# Estimates of fumarolic $SO_2$ fluxes from Putana volcano, Chile, using an ultraviolet imaging camera

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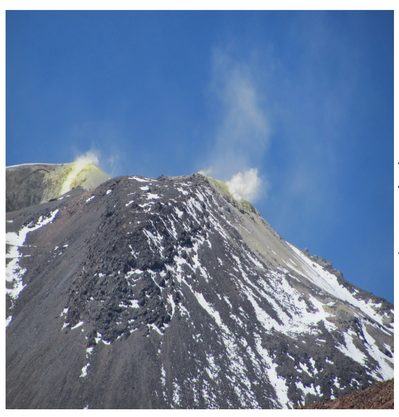
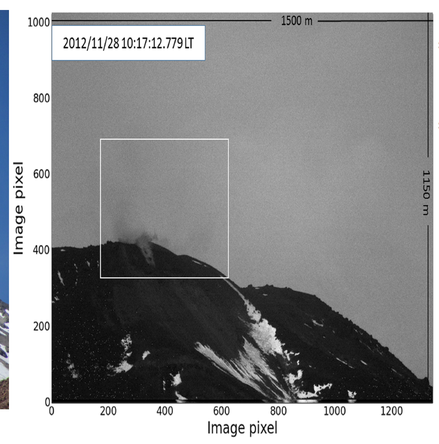
**Abstract** **Fumarolic activiy has been visible at the summit crater of Putana, Central Andes/Chile from long distances since the early 1800ś. On November 28, 2012 an ultraviolet (UV) imaging camera was transported to Putana and for about 30 minutes images of the fumaroles were recorded at high speed (12 Hz). These observations provide the first measurements of $SO_2$ fluxes from the fumarolic field of Putana and demonstrate the applicability of the UV camera to detect such emissions. The measurement series was used to assess whether the sampling rate of the data influences the estimate of the gas flux. The results suggest that measurements made at 10 s and 1 minute intervals capture the inherent (turbulent) variability in both the plume/wind speed and $SO_2$ flux. Relatively high $SO_2$ fluxes varying between 0.3 kg $s^{-1}$ and 1.4 kg $s^{-1}$, which translates to 26 t/d and 121 t/d assuming constant degassing throughout the day, were observed on November 28, 2012. Furthermore, we demonstrates how an optical flow algorithm can be integrated with the $SO_2$ retrieval to calculate $SO_2$ fluxes at pixel level.**

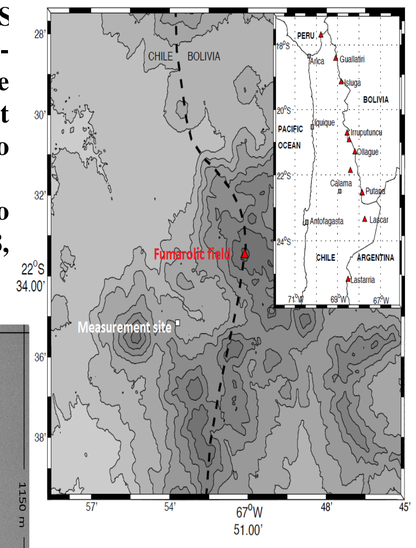
## Putana volcano

**Putana is a stratovolcano in the central Andes volcanic zone in northern Chile on the border with Bolivia (22°33'S 67°51'W) with a peak altitude of 5890 m. The map below shows the location of Putana volcano. The fumarolic field (red triangle) lies inside the main vent along the Chilean-Bolivia border, and the measurement site (white square) is located circa 6 km south-west from the volcano summit.**

**A photo of the solfatara (fumaroles) at the summit of Putana volcano and a raw image of fumaroles taken at 10:17 LT on November 28, 2012. The box indicates the sub-region used for the analysis.**



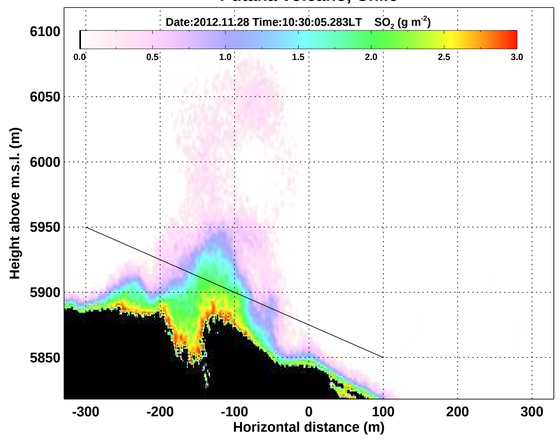



## $SO_2$ camera

**The UV camera (frequently called $SO_2$ camera) is in this work based on an uncooled Hamamatsu C8484 UV camera with high quantum efficiency in the UV from 280 nm onward (>30% at 300 nm). The camera is fast sampling (12 Hz) and has a custom-made four-position filterwheel equipped with two 10 nm wide filters centered at 310 nm and 325 nm, a UV broadband view and a blackened plate for automated dark-current measurement. The main specifications of this system, called Envicam-2, are given in the Table below**

