Advanced UAV
http://publish.mersin.edu.tr/index.php/uav
e-ISSN 2822-6976

Launching the SnifferV and Sniffer4D multigas detectors into the active crater of the Poás Volcano in Costa Rica using unmanned aerial systems

Ian Godfrey *[1], **José Pablo Sibaja Brenes** [1], **Maria Martínez Cruz** [2], **Geoffroy Avard** [2], **Khadija Meghraoui** [3]

[1]*Universidad Nacional, Laboratory of Atmospheric Chemistry Costa Rica, Igodfrey@mail.usf.edu; Jose.sibaja.brenes@una.cr*
[2]*Universidad Nacional, Volcanological and Seismological Observatory of Costa Rica, Maria.martinez.cruz@una.cr; geoffroy.avard@una.cr*
[3]*Hassan II Institute of Agronomy and Veterinary Medicine, Unit of Geospatial Technologies for Smart Decision, Morocco, k.meghraoui@iav.ac.ma*

Cite this study: Godfrey, I., Brenes, J. P. S., Cruz, M. M., Avard, G., & Meghraoui, K. (2023). Launching the SnifferV and Sniffer4D multigas detectors into the active crater of the Poás Volcano in Costa Rica using unmanned aerial systems. Advanced UAV, 3 (2), 153-176

Keywords
SnifferV
Drone
Poás Volcano
Crater Lake
Degassing

Research Article
Received:31.08.2023
Revised: 19.10.2023
Accepted:14.11.2023
Published:17.11.2023

Abstract

There are two Sniffer4D V2 devices we have been deploying in the field for scientific research with the Laboratory of Atmospheric Chemistry. We have successfully tested for volcanic emissions at the Turrialba volcano, Irazú volcano, Poás volcano, Arenal volcano and Tenorio volcano in Costa Rica. Sniffer4D - VOCs, O_2, SO_2, CO, CO_2, PM $_{1, 2.5, 10}$, NO_2, O_3, $NO_2 + O_3$ which was used at the Poás Volcano National Park in Costa Rica during February and April of 2022 was now paired with another device specifically configured for volcanic emissions. The SnifferV (Volcanic) - SO_2, CO, CxHy, H_2S, CHL, CO_2, H_2 and HF. These Sniffer devices log longitude and latitude, temperature and humidity and calculate the area tested per each measurement which allowed us to measure the exact fumaroles with precision. There were 3 objectives for our trip to the Poas Volcano National Park 1. The first objective was to attach the SnifferV to the Aki-01 and conduct a flight with this drone system to the degassing fumaroles next to Laguna Caliente inside the active volcano crater of the Poás Volcano National Park. 2. The second objective was to walk with both Sniffer devices to the dormant crater of the Poas Volcano National Park named the Botos Lagoon. 3. The third mission was to hike in between these two craters Laguna Caliente and Botos Lagoon and find an acceptable control station on the eastern rim of the active crater to take gas readings with both Sniffer units.

1. Introduction

For the first time that the International Union of Geological Sciences has made a list of the top 100 sites of geological importance. The Poás Volcano National Park in Costa Rica has made the list. Poás has fascinated scientists since the 19th century, when research here began. Poás is one of the most studied volcanoes in Central America. Scientists have tracked it from the start of the 19th century to the present day.

Its particularity comes not only from the geological characteristics of Laguna Caliente, but also from how eruptions have contributed to the ecosystems and landscape of the National Park. Because of its geological significance and due to the fact, it promotes research for the understanding of the planet itself, the Poás volcano is on the list of the top 100 places of the World Geological Heritage of the International Union of Geological Sciences IUGS.

500,000 visitors visited the Poás Volcano National Park each year before the 2017 eruption making the Poás Volcano one of the most popular tourist attractions in the country. 500,000 park visitors at $15 each is $7,500,000 per year for the SINAC Park Rangers and the Government of Costa Rica. Therefore, the Poás Volcano National Park does represent a strategic economical interest to the nation.

Before the 2017 increase of activity at the Poas volcano there was no limit to how many people could visit the park. On a busy day there were up to 4,000 people that entered to observe the active crater and the crater lake Laguna Caliente. Once the activity began the park closed. Once it reopened in 2019 there was a change to 1,500 people max per day, these people were allowed in the park in groups of 20 but it was required that they wore helmets and they were only allowed to observe the crater for 20 minutes. Since August 2022 the number of people per group has increased to 80 and they are allowed to stay longer than 20 minutes if they choose.

The Poas volcano has periodic eruptions and had a period of increased activity from 2017-2019. In the national park system of Costa Rica special SINAC permitting is required to use drones on this land. "Estudio de las emisions volcanicas y su afectacion a la poblacion cercana." Permit # 112000166 for The Laboratory of Atmospheric Chemistry, Universidad Nacional. There is a gas detector permanently placed at the Mirador or main lookout station at the Poas Volcano. Any SO2 concentrations > 5 ppm average out of a 1 minute of measurement will set off the alarm and the park will close for a period of time until the emissions disperse.

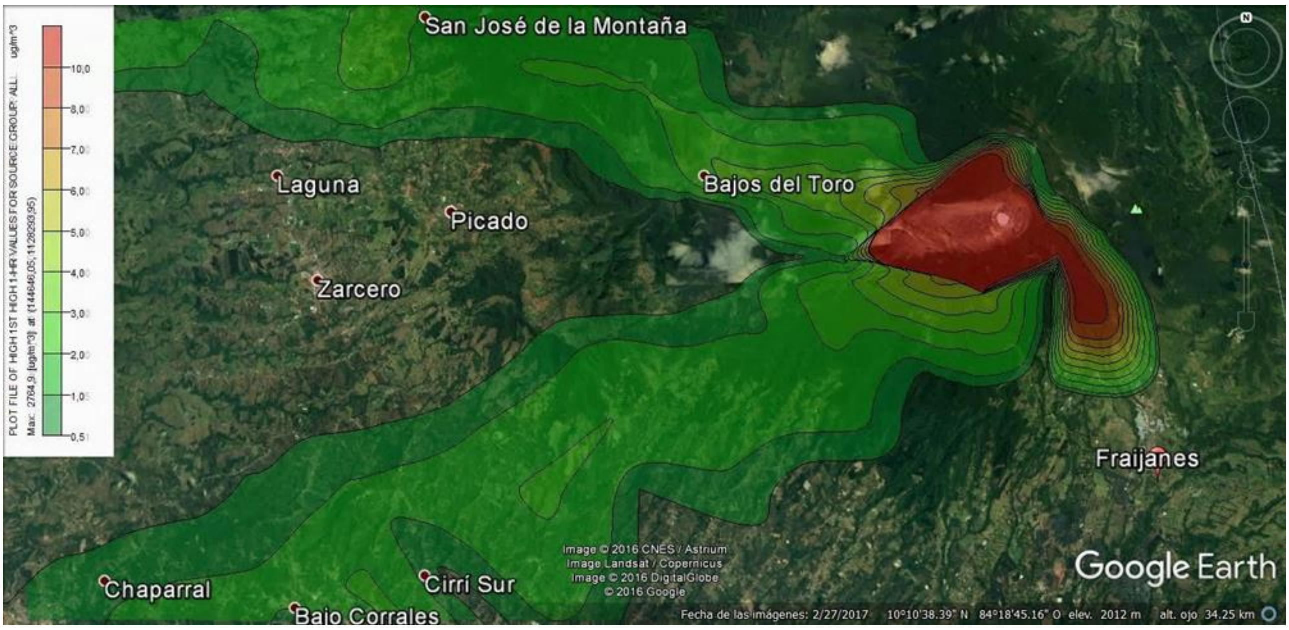


Figure 1. AERMOD Plot of the Poás Eruption on April 13th, 2017.

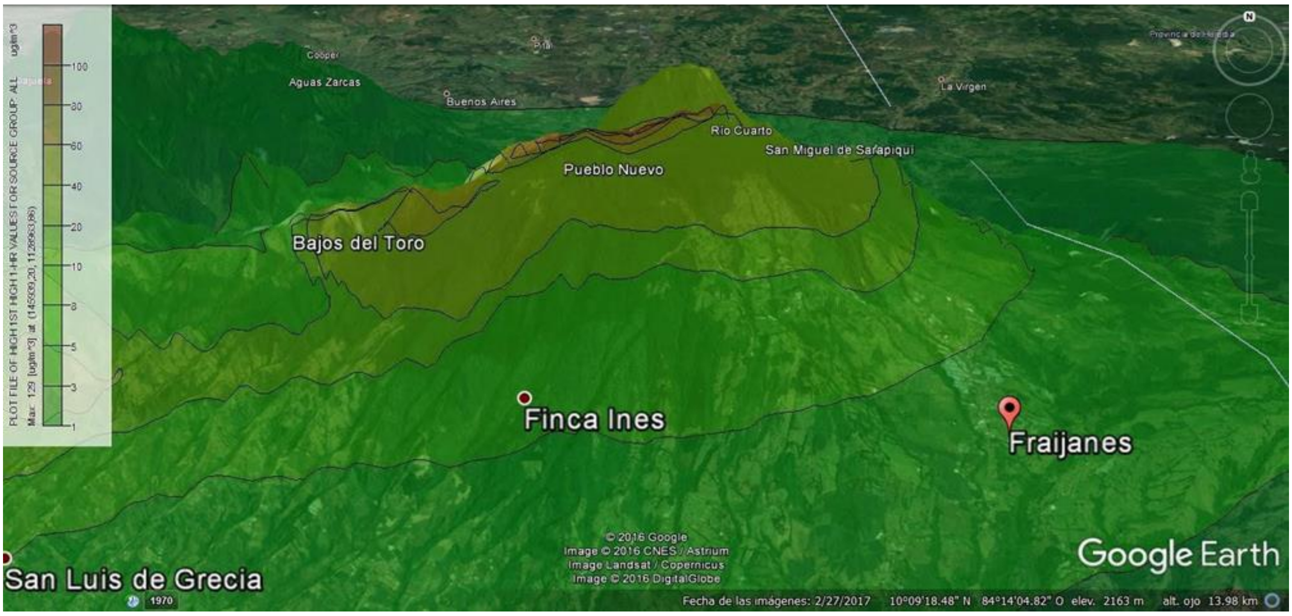


Figure 2. AERMOD Plot of the Poás Eruption on April 14th, 2017.

Early September 2022 a swarm of concerning seismic signals registered on the sizmoghaps located inside the Poás Volcano National Park. The seismographs which are strategically positioned around the Poás Volcano serve as an early warning detection system and precursor to any potential eruption. Because of the increased seismic activity professional researchers were called in to monitor and document any potential geomorphological features that may have changed and to track the volcanic emissions in the active crater of the volcano which holds an extremely hot hyper acidic crater lake Laguna Caliente.

The area to the north of the active crater lake Laguna Caliente started showing signs of increased activity on August 13th, 2022 and it was even more recognizable when ash started entering the light blue hyper acidic crater lake because a significant portion of the lake turned grey. The activity at Poás in early September had increased seismicity signals such as tremors with variable amplitudes and durations, and some long-period earthquakes with magnitudes greater than those recorded throughout all of 2022. The energy of the seismicity had also dramatically increased.

As of the first week of September SO2 emissions coming from the active crater were consistant at 100 tons per day, though on a few occasions the gas emissions were greater, most likely reaching to 300 tons per day. These were the degassing levels recorded from August17-18th Volcanic release of SO2 greater than 500 tons per day was recorded on 2 September. During the first week of September convection cells in the lake were more active and a new one formed in the northern part of Laguna Caliente. This data indicated disturbances in the shallow hydrothermal system of the volcano but did not reflect an influx of magma. Fumarolic degassing and lake convection continued from September 9-13. One Friday September 30th the Poás Volcano had to be closed for 1.5 hours because the SO2 emissions were increasing and the wind to the south blew these gases towards the main lookout point of the Poás volcano.

During 2022 through a collaboration with LAQAT-UNA we brought the Sniffer4D back to the Poás Volcano National Park and also brought a new Sniffer device specifically configured for measuring volcanic emissions named the SnifferV (Volcanic). At the east rim of the active crater of the Poás Volcano we measured volcanic emissions deriving from the active crater and Laguna Caliente. We also walked different sections of the park to monitor for volcanic pollutants in the ambient air quality. Laguna Caliente seen upclose during a cloudy day with fair visibility was photographed with a DJI Mavic 3 on September 17th, 2022.

The Sniffer4D V2 device can be integrated to a series of drones and flown into dangerous areas which helps keep researchers in these exclusive areas safe. The drone video around the eastern crater rim showed us precise locations of degassing fumaroles and we also scanned these fumaroles with thermal IR imaging cameras from FLIR Systems to potentially correlate thermal energy to emission release.

Figure 3. Laguna Caliente of the Poás Volcano September 2022.

