Bull Volcanol (2009) 71:747–751
DOI 10.1007/s00445-008-0260-8

RESEARCH ARTICLE

The dual-beam mini-DOAS technique—measurements of volcanic gas emission, plume height and plume speed with a single instrument

Mattias Johansson · Bo Galle · Yan Zhang · Claudia Rivera · Deliang Chen · Klaus Wyser

Received: 10 March 2008 / Accepted: 26 November 2008 / Published online: 20 January 2009

Abstract The largest error in determining volcanic gas fluxes using ground based optical remote sensing instruments is typically the determination of the plume speed, and in the case of fixed scanning instruments also the plume height. We here present a newly developed technique capable of measuring plume height, plume speed and gas flux using one single instrument by simultaneously collecting scattered sunlight in two directions. The angle between the two measurement directions is fixed, removing the need for time consuming in-field calibrations. The plume height and gas flux is measured by traversing the plume and the plume speed is measured by performing a stationary measurement underneath the plume. The instrument was tested in a field campaign in May 2005 at Mt. Etna, Italy, where the measured results are compared to wind fields derived from a meso-scale meteorological model (MM5). The test and comparison show that the instrument is functioning and capable of estimating wind speed at the plume height.

Keywords Volcanic gas · Emission · SO_2 · Wind speed · DOAS · Etna · MM5

Responsible editor: H. Delgado

M. Johansson (✉) · B. Galle · Y. Zhang · C. Rivera
Department of Radio and Space Science,
Chalmers University of Technology,
Gothenburg, Sweden
e-mail: mattias.johansson@chalmers.se

D. Chen
Department of Earth Sciences, Gothenburg University,
Gothenburg, Sweden

K. Wyser
Swedish Metrological and Hydrological Institute,
Norrköping, Sweden

Introduction

In 2001 the first successful measurements of volcanic gas emissions using the mini-DOAS (miniature-Differential Optical Absorption Spectrometer) were performed (Galle et al. 2002a). Since then the technique has been applied to measurements of gas emissions from numerous volcanoes worldwide (e.g. Bobrowski et al. 2003; Edmonds et al. 2003; Galle et al. 2002b; McGonigle et al. 2002; McGonigle et al. 2003). The instrument can be used as a mobile instrument (mobile mini-DOAS) or as a stationary instrument (scanning mini-DOAS).

One of the main sources of error in both mobile and scanning mini-DOAS measurements is the determination of the plume velocity, and for the scanning mini-DOAS measurements also the plume height. Different approaches have been used to obtain the plume speed, e.g. extrapolating the wind speed at ground level to plume height or using balloon sondes launched at airports up to hundreds of kilometres away, often inducing errors of more than 100% in the final flux-estimate. Since a typical stratovolcano constitutes a major obstacle, severely disturbing the wind-field on its leeward side, even a meteorological station located on top of the volcano does not correctly give the plume velocity a few kilometres downwind from the volcano. An alternative approach to this problem is to use temporal or spatial correlation of simultaneous SO_2 column measurements in two or more directions. This approach has previously been demonstrated by McGonigle et al. 2005a using three individual instruments, by Williams-Jones et al. 2005 using two instruments and by McGonigle et al. 2005b using one instrument with sequential measurements.

This paper describes a novel approach, the dual-beam mini-DOAS, which uses a double spectrometer coupled to a single telescope to make simultaneous SO_2 column measurements in two directions. Thus, measurement of flux, plume height and plume speed can be made with a single instrument without the need for elaborate calibration, synchronization or alignment of different systems. The instrument has been successfully used in several field campaigns in Nicaragua, Italy, Spain and Mexico and proven to be robust and field operable.

Experimental

The mini-DOAS instrument

The basic mini-DOAS system consists of a telescope collecting scattered sunlight which is led through an optical quartz fibre to a miniaturized spectrometer (see Galle et al. 2002a). The instrument determines the total number of molecules in a cross section of a gas plume, either by carrying the instrument by car or by foot under the entire extent of the plume or by equipping the instrument with a scanning device and performing scans from a location below the plume (Edmonds et al. 2003). The gas flux is then calculated by multiplying the total number of molecules in the cross section of the plume with the average plume velocity through this cross section.