| | |
|---|---|
| Optics | 25 mm UV lens F/2.8 |
| Image size | 1344 x 1024 pixels |
| Chip size | 4.65 µm |
| Total field-of-view | 14.3° x 10.9° |
| Filter 1 | 310 nm |
| Filter 2 | 325 nm |
| Filter 3 | empty |
| Filter 4 | dark |
| Sampling rate | 12 Hz [35.7 Hz 4x4 binning] |
| Exposure setting | 1 $\mu$s – 1 s |
| Detector | Hamamatsu C8484-16C |
| Digitization | 12 bits |




## $SO_2$ fluxes

**From UV camera measurements the $SO_2$ flux $s_e$ can be calculated as $s_e = wv_p$ with $w = \int_{z_1}^{z_0} \rho_{SO_2}(z)dz$ with the average plume speed $v_p$ and the integrated $SO_2$ path concentration $w$. $v_p$ has been retrieved from the displacement of features at the top of thermals in consecutive sets of difference images with time. $w$ has been calculated along a transect line across the plume, orthogonal to the main plume dispersal direction. The Figure above shows the $SO_2$ column density image of the the Putana fumaroles at 10:30 LT on November 28, 2012. The straight line indicates the integral section used for the calculation of the integrated path concentration $w$.**

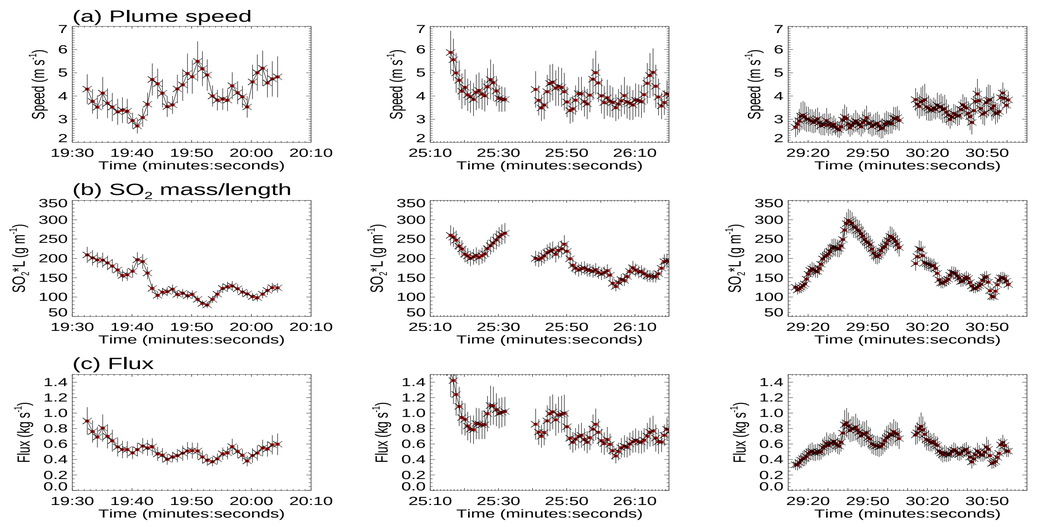
**An alternative method have been developed to determine the $SO_2$ fluxes. Graphic showing the method for calculating the the $SO_2$ flux at pixel-row, $p$ and line, $l$ based on a plume velocity vector ($v$) estimated from the optical flow algorithm and mass loading ($M$) estimated from the UV retrieval. An integral along the path $x_o$ to $x_1$, orthogonal to the plume velocity is performed to determine the mass per unit length ($m_l$). Multiplying $m_l$ by the plume velocity gives the the $SO_2$ flux at $p, l$. This value of the $SO_2$ flux is assigned to an area of dimension $|x_1 - x_0| \times |x_1 - x_0|$.**




## Measurements at Putana volcano

**The UV imaging camera was transported to Putana volcano by a 4WD vehicle and mounted at an altitude of 4935 m a.s.l. at 22°35'S, 67°53'W, approximately at a horizontal distance of 6150 m south-west of the volcano. Power was supplied by a car battery and measurements were made over only a short period of time starting at 10:16 local time (LT) on November 28, 2012.**

