Review of "A Novel Simplified Ground -Based TIR System for Volcanic Plume Geometry, SO2 Columnar Abundance, and Flux Retrievals"

We would like to sincerely thank the reviewer for his work and the time spent reading our article. His suggestions have helped to significantly clarify some parts of the paper.

The line numbers in the authors' comments refer to the new manuscript revised according to the reviewers' suggestions.

This paper presents a comprehensive methodology for retrieving SO_2 column density using a ground-based TIR system (2 IR cameras and one visible camera). The study is well-structured, detailing the three key steps: computing the instrument view geometry and the preparation of the data from both IR cameras (one broad band and one narrow band with a filter at 8.7µm), calibration (using the radiative transfer model called MODTRAN), and SO_2 retrieval (using look-up tables from MODTRAN). The authors provide an analysis of error propagation and uncertainty quantification, making the findings valuable for the atmospheric and volcanology communities. Overall, this is a well-executed study that presents a useful methodology for SO_2 flux retrievals, with a balanced discussion of its advantages and limitations.

Suggestions of technical corrections:

Line 37: "but are punctual" → "but are limited to specific locations"

OK, thanks, done.

Lines 50-51: "and as part of a continuous and real-time volcanic monitoring system." → ", and as part of a continuous, real-time volcanic monitoring system."

OK, thanks, done.

Lines 77-78: "manufacturer supplied" → "manufacturer-supplied"

OK, thanks, done.

Line 80: Why is the conversion into brightness temperature performed at 10.02 µm?

Thanks for the question. MODTRAN simulations were performed at 1 cm^{-1} step and the output radiances are in $mW\ m^{-2}\ sr^{-1}\ cm^{-1}$ units. The Broadband squared Spectral Response Function is considered equal to 1 between 1282 cm^{-1} (7.8 µm) and 714 cm^{-1} (14 µm). So, the average wavelength is 998 cm^{-1} which corresponds to 10.02 µm. We have added some details in the text to better clarify this aspect:

Line 77: "*As the figure shows, a simple top-hat function between 1282 cm^{-1} (7.8 µm) and 714 cm^{-1} (14 µm) was considered for BB since there is no specific information about it from SEEK Thermal. For NB, the manufacturer-supplied spectral transmittance (normalised to 1) of the 8.7 µm filter was used. The MODTRAN spectral radiances (in $mW\ m^{-2}\ sr^{-1}\ cm^{-1}$ units and at 1 cm^{-1} step) were weighted by the two SRFs and then converted into brightness temperatures by inverting the Planck function considering a central wavelength of 998 cm^{-1} (10.02 µm) and 1151 cm^{-1} (8.69 µm) respectively.*"

Figure 2a: The quality of the text box could be improved.

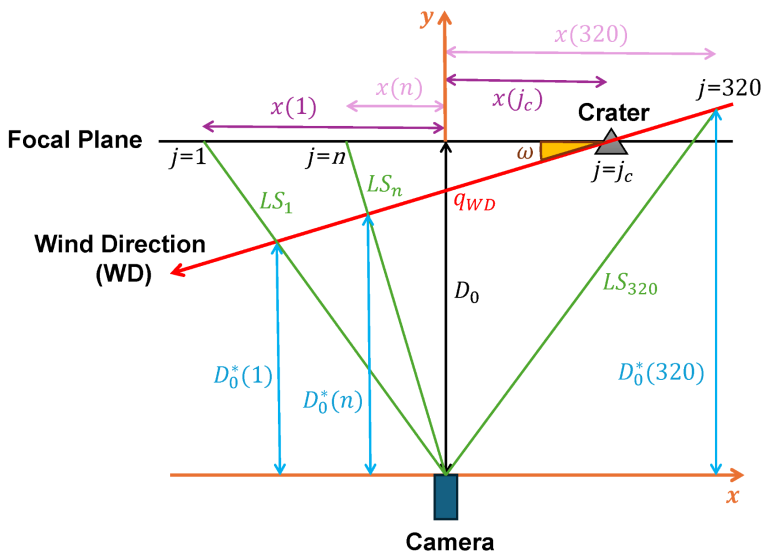
OK, thanks, done.

Line 145: In the legend of Figure 4, replace "m2" with "m²".

OK, thanks, done.

Lines 162-166: Equations 9, 10, 11, and 12 are not easy to conceptualise. To help the reader, a new illustration could be added to clearly show x(j) and explain mx and qx. Alternatively, additional text could be included to clarify these equations.

