly lower elevation angles. Typically RMS values are higher for

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lower elevation angles due to stronger absorptions and a stronger ring effect. Thus the given RMS does not represent the value which would be achieved at low elevation angles e.g. 0° - 5° .

- The text has been updated to make the values that we present more transparent as to whether they are typical or best achieved. Additionally, Fig. 5 has been updated to include information from field measurements using a lower elevation angle.

The manuscript focuses on spectral structures in the residual spectrum given by the RMS and also discusses noise tests. However a standard noise test, as typically performed for any spectroscopic instrument, to demonstrate the best achievable RMS value is completely missing. Such tests are performed with a light source without spectrally structured (e.g. halogen lamp) that spectral shifts of the spectrometer (e.g. due to the mentioned temperature fluctuation), can not lead to an increase of the RMS. Thus the real achievable limit in RMS can be determined which is typically higher than the theoretic value (from shot noise) due to other noise sources (e.g. electronic noise, optical noise).

- A standard noise test using a tungsten lamp has been performed, and the results included in Fig. 5.

Any discussion about temporal resolution is missing. As MAX-DOAS measurements rely on a series of measurement at different elevation angles which should be performed at almost same atmospheric conditions this would be essential. Also if the measurement quality could be improved with increasing photons due to longer integration, this will typically lead to unacceptable long measurement time for a sequence and are thus not applicable. Even longer integration times as described are in practise not possible. For a comparison to existing MAX-DOAS instruments it would be necessary to compare the performance at similar integration times.

- The temporal resolution of the instrument is handled in an implied way through the discussion of the effective slit area, as that it is this feature that determines over which

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temporal scales one has to collect light in order to reach certain photon counts. In comparing the instruments in Table 1, this instrument has the largest effective slit area and so it follows that it would be able to realize lower integration times to achieve a specified photon count limit. Text has been added to Sections 3.3, 3.4, and 4.2 to state the integration time used for the lab tests and field measurements. Text is currently in place stating the integration times used for the signal to noise tests described in Section 4.1 (p261 line 18).

If MAX-DOAS evaluations are performed in that way that for each measurement spectrum the reference spectrum close in time is used (as also done in section 4) the temperature fluctuation between these measurements is relevant, which could be very small even in comparison to the presented temperature stabilisation over 8 hours. Thus the improvement with enhanced temperature stabilisation can become irrelevant for MAX-DOAS observations.

- We tried to convey that the temperature stabilization is not irrelevant because even small temperature fluctuations can cause shifts in the wavelength pixel mapping (see Section 3.3) that can result in the “blurring” of absorption features that, in turn, can cause a certain amount of residual structure to remain after the DOAS analysis. Even small amounts of residual structure become problematic when attempting to measure trace gases with low concentrations such as BrO. As described in the introduction p251 lines 15-20, the RMS needed to detect trace amounts of BrO are on the order of $3\text{-}6 \times 10^{-5}$, which based purely on photon shot noise means that between 3×10^8 – 1×10^9 photons need to be collected. Based on our instrument’s performance in the field this requires at least a 1 min integration time – a timescale on which fluctuations in temperature are important.

The measurement results from the field observations at Pensacola, FL are not discussed or interpreted in terms of the chemistry. The given discussion is not put in context with the measurements. Thus either this discussion is removed or the discussion is extended to put the measurements in context.

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- The measurements and chemistry background presented in this manuscript were meant to serve as the motivation for the building of the instrument and the following studies, and we feel that any further discussion on these points would be inappropriate for this particular journal. A more robust treatment of the chemistry found in this manuscript is planned for a future publication.

Therefore mayor corrections and revisions are necessary prior publication in AMT. The authors have also to show what RMS is achieved under realistic MAX-DOAS conditions (small elevation angles, short integration times) and compare these to RMS values of state-of-the-art instruments.

- This has been addressed in the updated Fig. 5

Specific Comments:

P 247 Title: the word “first” is misleading, as these are not the first measurements of these trace gases.

- The title has been rearranged so that it reads, “Development and characterization of the CU ground MAX-DOAS instrument: lowering RMS noise and first measurements near Pensacola, FL of BrO, IO, and CHOCHO”.