Most importantly we tested SO_2, CO_2 and H_2S. CO_2 derives from the volcanic hydrothermal system and both SO_2 and H_2S derive from the magmatic source within the edifice of the volcano. The magmatic system of the volcano is obviously what is most important to monitor for the safety of park guests and the SINAC Park Rangers living within the National Park. Therefore, by logging and tracking these three gases specifically we can get ratios that help us understand the subterranean activity happening below the active crater and the interaction between the hydrothermal and magmatic systems of the Poás Volcano National Park. The Poás volcano main crater has three fumaroles known as the Fumarole Naranja, La Niña and Fumarole Este.

The Sniffer Mapper reports minimum, maximum and average SO_2 measurements. Users have the option to load geo tagged photos to contribute to the gas distribution data and final report generated by the software program. Data can be saved to a Micro SD card or data of air quality can be tracked in real time vis an onboard SIM Chip located inside the Sniffer4D V2. The Sniffer Mapper PC Software has a recommended configuration of

an Intel i5 core with at least 8 GB of data storage and a 1080p resolution of the screen. Sniffer Mapper also offers an option to overlay high definition orthophoto overtop of the satellite image map. This option allows for greater direct observation of important degassing regions like fumarolic fields and active volcano craters. This option allows for enhanced observation of the geological changes often associated with volcanic degassing. Researchers with LAQAT-UNA have been taking measurements using the Sniffer4D and SnifferV at the Poás Volcano using the Sniffer4D throughout the year of 2022, with the first series of measurements taking place in February of 2022.

There were three objectives for our trip to the Poás Volcano National Park:

1. Measure volcanic emissions from inside the active crater using the Aki-01 and SnifferV.
2. Test for any potential emissions inside the Botos Lagoon dormant crater of the Poás Volcano.
3. Monitor ambient air quality in Poás Volcano National Park at main lookout point where park visitors gather.

Figure 4 & 5. The Active Crater of the Poás Volcano National Park in 2019 and 2022.

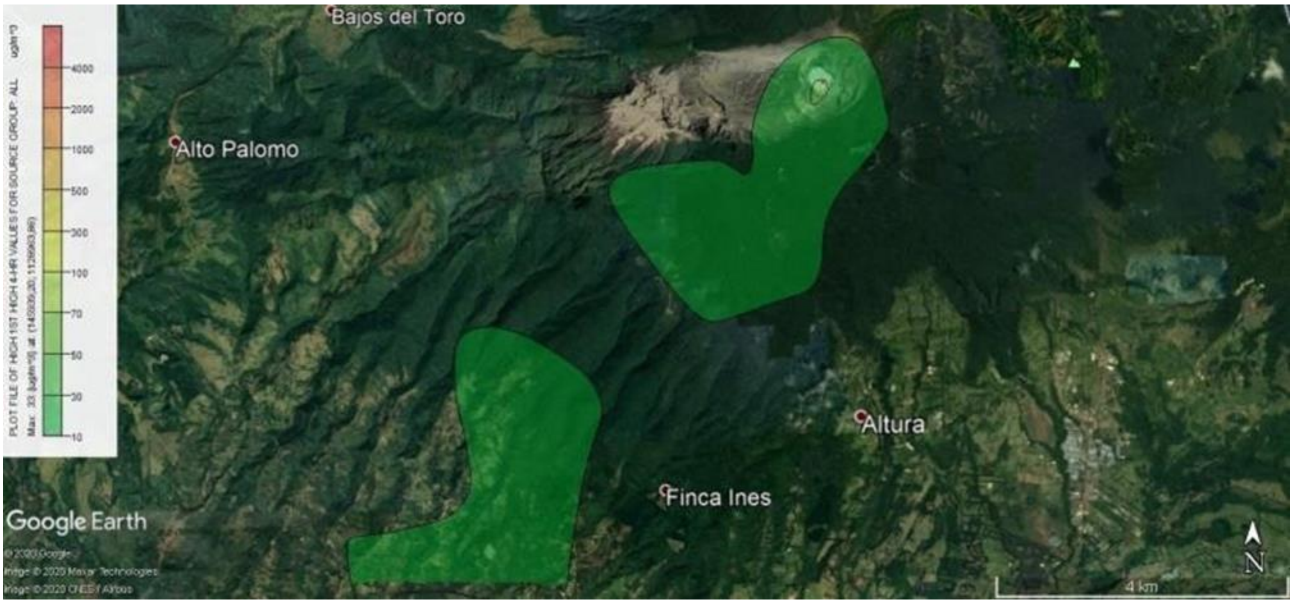


Figure 6. AERMOD Plot of the Poás Volcano SO2 Emissions on February 22th, 2022.

2. Material and Method

The Sniffer4D was attached to the Mavic 3 and Matrice 600-Pro with an integration kit created with a 3D printer. The Sniffer4D is placed upside down and the 3D printed mounting bracket is placed on top of the bottom of the device. The mounting bracket is then attached with 4 M2.5*6 screws in each corner. The Sniffer4D and attached mounting bracket are then placed onto the Mavic 3 drone and the assembly is permanently connected via 2 additional M2.5*6 screws at the bottom. The Sniffer4D is powered by the same battery as the UAS itself, via a power cable. The power cable aligns to the two outermost power connectors of the Mavic 3 battery. The power cable is secured with three small pieces of double-sided tape and is then attached to the Sniffer4D.The system has a total flight time of around 20 minutes depending on environmental conditions. There are two Sniffer4D Systems one designed for HAZMAT response the S4D and the other to log volcanic emissions S4V which can measure; S4D - NO_2, SO_2, O_2, VOC's, CO_2, CO, PM $_{1.0}$, PM $_{2.5}$, PM $_{10}$, O_3, NO_2+O_3 and S_4V - SO_2, CO_2, H_2S, HF, HCI, CO, CxHy/CH_4/LEL, H_2.

The Sniffer4D software program is named Mapper which can showcase the air quality and pollution dispersement as a grid, isoline or 3D plot. The drone was launched from the main lookout point of the Turrialba volcano on the southern edge of the Central Crater. The Sniffer4D can be used to showcase air quality data in real time via a SIM chip and associated data plan placed in the device which is connected to the local cellular network, allowing for real time pollution tracking. Monitoring the SO2/CO2 gas ratio is dangerous work, especially during times of increased activity. The device also records temperature and humidity making it an extremely valuable UAS payload for volcanology especially during eruptions that effect the surrounding area. Total payload weight was less than 500 grams and can be deployed with gas sampling module which can retrieve volcanic ash and particulate matter which can then be analyzed in the lab.


Figure 7 & 8. Remote Pilot Ian Godfrey Integrating the SnifferV to the Aki-01.

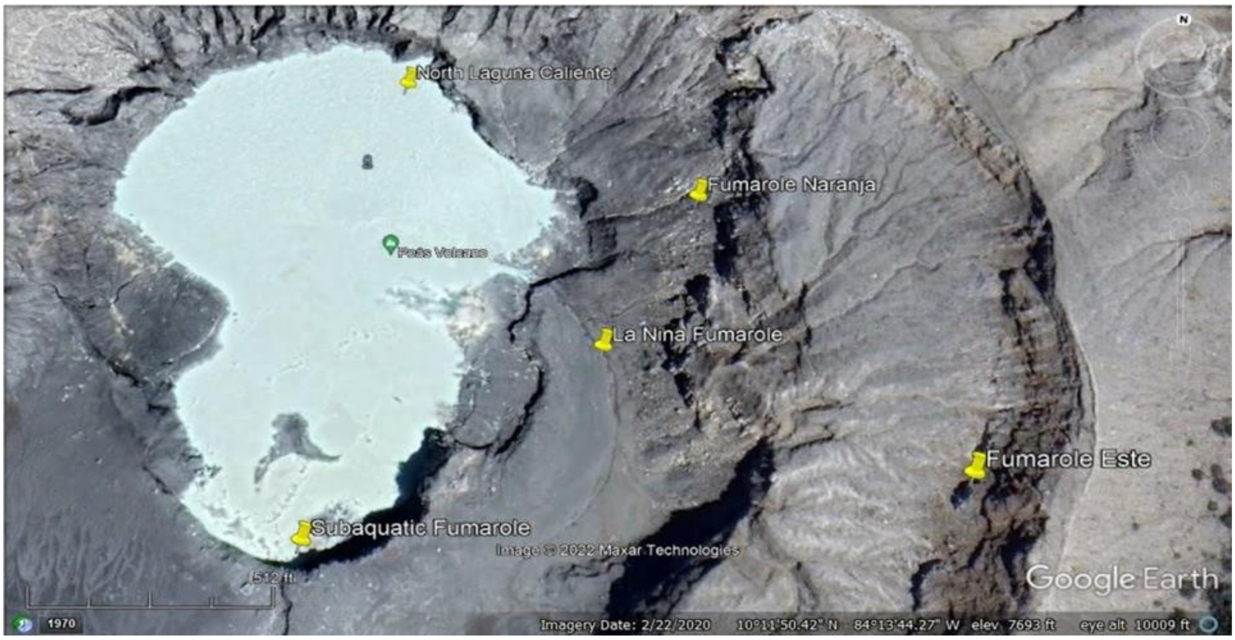


Figure 9. Fumarole Locations inside Active Crater of Poás Volcano.

2.1. Monitoring volcanic emissions at the Poas Volcano National Park using the Sniffer4D and SnifferV

There are several areas of significance which need monitoring for volcanic gases. Both the SINAC Park Rangers and the Red Cross of Costa Rica as well as park guests all have an interest in monitoring these gases for the safety of visitors observing the crater and enjoying the park. Main lookout point - There is a platform where guests gather to observe the active crater and Laguna Caliente, using both the Sniffer4D and the SnifferV we walked the entire lookout area and documented the ambient air quality from the main lookout point where everyone gathers for their pictures. Observational platform for the Botos Lagoon - Here is another gathering area for people enjoying the Poás Volcano National Park which needed to be documented for volcanic emissions. Since many people congregate and gather in large groups, documenting ambient air quality in these two areas is of strategic importance to the SINAC.

Detailed volcanic emission data came from two additional areas which are exclusive to researchers and scientists only. For example; during the month of September, we climbed into both craters to observe and document everything trying to see if there were any significant geological changes in the ambient air quality relative to the ambient air background levels.

1. The first and possibly most important objective was to attach the SnifferV to the Aki-01 and conduct a flight with this drone system to the degassing fumaroles next to Laguna Caliente inside the active volcano crater of the Poás Volcano National Park. There are 4 areas of degassing activity which we tried to monitor with this system. A. The Dome area which was destroyed in the 2017 eruption. B. Fumarole Este on the eastern shelf of the active crater. C. Fumarole Naranja the most significant fumarole showing signs of emissions on a consistent basis. D. The new area of increased activity to the north of the Laguna Caliente. This advanced payload flight was completed by two researchers from the Laboratory of Atmospheric Chemistry Universidad Nacional Costa Rica. The remote pilot in command was José Pablo Sibaja Brenes who was assisted by visual observer Ian Godfrey.

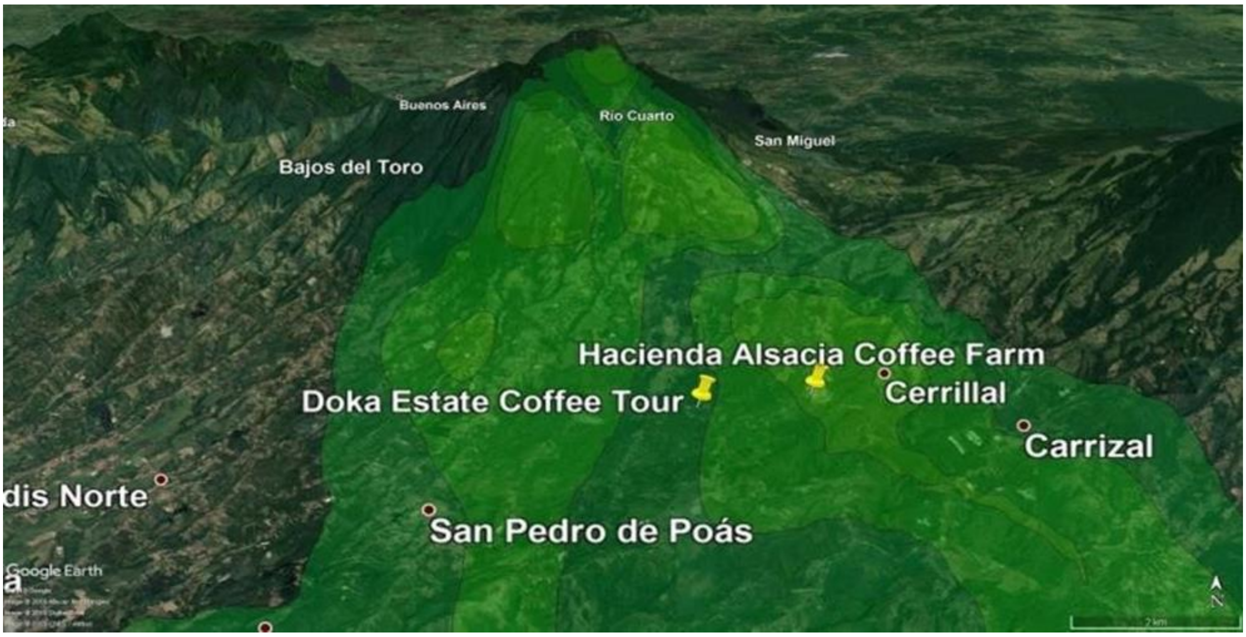


Figure 10. Poás Eruption September 30th, 2019 Dispersed Pollutants to Starbucks Coffee Farm.

