Pyplis* | A Python based software package for the analysis of volcanic SO2 emissions using UV SO2 cameras

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Main Features

- △ Easy setup of various data formats and camera specifications
- △ Detailed 3D **geometrical calculations**
- △ Routine for image based **correction of the signal dilution effect**
- △ Flexible options for **retrieval of plume background intensities**
- △ Engines for automised **cell and DOAS calibration**
- △ Optical flow and cross correlation based **plume velocity retrievals**
- △ Simultaneous **emission rate retrievals** for multiple retrieval lines

* due to a naming conflict, the software was renamed from ***piscope*** to ***pyplis***

Background

UV SO2 cameras have become a common tool for monitoring SO2 emission rates from volcanoes. The latter are inferred based on plume optical densities measured in two UV wavelength windows around 310 nm (distinct SO2 absorption, ``**on**-band´´) and 330 nm (weak SO2 absorption, ``**off**-band´´). The data analysis comprises geometrical calculations, the retrieval of plume background intensities and the camera calibration as well as the retrieval of gas velocities within the plume. Emission rates are then retrieved by integrating a projected plume cross section (PCS, e.g. a straight line crossing the plume).

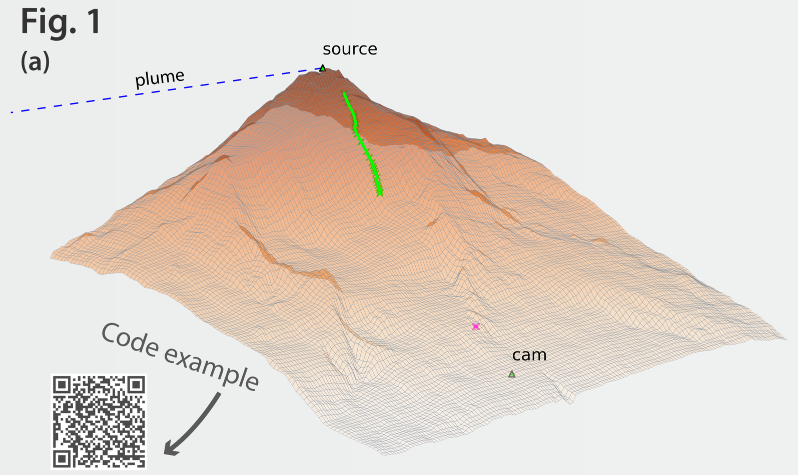
Pyplis is a cross platform, open source software toolbox for the analysis of UV SO2 camera data written in Python. The software comprises a comprehensive selection of algorithms based on the most commonly used analysis methods, and furthermore, including recent developments and newly developed methods.

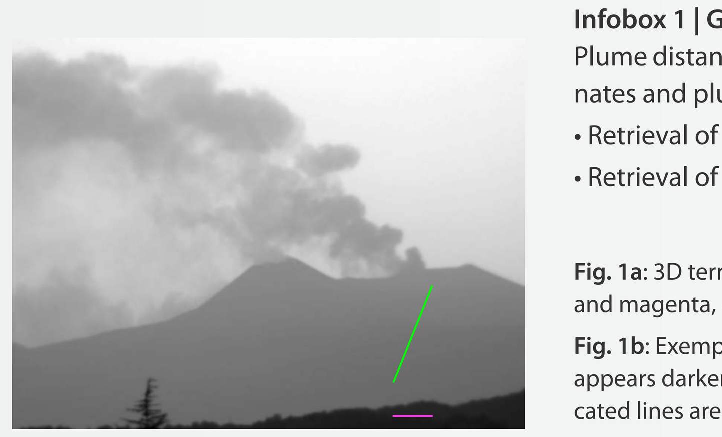
Here, we present the main features of Pyplis using an exemplary dataset recorded at Mt. Etna, Italy, on 16 September 2015. Pyplis is freely available and can be downloaded from the website together with an extensive collection of example scripts, providing an easy start into Pyplis. The Etna example data is freely accessible on the website.

