Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2017-335-RC1, 2017

Atmospheric Measurement Techniques Discussions

Interactive comment on "Multicopter measurements of volcanic gas emissions at Masaya (Nicaragua), Turrialba (Costa Rica) and Stromboli (Italy) volcanoes: Applications for volcano monitoring and insights into halogen speciation" *by* Julian Rüdiger et al.

C. Kern (Referee)

ckern@usgs.gov

Received and published: 21 December 2017

General comments

This manuscript describes volcanic gas measurements performed with various sensors mounted on a rotary wing unmanned aerial system (UAS). A wide range of different sensor types were applied – in-situ gas concentrations were measured using a combination of electrochemical and optical sensors. For the first time, denuder-based

Printer-friendly version

Discussion paper

sampling was conducted from a UAS. Also, a differential optical absorption spectrometer (DOAS) was flown underneath the volcanic gas plume to derive sulfur dioxide (SO2) emission rates. The authors describe how this suite of sensors was applied at Masaya, Turrialba and Stromboli Volcanoes to help constrain the plume gas composition and gas flux, and gain insights into halogen chemistry in volcanic plumes.

The strength of this article clearly lies in the breadth of UAS applications that are described. The combination of various sensor technologies targeting different observable parameters is intriguing and will be helpful for volcanic gas geochemists in framing future experiments. The various sensors are described in sufficient detail as to allow reproduction of this or development of similar sensor payloads targeting specific research questions.

The measurement results obtained during deployment at the authors' three study sites are also quite interesting, though they are somewhat difficult to interpret due to the limited amount of available UAS data and very limited supplemental information from other sources at each study site. For example, it remains unclear why C/S ratios measured by UAS at Stromboli are systematically higher than those measured by ground-based MultiGAS during the study period. Similarly, the three BrX/SO2 ratios measured at different distances from Stromboli's active vents do not follow a clear trend and are hard to interpret by themselves. Perhaps a bit more effort could be made to put these measurement results into context and/or offer possible explanations for the observations.

The manuscript is generally well written and the technical information contained within will be useful to the volcanology community. The content is within the scope of Atmospheric Measurement Techniques, and I recommend the article be published after the specific issues and minor corrections listed below are taken into consideration.

.

Specific issues

Title – Currently, the main focus of the manuscript appears to be the implementation of various sensors for characterizing volcanic degassing on a UAS platform. This is also in line with the scope of AMT. Unless the results section is significantly expanded, you might consider changing the title to something along the lines of "Implementation of electro-chemical, optical and denuder-based sensors and sampling techniques on UAS for volcanic gas measurements: examples from Masaya, Turrialba and Stromboli Volcanoes". This seems to capture the manuscript's focus a bit better than the current title.

P1L32 – 'spatial and temporal proximity to explosions'? Is the spatial and temporal evolution of the C/S ratio actually discussed in the manuscript? It seems like this is a bit of a reach. Perhaps better to say that changes in the C/S ratio were observed that may have been associated with explosive activity at Stromboli?

P1L31ff – Why are only the results from Stromboli mentioned explicitly in the abstract? Perhaps the most important results for each study site could be mentioned?

P2L13 – 'It has been shown. . .' This is much too general of a statement. There are accounts of increased C/S prior to eruptions. However, the opposite has also been observed (e.g. at Poas, see your reference de Moor et al 2016b). Please clarify.

P2L27 – 'It was observed. . .' Again, I feel like this statement is too general. I think that recent measurements at Cotopaxi seemed to show an increase in BrO/SO2 during a period of continuous activity? Is this true? Dr. Bobrowski would know more of the details. . . As you mention in the next sentence, BrO is a secondary compound formed in volcanic plumes from reaction of HBr with other species. Therefore, the link between measured BrO/SO2 ratios and volcanic activity will typically be quite complex and depend on a large number of environmental conditions.

