

### General Answer to Referee 3

The Referee is right when says that the numerical parameters reported in this work and the MODIS-TIR data of the examples are specific for Mt. Etna volcano. It was clearly written in the last sentence of the abstract: *“By recomputing the parameters of the polynomial relationships, the VPR procedure can be easily extended to other ash types and applied to different volcanoes.”* And also in the description of the procedure (pag. 8863 lines 15-20): *“In the present work the multispectral radiometer MODIS on board Terra and Aqua satellites (Barnes et al., 1998; <http://modis.gsfc.nasa.gov/>) has been considered and the procedure has been adapted for the Mt. Etna volcano (Sicily, Italy), using specific atmospheric profiles to compute the MODTRAN simulations used to prepare the procedure. Finally, the present version of the procedure is valid only for a specific ash type (see below)”*. To determine these parameters we used 30 years of monthly mean sea surface temperature (SST) of the Mediterranean Sea around Sicily and the monthly mean atmospheric profiles (PTH) measured at the WMO station of Trapani (Sicily) and used the altitude of the plume and the ash type considered typical of Mt. Etna.

To avoid any possible misunderstanding the title has been changed into ***“A new simplified approach for the simultaneous retrieval of SO<sub>2</sub> and ash properties in tropospheric volcanic clouds: an application to Mt. Etna volcano”***.

However, we remark that the proposed procedure scheme, applied in the article on two Mt. Etna eruptions, can be adapted to many different situations and volcanoes by using local surface characteristics and atmospheric profiles, plume geometries and ash types.

It is also true that we heavily used MODTRAN radiative transfer model (RTM). The whole paper is based on the MODTRAN simulations. Without the MODTRAN we could not estimate the parameters reported in the paper, but this great number of simulations alone are not enough to estimate ash and SO<sub>2</sub> in any plume of Mt. Etna volcano. The user of this procedure, in the framework described in the paper, does not need to use MODTRAN RTM anymore. In fact, we present two test cases of Mt. Etna volcano but only one set of parameters. Vice versa, the established LUTs procedure has to compute the Look-Up Tables (that is to run MODTRAN code) each time.

About the improved speed of the proposed procedure: once the defined parameters have been computed, the procedure is extremely fast if compared to the 'conventional' procedure that, as written above, requires the computation of a new LUT for each satellite image.

The VPR procedure is also easier to apply and less prone to retrieval errors because it requires only two inputs: the plume temperature and the plume altitude. Different is the case of the LUT approach that requires many different inputs: besides the plume altitude, it requires the plume thickness, the local atmospheric profiles of temperature, pressure and humidity, the surface temperature and surface emissivity. The retrieval of some of these parameters is critic and all are affected by an uncertainty that leads to meaningful retrieval errors.

In conclusion, the Referee 3 is right: we used MODTRAN to obtain the parameter values and they are specific for Mt. Etna volcano. No doubt about it, but this is what it is frequently done. NOAA uses Split Window algorithm to estimate the SST from TIR satellite data but the parameter values are often locally adapted; they are not the same for the whole globe and have been computed using a RTM like MODTRAN.

### Specific Comments

The authors wish to thank the Referee 3 for his detailed remarks and the deep reading of the work.

Page 8860

Line 5 – Here and throughout the manuscript, you refer to “atmospheric profiles”. Please be more specific. I assume temperature and pressure profiles are needed? Anything else?

It is true that the term “atmospheric profiles” doesn't uniquely specify which are the atmospheric fields considered. The WMO Upper Air sounding contains wind direction and speed, pressure, temperatures, and relative humidity. We'll add in the procedure description (page 8863) the exactly meteorological fields used to compute MODTRAN simulations: pressure, temperature and relative humidity (PTH).

*Line 5 – You state that “radiative transfer models are not required to perform the atmospheric corrections”. This seems to be a false statement. You later show that you need to correct your plume transmittances using a LUT built using the MODTRAN model. Also see General Comments above.*

See general answer.

*Page 8862*

*Line 21 – Which volcanic ash optical properties are relevant?*

The ash optical properties needed to run the radiative transfer model by considering a multi scattering atmosphere, are the single scattering albedo, the extinction coefficient and the phase function (asymmetry parameter). More, the extinction efficiency factor ( $Q_{\text{ext}}(\text{Re})$ , erroneously called “extinction coefficient” at p. 8871, line 17, and now corrected) is used in the Wen and Rose simplified equation to compute the ash mass.

