

## **Direct measurements in volcanic plumes using balloon-borne multi-gas and particles sensor systems. The Vulcano Island and Etna 2025 field campaigns**

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Volcanic emissions, consisting of particles (ash, water droplets, sulfates) and gases (primarily H<sub>2</sub>O, CO<sub>2</sub>, SO<sub>2</sub>, HCl, and H<sub>2</sub>S), have a significant impact on the environment, climate, public health, society, and aviation. Monitoring is typically performed using satellite platforms to ensure global coverage and ground-based systems to provide continuous, high-resolution data. However, accurately determining the composition of volcanic clouds remains challenging due to instrument limitations, uncertainties in optical properties and particle size distribution, and the difficulty of detecting certain gases in the presence of high background concentrations.

To address these challenges, in the frame of the VOLANDO (VOLcanic pLume chAracterization using soundNDing balloOns) project, a balloon-borne system has been equipped with sensors for gases (CO<sub>2</sub>, SO<sub>2</sub>, H<sub>2</sub>S, HCl), particles (concentration and size distribution) and atmospheric parameters (pressure, humidity, temperature) measurements. All sensors have been integrated in a package named “Volcanosonde”, able also to store the data onboard and transmit a subset to the ground in real time.

Direct measurements of gases and particles in the volcanic plume were obtained using two different configurations: a free-flying balloon and a tethered balloon. The latter configuration, with several volcanosondes spaced apart, allowed us to create time series of the different species at different heights in the plume.

This work describes the results obtained during two measurement campaigns conducted on Vulcano Island (Aeolian Islands-Sicily, Italy) and Mount Etna (Sicily, Italy) in April and June 2025, respectively. At Vulcano, the measurements obtained with the Volcanosondes were compared with those obtained from various standard multigas systems, while at Etna, a system consisting of a tethered balloon equipped with three volcanosondes spaced 50 m apart and placed to the base of the southeast crater (3100 m asl) and central craters (3350 m asl) was tested.

The results of the measurements carried out at Vulcano showed a good agreement between the gas estimates obtained from the volcanosonde sensors and the multigas ones, highlighting high CO<sub>2</sub>/SO<sub>2</sub> ratios, strong correlations between gas and particles, and a lognormal distribution of particle size. The measurements carried out at Etna have demonstrated the effectiveness of the tethered balloon configuration for estimating time series of different quantities, while also highlighting critical issues in the response of some sensors and durability problems caused by the interaction between volcanic gases and the balloons’ material.

Even considering the remaining critical issues, the developed approach has proven effective for in situ measurements of gases and particles, providing valuable information on the structure and composition of the volcanic plume. Initial testing using the same sensing capabilities but adapted to small drones was successfully initiated during the Mt. Etna field campaign.