Plume propagation direction determination with SO$_2$ cameras

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Abstract. SO$_2$ cameras are becoming an established tool for measuring sulfur dioxide (SO$_2$) fluxes in volcanic plumes with good precision and high temporal resolution. The primary result of SO$_2$ camera measurements are time series of two-dimensional SO$_2$ column density distributions (i.e. SO$_2$ column density images). However, it is frequently overlooked that, in order to determine the correct SO$_2$ fluxes, not only the SO$_2$ column density, but also the distance between the camera and the volcanic plume, has to be precisely known. This is because cameras only measure angular extents of objects while flux measurements require knowledge of the spatial plume extent. The distance to the plume may vary within the image array (i.e. the field of view of the SO$_2$ camera) since the plume propagation direction (i.e. the wind direction) might not be parallel to the image plane of the SO$_2$ camera. If the wind direction and thus the camera–plume distance are not well known, this error propagates into the determined SO$_2$ fluxes and can cause errors exceeding 50 %. This is a source of error which is independent of the frequently quoted (approximate) compensation of apparently higher SO$_2$ column densities and apparently lower plume propagation velocities at non-perpendicular plume observation angles.

Here, we propose a new method to estimate the propagation direction of the volcanic plume directly from SO$_2$ camera image time series by analysing apparent flux gradients along the image plane. From the plume propagation direction and the known location of the SO$_2$ source (i.e. volcanic vent) and camera position, the camera–plume distance can be determined. Besides being able to determine the plume propagation direction and thus the wind direction in the plume region directly from SO$_2$ camera images, we additionally found that it is possible to detect changes of the propagation direction at a time resolution of the order of minutes. In addition to theoretical studies we applied our method to SO$_2$ flux measurements at Mt Etna and demonstrate that we obtain considerably more precise (up to a factor of 2 error reduction) SO$_2$ fluxes. We conclude that studies on SO$_2$ flux variability become more reliable by excluding the possible influences of propagation direction variations.

1 Introduction

Prediction and monitoring of volcanic events is highly desirable. Besides conventional methods, like seismicity or deformation measurements, continuous monitoring of volcanic gas emissions is a still relatively new method for predicting volcanic eruptions. The four most common changes in volcanic behaviour preceding an eruption are earthquakes, deformation, thermal anomalies and an increase in degassing of the volcano. Moreover, not only can an increase in degassing behaviour be an indicator of an imminent eruption, but so can a change in the composition of the volcano’s degassing (see e.g. Bobrowski et al., 2015).

For short-term as well as long-term monitoring of volcanic degassing behaviour, in situ and remote-sensing techniques have been developed. While in situ techniques, such as alkaline traps and MultiGAS (Noguchi and Kamiya, 1963; Aiuppa et al., 2007) have been successfully applied, remote-sensing techniques have the particular advantage that they can be applied from a safe distance. Remote sensing started with the correlation spectrometer (COSPEC, Moffat and Millan, 1971 and Stoiber et al., 1983) but more recently the differential optical absorption spectroscopy (DOAS) technique (Platt and Stutz, 2008) is applied to volcanoes. Long-term remote-sensing monitoring of the SO$_2$ flux (e.g. by the Network for Observation of Volcanic and Atmospheric Change (NOVAC), Galle et al., 2010) provides insights into the standard behaviour of each individual volcano and deviations.
from the normal activity can be used to predict eruptions. More recently, the SO$_2$ camera (e.g. Mori and Burton, 2006) that can record two dimensional SO$_2$ column density distributions allowed unprecedented insight into chemical and dynamic processes in volcanic plumes.

The SO$_2$ camera is a UV sensitive camera utilizing one or more band-pass interference filters to measure the extinction optical density (OD) of SO$_2$. One of those interference filters has a central transmission wavelength at about 310–315 nm. This filter is used to determine the light extinction mainly due to SO$_2$ and aerosols. The light extinction due to aerosol exhibits a broadband structure when compared to the narrowband structure caused by the light attenuation due to SO$_2$. Therefore, a second filter is applied with a central wavelength of approximately 330 nm, where the SO$_2$ absorption is negligible, but which is close enough to cause only small changes in light extinction by aerosol (Lübcke et al., 2013). From the logarithm of the (suitably normalized) pixel-per-pixel ratio of two images taken through either filter, images of the SO$_2$ OD can be calculated. The SO$_2$ OD in turn is proportional to the SO$_2$ column density along the line of sight.