P 248 Line 6: The detection sensitivity is proportional to the RMS of the residual spectrum, but not necessary directly. There is no direct mathematical link between RMS and detection limit. This has to be defined by statistical analysis like done in Stutz and Platt 1996.

- The text “directly” has been removed from this line

P 248 Line 9: The RMS value $\sim 6 \times 10^{-6}$ is not proven in the manuscript, as it is not achieved. The values from figure 1 are $\sim 9 \times 10^{-5}$ for 64 added spectra and decrease to $\sim 1 \times 10^{-5}$ if 100 ratios are added. It is not proven that other noise sources (electronical, optical) except from photo statistic limit the RMS of the instrument. Therefore this statement is misleading.

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- This is not correct – the value of 6×10^{-6} is found in Fig. 5 panel (b) lower right blue triangle. Additionally, it is demonstrated through Fig. 5 that any other systematic noise contributors are insignificant as that they would manifest themselves as a significant deviation from the theoretical noise depicted (since this is calculated only considering photon shot noise).

P 248 Line 20: Please specify once FL.

- The text has been updated the explicitly state “Florida” at the first mention of the measurement site.

P 249 Line 3: Please give reference if you state that halogens are relevant for air quality. I don't thing so that this is the case for urban air quality.

- A reference will be included

P 249 Line 14: Please give references for the stated chemical reactions of BrO and bromine atoms.

- A reference has been included

P 250 Line 1: The first measurements of halogen oxides with DOAS are presented in Hausmann and Platt 1994. Please include this reference or state that you only mean passive DOAS observations.

- This reference has been included

P 250 Line 9: The influence of stratospheric absorbers is not always removed if you use a fixed zenith reference at low SZA. If the SZA is changing, the stratospheric absorber signal is changing. That means the stratospheric absorber is only removed for a spectrum recorded close in time to the reference spectrum for any other spectrum it is not completely removed. Thus the statement is wrong. But what you remove are the Fraunhofer lines.

- This statement has been corrected in the text

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P 250 Line 20: It is not proven that the RMS is not further improved for state-of-the-art instruments with further photo-count statistic. Possibly only a longer integration time was unpractical due to the required temporal resolution for MAX-DOAS measurements.

- To our knowledge all other MAX-DOAS state-of-the-art hardware use single stage temperature control, which is typically limited to the 0.1°C range. During acquisition these temperature oscillations can cause a “blurring” of spectral lines do to shifts and changes in the instrument line shape. Based on our findings these would limit the attainable RMS to on the order of $\sim 1 \times 10^{-4}$ – which is supported by the data found in Table 1.

P 251 Line 17: To which mixing ratio a dSCD of 1×10^{13} molec cm^{-2} relates? Is this relevant for atmospheric processes (give references)?

- Using the calculation of path length based on the O4 dSCD described in Sinreich et al. (2010) and using a typical O4 dSCD of 6×10^{43} molec² cm^{-5} this BrO dSCD relates to a mixing ratio of 2-3 ppt, which is atmospherically relevant for oxidizing gaseous elemental mercury.

P 252 Line 4: To which dSCD 2ppt relate?

- Again using the calculation described in Sinreich et al. (2010) and a typical O4 dSCD of 6×10^{43} molec² cm^{-5} this BrO mixing ratio relates to a dSCD of 9×10^{12} molec cm^{-2} .

P 252 Line 9: Define once abbreviation PSN for photo shot noise.

- Text has been updated to define this abbreviation at its first mention.

P 255 Line 22: Specify the temperature sensors (accuracy and temperature drift). What is the accuracy of the read out electronic?

- The temperature sensors that we use are Omega PT100 high precision RTDs (accuracy – 1/10 DIN) – the text has been updated to include this information.

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P 255 Line 25: Are the fibre adjustment mounting and the detector mounting within the temperature stabilised housing?

- Both the fiber adjustment mounting and the detector mounting are contained only within the primary temperature stabilization enclosure - text has been included here to describe this.

P 256 Line 9 – 19: Please shorten this section as this information was already given before or is irrelevant.

- Text has been updated so that the description of the controlling software will be moved to where it is more relevant (Section 2.2).

P 257 Line 10: Please be consistent in the given values and write 0.8 pixels for 10 °C, or 0.08 pixel °C⁻¹.

