Editorial: Remote sensing of volcanic gas emissions from the ground, air, and space

Citation for the original published paper (version of record):
Kern, C., Arellano, S., Campion, R. et al (2023). Editorial: Remote sensing of volcanic gas emissions from the ground, air, and space. Frontiers in Earth Science, 11.
http://dx.doi.org/10.3389/feart.2023.1340395

(article starts on next page)

TYPE Editorial
PUBLISHED 28 November 2023
DOI 10.3389/feart.2023.1340395

OPEN ACCESS

EDITED AND REVIEWED BY
Valerio Acocella,
Roma Tre University, Italy

*CORRESPONDENCE
Christoph Kern,
ckern@usgs.gov

RECEIVED 17 November 2023
ACCEPTED 20 November 2023
PUBLISHED 28 November 2023

CITATION
Kern C, Arellano S, Campion R, Hidalgo S and Kazahaya R (2023), Editorial: Remote sensing of volcanic gas emissions from the ground, air, and space.
Front. Earth Sci. 11:1340395.
doi: 10.3389/feart.2023.1340395

Editorial: Remote sensing of volcanic gas emissions from the ground, air, and space

Christoph Kern[1]*, Santiago Arellano[2], Robin Campion[3], Silvana Hidalgo[4] and Ryunosuke Kazahaya[5]

[1]United States Geological Survey, Volcano Science Center, Vancouver, WA, United States, [2]Department of Space, Earth and Environment, Chalmers University of Technology, Göteborg, Sweden, [3]Universidad Nacional Autónoma de México, México City, Mexico, [4]Instituto Geofísico, Escuela Politécnica Nacional, Quito, Ecuador, [5]Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan

KEYWORDS
volcanic gas emissions, remote sensing, volcanic processes, volcano monitoring, spectroscopy, volcanology

Editorial on the Research Topic
Remote sensing of volcanic gas emissions from the ground, air, and space

When magma rises in volcanic systems, volatile species exsolve from the melt and are outgassed to the atmosphere. The melt composition and temperature, depth at which degassing occurs, extent of gas-water-rock interactions, and volume of ascending magma are all factors that determine the composition and rate of gas emissions at the surface. Interpreted in a petrological framework, gas measurements thus provide information on these fundamental parameters of volcanic systems. Volcanic gases have traditionally been sampled in the field and later analyzed with standard laboratory methods (Giggenbach, 1975; Symonds et al., 1994), but remote sensing measurements are playing an increasingly central role in characterizing emissions and the volcanoes from which they originate. The 17 contributions in this Research Topic summarize the state-of-the-art in volcanic gas remote sensing and identify key areas in which the field could further improve our understanding of global volcanism and its impact on Earth's environment in the next decade.

First introduced approximately 20 years ago as a successor to the popular correlation spectrometer (COSPEC, Moffat and Millan, 1971), miniature differential optical absorption spectrometers (DOAS, Galle et al., 2002; Edmonds et al., 2003) today represent the most established form of ground-based volcanic gas remote sensing. DOAS instruments have been installed at > 50 volcanoes worldwide, many as part of the Network for Observation of Volcanic and Atmospheric Change (NOVAC, Galle et al., 2010; Arellano et al., 2021). These instruments allow for collection and analysis of continuous daytime observations of SO_2 emission rates which have shown to be of great value in characterizing volcanic systems. Gutiérrez et al. review the known record of gas emissions from Santa Ana and San Miguel volcanoes, El Salvador. The DOAS data are supplemented with *in situ* measurements of the volcanic gas composition, resulting in a detailed record of baseline activity to which future measurements can be compared. Kunrat et al. perform a statistical analysis of emission rates leading up to explosive episodes at Sinabung volcano (Indonesia) in 2016–2021. The authors find that SO_2 emissions were usually lower during the 3 days preceding explosions than was typical during periods of quiescence. They attribute this behavior to the blockage of degassing pathways by a solidifying lava dome at the volcano's summit and finally outline a methodology for forecasting explosions based on continuous SO_2 emissions data.

Next to DOAS instruments, SO_2 camera systems have become increasingly widely used to measure volcanic gases from the ground (Mori and Burton, 2006; Bluth et al., 2007; Kern et al., 2010a). Continuous observations from SO_2 cameras installed in the field are becoming increasingly feasible as technology matures and becomes more affordable. Wilkes et al. present the design of a filter-based SO_2 camera which uses Raspberry Pi components to implement an affordable system capable of continuous acquisition and data processing. They demonstrate this system at Kīlauea (Hawai'i, United States) and Láscar (Chile) volcanoes, and show how such instruments could help proliferate continuous SO_2 emission rate observations at volcanoes.