Figure 11. UAS Control Stations Where Remote Pilote Operated From.

Figure 12. Aki-01 Perspective of the Fumarole Naranja of the Poás Volcano September 17th, 2022.

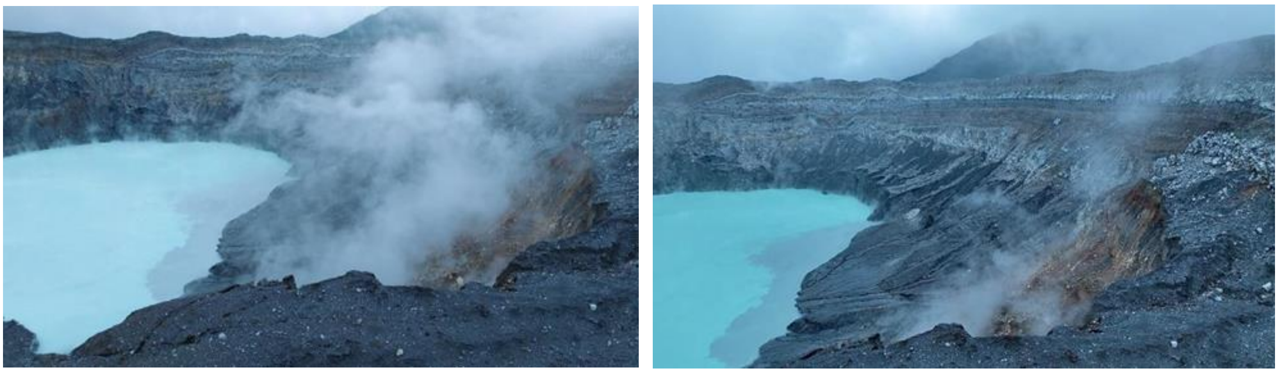


Figure 13 & 14. UAS Images of Fumarole Naranja, Poás Volcano National Park Saturday September 17th, 2022.

2. The second objective was to walk with both Sniffer devices to the dormant crater of the Poas Volcano National Park named the Botos Lagoon. The Botos Lagoon in the prehistoric dormant crater of the Poás Volcano, there are formations built of the ancient lava flows that now shape the park. Still it is of great importance to the government of Costa Rica, the SINAC Park Rangers and UNA to monitor this crater as well because there have been fluctuations in pH and gas measurements in the past. Therefore it's important for both OVSCORI-UNA and LAQAT-UNA to frequently monitor this crater lake as well as Laguna Caliente inside of the active crater.

Figure 15 & 16. Botos Lagoon of the Poás Volcano National park Costa Rica.

2.2. Entering the dormant crater Botos Lagoon

3. The third mission was to hike in between these two craters Laguna Caliente and Botos Lagoon and find an acceptable control station on the eastern rim of the active crater to take gas readings with both Sniffer units, we took a series of thermal images with the FLIR One Pro and also conducted an aerial survey of this section of the active crater. We hiked down in between these two craters down to the crater rim and began conducting our analysis.

Walking the active crater rim of Laguna Caliente where there are three active degassing fumaroles. By passing these three fumaroles on the rim of the volcano crater we were able to detect levels of degassing from each fumarole, we were also able to identify the specific gas species being released from these three fumaroles. By deploying both the Sniffer4D and SnifferV we were able to get a better understanding of the total degassing flux being released from the Poás Volcano.

2.3. Poás Findings

The emissions released during volcanic eruptions have a serious impact on atmospheric chemistry and climate changes. Gas monitoring at the Poás Volcano has been going on since long before the eruptions at the beginning of 2017. Valuable insight can be found by monitoring H2S/SO2, H2/H2O, H2/Ar, CO/CO2, CH4/CO2 and HC1/HF gas ratios. Sampling one single fumarole does not give significant information on the entire volcanic system and therefore scientists strive to periodically sample as many fumaroles as possible to gather a full view of the degassing of the entire volcano. UAS have become a valued tool in this fumarole monitoring process as they can be quickly launched into volcano craters offering relief to those who otherwise would have to enter the danger zone [1].

The Poás Volcano National Park is 2,697 meters or 8,848 feet in altitude and is located just 35 kilometers from San José, therefore due to the close proximity of the volcano to the capital city in Costa Rica there is a strategic important of monitoring the volcanic emissions being released from the Poás Volcano. Laguna Caliente located inside the active crater of Poás is extremely hot hyperacidic water filled with concentrated chlorine, fine sulfur particles and volcanic ash along with other various contributors. The 2017 eruption from Poás had a direct effect on the population living in the capital city [2].

2.4. Extreme Environments

The Laboratory of Atmospheric Chemistry and The Volcanic and Seismic Observatory of Universidad Nacional LAQATUNA & OVSCORI-UNA have implemented a consistent chemical evolution and volcanic activity monitoring program focused on watching for changes coming from Laguna Caliente. The crater lake Laguna Caliente is part of a complex hydrothermal system of the Poás Volcano. The hydrothermal system interacts with a shallow depth magma body below the active crater. Any fluctuations in water temperature, fumarole degassing and-or chemical-physical properties changing are of interest to the monitoring program [2].

The SnifferV contributed to the September 17th fumarole analysis of the active crater. Crater lakes like Laguna Caliente can pose an increased risk associated with an eruption because for example; toxic fluids erupting into the atmosphere can create various chemical reactions with a variety of consequences to the surrounding area. The potential eruption of Laguna Caliente and the toxic fluids it contains contributes to the formation of acid rain conditions and enhanced atmospheric pollution. On September 17th the SnifferV helped us carefully monitor exact gas species located around Laguna Caliente and track their dispersment as they moved out of the active crater and spread around the National Park of the Poás Volcano [2].

The exotic light blue vibrant color of the crater lakes located at the summit of Turrialba is mainly due to the scattering of light in the blue and green wavelengths due to the presence of colloidal particles deriving from the volcanic sediment and rocks the rainwater interacts with before collecting in the summit craters of the Turrialba Volcano National Park in Costa Rica. These particles become suspended in the crater lakes and can collect at the water's surface refracting the light in the blue and green wavelength particularly at the deepest part of the lake where more suspended particles can accumulate. Other factors do play a role in the color seen by observers such as temperature, pH levels, EC or electrical conductivity, total dissolved solids in the water body, density and the amount of total dissolved oxygen or O2. pH fluctuations have been shown to have direct color changing results as the changes in pH induces the growth of these particles from 184nm to 566nm and therefore the light scattering occurs mostly in the blue region of the visible spectrum [3].

Several aspects made the SnifferV ideal solution for volcanic emission monitoring; its ability to detect multiple gas species simultaneously, real time data processing and relaying, relayed location plotting with GPS coordinates, gas concentration and dispersment direction, and other valued data points contributed to the collective understanding of the volcanic risk associated with the Poás Volcano National Park. The SnifferV gathered and provided details on gas emissions being released from the Poás Volcano, the direction of the gas dispersment away from the fumarolic vents inside the active crater that can spread pollutants around the park. The majority of the emission data was gathered with the SnifferV on Thursday September 15th, Saturday September 17th, and Tuesday September 20th, 2022 with the assistance of LAQAT-UNA. Contributing valuable data about what types of gases are present and the potential hazard to park guests and SINAC Park Rangers. The Snifferv and Sniffer4D helped us identify the plume location and direction of dispersment from inside the park, the pair of devices helped us evaluate any potential hazards posed by the release of these emissions by monitor ambient air quality at the main lookout point where people gather to view the Laguna Caliente and active crater of the volcano.

Figure 17. DJI Mavic 3 Flying Inside the Active Crater of the Poás Volcano.

Figure 18. UAS Images of Laguna Caliente Poás Volcano National Park Saturday September 17th, 2022.

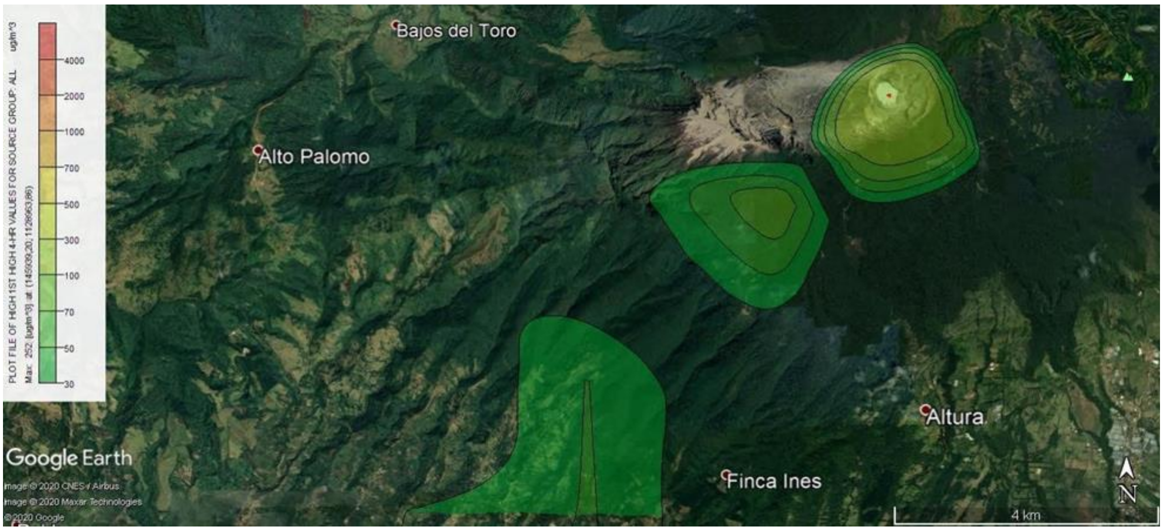


Figure 19. AERMOD Plot of the Poás Volcano SO_2 Emissions on September 15th 2022.

The Sniffer payload and associated Sniffer Mapper software program can help with general awareness of volcanic emissions at the Poás Volcano, the device contributed to the safety of the SINAC Park Rangers who live just 2 kilometers south of the active crater. The data gathered by the SnifferV contributed to helping offer additional emission data to the SINAC Park Rangers and the local communities living close by the active crater of the Poás Volcano by providing real time volcanic degassing information helping people by spreading awareness of dangerous SO2 levels being released from the volcano. During periods of increased activity or emission release, the SnifferV and UAS can continue surveillance operations around the active crater to help people know when they can safely return to observe the Laguna Caliente.

The Red Cross Costa Rica is always at the Poás Volcano National Park. The Red Cross is always ready to help anybody visiting in case anyone has a health problem requiring assistance. If there is an eruption, the Red Cross will help the park rangers to get the visitors to exit the park as fast as possible. The Aki-01 & SnifferV UAS flight mission provided useful information to the Red Cross of Costa Rica who also work at this National Park. By periodically deploying the SnifferV, LAQAT-UNA can analyze spatial distribution of volcanic emissions and eruptions, measure multiple gas species and associated concentration levels of both gases and particles; making the SnifferV and advanced and extremely useful air pollution monitoring system which greatly contributed to identifying the source of the volcanic plume by identifying fumaroles in the active crater and collecting important information on the pollutants transportation through the air around the park.

2.5. Flying Drones in Extreme Environments

The SnifferV performed well operating in conjunction with the Aki- 01 UAS. The Aki-01 and SnifferV flew a complex mission inside the active crater of the Poás Volcano. The flight path brought the SnifferV directly over all degassing fumaroles inside the crater and returned safely from a higher altitude to track the dispersment of emissions. Attached to the Aki-01 was a DJI Zenmuse Z30 high resolution camera which showed us a video recording of steam and gases being released from the surface of Laguna Caliente. The steam and gases coming from the crater lake water surface added to the complexity of the flight mission and risk to the UAS, however since these devices are built with the anti-EMI aluminum they are able to withstand acidic aerosols in this extreme environment.

Figure 20 & 21. José Pablo Sibaja Brenes Preparing the Aki-01 & SnifferV Payload September 17th, 2022.


