Degassing at Sabancaya volcano measured by UV cameras and the NOVAC network

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Analysis of NOVAC scanning DOAS data at Sabancaya for 27 April 2018

On 27 April 2018, the plume emitted from Sabancaya Volcano was captured by two NOVAC scanning DOAS stations. In the two-hour time window of our SO_2 camera measurements (approximately 14:00 to 16:00 UTC), the Ampato (SAD1) station recorded 14 plume scans, while the Hornillos (SAD3) station scanned the plume only 7 times. The difference in acquisition rate was likely due to differences in incident UV radiance and light throughput of the two optical scanning systems.

Each scan consists of 51 individual spectra recorded while scanning from one horizon to the other, plus a reference sky spectrum recorded straight overhead and a dark spectrum. Both stations featured 60 degree conical scanners such that the scanning plane wrapped slightly around the volcanic edifice (see Figure 3 in Galle et al. [2010]). The spectra within each scan were all analyzed using a standard DOAS approach [Platt and Stutz 2008] relative to the scan's reference sky spectrum. Afterwards, the retrieved column densities were adjusted such that the lowest columns measured within a scan yielded no SO_2 [Galle et al. 2010].

All spectra were analyzed in the standard NOVAC retrieval range of 310 to 325 nm. The spectral analysis was performed using the standard NOVAC observatory software (available at `https://novac-community.org/`). First, the dark spectrum was subtracted from each measurement spectrum. Next, a shift was applied to the measurements such that the Fraunhofer lines in each spectrum were aligned with the wavelengths of these line in a high-resolution solar atlas [Chance and Kurucz 2010]. In this manner, temperature-induced variations in the spectrometer's wavelength calibration were corrected for. Next, the optical depth was calculated by dividing each measurement by its respective sky spectrum and taking the negative logarithm. Finally, the absorption cross-sections of SO_2 and ozone [Bogumil et al. 2003; Vandaele et al. 2009], as well as a Ring correction spectrum [Grainger and Ring 1962] were fit to the optical depth.

Two example scans recorded on 27 April 2018 by the stations at Ampato and Hornillos are shown in Figure 1. During the measurement timeframe, the plume was consistently blown over the Hornillos DOAS station, which detected up to approximately 1,800 ppmm of SO_2 while pointing at the plume. This yields a wind direction of 223 degrees. At the same time, the station at Ampato detected the plume center at a scan angle of 62 deg. Given the fact that both stations use a conical scanning geometry, this puts the Ampato plume azimuth angle at 23 deg off north and the plume elevation angle at 28 deg above the horizon. Figure 2 shows that, while the Hornillos scanner intersected the plume about 3 km from the summit vent, the Ampato scanning plane intersected the plume about 8 km from the

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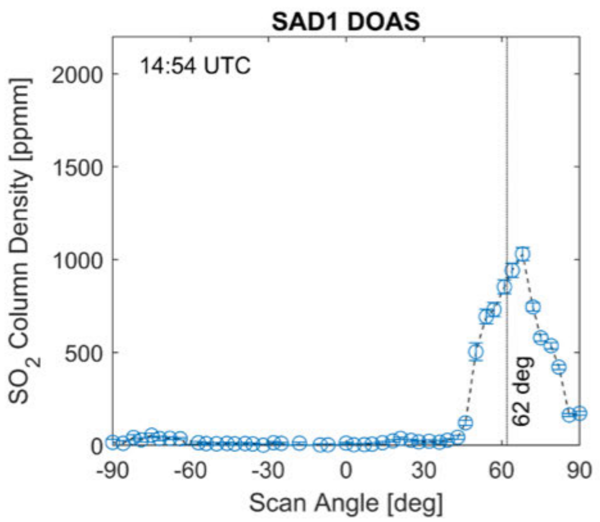

Figure 1: Two example scans recorded approximately coincidentally by the NOVAC scanning DOAS stations at Ampato (SAD1) and Hornillos (SAD3) on 27 April 2018. The measurement points show the SO_2 column density measured along the line of sight as the instrument scans from one horizon (-90 deg) to the other (+90 deg). The vertical lines indicate the plume center, as identified by the NOVAC observatory software.

crater. In fact, the plume was approximately 11 km from the instrument itself. Light dilution will be significant at such large distances [Kern et al. 2009; Mori et al. 2006], and hence it is not surprising that the Ampato scanner consistently measured lower SO_2 column densities. Also, since the plume intersects were so far apart, the scanning data does not allow accurate triangulation of the plume height, which may well have changed significantly between the two measurement points.