The propagation velocity of the plume and the distance between the plume and the camera are two important variables used to determine the SO$_2$ flux from volcanoes using imaging data. Usually the apparent propagation velocity (i.e. the angular velocity) of the plume can be derived directly from the camera image series. For that purpose, one correlates two integrated transects of the trace gas slant column density images of the moving plume and determines the time lag between the two signals (McGonigle et al., 2005). One can determine the velocity of the plume from the time lag, the angular distance between the two image columns and the distance of the plume. While this method is simple to implement, it only provides a spatial and temporal mean propagation velocity that neglects, for example, turbulence or propagation velocity variations over the extent of the plume. A more detailed plume velocity determination can be achieved using optical flow algorithms (Kern et al., 2015b). These algorithms determine the displacement of image intensity values for each pixel from one frame to the next frame, thus giving a detailed spatial and temporal plume velocity estimation if the direction of the plume is known.

In any case, an important prerequisite for the determination of absolute trace gas flux values is the precise knowledge of the distance between the plume and observing instrument (usually the SO$_2$ camera).

This distance is usually more difficult to (precisely) determine than it is generally assumed: while the geographic locations of the volcanic gas source (i.e. usually the crater) and the position of the instrument are almost always precisely known, the plume propagation direction (like the plume velocity) is not. It is advantageous to know the propagation direction of the plume to achieve a good estimation of the plume distance. This usually requires additional measurements, which are often hard to make at volcanoes due to the limited infrastructure. This paper is about the possibility of determining the plume propagation direction itself from a time series of SO$_2$ camera images of a volcanic plume.

## 2 Theory

The trace gas flux $\Phi$ is approximated from 2-D imaging data following the equation

$$\Phi = v \cdot \sum_i h_i \cdot S_i.$$  

where $v$ is the propagation velocity of the plume perpendicular to the viewing direction, $h_i$ is a side length of a pixel at the distance of the plume and $S_i$ denotes the SO$_2$ column densities of each respective pixel. The summation of the length of every pixel in the plume transect gives the overall diameter of the plume. The summation over every column density of these pixels gives the column density of the complete transect.

If the volcanic SO$_2$ plume moves within the image plane, the camera captures a scaled image of the field of view (FOV) of the camera image, with a scaling factor that is dependent on the plume distance. Thus, the diameter of the plume and its propagation velocity can be easily calculated once the plume distance is known. In a simplified approach which neglects radiation transport issues (as described e.g. by Kern et al., 2010) the column densities $S_i$ depend linearly on the length of the light path through the plume. For a cylindrically symmetric plume moving parallel to the object plane, the detector pixels at the centre of the plume capture column densities corresponding to the SO$_2$ concentration integrated along the plume diameter, while the detector pixels towards the border of the plume capture the light path along secants of the plume (see Fig. 1). Since the secants are not exactly parallel to the radius this causes an overestimation of the measured SO$_2$ column densities towards the edges of the detector. Furthermore, if the plume is inclined (by the angle $\alpha$, see Fig. 1) with respect to the image plane, deviations in the SO$_2$ flux determination of the plume will occur even in the centre of the image plane. In the following sections different approaches to take the geometry into account during the calculation of SO$_2$ fluxes will be discussed. The angle between the image plane and the tilted plume will be referred to as inclination angle $\alpha$. The inclination of the plume changes all the measured variables in Eq. (1).