Figure 22 & 23. LAQAT-UNA Red Cross SINAC Demonstration with Aki-01 and SnifferV September 17th, 2022.

The SnifferV performed well in this extreme environment. Careful consideration must be taken by remote pilots operating expensive UAS in extreme environmental or atmospheric conditions. The Aki-01 and SnifferV system preformed exceptionally well gathering information of volcanic emissions around Laguna Caliente. This information on volcanic emissions being released is relevant to upcoming eruptive activity. Therefore, an accurate multigas getection system like the SnifferV is an ideal payload for UAS designed for volcanic surveillance [4].

The SnifferV samples the air one time every second for the sampling rate making the SnifferV UAS ideal for a quick measurement pass through the plume which won't corrode the drone or SnifferV components. The SnifferV was designed with anti-EMI aluminum and is extremely robust in extremely corrosive

environments. The SnifferV has an IPX2 water resistant rating, and weighs 400-500 grams depending on the configuration. Each measurement of the gas is individually georeferenced for accurate 3D mapping on Sniffer Mapper when generating dispersment models. The SnifferV also collects data on temperature and relative humidity, providing crucial insights into the volcanic degassing and magmatic processes of an active volcano.

2.6. Remote Pilots Operating Drones in Extreme Environments

The Aki-01 is a Matrice 600-Pro drone specifically designed for atmospheric monitoring and collecting water samples from various crater lakes throughout Costa Rica. The Aki-01 is most commonly used by LAQAT-UNA to collect samples of water from Laguna Caliente for water chemistry analysis of the crater lake waters. Through operational experience of the Aki-01 from water sampling flights; Remote Pilot in Command José Pablo Sibaja Brenes was well prepared for the Aki-01 and SnifferV flight into the active crater of the Poás Volcano [5].


Figure 24 & 25. Aki-01 Perspective of the Aproach to Laguna Caliente September 17th, 2022.


Figure 26 & 27. Aki-01 Perspective of the Fumarole Naranja of the Poás Volcano September 17th, 2022.

Figure 28 & 29. North Laguna Caliente Area of the Poás Volcano.

2.7. UAS Flights Inside Active Volcano Craters

There are several crucial aspects to consider when planning a UAS flight mission into an active volcano crater. First the connection between the UAS and the remote controller may be interfered with, disrupted or disconnected entirely. The radio communication signal may be interrupted by the crater wall as the presence serves as a barrier or obstacle blocking part of the UAS signal connecting the drone to the remote controller [6].

During our September 17th flight missions into the active crater of the Poás Volcano we safely sampled three fumaroles from within the active crater, mapped gas concentration and dispersment in 30 minutes. During our analysis we also gave the Red Cross of Costa Rica a demonstration on how the SnifferV operated in extreme environmental conditions. UAS remote pilot in command José Pablo Sibaja Brenes explained that flying Aki-01 with this new payload was fine, there were no problems or wind difficulties. The drone made the trip around the active crater of Poás. The SnifferV didn't generate problems with electricity or weight to the drone.

UAS were used in volcanic surveillance flight missions to observe and collect water samples from the Yugama crater lake of the Kusatsu-Shirana Volcano in Japan during periods of calm and more active periods. These UAS pilots successfully sampled active crater lake water during periods of increased activity showing that advanced UAS like the Aki-01 and SnifferV can operate around active craters during periods of unrest. By preprograming GPS waypoints the Aki-01 and SnifferV payload system can repeatedly pass the exact same GPS location on various days to track and log emission changes and contributes to the data used to generate volcanic emission gas ratios [6].

Research published from the water sampling in Japan showed UAS in active craters should have preprogramed flight missions that do not allow the drone to get too close to the lake water surface, because there can frequently be very strong upward warm air currents, circular wind gusts within the crater itself and extremely acidic gas emissions which can corrode the electrical components of the drone. The crater lake water is around 0.1 [6].

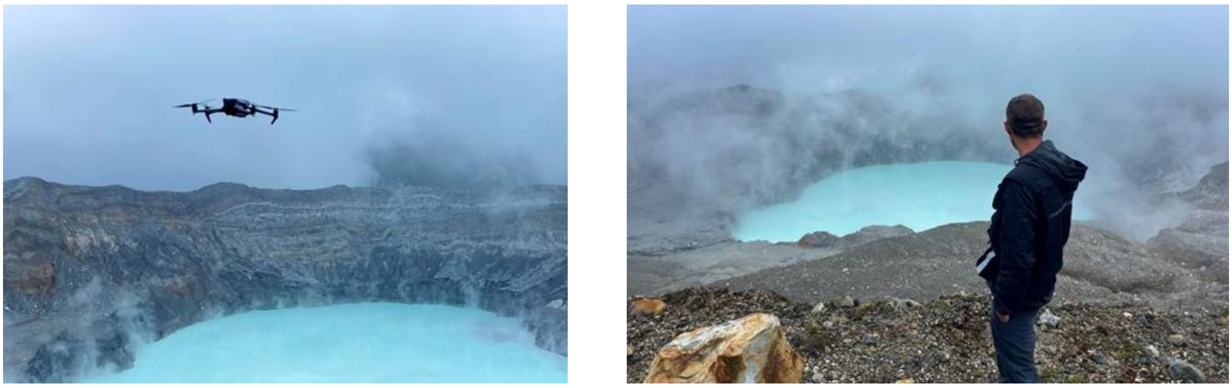


Figure 30 & 31. DJI Mavic 3 & Remote Pilot Ian Godfrey on the Eastern Rim of the Active Crater Poás Volcano.

Figure 32 & 33. UAS Perspective of Laguna Caliente of the Poás Volcano Spetember 17th, 2022.

Figure 34 & 35. UAS Images of Fumarole Naranja, Poás Volcano National Park Saturday September 17th, 2022.

Figure 36 & 37. Fumarole Este & Subaquatic Fumarole of Laguna Caliente September 17th, 2022.

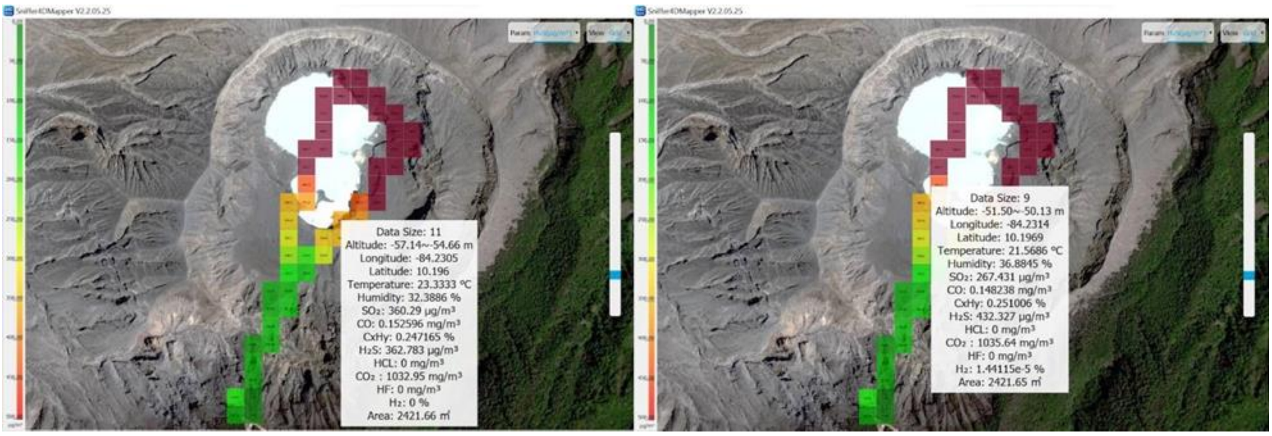


Figure 38 & 39. Sniffer Mapper Lake Gas Measurements from Subaquatic Fumarole September 17th, 2022.

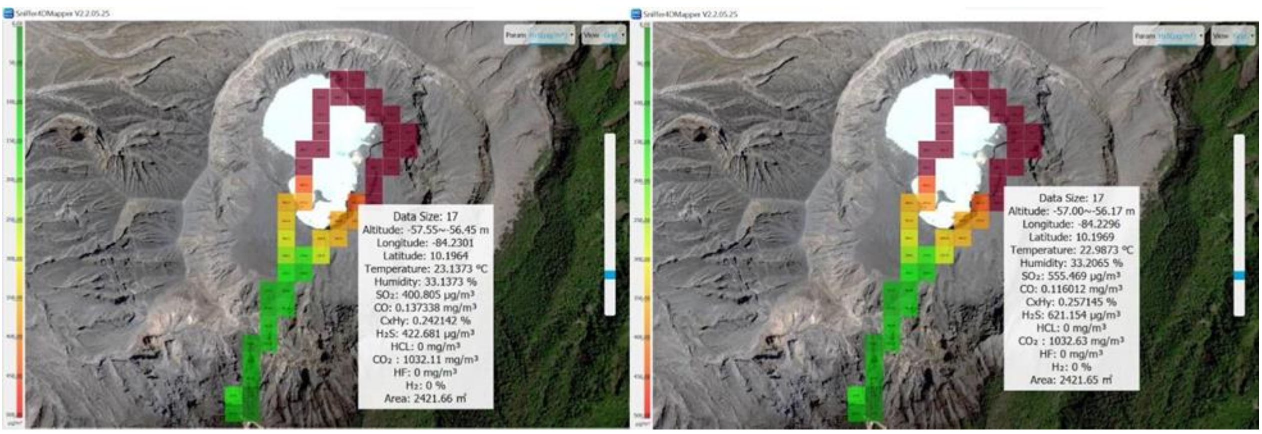


Figure 40 & 41. Sniffer Mapper Measurements from Fumarole La Niña September 17th, 2022.

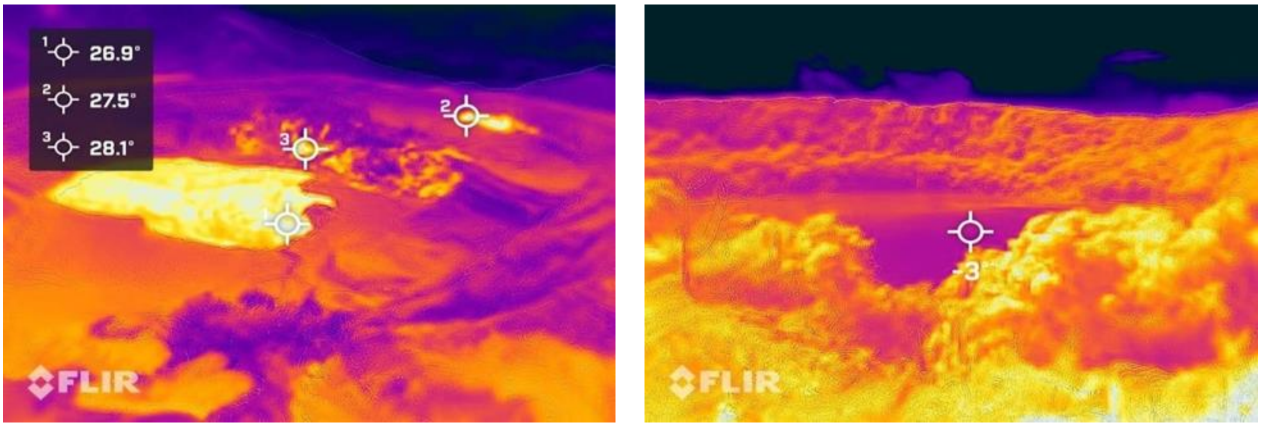


Figure 42 & 43. FLIR One Pro Thermal Images of the Laguna Caliente & Botos Lagoon September 17th, 2022.

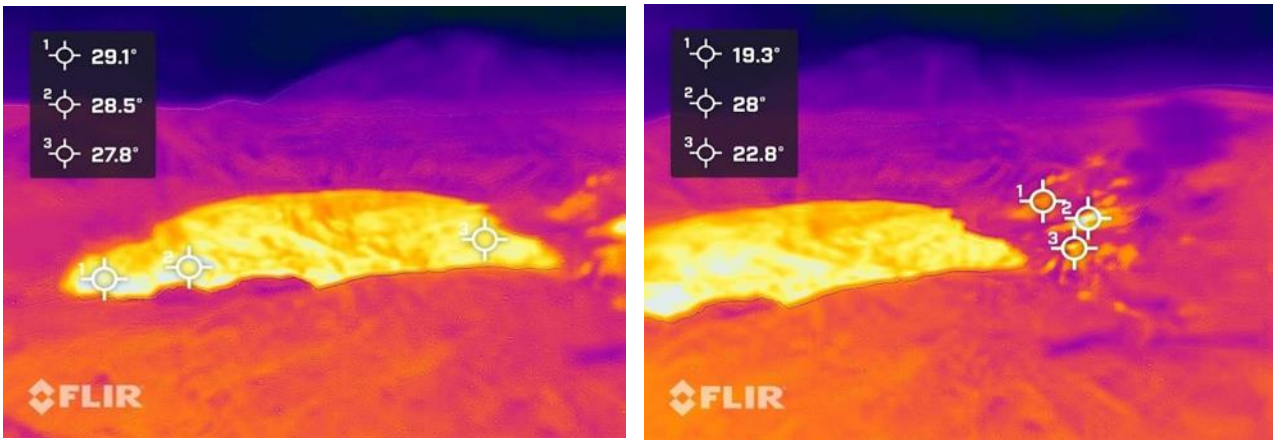


Figure 44 & 45. FLIR One Pro Thermal Images of the Laguna Caliente September 17th, 2022.

