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# Volcanosonda: A Novel, Lightweight and Low-Cost Instrument for In-Situ Characterization of Volcanic Clouds – A Cross-Comparison Experiment

Camilo Naranjo[1], Marcello Bitetto[2], Maria Fabrizia Buongiorno[1], Ernesto Corrales[3], Jorge Andres Diaz[3,4], Alessandro Filippeschi[5], Matteo Gemignani[5], Gaetano Giudice[6], Lorenzo Guerrieri[1], Irene Marsili[5], Luca Merucci[1], Malvina Silvestri[1], Dario Stelitano[1], Angelo Vitale[2], Riccardo Biondi[7], Salvo Marcuccio[5], Stefano Corradini[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia (INGV), ONT, Rome, Italy
[2]Università di Palermo, Dipartimento di Scienze della Terra e del Mare (DiSTeM), Palermo, Italy
[3]Universidad de Costa Rica (UCR), GasLab, CICANUM, San José, Costa Rica
[4]INFICON Inc., East Syracuse, New York, USA
[5]University of Pisa, Space Systems Laboratory, Dept. of Civil and Industrial Engineering, Pisa, Italy
[6]Istituto Nazionale di Geofisica e Vulcanologia (INGV), OE, Catania, Italy
[7]Fondazione CIMA, Savona, Italy

*Correspondence to*: Camilo Naranjo (camilo.naranjo@ingv.it)

**Abstract.** Retrievals of volcanic clouds generated by eruptions are essential for effective emergency management. However, current methods have significant uncertainties due to the challenges of accurately measuring certain critical parameters through remote sensing. To address this, a new lightweight and low-cost multi-gas sensor instrument, called Volcanosonda, has been developed. It is designed to be deployed into volcanic clouds using sounding balloons, enabling in-situ measurements to enhance the characterization of these critical parameters. This work presents the measurements and cross-comparison results from an experiment conducted on Vulcano Island using the Volcanosonda alongside four well-established multi-gas sensor instruments. The results show an overall agreement between the measurements of $SO_2$ and $CO_2$ and the estimated $CO_2/SO_2$ ratios.

## 1 Introduction

Volcanic eruptions inject large amounts of gases and particles into the atmosphere. These materials pose a significant threat to several aspects of human life: they can affect human health by causing respiratory issues (Stewart et al., 2021), impact the climate by increasing stratospheric aerosols that enhance Earth's albedo (Jenkins et al., 2023; Marshall et al., 2022), and disrupt aviation by causing engine failures, flight rerouting, and cancellations (Alexander, 2013; Prata and Rose, 2015).

Effective mitigation of these hazards requires accurate detection and quantification of volcanic cloud species (particles and gases as $CO_2$, $SO_2$, $H_2S$ and HCl) and geometry (cloud altitude and thickness). To achieve these goals, several remote sensing instruments are currently used to monitor volcanic clouds (Pardini et al., 2024): ground-based systems include UltraViolet-UV (Burton et al., 2015; Campion et al., 2015; Tamburello et al., 2011), VISible-VIS (Simona Scollo et al., 2014), and Thermal InfraRed-TIR cameras (Guerrieri et al., 2025; Prata et al., 2024), lidars (Scollo et al., 2012), radars (Marzano et al., 2006, 2012;

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Montopoli et al., 2014), and multi-gas sensor instruments (Aiuppa et al., 2005; Silvestri et al., 2023). Space-based observations take advantage of the wide coverage provided by satellites, using UV and TIR sensors (for an exhaustive bibliography see Corradini et al., 2021), and microwave sensors (Marzano et al., 2018), spaceborne lidars (Burton et al., 2012), as well as the Global Navigate Satellite System (GNSS) observations (Cegla et al., 2022; Cigala et al., 2019).

Despite the availability of these instruments, their sensitivity and spatial resolution are limited, and all of them measure volcanic cloud properties indirectly, leading to estimations with significant uncertainties (Corradini, 2008; Corradini et al., 2009; Pugnaghi et al., 2013). These uncertainties arise from several critical parameters that are difficult to retrieve accurately, such as ash particle size distribution (PSD), ash composition, cloud thickness, and ash concentration. Moreover, the retrieval of gases as $CO_2$ is particularly challenging due to its significant presence in the atmosphere. Accurate information about these parameters can only be obtained through in-situ measurements, which is an approach that remains highly challenging.

Previous efforts have focused on in-situ measurements using multi-gas sensor instruments deployed on drones, Unmanned Aerial Systems (UAS), and sounding balloons (Liu et al., 2020; Pieri et al., 2013; Silvestri et al., 2023; Stix et al., 2018; Vernier et al., 2020). However, the instruments employed in these measurements are often costly and weighty.

In order to improve the characterization of the cited critical volcanic clouds parameters, a new lightweight and low-cost multi-gas sensor system called "Volcanosonda" was developed within the framework of the VOlcanic pLume chAracterizatioN using sounDing ballOons (VOLANDO) project (https://progetti.ingv.it/it/volando), a project funded by the European Union – Next Generation EU within the Italian call "Progetti di Rilevante Interesse Nazionale" (PRIN). The Volcanosonda consists of a suite of sensors designed to measure the concentration and PSD of ash, as well as the concentrations of key volcanic gases ($SO_2$, $CO_2$), together with atmospheric parameters such as pressure, relative humidity, and temperature. The project aims to deploy the Volcanosonda into volcanic clouds using sounding balloons in free-flying and tethered configurations to perform in-situ measurements. These data are intended to improve and validate ash and $SO_2$ retrievals from both satellite and ground-based observations (Pieri et al., 2013; Vernier et al., 2020).

To test the new Volcanosonda and its sensors, an experiment was conducted at the La Fossa crater on Vulcano Island (Aeolian Islands, Italy). In this case, measurements were taken at a fixed position and while the instrument was carried during walking, simultaneously with other four mature and well-established multi-gas instruments: HAPSITE SCOUT miniGAS, MiniGas NTX-PRO (Pieri et al., 2013; Silvestri et al., 2023; Stix et al., 2018; Vernier et al., 2020), Multi-Gas Labvulc and Multigas Drone PP (Aiuppa et al., 2021, 2025; Burton et al., 2023; Liu et al., 2020) from University of Costa Rica, Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Nazionale Terremoti (INGV-ONT), the University of Palermo, and INGV-Osservatorio Etneo (OE) respectively. This experiment is part of a series of instrument tests conducted before deploying it in more intense events.

This work presents the results of the Vulcano Island field campaign, by analysing the Volcanosonda measurements, and making a cross-comparison between the different instruments. The data collected demonstrates the strong performance of the Volcanosonda and its good agreement with the other instruments, indicating that the new system is ready for deployment into larger volcanic clouds.

This paper is organized as follows: Section 2 introduces the selected test site. Section 3 describes the main features and

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components of the Volcanosonda, and the other four instruments used to collect the measurements, as well as the setup of the experiment. Section 4 presents the data analysis, including the results and discussion of the cross-comparison among instruments, with a focus on $SO_2$ and $CO_2$ measurements and the estimation of $CO_2/SO_2$ ratios. Finally, Section 6 provides the conclusions.

## 2 Test site

The test site selected for the test measurements was the La Fossa crater on Vulcano Island (see Figure 1b). Vulcano is a stratovolcano located in the Aeolian Islands Archipelago, in the southern Tyrrhenian Sea (38.404°N, 14.962°E, see Figure 1a). The volcano has a 3-km-wide crater and an elevation of 500 meters above sea level. The last major eruption at the La Fossa crater occurred between 1888 and 1890. Today, the predominant activity consists of fumarolic emissions, as shown in Figure 1c. This activity, along with low seismicity, makes the La Fossa crater a safe and ideal natural laboratory for conducting measurements to calibrate new instruments (Global Volcanism Program, 2025).