All the ash optical properties and the extinction efficiency factor are computed, from the volcanic ash refractive index tabulated by Volz (1973), using the Mie code developed by the Earth Observation Data Group (EODG) of the Atmospheric Oceanic and Planetary Physics Department of the Oxford University (<http://www.atm.ox.ac.uk/code/mie/index.html>) i.e. by considering the spherical particle approximation.

*Line 23 – “... make intense use of radiation transfer codes to evaluate the atmospheric corrections look up tables”. Please be more specific. What type of atmospheric corrections are made? What is the real difference between the established techniques (e.g. Corradini et al 2009) and yours? Don't you also use radiative transfer models to calculate atmospheric corrections? Also see General Comments above.*

Here we refer to the established procedure based on the LUT computation. Details on this method can be found in the cited Corradini et al., 2009 (also added in the text at p. 8874, line 7ff), while details of the simulations carried out for the computation of the proposed procedure parameters are described in the text (see p. 8869 from line 13 to 20). The main difference is that the simulations needed for the VPR approach are more general because they must be representative of all the yearly atmospheric conditions, surface characteristics and plume altitudes (they were computed considering 12 mean monthly WMO atmospheric profiles and surface temperatures, and 4 plumes altitudes). The established procedure LUT instead, is computed for each satellite image considering the best available atmospheric profiles (the closest in space and time), a single value of surface temperature and a plume altitude.

Therefore, when a new  $\text{SO}_2$  and ash retrieval will be required in a future Mt. Etna eruption, the application of the LUT technique will need to run MODTRAN RTM again, while the application of the VPR procedure will not. See also general answer.

*Page 8863*

*Line 7 – Please consider renaming your retrieval. It seems as though “Volcanic Plume Removal” procedure is a good name only for the first part of your retrieval in which the background radiance  $L_0$  is estimated. After that, many other calculations are made that really don't have anything to do with removing the volcanic plume. In fact, the goal of the retrieval is not to remove the plume, but rather to gain information on it. A suggestion for a better name might be “differential radiance” method or similar.*

The referee is right but we prefer to give more relevance to the first part of the algorithm that is really new.

*Line 8 – While the presented retrieval scheme does indeed calculate SO<sub>2</sub> and ash burdens from TIR data, it also requires a LUT of radiances simulated for the given scenario to make the appropriate corrections. Therefore, using the information contained in this manuscript, the retrieval could only be applied to Mt Etna. This sentence seems misleading and the topic should be revisited, as also suggested in the General Comments above.*

To avoid misunderstandings we have changed the title of the article. See general answer.

Page 8864

*Line 2 – Again, you state that atmospheric profiles are not needed. But they are actually used to calculate the correction factors you need later on...*

The atmospheric profiles were used once. For future Mt. Etna eruptions they will not be required anymore. See general answer.

Page 8865

*Line 17 – Why is band 28 discussed here if it is not actually used in the retrieval?*

It's simply an additional information. Band 28 is strongly affected by SO<sub>2</sub> absorption, and therefore can be used for a similar study.

*Line 23 – If the effect of the plume edges remaining visible in the background radiance even after the plume is “removed” can be easily avoided, why do you not fix this? It would seem that if it is easy to fix, it should be done, as it will likely make the measurement more accurate, right?*

The considered plume mask is the one used by the LUT procedure. For a better comparison of the results of the 2 different procedures, the same area was considered.

*Line 27 – What is the criterion that the points need to fulfill? Please be more specific.*

As can be seen in fig.1, the radiance if the plume is missing is the line tangent to the plume edges. This line is the linear regression of a set of data. This set of data contains all the edges points whose difference between the radiance of the line and the point is less than a fixed value for that row of the image. The detailed description of this method is not reported in the article because any other similar method of minimization can be used.