OK, we have modified fig. 5. We hope that now the equations are more clear.



New Fig. 5 inserted in the manuscript

Line 169: In Equation 3.8, does the reference correspond to Equation 8?

Thanks. The reference is to Equations from 3 to 8 so we changed the texts in “Eqs. 3–8” (en dashed has to be used to indicate a range).

General question regarding Section 3.1: How is the wind direction (ω) determined? Is it estimated during the field campaign, or is it derived from GEO (SEVIRI) or LEO (TROPOMI) data? If this is the case, it should be explicitly stated.

As written in lines 161-162, ω is not the wind direction but it’s the relative azimuth angle between the wind direction and the focal plane of the camera. In this case the wind direction was taken from an atmospheric forecasting model from ARPA (“Agenzia Regionale Prevenzione Ambiente”). Based on the wind direction and the camera position and orientation, ω = 26° from Piano del Vescovo while ω = 52° from Nicolosi. We added this sentence in the manuscript:

Line 179: *"Wind data was taken from the mesoscale model of the hydrometeorological service of Agenzia Regionale per la Protezione Ambientale (ARPA) Emilia Romagna, which is named ARPASIM (Scollo et al., 2009), and considering an hourly model output from 72-h weather forecast provided for Etna every 3 h."*

Lines 180-184: SEVIRI retrievals estimate a plume top altitude of 6.9 km at 00:55 UTC on April 1, 2021. You state that this is in good agreement with the VIRSO2 nighttime measurements. Could you specify the volcanic plume top altitude obtained using VIRSO2's field of view and geometric considerations, both with and without wind correction?

The comparison of the plume height from SEVIRI and from the VIRSO2 camera here is just qualitative. The purpose of this part is to describe the method and show the importance of considering the effect of the wind. An accurate quantitative comparison would require that the two measurements (from satellite and from ground) were taken at the same instant, but unfortunately, we started collecting measurements from Piano del Vescovo at 02:29 UTC. Anyway, the fig. 6b clearly shows that for this image (02:29 UTC) the top plume height is a bit lower than 7 km a.s.l. while in the fig. 6a (without wind correction) the top plume height is about 8.5 km asl (as written at line 184).

Lines 190-193: The error increases for ω > 45°. Could you provide an explanation for this? Additionally, what conclusions can be drawn from the comparison between this study and the tool provided by Snee et al. (2023)?

As written at line 161, ω ranges between -90° and +90°. These extreme values (ω=90° or ω=-90°) mean that the wind direction is parallel to the central line of sight of the camera D_0, that is the plume goes perpendicular to the focal plane. In this case it's impossible to apply the wind correction method (in the Eq. 9 the tangent becomes infinite). Apart from these two specific cases, the increasing of |ω| produces an increased sensitivity on wind direction and camera orientation. This means that small errors in these quantities can result in large errors in the wind-corrected height.

The comparison with the tool provided by Snee et al. (2023) wants to demonstrate the accuracy of our simple method for a relatively large number of cases. The calibration tool of Snee et al. (2023) uses a more complex and more accurate set of formulas, and it has already been published. The conclusions of this comparison are that if for |ω|<45° our simple method presented has a very low error.

We inserted a comment in the new manuscript (line 200):

"So, during field measurements, it would be desirable to position the VIRSO2 so that the camera's focal plane is parallel to the wind direction or tilted at an azimuth angle of no more than 45 degrees."

Lines 200-202: The text mentions "the next section," but the order of presentation is Sections 4.1, 4.3, and 4.2. Consider reordering the text to follow the sequence 4.1, 4.2, and 4.3, or, if this is not logical, switching the order of Sections 4.3 and 4.2.

OK, we changed the order of these sentences. The order of the Sections is logical and follows the steps of the calibration procedure (see the flowchart fig. 2a).

Line 208: "*Here different effects must be taken into account: at first, the non -perfect transmissivity of the 8.7 µm filter produces a "ghost image". Then, an adjustment is important also for the BB camera, considering that the clear sky temperature often doesn't match with the MODTRAN simulations. Finally, the filter temperature affects strongly the NB measurements, so a calibration of this band is necessary.*"

Lines 200-202: "at first, the non-perfect transmissivity of the 8.7 µm filter produces a 'ghost image.' Then, the filter temperature affects the NB measurements, and finally, an adjustment is necessary for the BB camera, considering that the clear sky temperature often does not match the MODTRAN simulations." The mention of "non-perfect transmissivity" and "filter temperature effects" for the NB measurements appears closely related. Additionally, some introductory information about the use of MODTRAN would be beneficial. Improving the clarity of these three lines would help the reader grasp the concept more easily.