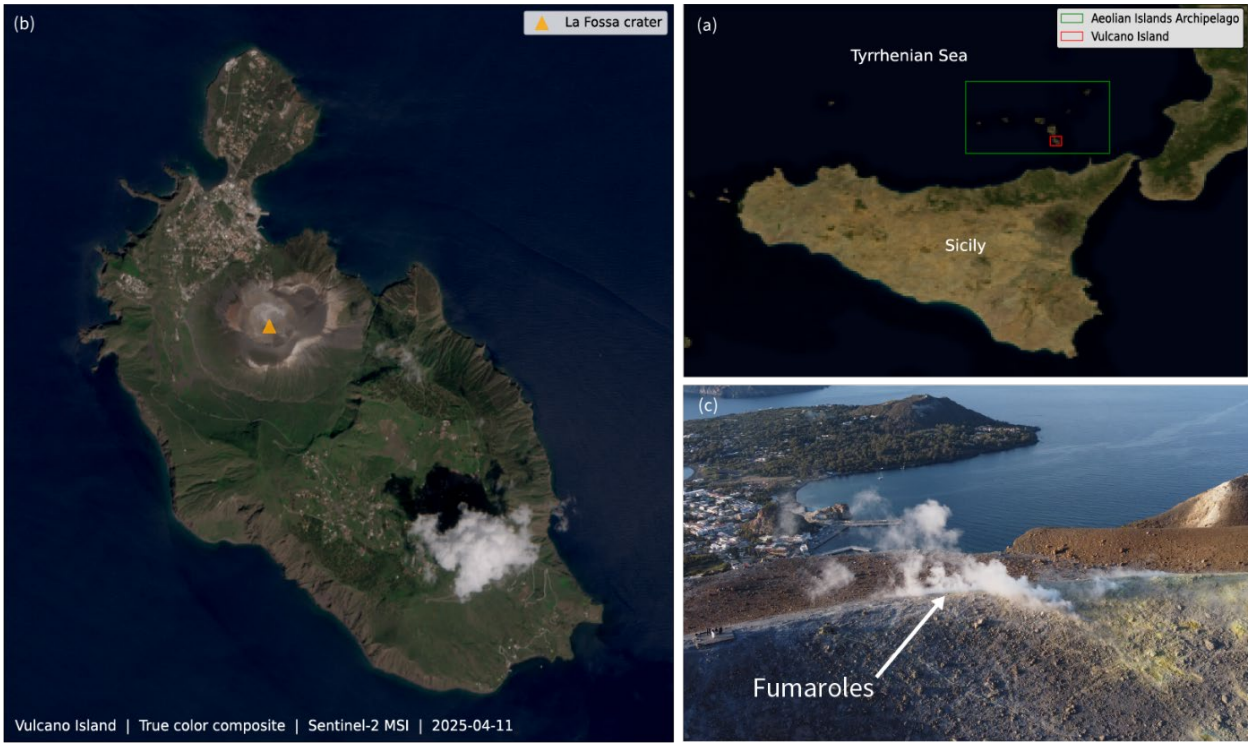


**Figure 1: Location map for the test site and fumarolic emissions. (a) Location of the Aeolian Islands Archipelago and Vulcano Island. (b) Vulcano Island, image captured by the Sentinel-2 satellite on April 11, 2025, one day after the field campaign. The orange triangle indicates the location of the La Fossa crater. (c) Northward-facing image taken by Jorge Andres Diaz using a drone on April 10, 2025, showing visible fumaroles along the rim of the La Fossa crater.**

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## 3 Instruments and Experiment

This section presents details on the instruments employed in the measurements and describes the experiment carried out during the field campaign.

### 3.1 Instruments

A total of five instruments were deployed during the field campaign, contributed by collaborating institutions including INGV-ONT, INGV-OE, the University of Pisa, the University of Palermo, and the University of Costa Rica. The following subsections provide a detailed description of the main technical characteristics of each instrument.

#### 3.1.1 Volcanosonda

The Volcanosonda instrument is a custom-designed multi-gas sensor package developed as part of the VOLANDO project, a joint effort between the Space Systems Laboratory of the University of Pisa and the Remote Sensing Group of INGV-ONT. The project aims to develop a small, lightweight, and low-cost instrument, which can be deployed into volcanic plumes using sounding balloons to perform in-situ measurements.

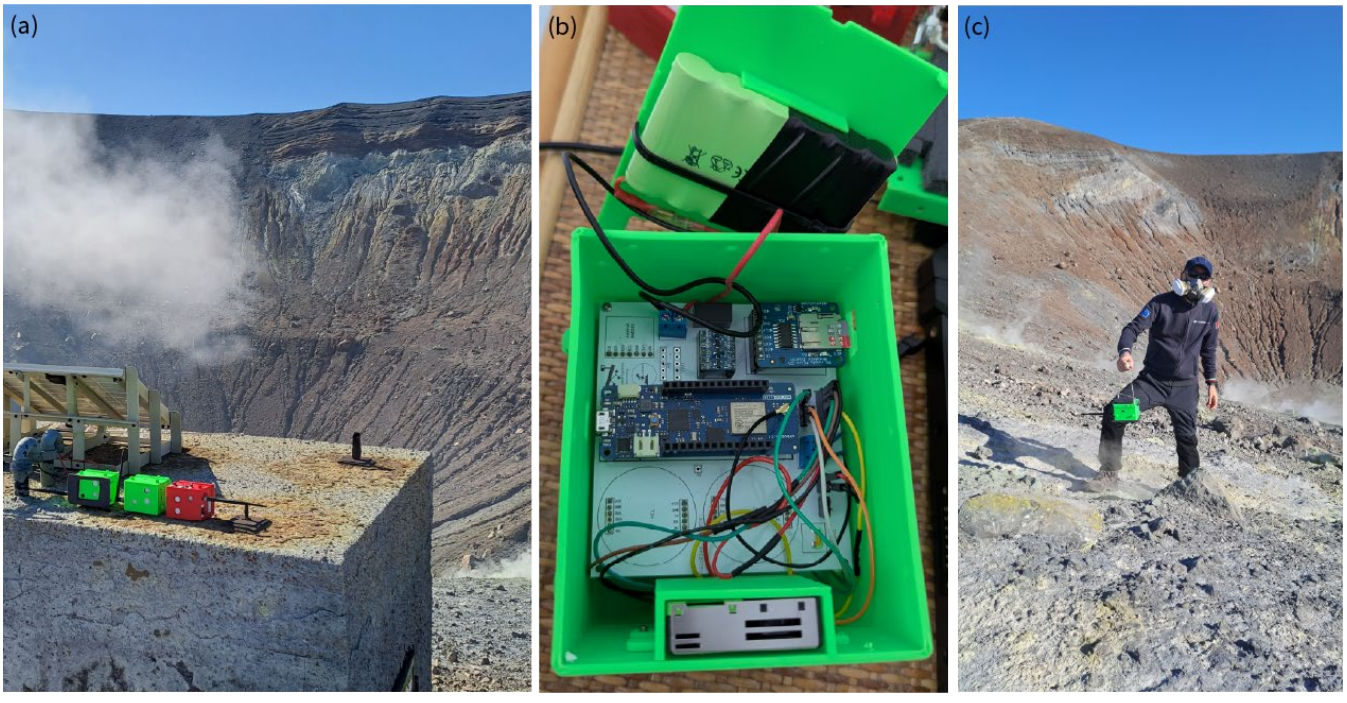


**Figure 2: Photos of the volcanosonda. (a) The volcanosonda named 1D, 3D and 7D at the La Fossa crater. (b) Internal view of the Volcanosonda instrument. (c) A Volcanosonda instrument being carried by an INGV researcher during the field campaign.**

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The Volcanosonda has dimensions of 14.0 cm × 11.7 cm × 9.5 cm and has a mass of 450 g. The instrument consists of a set of sensors integrated onto a circuit board, designed to measure ash concentration and key volcanic gases ($SO_2$ and $CO_2$), as well as atmospheric parameters including pressure, relative humidity, and temperature. The Volcanosonda acquires data at a frequency of 1 Hz, which is stored in onboard memory while simultaneously being transmitted to a ground station for real-time visualization via the Long Range (LoRa) protocol operating in the 868 MHz ISM band.

