Author's response to Review RC2 by Toshiya Mori

First, we like to gratefully thank for the constructive, detailed and helpful comments given by Toshiya Mori. We are convinced that the comments allowed us to improve the manuscript quality within the revision process.

For clarity we answer the specific comments directly (bold printed). The reviewer comment is set in italic font, the authors response in normal font. We added a figure in section 3.3 (Fig. 5 (b)), recalculated the coefficients of Eq. 8, and recalculated the Fig. 7 with new values of Eq. 8. On several occasions we changed and added sentences resulting in minor changes to the manuscript.

"2.2 The IFPICS prototype"

<u>Reviewer's comment:</u> *From Figure 2, it seems that the tilt angles of FPI is controlled by a stepping motor. However, there seems to be no description on how the tilt angles for the two settings A and B are controlled in the manuscript. Although the optics of the IFPICS are explained in detail, the mechanical part of the IFPICS is poorly explained. The mechanical part of the IFPICS prototype especially about the changing of the tilt angle should also be described in the manuscript. How long does it take to change the tilt angle? This may partly explain rather low frame rate of 0.2 Hz for the pair of images.*

<u>Author's response:</u> This is a valid comment. In the revised version we include the mechanical description of the IFPICS prototype:
The tilt angle for the two settings A and B is - as mentioned in the comment - controlled by a stepping motor. The motor has a step resolution of 0.9°. It is equipped with an additional planetary gearbox with a reduction ratio of 1 to 9 reducing the effective step resolution to 0.1°. The motor is controlled by a microcontroller combined with a stepping motor controller. The controller enables the operation of the stepper motor in micro-stepping mode thus further improving the angular resolution by a factor of 16, yielding a final resolution of 0.00625 degrees per motor step. An optical switch is used for position sensing of the stepper motor.
The time required for changing the tilt from setting A to setting B is of the order of 0.15 s. Hence, the low frame rate of the prototype of 0.2 Hz (5.5 seconds per pair of frames) mainly arises from controlling and triggering the employed UV detector.

We changed and extended the sentence: (submitted manuscript lines: 125 - 127):
"The static air-spaced FPI (*d*, *n* and *R* fixed, provided by *SLS Optics Ltd*.) can be tilted within the parallelised light path in order to tune its spectral transmission T^{eff}_{FPI} between setting A and B via variation of the incidence angle α (see Section 2.1)."

To (revised manuscript lines: 135 - 138):
"The FPI is the central optical element of the IFPICS prototype and is implemented as static air-spaced etalon with fixed *d, n*, and *R* (provided by *SLS Optics Ltd*.). The mirrors are separated using ultra low expansion glass spacers to maintain a constant mirror separation *d* and parallelism over the large clear aperture of 20 mm even in variable environmental conditions. In order to tune the spectral transmission T^{eff}_{FPI} between setting A and B a variation of the incidence angle α is applied."

We added the sentence: (revised manuscript lines: 138 - 141):
"The FPI can be tilted within the parallelised light path using a stepper motor. The stepper motor has a resolution of 0.9° per step, is equipped with a planetary gearbox (reduction rate 1/9) and operated in micro-stepping mode (1/16) resulting in a resolution of 0.00625°per motor step. The time required for tilting between our settings A and B is ≈ 0.15 s."

Table 1 and Equation 6
<u>Reviewer's comment</u>: Direct use of the parameter values in Table 1 into equation 6 seems inappropriate. Either the values in Table 1 or the equation 6 needed to be modified. The sine in eq. 6 is in radiance and the cosine is in degree. They should be matched. d and λ in eq. 6 needed to be in the same unit or conversion factor should be included in eq. 6.

<u>Author's response:</u> Thanks for that comment. We will include a note for the units required for sine and cosine calculation. For d and λ the units of µm and nm are indicated in Tab. 1.

We added the footnote to Tab. 1:
"*: used in units of radian in the instrument model Eq. 6 & 7"

Figure 6
<u>Reviewer's comment</u>: In Fig.6(b), CD S_{SO2} value between Row 400 and 415 (most part is hidden behind the "crater flank" label) seems to be shifted to positive side unlike those of other Rows (distributed around zero). As stated in the end of the figure caption of Fig. 5, IA is basically equal to IB for both background sky and flank. Is there any possibility of SO2 on the flank or is there any other reason to explain for the positive shift? According to a Global Volcanism Program report in "Global Volcanism Program, 2019. Report on Etna (Italy) (Crafford, A.E., and Venzke, E., eds.). Bulletin of the Global Volcanism Network, 44:10. Smithsonian Institution. https://doi.org/10.5479/si.GVP.BGVN201910-211060." There was a lava flow event between 19-21 July, 2019 (until a day before the observation) on the eastern flank of SEC. Probably part of the flow may have been in the view of the IFPICS at the time of the observation on 22 July, 2019. Is there any possibility detecting volcanic fume with SO2 from the lava flow?

