Advanced UAV

http://publish.mersin.edu.tr/index.php/uav

e-ISSN 2822-6976

Using UAS with Sniffer4D payload to document volcanic gas emissions for volcanic surveillance

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Cite this study: Godfrey, I., Brenes, J. P. S., Cruz, M. M., & Meghraoui, K. (2022). Using UAS with Sniffer4D payload to document volcanic gas emissions for volcanic surveillance. Advanced UAV, 2 (2), 86-99.

Keywords
Gas Detection
Atmospheric Chemistry
Volcanology
Climate Change
Volcanic Plume
Sniffer4D
Drones

Research Article
Received: 06.10.2022
Revised: 11.11.2022
Accepted: 19.11.2022
Published: 30.11.2022

Abstract

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. One 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. 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 2022 for readings of active emissions. 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. The UAS system deployed carried the Sniffer4D which tested for Temperature, Humidity and 9 additional parameters **-** Sulfur Dioxide SO_2 (µg/ m^3), Volatile Organic Compounds VOCs (ppm), Carbon Monoxide CO (mg/m^3), Carbon Dioxide CO_2 (%), Ozone O^3 (µg/ m^3), Nitrogen Dioxide NO_2 (µg/ m^3), O^3+NO_2 and Particulate Matter - PM 1.0, 2.5 & 10**.** 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 first time the Turrialba volcano has been tested for these parameters.

1. Introduction

Volcanic eruptions have long term effects of the atmospheric chemistry of the Earth. Water vapor H_2O, Carbon dioxide CO_2, are the two most abundant gases being released from active volcanoes. These two gases along with Sulfur dioxide SO_2, Hydrogen chloride HCI, Hydrogen fluoride HF, Hydrogen sulfide H_2S are the most common volcanic gases being emitted from active volcano vents. Still there are other trace species such as Hypobromite BrO, One-carbon molecules such as Carbon monoxide CO, Nitrogen dioxide NO_2, Carbon oxysulphide COS, Silicon tetrafluoride or tetrafluorosilane SiF_4 [1]. H_20 is normally the most abundant gas deriving from a magmatic source and like CO_2 it is relatively abundant in the atmosphere of the Earth. Other volcanic gases such as SO_2, HCI & HF derive from the same source but are not normally present in the atmosphere unless there is an eruption vent releasing these gas species into the nearby proximity.

CO_2 is the second most common gas species being naturally emitted from volcanoes. At the Poás and Turrialba volcanoes in Costa Rica diffuse degassing of CO_2 represents approximately 10% of total emissions abundant in magmatic gas. Diffuse degassing occurs when gas species pass through openings from porous volcanic edifice permeable to rainwater [2]. Researching all aspects of Sulfur dioxide and secondary sulfate aerosols is of strategic importance to the Laboratory of Atmospheric Chemistry because the microphysical dynamics of these particles in active eruption columns is essential to comprehending the radiative properties of these natural volcanic emissions and this is a key to understanding how they affect climatic changes across our planet. Measuring volcanic gases offers insight into subterranean processes happening deep within the Earth's interior [3].

The data collected with the Sniffer4D does contribute to the collective knowledge of the entire scientific community, and the SO_2 tracking data can be cross referenced to the NASA Atmospheric Chemistry and Dynamics Laboratory, Copernicus Atmospheric Monitoring Service European Commission and Global Network of Observation of Volcanic & Atmospheric Change (NOVAC). Active volcanoes releasing emissions have a direct impact on the Earth's atmospheric chemistry, and climatic patterns; therefore, monitoring eruption columns with UAS and gas detection payloads is of extreme importance to climatologists.

Particulates or Particulate Matter can also be measured with the Sniffer4D, data on PM 1.0, 2.5 & 10 can all be gathered. Particles also known as atmospheric aerosol particles, atmospheric particulate matter, particulate matter (PM), or suspended particulate matter (SPM) – are microscopic particles of solid or liquid matter suspended in the air. The term aerosol commonly refers to the particulate/air mixture, as opposed to the particulate matter alone. The main objective of launching this payload into the West Crater of Turrialba was completed by Ian Godfrey in 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 S4V - SO_2, CO_2, H_2S, HF, HCI, CO, CxHy/CH_4/LEL, H_2.