The $SO_2$ sensor is an electrochemical $SO_2$-2000 developed by SemeaTech, the $CO_2$ sensor is a low power Non-Dispersive InfraRed (NDIR) CozIR-LP (5000 ppm) developed by Gas Sensing Solutions and the particles concentration is measured using an optical particulate matter (PM) sensor SPS30 developed by Sensirion. The PM sensor provides the mass concentration for four particle size ranges: PM1, PM2.5, PM4, and PM10, which represent particles with diameters equal to or smaller than these values. The $SO_2$ sensor was calibrated at the Laboratory of the University of Palermo, and Table 1 provides a summary of the calibration measurements performed. Based on these data, the mean percentage error was determined to be approximately 18%. This value was subsequently used to calibrate all $SO_2$ measurements.

In contrast, for $CO_2$ measurements, only nominal pressure compensation was applied. According to the official documentation, the sensor is pre-calibrated at a reference pressure of 1013 mbar. When ambient pressure deviates from this value, the measurement varies by approximately 0.14% per mbar. The compensation was applied using Equation (1), where $V_o$ represents the original value, $V_c$ the compensated value and $\Delta P$ represents the pressure difference between the reference value of 1013 mbar and the ambient pressure at which the measurements were taken. According to the manufacturer, the $CO_2$ sensor accuracy is approximately ±30 ppm, with an additional ±3% of the measured value.

$$V_c = V_o + \left(\frac{\Delta P * 0.14}{100}\right) * V_o \qquad (1)$$

**Table 1.** Summary of the calibration procedure and results for the $SO_2$ sensor.

| Test N° | Reference conditions | | Measurements | | Percent error [%] |
|---|---|---|---|---|---|
| | Value ± 4,0 [ppm] | Flux [L/min] | Value [ppm] | Bias [ppm] | |
| 1 | 30.0 | 1.0 | 34.6 | 0.08 | 15.33 |
| 2 | 30.0 | 1.0 | 34.6 | 0.3 | 15.33 |
| 3 | 30.0 | 1.0 | 31.8 | 0.3 | 6.00 |
| 4 | 30.0 | 1.0 | 34.9 | 0.2 | 16.33 |
| 5 | 30.0 | 1.0 | 36.4 | 0.2 | 21.33 |
| 6 | 30.0 | 1.0 | 36.2 | 0.2 | 20.67 |
| 7 | 30.0 | 1.0 | 35.7 | 0.2 | 19.00 |
| 8 | 5.0 | 1.0 | 6.3 | 0.1 | 26.00 |
| 9 | 88.4 | 1.0 | 106.5 | 0.0 | 20.48 |

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### 3.1.2 MiniGas NTX-PRO

The miniGAS NTX-PRO (see Figure 3) (Pieri et al., 2013; Silvestri et al., 2023; Stix et al., 2018; Vernier et al., 2020) is a portable multi-gas concentration measurement device weighing 1.5 kg, equipped with sensors for temperature, pressure, relative humidity, $SO_2$, and $H_2S$ (electrochemical), along with a NDIR sensor for $CO_2$. It also includes a Global Navigation Satellite System (GNSS) module, onboard data storage, and a mid-range Radio Frequency (RF) telemetry system with a connectivity range of up to 1.5 km, enabling real-time and remote in situ gas data acquisition.

With dimensions of 28 cm × 12 cm × 12 cm, the miniGAS NTX PRO is enclosed in an aerodynamic carbon fiber casing that protects the electronics from rain, vapours, ash, and wind. Its compact design makes it suitable for integration into small multirotor or fixed-wing drones, ground vehicles, or for handheld use in the field.

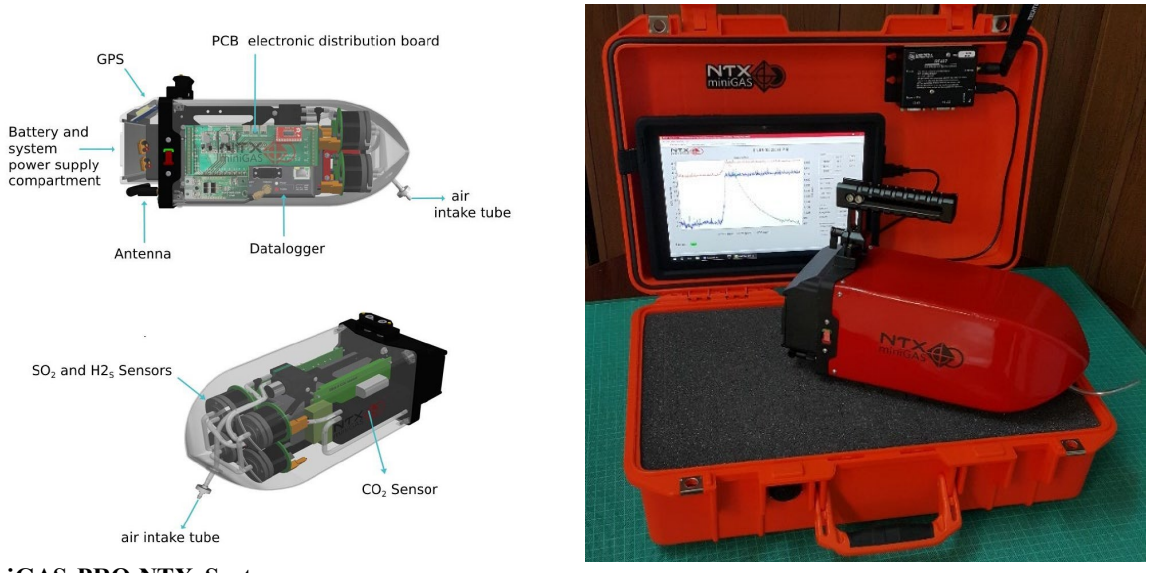


**Figure 3: MiniGAS PRO-NTX System.**

The PRO version incorporates a Campbell CR310 datalogger, which records measurements from a PP Systems SBA-5 OEM $CO_2$ infrared spectrometer (0–2000 ppm range) that also includes a solid-state water vapor pressure sensor (0–40 mbar range). Additionally, the datalogger captures signals from up to four City Technology (UK) electrochemical sensors: two for $SO_2$ (EZT3ST/F; 0–200 ppm and 2TD2G-1A; 0–10 ppm), one for $H_2S$ (2TC4E-1AEZT3H; 0–50 ppm), and an optional $H_2$ sensor (T3HYT; 0–100 ppm).

Gas is sampled via an inlet positioned 1.2 meters away from the drone's core, a distance chosen to minimize disturbance from rotor-induced airflow and to ensure sampling of a more representative, undisturbed plume. The sample is drawn through the system using ¼-inch Polytetrafluoroethylene (PTFE) tubing and a compact diaphragm pump operating at ~1.2 liters per minute. A 1.2 µm PTFE Teflon filter at the inlet prevents the entry of dust, particles, and fine droplets into the system.

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Environmental parameters such as time, temperature, pressure, relative humidity, and GNSS location are recorded alongside gas concentration data. All data are transmitted and stored at a 1 Hz sampling rate, with real-time communication to a laptop via a Campbell Scientific RF-407 RPSMA radio transmitter operating in the 915–928 MHz frequency band.

The main features of the miniGAS PRO are listed in Table 2. The instrument has been deployed in several field campaigns (Buongiorno et al., 2021, 2024; Diaz et al., 2015; de Moor et al., 2019; Pieri et al., 2013; Silvestri et al., 2015, 2016, 2021, 2023; Stix et al., 2018; Vernier et al., 2020).