Dual-beam mini-DOAS

The basic idea behind the dual-beam mini-DOAS instrument is to perform simultaneous SO_2 column measurements in two different viewing directions using one single instrument. This is accomplished with an SD2000 spectrometer (Ocean Optics Inc.) containing two separate spectrometers (280–420 nm, 0.6–0.8 nm resolution) connected to one common AD-converter. It is possible to measure with both spectrometers simultaneously and to read out both spectra at once. The collecting optics of the instrument is a single telescope (Fig. 1) containing a quartz lens (50 mm focal length) and a band pass filter (Hoya U-330). Two fibres, leading light into the spectrometers, are located in the focal plane of the lens and displaced an equal distance from the optical axis, giving two pointing directions with a fixed angular displacement. By using two 800 μm optical quartz fibres with a displacement of 6 mm between the fibres, a FOV for each spectrometer of 0.9° with a fixed separation of 6.9° between the optical axes is obtained.

Field measurements

We have performed a 2 week field campaign at Mt. Etna, Italy in May 2005 aimed at validation of the dual-beam technique. The spectra collected with the dual-beam mini-DOAS instrument have been evaluated for SO_2 in the range 309–324 nm using the cross section measured by Vandaele et al. 1994 and the DOASIS software (DOASIS—Kraus 2005).

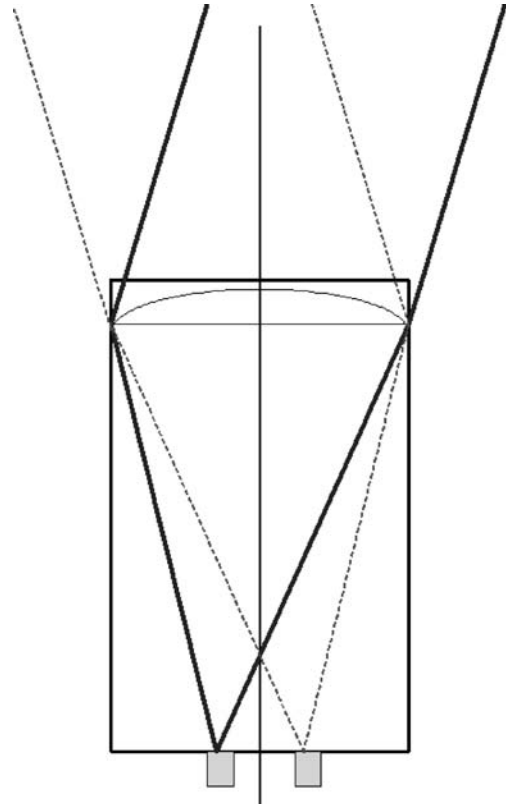

Fig. 1 The telescope of the dual-beam instrument focuses the light onto two fibre endings leading to two spectrometers giving two viewing directions (here shown exaggerated) with one telescope

To validate the wind speed measurements, a nested mesoscale meteorological model MM5, described by Grell et al. 1994, was set up for the region surrounding Mt. Etna to model the local-scale flow given a large scale meteorological analysis from the European Centre for Medium-Range Weather Forecasts (ECMWF). The model had two domains, where the inner covered 120×160 km with a horizontal resolution of 2 km and a vertical resolution of 500 m.

During the campaign, a series of plume height measurements were performed to investigate the consistency of the results. Plume heights can also be indirectly measured by using the fact that the flux from a mobile DOAS traverse is not dependent on the height of the plume whereas the flux from a scanning DOAS measurement is. The plume height can thus be inferred by scaling the scanning DOAS measurements to the same flux as simultaneously performed mobile DOAS measurements. An extensive set of this kind of measurements was performed on the 13th of May 2005 and the inferred plume heights have been compared with the plume heights derived using the dual-beam technique.

Plume height

Plume height can be measured by pointing the telescope vertically and traversing the plume with one viewing direction directly in front of the other (Fig. 2a).

The plume height is calculated by first projecting the measurement on a plane perpendicular to the plume direction. The plume height can then be calculated from the distance between the centres of mass of the two measurement series (X) as; $H = X/\tan(\phi)$. This can be made automatically by shifting one of the measurement series and determine the distance X as the shifted distance for which the correlation between the shifted and non-shifted measurement series peaks.

