A multi-purpose, multi-rotor drone system for long range and high-altitude volcanic gas plume measurements

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Supplement

S1. Data files

The Excel-book file amt-2020-452-raw_data contains all data used for the figures presented in this article. Each sheet is named according to the figures in which data was used and the instrument from which data was obtained, e.g. data_fig11&14_MultiGAS for the data used for figures 11 and 14 using the MultiGAS (Chalmers) instrument.

Most sheets contain the full dataset coming from the instrument, not all parameters are needed for the data presented in the figures of the article. Data that was used for the figures are marked with an orange/pink background.

The following descriptions correspond to the columns on each data-sheet:

data_Fig1_UAV

Data file extracted from a "ulog" file containing a series of parameters from the multi-rotor navigation sensors. The plotted columns contain:

Time stamp in μs

Roll angle

Pitch angle

Yaw angle

Thrust factor

Latitude UTM

Longitude UTM

x-distance from reference position

y-distance from reference position

z-distance from reference position (inverse of altitude)

data_fig5_Sunkist:

Data file as recorded by the Sunkist instrument. It contains:

Date UTC

Time UTC

CO_2 data at instrument resolution (calibration from U. Mainz) in ppm

SO_2 data at instrument resolution (calibration from U. Mainz) in ppm

Temperature in °C

Pressure in Pa

Relative humidity in %

data_fig8_MultiGAS, data_fig12&15_MultiGAS, and data_figS1_MultiGAS

Data files as recorded by the MultiGAS instrument, stored in internal memory, and sent to ground-station in real-time. It contains:

Time UTC

Date UTC

Lat UTM

Lon UTM

Temperature in °C

Pressure in Pa

Relative humidity in %

Altitude in m ASL

SO_2 signal (uncalibrated) from working electrode in ppb

H2S signal (uncalibrated) from working electrode in ppb

NO signal (uncalibrated) from working electrode in ppb

NO_2 signal (uncalibrated) from working electrode in ppb

NO_2 signal (uncalibrated) from auxiliary electrode in ppb

H2S signal (uncalibrated) from auxiliary electrode in ppb

NO signal (uncalibrated) from auxiliary electrode in ppb

SO_2 signal (uncalibrated) from auxiliary electrode in ppb

CO_2 signal (uncalibrated) from auxiliary electrode in ppm

x-tilt angle in deg

y-tilt angle in deg

z-tilt angle in deg

Wind speed from anemometer in m/s

Wind direction from anemometer in deg

Activation of pump for bag sampling (0/1)

data_fig9_UAV

Data file extracted from a "ulog" file containing a series of parameters from the multi-rotor navigation sensors. The plotted columns contain:

Time stamp in μs

Horizontal wind speed, calculated from components x and y of wind speed, in m/s

data_fig10_WindSpeed

Time series of wind speed obtained from three different methods: (i) modeled data from ECMWF ERA5 Re-analysis database (C3S, 2017) retrieved at hourly resolution, 0.25×0.25 deg horizontal resolution, and 16 pressure-levels from ground to about 10 km ASL. This data is then interpolated at the location of the summit of Manam. (ii) Wind data measured by the drone using anemometer and drift-method. (iii) Wind data measured from ground using the dual-beam method described in Johansson et al. (2009). The columns contain:

Date UTC

Time UTC

Horizontal component of wind speed in m/s

data_fig11&15_MobileDOAS

Data file produced from an evaluation with the MobileDOAS software (Johansson et al., 2010) of data collected by the instrument during a traverse with the drone. It contains

Time UTC

Latitude UTM

Longitue UTM

Altitude m ASL

SO_2 vertical column density in ppm*m

data_fig13_MultiGAS

Data from MultiGAS instrument after calibration and other corrections. It contains

SO_2 volume mixing ratio in plume in ppm

CO_2 volume mixing ration in plume in ppm

S2. Proof of concept of MultiGAS measurement with stabilized sample taken by the drone

A sample of the plume was taken by filling a Tedlar bag through remote activation of a pump when a signal of SO_2 was detected and then connected in closed loop to the MultiGAS sensor for several minutes after landing. This sampling method was applied several times during the field campaign in Manam in May 2019, but all samples with concentration of SO_2 higher than 10 ppm were used for attempting measurements of the isotopic composition of carbon.

The results of the 'practice' measurement are shown in Figure S1.