The order of these sentences is changed as suggested by the reviewer. Surely, the "non-perfect transmissivity" and the "temperature effects" of the NB filter are related but as shown in the following sections (4.1 and 4.3), these two problems are addressed and resolved separately. The use of MODTRAN (radiative transfer model) to obtain the quantitative retrieval of SO2 was already mentioned in the abstract and in the introduction. Then its use is deeply described in the following sections (4.2, 4.3, 5).

Line 206: The phrase "do not frame exactly the same scene" describes a common issue known as an X/Y shift between the two cameras. This terminology could be included for clarity.

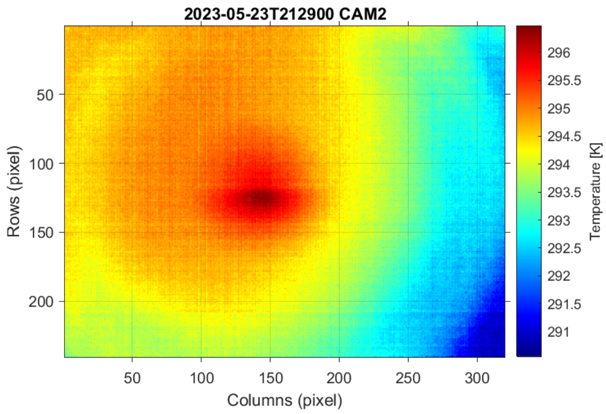
OK, thanks, done.

Line 213: "For the BB camera, this effect is small enough that a correction is not required (Prata et al., 2024)." Given that the vignetting effect results in a range of 4 K for the NB and only 0.4 K for the BB, it seems reasonable to assume that vignetting correction is not necessary for the BB camera.

Yes, exactly, the reviewer is right.

Lines 230-232: "A 'correction image' (Fig. 7c) is simply obtained as the difference between the black target temperature image Tn,NB(i, j) and its mean value MEAN(Tb,NB) over the 320 × 240 array." It is unclear why MEAN(Tb,NB) is subtracted from Tn,NB(i, j). Could you provide an explanation? Is this a way to normalise the ghosting effect? What is the purpose of applying this offset? Clarifying this would be helpful.

When a “black target” measurement is made (that is a measurement with a purpose -built black target placed in front of the camera), we obtain from NB camera an image containing only the “ghost image” (see the figure below).



Assuming that the black target has a uniform temperature (due to the high proximity of the sensor to the target this seems a correct assumption), to remove the “ghost” effect from this image it is enough to subtract the image itself with the real temperature of the black target. But, as written at line 231, given that this correction is only of a “geometric” type (at this step it doesn't matter if the resulting image is correct in temperature, because a temperature calibration of the NB is performed later, sect. 4.3), the actual temperature of the plate is not required. So here it is enough to subtract the image itself with a single temperature value, which can be for example the minimum value or the mean one. To clarify this important aspect, we inserted a new comment in the manuscript:

Line 253: *“It’s important to remark that at this step it doesn't matter if the resulting image T'_{NB} is correct in temperature, because the temperature calibration of the NB is performed later (Sect. 4.3); so, for example, using the minimum value of the black target image instead of the mean one, it wouldn't change the final result, that is the SO2 content.”*

If the “ghost” effect in the black target scene was exactly the same as the one in the scene with the volcanic plume, the “ghost” image would be perfectly removed. This usually doesn’t happen, because the ghost image depends to both the different temperatures of collected scene, as well as to any variations in the internal temperature of the instrument. For this reason, this simple geometric correction does not always give optimal results; in some cases, the “ghost” effect in the volcanic plume image is only partially removed (lines 256-260).

Line 287: In Equation 15, it appears that the term B is not explicitly defined.

B is the Planck function, we added this information in the text.

Line 306: In Figures 8a and 8b, using the same Y-axis range (e.g., 210–290 K) could improve visual consistency.

OK, thanks, done.

Line 313: In Section 4.3, you wrote, "as described in Sect. 4." Did you mean "As described in the introduction of Section 4"?

Yes, thanks, done.

Lines 322 &331: To fully understand Equations 16 and 17, it is crucial to define the term B.

OK, thanks, done.