In these measurements, it is necessary that the sampling rate is high enough to resolve the lag between the two time series. Higher time resolution will result in higher accuracy in determining the delay, but also result in noisier spectra since less light is received by the spectrometers. As a compromise, a time resolution of 1 to 2 s has been used for the measurements presented in this paper.

Plume speed

The plume speed is measured by locating the instrument under the centre of the plume and pointing the telescope vertically with one viewing direction directly upwind of the other (Fig. 3a). Recording the variation in gas column with high time resolution gives two time series of which one is slightly delayed to the other (Fig. 3b). This delay is determined by shifting a sub-window of one of the time series relative to the other, calculating the correlation between the two series and determining the time shift for which the correlation peaks (Williams-Jones et al. 2005). The plume speed is calculated by dividing the distance between the footprints of the two field of views at plume height, given by: $X = H * \tan(\phi)$, with the estimated delay between the two time series. This measurement should be performed in the centre of the plume, where the contrast and importance of knowing the speed is at a maximum. Since plume height is required to estimate the plume speed, it is preferred that at least one plume height measurement is performed before the plume speed measurement. This also gives the centre of mass of the plume, where the plume speed measurement should be performed and, since the measurement traverses the plume, it can also be used to calculate the emission of the source using the retrieved plume speed.

Notice that when using two beams, only the component of the wind vector along the axis of the instrument can be derived and it is therefore necessary to align the instrument with the direction of the wind. If one wishes to derive the full wind vector, the instrument can be equipped with a third spectrometer and a third fibre in the telescope (McGonigle et al. 2005a).

Experimental results

The set of plume height measurements collected during the campaign at Mt. Etna (Fig. 4a) shows that the spread in estimated plume heights over the day is reasonably low. The calculated altitude of the plume is generally below the altitude of the source (3,300 masl), which agrees with what was visually observed during the measurement week—the

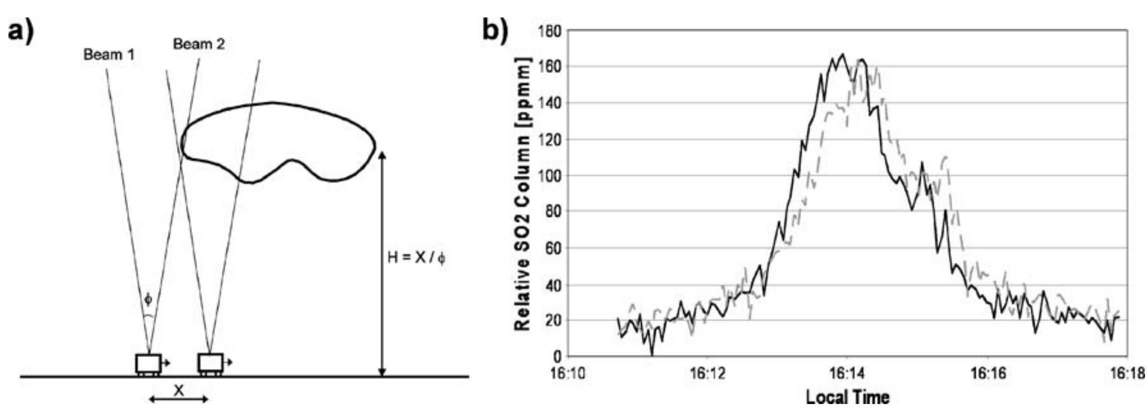

Fig. 2 A plume height measurement is performed by traversing the plume with one beam pointing forwards in the driving direction and the other pointing backwards (**a**). The measurement results in two time series slightly shifted with respect to each other. **b** Example of measurement performed at Mt. Etna on 10th of May 2005, the difference between the centre of mass of the two measurements gives a plume height of 3,037 m above the road of the measurement