- Text has been updated so that it is consistent

P 257 Line 13: Remove information about offset as it is irrelevant here.

- Offset information has been removed

P 257 Line 24: How are the values of $< 5 \times 10^{-5}$ to 1.5×10^{-4} read from the table for the presented instrument? What would be the RMS values for typical temperature stability of ~ 0.1 °C.

- These numbers are based on the temperature stability realized by the slit, which is only mounted within the primary temperature enclosure. So, the estimated temperature stability range for the slit would be between 0.06 °C to 0.16 °C and combining these values with the FWHM broadening dependency on temperature changes of 0.03 pixel/°C - gives pixel differences on the order of 1.8×10^{-3} – 4.8×10^{-3} . These pixel differences in FWHM correspond to the reported RMS values.

P 258 Line 5: “identical spectra” – Which spectra? (measured, Fraunhofer Spectrum, Literature cross sections). If you mean the zenith sky spectrum, this statement has to

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be clarified. Also a shift of this reference can be allowed in the DOAS analysis so that this error of the shift can be reduced. If you do not mean the zenith sky spectrum, this section 3.3 is unclear. Please clarify. It seems that you are talking until Line 12 from something different that after that (Notably, . . .). Please separate the two statements of a wavelength calibration of the reference measurement and spectrum and those of calibration accuracy of literature cross-sections.

- Text has been updated to clarify the reference to “identical spectra” and a more clear separation of the two statements (Notably, . . .) has also been added.

P 258 Line 12 – 14: In the DOAS analysis a shift of the literature cross-sections can be realised, so that this error can be reduced. Also different wavelength mappings of literature cross-sections have always to be corrected in DOAS analysis, but should be relative fixed between the cross-sections. Differences arise as different wavelength calibrations are used, e.g. the determination of the centre of an absorption line. Thus it is not clear why RMS structures should arise from wavelength uncertainties of the cross-sections especially if concentrations are very low.

- Shifts in the DOAS analysis do reduce errors, but are not perfect, which can still result in errors in the wavelength mapping. Additionally, the literature cross-sections are measured with a certain amount of uncertainty (0.01 and 6×10^{-3} pixels in the visible and UV, respectively – Section 3.3) and at very low RMS levels this could potentially be a limiting factor. We agree with the last statement of the reviewer in that if concentrations are low RMS structures due to these uncertainties should not be an issue. However, this is not the case for abundant trace gases (particularly NO₂ in the area where our measurements were made).

P259 Line 1: Detector non-linearity investigations do not contain a detector nonlinearity measurement which could clarify which saturation levels are applicable for the DOAS measurement with the given detector and if you work in the linear range. It is obvious that if you work in the range where the detector is non-linear (this seems to be the case

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for your 90% saturation), problems for the DOAS measurements arise. If this is not guaranteed the section becomes irrelevant. Also no information is given of the readout of the detector (binning, full imaging).

- The information from the manufacturer indicates that the non-linearity of this detector is <1% over the whole dynamic range, but this information is insufficient for the levels at which we work, which is why the presented tests were performed. These tests indicate that there is a certain amount of non-linearity to the detector but this is hard to quantify because the test were performed using solar stray light. However, the tests do indicate that this doesn't have to limit our ability to reach $1-4 \times 10^{-5}$ RMS levels (as shown in Fig. 3), but could possibly play a role at even lower RMS. Also, information on the readout of the detector can be found on p254 line 20 to p255 line 2.

P 259 Line 6 and Fig3: Which saturation is given in %? From maximum counts or full well capacity? For a pixel or the read out register? In which relation are the max. counts to the full well capacity in the applied detector read out mode?

- Saturation level is defined on p256 lines 10-12, and text has been added to indicate that this is determined from a single pixel (having the maximum in the pre-determined pixel range).

P 259 Line 21: If the saturation of one spectrum is reduced, the shot noise will increase what can partly cause the increase in RMS. How large is this contribution?

- In the tests described the saturation level differed, but the total number of photons was kept constant – so there should not be a difference do to photon shot noise. Text has been added to this section to clarify this point.

P 260 Line 3: Is 90% saturation still in the linear range of the detector?

- According to the manufacturer, yes it is.

P 260 Line 19: A same saturation level over a whole spectrum can not be achieved in practise as the spectral shape is changing for different elevation angles.

