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

Using Sniffer4D and SnifferV portable gas detectors for UAS monitoring of degassing at the Turrialba Volcano Costa Rica

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Cite this study: Godfrey, I., Avard, G., Brenes, J. P. S., Cruz, M. M., & Meghraoui, K. (2022). Using Sniffer4D and SnifferV portable gas detectors for UAS monitoring of degassing at the Turrialba Volcano Costa Rica. Advanced UAV, 3(1), 54-90

Keywords
Atmospheric Chemistry
Volcanology
Climate Change
Volcanic Plume
Sniffer4D

Research Article
Received:30.04.2023
Revised:24.05.2023
Accepted:28.05.2023
Published:01.06.2023

Abstract

Since the completion of the first Sniffer UAS payload research article titled; Using UAS with Sniffer4D Payload to Document Volcanic Gas Emissions for Volcanic Surveillance: In this study the UAS system deployed carried the Sniffer4D which tested for Temperature, Humidity and 9 additional parameters - Sulfur Dioxide SO_2 (µg/ m³), Volatile Organic Compounds VOCs (ppm), Carbon Monoxide CO (mg/m³), Carbon Dioxide CO_2 (µg/ m³), Ozone O^3(µg/ m³), Nitrogen Dioxide NO_2 (µg/ m³), O^3+NO_2 and Particulate Matter - PM 1.0, 2.5 & 10. We have since expanded our gas detection abilities by specifically configuring the Sniffer V (Volcanic), which has Sulfur Dioxide SO_2 (µg/ m³), Carbon Monoxide CO (mg/m³), Flammable Gas CxHy (%), Hydrogen Sulfide H_2S (µg/ m³), Carbon Dioxide CO_2 (µg/ m³), Hydrogen chloride HCI (µg/ m³), Hydrogen H_2 (%) and Hydrogen fluoride HF (µg/ m³). A consistent volcanic monitoring program is crucial to the safety of the population and the efficiency of the nation. Costa Rica´s National Commission for Risk Prevention the CNE helps manage this responsibility. The National Observatory for Volcanoes OVSCORI-UNA and the Atmospheric Chemistry Laboratory LAQAT-UNA of Universidad Nacional Costa Rica through a joint cooperation both have a strategic interest in monitoring and tracking volcanic activity. AN essential aspect of monitoring volcanoes is tracking the active emissions being released from the craters, subaerial and subaqueous fumaroles, and diffuse degassing through soil and cracks in the volcanic edifice. For this study the Sniffer4D gas detection payload was deployed on an UAS and flown directly into the active West Crater of the Turrialba volcano in September 2022 for readings of active emissions. The main objective was to characterize the volcanic plume of Turrialba for all of these parameters to establish a baseline that can be built upon in the future through additional measurements to determine changes in outgassing regime of the volcano. This was the second time the Turrialba volcano has been tested with Sniffer4D electrochemical gas detectors for these parameters.

1. Introduction

The Turrialba Volcano in Costa Rica is one of the most active stratovolcanoes in all of Central America. The Turrialba Volcano is located at 3,340 meters above sea level in the Cartago Province of Costa Rica. There are three craters at the summit of the Turrialba Volcano which are the East Crater, the Central Crater and the actively degassing West Crater. The degassing fumaroles seen at the summit of Turrialba correspond to a shallow magmatic system actively emitting SO_2 rich fluids [1].

The Turrialba Volcano is located just 15 miles from Cartago and only 20 miles from San Jose the capital city of Costa Rica where the majority of the population live. Therefore, the geographical location of the Turrialba Volcano makes the monitoring program implemented by the CNE extremely important. Costa Rica's National Commission on Risk Prevention and Emergency Response or CNE is responsible for alerting the population of communities living near the volcanoes of any potential risk associated with an eruption. Furthermore, the prevailing wind direction will disperse the volcanic emissions towards the central valley where the majority of the population in Costa Rica live. Implementing a consistent and continuous gas monitoring program at Turrialba is a national priority in Costa Rica [1].

The last major eruptive cycle seen coming from the Turrialba Volcano was from (1864-1866). Afterwards the Central Crater did exhibit some fumarolic degassing and therefore bringing the Sniffer devices through the Central Crater did yield some valuable results. From (2005-2007) new vents began releasing emissions from the active West Crater and Central Crater. These fluctuations in degassing at Turrialba were a result of changes in geochemistry. There were three stages of activity classification for the eruptive and degassing seen coming from the Turrialba Volcano which were; 1. Hydrothermal (1998 - 2001)/ 2. Hydrothermal - Magmatic (2001 - 2007)/ 3. Magmatic (2007 - 2008). According to the publication; CO_2-CH_4-H_2 gas system equilibrium shows the evolution of the deep fluid reservoir increasing in temperature and having increasingly oxidative conditions [1].

These types of ground based remote sensing measurements of SO_2 taken from methods such as Differential Optical Absorption Spectroscopy or DOAS have been integrated to UAS as well. In April of 2007 the Department of Geology for the University of Sherffield in the United Kingdom traversed underneath the volcanic plume of the La Fossa Crater for SO_2 flux calculations. This was one of the first UAS studies in atmospheric analysis of a volcanic plume that confirmed the potential for UAS in monitoring volcanic emissions [2].

The Laboratory of Atmospheric Chemistry LAQAT-UNA has been monitoring the status of the Turrialba Volcano for long term trends and this program consists of measuring volcanic emissions. The Sniffer 4D was first flown into the active West Crater of the Turrialba volcano in April of 2022. The test in April using UAS was designed for monitoring SO_2 and Particulate Matter PM using the Sniffer4D capable of testing for VOCs, O_2, SO_2, CO, CO_2, PM 1, 2.5 & 10, NO_2, O_3, NO_2 + O_3. Advancements to the system after the April UAS analysis leaded to another research trip to the Turrialba summit with the newly configured the SnifferV (Volcanic) which measures SO_2, CO, CxHy, H_2S, HCI, CO_2, H_2 and HF. The second UAS Sniffer analysis of volcanic emissions being released from the Turrialba Volcano took place in September of 2022.

Figure 1. UAS Image of Central Crater & Active West Crater of the Turrialba Volcano September 2022

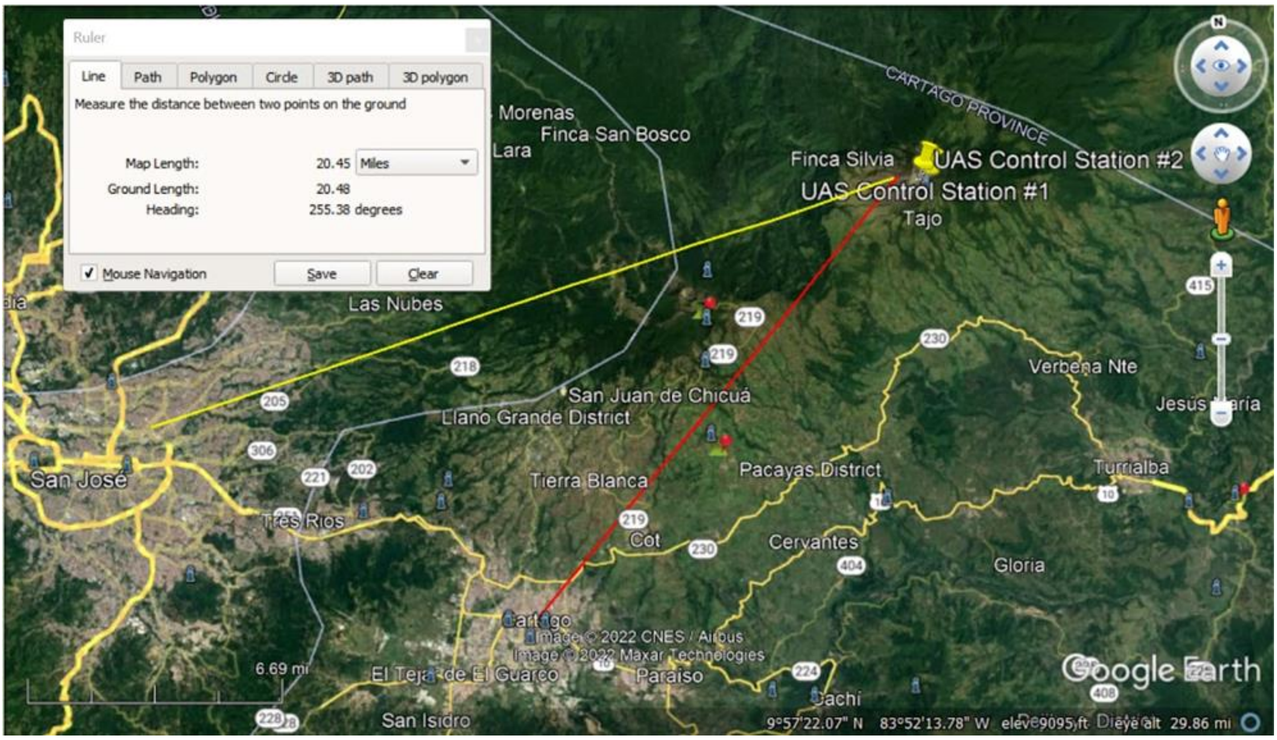


Figure 2. Distance from Turrialba Volcano to Cartago and San José

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, Irazu volcano, Poas volcano, Arenal volcano, Tenorio volcano and Turrialba volcano in Costa Rica.

The Autel EVO Lite + drone was a consumer drone used at the Turrialba volcano which greatly assisted with our observational research. We launched this drone first to make observations of the cloud coverage before launching the Aki-01 (Matrice-600 Pro) with the Sniffer4D payload. These consumer drones can be deployed in volcanic field work for many different reasons.

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 S4V - 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 SO_2/CO_2 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. 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.

The objective of this project was to visit the Turrialba Volcano National Park in Costa Rica with the LAQAT-UNA UAS fleet. The Turrialba volcano has periodic eruptions and had a period of increased activity from 2017-2021. 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.

Figure 3 & 4. Aki -01 (Matrice 600-Pro) at the Turrialba Volcano September 2022

The research conducted on September 27th, 2022 in collaboration with the Volcanic and Seismic Observatory of Costa Rica OVSCORI-UNA and the Laboratory of Atmospheric Chemistry LAQAT-UNA was scheduled and implemented perfectly by Mr. Jose Pablo Sibaja Brenes. The logistics of just arriving at the summit were extremely complex. The day before our visit was a full day of preparing and planning, gathering equipment, charging batteries, confirming our flight plans with the SINAC National Park administration and organizing transportation.

To accomplish these research objectives, we all woke up at 3:00am and met at the university by 5:00am, then had a 3-hour drive to the Turrialba Volcano National Park. Once we arrived, we met with the two park rangers who helped us reach the volcano summit. We then filled two four wheelers with gas and began attaching all of the scientific equipment to the two four wheelers. Each park ranger drove one of these all-terrain vehicles which were required to reach the summit of the Turrialba Volcano. Upon arrival Dr. Geoffory Avard of OVSCORI-UNA was already at the summit preparing the control station for our remote flights.

The Turrialba volcano is located 40 km or 25 miles East of San José the Capital city of Costa Rica where the majority of the population live. Between 2016-2017 an eruption column emerged 4,000 meters or 13,123 feet above the summit crater of the Turrialba volcano and dispersed ash in the capital resulting in airport closures. Thus, monitoring the Turrialba volcano is of great importance to the country.

Figure 5. Eruption that dispersed ash all the way to the Juan Santamaria International Airport March 12, 2015

Remote sensing of SO_2 emissions at Turrialba have been a successful undertaking in the past with several research articles resulting from this method of measurement. In the article titled; Space and ground-based measurements of sulphur dioxide emissions from Turrialba Volcano; researchers found: There were aerosols and acidic gas emissions being released from Turrialba which were contributing to the total environmental acidification of the Direct Impact Zone of the Turrialba Volcano located within a 2-mile radius around the active West Crater. By implementing UAS technology and the Sniffer4D and SnifferV gas detection payloads at the Turrialba summit, the Laboratory of Atmospheric Chemistry LAQAT-UNA has successfully measured SO_2 emissions coming from the active West Crater two times in 2022. "SO_2 is one of the most important volcanic gases and arguably the easiest to measure by remote sensing. It is characteristically from high temperature gases and is thus a good indicator of the presence of magma at shallow depth. Therefore, measurements of SO_2 flux are widely recognized as a valuable parameter for volcanic monitoring." [3].

Figure 6. Google Earth UAS control station locations at the Turrialba Volcano Summit

These Sniffer devices also log longitude and latitude, temperature and humidity and calculate the area tested per each measurement. The Sniffer Mapper software can showcase the Turrialba volcano flight path in 3D or a grid concentration with boxes to click which individually represent different GPS locations where the Sniffer4D tested for volcanic emissions. The SnifferV allowed us to collect additional volcanic emission data and the gas emissions being released from the active West Crater. This information was used to generate an AERMOD Plot of the emissions on September 27th, 2022 to show the direction of the pollutant's discernment.

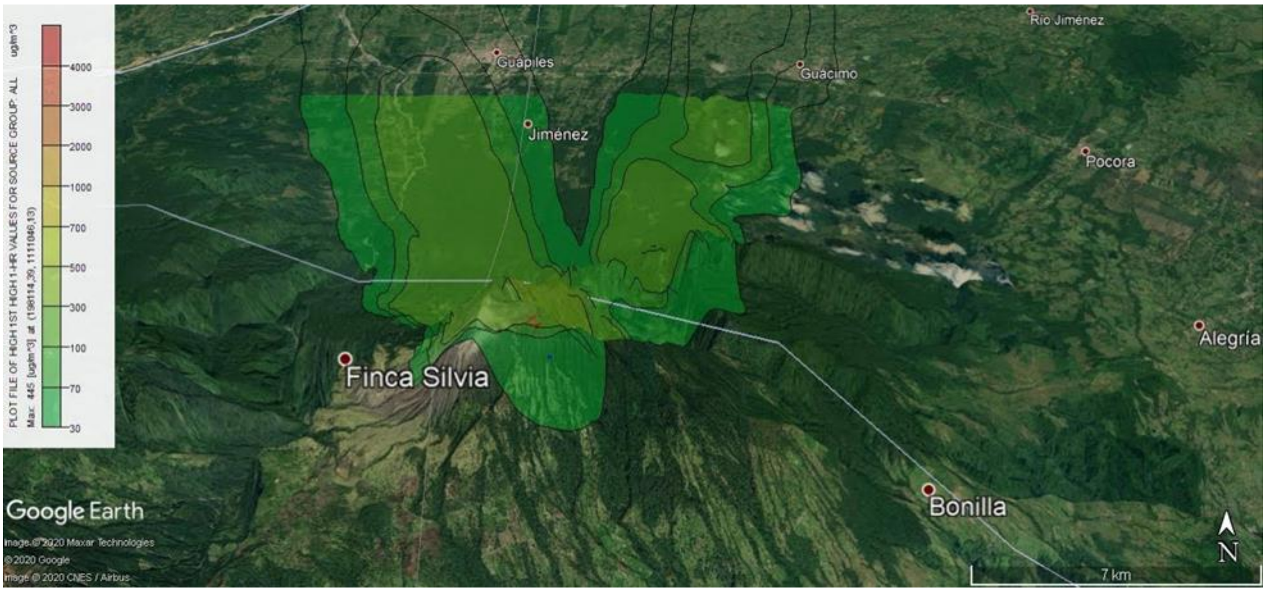


Figure 7. AERMOD plot of Turrialba Volcano Emissions of SO_2 September 27th, 2022

Screenshots from the Aki-01 (Matrice 600-Pro) flight with the SnifferV remote pilot in comand José Pablo overflew the central crater and went right up to the rim of the Active West Crater for a complete aerial survey of the Central Crater. During the flight the rim of the West Crater was surveyed for cracks, two were identified and documented. The camera used for the documenting of the active western crater rim was a Zenmuse Z30.