### 2.1 Small FOV angle approach

In a first simplified approach for a small FOV angle of a few degrees, the inclination deviations are negligible (below 10% change in SO$_2$ flux at $\alpha$ smaller than 2$^\circ$). Figure 1 shows a schematic sketch of the geometry of the set-up of an inclined plume. The actual plume extent in $x$ direction $x_R$ of a tilted plume imaged with the SO$_2$ camera is longer than the apparent plume extent $x_M$ projected on the image plane. It can be
velocities, the measured column densities depend linearly on the light path length \( x \) through the plume in a first order approximation for homogeneous plumes with an \( \text{SO}_2 \) concentration \( c \) (\( S = c \cdot s \)). Therefore, Eq. (3) can be rewritten as

\[
S_R = S_M \cdot \cos \alpha.
\]  

(4)

In this first assumption (\( \text{FOV} \leq 2^\circ \)) the deviations in the velocity and in the column density would cancel each other out in the flux calculation (see Eq. 1) as already noted by Mori and Burton (2006). Only the apparent plume diameter \( h_M \) (i.e. the vertical extent of the plume in the direction of the \( y \)-axis) would be affected and thus deviate from the true plume diameter \( h_R \), since the actual distance of the plume differs from the assumed distance, which causes a wrong scaling of the plume diameter on the image plane.

\[
h_R = h_M + \frac{1}{2} x_M \cdot \tan \alpha
\]  

(5)

It should be noted that the \( x_R \) and \( s_R \) over- and underestimations nearly cancel each other out for \( \text{SO}_2 \) cameras with a small FOV angle but also for a chosen small FOV angle within the large FOV angle of an \( \text{SO}_2 \) camera. However, the distance of the plume still needs to be known to determine the correct plume diameter and thus also the information about the propagation direction of the plume is a necessary prerequisite even in this approach.

2.1.1 Large FOV angle approach

Usually, \( \text{SO}_2 \) cameras have a relatively large FOV angle \( \gamma \) (typically several 10\(^\circ\), Fig. 2). Therefore, a more realistic approach includes the angular aperture of the FOV in the determination of the variation of the variables in Eq. (1).

For FOV angles of the \( \text{SO}_2 \) camera larger than 2\(^\circ\), the apparent plume extent in \( x \) direction and column densities are affected in a way that is different from the previous approach, when the plume is tilted with respect to the image plane (i.e. at non-zero alpha).

The plume length deviation equation (Eq. 2) changes if the FOV projection is taken into account. Additionally to the deviations \( x_K \) of an orthographic projection (every distance is projected with the same magnification factor, see grey section in plume length \( x_R \) in Fig. 2), the perspective projection leads to an addition of a length \( x'_K \) (see red section in plume length \( x_R \) in Fig. 2) for a plume moving away from the observer (\( \alpha > 0 \)) and subtraction of \( x'_K \) (i.e. \( x'_K \) becoming negative) if the plume moves towards the observer (\( \alpha < 0 \)). The additional length \( x'_K \) can be calculated with the law of sines.

\[
x'_K = \frac{x_M \cdot \tan \alpha}{\sin \gamma} \frac{\sin (90^\circ - \alpha - \gamma)}{\sin (90^\circ - \alpha - \gamma)}
\]  

(6)

\[
x_R = \frac{x_M}{\cos \alpha} \left( 1 + \frac{\sin \gamma \sin \alpha}{\sin (90^\circ - \alpha - \gamma)} \right)
\]  

(9)
The distance of the plume also changes for every FOV angle is not only dependent on the tilt angle \( \alpha \). Additionally, the length of the slant beam through the plume on \( \gamma \) an additional term describes the influence of the FOV angle with \( \cos \alpha \) Equation (9) can be rewritten as Eq. (10). Besides the scaling \( \cos \alpha \) from the small FOV angle approach (see Eq. 2), an additional term describes the influence of the FOV angle \( \gamma \) on \( x_R \).

\[
x_R = \frac{x_M}{\cos \alpha} \left( 1 - \tan (\gamma) \tan (\alpha) \right) \tan (\alpha) \tan (\alpha) \tag{10}
\]

Additionally, the length of the slant beam through the plume is not only dependent on the tilt angle \( \alpha \) but also on the FOV angle \( \gamma \) of the respective pixel following equation

\[
s_R = s_M \cdot \cos \left( \alpha + \frac{\gamma}{2} \right). \tag{11}
\]