Page 8866

*Line 5 – Why is band 28 not significantly affected by the surface characteristics (e.g. temperature)?*

The MODIS channel 28 is centred at 7.3 microns where the atmospheric water vapour absorption is extremely high and the atmospheric transmittance is extremely low (see Watson et al., 2004; Corradini et al., 2009). Because of that the surface radiation and the atmospheric downwelling radiation reflected by the surface cannot reach the space. This is the main reason why this channel can be used for the SO<sub>2</sub> retrievals only when the volcanic plumes rise over 3–4 km, i.e. above the most of the water vapour (see Corradini et al., 2009, 2010; Prata et al., 2010(\*)).

(\*) Prata, A. J., G. Gangale, L. Clarisse, and F. Karagulian (2010), Ash and sulfur dioxide in the 2008 eruptions of Okmok and Kasatochi: Insights from high spectral resolution satellite measurements, J. Geophys. Res., 115, D00L18, doi:10.1029/2009JD013556

*Line 12 – You state a single variable coupling Z and T is not sufficient because of seasonal effects. Wouldn't e.g. the geographic location and current weather conditions also affect these parameters individually?*

Yes, with “seasonality” we meant weather conditions. We'll change it in the text.

*Line 17ff – Please motivate equations 1 and 2 in the text. Besides explaining the meaning of each symbol, please state where the individual terms come from. E.g. for Equation 1, you might write “The radiance at the sensor position is given by the sum of the thermal emission from the Earth’s surface, the reflection of downwelling radiance on the surface, and upwelling radiance from TIR emission and scattering on gases and aerosols in the atmospheric column.”*

The equations 1 and 2 derive from the Schwarzschild Equation and they are well-known in the framework of TIR radiative transfer. We think that the symbol description is enough.

*Page 8867*

*Line 9 – You state that Eq 2 is more realistic for volcanic eruptions than diffuse degassing. While I understand the motivation for this statement, it will not always be true. Consider e.g. the eruption of Kilauea volcano (very strong plumes at very low altitudes) compared to the diffuse degassing at Mt. Etna in between periods of eruptive activity. Your model will likely describe the Etna plumes better. Please rephrase this statement to be more precise – plumes lifted to high altitudes (and cold temperatures, pristine atmospheric conditions? anything else?) will be better described by the model.*

Yes, the comment was about Mt. Etna or similar volcanoes. We’ll specify it in the text.

*Line 21ff – The concept of a modified plume temperature is introduced here. Please give more details on how this correction is derived. Is this a standard approach also used in other models? If so, please give a reference. Currently, the given empirical terms could not be easily adapted by a reader interested in applying the retrieval to a different volcano with different atmospheric conditions.*

The equation for the correction of the temperature is obtained from eq. 4 using the values of  $L_{up}$  and  $\tau_p$  simulated by MODTRAN; the values of T were then obtained by inversion of the Planck’s Function. We’ll clarify this in the text. It is a small improvement of the procedure. Clearly it is characteristic of Mt. Etna.

*Page 8868*

*Line 9 – Please explain how equation 6 was obtained. Isn’t the plume emission equal to the plume absorption according to Kirchhof’s Law? Doesn’t this mean  $\varepsilon = 1 - T_{pa}$ ? According to equation 3,  $\varepsilon$  would then be equal to  $1 - (T_p/T_{pd})$ , not  $T_{pd} - T_p$ . I assume I am missing something here... Please clarify...*

In the plume are present both the absorption and scattering mechanisms. Here the scattering has been considered only as loss of radiation. In case of only absorption it is valid eq. 4 (where  $\tau_p$  is  $\tau_{pa}$ ); if scattering is present the up-welling radiation from the plume becomes:

$$dL_{up} = (1 - \tau_{pa}) \cdot B(T) \cdot \tau_{pa} \cdot \tau_{pd}$$

The integral of  $dL_{up}$  has been approximated to eq. 6; this approximation it is quite common in literature (see for example “Leckner, The spectral distribution of solar radiation at the Earth’s surface – Elements of a model, Sol. Energy, 20(2), 143-150, 1978”).