When flying drones for plume quantification traverse is better than Scanning DOAS because it's directly under the plume and much easier to get a flux of total volcanic emission SO_2 output per day. In 2013 remote pilots and researchers operated a UAS at the Turrialba Volcano attempting to document the 3-day average of SO_2 degassing flux. The article outlined the fact that volcanic degassing is connected with the magmatic-hydrothermal system of the volcano. Therefore, monitoring the interactions between the magmatic-hydrothermal system of the volcano and associated degassing is a priority for the Turrialba volcanic observational program and gas detection equipment are a crucial part for proper risk management associated with the Turrialba Volcano [4].


Figure 8 & 9. Remote pilot operating the Aki-01 at the Turrialba Volcano

The findings from this field work were that UAS took accurate readings of SO_2 and from the data accumulated from the remote flight missions' researchers were able to calculate total emission flux from the degassing of the Turrialba Volcano from March 11-13, 2013. The conclusions of the research were in tune and in agreement with measurements of SO_2 that were taken from other methods such as ground based Differential Optical Absorbtion Spectroscopy or DOAS [4].

The research in 2013 began an era of using UAS as an instrument for detecting volcanic gas emissions and keeping teams of scientists' safe and out of the impact zone of any potential eruption. UAS have since been increasing in popularity for volcanic and geological application especially for monitoring volcanic degassing, measuring gases in the plume itself, and even collecting samples of gases from within the eruption column [4].

There were several serious lessons learned from the previous remote pilots who flew gas detection missions with UAS. In the research publication titled; Using Drones and Miniaturized Instrumentation to Study Degassing at Turrialba and Masaya Volcanoes, Central America; Journal of Geophysical Research for an article with Solid Earth (2018) the recent advancements in the drone industry are made clear. For example, in 2017 there was a 15-minute flight time with field conditions >30% battery remaining. The Aki-01 (DJI-Matrice 600 - Pro) has a 30-minute flight time with >30% battery upon returning to the home point. This illustrates the rapid advancements in the UAS sector over the past five years [5].

There was also a payload weight reduction by deploying the Sniffer4D V2 as a payload. The previous 1,500-gram multi-GAS system has now been reduced to >500 grams. An additional main point from the research paper was that two drones were lost flying through the gas plume. Volcanic emissions corrode electrical equipment. News reporters have had video cameras damaged rapidly at the Turrialba volcano; cameras, drones and gas detection hardware are all susceptible from this volcanic atmosphere. It's recommended to use waterproof or at least water-resistant electrical equipment so it has some kind of resistance to the volcanic emissions [5].

Recent developments in the manufacturing of both UAS and associated payload packages have resulted in more high endurance systems and more economical price points. These advancements have offered new opportunities for remotely monitoring dangerous areas of active volcanoes. UAS offer volcanologists the opportunity to survey these danger zones without any risks. Furthermore, UAS deployed by skilled remote pilots increase the likelihood of completing the flights through the emissions for volcanic plume analysis [6].

Plume traverse flights at consistent altitude are recommended because there is significant equilibrium time on either side of the plume. This method was used to monitor multiple gas species at Manam in Papua New Guinea for the characterization of volcanic emission flux study using UAS. These scientists used both fixed wing and multi rotor drone systems for this study [6].

The Sniffer4D was able to be integrated to multiple UAS and is able to detect and monitor multiple gas emission species and plot them with GPS coordinates onto an interactive map using the Sniffer Mapper software program. The Sniffer4D sampling rate is one measurement per second making the system extremely fast and accurate for quickly entering areas of significant emissions and returning with required information. The Sniffer4D is able to make UAS flights into and around volcanic gas plumes and return with information capable of generating the CO_2/SO_2, H_2O/CO_2, and CO_2/H_2O ratios.

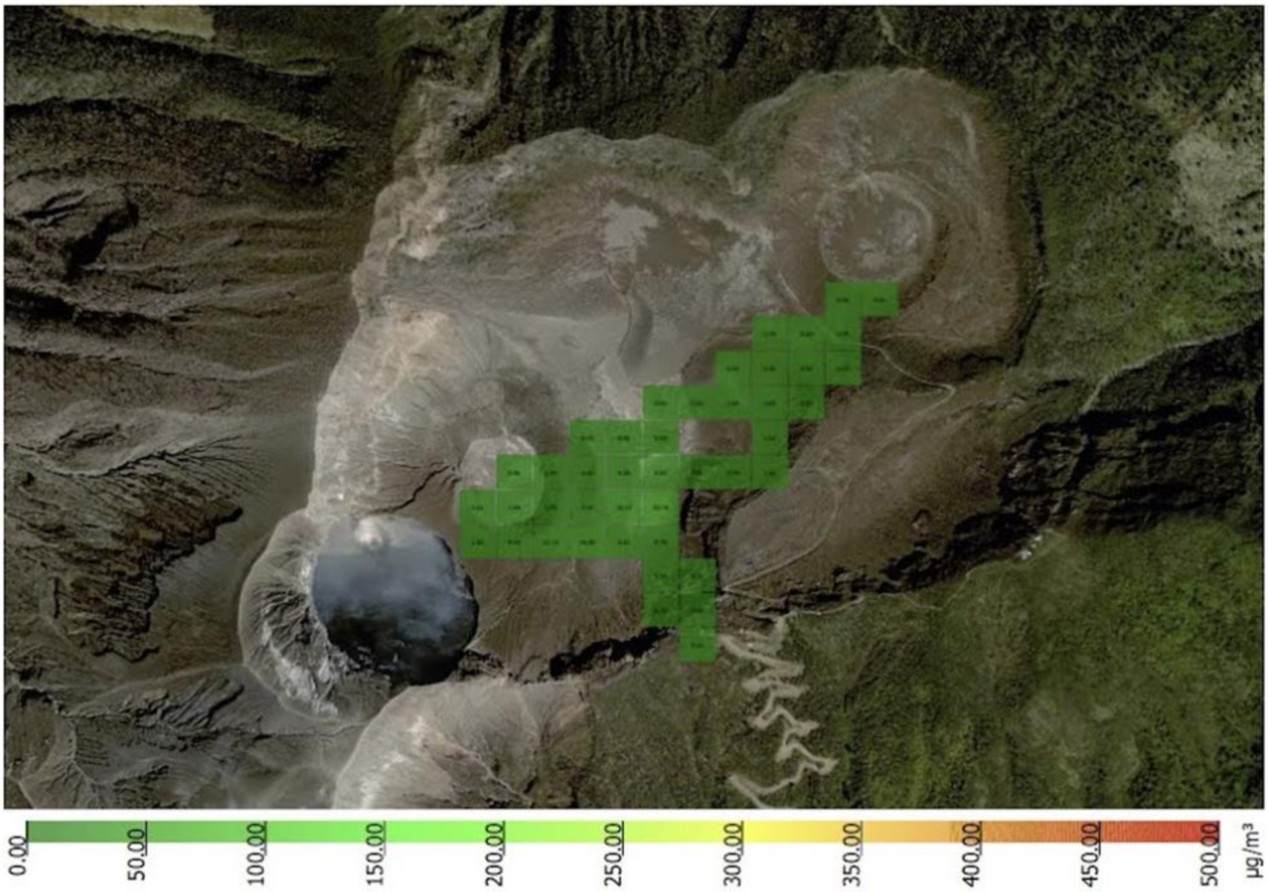


Figure 10. SO_2 Emissions tracked with Aki-01 in Sniffer Mapper software program

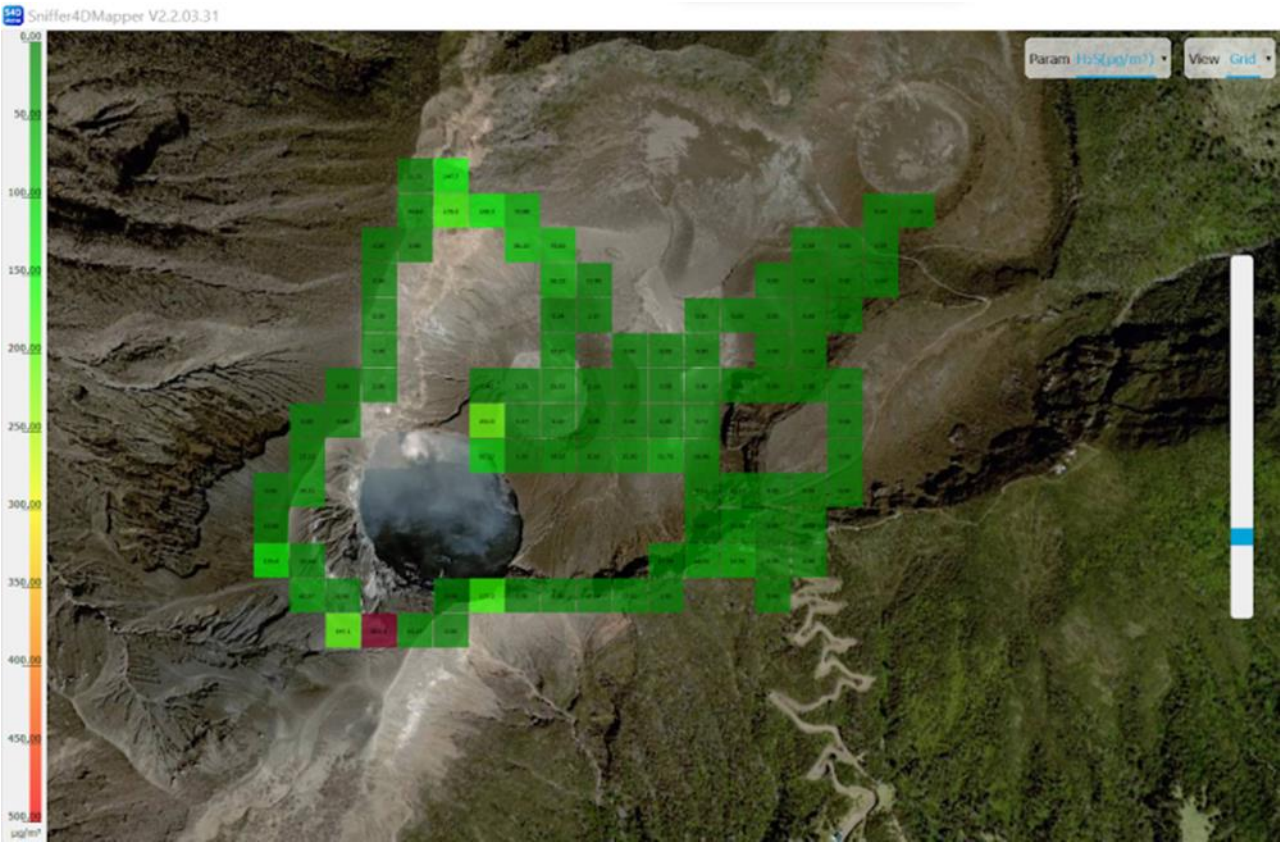


Figure 11. Sniffer Mapper volcanic emission analysis of H_2S Turrialba Volcano

3. Discussion

From April to September the rainy season of Central America was the atmospheric condition and the ability to use drones at the Turrialba Volcano was extremely limited. In September the roads leading to the summit were still muddy and 4 wheelers were required to transport the team and equipment to the Turrialba summit. Several geological changes were obvious and immediately upon reaching the summit the SnifferV and Sniffer4D were powered on for air quality analysis of the atmosphere in this volcanic environment. The Sniffer devices were strategically configured to monitor the active emissions degassing from the west crater and dispersing around the Turrialba Volcano National Park.

Several changes were identified with the Autel Lite + drone which was flown first to do a safety check. First noticeable difference was the presence of several crater lakes located within the summit caldera. Two lakes were located in the Central Crater. Another two were located in the East crater. All together four crater lakes were present in September during the UAS flight missions.

In the article titled; Study of Turquoise and Bright Sky Blue Appearing Freshwater Bodies, of Environmental Studies: 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 O_2. 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 [7].

"Suspended and dissolved particles influence the color of water. Turquoise and bright sky-blue appearing fresh water bodies are found in different parts of the world in different sets of environmental conditions. Glacial-fed lakes also appear turquoise, crater lakes also bear turquoise color and calcium carbonate rich water bodies also appear turquoise." [7].