Figure 1. Active West Crater of the Turrialba Volcano

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.

In 2022 our team reached the summit of the Turrialba volcano on a dry day with clear visibility and no strong or turbulent wind or any other harsh environmental conditions. We were caught in the mud about 4 kilometers or 2.4 miles from the summit crater. After a climb we reached the half-way point where we launched the drone to observe the last stretch of our pathway and make sure there was no significant degassing or explosive activity at the active West Crater. After the first UAS mission we continued our ascent and reached the main lookout point for the Turrialba Volcano National Park. UAS remote sensing approaches have shown exponential potential in the field of volcanology; UAS applications at the Turrialba volcano are a perfect example. The main objective of our UAS survey was to observe the crater interior which we estimated to have crater walls which have slopes of approximately 55^{o}. The depth of the West Crater was estimated to be 410 feet to 722 feet or 125 meters to 220 meters. The West Crater was estimated to have a width of 620 feet or 189 meters.

The Sniffer4D and Mavic 3 system deployed at Turrialba can help reveal additional valuable data concerning volcanic degassing and emission levels. This measurement system is very useful to the entire scientific community concerning volcanic monitoring and gas emission tracking, volcanic unrest and hazard assessment. Drones using GNSS system fixed waypoints can maneuver around the fumarole location this strategy allows the system to periodically check areas of significant volcanic emission activity and return to the exact same location when necessary. H_2S/SO_2 gas ratios fluctuate depending on temperature, pressure and redox conditions. Significant amounts of SO_2 and H_2S emissions deriving from hydrothermal sources are controlled by this chemical equation: $H_2S + 2H_2O \rightarrow SO_2 + 3H_2$. Increase in SO_2/H_2S represents a potential increase in magmatic influence relative to volcanic emissions [4]. SO_2 emissions represent magmatic intrusion from within the volcanic edifice itself.

Figure 2 & 3. Sniffer4D Mapper Report from the Turrialba Volcano and Associated UAS Image

3. Results

Toxic gas emissions such as Sulfur dioxide or SO_2 which are the direct result of burning fossil fuels contribute to climate change and acid rain in the region. SO_2 is also released from active volcanoes during periods of eruption and UAS are positioned to greatly assist volcanologists measuring these gases from safe distances. UAS capabilities can now greatly assist climate scientists by providing an aerial observation perspective which allows for increased data collection with improved safety. UAS also reduce risks associated with climbing and venturing into regions of increased volcanic activity such as an active crater.

The Sniffer4D detected and provided real time data to team of volcanologists and showcased 9 different gas emissions from one flight into the Turrialba volcano crater. Quantifying total gas flux from an eruption column serves a greater importance than measuring general gas concentration because total gas flux indicative of the level of volcanic outgassing and therefore level of activity [5].

OVSCORI-UNA ranks Turrialba's current level of activity at 3 meaning it is an erupting volcano. There were 2 rumblings on March 27 with no demonstration on the surface. The last Phreatic eruption from Turrialba came on February 28. The OVSCORI-UNA April 1st bulletin explained the daily number of tremors was decreasing. The increase in the amount of SO_2 measured in the atmosphere by satellite means reported the previous week was not confirmed the week of April 1st, 2022 in the weekly report.

The following weekly report showed seismicity remained stable the week of our visit, although there was an increase in the number and duration of short tremors, which are low amplitude. Degassing of Turrialba remained stable, on average weekly CO_2/SO_2 of 22.8 +/- 3.3 and H_2S/SO_2 of 0.25 +/- 0.21. On 7 April 2022, the maximum SO_2 concentration in the ambient air of Coronado (downwind of the Turrialba volcano) was 0.82 ppb and PM10=33.7 $\mu g/m^3$.

