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Atmospheric Measurement Techniques
Discussions

Interactive comment on "Retrieval of sulphur dioxide from a ground-based thermal infrared imaging camera" *by* A. J. Prata and C. Bernardo

Anonymous Referee #1

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General comment: The paper presents a novel instrument based on a thermal camera combined with various bandpass filters. The sequence of picture taken with the different bandpass filters provides spectral information from the radiation emitted by the atmosphere and present how SO2 can be reconstructed for each pixel. The algorithm using the plume-clear-sky difference, and do not need to solve the whole radiative transfer. The background depends on the elevation angle and is retrieved outside the plume and described as polynomial , which mainly subtract the elevation dependence of the thermal radiation, individually for each bandpass. The design of the instrument mainly given by the choose of the spectral bandpass filter (4 of the 5 filters) is optimized for ground based observations. The imaging device has been successfully applied to SO2 plumes of industrial complex and Volcanoes. The research is original, novel and

important and the topic meets the scope of the journal and should be published after some minor revisions.

Specific comments It would be nice, if the authors give a short discussion-section in addition to the compact conclusion. In the discussion they should compare their new instrument with other works, regarding the new technical instrument and the measurements. Mainly a) regarding to a comparison UV versus IR Camera and b) comparability of results from field trip to known results from the literature (Etna, Stromboli, Stuck emission) a) Thats interesting due to the multi scattering issue in the UV based measurements, which does not affect the presented method and the in the introduction mentioned imaging devices using UV especially as at least one of the authors. The article present a new device + retrieval method and also new measurements, but the authors do not put their finding and measurements in context of other known measurements, please compare your results (typical slant columns and flux) to other measurements of the specific volcanoes and similar stuck emissions. At this stage of the novel method such a comparison might validate somehow the measurements. The mentioned comparison in Australia Port Victoria with a UV device is very interresting, why you do not show this comparison?

The description of the algorithm: Complete understanding what actually does the SO2 quantization is quite hard and not easy possible, with the current description. The formalism and the retrieval algorithm using brightness temperature differences, the instrument are recording or at least could recored images with five different bandpass filter, but the algorithm seems to use only a subset (two filters) for the data analyses and another to get a plume temperature. The authors give the complete glossary and theory, however it is still quite hard to follow, the derivation of the central formula, at least for me, maybe because of the plenty of variables. And it might be necessary to add some helpful information maybe also additional a "B" for all brightness temperatures and using "T" just for the real (Plume) temperature, would give more help in the description of the retrieval algorithm.

Two things might be easily misleading and maybe some words could help: eq 1. : if you separate in foreground, plume and background: you would get: I= I_f+ exp (-tau foreground) I_P+ exp(-(tau_foreground+tau_plume)) I_B or if you take the re absorption as part of the terms I_p, I_B you could explicitly maybe clarify this in : P6.line 6 The plume radiance may be considered to consist of a positive part emitted radiation, and a negative part radiation from the background atmospheric emission that has been attenuated as it traverses through the plume. I am sure you do it correctly in the part, where you derive the formula, but showing it just as a sum is maybe misleading.

Actually there are some question which I did not understood clearly but they should be clear for the reader: 1. From 5 filters only 3 are used to determine SO2: a) 8.6-bandpass (SO2,H2O) and 12 -bandpass (H2O) for the separation of SO2 and H2O in the plume. b) 10-bandpass to get the plume temperature. How do you get the temperature, the 10 micron band, might be dominated by the ozone feacher which originate in the stratosphere ???. (Do you combine the 12micron with the 10 micron window and use the Modtran calculation to obtain a different coefficient k_H2O?) c) Who wrote the filters are "havely influenced by knowledge of the atmosphere", please give this thoughts explicitly and for each filter maybe with a graph. I think you report the information somewhere, but it would help to do it on this point. Explain for each filter why you choosed i.

2. The retrieval algorithm aims to get the result by calculation, not by iterative methods (fits and) is therefore fast and can be applied to a image-device which records various frames per second. The way to get such a calculation (formula 2) are approximations (Linearisation ,Taylor). In the thermal infrared Brightness temperature is almost given by the product of emissivity and temperature, and therefore it can be approximated very well by an Taylor series, maybe you can mention that. 3. While other methods using a forward model like modtran (as mentioned in the paper) and have to take explicitly take interference like O3, CH4, N2O into account the method here does not need that as the a clear-sky brightness temperature is reconstructed from pixels outside the

plume. Individually for each spectral region. Did you try: 1.calculating a set(=Image) of synthetic spectrum with modtran,2. calculating the resulting brightness temperature and 3. try the reconstruction of the slant So2 column and the plume temperature, to test the algorithm? 4. The authors state that it is difficult to separate foreground and background thermal emission radiation, they state that it is not so important, but actually the re-absorption in the foreground due to H2O, CH4, N2O as the absorption of the background in the plume is somewhat crucial for a quantification, at least if there is higher humidity. In the end, do you take it into account or not?

