Supplement of “Implementation of electrochemical, optical and denuder-based sensors and sampling techniques on UAV for volcanic gas measurements: examples from Masaya, Turrialba and Stromboli Volcanoes ”

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I) Additional figures

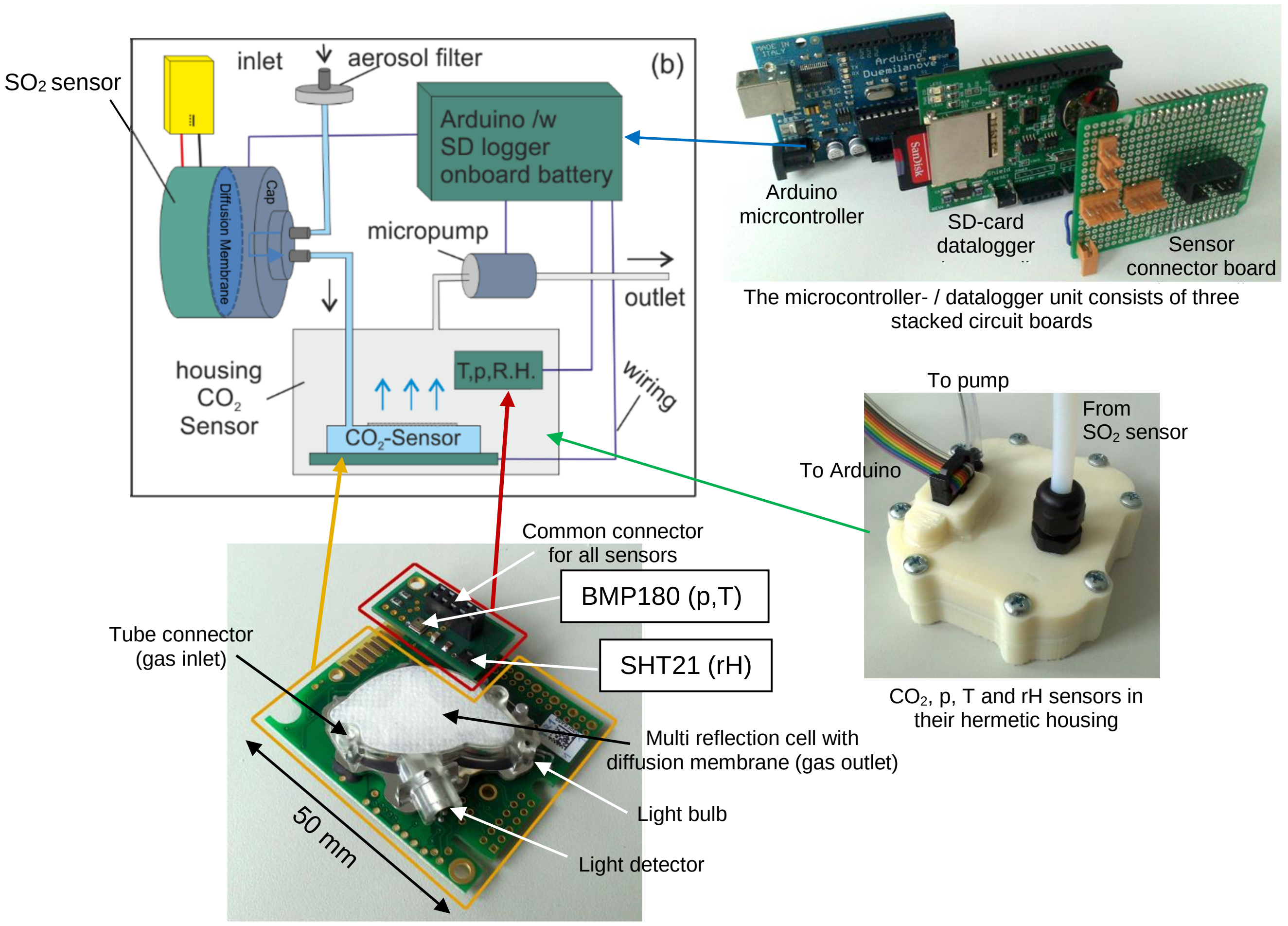


Figure S1: Detailed overview of the Sunkist system components.