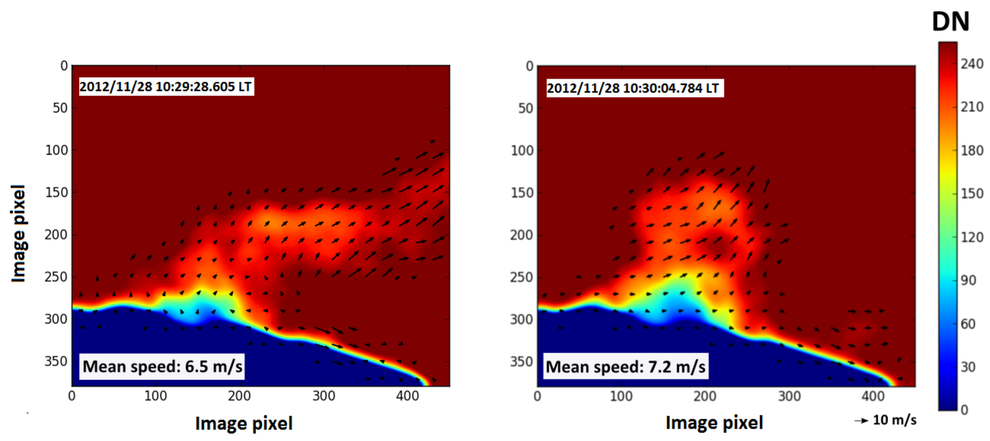
**The image below shows estimates of plume speeds [m $s^{-1}$] (a: upper row panels), integrated $SO_2$ column mass [g $m^{-1}$] (b: middle row panels), and $SO_2$ flux [kg $s^{-1}$] (c: lower row panels) for three time periods on November 28, 2012.**



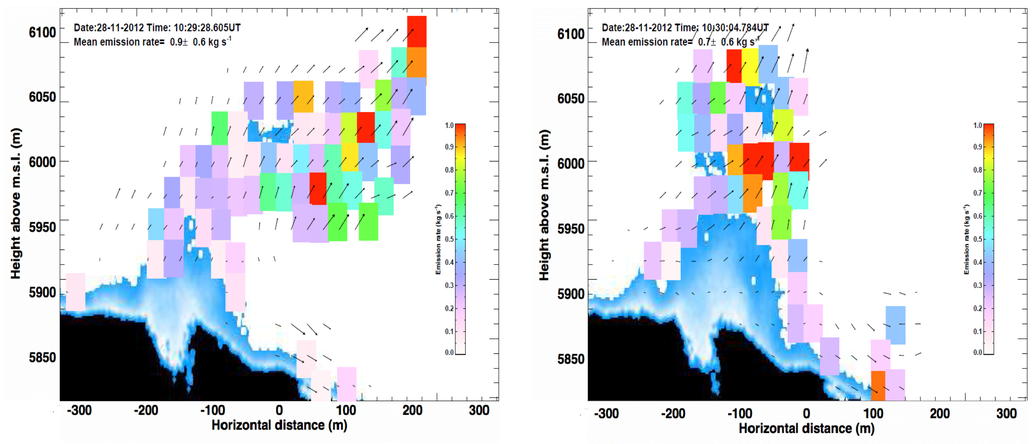

**Mean and standard deviation of the flux of $SO_2$ from the Putana fumaroles are given in the Table. Statistics have been calculated over different time ranges. The actual data were sampled at 0.1 s intervals and values are provided at 10 s intervals and an overall value for 3 min 20 s. A mean flux $s_e$ of $\sim$ 0.6 $\pm$ 0.2 kg $s^{-1}$ is found.**

| Period | $s_e$ (kg $s^{-1}$) | $\pm\sigma$ (kg $s^{-1}$) |
|---|---|---|
| 10 s | 0.64 | 0.17 |
| 20 s | 1.01 | 0.22 |
| 30 s | 0.53 | 0.14 |
| 40 s | 0.71 | 0.16 |
| 50 s | 0.62 | 0.14 |
| 50 s | 0.53 | 0.12 |
| 3 min 20 s | 0.64 | 0.20 |

**Estimates of plume speeds [m $s^{-1}$] using an optical flow algorithm. Plume-speed vectors are overlain on top of the digital number $DN$ for two images taken at 10:29:29 LT (left panel) and 10:30:05 LT (right panel).**




**$SO_2$ fluxes for the Putana fumarole field observed on November 28, 2012 at 10:29:29 LT (upper panel) and at 10:30:05 LT (lower panel). Mean fluxes are 0.9 $\pm$ 0.6 kg $s^{-1}$ (at 10:29:29 LT) and 0.7 $\pm$ 0.6 kg s $^{-1}$ (at 10:30:05 LT).**




## Conclusions

We provide the first estimates of $SO_2$ fluxes from the fumarolic field of Putana from observations with an ultraviolet imaging camera made on November 28, 2012. Relatively high $SO_2$ fluxes varying between 0.3 kg $s^{-1}$ and 1.4 kg $s^{-1}$, which translates to 26 t/d and 121 t/d assuming constant degassing throughout the day. Furthermore, we demonstrates how an optical flow algorithm can be integrated with the $SO_2$ retrieval to calculate $SO_2$ fluxes at pixel level.

References: Stebel K., Amigo, A., Thomas, H. and Prata, A.I, 2014: First estimates of fumarolic $SO_2$ fluxes from Putana volcano, Chile, using an ultraviolet imaging camera, *Journal of Volcanology and Geothermal Res.*, in revision.