<u>Author's response:</u> Yes, indeed there was a lava flow event at Mt. Etna close to the time we were measuring. However, we do not expect to detect its fume. The enhanced signal can most likely be explained by the low level of light scattered from the crater flank and the thereby increasing influence of hardware systematics of the detector and statistical fluctuations.

Lines 194-200:" The SZA during the time of the measurement is (78±3) (NOAA) witha VCDO3retrieved calibration function...with x0 = 1.0×10^{13}, x1 = 1.1×10^{19}, x2 =9.3×10^{18}, x3 = 7.9×10^{18}, and x4 = 1.6×10^{19}in units of molec cm^{-2} respectively."
<u>Reviewer's comment:</u> Reading here and the figure caption of Fig. 6, x0-x4 parameters is supposed to correspond to SZA=78 degrees. As I plotted Eq. 8 with x0-x4 values, it seems the conversion function correspond to SZA 25 degrees. Please give the

parameters for SZA=78 degrees corresponding to the observation. If the conversion function withx0-x4 given in the manuscript are used for calculation of SO2 CD distributions in Fig.6, SO2CD need to be recalculated using appropriate conversion function.

Author's response: Yes, the given polynomial parameters accidentally corresponded to an SZA of 25 degrees. However, it was only a copy error of from the model code values into the manuscript. All calculations were performed with the correct calibration function as given in the following:
x0 = 1.04×10^{13}, x1 = 1.81×10^{19}, x2 =1.73×10^{19}, x3 = 1.69×10^{18}, and x4 = 6.77×10^{19}.

Equation 8

Reviewer's comment: According to equation 1, AA is zero, if SO2 CD (S) is zero. Considering this,0th order parameter x0 may not be needed or may be set to zero in the 4th order polynomial fitting.

Author's response: Yes, that is true as we retrieve the calibration function from a numerical model. We changed our polynomial fitting using a y-intercept fixed to zero. The new calibration function reads:
x0 = 0, x1 = 1.81×10^{19}, x2 =1.72×10^{19}, x3 = 1.73×10^{19}, and x4 = 6.64×10^{19}.
We recalculated Fig. 6 (now Fig. 7) using the new calibration function. The changes are marginal and slightly visible in the noise of the crater flank in Fig. 7 (b).

We changed the sentence (submitted manuscript line: 197 - 198):
"[…] with x0 = 1.0×10^{13}, x1 = 1.1×10^{19}, x2 =9.3×10^{19}, x3 = 7.9×10^{18}, and x4 = 1.6×10^{19} in units of molec cm^{-2} respectively."

To (revised manuscript lines: 219 - 220):
"[…] with x0 = 0, x1 = 1.8×10^{19}, x2 =1.7×10^{19}, x3 = 1.7×10^{19}, and x4 = 6.6×10^{19} in units of molec cm^{-2} respectively with x0 fixed to zero."

We recalculated Fig. 6 (revised manuscript Fig. 7):

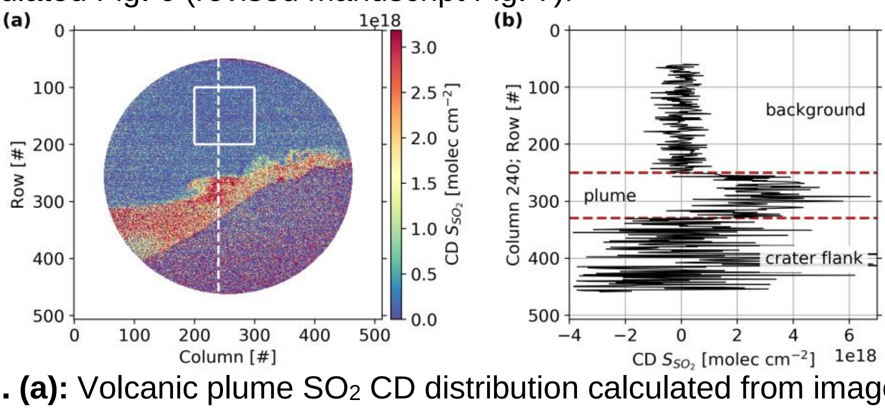

Figure 7. (a): Volcanic plume SO_2 CD distribution calculated from images acquired with the IFPICS prototype and using the instrument forward model conversion function $S_{\mathrm{SO2}}(\tilde{\tau})$ (see Eq. 8). The plume free area indicated by a white square (100 x 100 pixel) is used to correct for atmospheric background and to obtain an estimation for the detection limit. **(b):** Individual SO_2 CD column 240 (indicated by dashed white line in (a)) showing that background, plume, and crater flank region are clearly distinguishable. High scattering in the crater flank region is induced by low radiance.