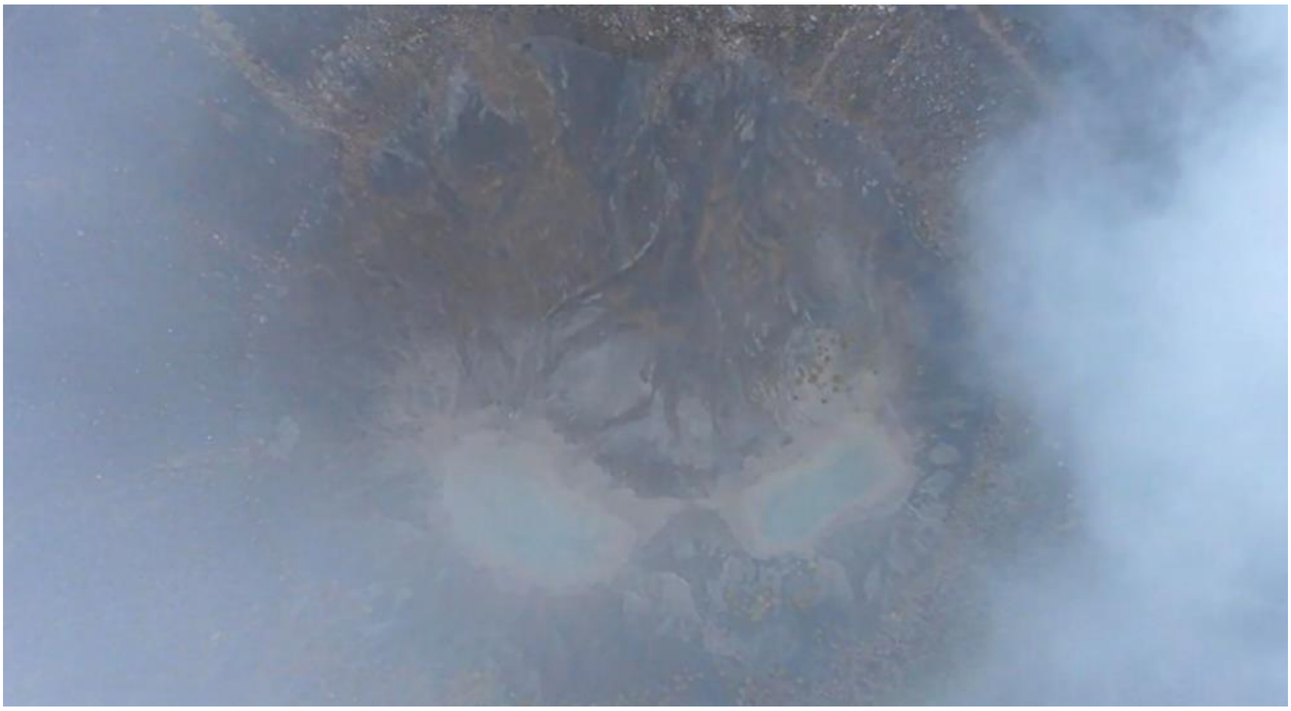


Figure 12. UAS image of east crater of the Turrialba Volcano September 2022

Figure 13. UAS image of east crater of the Turrialba Volcano September 2022

Figure 14 & 15. UAS image of east crater of the Turrialba Volcano September 2022

Figure 16 & 17. UAS image of east crater of the Turrialba Volcano September 2022

Figure 18 & 19. UAS image of east crater of the Turrialba Volcano September 2022

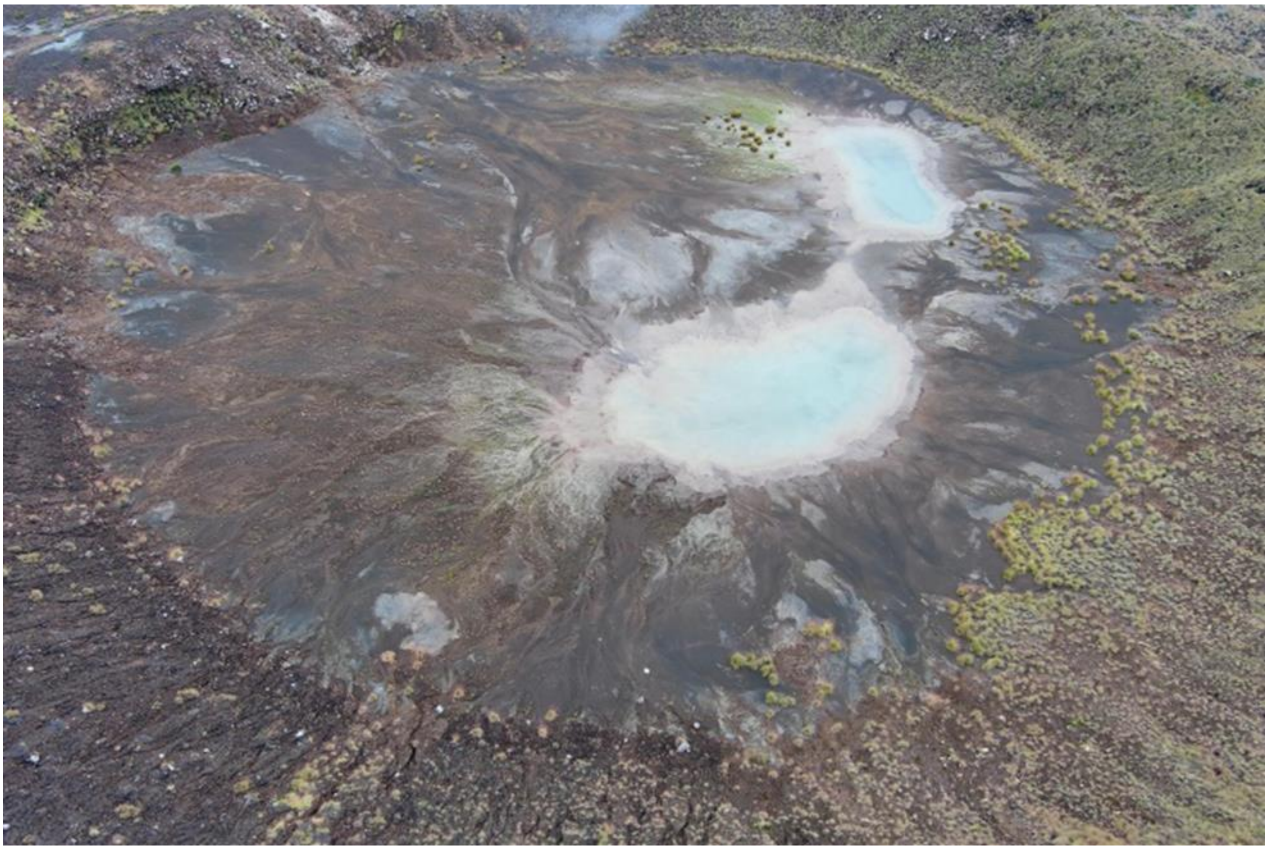


Figure 20. UAS image of east crater of the Turrialba Volcano September 2022

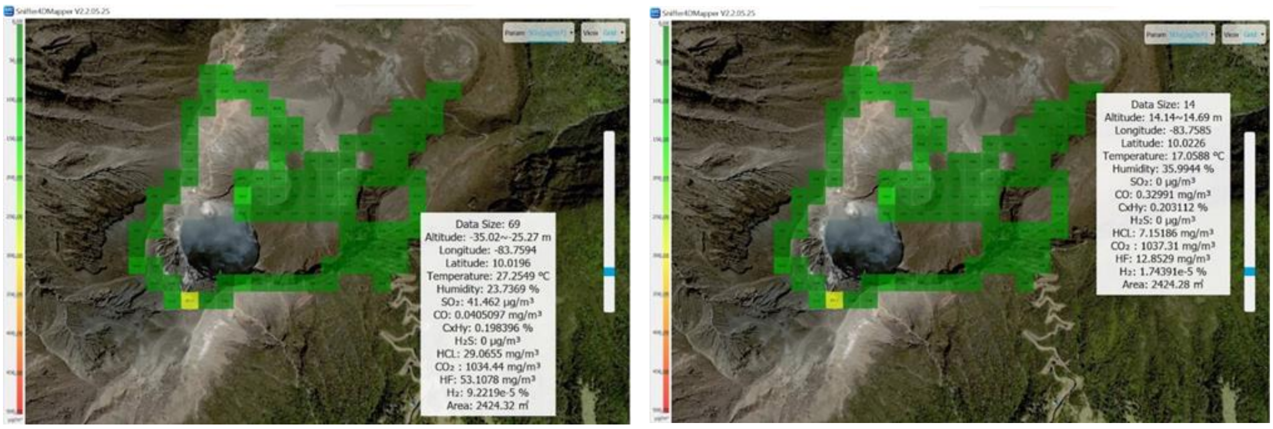


Figure 21 & 22. SnifferV & Sniffer4D ambient air monitoring at the east crater of the Turrialba Volcano

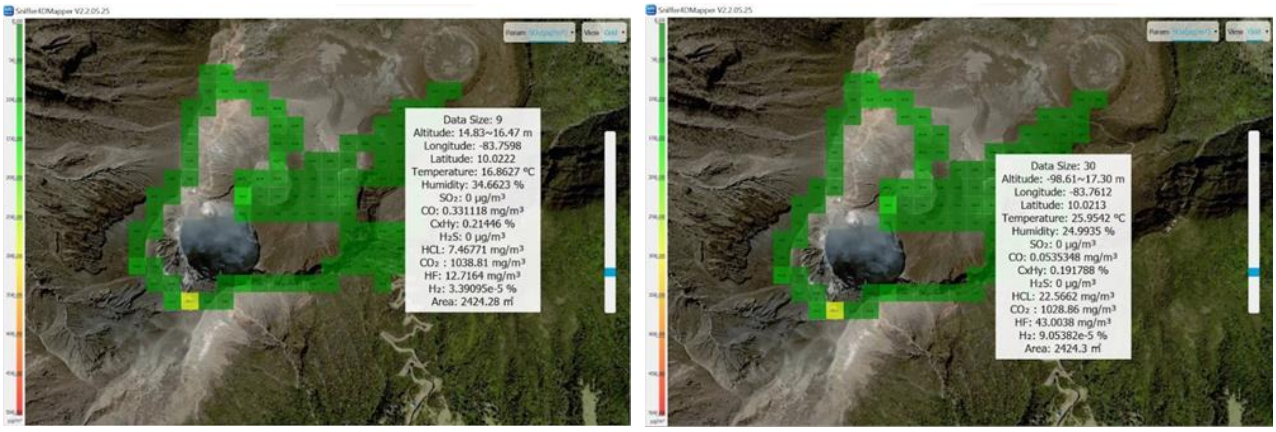


Figure 23 & 24. SnifferV & Sniffer4D ambient air monitoring at the east crater of the Turrialba Volcano

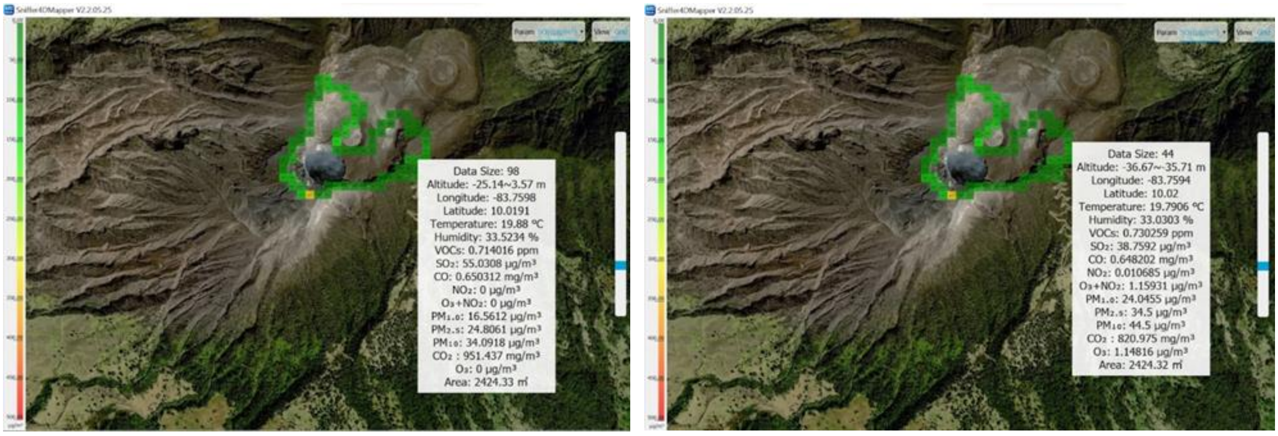


Figure 25 & 26. Sniffer4D measurements from the east crater area of the Turrialba Volcano


Figure 27. UAS image of east crater of the Turrialba Volcano September 2022

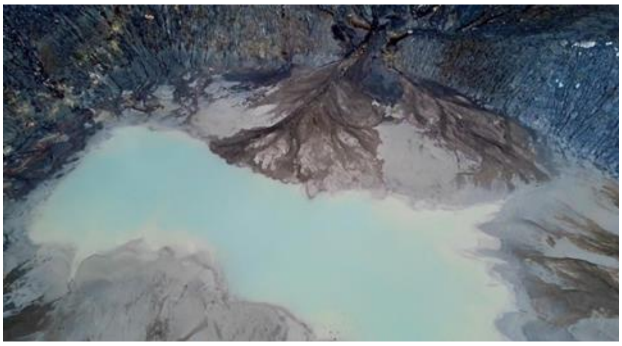



Figure 28 & 29. UAS image of central crater of the Turrialba Volcano


Figure 30 & 31. UAS image of central crater of the Turrialba Volcano


Figure 32 & 33. UAS image of central crater of the Turrialba Volcano


Figure 34 & 35. UAS image of central crater of the Turrialba Volcano


Figure 36 & 37. UAS image of crater lake of the Turrialba Volcano


Figure 38 & 39. UAS image of LAQAT-UNA researchers inside the central crater of the Turrialba Volcano


Figure 40 & 41. UAS image of LAQAT-UNA researchers inside the central crater of the Turrialba Volcano

Figure 42. UAS image of crater lake of the Turrialba Volcano

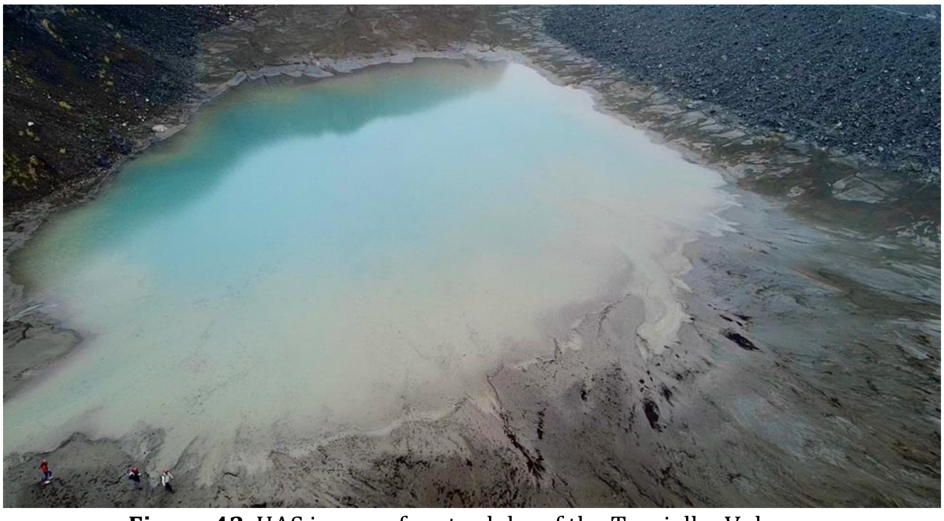


Figure 43. UAS image of crater lake of the Turrialba Volcano

Figure 44 & 45. UAS image of crater lake of the Turrialba Volcano

Figure 46. UAS image of crater lake of the Turrialba Volcano September 2022

Figure 47. UAS image of water flow area leading to crater lake of the Turrialba Volcano September 2022

Figure 48. UAS image of approach to central crater of the Turrialba Volcano

New UAS now integrated with pre-existing sensor technology are now able to generate real time 3-D volcanic emission maps showing gas concentrations of the Turrialba Volcano in Costa Rica [8].

The Department of Earth Science for the University of Cambridge has taken particular interest in the advancements in the UAS sector. Researchers from Cambridge visited Chile where they studied the outgassing of the Villarrica Volcano using UAS. These scientists outlined research explaining that they studied the degassing of volcanoes because they are one way to study both magmatic and hydrothermal systems below the volcano itself. They showed how gas ratios such as CO_2/SO_2 helped contribute to timely forecasts in eruptive events [9].

UAS are now taking remote measurement equipment and taking the instruments directly into degassing fumaroles, around fumaroles in a circular fashion at various altitudes, and underneath volcanic plumes for specialized experiments in atmospheric chemistry. UAS were used for plume mapping and static hover directly inside the plume for total gas flux per day calculations. Open vent degassing volcanoes represent the best natural environment for the field work research and development required for the development of the ideal volcanic surveillance UAS. This type of UAS and multi gas monitoring system will be specifically configured for volcanic surveillance and will have high resolution thermal imaging capabilities. In the future these types of UAS will be much less susceptible to corrosion.

Due to significant moisture and rainfall in Costa Rica during the month of September there was a gas plume consisting mostly of water vapor stretching around 100 meters above the active West Crater.