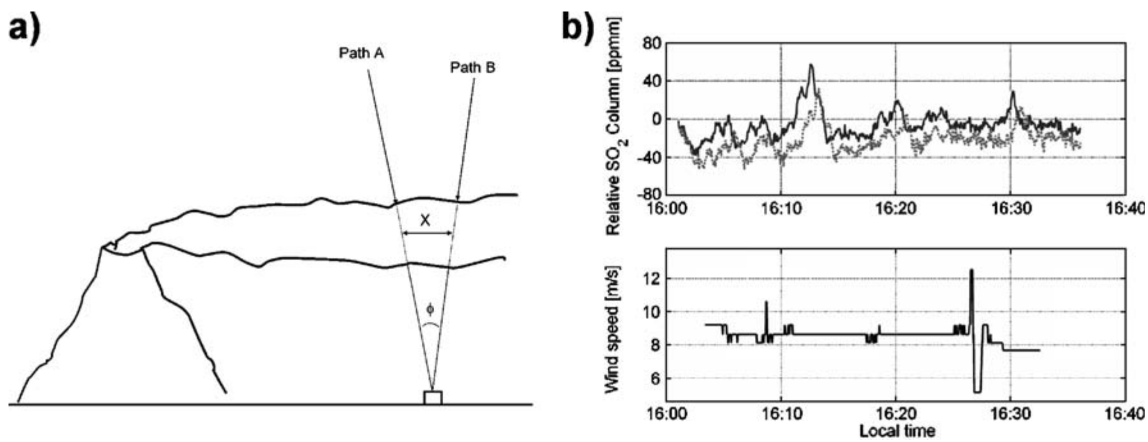

Fig. 3 The plume speed is measured by placing the instrument under the centre of the plume (**a**) with one spectrometer looking further upwind (path A) than the other (path B). **b** Example of a time series measured at Mt. Etna on the 9th of May 2005. The plume speed is calculated using a moving 5 min average and an assumed plume height of 2,700 m above the measurement site. Notice that a small period occurs without major structures at around 16:25 and that the resulting plume speed is not reliable at that time

plume followed the slope of the mountain down some hundred meters before detaching.

A comparison was done between the plume height measurements performed on the 13th of May using the dual-beam technique, and the technique of scaling fluxes from scanning mini-DOAS measurements. The result showed a difference in estimated plume height generally below 20% between the two methods.

The comparison between the modelled wind speeds and the plume speeds measured using the dual-beam technique can be seen in Fig. 4b. The daily averaged measured plume height (Fig. 4a) was used to calculate the plume speed and wind speeds from the model are extracted at the same altitude. Figure 4b also shows the measured wind speed from the daily soundings at the airport in Trapani, the previous source of wind information for the regular flux-measurements of SO_2 at Mt. Etna. The comparison shows a good agreement between the dual-beam measurement and the modelled wind speed with the exception of three measurement points.

At least three factors can influence agreement in the comparison with the model:

1. The plume height varies during the day and the daily average may not represent the plume height at the time of the measurement well. For example on the 11th of May the measured plume heights range from 1,250 to 3,050 m.
2. The instrument might not always be aligned with the wind-direction, causing an under-estimation of the wind speed.
3. The timing of temporal changes in wind during passage of a weather system may not be well simulated in the model. This is most likely the case on the 13th of May when the model shows a much more rapid decline in wind speed than the dual-beam measurements does during the same time.