5. The fact that there is almost no scattering effect in the IR or more exact the thermal infrared as the authors call it, is more an advantage in comparison to UV-SO2 cameras than an important error source to concern about, maybe this error might be moved to the end. 6. For all thermal infrared application is the estimation of the real temperature the most important error source. The authors should explicitly state how they calculate the plume temperature (from the 10 micron-Bandpass Filter, and how this calculation is justified, Love et al (2001) and actually only described in the textbook, Remote Sensing of Active Volcanism DOI: 10.1029/GM116 discuss the use of saturated water lines or the use of intercomparison with UV measurements.... .) Harig et al. 2002 (SPIE) are using saturated water lines , but they use the spectral region of 1200cm (8microns) to determine the temperature. In Stremme et al. 2012 the ambient temperature reported by the nearest radiosonde result in the same slant column as the slant column reconstructed from temperature insensitive absorption measurements. 7. If the author can get the temperature in some way from the 10 micron window, they should definitifely describe this very detailed and report them, and discuss their findings in the context of other works, using thermal emission spectroscopy. A simple comparison of the temperature with the radiosonding (or if not aviable NCEP profiles at some other sides, but radiosondes are mentioned) can be seen as work towards validation of their algorithm. 8. If the algorithm solves the problem (with some parameter), I wonder how many quantities could be determind from the 5 filters: Plume Temperature (1), SO2 (2), H2O (3), Emisivity of droplets+particles (4) in the plume. Probably the authors state this, in

the beginning of field-trip section 5, but it is also an part which might be discussed in the fin of the retrieval-section 3.

Maybe some general hits at the beginning could help the reader. A crucial question for me is why the effective-emisivity reported in eq.2 and eq. 4 has no index i, j (or 8.6,12, or SO2, H2O...). Which are the main reason to derive the formula using brightness temperatures and not the absolute radiation? Maybe because it gives a more intuitive feeling numbers between 0 and 300K or as the thermal cameras gives their output with this unit? Or because there is a almost linear connection between emissivity and and Brightness temperature/ real Temperature at 1000cm-1 (10 microns).

Some suggestion: "do not use i,j 1,2, but 8.6,12 and H2O and SO2, whater drops..." :

The figures give better hint what actually is done, but the description seems to mix a general concept, doing retrieval with various band pass filters or channels T_i,j with a description where the indice is used as example for 8.6 microns and j for 12 microns as the authors do in the error analysis or unfortunately otherwise around (eq. 11,12,13,14: i=8.6, j=12 and after 19 (j == 8.6 and i=12).

I guess using 8.6,and 12 the paper would be easier to understand. Maybe you could start with i,j and repeat eq.3 with the correct an concrete indice "8.6", and "12"

I guess also that you should show eq. 26 directly after eq.1 and also mention that this is an approximation, actually I think you just assume here consequently that I_f ==0 (the foreground, as eq. 13 and 14 takes re- absorption in the plume for the whole I_o into account. I think thats ok, you do an approximation and you treat this topic in the error part (type 2), but it is not so clear.

The only concern I really have is the estimation of the plume temperature in channel "10". I do not understand why you want the most transparent channel, I would suggest to look for the saturated water lines (=> emissivity=1) maybe in channel 7.3 , that would be consequently with assuming no foreground.

Or you could use two channel which have a known relation in the transparency for water vapor with respect to channel 12. Please could you report the temperatures T_p used in the presented events, in a table.

You calculated kˆ8.6_H2O, kˆ10_H2O,kˆ12_H2O,... using Modtran, and also kˆ8.6_SO2, it would help to show it in a additional table. You mention it similar in the error discussion. But it would help to understand which input for the retrieval you use.

Technical information about the time distance between 2 images with different filters is missig. But if you do so, you will be not consistent con eq. ,10 and 11.

equation 10 should make a difference between the foreground I_f and the background I_b, and could not simple use the sum of both as I_o, without doing the explicit assumption about it.

The location of the plume which separate the foreground and background has influence, due to the reabsorpion por probably mainly the H2O lines this effect should be taken into account, if you do not assume explicitly I_f=0.

Minor corrections /suggestions:

could you includegraphes for all filters (Transpearency + filter) 1. 8.6 microns= 1162cm-1 SO2 2. 10 micron= 1000cm-1 O3 3. 11 micron = 909cm-1 H2O 4 . 12 micron= 833cm-1 5. all 7-14 micron= 714-1429cm-1

Table 2. Theoretical NEΔT 's (mK) for the five channels of the thermal infrared imaging camera and for four different scene temperatures:

you show just the 4 narrow bands, either change 5-> 4 in the captain or calculate and present the average noise equivalent temperature in the 7-14 micron band in the table as well. (text says 7-14, but image shows 8-14, please check for consistency.

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