*Page 8869*

*Line 5 – You state that the two values for  $T_{pdv}$  are empirically chosen from MODTRAN results. However, you do not explain how these were obtained. It is therefore not clear how someone wanting to apply this retrieval to a different location, volcano, and atmospheric conditions would choose these values. Or are they robust enough such that they can be used anywhere? Please provide more details on how the empirical values were obtained.*

In literature (e.g. “Watson et al., 2004”) the value of  $\tau_{pd}$  is between 0.9 and 1. During the set-up of the procedure, we compared plume transmittance  $\tau_p$  derived from MODTRAN simulations with that obtained by eq. (8) with some  $\tau_{pdv}$  values chosen between 0.9-1. First we considered a unique

constant  $\tau_{pdv}$  but we immediately realized that a value of  $\tau_{pdv}$  close to 1 worked better for the transparent pixels in the plume, while a smaller value better represented the optically thick pixels in the plume. The current couple of empirical values reported in the paper gives the quite good described results (fig. 3). Clearly these values are specific for Mt. Etna.

Page 8870

*Line 8 – You state that neglecting the scattering term from equation 7 appears to work better when  $Tp_{31}$  is larger than 0.95. This is probably true, but how do you know? Please explain. Also, you might point out that in this case, the MODTRAN correction polynomial (eq 9) is not used, so the ensemble of simulations (which essentially represents a LUT) is not needed. Under these conditions, the retrieval is essentially a conventional differential absorption approach (give some references).*

This is a final control performed to avoid that the SO<sub>2</sub> transmittances become greater than 1, in case of very low presence of ash.

Page 8871

*Line 4ff – This section is a bit difficult to follow. Since you do not explicitly show the dependence of AOD (in band 32) on AOD550, it is not clear that the ratio of slopes shown in equation 12 is indeed dependent on the effective radius (although you do show this later). I suggest simplifying this a bit by referencing studies showing that the Angstrom Exponent depends on effective particle size. This proves that the ratio of AOD at two different wavelengths contains information on particle size.*

We'll specify in the text that a similar relationship exist for band 32 too. It is known that Angstrom Exponent is related to the particle size distribution, but we don't believe that this simplifies the description of eqs. 11 and 12. As described in the article, these relations were obtained by means of MODTRAN simulations.

*Line 17 – Where is  $Q_{ext}(Re)$  taken from? Volz et al? Please cite reference.*

See above (answer to comment Page 8862, Line 21).

Page 8875

*Line 4ff – Again you write that only the spectral data and plume altitude and temperature are needed. But this is only true for Mt. Etna, since the correction polynomials are specific to this measurement geometry and atmospheric conditions.*

See general answer.

*Line 4-24 – Since you state earlier in the manuscript that the retrieved values depend on both the altitude and the temperature of the plume, and that the two variables cannot be combined into one because they can vary independent of one another and e.g. depend on seasonality. Why then do you couple the two variables here in your sensitivity study? Wouldn't it be better to do two separate sensitivity studies – one for altitude and one for temperature? Which of these variables is actually better constrained? It seems that maybe the altitude itself plays less important of a role as getting the temperature right, especially for plumes in remote areas of the world.*

A correlation between temperature and altitude exist but it changes depending on weather conditions. By knowing the temperature vertical profile (as in these cases) it is possible to compute the temperature at a fixed altitude by linear interpolation. This sensitivity study is related to the 2 real test cases considered. In this way we could compare the retrieval errors of VPR and LUT procedure (see page 8875, line 23).

Page 8877

*Line 10 – How exactly do the LUT used in the LUT procedures (please give reference) differ from the MODTRAN simulations that were conducted in the scope of this study to derive the calibration*

*polynomial? Aren't these very similar as well, and couldn't this be the reason why the retrieval results are so similar?*

See above (answer to comment Page 8862, Line 23).

*Line 26 – Again you state you do not need radiative transfer models or atmospheric profiles, and yet you need both of these to derive the correction polynomials.*

See general answer.

*Page 8878*

*Line 1 – Couldn't one argue that the retrieval, as it is presented here, can only be applied to Mt. Etna? If you tried to apply it anywhere else, wouldn't you need both atmospheric profiles and radiative transfer calculations to derive new correction factors?*

See general answer.

### **Technical Corrections**

*Page 8859*

*Title: Suggest rewording title to “A new simplified approach for the simultaneous retrieval of SO<sub>2</sub> and ash properties in tropospheric volcanic clouds”. The SO<sub>2</sub> and ash are in the clouds, not the retrieval.*

Done

*Page 8860*

*Line 4 – “...only 2 input parameters...” What about the spectral radiance information? This is also needed!*

Yes, referee #3 is right. In fact in the previous sentence it has been specified that the proposed procedure makes use of TIR MODIS data.