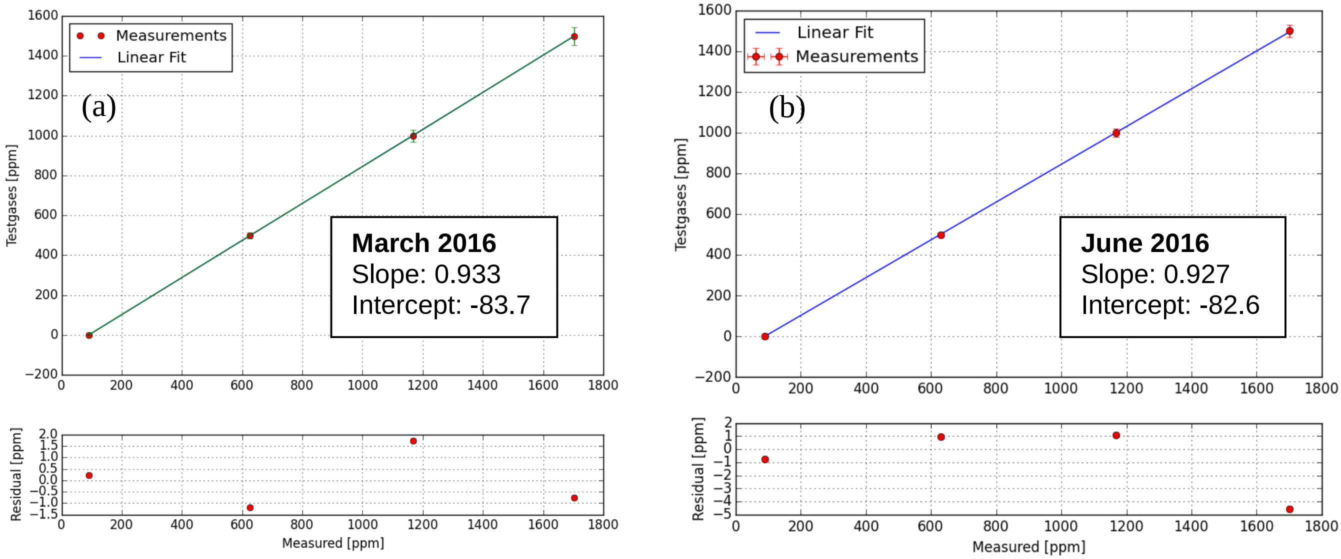


Figure S2: Example calibration curves of the K30 CO_2 sensor inside the Sunkist Multi-GAS system. The calibrations shown, were performed (a) before and (b) after the campaign to Stromboli volcano. Mixing ratios of the applied readily mixed test gases were 0, 500, 1000 and 1500 ppm CO_2 in N_2. The upper plot shows the correlation between the test gas mixing ratios (y-axis) and the Sunkist output signal (x-axis). The lower plots show the deviation of the measurement points from the linear regression line.

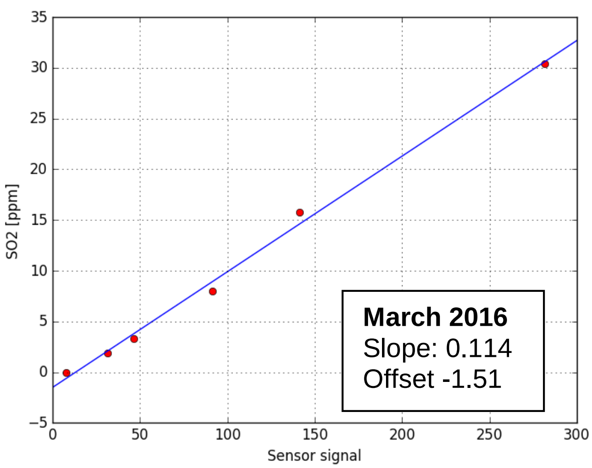


Figure S3: Example calibration curve of the 3MST/F SO_2 sensor inside the Sunkist Multi-GAS system. The test gas mixing ratios were 30.390, 15.769, 7.991, 3.296, 1.921 and 0.0 ppm and were achieved by mixing a 30 ppm SO_2 (in N_2) test gas with pure N_2. The plot shows the sensor response (x-axis) as a function of the applied test gas concentration (y-axis).

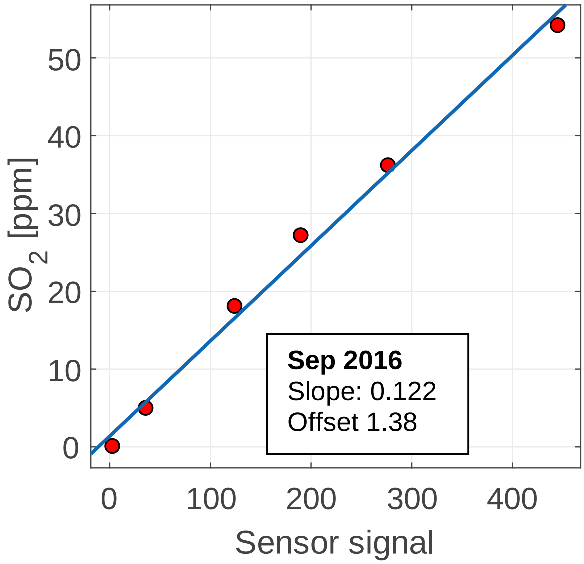


Figure S4: Example calibration curve of the 3MST/F SO_2 sensor inside the Black Box sampling system. The test gas mixing ratios were 4.9, 18.0, 27.1, 36.1, 54.1 and 0.0 ppm and were achieved by mixing a 54.1 ppm SO_2 (in N_2) test gas with pure SO_2-free air. The plot shows the sensor response (x-axis) as a function of the applied test gas concentration (y-axis).

