Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2016-237-AC1, 2016

Atmospheric Measurement Techniques Discussions

Interactive comment on "The AOTF-based NO_2 camera" *by* Emmanuel Dekemper et al.

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Received and published: 16 November 2016

Dear Dr Kern,
Thank you for the positive recommendation and the in-depth review of our manuscript. Your thorough analysis greatly improved a number of weaknesses still present in the discussion version. Here below we address all your questions/comments, hoping that our answers will meet your expectancies.

- p.2,L3: U. Platt's reference for DOAS.
Agreed, the reference to Lohberger et al. (2004) has been replaced by Platt et al (1979).

- p.2,L9: Potential advantage of DOAS grating spectrometer over NO2 camera.
As written in the text (p.2, L6-9), there is no qestioning of the performance of the classical DOAS approach regarding detection limit or accuracy. Clearly, the NO2 camera

concept still needs further development and use before it approaches the same level of performance. The clear advantage of the NO2 camera over DOAS imaging systems is with the spatio-temporal resolution and the integrity of the data product (maps of NO2 SCDs). Even if the NO2 camera must degrade its instantaneous temporal resolution (exposure times of typically 0.5-1 second) by performing data averaging in order to mitigate plume transient features, the overall plume is imaged every time. The retrieved NO2 SCD map truly represents the mean SCD field. This is not the case with scanning spectrometers because only a small portion of the scene is probed at a time. Transient features in the plume not observed by the DOAS instrument at a given time can significantly affect the mean image. We think the current version of the manuscript is reflecting this position without trying to prove that the NO2 camera is a better instrument in general.

- p.2,L11: Disagreement with the statement on the advent of SO2 camera as main volcanic SO2 measurement technique.
Point taken, the sentence will be changed to: "In volcanology for instance, the so-called SO2 cameras are now increasingly complementing the measurements performed with classical dispersive techniques (grating spectrometers). Their concept ..."

- p.3,L9: Possibility of having all light rays travelling parallel through the AOTF.
We confirm that it is feasible to make all chief rays travel parallel through the AOTF. This is the role of the telecentric design: selecting only the chief rays and a very narrow cone of surrounding beams. It is achieved by placing a pupil at the focal plane of the first lens. This is crucial for preserving the spectral purity of the image. By ensuring that all rays hit the AOTF crystal surface with the same angle (+/- tolerance), the same wavelength will be selected across the field of view. On the other side, it is true that this design reduces the throughput of the instrument. But one cannot waive the physical principles of the AOTF such that the telecentricity must be obeyed within the tolerances of the acceptance angle of the AOTF.

- p.3,L21: Dependence of the acoustic power on the optical wavelength.

The efficiency of the acousto-optic (AO) interaction relies on the coupling between the light electric field and the elastic modulations created by the acoustic wave (which perturbate the dielectric susceptibility of the medium). The ease of the coupling depends on the physical properties of the crystal: refractive indices (n_o, n_e), elasto-optic coefficient (p), mass density (ρ), acoustic wave phase velocity (v). In acousto-optics, a figure of merit is often used to quickly assess which material is good for AO: $M_2 = n_e^3 n_o^3 p^2/(\rho v^3)$. As an example, TeO2 is generally the preferred choice in VIS-SWIR applications as its M_2 is several orders of magnitude higher than the M_2 of quartz. As a consequence, a TeO2-based AOTF requires much less acoustic power than other materials for the same efficiency. The reason why it changes with wavelength is because of the dependence on the refractive indices.

- p.4,L5: Resolvable spots.
The number of resolvable spots is a relatively common concept in imaging optics which has to do with the modulation transfer function (MTF), i.e. the capability for the imaging system to resolve sharp contrasts (and not blur edges or lines). This is a purely spatial concept. As other optical parts, the AOTF is not capable of infinite spatial resolution. Besides the basic purity of the crystal, the divergence of the optical beam is also playing a role. Propagation angles are crucial in an AOTF: within the narrow cone of light surrounding a chief ray, the slight divergence of the beams causes a slight difference of diffraction angle, ending up with a decrease of the imaging quality. This effect is particularly true in the plane of the AO interaction, this is why the number of resolvable spots is different in both directions. The paper cited in the beginning of the paragraph (p.3,L25: Voloshinov et al. 2007) is a good reference for all these concepts.