The amount of SO_2 measured in the atmosphere by satellite means reported last week remained but without particular trend. Inspection of the bottom of the West Crater with the drone showed some fumaroles at the bottom of the crater mainly in the sector to the east releasing water vapor and sulfur gases. The fumaroles record temperatures of at least 113° F measured remotely with infrared FLIR One Pro thermograph. OVSCORI-UNA April 8st, 2022 weekly report; the week of our visit to the Turrialba crater.

Potential hazards associated with the Turrialba volcano include gases, ash emission, proximal ballistics and acid rain. An active, sleeping or awake volcano can generate eruptions in a way unpredictable, that is, without appreciable precursor signals in real time. In addition, the limited human resources of OVSCORI-UNA do not allow a continuous surveillance of volcanoes. Therefore, the portability and maneuverability of the Sniffer4D is a distinct advantage for these types of institutions tasked with monitoring complex active volcanic systems [6].

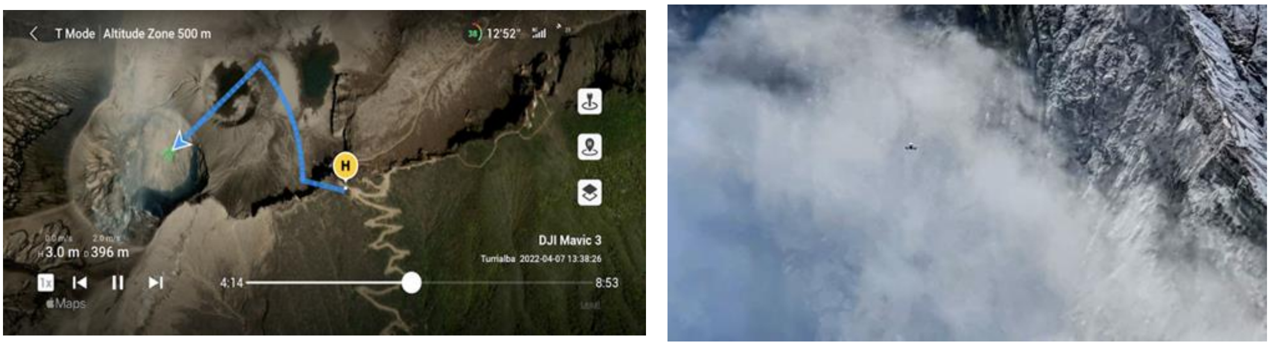


Figure 4 & 5. Sniffer4D Flight Path and Image of UAS Mission

Figure 6 & 7. UAS Flight Approaching the Active West Crater

Figure 8 & 9. UAS Flight Arriving at the Active West Crater

During the Sniffer4 UAS test flights at the Turrialba summit a total of 2,424 square meters was covered. The measurement set closest to the active West Crater was taken from the eastern crater rim, although the prevailing winds carry these volcanic emissions to the west. Due to battery capacity and time limitations per flight the eastern rim of the crater was the farthest section the device was sent too. The Sniffer4D recorded a temperature of 22.0877°C or 71.75786°F and Relative Humidity of 19.1234% at the Turrialba summit. Particulate matter log was PM1.0-1.82353, PM2.5-1.88235, PM10-2.05882 for the measurement closest to the crater. Volatile Organic

Compounds were recorded at .187779 ppm. Carbon Monoxide CO was 0.147148 mg/m^3 and Nitrogen Dioxide or NO_2 was 0 μg/m^3. Ozone or O_3 was 1.8456 μg/m^3 and O_3+NO_2 was 1.8456 μg/m^3. The Sniffer4D recorded Sulfur Dioxide or SO_2 at 0 μg/m^3.