**Table 2.** MiniGAS PRO-NTX Components.

| Parameter | Description |
|---|---|
| Data logger | Campbell CR310 |
| $CO_2$ Sensor | 0–2000 ppm. PP System IR Spectrometer (SBA-5 OEM) |
| $H_2O$ Sensor | 0–40 mbar range. Solid-state H2O partial pressure. |
| $SO_2$ Sensor (High) | 0–200 ppm. Electrochemical City Technology. ECEZT3ST/F |
| $SO_2$ Sensor (Low) | 0–10 ppm. Electrochemical City Technology 2TD2G-1A |
| $H_2S$ Sensor | 0–50 ppm. Electrochemical City Technology 2TC4E-1AEZT3H; |
| Pump | 1.2 lpm Thomas diaphragm pump |
| GNSS | Garmin 18x 5Hz GPS Navigator |
| Temperature | Thermocouple Type-K Glass Insulated |
| Radio | 915–928 Mz . RF-407 RPSMA radio transmitter Campbell Scientific |
| Battery | LiPO 2200mAh. 11.1V. 5hr operation / Hot swappable |

### 3.1.3 HAPSITE SCOUT miniGAS

The HAPSITE Scout (see Figure 4) (Pieri et al., 2013; Silvestri et al., 2023; Stix et al., 2018; Vernier et al., 2020) is a portable multi-gas analysis system similar to the miniGAS NTX-PRO version but developed in 2024 by INFICON, an international technology company specialized in the manufacture of instruments, sensor technologies, and process control monitoring for vacuum and gas analysis. It is designed for drone, UAV and robotic integration as well as hand portable and vehicle mobility surveys. It also incorporates a gas concentrator cartridge to collect a specific sample for further Gas Chromatography with Mass Spectrometry (GC-MS) analysis after collection. Figure 4 shows the Scout miniGAS attached to a drone for volcanic plume concentration mapping.

The Hapsite Scout uses the same sensors and geometry as the miniGAS NTX-PRO as described in Table 2 and Figure 3, with the addition of the gas sampling cartridge. The cartridge can also be substituted by a 1 L sample bag for sample collection and analysis.

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**Figure 4: Hapsite Scout miniGAS System.**

### 3.1.4 Multi-Gas LabVulc

The Multi-GAS LabVulc (Aiuppa et al., 2021, 2025; Burton et al., 2023; Liu et al., 2020) is a custom-made multi-component gas analyzer system designed for the real-time measurement of volcanic gases, specifically $CO_2$, $SO_2$, $H_2S$, $H_2$, and $H_2O$, at a frequency of 1 Hz. Compact, lightweight, and robust, the instrument is built for field use, especially during campaign-based volcanic gas surveys.

Weighing only 4 kg and housed in a rugged Peli case (33 × 29 × 15 cm), the system integrates commercially available components within a user-friendly and reliable setup. At the core of the instrument is a Campbell Scientific CR6 datalogger with integrated Wi-Fi, which manages data acquisition and communication. The system records $CO_2$ concentrations using a NDIR sensor (0–1% range) that also includes a pressure sensor, while additional electrochemical sensors (City Technology, UK) monitor $SO_2$, $H_2S$, and $H_2$, each up to 200 ppm. Environmental parameters such as temperature, atmospheric pressure, relative humidity, and GNSS location are also recorded continuously.

Gas sampling is carried out using ¼ inch PTFE tubing and a compact diaphragm pump with a flow rate of approximately 1.2 liters per minute. A 1 µm PTFE Teflon filter at the inlet prevents dust, particles, and fine droplets from entering the system, ensuring sensor protection and data integrity.

The instrument is powered by a rechargeable Lithium polymer (LiPO) 4S or Lithium iron phosphate ($LiFePO_4$) battery, allowing for fully portable operation. It supports two main operational modes: a portable mode, where acquisition is manually started and stopped by the operator during field surveys, and a permanent mode suitable for fix monitoring installations.

All acquired data are stored in Comma-Separated Values (CSV) format, with each recording session saved as a separate file. The system allows real-time data visualization on tablets or smartphones (iOS or Android) via a 2.4 GHz Wi-Fi connection using the Campbell Scientific LoggerLink App.

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**Figure 5: Multi-GAS LabVulc.**

With its compact design, precise measurements, and ease of use, the Multi-GAS LabVulc is particularly suited for monitoring fumarolic emissions, plume and conducting volcanic gas studies in the field.

Sensor calibration is performed in the laboratory using a gas mixer to prepare mixtures of synthetic air and standard gases. The main features of the Multi-Gas LabVulc are listed in Table 3.

**Table 3.** Multi-GAS LabVulc Components.

| Parameter | Description |
|---|---|
| Data logger | Campbell Scientific CR6 WiFi |
| $CO_2$ Sensor | 0-1 %. Edinburgh Gascard NG infrared gas sensor |
| $SO_2$ Sensor | 0–200 ppm. Electrochemical; City Technology. (Part n° TD2G-1A) |
| $H_2S$ Sensor | 0–200 ppm. Electrochemical; City Technology. (Part n° TC4G-1A) |
| $H_2$ Sensor | 0–200 ppm. Electrochemical; City Technology. (Part n° TE1G-1A) |
| Pump | 1.2 lpm, Xavitech pump |
| GNSS | Adafruit Ultimate GPS Breakout |
| Rh/T | Humidity / temperature sensors KVM series |
| Pressure | Sensor on board Edinburgh Gascard |
| Transmission | WiFi 2.4 Giga – Tablet Android – LoggerLink Campbell App |
| Battery | LiPO 4S 5000 mAh 14.8V - with DC-DC stepdown |

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### 3.1.5 Multigas Drone PP

The Multi-GAS Drone PP (Aiuppa et al., 2021, 2025; Burton et al., 2023; Liu et al., 2020) is also a custom-made multi-component gas analyzer system designed for the real-time measurement of volcanic gases, specifically $CO_2$, $SO_2$, $H_2S$, and $H_2O$, at a frequency of 1 Hz similar to the Multi-Gas LabVulc. Compact, lightweight, and robust, the instrument is built for field use, especially during campaign-based volcanic gas surveys using drones.


**Figure 6: Multi-GAS Drone PP.**

Weighing only 875 g and housed in a light 3D printed case (13 × 9 × 16 cm), the system integrates commercially available components within a user-friendly and reliable setup. At the core of the instrument is a custom-made (INGV developed) Teodora board datalogger, based on a Teensy microcontroller, with integrated Wi-Fi or radio link, which manages data acquisition and communication. The system records $CO_2$ concentrations using a PP System IR Spectrometer sensor, the additional electrochemical sensors (City Technology, UK) monitor $SO_2$ (200 ppm range) and $H_2S$ (up to 50 ppm). Environmental parameters such as temperature, atmospheric pressure, and GNSS location are also recorded continuously. Gas sampling and powering of the instrument are done similarly to the Multi-Gas LabVulc setup. The instrument supports drone mode operations but is also possible to use in a portable mode, where acquisition is manually started and stopped by the operator during field surveys, and a permanent mode suitable for fix monitoring installations.

All acquired data are stored in CSV format and the system allows real-time data visualization on tablets or smartphones (iOS or Android) via a 2.4 GHz Wi-Fi connection or a radio link for drone mode, using a custom-made webserver app (developed at INGV-OE and Di3A-UniCT).

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The Multi-GAS Drone PP is particularly suited for monitoring, plume and conducting volcanic gas studies in the field using fixed or rotary wing drones.

Sensor calibration is performed in the laboratory using a gas mixer to prepare mixtures of synthetic air and standard gases. The main features of the Multi-Gas Drone PP are listed in Table 4.

