**Atmospheric
Measurement
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Discussions**

Interactive comment on "Theoretical description of functionality, applications, and limitations of SO$_2$ cameras for the remote sensing of volcanic plumes" *by* C. Kern et al.

Anonymous Referee #1

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This paper describes a two dimensional CCD camera designed specifically for quantifying SO$_2$ column densities (especially those in volcanic plumes) by measuring scattered solar radiation in the UV. It covers the theoretical basis for SO$_2$ measurement, the practical difficulties in accurate calibration, and the unique advantages over other SO$_2$ remote sensing techniques. Despite some unresolved issues, this camera has shown great potentials with the successful demonstrations of continuous image captures of SO$_2$ columns with a fast frame rate. Furthermore, comparisons of the column amounts measured by the SO$_2$ camera with coincident passive DOAS measurements show that good agreement between the two has been achieved, illustrating that this camera can be used for quantitative SO$_2$ measurements. I recommend acceptance for publication

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after revision that takes care the issues listed below.

The main problem of this paper is the inadequate description of the assumptions used in the measurement principle and the lack of analysis of impacts on the measurements due to deviations from these assumptions.

Specifically, the first assumption was implicitly made on page 535, in writing down equations (1) to (3). The authors assume that all photons that reach the CCD detectors in the camera have to pass the SO_2 plume. This assumption should be explicitly stated in the paper. It is valid if photons scattered into the camera by air mass between the camera and the plume, and photons reflected by aerosols in the plume are negligible. Clearly when photon contribution deviates from this assumption, such as in the cases of long distances between the camera and the plume and bright aerosols within the plume, accuracy of the derived SO_2 column amount decreases, as more photons arriving at the camera without experiencing the SO_2 absorption.

Additional assumptions about aerosol absorption and scattering are also implicitly made in section 2.1 of the paper. As correctly described in section 2.1, aerosols can reduce the number of photons that pass through the SO_2 plume by scattering away the radiation (this intensity reduction is denoted by $I_-(\lambda)$) entering from the back side, and at the same time can increase the number of photons without experience the SO_2 absorption by scattering radiation into the field of view (this intensity addition is denoted by $I_+(\lambda)$). In writing down equation 10, the authors have made an implicit assumption that the photon reduction $I_-(\lambda)$ and addition $I_+(\lambda)$ can be neglected. Another assumption about aerosol absorption is made in equation 10, i.e., the aerosol absorptions in wavelength band A and band B are the same. Though not exactly true due to the spectral dependence of aerosol absorption, this assumption is probably quite good because of the small wavelength separation between bands A and B. The assumption about aerosol scattering contributions is valid only for small scattering optical thickness, but fails when it is large. One can easily see this by writing $I_A(\lambda)$ explicitly with addition and subtraction of scattering intensity, $I_A(\lambda) = (I_{0,A}(\lambda) - I_-(\lambda)) \exp(-\tau_g(\lambda) - \tau_a(\lambda)) + I_+(\lambda)$, where

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$\tau_g(\lambda) = \sigma(\lambda)S$, is the SO_2 absorption optical thickness, and $\tau_a(\lambda)$ is the aerosol absorption optical thickness. Putting this equation into $I_{M,A}(\lambda)$, and similarly into $I_{M,B}(\lambda)$, one notices that in general the aerosol scattering terms from bands A and B do not cancel out each other in equation 10. Only with the assumption that $I_-(\lambda)$ and $I_+(\lambda)$ are negligible and that $\tau_a(\lambda)$ is independent of λ, can one arrive at $\tau = AA$, that is directly related to the SO_2 column density.

In summary, adding measurement with filter B does not necessary take care the error due to scattering. The statement in the abstract (Page 532, lines 6 - 8), "the effect of aerosol scattering can be eliminated by additionally measuring the incident radiation around 325 nm where the absorption of SO_2 is no longer significant, thus rendering the method applicable to optically opaque plumes", is not correct in two aspects: 1) the word 'eliminated' is too strong, replacing it with 'reduce', which is more appropriate due to the λ dependence of aerosol absorption, 2) replace 'optically opaque' with 'optically thin', because SO_2 measurement can not be achieved for optically opaque plume, simply because little or no photon experienced its absorption would reach the camera, therefore this statement need to be rewritten.

I recommend the authors rewrite section 2.1, with explicit expression about aerosol scattering and absorption, and derive the apparent absorption for SO_2, and clearly state the approximations needed for accurate SO_2 retrievals. Also the statement, ".... cameras for remote around 325 nm where the absorption of SO_2 is no longer significant ...", is true for small SO_2 loading only. When the loading is large, the absorption is quite significant at 325 nm, resulting in SO_2 estimate error. Due to non-linear SO_2 absorption, the radiation intensity at band A is reduced disproportionally compared to that at band B for large SO_2 absorption, making the calibration of the instrument even more difficult. In other words, this SO_2 camera is more accurate when measuring low loading SO_2 plume.

Other corrections needed for this paper is listed below.

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1) Page 532, line 17, change "The thus" to "Thus the"

2) Page 534, line 5 - 8, move 'only' to after 'a single direction'.

3) Page 536, line 2 -3, "Therefore, the column density S is typically a function of the wavelength λ". Please rephrase this statement, because column density by definition is not a function of wavelength. Photons at different wavelength go through different average paths to reach the detectors, therefore experience different amount of the absorption due to the same column density. If a correct radiative transfer is done, different photon paths will be correctly accounted for, and the inversion should yield the same column amount for different wavelengths.

4) Page 537, line 16, "In all other cases there is no analytical solution of equation (8) for the column density S, because the incident scattered solar radiation spectrum $I_S(\lambda)$, the filter spectral transmittance $T_A(\lambda)$ and the quantum yield of the detector $Q(\lambda)$ are not analytical functions." This statement seem to be out of place: no solution of equation 8 has nothing to do with whether analytical expressions are available or not for $I_S(\lambda)$, $T_A(\lambda)$, and $Q(\lambda)$. Equation (8) can not be solved (neither analytically or numerically), because $I_S(\lambda)$ is not known and is not directly measured. Assuming that $I_S(\lambda)$, $T_A(\lambda)$, and $Q(\lambda)$ can be measured with sufficient accuracy, conceivably one can numerically solve equation 8 by adjusting the value of S until the equation is satisfied. Getting the value of S is the goal. However one achieves this, analytically or numerically, is not quite important.

Interactive comment on Atmos. Meas. Tech. Discuss., 3, 531, 2010.

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