The distance of the plume also changes for every FOV angle in dependence of the inclination of the plume.

\[
d_R = \frac{r}{\tan (\frac{\gamma}{2})} = \tan \alpha \cdot r + d_M \tag{12}
\]

\[
r = \tan \left( \frac{\gamma}{2} \right) \tan \alpha \cdot r + \tan \left( \frac{\gamma}{2} \right) \cdot d_M \tag{13}
\]

\[
r \cdot \left( 1 - \tan \left( \frac{\gamma}{2} \right) \tan \alpha \right) = \tan \left( \frac{\gamma}{2} \right) \cdot d_M \tag{14}
\]

\[
r = \frac{\tan \left( \frac{\gamma}{2} \right) \cdot d_M}{1 - \tan \left( \frac{\gamma}{2} \right) \tan \alpha} \tag{15}
\]

\[
d_R = \frac{\tan \left( \frac{\gamma}{2} \right) \cdot d_M}{\tan \left( \frac{\gamma}{2} \right) \cdot (1 - \tan \left( \frac{\gamma}{2} \right) \tan \alpha)} \tag{16}
\]

\[
d_R = \frac{d_M}{1 - \tan \left( \frac{\gamma}{2} \right) \tan \alpha} \tag{17}
\]

Figure 3 shows the deviations of the tilt-corrected values of the variables (with index \( R \)) from the measured values of the variables (indicated by the index \( M \)) as a function of the inclination angle \( \alpha \). The distance of the plume in the midst of the FOV is known but since the direction of the plume is not known, the distances in other positions of the image are also not known. The camera’s FOV angle is chosen as 24° which is in the range of commonly used SO\(_2\) camera FOV today (Kern et al., 2015a). The graphs show the deviations for half of the image plane from its centre to an angle \( \gamma/2 \) of 12° where half of the image plane is assumed to be a single detector pixel. An orthographic projection (produced by a telecentric optical set-up; e.g. Jähne, 2005) leads to the blue lines in Fig. 3. Its characteristic is that an object is projected to the same size independent of its distance to the camera. The red lines in Fig. 3 represent the deviations due to a perspective projection that is used in SO\(_2\) camera measurement set-ups. The projected size of an object is dependent on the distance for a perspective projection. Figure 4 shows the combined deviations that would influence the flux determination.

These calculations cover half of the actual FOV angle of the camera. If the plume is inclined with the angle \( \alpha \) towards the image plane, it is tilted by a negative angle \(-\alpha\) for the respective other half of the FOV. Therefore the over- and underestimations of the actual SO\(_2\) flux differ on both sides of the field of view.

Usually the SO\(_2\) camera detectors consist of several hundred pixels. Equation (18) represents the deviations in the plume length and therefore in the plume propagation velocity if the FOV angle is divided in a finite absolute number of pixels \( p \) for every pixel \( i \) in \( p \).

\[
s_R (i, x_M) = \frac{x_M}{\cos \alpha} \left[ 1 + \frac{i^2}{p} \tan \gamma \tan \alpha \right]
\]

\[
- \left( \frac{i - 1}{p} \right)^2 \left[ \tan \gamma \tan \alpha \right] \tag{18}
\]

Equation (19) represents the deviations in the measured column densities if the FOV angle is divided in a finite absolute number of pixels \( p \) for every pixel \( i \) in \( p \).

\[
s_R (i, s_M) = s_M \cdot \cos \left( \alpha + \tan^{-1} \left( \frac{i - 1}{p} \tan \gamma \right) \right)
\]
Figure 3. Mean deviations of the plume extent in the $x$ direction ($x_R$), plume distance ($d_M$) and column density ($s_R$), used in the flux determination for the right half of the image plane of an SO$_2$ camera with an FOV angle of 24° (for the left half of the detector the inclination deviations would be vice versa). The blue lines show the ratio between the ground truth (i.e. the geometric accurate) variables and the measured variables for a telecentric (an orthographic projection where the apparent size does not depend on the distance) approach. The red lines show the same ratio for a perspective approach.