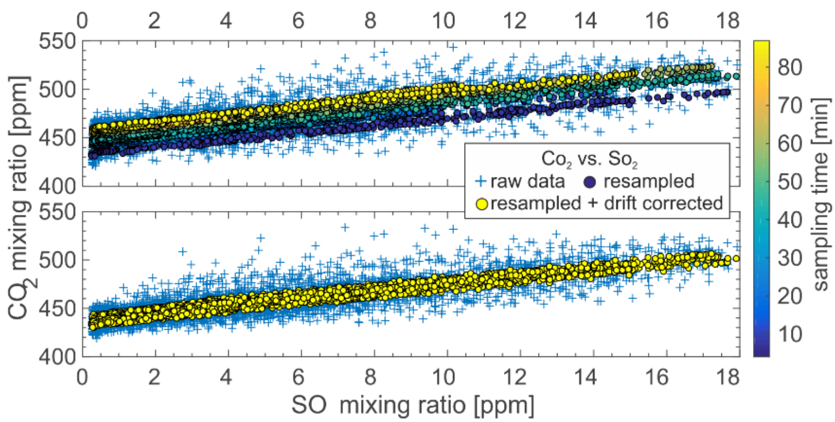


Figure S5: CO_2 over SO_2 mixing ratios of the *Sunkist* unit; comparison between raw data, time response factor corrected (resampled) data and CO_2 drift corrected data (14.07.2016) at Masaya volcano; CO_2/SO_2 = 3.63+/- 0.43.

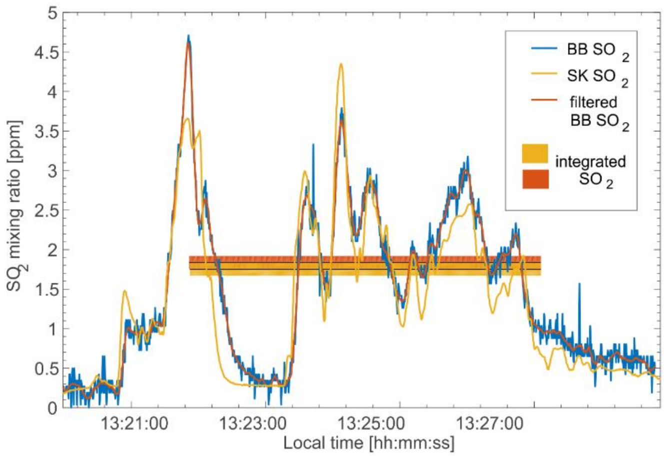


Figure S6: Comparison of the two SO_2 sensor data time series from Sunkist and Black Box

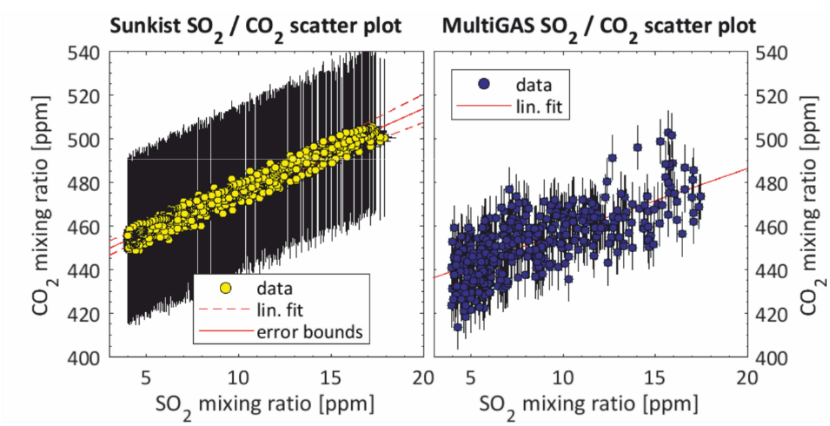


Figure S7: Scatter plot of CO_2 vs SO_2 mixing ratios of the Sunkist (SK) (left) and Multi-GAS (MG) (right) instruments; SK CO_2/SO_2 = 3.63+/- 0.43 (background CO_2 = 439 ppm); MG CO_2/SO_2 = 2.94 +/- 0.30 (background CO_2 = 413 ppm);.