We used both the Autel Lite + UAS the Aki-01 UAS at the summit for atmospheric and volcanic analysis. The Aki-01 was used with the SnifferV payload gas detection package, and Dr. Geoffory Avard carried the two Sniffers integrated to a backpack with batteries cables and electrical tape and walked the entire radius of the active west crater. During the walk he stopped at the fumarole area on the ridge of the west crater which is the area showing the most obvious signs of degassing for the best and most accurate gas measurements with the Sniffer devices.

By using the Sniffer Mapper, we were able to easily review all accumulated data at each GPS location and run an analysis of SO_2, CO_2 and H_2S where we tracked the minimum and most importantly the maximum concentrations which are most relevant as they tell us the most about the quantity of volcanic emissions being released from the degassing site, in this case the west crater of the Turrialba Volcano.

Figure 49 & 50. UAS image of central crater of the Turrialba Volcano

There is a relevant Excel file attached to the paper to show how the software Sniffer Mapper can easily generate full volcanic emission reports which can be easily shared with the entire team. By using the Sniffer4D, which monitors particulate matter we were also able to generate PM Ratios of PM10/2.5, PM10/1 and PM2.5/1

UAS flights with gas detection equipment like the Sniffer4D moving through environments with a volcanic atmosphere have helped scientists in Japan determine whether volcanic degassing was associated with the magmatic or hydrothermal systems of the Mt. Ontake Volcano [9].

Figure 51. UAS image of central crater of the Turrialba Volcano September 2022

Figure 52. UAS image of central crater of the Turrialba Volcano September 2022

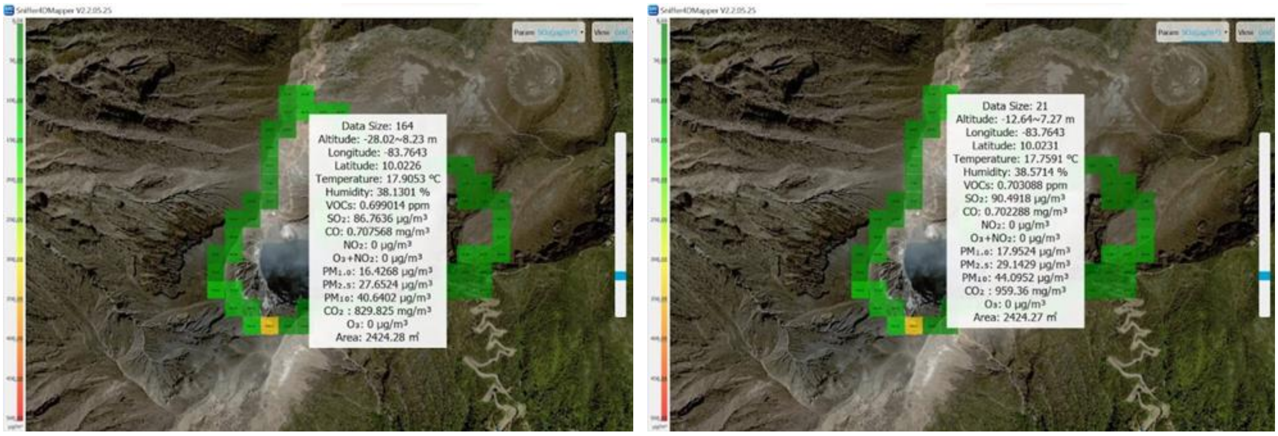


Figure 53 & 54. Sniffer4D measurements from the central crater of the Turrialba Volcano

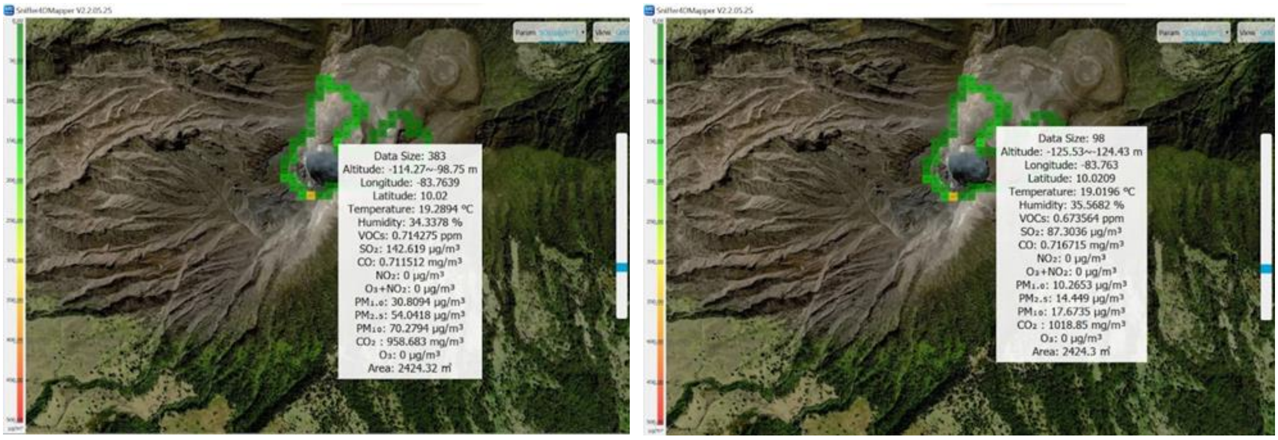


Figure 55 & 56. Sniffer4D measurements from the central crater of the Turrialba Volcano

Figure 57. UAS image of central crater of the Turrialba Volcano September 2022

Figure 58. UAS image of central crater of the Turrialba Volcano September 2022

Figure 59. UAS image of central crater of the Turrialba Volcano

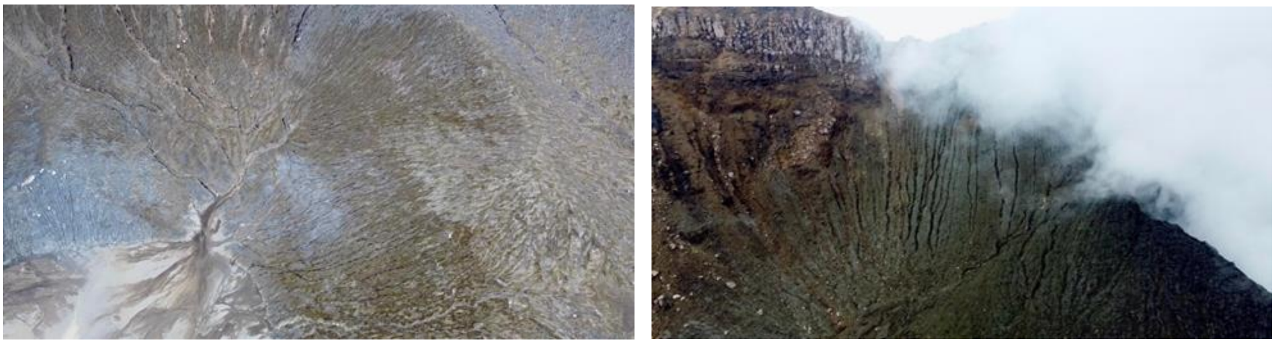


Figure 60 & 61. UAS image of central crater of the Turrialba Volcano


Figure 62 & 63. UAS image of central crater of the Turrialba Volcano

Figure 64. UAS image of central crater of the Turrialba Volcano

Figure 65. UAS image of LAQAT-UNA researchers inside the central crater of the Turrialba Volcano

Figure 66 & 67. SnifferV & Sniffer4D emission tracking inside the central crater of the Turrialba Volcano

Figure 68 & 69. UAS analysis of central crater lake view from Rim of West Crater by Dr. Geoffroy Avard