With robust technology now available, Delle Donne et al. installed two SO_2 cameras on opposite sides of Stromboli volcano's active summit, both of which acquired imagery during daytime for a full year (June 2017 to June 2018). The authors find that explosions were more likely during periods of high passive emission rates as magma supply to the shallow system increased, but that ~90% of SO_2 emissions occur passively rather than during explosive events. Layana et al. characterize the evolution of the magmatic-hydrothermal system beneath Lastarria volcano (Chile) from 1998 to 2019 by combining observations from scanning DOAS instruments, SO_2 cameras, and direct sampling campaigns. They find evidence for pressurization of a deep magma chamber and volatiles interacting with a shallow hydrothermal system on their way to the surface.

The recent introduction of a Fabry-Pérot interferometer (FPI) as a dispersive element in place of the simple bandpass filters used in the original design have also allowed the development of cameras with higher sensitivity and selectivity to SO_2 (Kuhn et al., 2014; Fuchs et al., 2021). Nies et al. have now adapted this design to enable high spatio-temporal resolution measurements of BrO for the first time. Using their prototype at Mount Etna, the authors were able to record BrO imagery at ~10s time resolution and, by comparison to imagery from a second FPI camera tuned to SO_2, derive BrO/SO_2 ratios from the data. Kuhn et al. take the FPI technology in a slightly different direction. Instead of collecting spatially resolved imagery, the authors' design focuses on a single viewing direction but achieves a spectral resolution that is 1–3 orders of magnitude superior to grating spectrometers. This allows them to target hitherto inaccessible gas species, for example, achieving a ~20 ppb detection limit for the hydroxyl radical (OH) over an active lava flow at Nyiragongo volcano, Democratic Republic of the Congo.

Passive DOAS and SO_2/BrO camera observations use scattered sunlight as a light source. The required ultraviolet (UV)/visible wavelengths limit the gas species that are observable with these techniques. Fourier transform infrared spectrometers (FTIR, Francis et al., 1998; Oppenheimer et al., 1998), on the other hand, can measure many more species contained in volcanic gases if a source of infrared (IR) radiation is available. Using the lava lake at Masaya volcano (Nicaragua) as a light source, Kazahaya et al. combined FTIR measurements of gases with *in situ* measurements. The authors find that the CO/CO_2 ratio of 10^{-3} agreed with values predicted by high-temperature thermodynamic magma-gas equilibrium models, but that the H_2/H_2O ratio was orders of magnitude lower than expected values. They attribute this discrepancy to ongoing oxidation of H_2 as magmatic gas is mixed with air at high temperature inside Masaya's Santiago crater.

Rather than using hot lava as a source of IR radiation, Stremme et al. aimed a stationary FTIR spectrometer directly at the Sun to make measurements of the plume emitted from Popocatépetl volcano, Mexico, between 2012 and 2016. The authors were able to derive CO_2/HCl ratios as well as CO_2 and HCl emission rates, which averaged 11.4 ± 4.4, (41.2 ± 16.7) kg/s and (30 ± 0.3) kg/s during the measurement period. Taquet et al. later collocated two UV spectrometers with the FTIR instrument to retrieve SO_2 and BrO column densities during 2017–2019. This setup allowed them to measure BrO/HCl for the first time at Popocatépetl. They postulate an upper bound for the Br/Cl ratio of ~1.1×10^{-3} and note an apparent correlation of HCl/SO_2 ratios with lava dome extrusion rates. Smekens et al. explore a novel use of FTIR spectroscopy. Rather than measuring the absorption of IR radiation by gases in the light path, the authors report on experiments seeking to estimate SO_2 and aerosol abundances from measurements of their IR emission.

Remote sensing measurements from satellite platforms provide an opportunity to track degassing at volcanoes in remote locations. Carn et al. apply a suite of satellite instruments to characterize gas and aerosol emissions from the 2021–2022 submarine eruption of Hunga Tonga-Hunga Ha'apai volcano, Tonga. The authors demonstrate how volumetric flow rates can be derived from bi-hourly imagery of gas and aerosol clouds captured by the Earth Polychromatic Imaging Camera (EPIC) aboard the Deep Space Climate Observatory (DSCOVR). The relatively modest SO_2 release of ~0.6–0.7 Tg measured for the entire eruptive episode is ~2 orders of magnitude lower than expected from petrological considerations, a circumstance that the authors hypothesize may be attributed to the rapid reaction of SO_2 with water in the plume.

In another study only made possible by the availability of satellite remote sensing data, Campion and Coppola examine the long-term relationship between volcanic radiative power (VRP) and SO_2 emission rates at volcanoes hosting lava lakes. The authors find that VRP and SO_2 emission rates are anti-correlated at volcanoes with large lava lakes and attribute this observation to the limitation of thermal energy flux through magmatic foams that commonly form in shallow magma reservoirs during the early stages of lava lake formation.