- p.7,L7: Wavelength selection.
The reasons driving the selection of the two wavelengths are discussed in the first two paragraphs of section 3 on page 4: it is a matter of maximizing the differential optical depth while minimizing the spectral interval to avoid interference by aerosols or Rayleigh scattering.

This could be made clearer by changing the text surrounding eq.8 and 9. Starting at p.7, L6, the new text will be:
"If the spectral interval between λ_w and λ_s is small enough that the approximation $\tau_\star(\lambda_w) = \tau_\star(\lambda_s)$ holds, then the ratio of the transmittances $T(\lambda_w)/T(\lambda_s)$ is a measured quantity which only depends on the NO2 content of the plume. Introducing the relative instrument response at pixel ij: $\rho_{ij}(\lambda) = r_{ij}(\lambda)/r(\lambda)$, we find:
EQ.(8).
Finally, the NO2 SCD subtended by the area of the plume observed by pixel ij follows by taking the logarithm of the ratio of transmittances:
EQ.(9).
Clearly, the best sensitivity is reached by maximizing the differential optical thickness when selecting λ_w and λ_s."

- p.9,L14: Temperature effect on the AOTF passband.
You are perfectly correct: drifts in crystal temperature displace the central wavelength of the AOTF passband. At the time of the reported experiment, the driving electronics was not capable of adjusting the acoustic frequency to compensate for the drift in temperature. This led us to live with sub-optimal values of differential optical thicknesses.
However, the temperature was monitored during the experiment which allowed for recalibration of the wavelength scale during the post-measurement processing. Thanks to that, a maximum of 10% error is accounted for in the error budget: because the final wavelength uncertainty is about 0.1nm, which ends up with changes of not more than 10% in this region of the NO2 spectrum.

- p.11,L1: The relative error of 0.5%.
The relative error we are mentioning here is on the background signal C_0, not on the NO2 SCD. This value of 0.5% is in line with the discussion in the third paragraph of section 3.4 which deals with the various error sources. It was estimated from the sample statistics that served to compute the average value for C_0.
The sentence will be changed to make it clearer: "The relative error on C_0 is about

0.5% ...".

- p.12: Optical thickness of the plume, presence of aerosols.
During the measurement campaign, the content of the exhaust plume often changed, sometimes within a few seconds. Actually, most of the time, the smokes were white and opaque, possibly caused by some smoke washing process. In this paper, we are only showing results applicable to optically thin smokes. The sample results illustrating the paper (fig.5) have been taken in this situation. The smokes were slightly brownish while clouds could also be observed passing behind. By comparing the background signal with the plume signal, it appears that the plume optical thickness at the measurement wavelengths was around 0.06-0.08 above the 2nd stack, and 0.04-0.06 above the 3rd stack.
This point will be added in the text with a new sentence at the end of p.10,L4: "In particular, the smokes were optically thin, with the blue sky clearly visible in the background. This ensures that absorption is the dominant process over scattering for the extinction of light rays crossing the plumes (Beer-Lambert regime). The optical thickness of the smokes was always smaller than 0.1 at our measurement wavelengths."

Technical corrections:

Unless for the particular points discussed below, all the suggested technical corrections have been accepted.

- p.2,L31: "atmospheric constituents" is changed to "atmospheric species concentration profiles"

- p.3,L3: "breadboard" is a shorthand name for a lab optical setup used to prove a

concept. But we understand that readers may not be familiar with this convention so we change all occurences of "breadboard" by "prototype".

- p.5,Fig.3: "Measured" replaced by "NO2 camera".

- p.7,L13: rho is defined in p.7,L8. It represents the instrument response at pixel ij embracing the effects of the optics, the AOTF and the detector, relative to an average value.

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