Figure 70 & 71. UAS image of central crater of the Turrialba Volcano

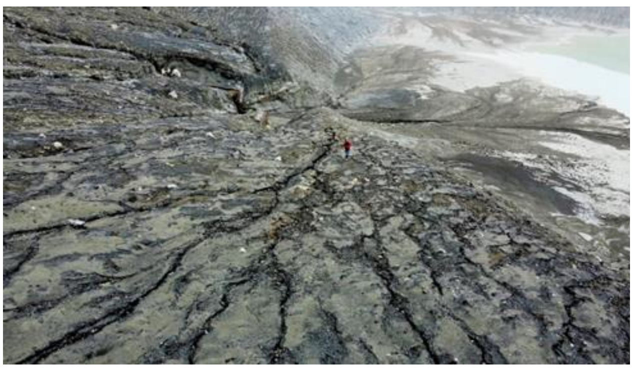


Figure 72 & 73. UAS image of central crater of the Turrialba Volcano

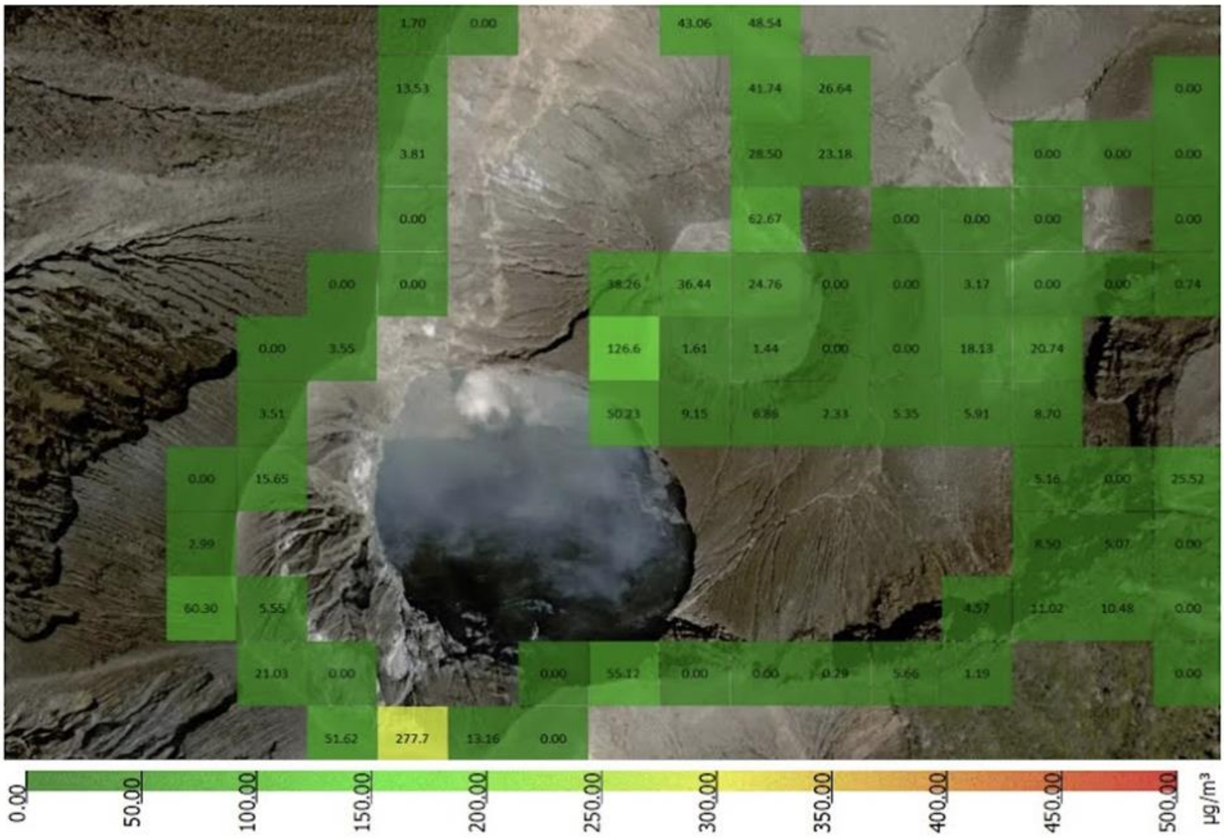


Figure 74. SO_2 Emissions tracked in Sniffer Mapper software program

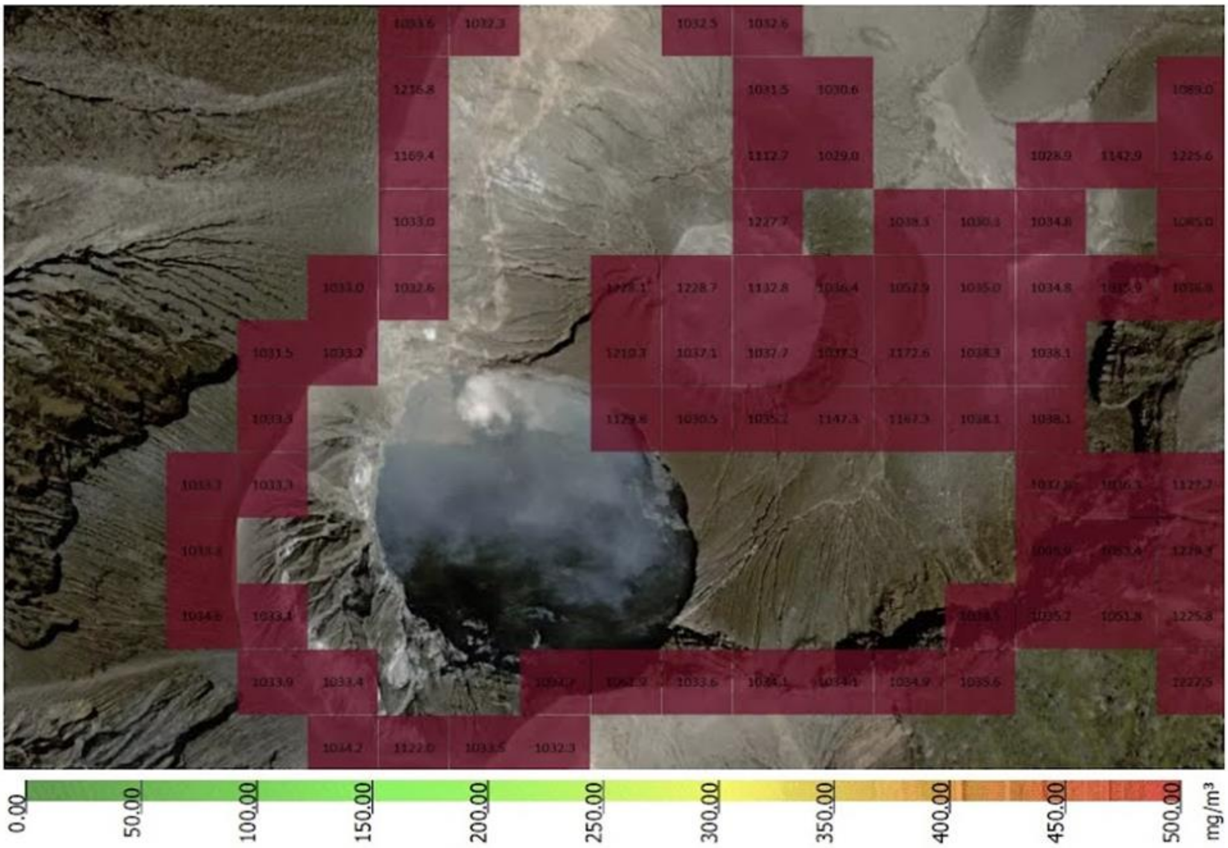


Figure 75. CO_2 emissions tracked in Sniffer Mapper software program

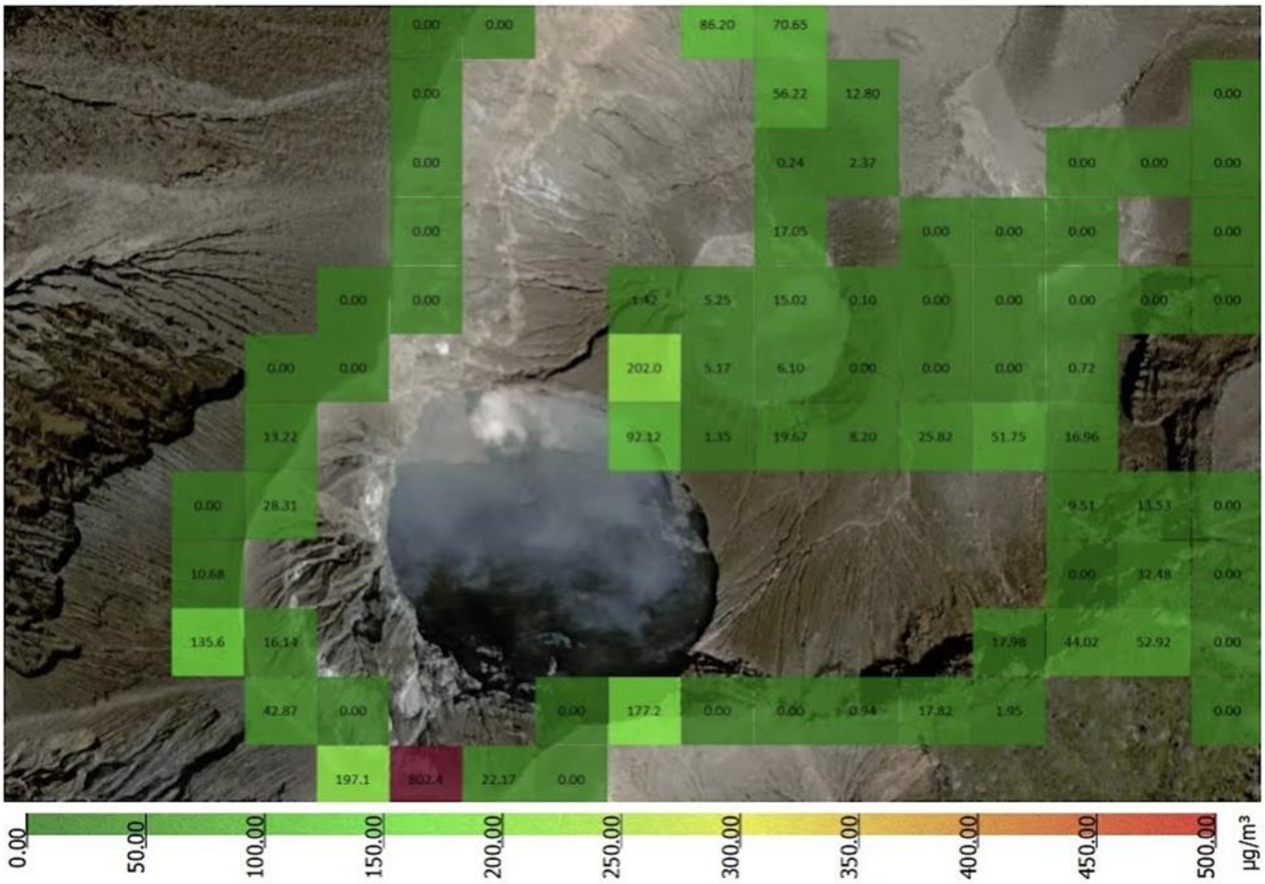


Figure 76. H_2S emissions tracked in Sniffer Mapper software program

The complete survey of the Turrialba volcano summit was completed on September 27th, 2022 with the assistance of Universidad Nacional de Costa Rica. We deployed both the Sniffer4D and SnifferV for this complete analysis of volcanic emissions.

1. The first part of the gas emission survey was an aerial measurement conducted by remote pilot in command José Pablo Sibaja Brenes of the Laboratory of Atmospheric Chemistry using the Aki-01 (DJI Matrice 600-Pro). We attached the SnifferV to the Aki-01 in less than 5 minutes and allowed the device to warm up for an additional 5 minutes. The actual flight mission was conducted from 10:43-11:08 am. The flight mission was set for 20 minutes exactly and the Aki-01 was landed successfully with sufficient battery power.
2. The two Sniffer devices were then walked around the active West Crater of the Turrialba Volcano National Park by Dr. Geoffroy Avard who passes very close to the fumarolic field where the most obvious degassing occurs. The radius walk around the crater was from 11:10am -12:10pm. It tools one hour to successfully survey the western ridge of the crater which was the most important area due to the trade winds blowing west and dispersing the volcanic gases being released.
3. Central crater walk was from 12:10pm-12:28 and lasted for a total of 18 minutes. The walk through the Central Crater and up to the eastern rim of the West Crater proved to yield some valuable data relative to the state of degassing seen coming from the Turrialba volcano. After the completed analysis we kept the two Sniffer4D V2 units running during our rest period and during the return walk to our starting point at the main lookout point located on the southern crater edge at the summit of the Turrialba volcano. The complete survey was finished at 1:22pm Costa Rica time just before the cloud coverage moved in.
4. Multi-GAS Comparison - The data sets collected at the summit of the Turrialba volcano which were obtained as seporate measurement sets can be combined using the Sniffer Mapper software which allowed us to combine these individual measurements to review and evaluate the total ambient air quality for the summit of the Turrialba volcano as a whole.

Figure 77. UAS image of active west crater of the Turrialba Volcano September 2022

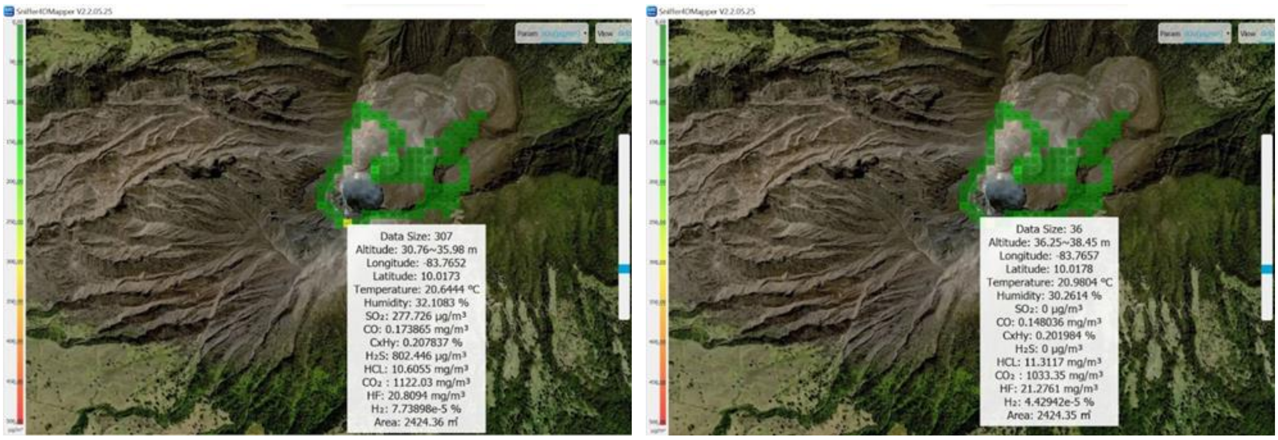


Figure 78 & 79. SnifferV & Sniffer4D emission tracking the active west crater of the Turrialba Volcano

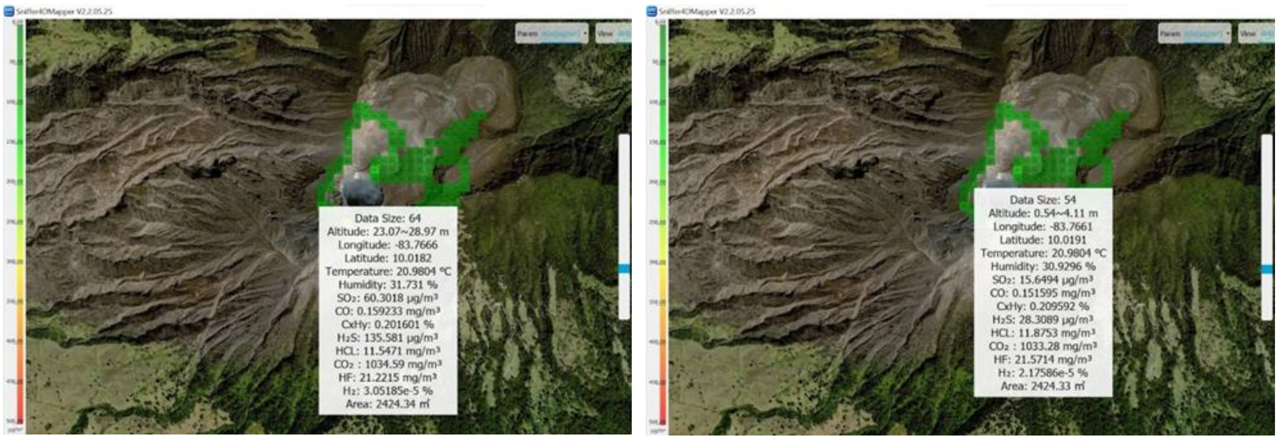


Figure 80 & 81. SnifferV & Sniffer4D emission tracking the active west crater of the Turrialba Volcano

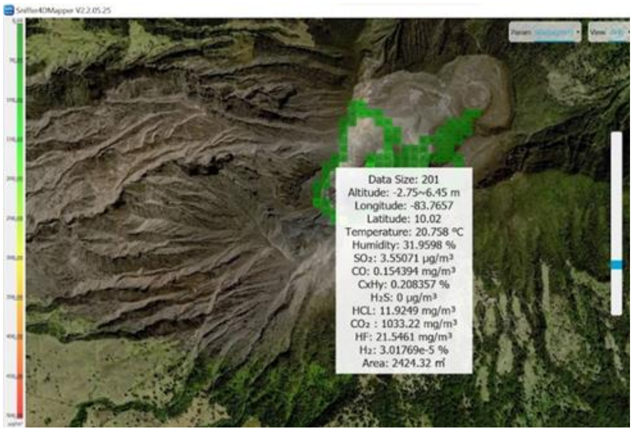


Figure 82 & 83. SnifferV & Sniffer4D emission tracking the active west crater of the Turrialba Volcano

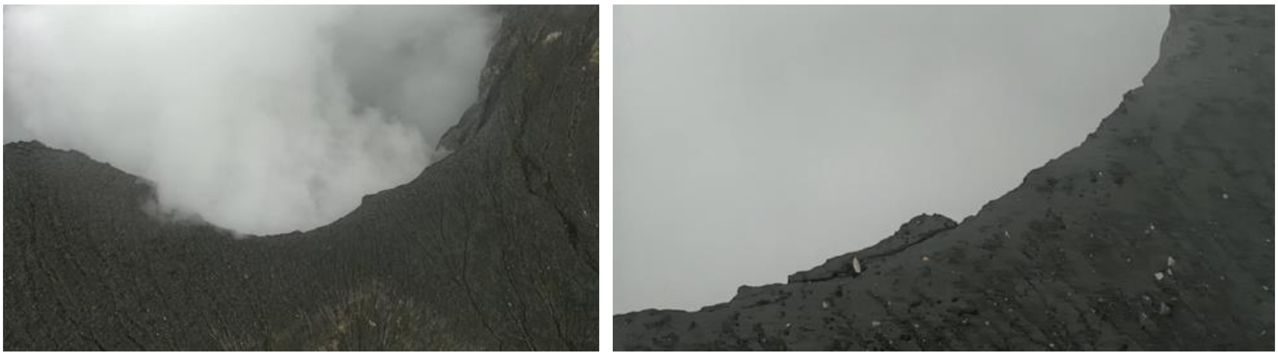


Figure 84 & 85. Active west crater rim cracking analysis

Figure 86. UAS image of active west crater of the Turrialba Volcano September 2022

Figure 87. Sniffer4D measurements from the active west crater of the Turrialba Volcano

On September 27th, 2022 there are a category 4 Hurricane Ian in the Guld of Mexico approaching the west coast of Florida. It was Hurricane Ian that actually had an impact on the atmospheric conditions in Costa Rica. During our September survey of the Turrialba Volcano emissions the wind direction was actually to the north, something not commonly observed in the Central American Country. The SO_2 and other gases were very low during the day of our survey, still some emissions still have an impact on the local farms and dary sites. The Laboratory of Atmospheric Chemistry director José Pable Sibaja Brenen created the associated AERMOD Plot illustrating the direction of the volcanic gas discernment.

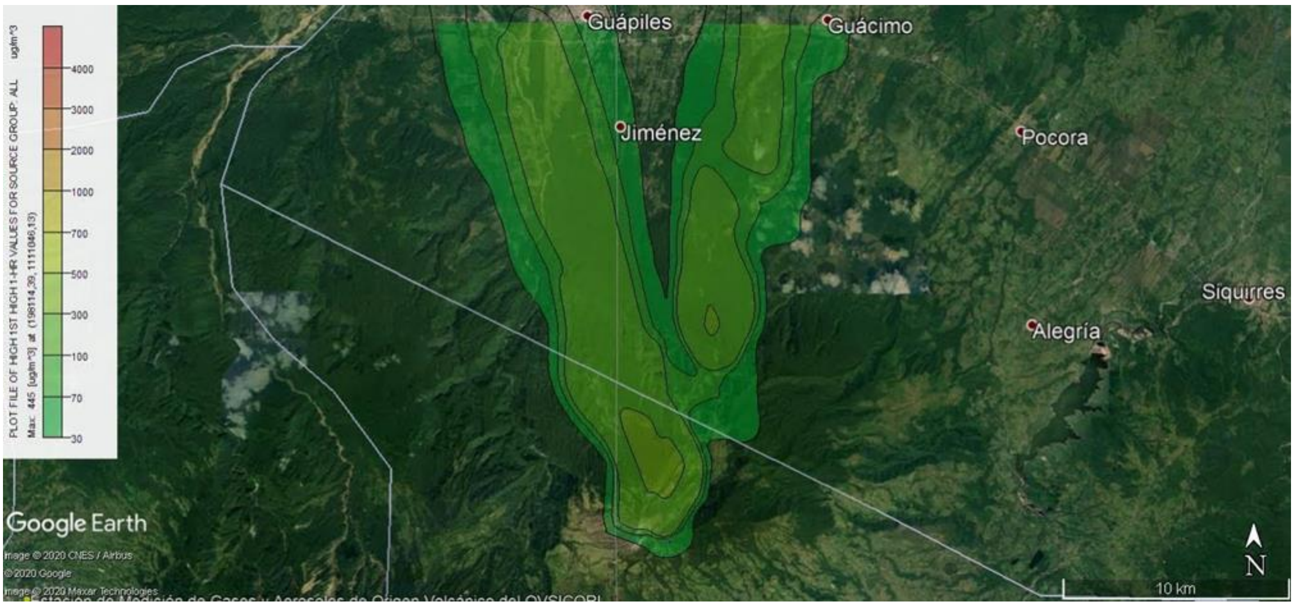


Figure 88. AERMOD plot of Turrialba Volcano emissions of SO_2 September 27th, 2022