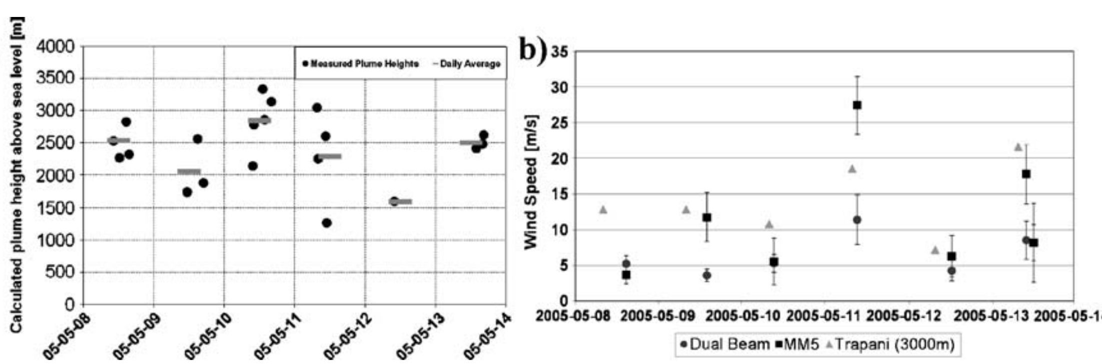

Fig. 4 **a** Plume heights (*circles*) measured at Mt. Etna using the dual-beam technique during 1 week in May 2005, with daily averages shown as *lines*. N.B., there is only one measurement on the 12th of May. **b** Comparison between wind speeds from dual-beam measurements (*circles*), modelled using MM5 (*squares*) and measured sounding data from the airport in Trapani extracted at 3,000 masl (*triangles*). Modelled wind speeds are extracted at the plume height derived from the measurements in (**a**). *Error bars* on the modelled data are the standard deviation of the wind speeds in the 9×9×9 grid points surrounding the extracted data point. The errors in the dual-beam measurement are calculated assuming an uncertainty of 500 m in the plume height

Discussion & conclusion

This paper has presented a method for performing measurements of plume height and plume speed using a single instrument, making the measurements much easier to perform in the field than previously proposed methods. The results from the measurements performed indicate that the plume heights and plume speeds retrieved with the proposed instrument are reliable.

By first making a number of plume height measurements, which also gives the centre of the plume and the total number of molecules in a cross section of the plume, and then making a plume speed measurement it is easy to perform flux measurements with far higher accuracy than today. This measurement series should then be repeated to improve statistics and minimize influence of changing wind directions or puffing of the plume.

References

Bobrowski N, Hönninger G, Platt U, Galle B (2003) Detection of bromine monoxide in a volcanic plume. Nature 423:273–276

Kraus S (2005) DOASIS ver 3.2.2734. Available at: http://www.iup.uni-heidelberg.de/bugtracker/projects/doasis/

Edmonds M, Herd RA, Galle B, Oppenheimer CM (2003) Automated, high time resolution measurements of SO_2 flux at Soufrière Hills Volcano, Montserrat. Bull Volcanol 65:578–586

Galle B, Oppenheimer C, Geyer A, McGonigle AJS, Edmonds M, Horrocks L (2002a) A miniaturised ultraviolet spectrometer for remote sensing of SO_2 fluxes: a new tool for volcano surveillance. J Volcanol Geotherm Res 119:241–254

Galle B, Edmonds M, Geyer A, Herd RA (2002b) A novel spectroscopic system for continuous measurements of volcanic SO_2 emissions with high time resolution. Montagne Pelée 1902–2002, Explosive Volcanism in Subduction Zones, IAVCEI conference, Saint Pierre Martinique

Grell G, Dudhia J, Stauffer D (1994) A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 138 pp [Available from National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000.]

McGonigle AJS, Oppenheimer C, Galle B, Mather TA, Pyle DM (2002) Walking traverse and scanning DOAS measurements of volcanic gas emission rates. Geophys Res Lett 29:46. doi:10.1029/2002GL015827

McGonigle AJS, Oppenheimer C, Hayes AR, Galle B, Edmonds M, Caltabiano T, Salerno G, Burton M, Mather TA (2003) Sulphur dioxide fluxes from Mount Etna, Vulcano, and Stromboli measured with an automated scanning ultraviolet spectrometer. J Geophys Res B Solid Earth Planets 108:2455. doi:10.1029/2002JB002261

McGonigle AJS, Hilton DR, Fischer TP, Oppenheimer C (2005a) Plume velocity determination for volcanic SO_2 flux measurements. Geophys Res Lett 32:L11302. doi:10.1029/2005GL022470

McGonigle AJS, Inguaggiato S, Aiuppa A, Hayes AR, Oppenheimer C (2005b) Accurate measurement of volcanic SO_2 flux: determination of plume transport speed and integrated SO_2 concentration with a single device. Geochem Geophys Geosyst 6:Q02003. doi:10.1029/2004GC000845

Vandaele AC, Simon PC, Guilmot JM, Carleer M, Colin R (1994) SO2 absorption cross-section measurement in the UV using a Fourier-transform spectrometer. J Geophys Res Atmos 99:25599–25605

Williams-Jones G, Horton KA, Elias T, Garbeil H, Mouginis-Mark PJ, Sutton AJ, Harris AJL (2005) Accurately measuring volcanic plume velocity with multiple UV spectrometers. Bull Volcanol 68:328–332