Equation (19) represents the deviations in the measured distance for every pixel $i$ for a tilted plume.

$$d_R (i, d_M) = \frac{d_M}{1 - \alpha \tan \gamma \left[ \frac{1}{p} \tan \gamma - \frac{1}{2} \cdot \tan^{-1} \left( \frac{1}{p} \tan \gamma \right) \right]}$$

Equations (18), (19) and (20) are defined for the case that the best known distance between the observer and the plume is in the centre of the FOV. If the best known distance is not in the centre of the FOV, the equations can be adjusted since the distance correction $d_R$ and the inclination velocity correction $x_R$ change (see also Fig. 7).

With $n$ as the number of pixels, the known position is shifted to the side of the FOV, we can derive the new distance of the centre of the FOV as

$$d_M' = d_M + d_P$$

$$d_P = n \cdot x_M \cdot \tan \alpha = \frac{n}{p} \cdot d_M \cdot \tan \gamma \tan \alpha$$

$$d_M' = d_M \cdot \left( 1 + \frac{n}{p} \tan \alpha \tan \gamma \right).$$

Figure 4. Combined deviations of the three variables of the flux determination for the right half of the image of an SO$_2$ camera with an FOV angle of 24°.

Figure 5 shows the deviation in each measurement variable separately for an SO$_2$ camera, again with a typical FOV of 24°, while Fig. 6 shows the combined deviation of the flux measurement due to the perspective influence on the three variables. For an SO$_2$ camera with a typical FOV of 24° the deviations in the ratio $x_M$ easily exceed 50% at plume direction tilts of $> 30°$. As a consequence, the SO$_2$ flux deviation already exceeds 10% in parts of the SO$_2$ camera images for a plume tilt angle larger than 15°.

If we want to determine the plume propagation direction, we can measure the SO$_2$ flux for a given distance at different positions of the plume. If the apparent SO$_2$ flux is the same at different positions in the plume, the plume lies within the image plane. Otherwise we observe an apparent gradient in the measured flux across the image, which, however, contains information on the plume propagation direction. Dividing the measured fluxes by the respective deviations for the investigated pixel columns for every possible tilt angle $\alpha$ and minimizing the observed gradient yields the information about the mean plume propagation direction during the time period needed for the parcel to move across the field of view. The assumption that the SO$_2$ flux is conserved can be made since the mean lifetime of SO$_2$ in the troposphere is usually of the order of several days (e.g. Eisinger and Burrows, 1998) while the typical time for the plume to cross the field of view of the camera is of the order of a few minutes. Note that the SO$_2$ flux originating from the volcano should vary for our method to work. The second necessary prerequisite is that the advective transport is larger than the turbulent transport of the plume parcel. Kern (2009) showed that usually the turbulent transport only contributes to about 0.2% of the gas transport in the plume.
Figure 5. Ratio of the real variables to the measured variables of the velocity (upper panel), plume distance or diameter (middle panel) and column densities (lower panel) for an SO\(_2\) camera with an FOV angle of 24°. The relative deviations of distance are the same as for the diameter (\(\frac{d_R}{d_M} = \frac{d_R}{d_M}\)). Relative deviations larger than 0.5 from the measured data are shaded white.

Accordingly the new measured lengths of the pixels \(x'_M\) can be calculated as

\[
x'_M = x_M \cdot \left(1 + \frac{n \tan \alpha \tan \gamma}{P}\right).
\] (24)

3 Application

We used the considerations developed in Sect. 2 (together with the usually well-justified assumption of a constant SO\(_2\) flux) to design an algorithm which allows us to determine the wind direction directly from SO\(_2\) camera plume images without the need for further data or assumptions. The new algorithm has been applied to an SO\(_2\) camera measurement data set taken at Mt Etna, Sicily on 9 July 2014. Not only the possibility of the inclination angle estimation, but also the possibility of observation of a wind direction change, was investigated. Figure 8 shows the geometry of the data set.