*Line 8 – You interpolate the “radiances surrounding the volcanic plume”, not the radiances on the edge of the plume...*

Done

*Line 9 – “... procedure described here...”*

Done

*Line 10 – “measured BY the sensor”*

Done

*Line 12 – Not sure what you mean by “highlights the plume presence”.*

This phrase will be modified in the paper to clarify the method.

*Line 14 – Recommend either removing the word “rather” or please be more specific. How uniform?*

Done

*Line 15 – Here and throughout the manuscript, recommend referring to “ocean” instead of “sea”.*

Done, except when explicitly referring to the Etna case study and the Mediterranean Sea.

*Line 18 – Recommend removing “In the aforementioned bands”. This is implied.*

Done

Page 8861

Line 1 – Remove “the” before “60%” and before “80%”

Done

Line 3 – “... recent eruptions OCCURING...”

Done

Line 4 – Replace “the well known” with “established”

Done

Line 5 – “... based ON look-up tables.”

Done

Line 6 – “By recomputing the parameters of the polynomial relationship” is too vague. Readers not yet familiar with the contents of the manuscript will not understand this. Please be more specific.

Yes, this phrase will be modified in the paper to clarify the concept.

Line 10 – Replace “either” with “both”

Done

Line 13 – Remove the word “buoyant”. It does not appear to make sense here.

Done

Line 14 – “and with THE scales and types...”

Done

Line 16 – Remove “the” before “aviation safety”.

Done

Line 16 – “timely ALERTS...”

Done

Line 17 – “information are needed...”. What type of information?

Information on the extent and the location of the ash cloud. But “and information” has been removed here since this is specified in the next sentence.

Line 26 – Suggest writing “They provide the spatial distribution of a volcanic ash cloud’s total mass, mean effective...”

Done

Page 8862

Line 3 – Remove “the” before “volcanic SO<sub>2</sub> emission”

Done

Line 5 – Remove “the” before “climate”

Done

Line 9 – “airborne and SATELLITE-BORNE”

Done

Line 10 – Replace “provided with” with “that have”

Done

*Line 11 – “later extended to INCLUDE the 7.3...”*

Done

*Line 16 – “with THE 7.3  $\mu\text{m}$ ...”*

Done

*Line 18 – “frequently, and if the correction is not applied, the...”*

Done

*Line 21 – specify which atmospheric profiles.*

P,T,H. Now in the text

*Line 22 – Here and throughout the manuscript, please use “plume altitude” instead of “plume height”. Plume altitude is always assumed above sea level, whereas plume height might be measured above the vent.*

Done

*Line 26 – “the need FOR a quick...”*

Done

*Line 27 – Why is global coverage only a potential? I thought global coverage is achieved by these sensors. Recommend removing the word “potential”*

Done

*Line 28 – “derived from the multi-spectral TIR image itself...”*

Done

*Line 29 – change “plume height” to “plume altitude”.*

Done

*Line 29 – “temperature, while still yielding reliable results”.*

Done

*Page 8863*

*Line 2 – “the theoretical and experimental comparisons”. Please be more specific. What are you comparing to what here?*

Done. The sentence has been changed in: “In Section 3 the procedure is tested with the retrieval of SO<sub>2</sub> and ash properties from simulated radiances, and in Section 4 the results obtained with the VPR procedure are compared with the results of the conventional LUT retrieval approach (Corradini et al., 2009) in two Etna eruption case studies.”

*Line 4 – “results of the CONVENTIONAL LUT retrieval approach (GIVE REFERENCE)”*

Done

*Line 6 – “conclusions are SUMMARIZED.”*

Done



*Line 8 – Suggest rewording : “The ...procedure computes the ash AOD and effective radius as well as the SO<sub>2</sub> vertical column density from multi-spectral TIR images”. Also see Specific Comment above.*

Done. The sentence has been changed.