The Sniffer4D measurements were taken about 9 meters or 30 feet above the crater floor. In total 17 sections were measured at the Turrialba summit. The Sniffer4D Mapper Software allows for custom visualization. It's possible to adjust the size of the grip on our Mapper to get more specific data. The minimum unit of the grid is 25 square feet, representing that the actual side length of the detection area is 5 meters. The size of the grid indicates the size of the detection area, the smaller the grid is the more specific the data will be and with a higher resolution, to the contrary; the larger the grid is meaning the data will be in a lower resolution and data is calculated by the averaging values from multiple areas. Users can see the general concentration distribution from large grids and then spot the high-concentration area, then they can adjust to small grids and get more specific data in that area.

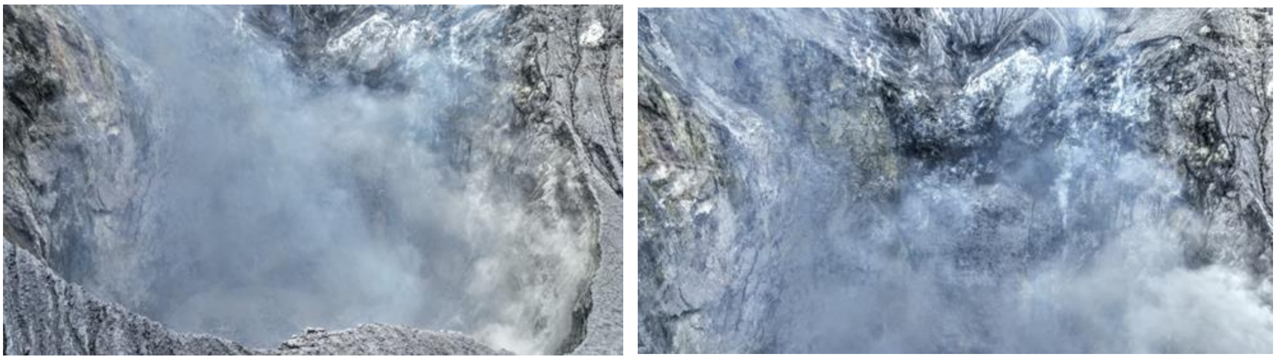


Figure 10 & 11. Active West Crater of the Turrialba Volcano UAS Sniffer4D Flight Mission

Figure 12 & 13. Active West Crater of the Turrialba Volcano UAS Sniffer4D Flight Mission

Figure 14 & 15. Active West Crater of the Turrialba Volcano UAS Sniffer4D Flight Mission

Comparing the results from the MultiGas and Sniffer4D helped the team learn several lessons for improvement to the methodology. On 7 April 2022 at 1 pm we measured PM10 at 2.05882 μg/m3 with the Sniffer 4D. The same day the maximum PM10 concentrations were 33.7 μg/m^3 at the station in Coronado downwind from the Turrialba volcano. The fluctuations in data show the significance of the prevailing wind direction. SO_2 emissions were recorded at 0 with the Sniffer4D because the prevailing winds carry the gases west. The Sniffer4D was at the eastern crater rim at its closest point. Turrialba is still releasing magmatic gases among them the SO_2. The SO_2 module inside the Sniffer4D has a minimum detection limit of 5 ppb for the high-resolution SO_2 and 50 ppb for the wide-range SO_2 modules. The minimum detection limit for particular matter PM2.5 & 10 is 1μg/m^3.

Coronado reports higher concentrations of PM than the measurements carried out by the Sniffer just besides the crater rim because the Sniffer 4D UAS did not measure the entire plume of Turrialba nor did it take a measurement downwind from the active West Crater and therefore the results are very different.

Figure 16 & 17. Sniffer4D Mapper Reports at the Turrialba Volcano for Emissions April 7th, 2022 at 1 pm

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.

Figure 18. AERMOD Plot from April 8th, 2022 the day of investigation with the Sniffer4D the SO2 emission that day was around (151 +- 142) ton/day which was supported by the Sniffer4D data from the crater

The low levels of SO_2 concentration measured by the Sniffer4D at the summit of the Turrialba volcano are consistent with the AERMOD Plot model due to the prevailing wind direction to the west. The Sniffer4D measurement with the UAS was made of the east side of the West Crater of the Turrialba volcano.