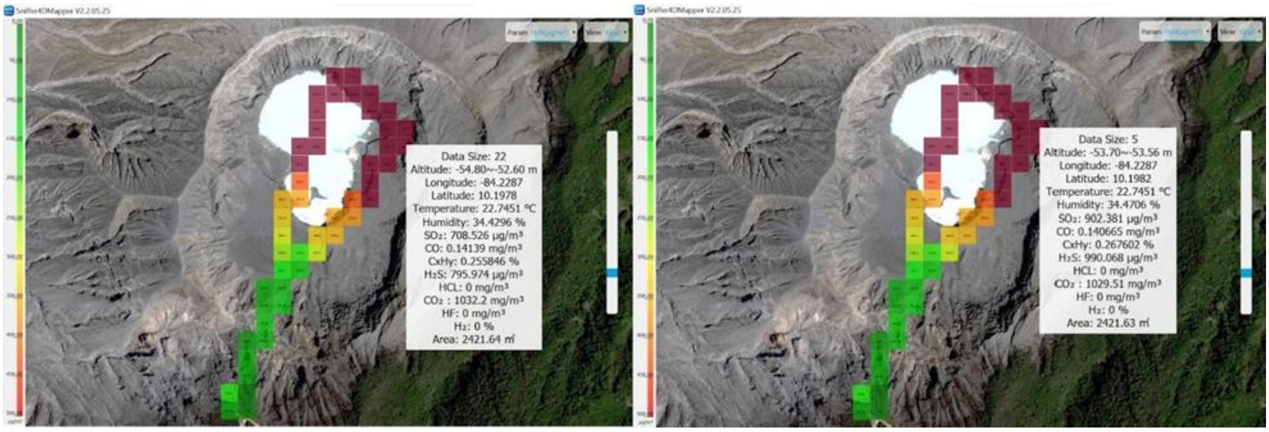


Figure 46 & 47. Sniffer Mapper Measurements from Fumarole Naranja September 17th, 2022.

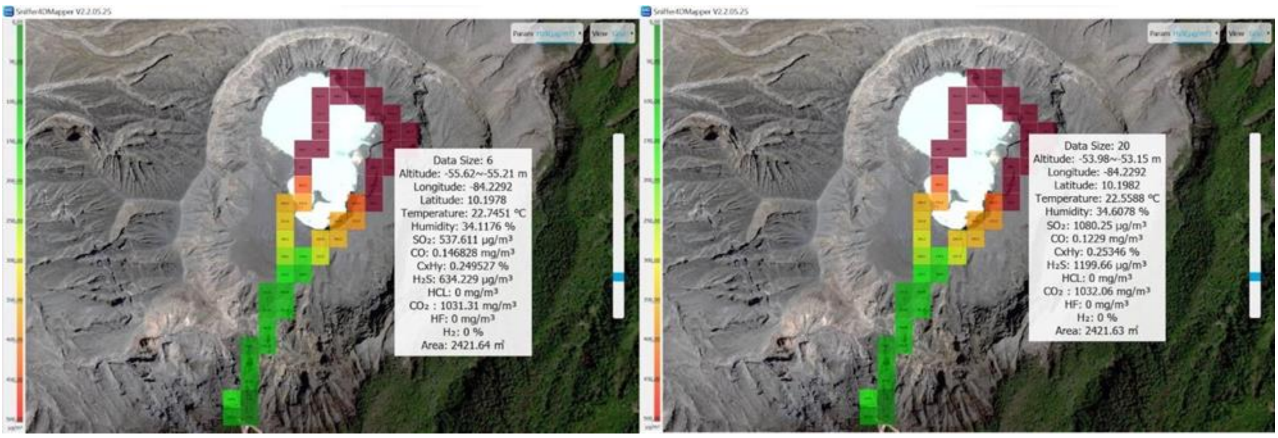


Figure 48 & 49. Sniffer Mapper Measurements from Fumarole Naranja September 17th, 2022.

2.8. Supporting UAS Work

UAS have also contributed to volcanic monitoring programs in Indonesia, a nation with many active volcanic systems. Here they used UAS at Mount Sinabung where volcanologists used advanced Lidar, thermal imaging technology and other atmospheric monitoring equipment. Due to the extreme activity seen inside active volcano craters and the dangers they pose to researchers who enter them, UAS have become the ideal solution for mapping volcanic formations, gathering thermal data, and sampling gases being released from fumaroles. The Aki-01 and SnifferV flight at the Poás Volcano National Park by LAQAT-UNA showcase the advancements in multigas detection payload package for UAS [7].

2.9. Sniffer Mapper

The software program for the SnifferV can provide rapid evaluation of a volcanic plume. In less than 24 hours after an eruption safety checks for pollutants of SO_2 and particle concentrations can be carried out at the active crater, in additional areas of the National Park, and in the community areas surrounding the volcano. The SnifferV reports show the volcanic emissions plotted into the GPS grid locations and can be turned over to governmental decision makers in record time. These Sniffer Mapper reports outline volcanic emission data in a quick summary report which can easily be shared to facilitate risk management and decision making.

Figure 50 & 51. SnifferV Inside the Active Crater of the Poás Volcano National Park.

When evaluating the data obtained by the Aki-01 SnifferV UAS flights we saw that gas intensity and concentration of each pollutant was individually plotted into Sniffer Mapper with the danger zones reflected in by the red color of the grid section, and numbers showing maximum gas level concentrations for that specific GPS location. The SnifferV can be used at ground level by walking the device or by flying the SnifferV using UAS at low altitude for precisely plotted grid distributions. Or the SnifferV unit can be integrated to UAS which can be flown at various altitudes and can reveal gas concentrations at different levels of the atmosphere.

Our UAS flight data from the SnifferV inside the active crater circling Laguna Caliente shows how this gas detection system can successfully map volcanic emissions, adding another layer to the already popular UAS applications in volcanology. By expanding UAS applications and building upon previously successful applications such as collecting topographical data, supporting hazard management and support volcanic risk assessment; the collection of valuable emission data has also become a vital UAS application in volcanology. Advancements in both UAS and payload sensors are expected to bring various now opportunities in the future. UAS are quickly becoming an essential tool for tracking and understanding volcanic systems [8].

Figure 52 & 53. SnifferV at the Fumarole Naranja of the Poás Volcano September 17th, 2022.

The Aki-01 and SnifferV flight missions at Poás show how this system can facilitate the higher frequency of gas measurements at volcanic systems by deploying the Sniffer device and UAS. This strategy allows for data to be more easily processed in the lab by exporting both Sniffer Mapper reports and CSV files for Microsoft Excel. The emission data tracked at the Poás Volcano inside the active crater and around Laguna Caliente was quickly shared with various departments in the university and additional governmental institutions [8].

This was not the first time drones were used at the Poás Volcano for gas measurements. Drones were actually a fundamental part of volcanic observations for OVSCORI-UNA during the 2017 eruptive activity seen coming from Poás. In the publication titled; Insights on Hydrothermal-Magmatic Interactions and Eruptive Processes at Poás Volcano (Costa Rica) From High-Frequency Gas Monitoring and Drone Measurements in the Geophysical Research Letters for 2019 scientists explained: Drastic fluctuations is gas concentrations being released from the fumaroles surrounding Laguna Caliente preceded strong eruptions. It's because these drastic fluctuations is volcanic emissions being a precursor to eruptions that we decided to specifically configure the SnifferV with SO2, CO2 and H_2S. It's these fluctuations is gas species that were recognized before the 2017 eruption from the Poás Volcano [9].

Periodically logging and building data sets of SnifferV readings of SO_2, CO_2 and H_2S are a vital part of the implemented volcanic monitoring program and the new technological advancements in multigas payloads for UAS such as the SnifferV has contributed to rapid emission data collection from inside the active crater of the Poás Volcano. During eruptive periods UAS become increasingly useful for continuing the observations of Laguna Caliente [9].

Laguna Caliente is a shallow manifestation of a complex hydrothermal volcanic system which frequently receives contributions of gases from the magmatic chamber. Phreatic eruptions are released through the active crater holding Laguna Caliente, these types of eruptions are associated with increasing SO_2/CO_2 showing the significance of the magmatic gases being released before the eruption [9].


Figure 54 & 55. Laguna Caliente from Remote Pilot Location and UAS Perspective from Flight.

Figure 56. UAS Perspective of Laguna Caliente September 17th, 2022.

Environmental monitoring of extreme environments like Laguna Caliente of the Poás Volcano is quickly becoming the foundation for diagnosing the effects of climate change and interplanetary science. By using the Aki-

01 and SnifferV volcanic multigas detection system we were able to monitor and map the ambient air quality in an extreme volcanic environment. The SnifferV delivered valued volcanic emission results from measurements taken every second within the active crater of the Poás Volcano. It´s these types of results that help with assessing, managing and forecasting volcanic events within the National Park [10].

For anyone seeking further knowledge about the Poás Volcano National Park there is a recommended book titled "Poás Volcano The Pulsing Heart of Central Americal Volcanic Zone" which is a collection of some of the most detailed and advanced academic publications of the volcano produced by Springer, Active Volcanoes of the World.

Figure 57 & 58 – Aki-01 Perspective of Fumarole Nranja and North Laguna Caliente September 17th, 2022.

2.10. Sniffer Mapper Reports Aki-01 & SnifferV

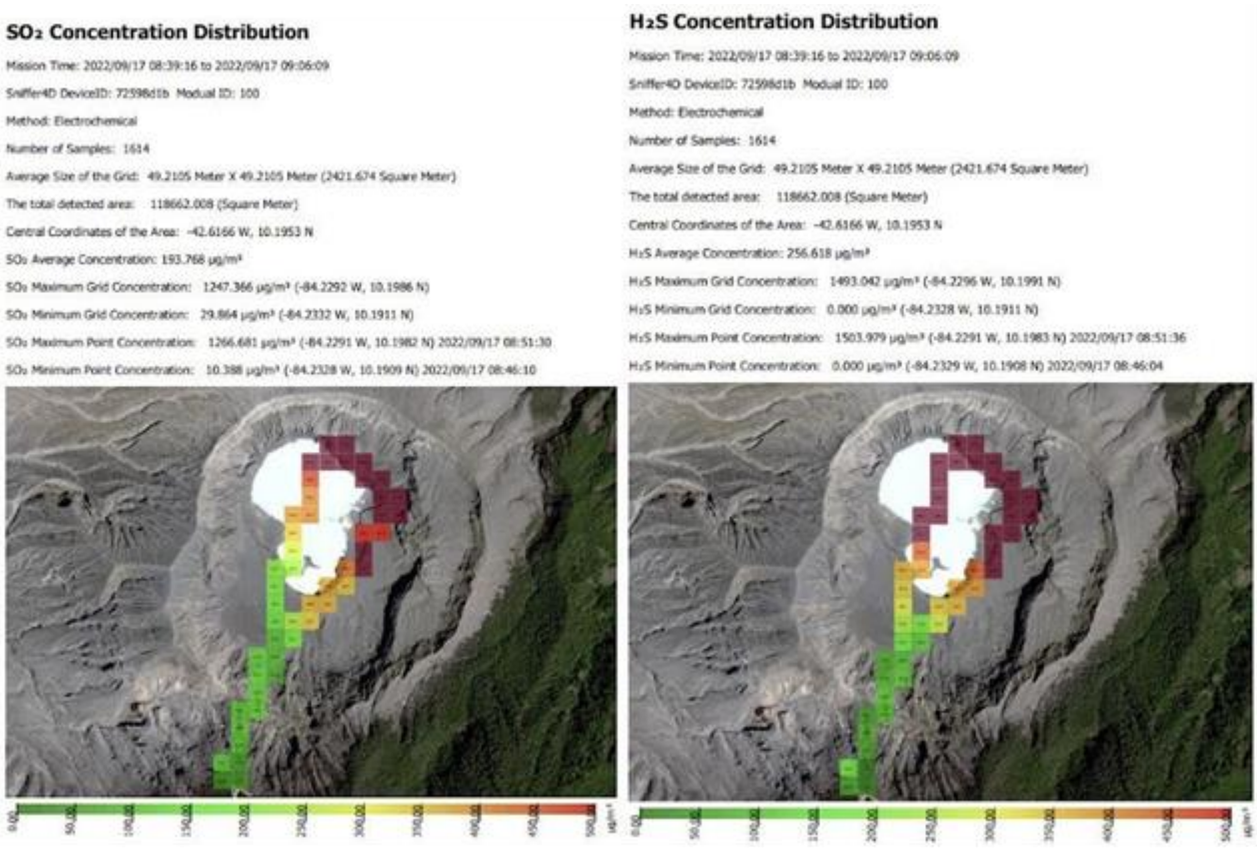


Figure 59 & 60. Sniffer Mapper Reports on SO_2 and H_2S from Inside the Active Crater of the Poás Volcano.

