



A multi-gas sensor system lifted by a tethered aerostat for real time in-situ investigation of volcanic plumes

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Volcanic eruptions eject a large amount of aerosols and gases in the atmosphere with severe implications on the environment, climate and life on Earth and, in recent times, human society and aviation. Currently, the main technique for observing volcanic clouds relies on remote sensors both from satellites and ground observatories, also using multispectral cameras. However, the composition of volcanic clouds is difficult to assess due to physical limitations of the instruments' detection capability: satellite and ground based remote sensing systems, generally used to detect and retrieve plume particles and gases, are limited by instrument sensitivity, spatial resolution and uncertainties of particles optical properties and size distribution. Moreover, the presence of high concentration of some gases in the atmosphere (e.g. CO₂) makes their estimation impossible inside the volcanic cloud. Therefore, in-situ measurements are necessary to collect ground truth data to validate the remote sensing models and obtain an accurate characterization of a volcanic cloud.

Drone-mounted sensors could compromise the measurements within the plume due to the disturbances caused by the propellers. Additionally, the drone could be contaminated and damaged by the ash. As a less invasive and less expensive alternative, our groups at the Space Systems Laboratory of the University of Pisa together with INGV developed a novel method for in-situ measurements in volcanic clouds: a custom multi-gas sensor package ("Volcanosonde") lifted by a tethered aerostat inside the plume. A volcanosonde is composed of a set of sensors, integrated on a circuit board, which record the concentrations of the main constituents of a volcanic plume (SO₂, HCl, CO₂, PM1 – 10) together with the atmospheric parameters (pressure, relative humidity and temperature). In the volcanosonde, data packets are acquired with a frequency of 1 Hz and stored onto an onboard memory, while a timewise subsampled subset of the data is transmitted to a ground station for real-time visualization via LoRa protocol over the 868 MHz ISM band.

We tested the developed apparatus during a measurement campaign in August 2024 on Mt. Etna, Sicily, in the frame of "VOLANDO", a PRIN project funded by the European Union- Next Generation

EU. The system consisted of a sounding balloon including three volcanosondes attached at 50 m intervals on the retaining rope, a stand-alone Optical Particle Counter and a GNSS receiver. The helium-inflated aerostat was raised to 400 m a.g.l. allowing the sondes to enter the plume and make uninterrupted measurements for 3 hours. The experiment was repeated on different days, effectively collecting in-situ data.

The system showed excellent flight behavior and was relatively easy to handle, even in no flat volcanic terrain, allowing for quick re-location of the flying balloon and the attached sondes over several areas of interest. Real time monitoring of the measurements provided the operators with indication of the quality of data collected and guided the right positioning of the flying platform so to achieve an optimal positioning of the volcanosondes within the plume. We estimate that a crew of two with minimal training can operate the tethered balloon autonomously under good weather conditions.