*Line 10 – “algorithm INPUT parameters”*

Done

*Line 11 – “and ash optical properties, SEE BELOW), the retrieval ONLY REQUIRES KNOWLEDGE OF the volcanic cloud altitude...”*

Done

*Line 17 – “... has been adapted TO Mt. Etna...”*

Done

*Line 18 – Again, please specify what you mean by “atmospheric profiles”.*

Done

*Line 18 – at this point, it is unclear what you mean by “compute the MODTRAN simulations used to prepare the procedure.” Please explain what this means.*

The detailed description of the procedure is explained later. A call to look forward in the text has been added.

*Line 19 – “the present INPUT PARAMETERIZATION of the procedure is valid only for a specific ash type (Volz et al)”.*

Done

*Line 21 – Either remove “more times a day” or specifically state how often “global coverage is achieved”.*

Usually there are 4 image per day, but in some cases (area of interest on the edge of the MODIS image) also more than 4 observations per day are possible. Therefore we think that it's better the general form “more times a day”.

*Line 23 – “atmospheric TRANSMISSION windows”*

Done

*Line 24 – “radiance that reaches the sensor is PARTIALLY ABSORBED AND SCATTERED by the atmosphere”*

Done

*Line 25 – Please state precisely what you mean by “atmospheric corrections”. What is being corrected? Please give references!*

The terms  $L_u$ ,  $L_d$ , and  $\tau$  in the radiative transfer equation (see Eq. 1 in the text) are the terms we are referring to as “atmospheric corrections”. That is, the path radiance, the down-welling radiance and the atmospheric transmittance. The reference to (Teggi et al., 1999) will be add in the article.

Teggi, S., M. P. Bogliolo, M. F. Buongiorno, S. Pugnaghi, and A. Sterni (1999), Evaluation of SO<sub>2</sub> emission from Mount Etna using diurnal and nocturnal multispectral IR and visible imaging spectrometer thermal IR remote sensing images and radiative transfer models, J. Geophys. Res., 104(B9), 20,069–20,079.

*Line 26 – It is not clear to me why you want to “study the surface characteristics”. Do you do actually do this?*

No we don't. Reference to the “study of surface characteristics” has been removed from the text.

*Line 27 – “remotely sensed TIR data”*

Done

*Page 8864*

*Line 2 – replace “means no” with “eliminates the”*

Done

*Line 2 – again, what “atmospheric profiles”?*

Done

*Line 2 – replace “and no need” with “and THE need”*

Done

*Line 4 – “during VOLCANIC CRISES when a ...”*

Done

*Line 5 – “are partially paid for by a decreased precision...”*

Done

*Line 9 – “have been obtained on this DIFFERENTIAL basis and their great DISSEMINATION is due to their simplicity, USER-FRIENDLINESS, and HIGH SPEED.*

Done

*Line 12 – “faster, and YET STILL reliable ...”*

Done

*Line 20 – “(AOD550) are derived;”*

Done

*Line 22 – “to compute the transmittance in band 29 that is due only to the ash”. I think it would be better to speak of “radiance attenuation” here, as the ash does not actually cause the transmittance.*

Done

*Line 24 – Recommend replacing the last sentence in this section with “Details of the algorithm are described in the following.”*

Done

*Line 27 – “When a volcanic plume is imaged in the TIR, a dip in the radiance is typically observed along a line normal to the plume axis.”*

Done

*Line 28 – Here and throughout the following text, I recommend replacing “valley” with “absorption feature”.*

Done

*Page 8865*

*Line 2 – I’m not sure that it would ALWAYS be present (e.g. if no SO2 and very little ash were there). This is not a necessary statement.*

Done

*Line 4 – “radiance that would be detected by the sensor...”*

Done

*Line 6 – “but works quite well even if... or a uniform cloud (SEE BELOW)”*

Done

*Line 10 – “The radiance in the absence of the plume is obtained...”*

Done

*Line 12ff – Recommend rewording to “Obtaining the background radiance by linear extrapolation of the radiance measured in the area surrounding the plume.”*

Done, but it’s an “interpolation”, not an “extrapolation”.