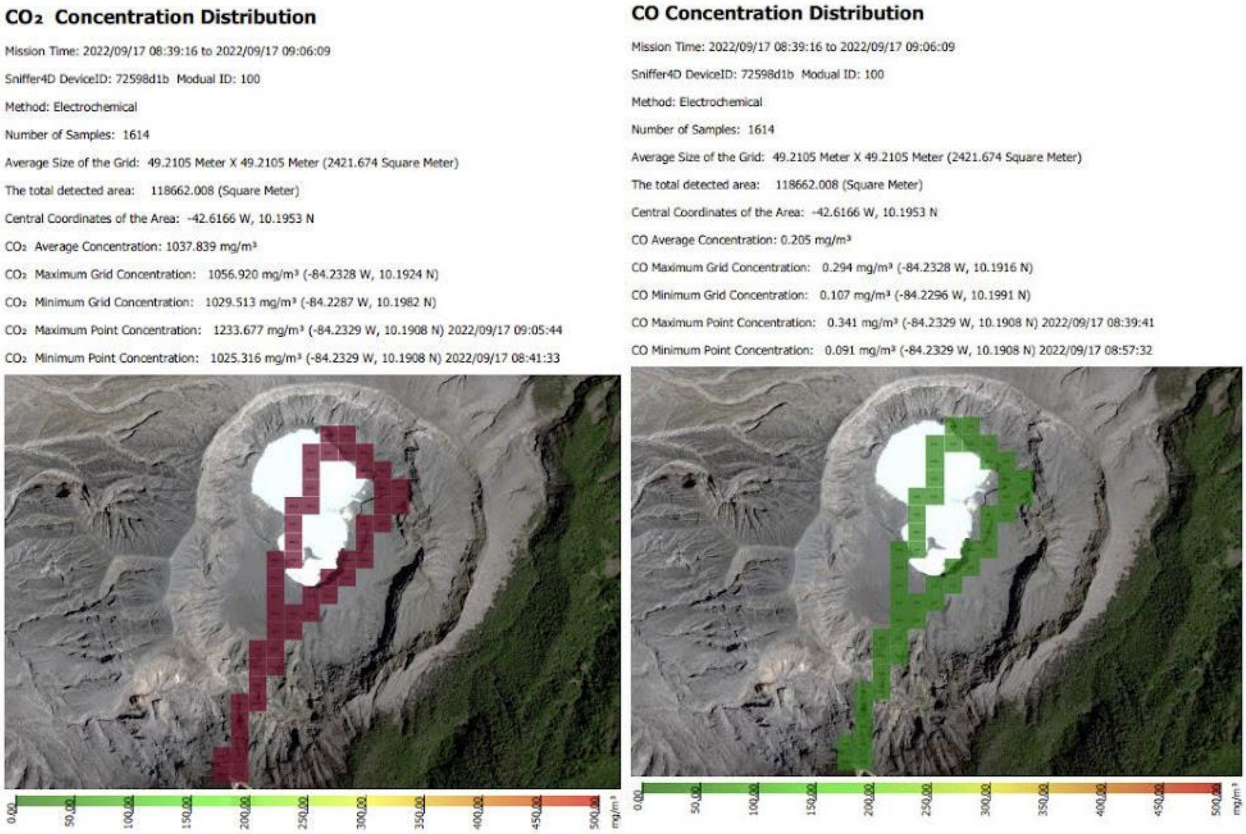


Figure 61 & 62. Sniffer Mapper Reports on CO_2 and CO from Inside the Active Crater of the Poás Volcano.

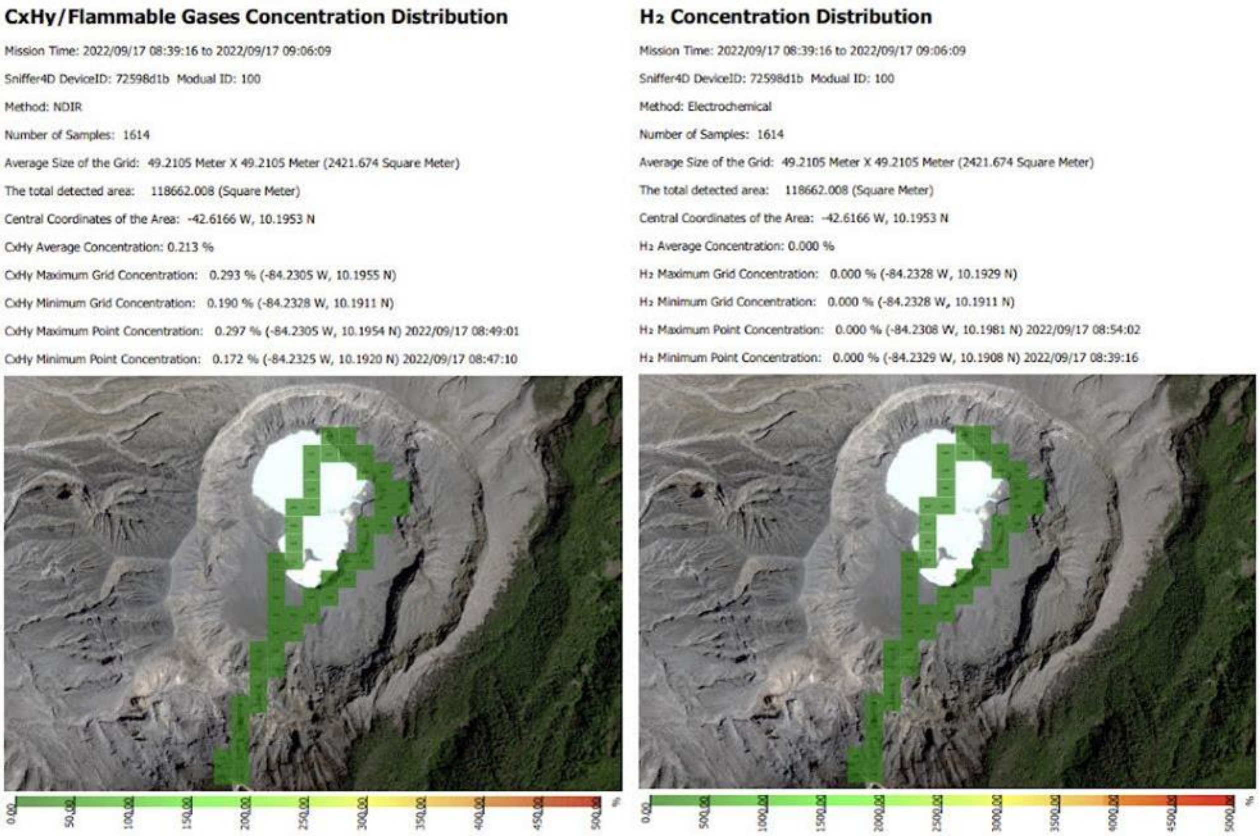
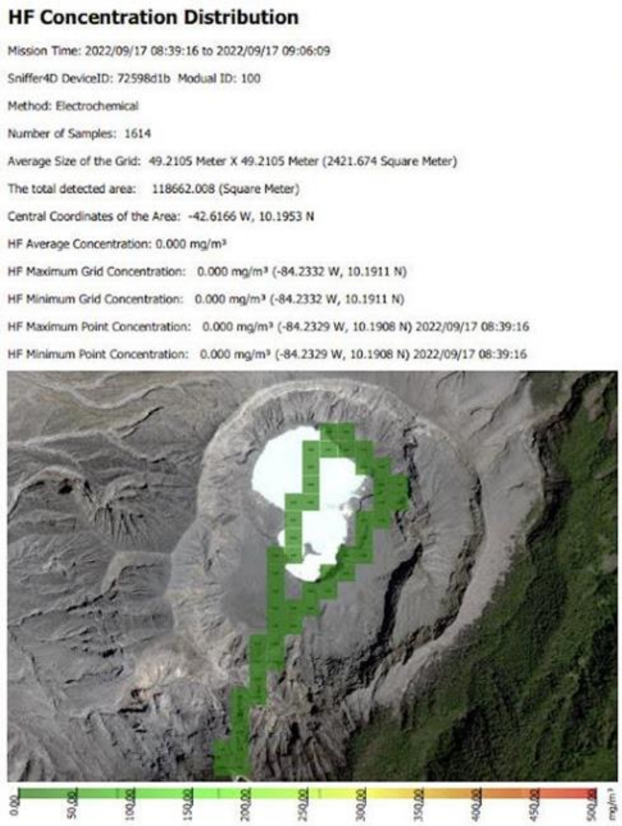


Figure 63 & 64. Sniffer Mapper Reports on C_xH_y and H_2 from Inside the Active Crater of the Poás Volcano.



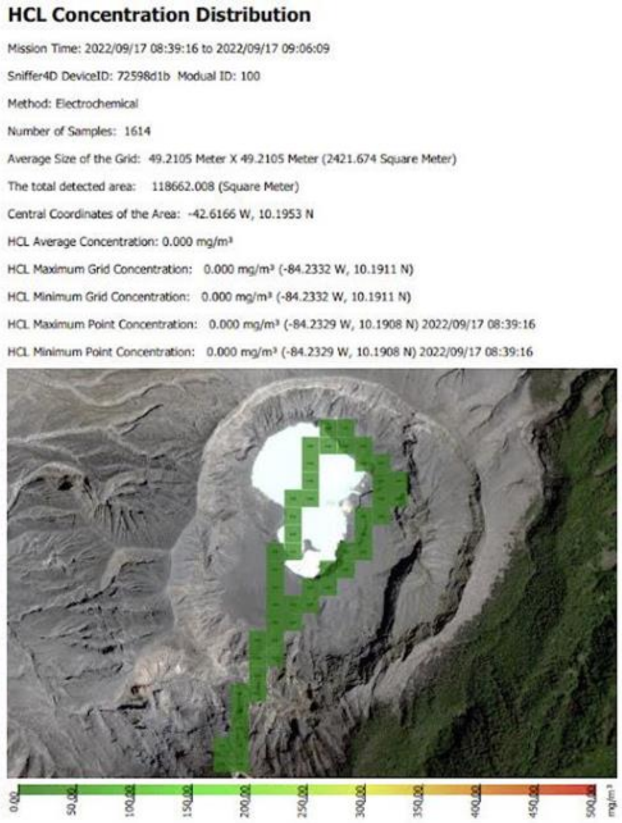
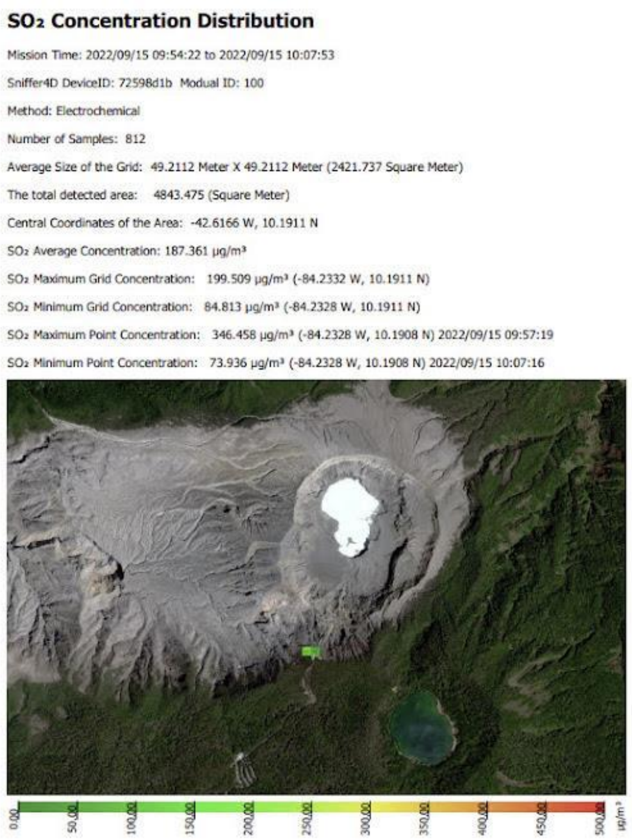


Figure 65 & 66. Sniffer Mapper Reports on HFand HCL from Inside the Active Crater of the Poás Volcano.