△1 Measurement geometry and signal dilution correction

Code example

Fig. 1





Infobox 1 | Geometrical calculations

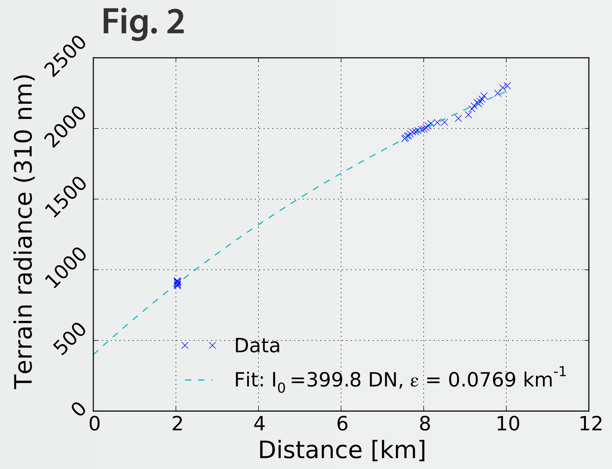
Plume distances (required for emission rate retrieval) are retrieved on a pixel-level based on camera coordinates and plume azimuth. **More features include**:

- Retrieval of camera viewing direction using distinct features in the images (e.g. volcano summit)
- Retrieval of distances to local terrain features in the images on pixel-level (see Fig. 1)

Fig. 1a: 3D terrain map of the measurement setup including 2 topographic profile lines (green and magenta, defined in the image, cf. Fig. 1b) used for the signal dilution analysis (Fig. 2)

Fig. 1b: Exemplary on-band (310 nm) image. Due to SO2 absorption the Etna plume appears darker than the sky background. Measured intensities along the two indicated lines are used to estimate the scattering extinction (cf. Fig. 2).

Fig. 2



Equation 1 | Atmospheric scattering model

$$I_{\mathrm{meas}}(\lambda) = I_0(\lambda)e^{-\epsilon(\lambda)d} + I_A(\lambda)\left(1 - e^{-\epsilon(\lambda)d}\right)$$

- $I_{\mathrm{meas}}(\lambda)$: measured intensity of terrain feature
- $I_0(\lambda)$: initial intensity of terrain feature
- d : distance to terrain feature
- $I_A(\lambda)$: average ambient intensity
- $\epsilon(\lambda)$: scattering extinction coefficient

Fig. 2: Retrieval of extinction coefficients
Exemplary dilution analysis (cf. Infobox 2) using the two topographic lines shown in Fig. 1, resulting in an on-band extinction coefficient of $\epsilon_{310} = 0.0769$ km^{-1}.

Infobox 2 | Image based correction for the signal dilution effect

Distant terrain features appear brighter (cf. lines in Fig. 1b). This is due to atmospheric scattering and can result in significant underestimations in the emission rates. A first order correction for this so called signal dilution effect can be performed using local terrain features in the images located at different distances [1]. The method yields atmospheric scattering extinction coefficients (Fig. 2) using an approximative scattering model (Eq. 1) and brightness values measured along suitable terrain features in the images (cf. Fig. 1). The required distances to these features can be retrieved automatically in Pyplis (cf. Infobox 1, Fig. 1).

△2 Plume background analysis

Code example

Equation 2 | Optical density (OD)

$$\tau = \ln\left(\frac{I_0}{I}\right)$$

- I : measured plume intensity
- I_0 : corresponding background intensity

Equation 3 | SO2 apparent absorbance (AA)

$$\tau_{\mathrm{AA}} = \tau_{\mathrm{on}} - \tau_{\mathrm{off}}$$

Infobox 3 | Calculation of optical density (OD) images

The calculation of OD images (Eq. 2) requires knowlegde of the sky background intensities behind the plume. These can either be retrieved from the plume images directly (by fitting a 2D polynomial to clear sky areas, cf. Fig. 3a) or using a sky reference image which is scaled using a gas free sky area in the plume image (cf. *scale_rect* in Fig. 3). The latter may include further corrections to account for variations in the sky background curvature between the two images (cf. Fig 3b).