3.1 Plume propagation direction determination

Figure 9 shows the SO\(_2\) fluxes at three different positions in the FOV of the SO\(_2\) camera for a measurement data set taken at Mt Etna. The upper panel shows the SO\(_2\) flux for each of these positions not corrected for inclination. The lower panel shows the fluxes corrected for the inclination. During the measurement campaign, in addition to the SO\(_2\) camera measurements, measurements were taken by a car-based DOAS instrument pointing to the zenith and traversing the plume (see e.g. McGonigle et al., 2002; Galle et al., 2003). The centre of the plume can be found by evaluating the SO\(_2\) column density and determining the location with the maximum values. Thus, the wind direction could be estimated, giving an inclination of the plume of about 38°. This information was then used to verify the applicability of the developed algorithm to the SO\(_2\) camera data sets. Figure 10 shows the fluxes at seven different positions in the camera image from the data set taken at Etna on 9 July 2014. The SO\(_2\) flux was calculated assuming different plume inclination angles. Figure 10 shows that the SO\(_2\) fluxes are nearly the same if the plume is tilted about 40° in the backward direction with an uncertainty of ±5°. This result agrees with the result from the traverse measurements within a margin of ±2°.
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3.2 Real-time tracking of changes in the wind direction

If there are changes in the propagation direction of the plume during SO$_2$ camera measurements, it is possible to detect these changes on timescale of minutes. Figure 11 shows a change in the ratio between the apparent SO$_2$ flux determined in two different positions of the plume within the FOV of the camera. During 2 h of measurements between 11:32 and 13:23 UTC, on 9 July 2014, the wind direction was stable for about 1 h (A). For this period the ratio between the two flux measurement positions was mostly constant, except for slight fluctuations. Then the inclination angle changed by about $20^\circ$, which we attribute to a change of the wind direction (B). In this phase of the observation the ratio between the two flux measurements is decreasing. Later, the new wind direction stabilizes in (C), with a new constant ratio between the two flux measurements. The SO$_2$ plume also exhibits a slight contribution due to turbulent transport. The turbulent transport usually contributes less than 0.2% to the propagation of the plume (Kern, 2009).
4 Conclusions

We showed that an inclined plume causes apparent spatial flux gradients in the SO$_2$ camera measurement images. The frequently implicitly (e.g. Smekens et al., 2015) or explicitly (e.g. Mori and Burton, 2006) assumed compensation effect only occurs at very small inclination angles (< 15°) or small FOV (< 2°). For an SO$_2$ camera with an FOV angle of 24° a tilt angle of 15° already causes flux deviations larger than 10% in parts of the SO$_2$ camera’s images for evaluations relying on the compensation effect. However, these gradients are unambiguous for every possible inclination angle of the volcanic plume with respect to the image plane of the SO$_2$ camera. Therefore, they can not only be corrected but can also be used to determine the direction of the plume (i.e. the wind direction at the location of the plume). On longer timescales that exceed the travel time of the plume parcel across the FOV (several minutes), even the change in the mean wind direction can be observed. On the other hand, if these errors in plume inclination are ignored they can give rise to erroneous observations of fluxes, in particular fake flux changes with plume age or over time can occur. If these changes in flux are attributed to chemical processes in plumes (e.g. SO$_2$ oxidation) or of volcanic degassing patterns, the wrong conclusions with respect to chemical processes in volcanic plumes or wrong interpretation on degassing behaviour may be drawn.

While the proposed algorithm is applicable to straight and bent plumes (i.e. plumes where the wind direction changes within the field of view), so far the combined effects of this study and radiative transfer issues have not yet been addressed. Additionally, if several plumes are masking each other, the proposed algorithm may not work.

Recent improvements in the velocity determination of volcanic plumes using image processing methods like optical flow algorithms can be combined with the proposed perspective correction method for a robust SO$_2$ flux determination.

5 Data availability

The raw measurement data (spectra and images, more than 1 GB in size) of the SO$_2$ camera can be obtained on request from the authors.

Competing interests. The authors declare that they have no conflict of interest.

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