*Line 17 – “original MEASURED radiance...”*

Done

*Line 18 – “THIS IMAGE WAS MEASURED BY MODIS Terra during...”*

Done

*Line 19 – “UTC; the plume was over the ocean”*

Done

*Line 20 – “the thick colored line represents the BACKGROUND RADIANCE, I.E. THE RADIANCE OBTAINED FROM EXTRAPOLATION OF THE RADIANCE IN THE AREA SURROUNDING THE PLUME.”*

Changed, but with “interpolation”.

*Line 28 – Start this paragraph with “Fig 1b shows another scan line normal to the plume in the same MODIS image. However, this time a location is chosen at which the left edge of the plume is over the ocean while...”*

Done

*Page 8866*

*Line 2 – Remove “the” between “all” and “three”.*

Done

*Line 2 – “atmospheric transmission window”*

Done

*Line 7 – Replace “shortly sketched” with “schematically described”*

Done

*Line 10 – “... input parameters, and these must be adjusted for every measurement to match the best estimate of the current conditions”.*

Maybe here we don’t understand exactly the point raised by referee 3. For each image the VPR procedure requires  $T_p$  and  $Z_p$  as input parameters.

*Line 11 – Replace “data” with “variable”*

Done

*Line 15 – “In the absence of the plume, and neglecting...”*

Done

*Line 15 – Here and throughout the manuscript, you use the term “atmospheric diffusion”. I assume you mean “atmospheric scattering”. “Atmospheric diffusion” typically means the diffusion of gases in the atmosphere, i.e. it deals with the transport of gases. An example would be a plume broadening and eventually diffusing into the background air. I’m pretty sure you mean “scattering”. Please change this throughout the manuscript.*

Yes, Referee 3 is right. We mean scattering. Done.

*Line 16 – “radiance at the sensor POSITION is:”*

Done

*Line 21 – “THIS dependence has been omitted...”*

Done

*Line 22 – “In the presence of a volcanic plume, we assume...”*

Done

*Page 8867*

*Line 1 – It is not clear to me why this section needs a new heading. In fact, the statements made in this first paragraph directly relate to the equations you just introduced in the last section. Therefore, these statements should clearly be in the same section as equations 1 and 2, and should directly follow the equations.*

Yes, Referee 3 is right. We’ll change it !

*Line 2 – “In Eq. 2 we have: (1) neglected the increase...”*

Done

*Line 2 – “because of DOWNWARD SCATTERING WITHIN THE PLUME”*

Done

*Line 5 – “assumed the layer of atmosphere above the plume to be completely transparent...”*

Done

*Line 13 – Since “diffusion” needs to be changed to “scattering”, Tpd should be renamed to Tps in equation 3 and throughout the manuscript.*

Done.

*Page 8868*

*Line 6 – As mentioned before, please be sure to change DIFFUSION to SCATTERING, here and throughout the manuscript.*

Done

*Line 18 – “...computed using ONE OF TWO EMPIRICAL values Tpdv...”. Also note that Tpdv should be remaned to Tpsv, see above.*

Done.

Page 8869

Line 1 – 6 – Please reword. This paragraph is hard to understand. Explain that  $T_{psv} = 0.965$  is tried first. If  $T_p'$  is then found to be smaller than 0.75,  $T_{psv}$  is changed to 0.98. Also, “The relation  $\mu = 1/\cos\theta$  is used to correct for the increase in path length of the slant column density when compared to the vertical column.”

Done

Line 9 – Which physical effects are not well explained by the model? I assume you are referring to the 3 effects described under point 2.3? Please insert “(see section...)”

Not only the 3 effects described in section 2.3, but also other details like the chosen values of  $T_{psv}$  can contribute to this not good explanation of the plume transmittance computed in the first step. So the text has not been changed, because it has a more general meaning.

Line 23 – The word “separately” here seems to imply that the simulations were performed separately, but this is probably not the case, or is it? Can’t you use the same MODTRAN simulations and simply multiply by the two different MODIS response functions? In this case, I would omit the word “separately”.

Referee 3 is right. Done

Page 8870

Line 3 – Please insert “... where  $a_n$  are the fit coefficients derived from the best fit of a third order polynomial to the plot of MODTRAN transmittance vs  $T_p'$  (see Fig 3)” after equation 9.

Done

Line 16 – “The thick straight line REPRESENTS A SLOPE OF UNITY”.