Figure 89 & 90. Active west crater Rim from Sniffer4D and SnifferV Walk

Figure 91 & 92. Sniffer4D measurements tracking from the active west crater of the Turrialba Volcano

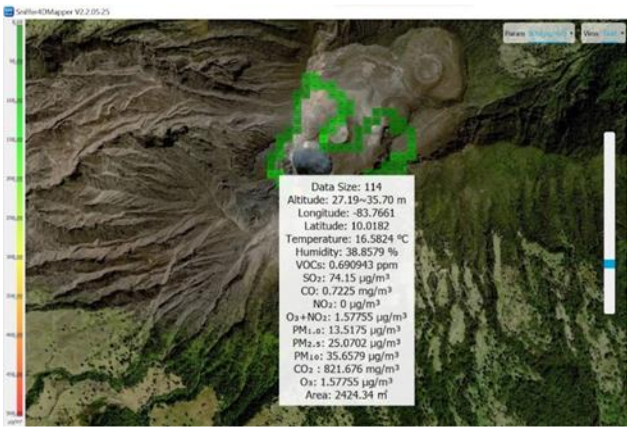
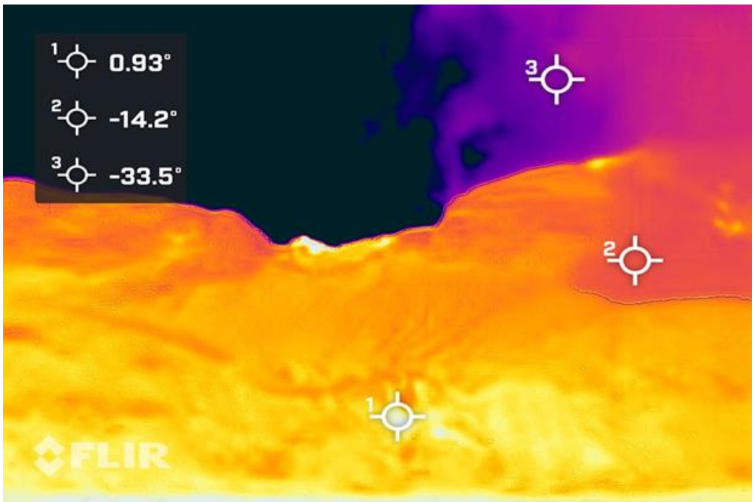


Figure 93 & 94. Sniffer4D measurements tracking from the active west crater of the Turrialba Volcano

Figure 95. Sniffer4D measurements from the active west crater of the Turrialba Volcano

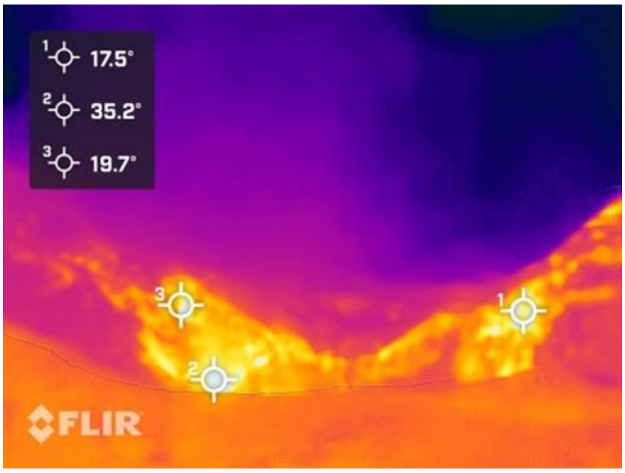
Figure 96. UAS image of active west crater of the Turrialba Volcano September 2022



TEMPERATURES	
Spot 1	0.93 °C
Spot 2	-14.2 °C
Spot 3	-33.5 °C

PARAMETERS	
Emissivity	0.3
Distance	1 m
Reflected Temperature	22 °C
Relative Humidity	50 %
Atmospheric Temperature	20 °C
Atmospheric Transmission	0.99
External Optics Temperature	25 °C
External Optics Transmission	1

Figure 97 & 98. FLIR One Pro thermal analysis of west crater Turrialba Volcano September 2022



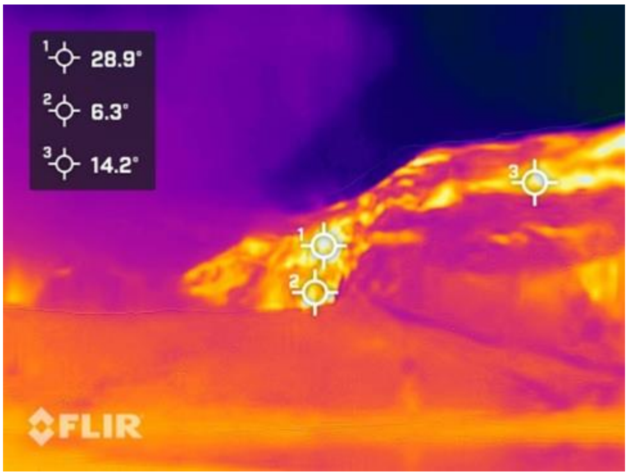
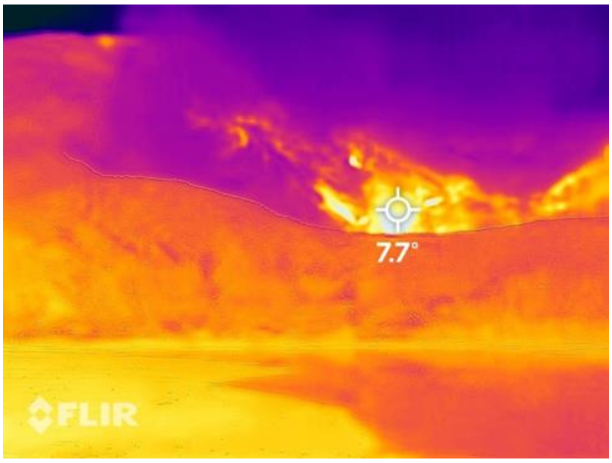


Figure 99 & 100. FLIR One pro thermal analysis of west crater Turrialba Volcano September 2022



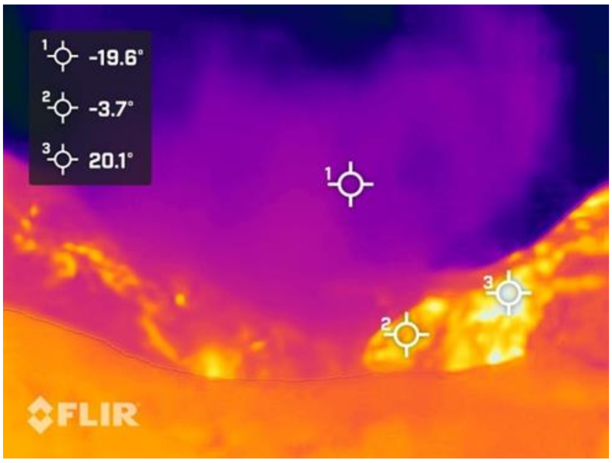


Figure 101 & 102. FLIR One Pro thermal analysis of west crater Turrialba Volcano September 2022

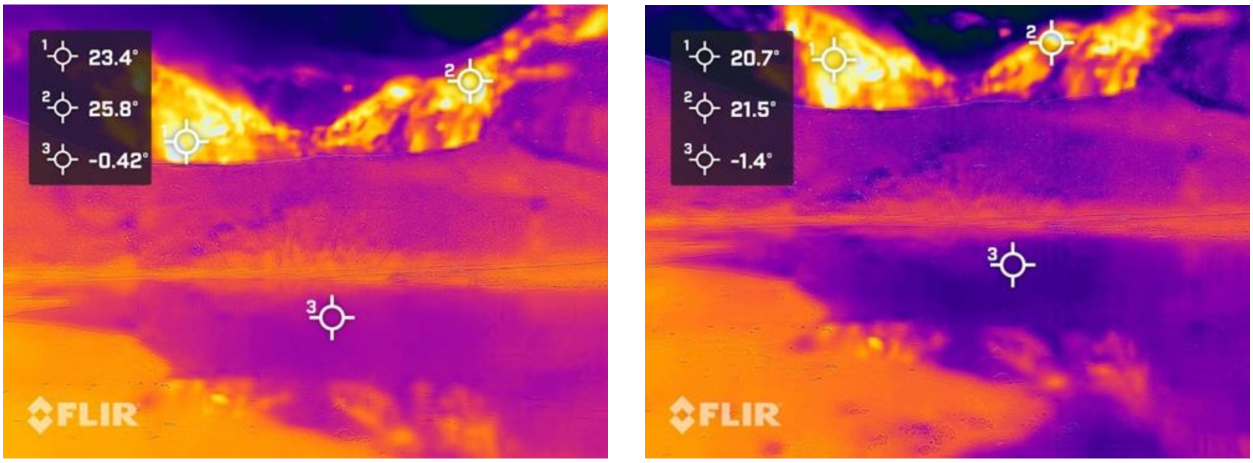


Figure 103 & 104. FLIR One pro thermal analysis of west crater Turrialba Volcano September 2022

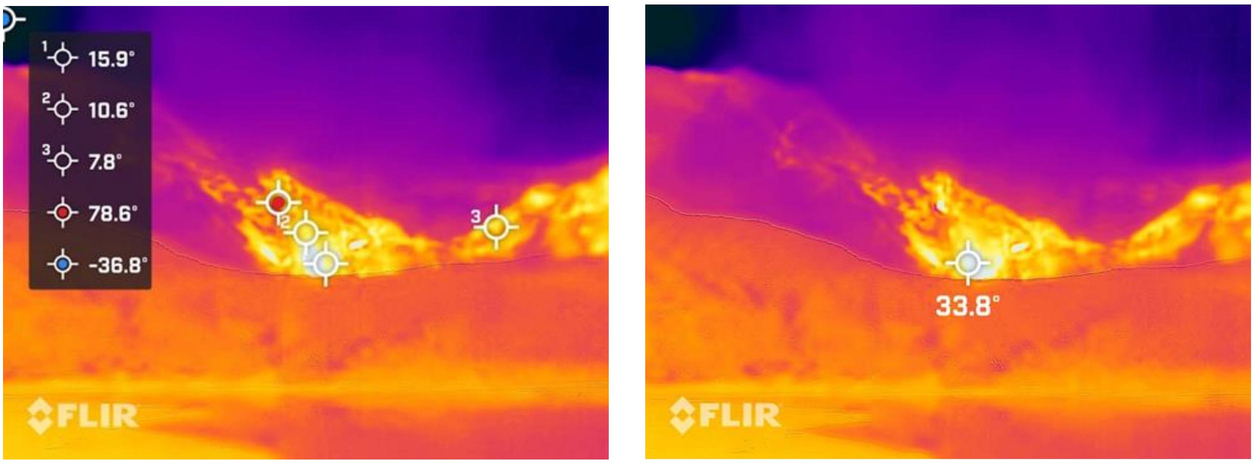


Figure 105 & 106. FLIR One Pro thermal analysis of west crater Turrialba Volcano September 2022

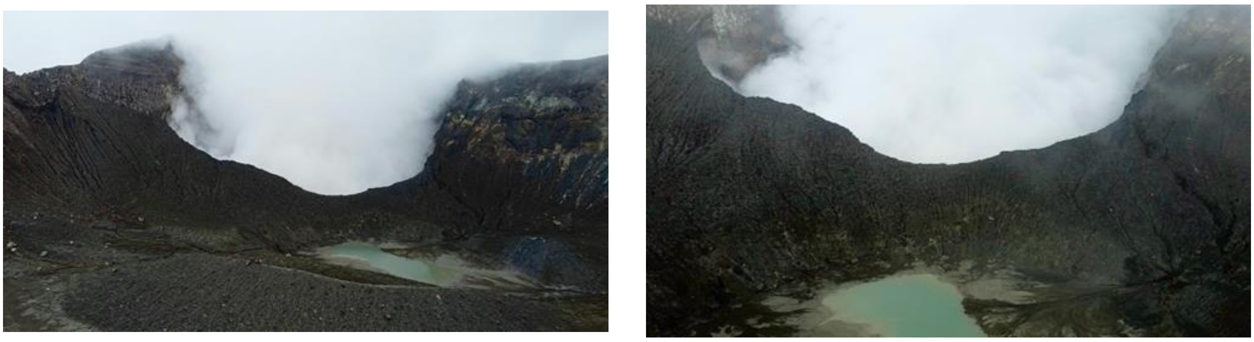
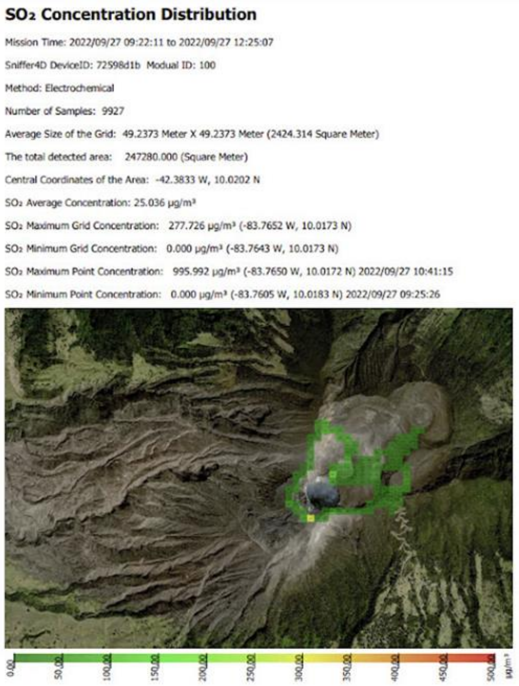


Figure 107 & 108. UAS image of active west crater of the Turrialba Volcano

Figure 109 & 110. UAS image of active west crater of the Turrialba Volcano

4. Results



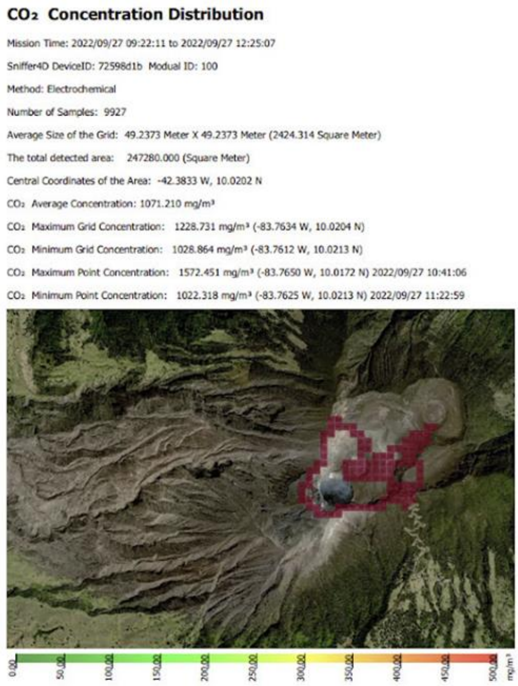


Figure 111 & 112. SO_2 CO_2 emissions tracked with Aki-01 in Sniffer Mapper software program