P5L5 – Clearly, Masaya is a large contributor to total arc emissions, but recently I believe that Turrialba has had similar emission rates. Dr. de Moor would know this better than I do, but characterizing Masaya as the 'single largest contributor' may no

longer be quite accurate. See de Moor et al 2017:

de Moor, J. M., Kern, C., Avard, G., Muller, C., Aiuppa, A., Saballos, A., ... Fischer, T. P. (2017). A new sulfur and carbon degassing inventory for the Southern Central American Volcanic Arc : The importance of accurate time-series datasets and possible tectonic processes responsible for temporal variations in arc-scale volatile emissions. Geochemistry Geophysics Geosystems, 18, 1–32. https://doi.org/doi: 10.1002/2017GC007141

P5L23 – Does ash deposition really make maintenance risky or impossible? Please explain why. Obviously it makes frequent, tedious maintenance necessary. And if stations are very close to the summit, then ballistics pose a real threat that would make maintenance risky or impossible. But ash?

P7L15 – Is the light source really a 'small light bulb'? I always thought it was a diode. The datasheet says 'IR lamp' which might really be a light bulb but I'm not sure... Thanks for clarifying.

Table 1 – I have a few questions on information in this table: (1) the specifications on both instruments seem to require non-condensing plumes, yet the manuscript later describes problems with telemetry associated with condensed plumes. Could you comment further on the issue of condensation? How would it affect the measurements? Would you be able to determine and filter out poor quality data collected in condensed areas of the plume? Or how to deal with this? (2) I guess the 1/T temperature dependence of the CO2 sensor is simply from the ideal gas law? T would then be the air temperature, correct? (3) Later on in the manuscript, you explain that the pressure dependent diffusivity of the SO2 sensor membrane makes the readout insensitive to pressure, yet a (small) correction is listed here. This is probably a second-order effect, but it's probably worth pointing out for consistency. (4) I assume that 'resolution' is the precision of the sensor? If not, could you give the precision? Also, what is the assumed integration time for the values given? I assume you could improve precision

by increasing the integration time, correct?

P10L3 – Can you be a bit more specific with regards to which species can be detected with your denuder system? You mention reactive bromine (BrX). Am I correct in assuming that gaseous HBr cannot be detected? What about the other gaseous species involved in the 'bromine explosion' mechanism, i.e. Br2, Br, HOBr? They can all be detected? And what about bromine taken up onto aerosols? I guess it would be invisible to the instrument?

P11L2 and Author Comment from 15 Dec 2017 – There is significant literature on the issue of comparing data from sensors with different response times. For example, it would be good to cite one or both of these studies:

Roberts, T. J., Saffell, J. R., Oppenheimer, C., & Lurton, T. (2014). Electrochemical sensors applied to pollution monitoring: Measurement error and gas ratio bias âĂŤ A volcano plume case study. Journal of Volcanology and Geothermal Research, 281, 85–96. https://doi.org/10.1016/j.jvolgeores.2014.02.023

Roberts, T. J., Braban, C. F., Oppenheimer, C., Martin, R. S., Freshwater, R. A., Dawson, D. H., . . . Jones, R. L. (2012). Electrochemical sensing of volcanic gases. Chemical Geology, 332–333, 74–91. https://doi.org/10.1016/j.chemgeo.2012.08.027

In the author comment from 15 Dec 2017, an EGU presentation is cited in this context, but I was not able to find the presentation online. Only the abstract is available, and this makes no mention of a method used to correct for different sensor response times. Also, please clarify how exactly the 'response time factor' is defined.

P11L22 – How long was the denuder sampling period? I.e. how long did the instrument need to hover in the plume to collect a good sample?

P13L14 – This is where condensed water is mentioned, despite the fact that the sensors are specified to require non-condensing conditions. Please explain the caveats with these measurements if possible.

P14L8 – At Stromboli, explosions may be associated with CO2-rich gas slugs rising through the conduit and venting into the atmosphere. However, in this model, all the CO2 and SO2 is emitted from the vent itself. Once in the atmosphere, the gas is diluted of course, but as far as I can tell, the ratio of volcano CO2 to SO2 should remain constant over time and space. It is not at all clear to me why the C/S ratio would be different once the plume becomes more dilute. Please explain the mechanism that you are suggesting may change that ratio as the plume moves in space and time.