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- This is correct. Our data acquisition software has the capability to define a pixel range over which the saturation level is determined which allows the data to be optimized for a specific wavelength range. Text describing this feature has been added to Section 2.2.

P 260 Line 25 – 27: This sentence is unimportant.

- This text has been removed

P 261 Line 10: This section does not contain a signal-to-noise test with a spectral unstructured emitter like a halogen lamp. The content of the section is difficult to follow due to different kind of modes of operation, applied methods and evaluation. Please clarify.

- A noise test using a tungsten lamp has been performed and the results included in this section. Additionally, the text in this section has been updated accordingly and made to be more clear in the description of the different modes of operation and data evaluation methods.

P 261 Line 11- 13: Remove sentence as it is irrelevant. What is intelligent for an averaging module?

- This is merely a statement informing on the tool used for data processing, which is a custom developed LabVIEW-based program – Intelligent Averaging Module is the name we call it. This is a sophisticated tool that has the capability to make use of large variety of parameters when processing data. A footnote has been added to the text in order to make this more transparent.

P 261 Line 16/17: In the second operation mode measurements are taken for 80° and 25°. The further presented RMS values in Fig. 5 are based on these angles. Why do you show noise values only for these high (25°) elevation angle? For MAX-DOAS the measurements at very low elevation angles (0°-5°) are most important as they are much more sensitive to trace gases near the ground and thus contain most

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information. In the analysis the RMS is typically higher for such low elevation angles as than the trace gas absorption and the ring effect is stronger. Small errors in both spectral structures increase the RMS. Thus the presented RMS does not represent the values achieved for low elevation angles which are most important for MAX-DOAS.

- Figure 5 has been updated to also include a lower elevation angle.

P 261 from Line 261: Please move the description of the analysis for the different fit ranges (BrO, IO, CHOCHO) to point 4, as it is also relevant for 4.2.

- Text in this section has been modified.

P 261 Line 26: Why do you use the reference from Hönninger and not one published in the literature (e.g. Spietz et al., 2005).

- This cross-section is used for historical reasons.

P 262 Line 4: You write here that you use a reference close in time to the measurement. But on P 250 Line 9 you write that the reference spectrum is recorded at low SZA. Please correct the statement on P 250.

- The statement on p250 line 9 was meant as a generalized statement about the DOAS analysis, not necessarily reflecting the method we used. The text on p250 has been modified accordingly to clarify this point.

P 262 Line 8 and following: How does the two methods relate to the two modes of operation?

- All the text in Section 4.1 has been modified to clarify the different modes of operation and analysis methods.

P 262 Line 14: The wavelength region 415-440nm for the CHOCHO fit is not consistent with the fit shown in Figure 8. Please state why the IO reference is omitted for the CHOCHO fit and why CHOCHO is omitted for the IO fit.

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- The fit shown in Fig. 8 is from the analysis of the field data, for which a different fitting window was used for CHOCHO. The fits in Fig. 8 are optimized for the retrieval of IO and CHOCHO, respectively, and so the absorption of the other gas (CHOCHO in the IO fit and IO in the CHOCHO fit) is very weak making it unnecessary to include in the figure.

P 262 Line 17 – 18: remove sentence as it is redundant.

- The text has been updated and this sentence removed.

P 262 Line 19: replace “IAM” by “software”

- The text in this line has been modified.

P 263 Line 3: The values of 1×10^{-5} and 6×10^{-6} are the absolute best achieved values in Fig. 5, but they are not the average values for a specific amount of counts. These are in the order of $\sim 4 \times 10^{-5}$ and 1×10^{-5} . The given values are misleading. The values for the added spectra are even much higher. What is the according temporal resolution for all these measurements?

- In this line we are trying to demonstrate the best achieved RMS, not average values – the text has been modified to make this point more transparent. The temporal resolution varies depending on how many photons were collected and the mode in which the instrument was used. The presented field measurements were recorded at 1 min integration times, while the spectra from the noise tests had 5 s integration times (then in the different analysis methods these spectra were added).

P 263 Line 4: What is the integration time to record $>10^{10}$ photons?