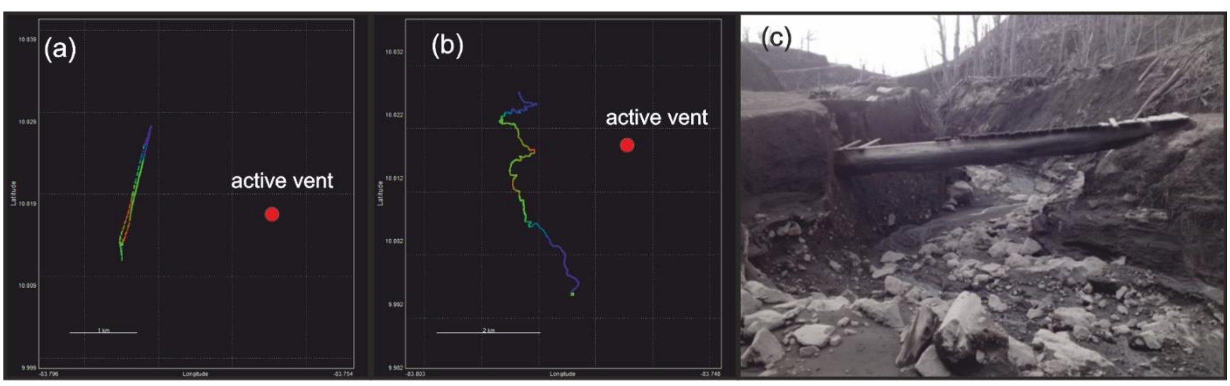


Figure S8: (a) flight path and color-coded column amounts during the transversal flight (approximately 10 minutes flight time); (b) example for a car operated traverse with color-coded SO_2 column amounts (approx. 45 minutes measurement time); (c) collapsed bridge at the downwind flanks of Turrialba volcano making car operations impossible.

II) Wiring of the Black Box unit, see PDF

III) Arduino Code: see PDF or code files

IV) Simplified analytical approach to estimate the spatial origin of sample air in multicopter measurements

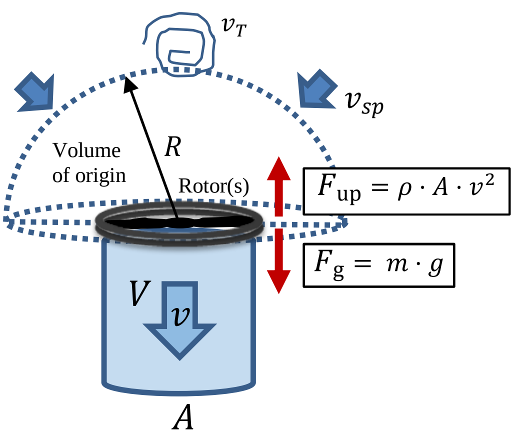
We hereby present a very simplified approach, to calculate the volume of sample air origin in general multicopter measurements. This method is not accurate but provides a rough estimate, which might be sufficient to judge, whether the suction of far away air masses into the system is a severe issue in a particular measurement application.

To keep a multicopter at constant altitude, the rotors need to accelerate a distinct air mass V to a downward speed v to obtain an upward force F_{up} which compensates the gravitational force F_{g}. From momentum conservation follows, that:

$$F_{\mathrm{g}} = F_{\mathrm{up}} \quad \Leftrightarrow \quad m \cdot g = \rho \cdot A \cdot v^2 \quad \Leftrightarrow \quad v = \sqrt{\frac{m \cdot g}{\rho \cdot A}}$$

With:

$$\rho = \text{density of the sourrounding air}$$
$$g = \text{acceleration of gravity} = 9.81\ \mathrm{m/s^2}$$
$$A = \text{UAV's total rotor surface}$$
$$m = \text{UAV's total mass}$$



Further we assume, that the necessary air mass is attracted by the rotors isotropically from the upper half-space. Now imagine a half sphere with radius R and surface $A_{sp} = 2 \cdot \pi \cdot R^2$ above the copter. Because of mass conservation the air speed on the sphere surface is $v_{sp} = \frac{A}{A_{sp}} \cdot v$. We further define v_T as the speed of atmospheric air turbulences, which can typically be approximated to be one tenth of the actual wind speed. Now "critical" R can be calculated for the case $v_{sp} = v_T$, which corresponds to the distance at which natural atmospheric air movements and suction flow by the copter cannot be distinguished anymore. Insertion of the aforementioned equations yields:

$$v_{sp} = v_T \qquad \Leftrightarrow \qquad \boxed{R = \sqrt{\frac{5 \cdot \sqrt{\frac{m \cdot g \cdot A}{\rho}}}{\pi \, v_w}}}$$

With v_w being the mean wind speed.

Typical encountered conditions during the presented measurement flights were:

$$\rho = 1 \text{ kg/m}^3$$
$$g = 9.81 \text{ m/s}^2$$
$$A = 0.33 \text{ m}^2$$
$$m = 3 \text{ kg}$$
$$v_w = 8 \text{ m/}s$$

Insertion yields an R of only 0.8 metres.