P14L14 – You state that the MultiGAS measurements broadly agree with the UAS measurements, but fail to mention that there appears to be quite a large systematic difference between the average values obtained by the two instruments. According to Figure 7, the MultiGAS seems to measure C/S of no more than 15, with an average of about 7, whereas the UAS instrument measured between about 10 and 65, with an average of around 30. This is a significant difference and should be addressed in the text. Simply stating that the measurements were not taken at the identical time and place is a little weak in terms of an explanation, especially given my previous comment.

P14L17 – I don't understand why high C/S ratios should be left aside. You do have at least some observations of ongoing eruptive activity during the time that you were there for the UAS measurements, and clearly the datasets overlap in time so in first order approximation, you would think that the same activity was sampled by both instruments. Can you please clarify?

Table 2 – I assume that the 'lower SO2 limit' refers to a limit below which the data was not used for deriving C/S ratios. Can you please explain how this limit was chosen and why it varied for different datasets?

Figure 6 – Either I'm not understanding or something appears to be amiss with this figure and/or the caption. The bottom two plots are labeled the same. I assume that the bottom plot should actually be the MG SO2 mixing ratio, correct? And in the caption, I assume that you mean that the SK CO2 raw data is shown in grey and the resampled

CO2 data is shown in black, correct?

P17L10 – Here you point out that BrX/SO2 appears to vary with CO2/SO2, though no trend can be derived from the three obtained data points. What does this observation really mean? If BrX/SO2 was in some way proportional or anti-proportional to CO2/SO2, then one might attribute the change to various gas compositions being emitted from the volcano at different times. However, a varying dependency seems to negate this explanation as being primarily responsible. So what could possible cause this? Or is this a sign that something is wrong with the derived CO2/SO2? (also see previous comments on comparison to MultiGAS).

Figure 7 – What criteria were used to select valid MultiGAS data? You mention the different SO2 lower limits for the SK, but what about the MultiGAS? Also, as mentioned before, I think the systematic difference shown here is a bit alarming and needs some careful thought and discussion.

P20L25 – What do you mean by 'previously unstudied plume regions'? Areas very close to the vent? What do you think are the limitations on this, e.g. with regards to heat exposure, ash concentration etc.?

P20L25 – I may be wrong, but I think that UAS operations with pre-programmed flight paths have already been done, see e.g.

Mori, T., Hashimoto, T., Terada, A., Yoshimoto, M., Kazahaya, R., Shinohara, H., & Tanaka, R. (2016). Volcanic plume measurements using a UAV for the 2014 Mt. Ontake eruption the Phreatic Eruption of Mt. Ontake Volcano in 2014 5. Volcanology. Earth, Planets and Space, 68(1). https://doi.org/10.1186/s40623-016-0418-0

.

Minor corrections

The manuscript would benefit from careful proof-reading. A significant number of minor corrections would improve the legibility of the text. Listed below are some of the more

important corrections needed for clarity, but there are likely several others.

P1L18 – . . . (e.g. carbon dioxide) TO THE ATMOSPHERE.

P1L19 – Consider rewording this sentence to something like: The relative abundance of carbon and sulfur in volcanic gas as well as the total sulfur dioxide emission rate from a volcanic vent are established parameters in current volcano monitoring strategies, and they oftentimes allow insights into subsurface processes. On the other hand, chemical reactions involving halogens are thought to have local to regional impact on the atmospheric chemistry around passively degassing volcanoes.

P1L21 – Recommend removing 'on board'

P1L22 – Recommend removing 'with such new measurement strategy'

P1L23 – Consider appending the altitudes to the individual volcanoes, e.g. Turrialba Volcano (3,300 m), Stromboli Volcano (930 m) . . .