Line 351: In Section 4.3, you wrote, "as already reported in Sect. 4." Please specify whether this refers to the introduction of Section 4, Section 4.1, or Section 4.2.

OK, it's the introduction, done.

Lines 350-355: It would be helpful to explicitly define T_{BB}(sky), T_{BB}(ground), T'_{NB}(sky), and T'_{NB}(ground).

OK, thanks, we have added in the text at Line 368: *"The labels (sky) and (ground) represent the average temperatures of two small areas of the image related to clear sky and ground respectively (Fig. 9a)."*

Line 374: In Figure 10a, there still appears to be some vignetting effect. If confirmed, this should be mentioned.

OK, thanks, we have added in the text at Line 402: *"As already noted in Fig. 8a, some small border effects (vignetting) are present in the BB image, so we obtained some DT_{BB} values > 0 which are not related to the plume's presence."*

Line 401: Equation 22 does not seem to match Figure 11. The equation states:

$BH = D_0 \tan(\theta)$

However, if $\mathbf{B_{MP}}$ represents the mean altitude of the MODTRAN plume layer above sea level, the correct expression should be:

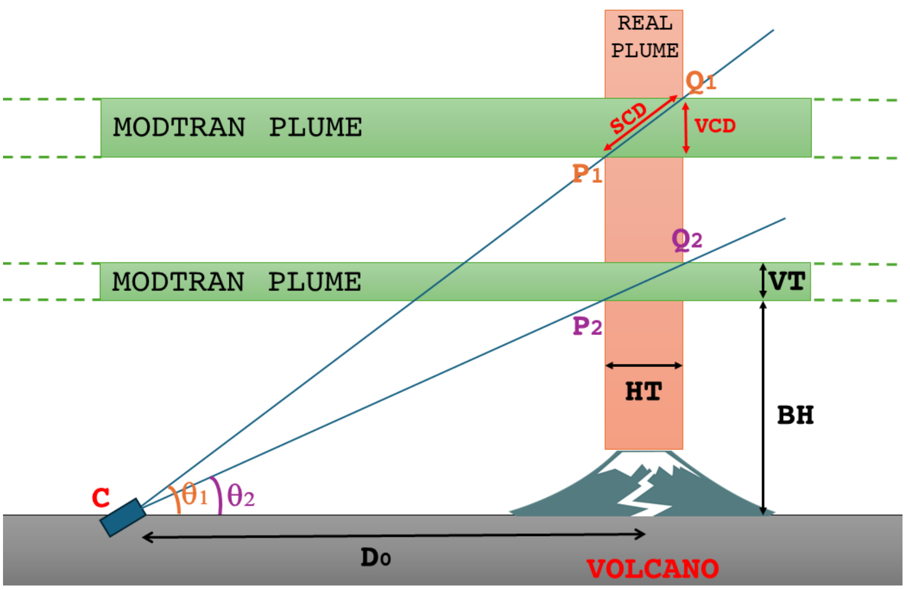
$B_{MP} = (D_0 + HT/2) \tan(\theta) + h_0$

B_{MP} should also be added to Figure 11.

OK thanks, there was a small error in fig. 11 that now we have corrected (D_0 was wrongly indicated). The D_0 distance (perpendicular distance between the camera and the image plane) is computed considering the geographical position (Lat; Lon) of the camera and the vent and the column position "*jc*" of the vent in the VIRSO2 image (the angle $\varphi(jc)$ is known). So, we think that Eq. 22 which permits to compute the bottom altitude of the plume is correct as it is:

$$BH = \left(D_0 - \frac{HT}{2}\right) \cdot tan\,(\theta)\ + h_0$$

In the MODTRAN model we must insert the top and the bottom of the plume altitude. The BH and VT parameters (Eqs. 22-23) give us this information. The mean altitude of the plume (as suggested by the reviewer) is not necessary.



New Fig.11 inserted in the manuscript

Line 415: It may be useful to remind the reader that T_s represents the clear sky temperature.

Sorry, here there was a typo in the text. We have added the missing sentence at Line 445: *"As mentioned in Sect 4.2, the MODTRAN LUTs were recomputed with a more appropriate sky temperature, in this case: Ts = 226 K."*

Line 429: In Figure 13a, there still appears to be some vignetting effect. If confirmed, this should be mentioned.

OK thanks, we added at Line 456: *"In the upper part of the image, some edge effects still remain. These pixels must be excluded in the computation of SO2 mass and flux (Sect. 6)."*