The TROPOMI instrument onboard ESA's Sentinel 5 Precursor satellite has become an extremely valuable resource for the volcanology community, as its ~3.5 × 5 km spatial resolution allows detection of smaller plumes than previously possible (Theys et al., 2019). As the quality and quantity of satellite remote sensing data products continues to increase, the sheer data volume makes manual analysis impossible and advanced algorithms for retrieving gas abundances, plume detection, source identification, and emission rate determination are gaining in importance. Markus et al. test a variety of plume identification algorithms on the operational TROPOMI SO_2 product and identify the DBSCAN multi-class classification algorithms (Ester et al., 1996) as the most promising category for plume classification and segmentation in operational environments. In situations where even greater resolution or sensitivity are needed, airborne Imaging DOAS techniques offer a solution (Louban et al., 2009; General et al., 2014a). Kern and Kelly describe the implementation of an airborne Imaging DOAS system specifically for remote sensing of volcanic emissions and demonstrate its capabilities in an airborne gas survey of volcanoes in Alaska. The authors use the imagery, combined with the results of *in situ* measurements from a suite of on-board trace gas sensors, to characterize background activity at Iliamna Volcano, Mount Douglas, Mount Martin and Mount Mageik.

The general improvement of accuracy and precision of existing techniques is also of high priority, as improved data quality will allow for more detailed studies of volcanic processes. For techniques that use scattered solar radiation as a light source, a large source of error typically stems from uncertainties in radiative transfer, i.e., the path that measured photons have taken between the Sun and an observing instrument (Millan, 1980; Kern et al., 2010b; Galle et al., 2010). Galle et al. present an algorithm for correction of light dilution in DOAS volcanic plume measurements. They model each measured spectrum as the sum of contributions from two different light paths, one passing through the volcanic plume along the line-of-sight of the instrument, and the other passing around the plume. The relative intensity of the two contributions is then retrieved from DOAS analyses in two separate wavelength bands yielding a dilution-corrected SO_2 column density. Uncertainties in radiative transfer also affect satellite measurements. Yamaguchi et al. use TROPOMI data to investigate the time series of SO_2 emission rates from Mount Tokachi (Hokkaido, Japan). The availability of >100 high-quality images from 2019 to 2022 greatly improved emission estimates from this remote volcano. The authors note, however, that increased ground albedos from seasonal snow cover potentially cause overestimations of SO_2 emission rates.

Remote sensing already plays an important role in volcano monitoring and research today. But the contributions in this volume show how technological advances, innovative applications, improved retrieval techniques, and multi-disciplinary studies can be further improved to help answer additional fundamental questions about volcanism and the emission of volatiles to the atmosphere, as well as provide diagnostic information for use by observatories in eruption forecasts.

Author contributions

CK: Conceptualization, Writing–original draft, Writing–review and editing. SA: Conceptualization, Writing–review and editing. RC: Conceptualization, Writing–review and editing. SH: Conceptualization, Writing–review and editing. RK: Conceptualization, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Author Disclaimer

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Arellano, S., Galle, B., Apaza, F., Avard, G., Barrington, C., Bobrowski, N., et al. (2021). Synoptic analysis of a decade of daily measurements of SO_2 emission in the troposphere from volcanoes of the global ground-based network for observation of volcanic and atmospheric Change. *Earth Syst. Sci. Data* 13, 1167–1188. doi:10.5194/essd-13-1167-2021

Bluth, G. J. S., Shannon, J. M., Watson, I. M., Prata, A. J., and Realmuto, V. J. (2007). Development of an ultra-violet digital camera for volcanic SO_2 imaging. *J. Volcanol. Geotherm. Res.* 161, 47–56. doi:10.1016/j.jvolgeores.2006.11.004

Edmonds, M., Herd, R. A., Galle, B., and Oppenheimer, C. M. (2003). Automated, high time-resolution measurements of SO_2 flux at Soufriere Hills Volcano, Montserrat. *Bull. Volcanol.* 65, 578–586. doi:10.1007/s00445-003-0286-x

Ester, M., Kriegel, H.-P., Sander, J., and Xu, X. (1996). A density-based algorithm for discovering clusters in large spatial databases with noise. *Proc. Second Int. Conf. Knowl. Discov. Data Min.*, 226. doi:10.5555/3001460.3001507

Francis, P., Burton, M. R., and Oppenheimer, C. (1998). Remote measurements of volcanic gas compositions by solar occultation spectroscopy. *Nature* 396, 567–570. doi:10.1038/25115