P1L27 – Remove ',' after including

P2L6 – Consider mentioning v. Glasow et al 2009 for a more complete treatise of plume chemistry? von Glasow, R., Bobrowski, N., & Kern, C. (2009). The effects of volcanic eruptions on atmospheric chemistry. Chemical Geology, 263(1–4), 131–142. https://doi.org/10.1016/j.chemgeo.2008.08.020

P2L11 – There are a few other recent articles that could be mentioned in this context:

Mason, E., Edmonds, M., & Turchyn, A. V. (2017). Remobilization of Crustal Carbon May Dominate Volcanic Arc Emissions. Science, 357, 290–294. https://doi.org/10.1126/science.aan5049

de Moor, J. M., Kern, C., Avard, G., Muller, C., Aiuppa, A., Saballos, A., . . . Fischer, T. P. (2017). A new sulfur and carbon degassing inventory for the Southern Central American Volcanic Arc : The importance of accurate time-series datasets and possible tectonic processes responsible for temporal variations in arc-scale volatile

emissions. Geochemistry Geophysics Geosystems, 18, 1–32. https://doi.org/doi: 10.1002/2017GC007141

P2L12 – the observation of gas composition changes HAS BECOME an important tool

P2L18 - . . . characterization of volcanic ACTIVITY IS GAS EMISSION RATE. Particularly, the determination of SO2 FLUX has become. . .

P2L21 - . . . manned AIRCRAFT, . . .

P2L22 - . . .poorly accessible TERRAIN.

P3L13 – crater rim MAY BE ASSOCIATED WITH a considerable . . .

P3L14 – Perhaps be more general and say that gas monitoring stations are deployed in close proximity to active volcanic vents (rather than 'at the crater rim')

P3L25 – please specify that 'DRONE-BASED sampling' has not yet been reported.

P3L27 – Change 'systems' to 'system'.

P4L7 – 'horseshoe-shaped area THAT IS NOT SAFELY ACCESSIBLE ON FOOT'

P4L8 – 'well accessible, and numerous monitoring stations have been installed here for continuous observation of the ongoing volcanic activity'

P4:14 – The UAV was mostly launched at the northern shelter

Figure 1 caption – Overview OF the sampling. . .

P5L9 – the 'DCO-DECADE' and NOVAC acronyms should probably be explained and perhaps a reference can be added where more information can be found on DCO-DECADE?

P6L9 - . . .using PROPELLERS with a diameter. . .

P6L17 . . . areas of dense plume IN WHICH to hover the system. . .

P7L1 – within a radius of a few meters AROUND THE INLET.

P7L2 – please clarify what you mean by ‘which represents homogeneous conditions for a widely spread out plume’. I did not understand this phrase.

Figure 3 caption – (c) interior view OF the . . .

P9L6 . . . foam case AND HAS a total weight of 500 g.

P9L8 – Gas was pumped through the sensors in series.

P9L20 - . . . to ensure that weight requirements WERE MET.

P9L23 – change ‘mixing ration’ to ‘mixing ratio’.

P10L21 – Consider replacing ‘Evaluation’ with ‘Validation’

P13L7 - . . .above ground level OF 1080 m was recorded

P14L4 – These flights covered distances OF between 11 and 419 m from the vent

P14L5 – Consider changing ‘gas masses’ to ‘gas clouds’ or similar to avoid confusion with a measure of weight.

P14L8 – change ‘explosion’ to ‘explosions’

P14L13 – Recommend removing ‘has’

P14L15 – Remove ‘an’ before ordinary

P14L16 - . . . both instruments DID not MEASURE SIMULTANEOUSLY or. . .

P17L4 - . . . bromine SPECIATION in volcanic plumes has been THE subject of. . .

P17L8 - . . . The DATA PRESENTED HERE for the first minute after emission HIGHLIGHT the potential. . .

P17L9 - . . . thus OBTAIN a better understanding. . .

Figure 7 caption – Perhaps include the volcano name (Stromboli) in the caption to clarify the measurement location.

P19L1 – . . . can significantly change THE PLUME'S travel direction. . .

P20L16 – Consider changing 'high-class' to 'more sophisticated'

P20L24 – . . . gain INSIGHTS into . . .

P20L25 - . . . this method COULD yield data from. . .

Supplementary Material – is there a PDF document missing here? There is mention of a PDF containing the wiring diagram of the Black Box unit, but I don't see that here. Please double check on this. Thank you!

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2017-335, 2017.

Printer-friendly version

Discussion paper