**Table 4.** Multi-GAS Drone PP Components.

| Parameter | Description |
|---|---|
| Data logger | Teodora main board - Teensy 3.5 microcontroller |
| $CO_2$ Sensor | 0–5000 ppm. PP System IR Spectrometer (SBA-5 OEM) |
| $SO_2$ Sensor | 0–200 ppm. Electrochemical; City Technology. (Part n° TD2G-1A) |
| $H_2S$ Sensor | 0–50 ppm. Electrochemical; City Technology. (Part n° TC4E-1A) |
| Pump | 0.4 lpm Thomas diaphragm pump |
| GNSS | Adafruit Ultimate GPS Breakout |
| PTU | Pressure, Humidity, Temperature sensors: BlueDot BME280 Breakout Board |
| Transmission | RFD868 Long-range radio data modem operating in the 865-870MHz frequency band |
| UBEC | Matek UBEC DUO, 4A/5-12V & 4A/5V |
| Battery | LiPO 4S 1300 mAh 14.8V |

### 3.2 Experiment

The objective of the experiment was to test the new Volcanosonda instruments and compare its measurements with other mature and well-established multi-gas instruments.

The experiment was carried out on the rim of the La Fossa crater on April 10, 2025, beginning at 10:26 local time (LT). At this time, all five instruments were positioned together in a fixed location (see Figure 7a), indicated by the yellow star in Figures 7c and 7d. The instruments collected measurements at this fixed point for approximately 25 minutes.

Afterward, the instruments were carried along the crater rim to acquire measurements while passing through the fumarolic area, as shown in Figure 7b and by the path indicated in Figure 7d. The first transect started at the yellow star and ended at the red point indicated in Figure 7c and 7d (~10 minutes). Finally, a second transect was conducted from the red point to the green point, also shown in Figure 7c and 7d (~14 minutes).

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**Figure 7. Description of the experiment. (a) Instruments positioned together at a fixed location for data collection. (b) Instruments being carried along the rim of the La Fossa crater, passing through the fumarolic area. (c) West-facing photo showing the crater rim, visible fumaroles and key reference points: start (yellow), middle (red) and end (green). (d) Satellite view of the crater with the key reference points and the path followed during the experiment.**

## 4 Data Analysis

This section presents the measurements acquired by the Volcanosonda sensors, along with the results of the cross-comparison with the data collected by the other four instruments: HAPSITE SCOUT miniGAS, MiniGas NTX-PRO, Multi-Gas Labvulc, and Multigas Drone PP.

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The experiment spanned approximately 50 minutes and was divided into three key time intervals for analysis. The first interval (T1) corresponds to the measurements collected at a fixed position at the start point and at the beginning of the first transect, before entering the fumarolic area. The second interval (T2) includes data gathered during the first transect, from the start point to the middle point. The third interval (T3) corresponds to the second transect, conducted from the middle point to the end point. Both the individual intervals and the complete time series are analysed to provide a comprehensive overview of the experiment.

### 4.1 Volcanosonda measurements

All measurements collected by the Volcanosonda sensors are presented in Figure 8, which also indicates the three-time intervals (T1, T2 and T3). Figure 8a shows the data for temperature and relative humidity (RH). It is notable that RH remains relatively constant during T1, while significant variations occur during T2 and T3, corresponding to the periods when the instruments passed through the fumarolic area.

The data for $SO_2$ and pressure are shown in Figure 8b. It can be observed that $SO_2$ concentrations during T1 are low, with a mean value of 10 ppmv, while during T2 and T3, when the instrument was within the fumarolic area, the concentrations increase significantly, reaching maximum values of approximately 150 ppmv and a mean of 30.8 and 25.9 ppmv respectively. The pressure values show a descending trend from T2 and T3, which is consistent with the topography of the crater rim; as shown in Figure 7c, the middle point (marked in red) is slightly elevated compared to the start point.

In Figure 8c, $CO_2$ concentrations are shown alongside $SO_2$ concentrations for comparison. As explained in Section 3.1.1, the data presented have been corrected for pressure and calibrated for $CO_2$ and $SO_2$, respectively. During T1, the mean $CO_2$ concentration was 548 ppmv. This value increased to 891.4 ppmv during T2 and 966.1 ppmv during T3, with maximum concentrations surpassing 2300 ppmv. Figure 8c also shows a good agreement between $CO_2$ and $SO_2$ concentrations, this is consistent with results obtained in previous works (Silvestri et al., 2023; Vernier et al., 2020). However, the $CO_2$ data show a noticeable delay relative to the $SO_2$ data, likely due to the response time of the $CO_2$ sensor. The response time is nominally around 30 seconds for the $CO_2$ sensor, but it is limited by diffusion through the membrane windows of the sensor, which becomes critical during rapid changes in concentration. This simultaneous analysis of $CO_2$ and $SO_2$ concentrations offers key information about volcanic gas composition and emission dynamics (Aiuppa et al., 2005).

Figure 8d presents the $PM_{10}$ concentrations alongside the $SO_2$ data and Figure 8e displays the full set of particulate matter (PM) concentrations, all of which exhibit similar behavior across the three-time intervals. Finally, Figures 8f–8i present the mean PM concentrations across four particle size ranges (0.0–1.0, 1.0–2.5, 2.5–4.0, and 4.0–10.0 µm). Concentrations are reported for each time interval (T1, T2, T3) and for the entire time series, showing a log-normal distribution.

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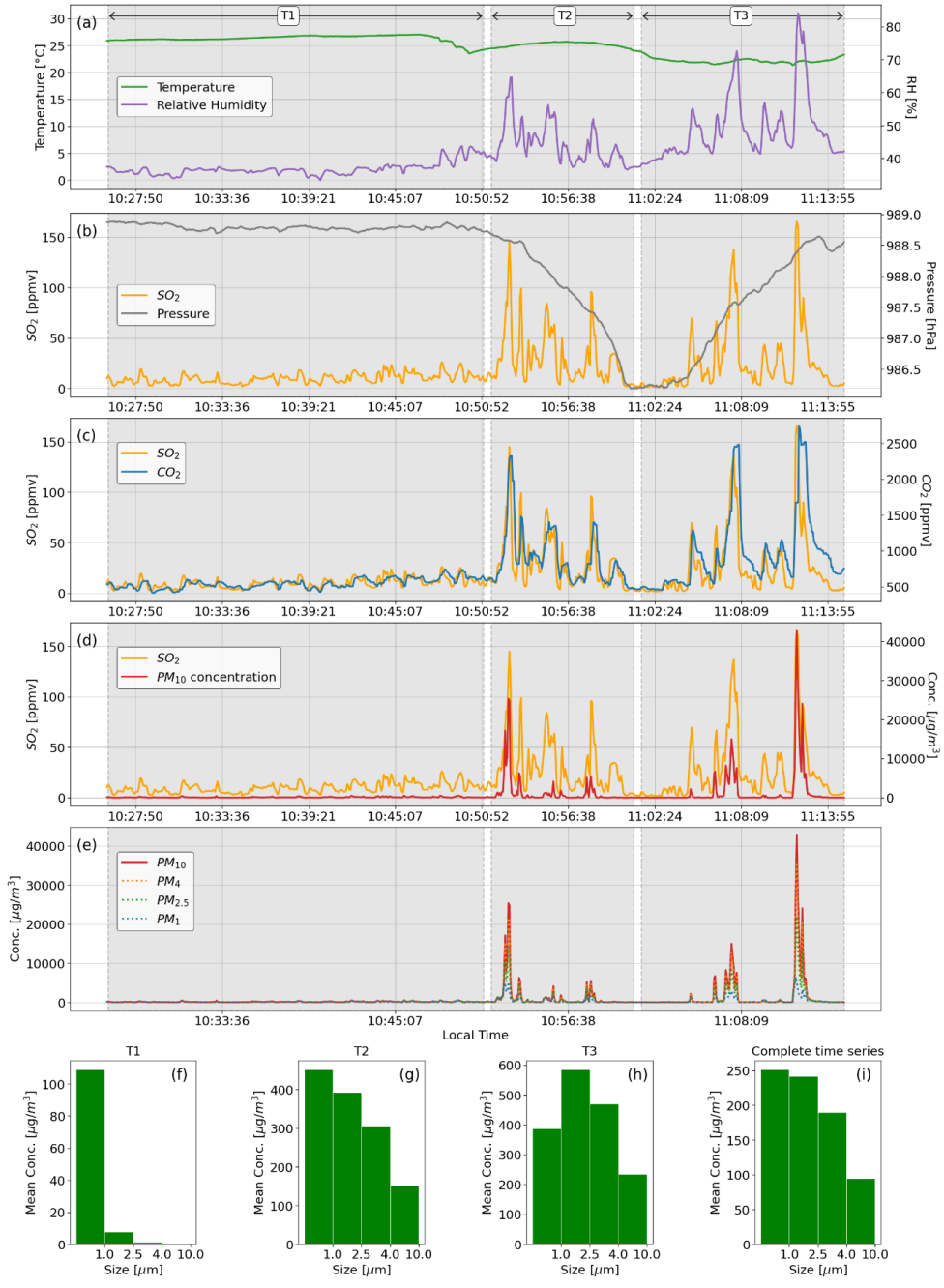