Done

Line 17 – “The three scatter plots show a good agreement (GIVE R2 VALUES) BETWEEN THE MODTRAN PLUME TRANSMITTANCES AND THOSE DERIVED WITH OUR SIMPLIFIED MODEL.”

Done

Line 22 – “... and AOD depends on ...”

Done

Line 23 – “Fig. 4, which was obtained...”

Done

Page 8871

Line 10 – “KNOWING  $m_{31}/m_{32}$  from ...”

Done

Line 12 – “finally the AOD550 is computed using Eq 11.”

Done

Line 16 – “is the MEAN density of the ash particles and...”

Done

Page 8872

Line 8 – Start this sentence with “Arvani (2012) showed that...”

Done

*Line 12 – Please explain Eq 15 better: “An additional third degree polynomial was fit to...”*

Done

*Line 21 – Replace “usual” with “before”*

Done

*Line 22 – “and beta (..) WAS EMPIRICALLY DERIVED FROM THE MODTRAN SIMULATIONS:”. Then remove the last sentence on this page.*

Done

*Page 8873*

*Line 1 - Consider changing the title of this section to something more descriptive, e.g. “Retrieval of SO<sub>2</sub> and ash properties from simulated radiances”*

Done

*Line 2 – Remove “theoretical part”. You are testing the whole procedure here.*

Done

*Line 2ff – Please change the verb tenses in this and the following section from present perfect to simple past. For example, instead of writing a comparison “has been performed”, please write the comparison “was performed”. Generally, “has been” becomes “was” and “have been” becomes “were”. This will improve the legibility of the text and show that these actions were performed by you, not someone else before you.*

Done

*Line 7 – I do not understand the sentence beginning with “This has been computed as the monthly average...”. Please reword and clarify what was actually done.*

Done

*Line 11 – Recommend changing this sentence to “Finally, using the described retrieval procedure, SO<sub>2</sub> column densities and ash properties (AOD<sub>550</sub> and Re) were derived for the entire set of simulated radiances and compared to the MODTRAN input parameters used to generate these radiances.”*

Done

*Line 17 - Consider changing the title of this section to something more descriptive, e.g. “Retrieval of SO<sub>2</sub> and ash properties from an example MODIS dataset and comparison to conventional retrievals”*

Changed in: “Retrieval of SO<sub>2</sub> and ash properties from two MODIS images”.

*Page 8874*

*Line 1 – “... characterized by A higher plume...”*

Done

*Lines 1-17 – Please change verb tenses from present perfect to simple past. See comment above.*

Done

*Line 26 – “the fluxes HAVE common trends.”*

Done

Page 8875

Line 1 – *The meaning of this last sentence of the section unclear. Please rephrase.*

Done.

Line 4 – *replace “characteristic” with “advantage”.*

Done

Line 6 – *“UNCERTANTY OF these parameters clearly AFFECTS...”*

Done

Line 8 – *“SO<sub>2</sub> and total ash mass retrieval errors due to uncertainty in the input plume altitude”*

Done

Line 20 – *remove “always”*

Done

Line 20 – *Please rephrase the last sentence in this section, its meaning is currently not clear.*

Done

Page 8876

Line 2 – *Begin section with “Here, the Volcanic Plume Removal procedure...” Note the recommendation above suggesting the name of the procedure is changed.*

Done

Line 4 – *End sentence with “remotely sensed TIR data was described.”*

Done

Line 5 – *Add a “:” after “simple”*

Done

Line 6 – *“independent OF the surface...”*

Done

Line 8 – *“...above the plume is less negligible for low plume altitudes.”*

Done

Line 12 – *remove “quite”*

Done

Line 13 – *“Specific TO ...”*

Done

Line 14 – *Suggest removing the second half of the sentence starting with “because it is...”, or making this part into a separate sentence.*

Done. New sentence starting with “The polynomial coefficients are dependent from...”

Line 20 – *“usual TROPOSPHERIC plume”*

Done

Page 8877

*Line 7-10 – please reword this sentence/ make 2 sentences out of it.*

Done

*Line 12 – The sentence beginning with “In particular...” is not clear. What are you comparing to what? What do you mean by the “same differences”?*

Done

*Line 14 – “... in the furthest downwind part of the plume”.*

Done