Fig. 3

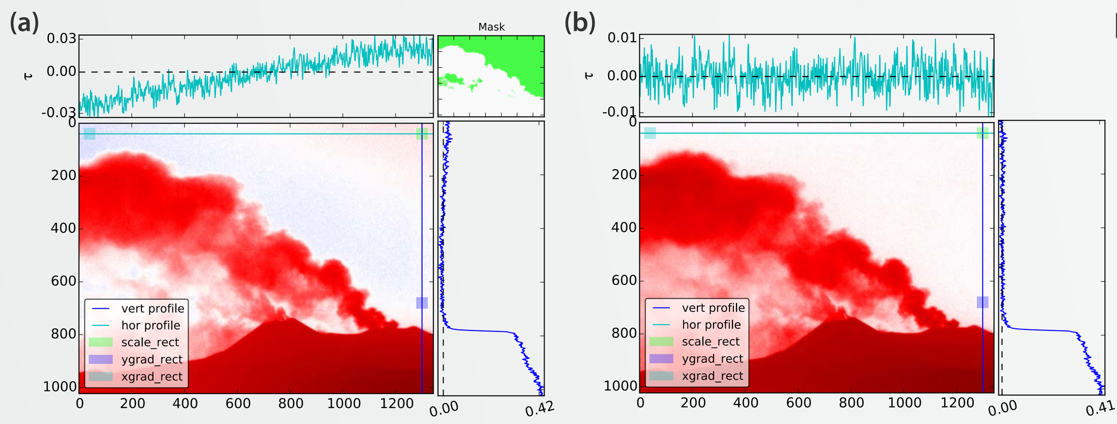


Fig. 3: Exemplary optical density images
Two exemplary on-band OD images calculated using a masked 2D polynomial fit (a) and using an additional sky background image (b), including 2. order horizontal and vertical sky gradient corrections along the indicated vertical and horizontal profile lines.

△3 Camera calibration

Equation 4 | SO2 column density

$$S_{\mathrm{SO_2}} = \int_{\mathcal{C}} c_{\mathrm{SO_2}}(x,y,z)\,ds$$

- $S_{\mathrm{SO_2}}$: $\mathrm{SO_2}$ − column density (CD)
- $\mathcal{C}$: photon trajectory
- $c_{\mathrm{SO_2}}$: $\mathrm{SO_2}$ concentration distribution

Infobox 4 | Cell calibration

The camera calibration (conversion of ODs into SO2-CDs (see Eq. 4) can be performed by consecutively placing a number of SO2 gas cells in front of the camera while pointing into a clear sky area. The calibration curve (cf. Fig. 5) is retrieved from cell AA images and the corresponding (known) SO2-CDs of the cells.

Fig. 4

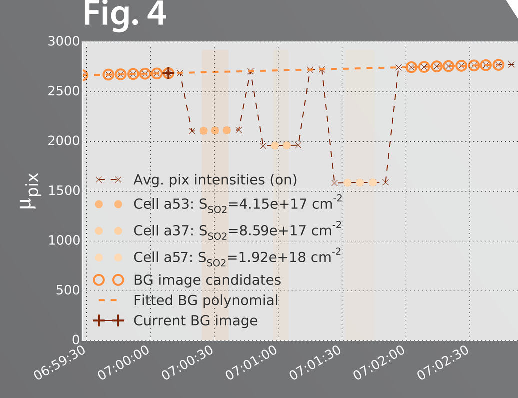


Fig. 4: Automatic cell search algorithm
Time series of average pixel intensities from on-band images (dashed line) including automatically detected time windows of individual cells based on a gradient analysis of the signal.

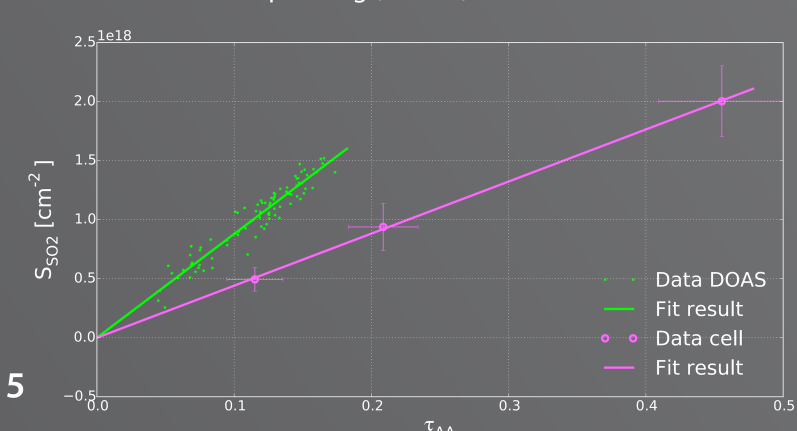


Fig. 5

Fig. 5 (left): Cell and DOAS calibration curves
Exemplary AA cell (magenta) and DOAS calibration data (green) including fitted polynomials.

Fig. 6

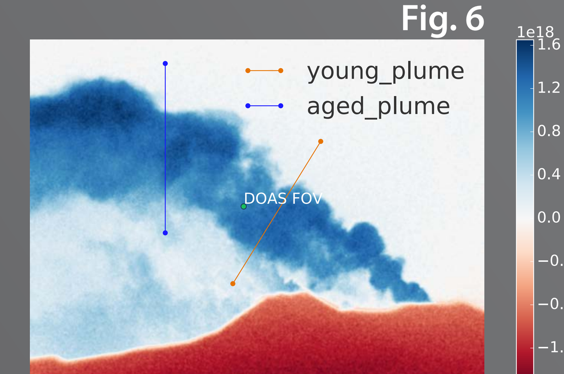


Fig. 6: Calibrated SO2 CD image
Figure showing a calibrated SO2-CD image including two exemplary PCS lines and the position of the DOAS FOV.