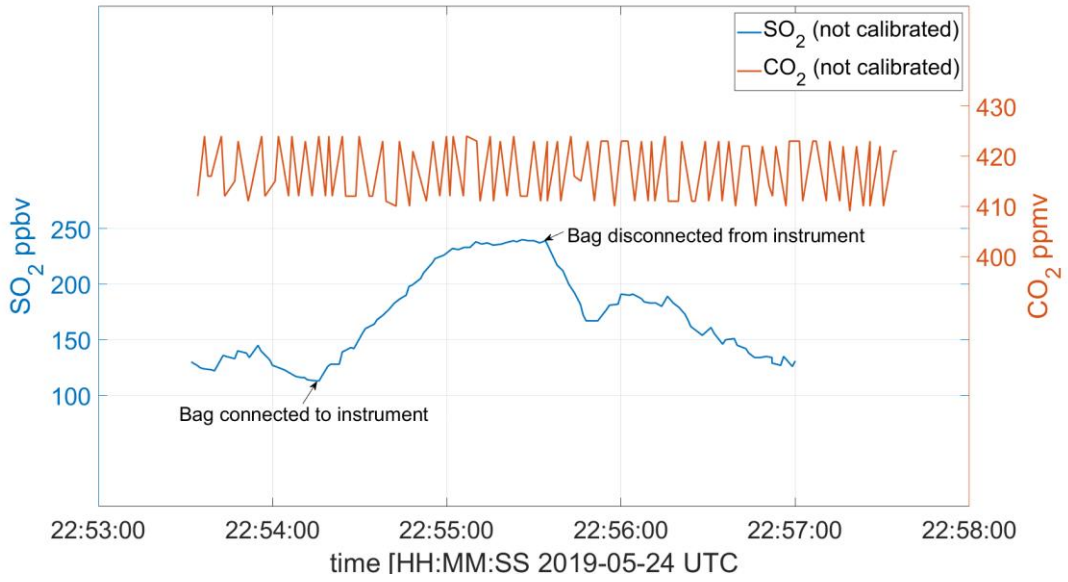


Figure S1. Time series of uncalibrated signals observed in the field on 22 May 2019 after connecting a Tedlar bag filled by remote activation of a pump onboard the drone to the MultiGAS instrument in closed-loop

As clearly shown, the SO_2 signal is detectable and its curve of growth stabilized in about 30 s (t_{90}), which matches well with the manufacturer's specifications. But the signal, after calibration, is less than 1 ppm and therefore the CO_2 signal above background is below the detection limit of the instrument (remember the molar ratio for both species at Manam was found to be ~1).

The figure also shows a noise picked up by the CO_2 sensor, which we attribute to the radio. This signal is subtracted together with the background as part of the corrections.

S3. Calibration tests of MultiGAS CO_2 and SO_2 sensors

Calibration tests were performed to characterize the responses of the CO_2 and SO_2 sensors for the MultiGAS instrument (Xu, 2019). We used a mixture of CO_2 and SO_2 at nominal concentrations of 4.293 ± 0.086% (mol) and 203.9 ± 4.1 ppm (mol), respectively (i.e. in a ratio of 210.5:1), and mix it with pure N_2 to prepare diluted mixtures at 0, 0.5, 1, 2, and 4 ppm SO_2. The mixture was controlled by a dynamic gas calibrator (Thermo Scientific, model 146i) with a flow rate of 5 l/min. The mixture was pumped into the inlet of the MultiGAS at a constant flow rate of 0.5 l/min and ambient temperature (27.8°C) and pressure (102 kPa). Besides the MultiGAS system used in Manam (referred as "flow through" in the figures below, due to the use of an active pump), another system with the sensors exposed passively to the gas ("diffusion") was tested, and they were compared to a reference system using a more precise instrument based on a LI-COR 7200 sensor, which has a time response t_{90} of 0.1 s and 0.3 ppm precision ("sniffer"). Each mixture was measured for periods of about 30 minutes until the gas calibrator was stabilized. The results of the measurements are shown in Figure S2.