Line 203:" The atmospheric background is $S_{SO2,bg}$= 4.3×10^{16}molec cm^{-2}"
Reviewer's comment: Definition of atmospheric background S_{SO2} is not clear. Does this value correspond to the difference of S_{SO2} between plume direction and flat-field image direction or to the absolute atmospheric background value for observation direction?

Author's response: Thanks for that comment, we shall clarify the definition of the atmospheric background $S_{SO2,bg}$ in the revised manuscript:
The $S_{SO2,bg}$ accounts for the difference in S_{SO2} between the plume direction and flat-field image direction.

We added the sentence (revised manuscript lines: 227 - 229):
"Since the $S_{SO2,bg}$ is determined from an evaluated CD distribution image it accounts for the residual signal in S_{SO2} between the direction of the volcanic plume and the direction of the flat-field images used in the evaluation."

Lines 230-231: "Furthermore, the small interference to broadband effects extends the range of meteorological conditions acceptable for field measurement.
Reviewer's comment: I agree that one of the major advantages of the IFPICS is extension of acceptable meteorological ranges in the field measurements such as minimal influence of background clouds. I suppose the author need to explain more specific on this. Personally, I feel slightly pity because the authors did not show clear example images corresponding to outcome of "the small interference to broadband effects" in this manuscript, which would definitely convince the readers of the clear advantages of the new IFPICS compared to the conventional SO2 cameras.

Author's response: Yes, this is a valid comment. We do expect a weaker influence on broadband interferences for example induced by background clouds in contrast to traditional filter based SO_2 cameras. This statement is based on model calculations as shown in Kuhn et al., 2014. However, within this work our main goal was to demonstrate the feasibility of the IFPICS technique to detect volcanic SO_2 emissions. Hence, in our up to now limited data set we only took data under good weather conditions without background sky clouds. This fact limits our dataset, and unfortunately, we cannot provide exemplary images yet. Despite that fact, we certainly plan to address this topic in near future studies. For this manuscript we will weaken our statement on this topic.

We changed the sentence (submitted manuscript lines: 230 - 231):
"Furthermore, the small interference to broadband effects extends the range of meteorological conditions acceptable for field measurement. "

To (revised manuscript lines: 282 - 284):
"Furthermore, the expected smaller interference to broadband effects in comparison to traditional SO_2 imaging techniques should allow to extend the range of meteorological conditions acceptable for field measurement (see Kuhn et al., 2014). "

Minor comments:

- **Line 190: "The circular shape of the retrieved image arises from the FPI's circular clear aperture limiting the imaging FOV." And line 216:" a high spatial and temporal resolution (400×400 pixel, 1 s integration time)"**
  <u>Reviewer's comment</u>: The 2D UV-sensitive CMOS sensor (SCM2020-UV) is originally a 2000x2000 pixels sensor. It seems 4x4 pixel binning is applied to the images. If so, please indicate in the manuscript.

  <u>Author's response</u>: Yes, indeed. We applied 4x4 pixel binning and will include this information in the revised version of the manuscript.

  We changed the sentence (submitted manuscript lines: 117 - 118):
  "A 2D UV-sensitive CMOS sensor (SCM2020-UV provided by *EHD imaging*) is used to acquire images."

  To (revised manuscript lines: 125 - 126):
  "A 2D UV-sensitive CMOS sensor (SCM2020-UV provided by *EHD imaging*) is used to acquire images. The sensor is operated in 4x4 binning mode yielding a final image resolution of 512x512pixel."

  We changed the sentence (submitted manuscript lines: 215 – 216):
  "We were able to unequivocally resolve the dynamical evolution of SO_2 in a volcanic plume with a high spatial and temporal resolution (400x400 pixel, 1 s integration time)."

  To: (revised manuscript lines: 262 - 263):
  "We were able to unequivocally resolve the dynamical evolution of SO_2 in a volcanic plume with a high spatial and temporal resolution (400x400 pixel, 1 s integration time, 4x4 binning)."

  We changed the sentence (submitted manuscript line: 149):
  "The exposure time was set to 1 s for all acquired images."