Fuchs, C., Kuhn, J., Bobrowski, N., and Platt, U. (2021). Quantitative imaging of volcanic SO_2 plumes using Fabry-Pérot interferometer correlation spectroscopy. *Atmos. Meas. Tech.* 14, 295–307. doi:10.5194/amt-14-295-2021

Galle, B., Johansson, M., Rivera, C., Zhang, Y., Kihlman, M., Kern, C., et al. (2010). Network for Observation of Volcanic and Atmospheric Change (NOVAC)—a global network for volcanic gas monitoring: Network layout and instrument description. *J. Geophys. Res.* 115, D05304. doi:10.1029/2009JD011823

Galle, B., Oppenheimer, C., Geyer, A., Mcgonigle, A. J. S., Edmonds, M., and Horrocks, L. (2002). A miniaturised ultraviolet spectrometer for remote sensing of SO_2 fluxes: a new tool for volcano surveillance. *J. Volcanol. Geotherm. Res.* 119, 241–254. doi:10.1016/S0377-0273(02)00356-6

General, S., Bobrowski, N., Pöhler, D., Weber, K., Fischer, C., and Platt, U. (2014b). Airborne I-DOAS measurements at Mt. Etna: BrO and OClO evolution in the plume. *J. Volcanol. Geotherm. Res.* 300, 175–186. doi:10.1016/j.jvolgeores.2014.05.012

General, S., Pöhler, D., Sihler, H., Bobrowski, N., Frieß, U., Zielcke, J., et al. (2014a). The Heidelberg Airborne Imaging DOAS Instrument (HAIDI) – a novel Imaging DOAS device for 2-D and 3-D imaging of trace gases and aerosols. *Atmos. Meas. Tech.* 7, 3459–3485. doi:10.5194/amt-7-3459-2014

Giggenbach, W. F. (1975). A simple method for the collection and analysis of volcanic gas samples. *Bull. Volcanol.* 39, 132–145. doi:10.1007/BF02596953

Kern, C., Deutschmann, T., Vogel, L., Wöhrbach, M., Wagner, T., and Platt, U. (2010b). Radiative transfer corrections for accurate spectroscopic measurements of volcanic gas emissions. *Bull. Volcanol.* 72, 233–247. doi:10.1007/s00445-009-0313-7

Kern, C., Kick, F., Lübcke, P., Vogel, L., Wöhrbach, M., and Platt, U. (2010a). Theoretical description of functionality, applications, and limitations of SO_2 cameras for the remote sensing of volcanic plumes. *Atmos. Meas. Tech.* 3, 733–749. doi:10.5194/amt-3-733-2010

Kuhn, J., Bobrowski, N., Lübcke, P., Vogel, L., and Platt, U. (2014). A Fabry-Perot interferometer-based camera for two-dimensional mapping of SO_2 distributions. *Atmos. Meas. Tech.* 7, 3705–3715. doi:10.5194/amt-7-3705-2014

Louban, I., Bobrowski, N., Rouwet, D., Inguaggiato, S., and Platt, U. (2009). Imaging DOAS for volcanological applications. *Bull. Volcanol.* 71, 753–765. doi:10.1007/s00445-008-0262-6

Millan, M. (1980). Remote sensing of air pollutants. A study of some atmospheric scattering effects. *Atmos. Environ.* 14, 1241–1253. doi:10.1016/0004-6981(80)90226-7

Moffat, A. J., and Millan, M. M. (1971). The applications of optical correlation techniques to the remote sensing of SO_2 plumes using sky light. *Atmos. Environ.* 5, 677–690. doi:10.1016/0004-6981(71)90125-9

Mori, T., and Burton, M. (2006). The SO_2 camera: a simple, fast and cheap method for ground-based imaging of SO2 in volcanic plumes. *Geophys Res. Lett.* 33, 1–5. doi:10.1029/2006GL027916

Oppenheimer, C., Francis, P., Burton, M., Maciejewski, A. J. H., and Boardman, L. (1998). Remote measurement of volcanic gases by Fourier transform infrared spectroscopy. *Appl. Phys. B* 67, 505–515. doi:10.1007/s003400050536

Symonds, R. B., Rose, W. I., Bluth, G. J. S., and Gerlach, T. M. (1994). "Volcanic-gas studies: methods, results, and applications," in *Volatiles in magmas*. Editors M. R. Carroll and J. R. Hollaway China, (Mineralogical Society of America), 30, 1–66.

Theys, N., Hedelt, P., De Smedt, I., Lerot, C., Yu, H., Vlietinck, J., et al. (2019). Global monitoring of volcanic SO_2 degassing from space with unprecedented resolution. *Sci. Rep.* 9, 1–10. doi:10.1038/s41598-019-39279-y