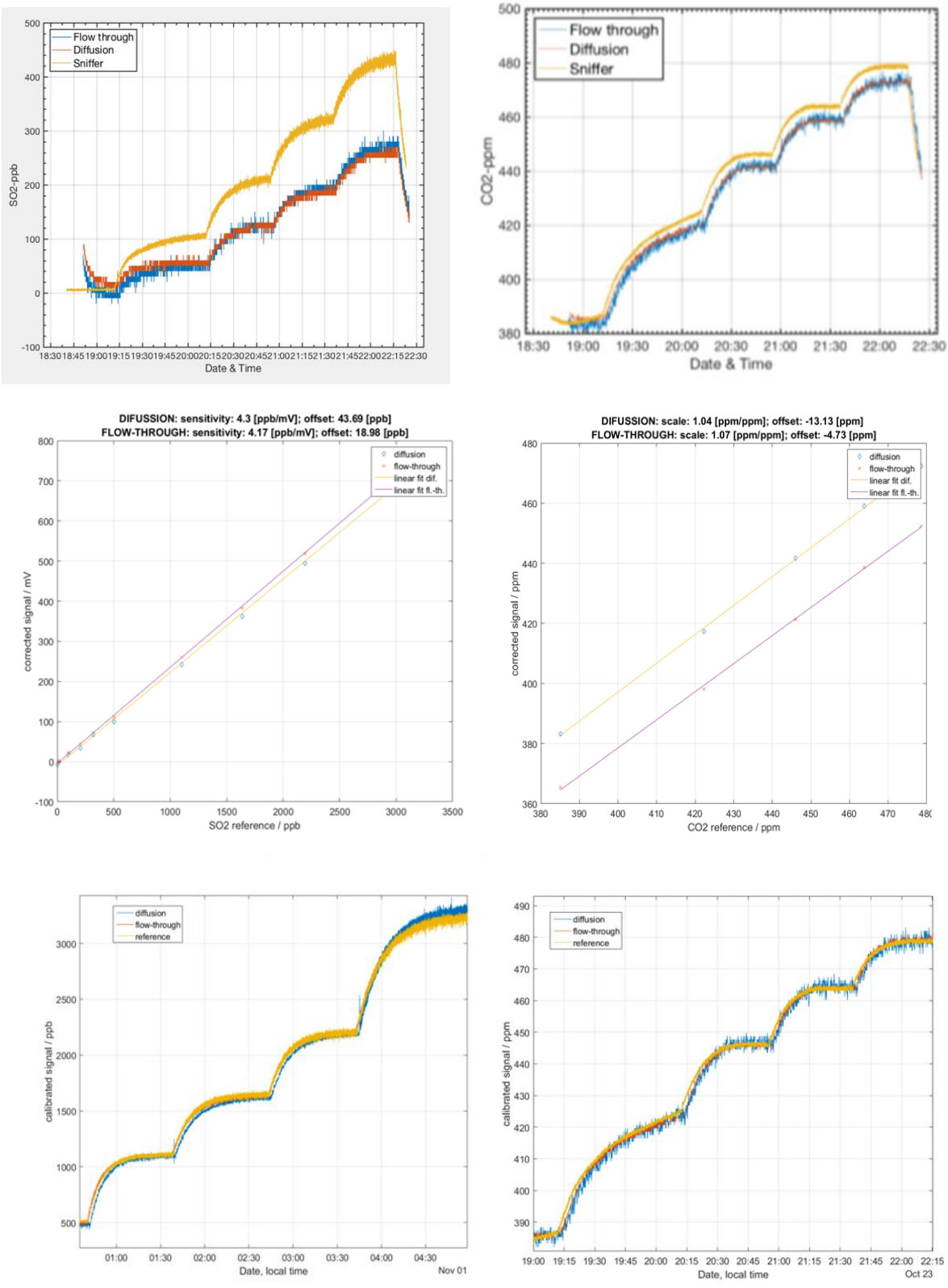
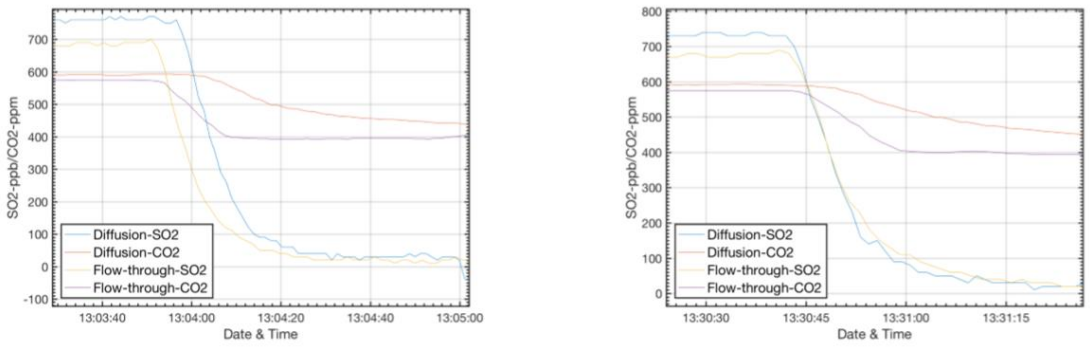


Figure S2. Calibration measurements for the MultiGAS instrument used in Manam (flow-through), in comparison with two another model of MultiGAS with sensors directly exposed to the gas without a pump (diffusion) and with a reference instrument based on a LI-COR 7200 sensor. The instruments were exposed to known concentrations of gas from which the calibration constants (offset and sensitivity) were derived. The upper panels show the measured signals using the calibration constants from the manufacturer, the middle panels show the calibration curves to derive the effective constants and the lower panels showed the calibrated signals. The flow-through instrument showed much lower noise and it was chosen for the measurements at Manam (figures from Xu, 2019).

Additionally, an experiment was designed to characterize the time response of the sensors. For this, the instruments were placed inside a box with a stable mixture of CO_2 and SO_2 and then the instruments were suddenly removed out of the box to be exposed to ambient concentrations of these gases. This sudden change in concentration mimics a step calibration function. From the decay in signal it was possible to estimate the response times at 90% level (t_{90}) of the sensors. The experiment was repeated two times and responses times of 20-25 s and 20 s were found for the MultiGAS (flow-through) SO_2 and CO_2 sensors, respectively. The results are shown in Figure S3.



(a) First time. (b) Second time.

Figure S3. Response-time experiments showing the decay in signal when the sensors of the MultiGAS instruments (diffusion and flow-through) were exposed to a stable concentration of SO2 and SO2 and then removed suddenly to ambient concentration. Notice the quicker response of the system using a pump (flow-through, used in Manam) and the stabilization after response times of 20-25 s for SO_2 and 20 s for CO_2.

References

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