**Figure 8. Volcanosonda measurements. The three defined time intervals (T1, T2, and T3) are also specified in the figures. (a) Temperature and relative humidity measurements. (b) $SO_2$ and pressure measurements. (c) $SO_2$ and $CO_2$ measurements. (d) $SO_2$ and $PM_{10}$ measurements. (e) PM concentration measurements for $PM_1$, $PM_{2.5}$, $PM_4$, and $PM_{10}$. (f)-(i) Mean PM concentrations for four particle size ranges (0.0–1.0, 1.0–2.5, 2.5–4.0, and 4.0–10.0 µm) reported for each time interval (T1, T2, T3) and the complete time series.**

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### 4.2 Comparative Analysis of Measurements

This subsection presents the cross-comparison of measurements collected by the five instruments. Figure 9a shows the $CO_2$ measurements across all instruments, while Figure 9b presents the corresponding $SO_2$ measurements. An appreciable agreement is observed among the measurement data collected across the instruments. Table 5 presents the mean $CO_2$ and $SO_2$ concentrations, which confirm the observed correspondence. That agreement is observed across instruments and across the different time intervals.

When examining the Volcanosonda $SO_2$ data and comparing it with the other instruments, the agreement appears stronger than that observed for $CO_2$ measurements. The discrepancies observed in the $CO_2$ measurements may be attributed to the fact that the sampled gas was not identical across instruments, as the measurements were taken while carrying the instruments by hand and walking one after the other, as illustrated in Figure 7b. Additionally, with reference to the $CO_2$ sensor, these differences could be influenced by the apparently slower response time and the accuracy of the $CO_2$ sensor.

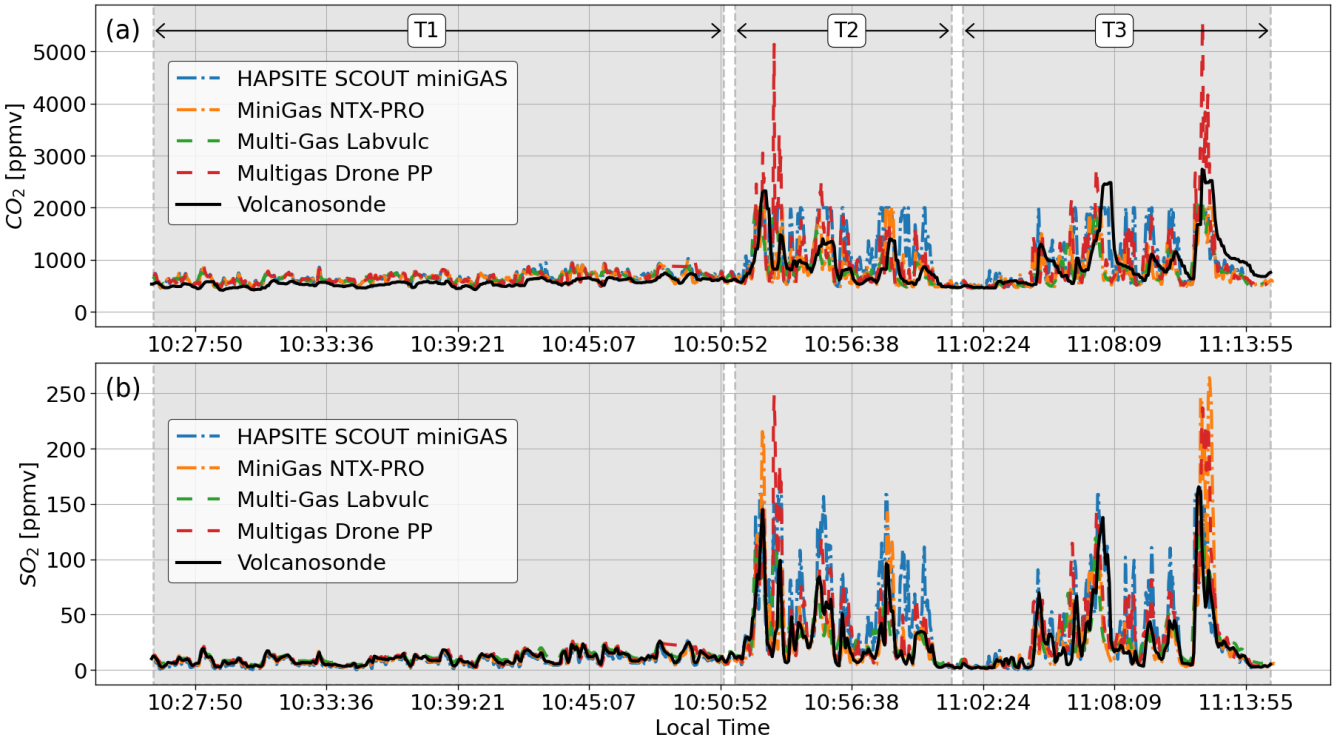


**Figure 9. Measurement Comparison. (a) $CO_2$ data and (b) $SO_2$ data collected by the five instruments. The gray shaded areas indicate the defined time intervals.**

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**Table 5.** Mean $CO_2$ and $SO_2$ concentrations (in ppmv) obtained from each instrument across the defined time intervals (T1, T2, T3) and for the entire time series.

| Variable | Time interval | Instruments | | | | |
|---|---|---|---|---|---|---|
| | | Volcanosonda | HAPSITE SCOUT miniGAS | MiniGas NTX-PRO | Multi-Gas Labvulc | Multigas Drone PP |
| $CO_2$ | T1 | 548.0 ± 17 | 658.9 ± 7 | 646.9 ± 6 | 649.9 ± 13 | 649.4 ± 6 |
| | T2 | 891.4 ± 28 | 1088.2 ± 11 | 823.4 ± 8 | 860.8 ± 17 | 1011.2 ± 10 |
| | T3 | 966.1 ± 30 | 880.5 ± 9 | 754.2 ± 8 | 778.6 ± 16 | 927.9 ± 9 |
| | Total time series | 727.8 ± 23 | 787.9 ± 8 | 707.3 ± 7 | 724.9 ± 14 | 797.7 ± 8 |
| $SO_2$ | T1 | 10.0 ± 2 | 8.2 ± 0.2 | 9.2 ± 0.2 | 11.8 ± 0.2 | 10.2 ± 0.2 |
| | T2 | 30.8 ± 6 | 40.1 ± 0.8 | 26.7 ± 0.5 | 31.4 ± 0.6 | 39.5 ± 0.8 |
| | T3 | 25.9 ± 5 | 24.6 ± 0.5 | 21.6 ± 0.4 | 25.0 ± 0.5 | 33.3 ± 0.7 |
| | Total time series | 18.2 ± 3 | 17.6 ± 0.4 | 15.8 ± 0.3 | 19.2 ± 0.4 | 22.5 ± 0.5 |

Subsequently, the $CO_2$ and $SO_2$ measurements from each instrument were time-shifted using cross-correlation analysis. This procedure was performed using the RatioCalc software (Tamburello, 2015) enabling alignment of the signal peaks, as demonstrated in Figure 10. This alignment is important for estimating the $CO_2/SO_2$ ratio, which is discussed in the following subsection. The aligned $CO_2$ and $SO_2$ measurements for all five instruments are presented in Figures 10a–10e, illustrating the correlation between the $CO_2$ and $SO_2$ measurements across the instruments.