- The spectra that have $>10^{10}$ photons were created by two methods: 1) by adding 500 spectra and 2) by adding 1000 spectra. These are the spectra with 5s integration time and so they correspond to ~ 42 min and ~ 85 min, respectively. For the lamp spectra each $>10^{10}$ photon spectrum took ~ 15 min.

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P 263 Line 10: The finding that the RMS increases if delta t increases is not new. That is why several groups already evaluate DOAS spectra to a reference close in time and not to one reference a day taken at small SZA, like first described in this work (P 250 Line 9). Also than small temperature fluctuation over longer periods become unimportant as the spectral characteristic has only to be absolute stable between measurement and reference spectrum.

- The reference to the results of increasing RMS with time is used here in the context of motivating to use of such a light strong instrument such as the one described. Additionally, as shown in Section 3.3 the effect of even very small temperature fluctuations (i.e. small timescales) become important when attempting to reach RMS values $<1 \times 10^{-4}$.

P 263 Line 17: Your conclusion is not proven by your given values. With your achieved temperature stability of 0.005° and the values given in Table 2 the increased RMS can not be explained! Thus I conclude that other reasons are responsible and thus such a good temperature stabilisation is not necessary. How would the RMS values vary for different delta t for a light source without spectral structures (halogen lamp)?

- We would not use a temperature stabilization value of 0.005°C for such a calculation as that would be the best possible temperature stabilization. Since the slit mounting is located only inside the primary temperature stabilizing enclosure (temperature stabilization $\sim 0.16^\circ\text{C}$), so the temperature stability that is actually realized by the slit is between 0.06°C and 0.16°C . It is from these numbers that the RMS values presented on p257 line24 are calculated.

P 264 Line 5-11: Why the numbers of spectra for the different trace gases are given? These values are irrelevant as they are not put in any context. Please shorten this section. Why O4 is not always detected?

- The numbers for each gas are given to demonstrate the duty cycle of the instrument in the detection for individual gases. The duty cycle for O4 is not 100% because a rather conservative criterion is applied to all measurements to prevent the reporting of

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questionable results.

P 264 Line 15-19: Where is the proof for using these scaling factors? Please compare e.g. to Stutz and Platt, 1996.

- The use of these scaling factors is based on the amount of structure left in our residual spectra – a scaling factor of 2 roughly corresponds to 6 times the fit error produced from the DOAS analysis and represents a conservative estimate for the detection limit. The detection limit as determined from Stutz and Platt, 1996 is only valid for a purely statistical residual, which we do not realize.

P 264 Line 22: Geometric AMF are a very strong simplification which is e.g. only valid at small SZA and at clear sky conditions. Please clarify this, as thus also the following values can contain large errors.

- The use of geometric AMFs was implemented because as full radiative transfer calculations were performed it was found that uncertainties in the vertical distributions led to errors of the same order of magnitude as using the geometric approximation..

P 264 Line 25: How can you calculate average BrO dSCDs if it is most of the time below the detection limit?

- There are a certain number of significant measurements of BrO and from these a relative average can be calculated.

P 264 Line 28 to P 265 Line 17: This section is not put in context to the measurement values and thus these statements are not proven here. In the form they are written in the manuscript this section is redundant. If you can, calculate the BrO mixing ratio from your observation and put them in context to the mercury oxidation from Holmes et al., 2009. What MAX-DOAS sensitivity is required to observe 2 ppt of BrO?

- The purpose of this section is to show the scientific motivation for the building and testing of the instrument described and we feel any further discussion into interpretation of the measurements in the context of mercury chemistry would be inappropriate

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for this publication and will be addressed in a future publication. Text describing the sensitivity needed to measure trace amounts of BrO can be found in the Introduction p251 lines 15-23.

P 265 Line 25: not “measure RMS” but “achieve RMS”. RMS values smaller than 10^{-5} are not proven in the manuscript (see statements above).

- The text here will be changed to “achieve RMS”. RMS values $<10^{-5}$ are achieved and can be found in Fig. 5 panel (b) lower right blue triangles.

P 266 Line 2: The RMS values from the field campaign are very good, but much higher than the proposed RMS values. They are thus not much better than other research grade MAX-DOAS instruments (Table 1).

- It was not our intention to imply that this instrument out performs other research grade MAX-DOAS instrumentation, but that it performs at least as well.