Watch video

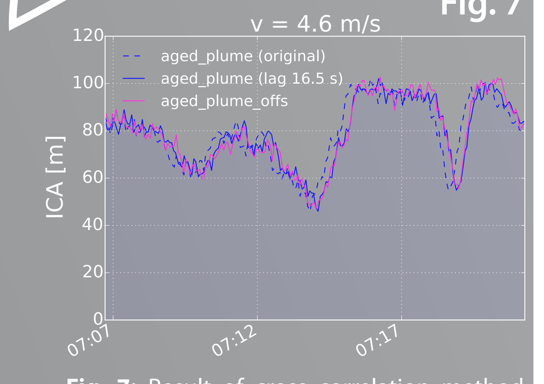
Code example

Infobox 5 | DOAS calibration

The DOAS calibration is performed using plume SO2-CDs retrieved with a co-located DOAS spectrometer. Position and shape of the DOAS FOV within the camera images (cf. Fig. 6) can be retrieved using either of the two methods suggested by [2] and [3]. Both methods identify the pixel region showing highest correlation between a time series of DOAS SO2-CDs and camera images. The calibration curve (Fig. 5) is then retrieved from a time series of AA values (extracted within the DOAS FOV) and the corresponding DOAS SO2-CDs. The DOAS calibration is more accurate in case aerosols are abundant in the plume [2].

△4 Gas velocities

Fig. 7



Infobox 6 | Cross correlation

The plume velocity is retrieved from a time-series of images based on the cross correlation lag between the integrated-column-amount (ICA) of two plume intersections (e.g. [4], cf. Fig. 7).

Fig. 7: Result of cross correlation method showing ICA time-series of the blue and magenta lines indicated in Fig. 8 (below).

Infobox 7 | Optical flow

Optical flow (OF) algorithms detect motion in consecutive frames allowing for the retrieval of gas velocities on pixel-level (e.g. [5]). An estimate of the gas velocity within low contrast image regions (where the OF algorithm fails to detect motion) can be inferred based on distinct peaks in histograms calculated from the optical flow field (Fig. 8). Pyplis includes an implementation of the Farnebäck optical flow algorithm [6].

Fig. 8

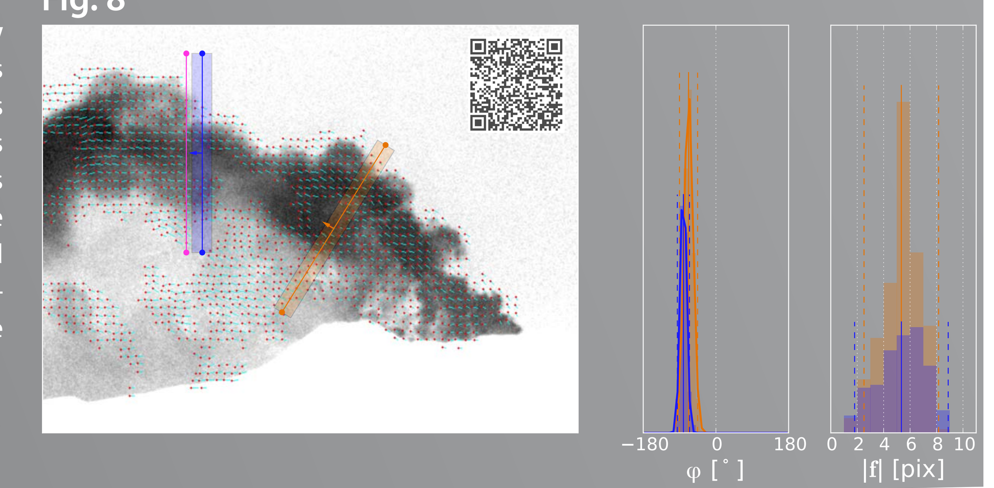


Fig. 8: Exemplary Farnebäck optical flow field (left) including histograms of the flow vector orientation angles (middle) and magnitudes (right) for two different ROIs and the indicated PCS lines (blue, orange).