Miniaturized gas instrumentation mounted on low-cost drones has enormous potential for safely, rapidly, accurately, and percisely characterizing the gas output of a volcano at all stages of activity. If done carefully, such measurements can be made even when the volcano is erupting. Such an approach allows an excellent snapshot of the current degassing state of an active volcano. Gas ratios and SO_2 fluxes can be measured by drone with data quality comparable to other methods [7].

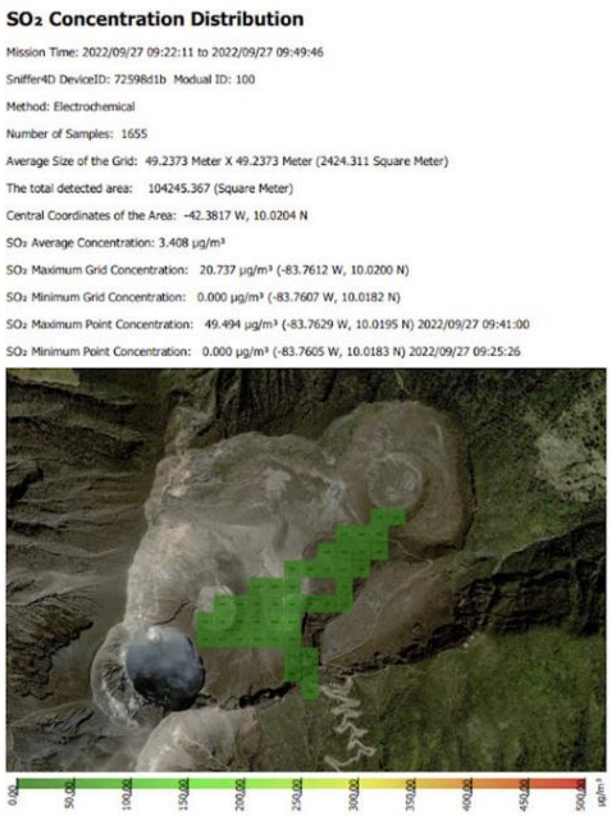
The complete survey of the Turrialba volcano summit was completed on September 27th, 2022 with the assistance of Universidad Nacional de Costa Rica. We deployed both the Sniffer4D and SnifferV for this complete analysis of volcanic emissions.

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. Geoffory 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 separate 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.