#### 4.2.1 $CO_2/SO_2$ ratios

The previously aligned $CO_2$ and $SO_2$ data were used to estimate the instantaneous $CO_2/SO_2$ ratios for each instrument, which are presented in Figure 11, where the comparison shows a generally good agreement across the instruments. The determination of the volcanic $CO_2/SO_2$ ratios represent a key parameter in volcano monitoring because it is a marker based on the contrasting solubility properties of $CO_2$ and $SO_2$ (Aiuppa et al., 2025; Tamburello, 2015).

Additionally, the $CO_2/SO_2$ ratios for each instrument during each time interval, were estimated using the RatioCalc software (Tamburello, 2015). For this estimation the saturated values, especially those present in the HAPSITE SCOUT miniGAS and MiniGas NTX-PRO data (see Figure 10b and 10c) were not considered in the analysis.

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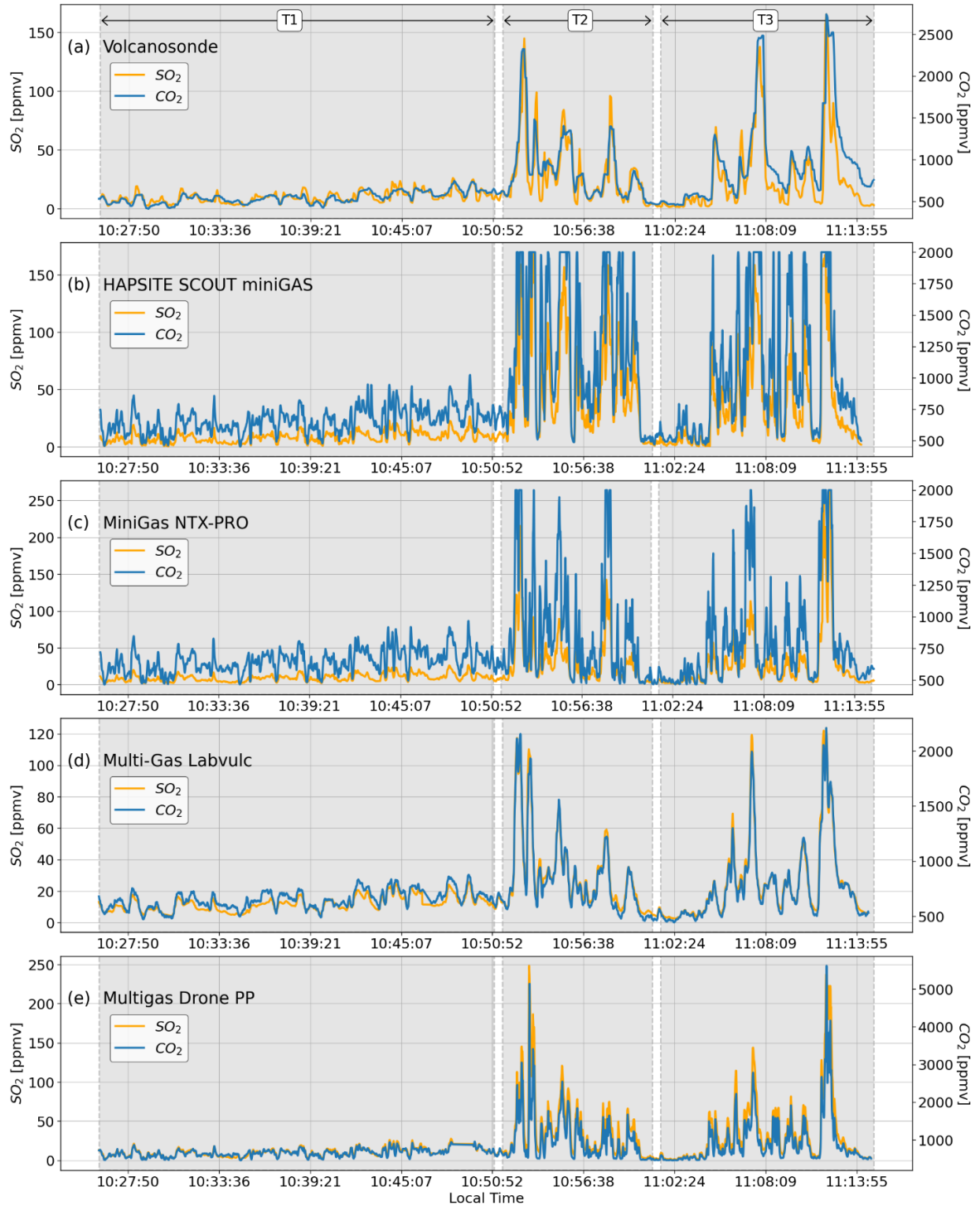


**Figure 10. Aligned $CO_2$ and $SO_2$ measurements for: (a) Volcanosonda, (b) HAPSITE SCOUT miniGAS, (c) MiniGas NTX-PRO, (d) Multi-Gas Labvulc and (e) Multigas Drone PP.**

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The $CO_2/SO_2$ ratios correspond to the slope values obtained from a linear regression model applied to the measurement data (Aiuppa et al., 2005; Stix et al., 2018; Tamburello, 2015). The resulting ratio values are summarized in Table 6, while the corresponding model fits are illustrated in Figure 12, which also includes the coefficients of determination ($R^2$) for each case. The coefficients $R^2$ quantify how strong is the correlation between $CO_2$ and $SO_2$ measurements for each instrument across the defined time intervals (T1, T2, T3) and for the complete time series.

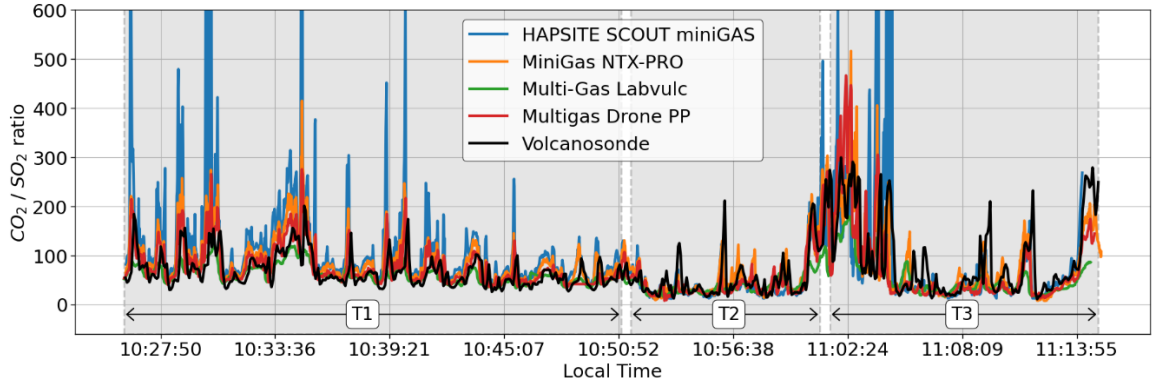


**Figure 11. Instantaneous $CO_2/SO_2$ ratio comparison.**

**Table 6.** Summary of $CO_2/SO_2$ ratios for each instrument.

| Time interval | Instruments | | | | |
|---|---|---|---|---|---|
| | **Volcanosonda** | **HAPSITE SCOUT miniGAS** | **MiniGas NTX-PRO** | **Multi-Gas Labvulc** | **Multigas Drone PP** |
| T1 | 11.12 | 19.52 | 17.11 | 16.47 | 17.75 |
| T2 | 12.56 | 13.62 | 13.67 | 14,48 | 14.52 |
| T3 | 14.64 | 15.62 | 11.54 | 13,97 | 14,87 |
| Total time series | 14.89 | 15.05 | 12.10 | 13,61 | 14,35 |