  To (revised manuscript lines: 167 - 169):
  "The exposure time was set to 1 s for all measurements and 4x4 binning (total spatial resolution of 512x512 pixels) was applied to all acquired images."

- **Lines 205-207:" The similar plume free area (white square, 100×100 pixel, in Fig.6, (a)) is further used to give an estimation for the SO2 detection limit of the IFPICS prototype by calculating the 1-σ pixel-pixel standard deviation. The obtained detection limit is 5.5×10^{17}molec $cm^{-2}s^{-1/2}$given by the noise equivalent signal."**
  <u>Reviewer's comment</u>: Please explain how the detection limit was calculated more in detail. 1-sigma pixel-pixel standard deviation does not seem to give the detection limit unit indicated here.

  <u>Author's response</u>: Thank you for this comment. We used the 100x100 pixel area and calculated the respective standard deviation for these pixel. This yields the stated detection limit of 5.5×10^{17}molec cm^{-2}. The unit of $s^{-1/2}$ arises from the

time dependency of the photon shot noise which is proportional to 1/sqrt(t) with the exposure time t. As the images have been obtained with an exposure time of 1s the unit of $s^{-1/2}$ can be included. We will clarify this statement in the revised manuscript:

We changed the sentence (submitted manuscript line: 207):
“The obtained detection limit is 5.5×10^{17}molec cm^{-2} $s^{-1/2}$ given by the noise equivalent signal.”

To (revised manuscript lines: 231 - 232):
“The obtained detection limit for an exposure time of one second is 5.5×10^{17} molec cm^{-2} given by the noise equivalent signal. “

- **Figure caption of Fig. A1:” acquired with the IFPICS prototype on 22. July 2019, 08:50- 09:10 CET”**
  Delete “.” after “on 22”
  Corrected as proposed

Other comment:
<u>Reviewer’s comment</u>: It would be helpful, especially for non-volcanological readers, to show visual image of the plume from the observation site if available.

<u>Author’s response</u>: We added a visual image to Fig. 4 (revised manuscript: Fig. 5).

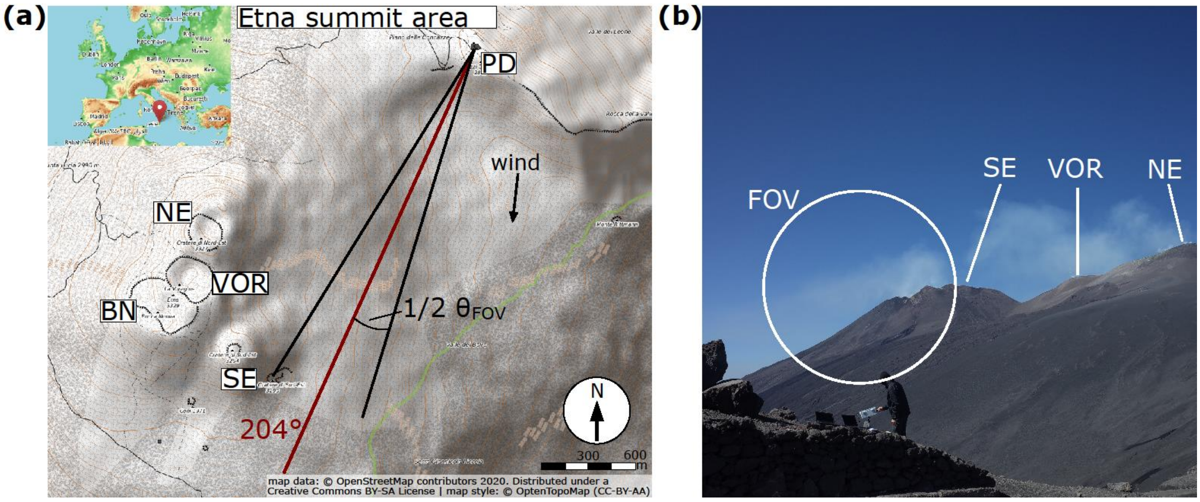

Figure 5. (a): Topographic map of the Mt. Etna summit area, North East crater (NE), Voragine (VOR), Bocca Nuova (BN), South East crater (SE) and measurement location at the Osservatorio Vulcanologico Pizzi Deneri (PD) are indicated. The viewing direction on 22 July 2019 is 204° (red drawn) with an FOV of θ = 18° (black drawn) and an elevation of 5°. The FOV is partly covering the plume emanating from SE crater. The average wind direction is ≈5° with a speed of ≈ 6 m s^{-1} (wind data from UWYO). **(b)**: Visual image of the volcanic plume on 22 July 2019 with indicated camera field of view (FOV).