2.11. Ambient Air Quality at Main Lookout



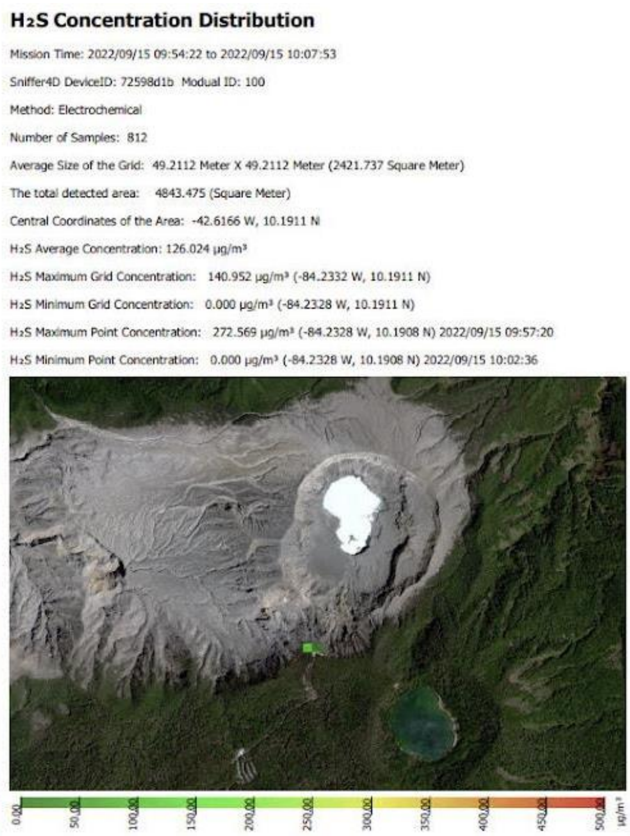


Figure 67 & 68. SnifferMapper SO_2 & H_2S Reports from the Main Lookout of the Poás Volcano.

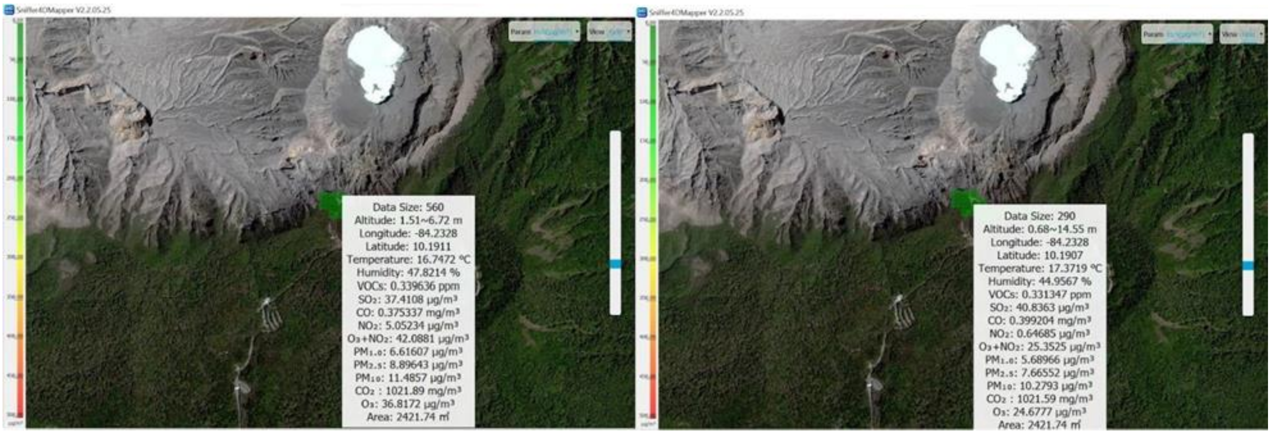


Figure 69 & 70. Sniffer4D Measurements from Mail Lookout of the Poás Volcano September 15th, 2022.

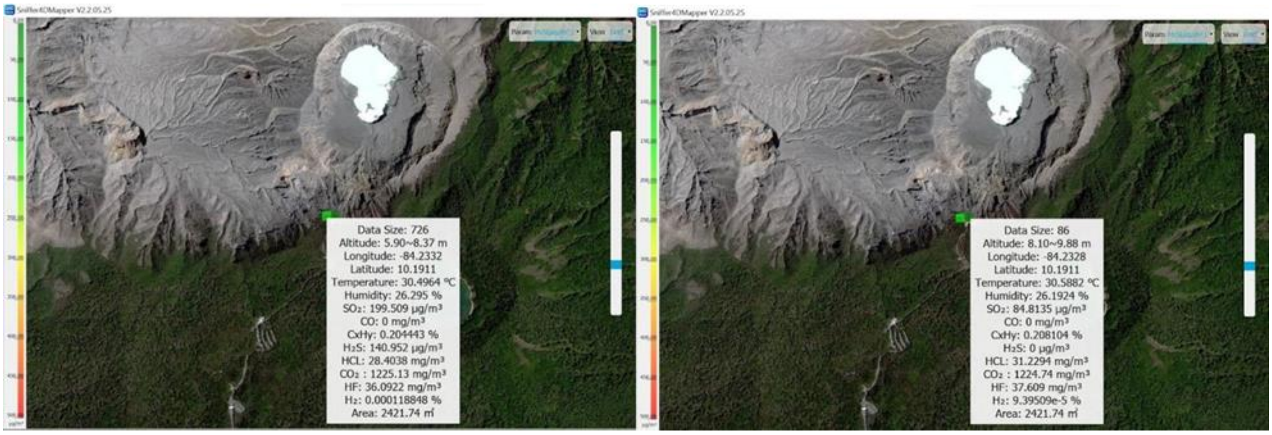


Figure 71 & 72. Sniffer4D Measurements from Mail Lookout of the Poás Volcano September 15th, 2022.

2.12. Sniffer V & Sniffer4D Analysis of Botos Lagoon

Figure 73. Botos Lagoon and Laguna Caliente of the Poás Volcano National Park Costa Rica.

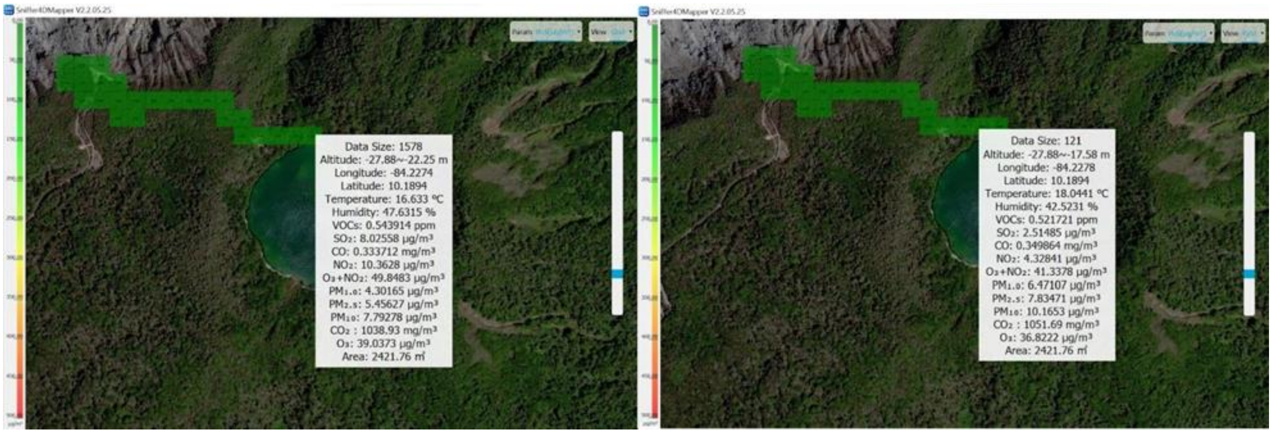


Figure 74 & 75. Sniffer4D Measurements from at the Botos Crater of the Poás Volcano September 15th, 2022.

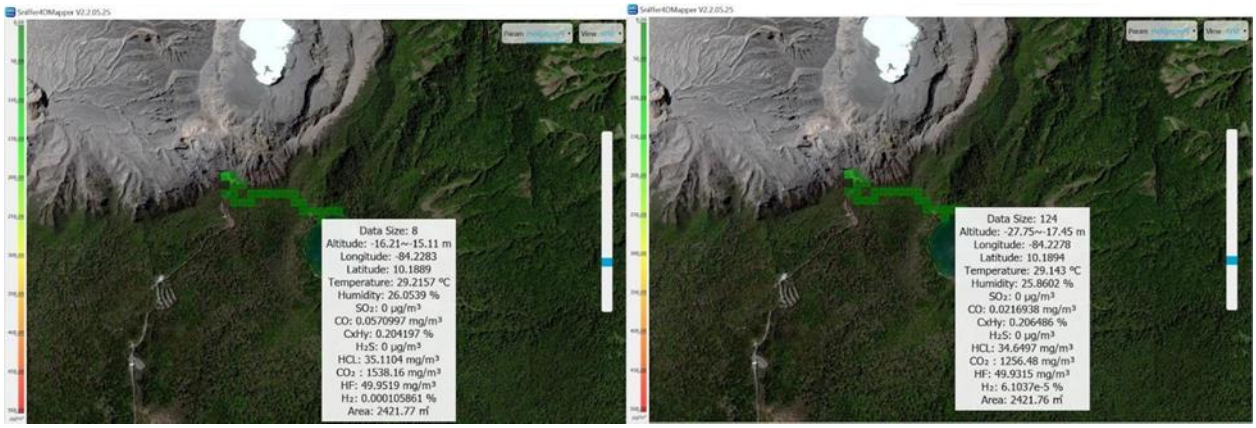


Figure 76 & 77. SnifferV Measurements from at the Botos Crater of the Poás Volcano September 15th, 2022.

3. Conclusion

Laguna Caliente the active volcanic crater of the Poás Volcano National Park. Images and videos collected during these flights showed a distinctively darker color of the lake water to the north of the Laguna Caliente. This grey area is made of sediments and sulfur remobilized by a subaquatic fumarole. That fumarole is very far to the north of Laguna Caliente. The subaquatic fumarole is close to the cliff and is sporadically active or discontinuous. Several times in September we flew consumer drones over Laguna Caliente to observe the northern section of the lake watching for any signs of the discontinuous subaquatic fumarole.

OVSCORI-UNA scientists observed it for the first time on August 13, 2022. It got more and more vigorous with time and reached a maximum of activity between Sept 3 and Sept 9. That week it activated several times per day, for 1 to 3 hours, and really looked like vigorous bubbling coming from the depths of Laguna Caliente. Since Sept 9, its activity decreased significantly in duration and amplitude. We used the UAS to continue observing the northern areas of Laguna Caliente during the rest of September to try and observe this subaquatic fumarole. It is pretty rare to observe it today from the Main Lookout point but the use of UAS made it easier to monitor this area without entering the active crater.

The interpretation of this phenomena observed with UAS is quite remarkable. The fact that this fumarole appeared more or less at the same time as a seismic increase of activity: increase of seismic energy tremor amplitude is very interesting. The change of activity seismic, deformation and gas release pointed to a superficial pressurization. The tendency got so clear by the beginning of September that we sent an alert to the authorities on Sept. 8, occurrence of phreatic eruptions was our most likely scenario, with a potential of affectation of the public area. But the next day the tendency stopped and reversed. Today we consider the volcano back to its steady low activity state. Hence, it seems that this fumarole opened as a consequence of that shallow pressurization, and was effective enough to release the pressure, preventing a phreatic eruption from occurring. Many other times we observe large areas of dark material in the lake which are due to the rain.

Future advancement in volcanic gases and atmospheric monitoring with the Sniffer4D are expected. TheSniffer4D also works well on Non-DJI and fixed wing drone and the integration process is simple. Adding the Sniffer4D as a payload integrated onto a fixed wing drone with thermal imaging capabilities will be an ideal solution for a volcanic monitoring UAS because we could generate thermal DSM seeking and showing where any potential thermal anomalies exist and with the onboard Sniffer4D we would also be able to track and log any potential volcanic emissions during the flight and map them with the corresponding GPS coordinates. By deploying portable gas detection equipment, we were able to monitor specific areas of strategic interest to volcanologists and scientists of the Universidad Nacional. Future advancement in volcanic gases and atmospheric monitoring with the Sniffer4D can be implemented at the Poás Volcano by having researchers from LAQAT-UNA periodically flying the Aki-01 at the Laguna Caliente area of the active crater.

Figure 78 & 79. Images of Grey Section of Laguna Caliente Poás Volcano National Park September 17th, 2022.