△5 SO2 emission rate retrieval

Code example

Watch video

Equation 5 | Emission rate integral

$$\Phi(\boldsymbol{\ell}) = f^{-1}\sum_{m=1}^{M} S_{\mathrm{SO2}}(m)\cdot\langle\boldsymbol{v}(m)\cdot\hat{\boldsymbol{n}}\rangle\cdot d_{\mathrm{pl}}(m)\cdot\Delta s(m)$$

- $\Phi(\boldsymbol{\ell})$: emission rate through PCS line $\boldsymbol{\ell}$
- f : camera focal length
- $S_{\mathrm{SO2}}(m)$: $\mathrm{SO_2}$ − CD at pixel pos. m on $\boldsymbol{\ell}$
- $\boldsymbol{v}(m)$: gas velocity vector at pixel pos. m on $\boldsymbol{\ell}$
- $\hat{\boldsymbol{n}}$: normal vector of $\boldsymbol{\ell}$
- $d_{\mathrm{pl}}(m)$: plume distance at pixel pos. m on $\boldsymbol{\ell}$
- $\Delta s(m)$: discrete integration step at pixel pos. m on $\boldsymbol{\ell}$

Infobox 8 | SO2 emission rate analysis

Emission rates are retrieved from calibrated SO2-CD images using Eq. 5. The integration can be performed along linear plume intersections (see e.g. Fig. 6). Plume distances are calculated from the measurement geometry (see Infobox 1). Gas velocities can either be retrieved using an optical flow algorithm or using signal cross correlation (cf. Infoboxes 6 & 7).

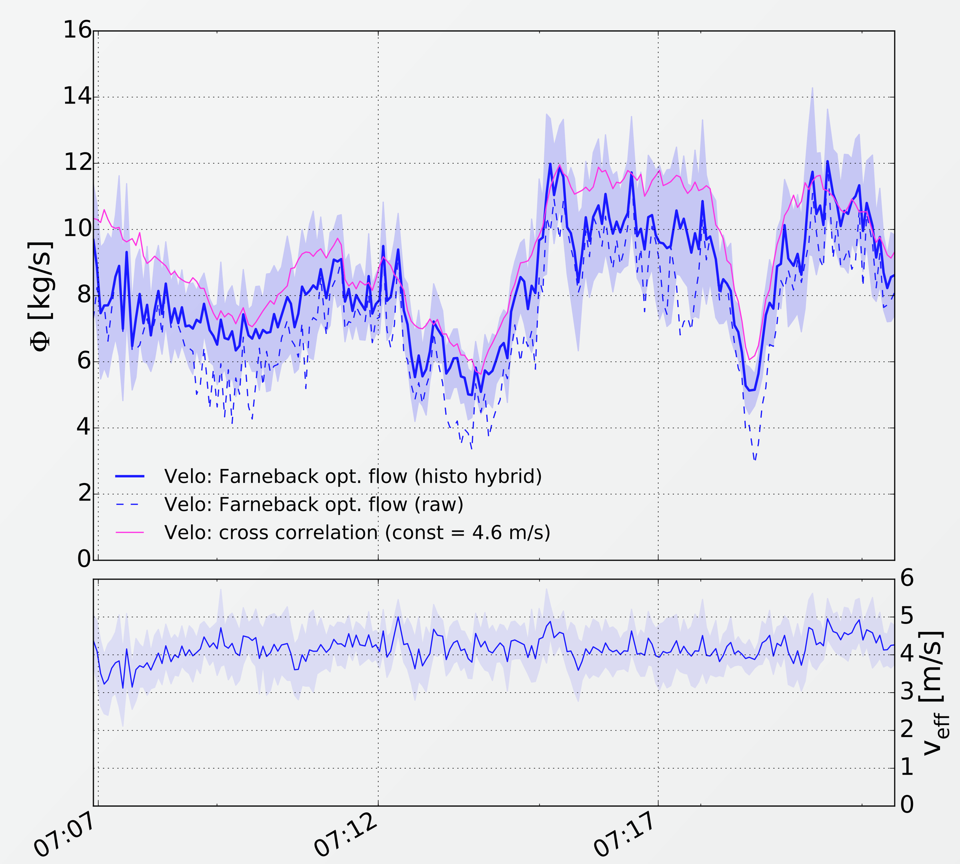


Fig. 9: Etna emission rates
Time series of Etna emission rates (top) and effective gas velocities (from optical flow analysis) for the blue retrieval line shown in Figs. 6 & 8 (aged plume). The emission rates were calculated from dilution corrected SO2-CD images using 1. velocities retrieved from the cross correlation analysis (magenta), 2. the optical flow raw output (blue dashed) and 3. the optical flow data including a histogram based correction within low contrast image regions (cf. Infobox 7, Fig. 8).

△ Links and Downloads

Website: http://pyplis.readthedocs.io/en/latest/index.html
Source code (Github): https://github.com/jgliss/pyplis
PyPi: https://pypi.python.org/pypi/pyplis

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△ References

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