In general, the $CO_2/SO_2$ ratios obtained for the Volcanosonda are in good agreement with the ratios obtained for the other four instruments, as we can see in Table 6. It should be noted, however, that a trend is observed across the T1, T2, and T3 intervals for the four other instruments, in which the $CO_2/SO_2$ ratios during T1 are slightly higher than those during T2 and T3. This trend is reasonable, as during T2 and T3 the instruments went into the fumarolic area, where $SO_2$ concentrations increased, leading to lower $CO_2/SO_2$ ratios (Aiuppa et al., 2005; Vernier et al., 2020). Whereas during T1, the Volcanosonda reported its lowest $CO_2/SO_2$ ratio, with a value of 11.12. Another notable difference is observed in Figure 12a, where the linear regression for the Volcanosonda during T1 shows an $R^2$ value of 0.64, the lowest among all the analyses performed across the instruments. These discrepancies may likely be attributed to the accuracy and time response of the $CO_2$ sensor, as mentioned previously in the sections 4.1 and 4.2.

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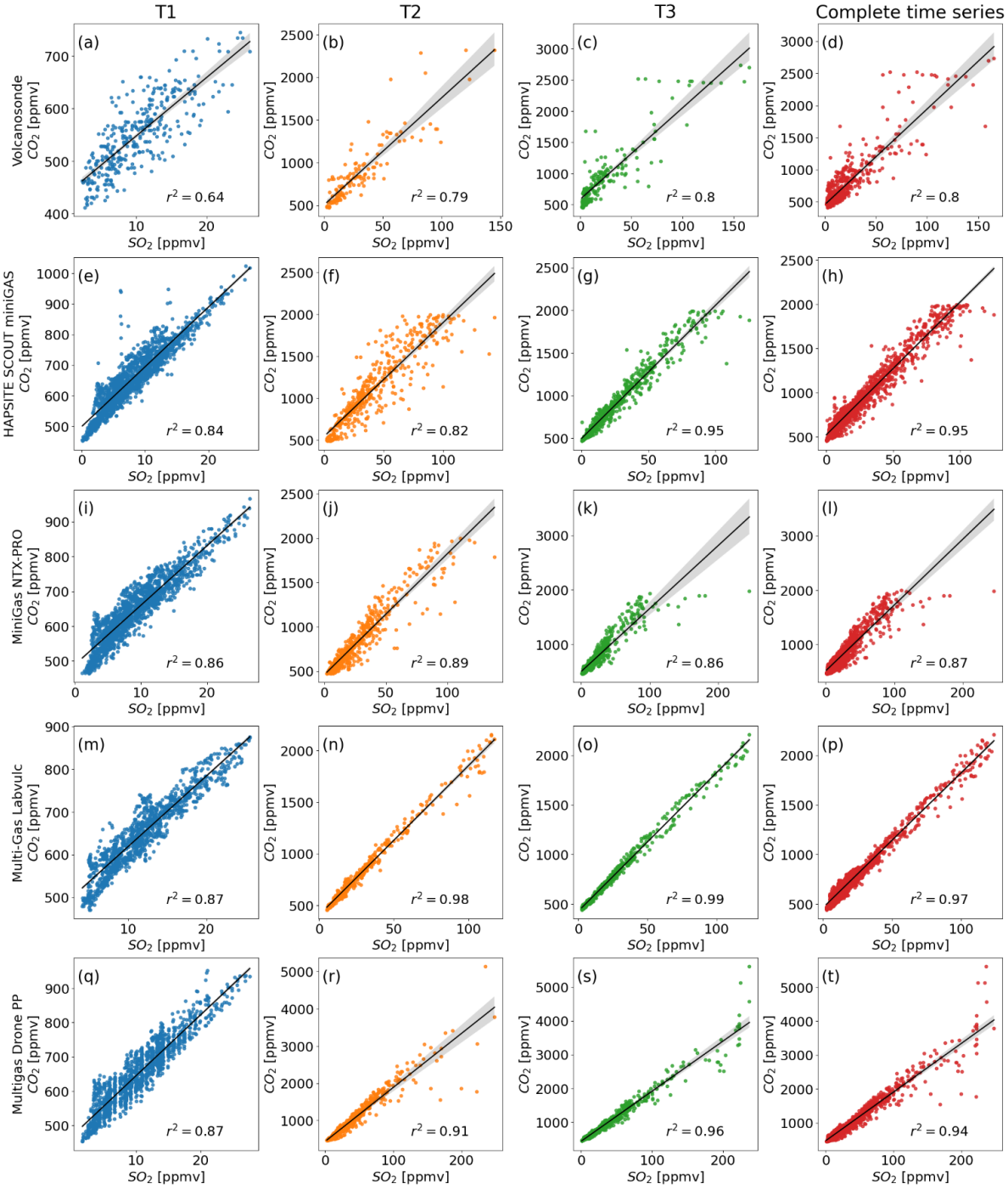


**Figure 12. Linear regression comparison between $CO_2$ and $SO_2$ measurements. The columns represent the time intervals (T1, T2, and T3), while the rows correspond to each instrument. The coefficients of determination ($R^2$) are displayed for each case.**

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## 4 Conclusions

This work presents the experiment results from a new lightweight and low-cost multi-gas sensor instrument called "Volcanosonda", which was developed to fly into volcanic clouds to perform in-situ measurements. The principal objective of this new multi-gas sensor is to enhance the characterization of several volcanic cloud parameters that are difficult to retrieve accurately, such as ash PSD, particles and gases concentration and cloud geometry (altitude and thickness). With all this information the idea is then to improve and validate ash and $SO_2$ retrievals from both satellite and ground-based observations.

Other authors have been carried out in-situ measurements using multi-gas sensor instruments (Pieri et al., 2013; Silvestri et al., 2023; Stix et al., 2018; Vernier et al., 2020), but the novel of the Volcanosonda is the lightweight and low-cost. Therefore, a cross-comparison experiment was performed using four other mature and well-established multi-gas instruments. Compared to the other multi-gas instruments the Volcanosonda is 50% to 90% lighter.

The results showed that the Volcanosonda's measurements of $CO_2$ and $SO_2$ concentrations agreed with those of the other instruments. This agreement is evident from the $CO_2/SO_2$ ratio values and the $R^2$ values presented in Table 6 and Figure 12, respectively. The $R^2$ value for the Volcanosonda is 0.64 for T1 and approximately 0.8 for the other time slots. Although these $R^2$ values are slightly lower than those of the other instruments, they still indicate a strong correlation between the $CO_2$ and $SO_2$ measurements.

We identify some differences, especially with the $CO_2$ sensor measurements. We think the differences are related to the time response of the sensor, which becomes critical during rapid changes in concentration. Future work should focus on characterizing the $CO_2$ sensor time response for this application.

However, the other sensors like the $SO_2$ and the optical particulate matter have an optimal performance. Our results are encouraging and our new Volcanosonda instrument is ready for deployment into larger volcanic clouds and helping to enhance the retrieval of volcanic clouds.

## Data availability

All data analysed in this study were obtained from the five instruments described above and will be made available upon reasonable request.

## Author contributions

Writing (original draft preparation): CN and SC. Conceptualization: CN and SC. Data curation: CN, MB, EC, JAD, AF, GG. Formal Analysis: CN, SC, RB, AF, MG, LG, IM, LM, DS. Funding acquisition: SC, RB, SM. Investigation (Data collection): CN, SC, MB, MFB, JAD, AF, GG, MS, AV. Methodology: CN, SC, GG. Project administration: SC, RB, SM. Software: CN and AF. Supervision: SC, RB, SM. Visualization: CN. Writing (review and editing): All authors.

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## Competing interests Data availability

Authors declare no competing interests related to this work.

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