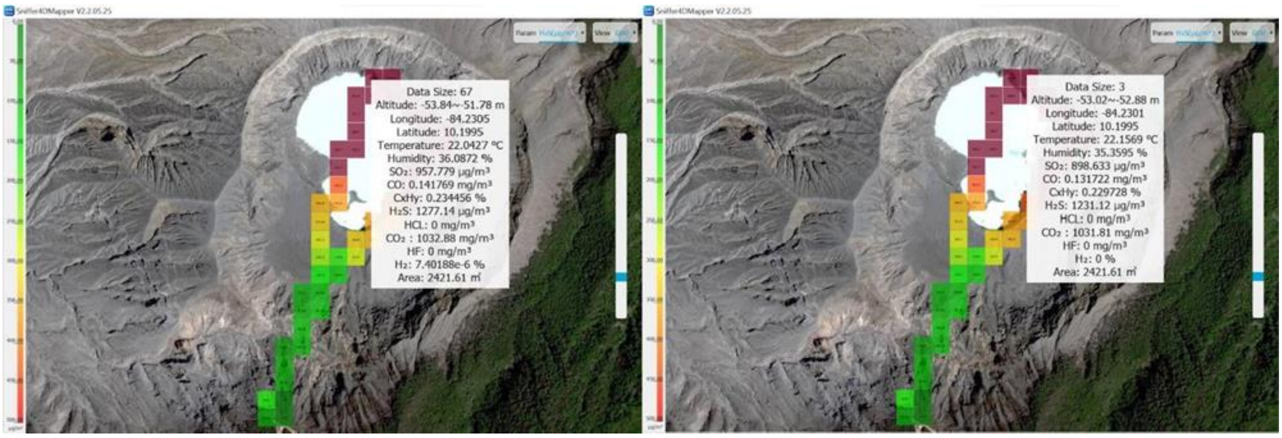


Figure 80 & 81. Sniffer Mapper Measurements from North Laguna Caliente September 17th, 2022.

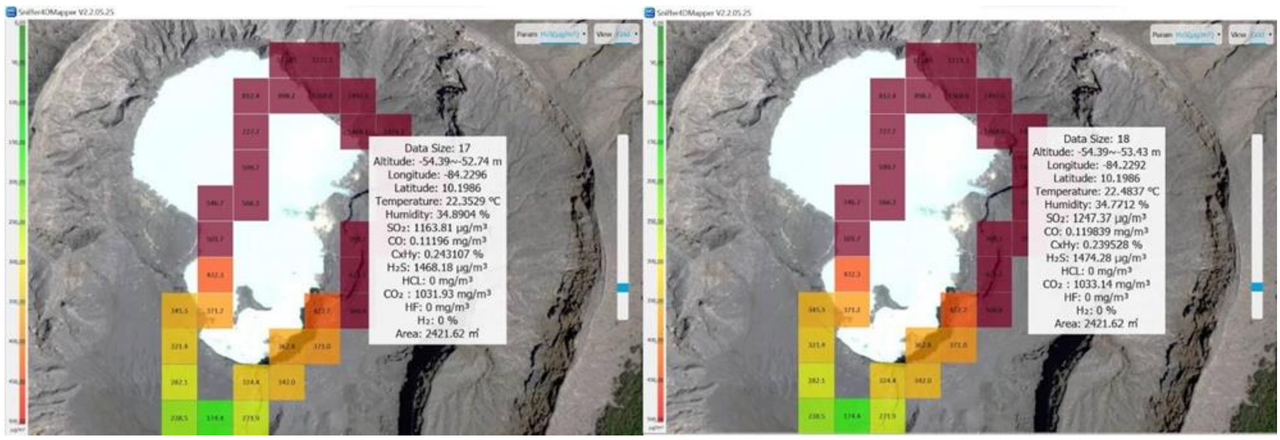


Figure 82 & 83. Sniffer Mapper Measurements from North Laguna Caliente September 17th, 2022.

The Sniffer4D collected valuable volcanic emission data of the active crater of the Poás Volcano in September of 2022 of several occasions. The information obtained by the Sniffer4D and SnifferV increases available information for planning, decision making, and responses to potential volcanic eruptions. The data contributes to response times to events, situational awareness, safety of park guests, time frame forecasting of eruption cycle, public safety, risk management strategies for volcanic national parks and Hazmat operations. Since there were some geological changes in the northern sector of Laguna Caliente during the first week of September 2022, the rest of the month was the ideal time for sampling and monitoring volcanic emissions being released from the active crater of the Poás Volcano National Park in Costa Rica.

Our demonstration showed how the SnifferV integrated to UAS such as the Aki-01 or M3 contributed to the volcanic surveillance program at the Poás Volcano. The device helped identify the volcanic plume, measured and quantified multiple gas species in three separate zones of fumaroles within the active crater. Since the increased activity at Poás early September these gas monitoring UAS flights were of strategic importance. Using the Aki-01 as a transportation method we conducted a plume analysis of the northern area where numerous gas species were detected by the UAS. The emissions measured and concentrations confirmed the feasibility of using the SnifferV and UAS system for volcanic emission tracking. The SnifferV and UAS was specifically configured by researchers from LAQAT-UNA shows the ability of a drone based atmospheric surveillance system.

This system can be used for industrial emission inspections, atmospheric chemistry, scientific research and environmental monitoring. Most significantly here in the Central American Volcanic Arch, the SnifferV can accurately and safely monitor volcanic emissions and relay the information back to laboratories and observatories in real time assisting with decision making for park safety. This system greatly reduces the need for personnel to enter the danger zones of the volcanic system.

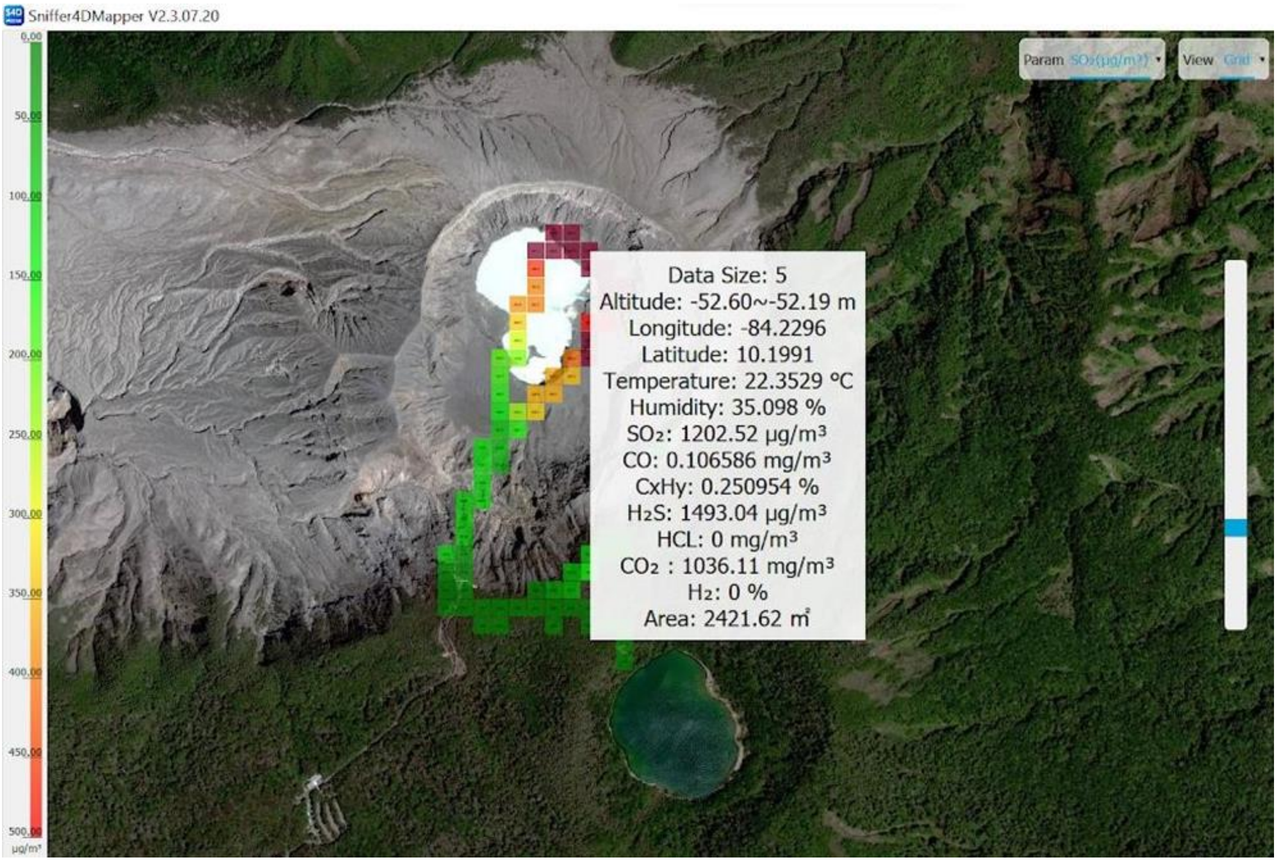


Figure 84. Sniffer Mapper Report from the Entire Multigas Mapping Survey September 17th, 2022.

Funding

This research received no external funding.

Author contributions

Ian Godfrey: Drone research project was designed and managed **José Pablo Sibaja Brenes:** The atmospheric AERMOD plots were created **Maria Martínez Cruz:** Geological and volcanic aspects of the findings were interpreted **Geoffroy Avard:** Safety and logistics **Khadija Meghraoui:** Drone system and geospatial methods

Conflicts of interest

The authors declare no conflicts of interest.

References

1. Vaselli, O., Tassi, F., Fischer, T. P., Tardani, D., Fernández, E., del Mar Martínez, M., ... & Bini, G. (2019). The last eighteen years (1998–2014) of fumarolic degassing at the Poás volcano (Costa Rica) and renewal activity. Poás Volcano: The Pulsing Heart of Central America Volcanic Zone, 235-260. https://doi.org/10.1007/978-3-319-02156-0_10
2. Martinez, M., Fernández, E., Valdés, J., Barboza, V., Van der Laat, R., Duarte, E., ... & Marino, T. (2000). Chemical evolution and volcanic activity of the active crater lake of Poás volcano, Costa Rica, 1993–1997. Journal of Volcanology and Geothermal Research, 97(1-4), 127-141. https://doi.org/10.1016/S0377-0273(99)00165-1
3. Kumar, V. (2016). Study on turquoise and bright sky-blue appearing freshwater bodies. International Journal of Geology, Earth and Environmental Science, 6(1), 119-128.
4. Amici, S., Turci, M., Giulietti, F., Giammanco, S., Buongiorno, M. F., La Spina, A., & Spampinato, L. (2013). Volcanic environments monitoring by drones mud volcano case study. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 40, 5-10. https://doi.org/10.5194/isprsarchives-XL-1-W2-5-2013
5. Sibaja-Brenes, J. P., Terada, A., Solís, R. A., Luna, M. C., Castro, D. U., Ramírez, D. P., ... & Cruz, M. M. (2023). Drone monitoring of volcanic lakes in Costa Rica: a new approach. Drone Systems and Applications, 11, 1-14. https://doi.org/10.1139/dsa-2022-0023
6. Terada, A., Morita, Y., Hashimoto, T., Mori, T., Ohba, T., Yaguchi, M., & Kanda, W. (2018). Water sampling using a drone at Yugama crater lake, Kusatsu-Shirane volcano, Japan. Earth, Planets and Space, 70(1), 1-9. https://doi.org/10.1186/s40623-018-0835-3
7. Tarigan, A. P. M., Suwardhi, D., Fajri, M. N., & Fahmi, F. (2017, March). Mapping a volcano hazard area of Mount Sinabung using drone: preliminary results. In IOP Conference Series: Materials Science and Engineering, 180(1), 012277. https://doi.org/10.1088/1757-899X/180/1/012277
8. James, M. R., Carr, B., D'Arcy, F., Diefenbach, A., Dietterich, H., Fornaciai, A., ... & Zorn, E. (2020). Volcanological applications of unoccupied aircraft systems (UAS): Developments, strategies, and future challenges. Volcanica, 3(1), 67-114. https://doi.org/10.30909/vol.03.01.67114
9. De Moor, J. M., Stix, J., Avard, G., Muller, C., Corrales, E., Diaz, J. A., ... & Fischer, T. P. (2019). Insights on hydrothermal-magmatic interactions and eruptive processes at Poás Volcano (Costa Rica) from high-frequency gas monitoring and drone measurements. Geophysical Research Letters, 46(3), 1293-1302. https://doi.org/10.1029/2018GL080301
10. Manfreda, S., McCabe, M. F., Miller, P. E., Lucas, R., Pajuelo Madrigal, V., Mallinis, G., ... & Toth, B. (2018). On the use of unmanned aerial systems for environmental monitoring. Remote sensing, 10(4), 641. https://doi.org/10.3390/rs10040641