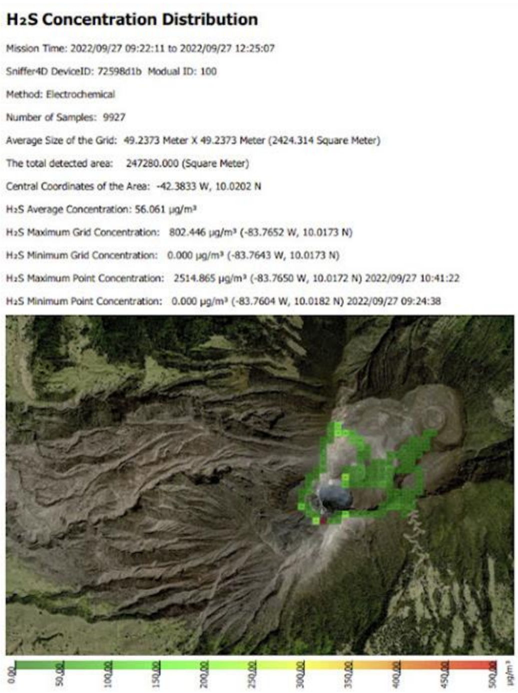


Figure 113 & 114. H_2S & HF emissions tracked with Aki-01 in Sniffer Mapper software program

Humidity Maximum Point Concentration: 47.059 % (-83.7604 W, 10.0182 N) 2022/09/27 10:08:59

Humidity Minimum Point Concentration: 30.980 % (-83.7601 W, 10.0182 N) 2022/09/27 12:22:20

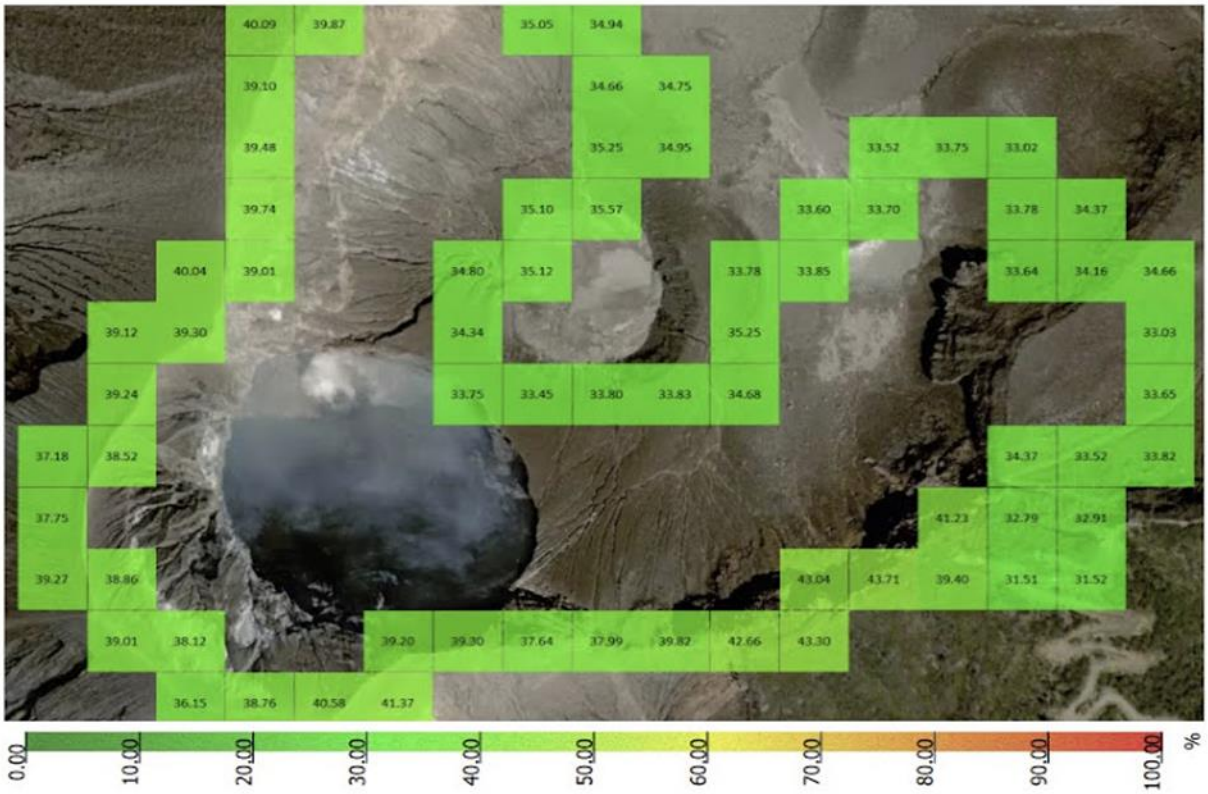


Figure 115. Humidity tracking on the Sniffer4D at the west & central craters of the Turrialba Volcano

Temperature Maximum Point Concentration: 20.392 °C (-83.7596 W, 10.0181 N) 2022/09/27 12:21:35

Temperature Minimum Point Concentration: 15.490 °C (-83.7604 W, 10.0182 N) 2022/09/27 10:11:47

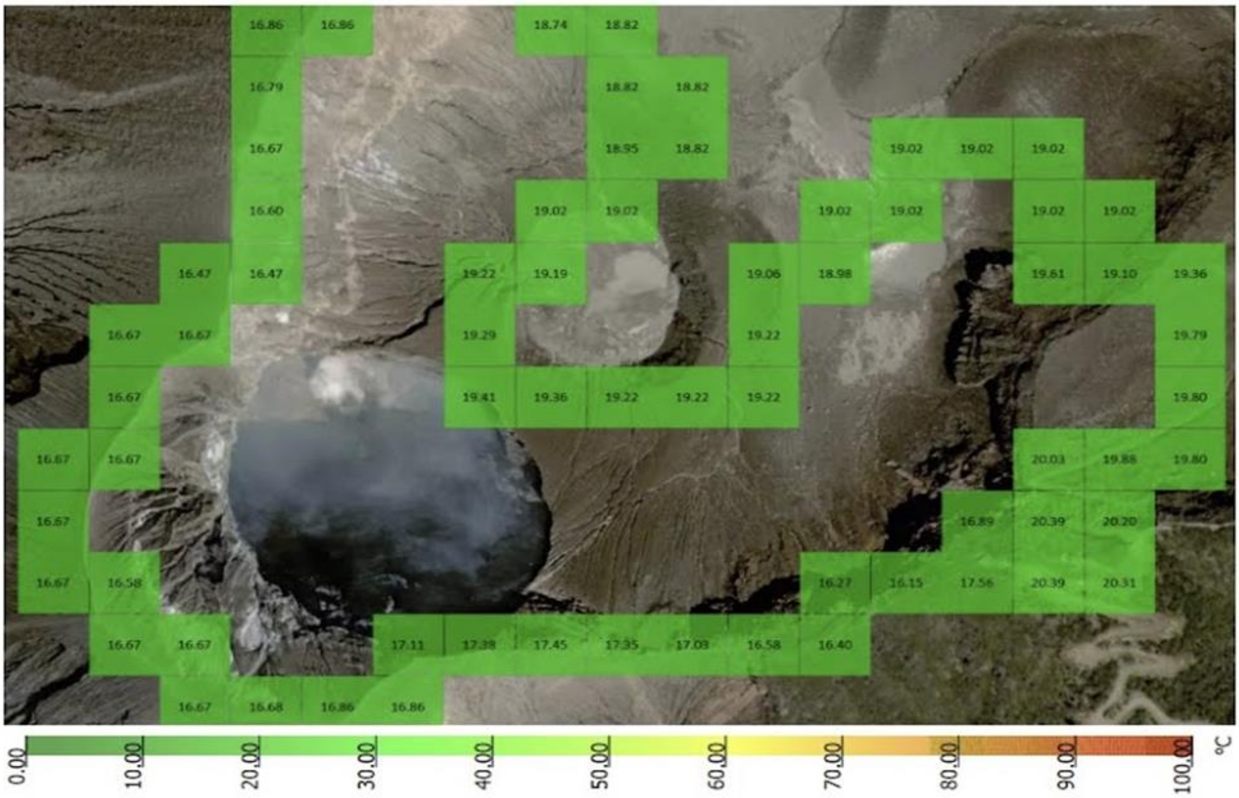
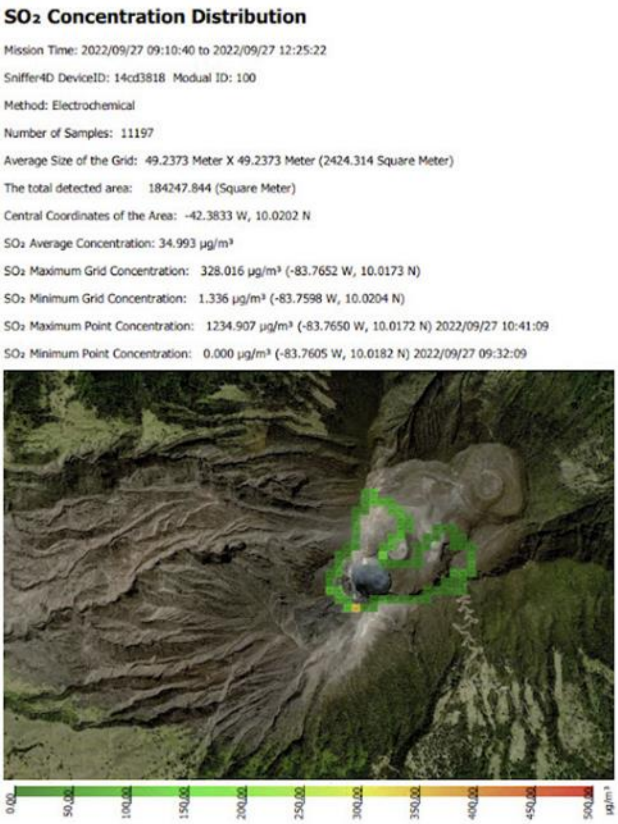


Figure 116. Temperature tracking on the Sniffer4D at the active west crater & central crater



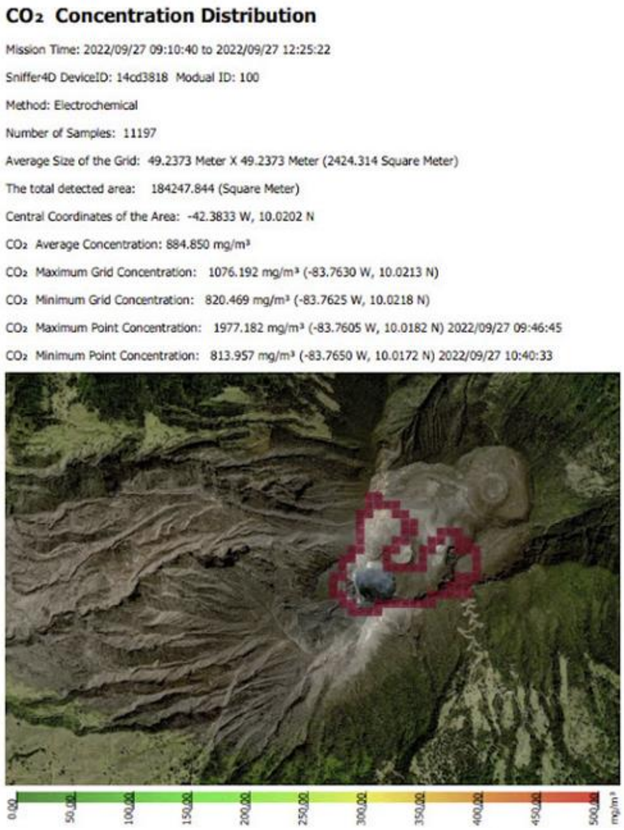
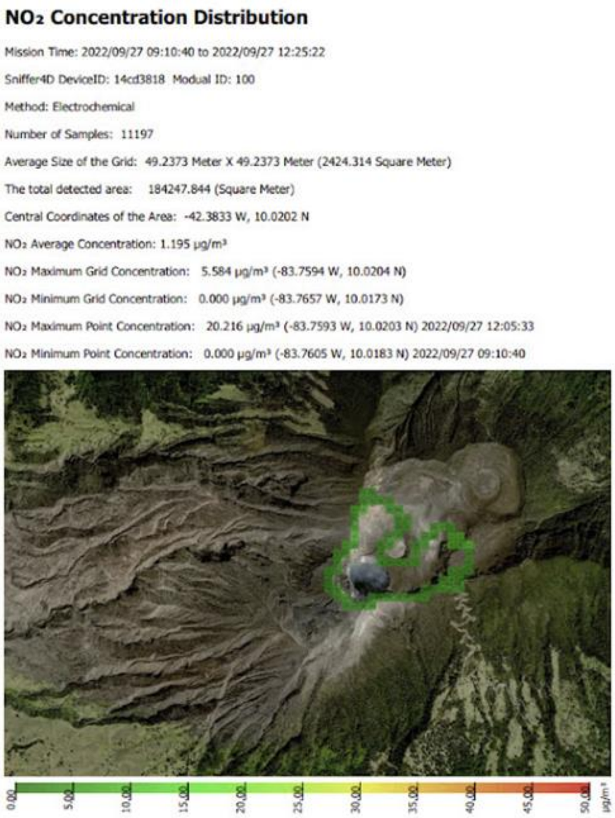


Figure 117 & 118. Sniffer Mapper report from Turrialba Volcano for SO_2 & CO_2 distributions



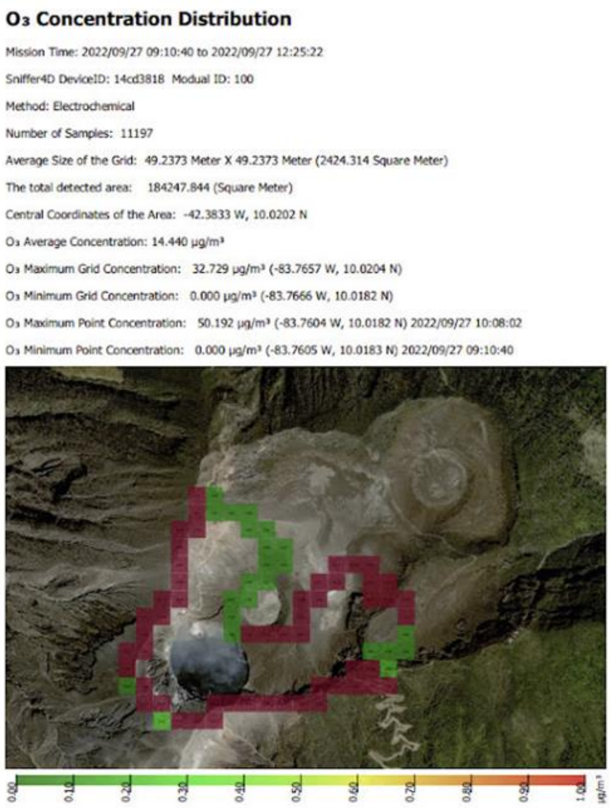


Figure 119 & 120. Sniffer Mapper report from Turrialba Volcano for NO_2 & O_3 distributions