P 266 Line 12: “BrO located above 6km” – MAX-DOAS is not sensitive to even lower elevations. How do you determine these 6km? Please give reference. Also in Line 17 “within a few km” – please give reference.

- This was determined by a sensitivity study where a gauss shaped layer of ~ 3 ppt BrO at maximum was moved from elevations between 0-6 km. At about 6 km altitude and above we would be unable to distinguish the tropospheric BrO signal from the stratospheric BrO signal – but this is highly dependent on the BrO vertical distribution. The sensitivity study was based on findings by Theys et al. (2007) who saw indications on a BrO maximum at 6km altitude. The text has been updated to include a reference for the second statement.

Table 1: Please include the temporal resolution as this significantly influence the achieved RMS. What is the wavelength range for the evaluation for the achieved RMS? A larger range typically leads to higher RMS values.

- As described in the response to the general comment on temporal resolution, this is

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included indirectly through the reporting of the effective slit area, which determines at which temporal resolution a particular instrument can operate. Text has been added to the caption for Table 1 to indicate the typical wavelength range used for the analyses.

Table 2: To which temperature stability of the presented instrument these values are related?

- The spectrum used for this analysis was taken while the instrument was stabilized to within the bounds reported on p256 lines 1-5.

Table 4: Information is redundant as it is already given in Fig 6.

- Noted this table has been removed from the updated version of the manuscript.

Fig. 1: Please improve the figure to clarify the setup in the instrument rack (e.g. principle sketch). From the picture the setup is not clear.

- Figure 1 has been modified so that the set-up inside the instrument rack can be more clearly seen.

Fig. 4.: The different plots are difficult to relate to the different analysis. Please clarify and state where you use the two fit scenarios a) and b).

- The caption for Fig. 4 has been modified to more clearly reflect the presented measurements.

Fig. 5.: Include integration time to the accumulated photons, as this is essential for MAX-DOAS. Are the averaged ratios are relevant for MAX-DOAS measurements due to their low temporal resolution? Why do you show these RMS values for 25° which is not a main MAX-DOAS elevation angle? RMS values are typically higher for lower elevation angles. The achieved average RMS values are in the range of the research grade MAX-DOAS RMS.

- The text has been updated to include integration times of the field data, and the integration times for the noise tests can be found on p261 line 18 – these spectra were

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subsequently added to produce the data found in Fig. 5. The summed ratios are used because of the lower temporal resolution used to create the ratios and the summing helps to get to what would be higher photon numbers. The values for the 25° elevation angle were only included because this is the angle which was used to convert dSCDs to VCDs in the results section, and this is the angle best suited for the use of geometric AMFs. In any case, Fig. 5 has been updated to also include data from a lower elevation angle.

Fig. 7 and 8: The achieved RMS values here are very good, but much higher than those proposed from Fig. 5 and written in the manuscript.

- The RMS values presented in Fig. 7 and 8 are well within the stated range for this instrument's RMS (Table 1) and among the lower values found in Fig. 5 for the field data (green circles/diamonds). They are only higher than the lowest RMS values achieved in the signal to noise tests demonstrating the capabilities of the instrument.

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Fig. 1. Figure 1: updated so the inside of the rack can more easily be seen - additionally the caption has been appropriately modified

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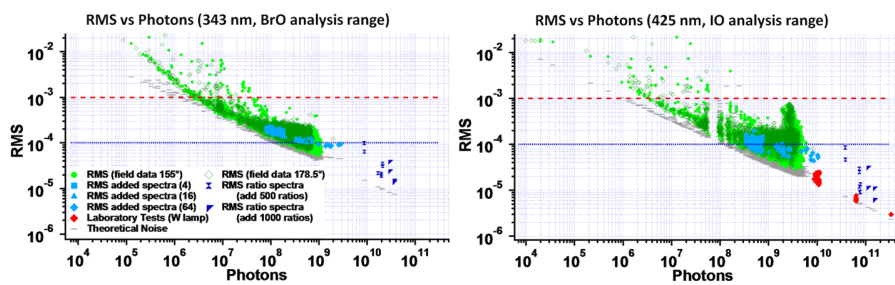


Fig. 2. Figure 5: Here an additional elevation angle for the field data has been added as well as the results of the signal to noise tests using a tungsten lamp

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