In the given measurement geometry, the plume scans recorded by the Hornillos station are expected to yield more reliable emission rates, so we focus on this first. For the flux analysis, we assumed that the plume was centered 1,000 m above the instrument, which puts it approximately 200 m above the volcano's summit and is in qualitative agreement with visual observations of the measurement conditions. Using this plume height and wind speeds obtained from the NOAA-GDAS, the SO_2 emission rates were calculated for each scan in the time window of the SO_2 camera observations. The results are plotted in Figure 3 (blue line). In the depicted time window, the Hornillos instrument scanned the plume 11 times. For 8 of these, the software estimated a plume completeness of 85 % or higher (circles in Figure 3). From 13:30 to 15:00 UTC, emission rates appeared to ramp up from about 18 to 31 kg/s. Between 15:00 and 16:20, they dropped slightly to 27 kg/s.

Though the results are less reliable due to the long distance from this instrument to the plume, the Ampato data are also shown for completeness (red line). For the analysis of the Ampato emission rates, we used the same wind speed information (from NOAA GDAS), but in this case we did not have to assume a plume

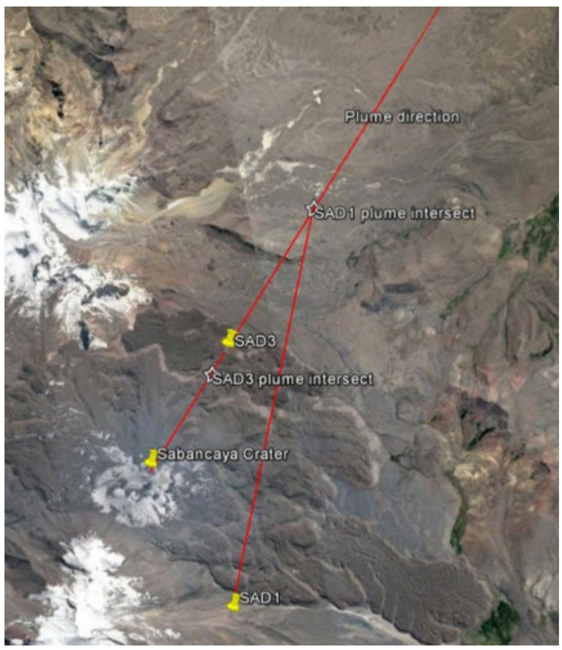

Figure 2: Geometry of the scanning DOAS measurements taken at approx. 15:00 UTC at Sabancaya Volcano. The upper red line indicates the plume direction (directly overhead of Hornillos, SAD3). The lower red line indicates the Ampato (SAD1) scanner viewing direction for which the maximum SO_2 column density was obtained. Notice that the Hornillos (SAD3) scan intersects the plume about 3 km from the vent, while the Ampato (SAD1) scan intersects the plume 8 km downwind and 11 km from the instrument itself.

height. Instead, we simply fixed the plume direction to 43 (equivalent to a wind direction of 223) and obtained

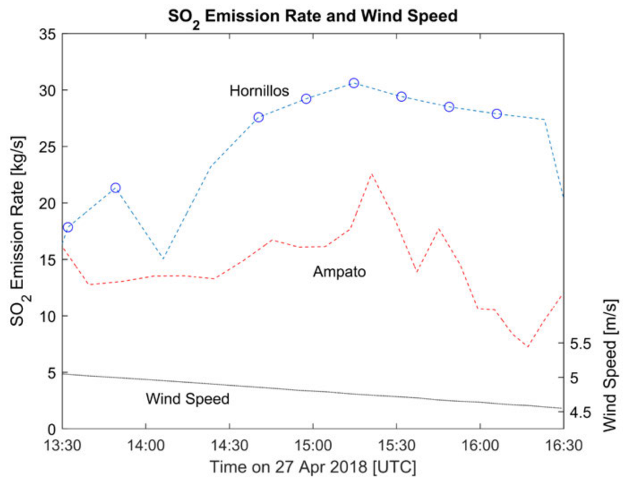

Figure 3: SO_2 emission rates obtained from the NOVAC scanning DOAS instruments installed at Ampato (red line) and Hornillos (blue line). The circles indicate plume scans for which the NOVAC software determined a plume completeness of 85% or higher. Also shown is the wind speed used for the analysis of emission rates (from NOAA GDAS).

the distance to the plume by triangulation. The plume distance was approximately 11 km, but varied slightly depending on the location of the plume center in each scan.

The Ampato values are lower than those reported by the Hornillos station, with a maximum emission rate of 22 kg/s at 15:26, then dropping below 10 kg/s after 16:00. However, note that none of the scans had an estimated plume completeness greater than 85 %. Therefore, it is likely that some of the plume was missed behind the horizon. Also, as mentioned before, the light dilution effect would significantly reduce the measured signal for scans recorded at such a great distance from the plume (about 11 km).

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