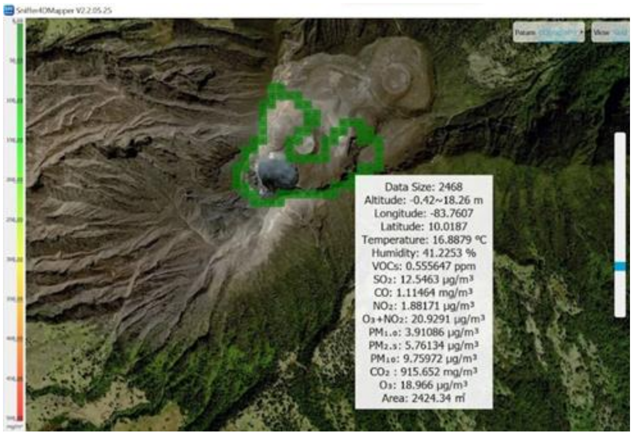
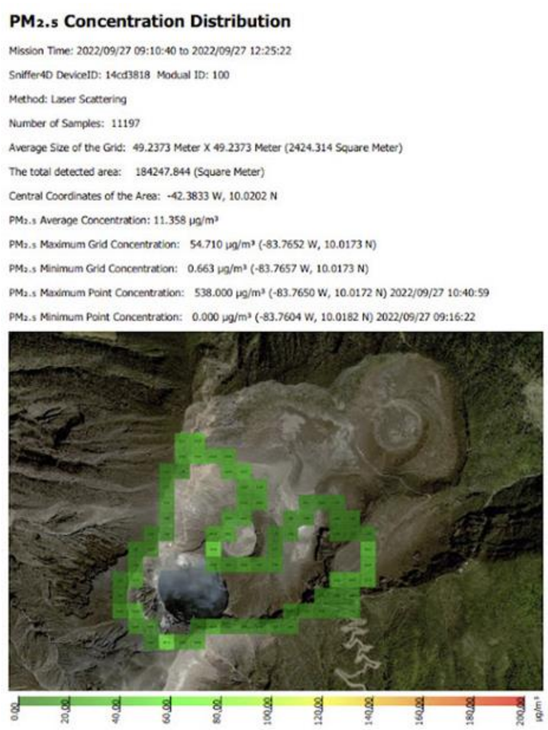


Figure 121 & 122. Sniffer Mapper report from main lookout poing the south crater Rim of the Volcano

Figure 123 & 124. Sniffer Mapper report from north central crater Rim of the Turrialba Volcano



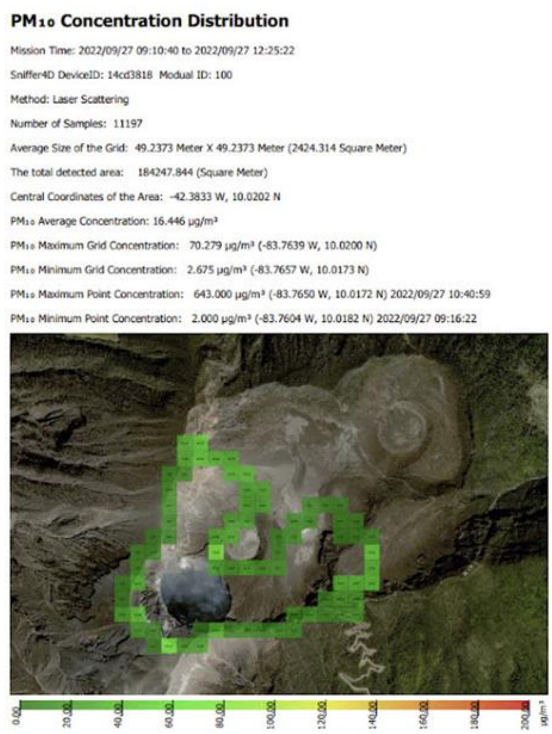
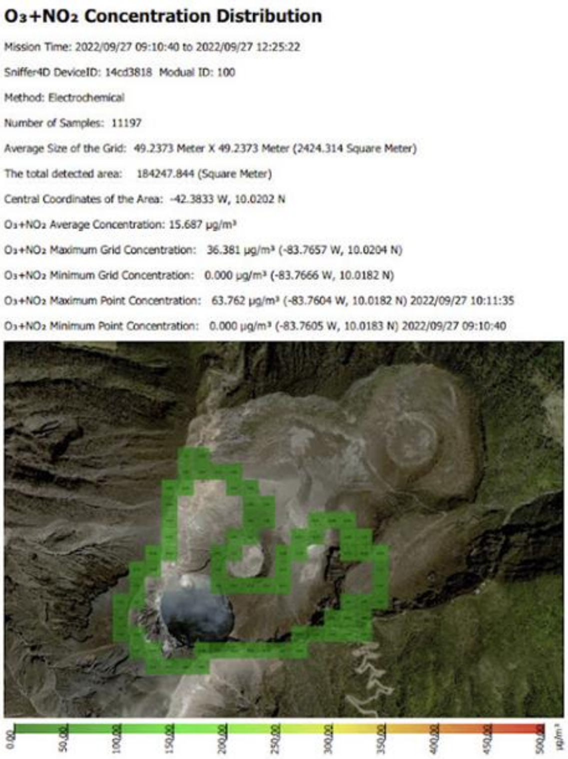


Figure 125 & 126. Sniffer Mapper report from Turrialba Volcano for PM 2.5 & PM 10 distributions



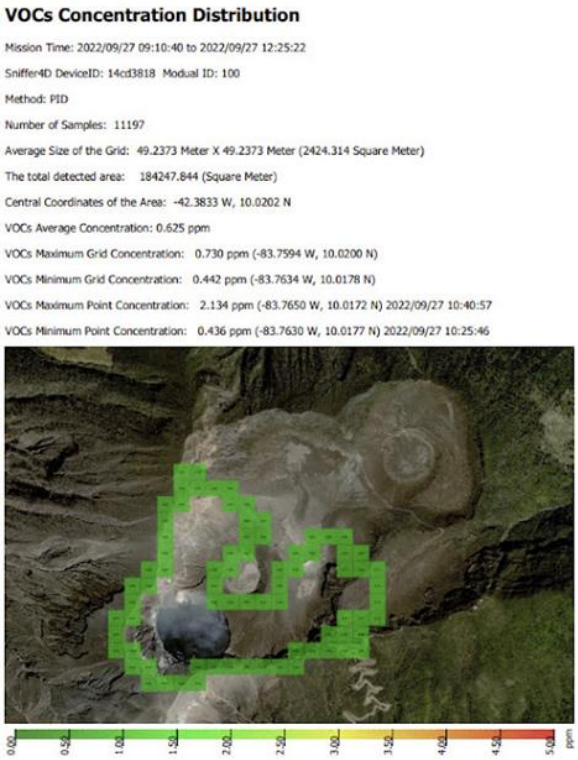


Figure 127 & 128. Sniffer Mapper report from Turrialba Volcano for O_3 & VOC distributions

5. Conclusion

The Sniffers measures the gas entities in mg/m³ or μg/m³. For comparison reasons, we will need to convert those measurements in ppm (mol) using the following formula: Concentration (ppm mol) = concentration (mg/m³) x molar volume of gas (= 24.45 L/mol) / molar weight. This conversion done, it will be possible to calculate gas ratio for analysis and interpretation purposes. We will use Ratiocalc_3 to determine CO_2/SO_2, H_2S/SO_2, HCl/SO_2 and HF/SO_2 gas ratio. The spatial distribution of these measurements is defined and plot by both Ratiocalc and QGIS. At the day of this report, the conversion into ppm seems wrong as the values obtained are not of the right order of magnitude. Hence results will be shown in mg/m³ and μg/m³ and no gas ratio can be considered correct in this preliminary report.

During the Turrialba campaign, the wind direction was toward the north and east. The drone flight took measurements around the Central Crater, and a walk on the crater rim took measurements all around the active crater. The SnifferV CSV data sets were used to generate a gas concentration spatial distribution chart from drone and walking measurements at the Turrialba summit.

Volcanic emissions at Turrialba were randomly distributed; still the SnifferV detected a gas concentration anomaly for CO_2 but hardly any detection of SO_2 and H_2S which is due to the plume direction and atmospheric instability that day. However, a peak of SO_2 and H_2S is noticeable in the south fumarolic field of the active West Crater, and on the northeast rim of the West Crater, i.e., when the instrument was on the very edge of the West Crater.

This illustrates the limits of drone measurements versus walking measurements, as generally a Remote pilot avoids the gas plume, or at least the most concentrated part of it for stability of the drone and corrosion reasons.

We observe that SO_2 and H_2S present gas concentration anomalies at the same place. HCl and HF also present gas concentration anomalies at the same place but those are different than SO_2 & H_2S. CO_2 presents anomalies in some of the combined places already identified. That suggests that gas ratios may show different signatures. Finally, it is noticeable that there is no HCl or HF peak detected, only diffuse low values, and even less where the SO_2 shows the best detection of the volcanic plume.

6. Future Advancements

UAS for atmospheric chemistry application has been one of the most impactful sectors of all drone applications. UAS can be used for not just volcanic emission measurements but industrial emission monitoring and ambient air quality measurements. Advancements in portable gas detectors capable of detecting multiple gas species and are able to be integrated onto various transportation methods are the ideal solution. Integrating analytical sensors such as electrochemical gas detectors onboard different types of UAS is an expensive undertaking. Companies such as DJI, FLIR Systems, Autel Robotics, Parrot Drones, Delair, Wingtra, Skydio and Soarability are all making large investments into research and development for these advanced methods of gas detection and mapping. The research time and innovation hours experimenting in the laboratory will be the most difficult to quantify and value, monetarily speaking. Further advancements are expected in this area of UAS development with smaller, more durable and more affordable UAS and payloads forecasted in the years to come [11].

The Department of Chemistry, University of Kentucky was quite interested in measuring trace tropospheric gases with drones in 2017 because trace tropospheric gases help maintain a stable climate. Trace tropospheric gases contribute to a stable climate here on Earth by absorbing infrared radiation in the troposphere. This chemistry department found the most common types of UAS payloads for measuring gases were electrochemical sensors like the Sniffer4D, photoionization, infrared, semiconductor and laser absorption gas detection payloads for UAS. Ozone O_3, Carbon Monoxide CO, Carbon Dioxide CO_2, Nitrous Dioxide NO_2, Sulfur Dioxide SO_2, Methane CH_4, and Volatile Organic Compounds VOCs are all pollutants being monitored by various government institutions such as the CNE in Costa Rica and the Environmental Protection Agency EPS in the United States for implications on human health via air quality [10].

Remote sensing has now made it possible to acquire data on sites that will be difficult to access, and to provide precise data concerning the studied area [11].

This is particularly the case for the monitoring of volcanoes, a rich field with information involving different stakeholders [12].

It is also the main component of the volcano risk reduction strategy, in order to offer the various possibilities of protection. Generally, remote sensing data based on satellite platforms such as Sentinel and Landsat make it possible to acquire information on large scales. However, remote sensing is facing today a significant expansion of UAV platforms, which allow today data to be acquired with an efficient way to meet the increasing demands of spatial, temporal and spectral resolution [13].

Fluctuations in atmospheric pressure and temperature can affect electrochemical sensors. Atmospheric pressure changes can result in shifts in concentrations of gases detected. The fusion of using UAS in Volcanism and scientific research is an important public safety application. By using drones with dual radiometric sensors such as 8k for high resolution, FLIR Boston radiometric sensor thermal imaging 640x812 can obtain detailed images during both day and night. This technology would be very useful for the Arenal Volcano summit. Thermal Analysis of the volcano craters and other areas of geothermal manifestation like hot springs are an essential aspect of UAS volcanic surveillance. This application has a direct impact especially for volcanoes where large populations of people live nearby. In Costa Rica while working with LAQAT-UNA the SnifferV conducted analysis of industrial areas and multinational companies manufacturing in Costa Rica.

Development and Engineering -Thermal drones can be used to great extent by development and engineering firms seeking new land regions to build on for their new projects. These firms effectively reduce and risks associated with thermal anomalies, hot spring emergence and rock failure by conducting a survey of the area in question using a Thermal Drone and creating a Digital Surface Model or DSM. Many engineering companies in the developed world are still new to these technologies and methods which can reduce risk associated with the construction process and increasing project optimization from the very beginning. In Costa Rica the entire nation is volcanic. The countries energy company ICE contracted the Japanese company Mitsubishi to manufacturer an advanced geothermal power plant called the Miravallas III.

Thermal Drones can be used to monitor these types of facilities for thermal anomalies and heat detection around areas of the plant difficult to reach by foot. Thermal drones can help volcanological institutions survey areas with challenging terrain such as glaciers in Iceland and thick tropical jungle regions in Costa Rica. They also provide an additional way to collect data of certain water resources. For example, the periodic check of ground water resources such as temperature and potential mineralization. Rock Failure – In volcanic nations, engineering companies and development firms must manage risk to new projects by implementing detailed land surveys before the construction process begins.

Due to the magmatic heat and accumulating pressure associated with the magma chamber; Heat moves up closer to the surface. Sometimes rock structures will start to break down and turn into clay once the volcanic gases start being released and the fumarole forms, these rock structures completely fail. If this happens during a development project it will be a complete failure which could potentially lead to bankruptcy. Therefore, managing these risks by deploying Thermal Drones makes the engineering project chances of success increase significantly. Orthophotogrammetry is an important methodology to document the eruption and deposit zones. Disaster Management departments can greatly benefit from Thermal Drones which can be very beneficial for natural disaster management among other applications.

At Rincón de la Vieja and Turrialba volcanoes arguably the two most active volcanoes in Costa Rica any instruments placed at the summit or crater rim are commonly very short lived due to the frequency of eruptions. Thermal Drones allow for volcanologists to take the IR radiometric sensor to be brought up to the summit crater for analysis and then quickly returned to the safe zone. By deploying Thermal Drones in this volcanic region, we can collect thermal reading of the crater lake, fumarole regions both in the crater and on the slopes of the volcano.

This technology will greatly contribute to volcanic gas monitoring, identification of new hot springs and the consistent monitoring of known volcanic hot springs. Scientists who seek to observe and study the Rincón de la Vieja crater much embark on a rigorous four hour climb through extremely difficult terrain. It is the most difficult volcano to climb in Costa Rica and the most dangerous due to activity.

By implementing Thermal Drone technology these scientists can reduce risk to the life by not entering the High-Risk Volcanic Zone at all, they reduce risk to their raspatory system by not exposing themselves to and volcanic gases particulate matter or ash being ejected from the volcano. By deploying Thermal Drones these researchers ensure that the proper analysis of the summit crater is still completed successfully. By using the GNSS feature on many UAV today these scientists and climatologists are able to auto fly the Thermal Drone into the crater, conduct a public safety analysis which helps local communities and governments by providing additional valuable information about the volcano located close to these towns. Thermal Drones can greatly contribute to the early warning detection systems for volcano eruptions.

Figure 129 & 130. Remote Pilot inside the central crater of the Turrialba Volcano UAS image

Acknowledgement

This study was partly presented at the 4th Advanced Engineering Days [14].

Funding

This research received no external funding.

Author contributions

Ian Godfrey: Conceptualization, Methodology, Software **Geoffroy Avard:** Data curation, Writing-Original draft preparation, Software, Validation. **José Pablo Sibaja Brenes:** Data curation, Writing-Original draft preparation, **Maria Martínez Cruz:** Visualization, Investigation, **Khadija Meghraoui:** Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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