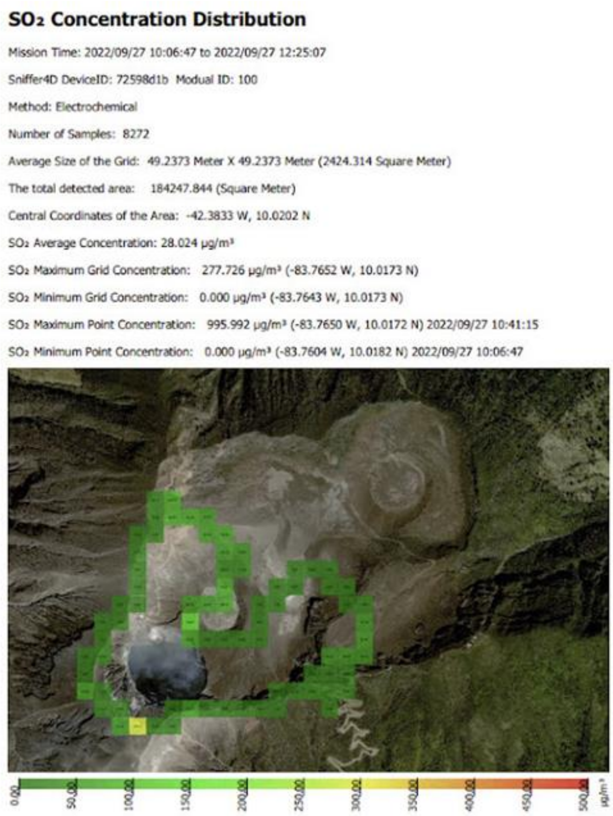
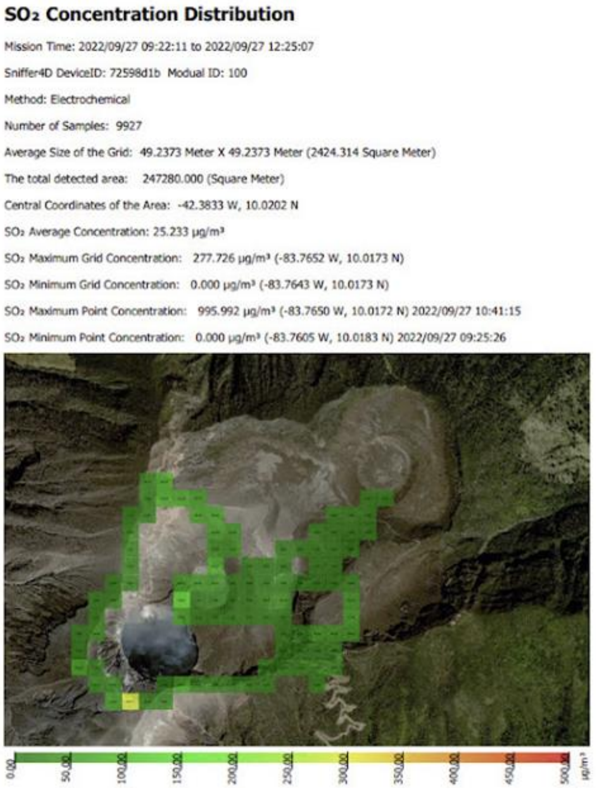


Figure 19 & 20. Reports from Sniffer Mapper software program



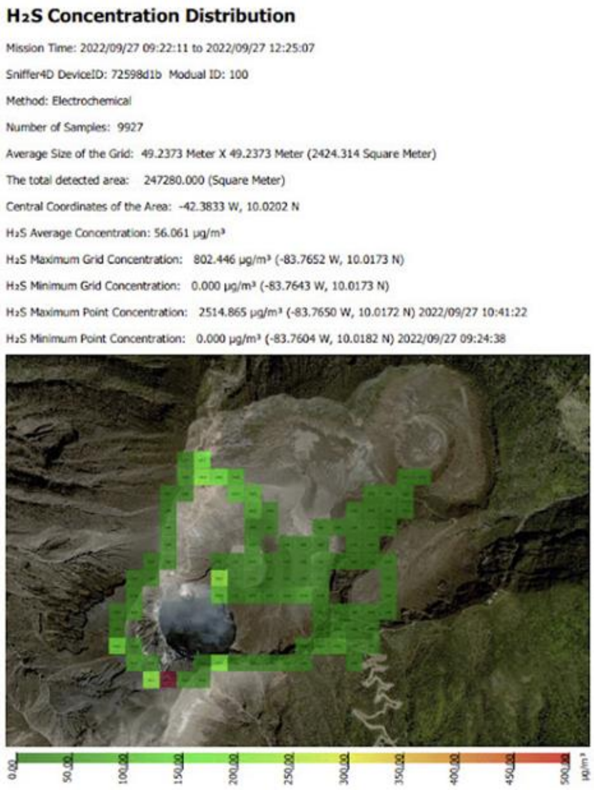


Figure 21 & 22. Reports from Sniffer Mapper software program

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	#Created by: Sniffer4DMapper 2.2.05.25															
2	ProjectName : Turrialba Volcano UNA :															
3	Time Stamp	Abs.Alt m	Longitude	Latitude	Temperat	Humidity	Pressure Pa	SO2 μg/m³	CO mg/m³	CxHy/F	H2S μg/m³	HCL mg/m³	CO2 mg/m³	HF mg/m³	H2 %	Serial No.
4	2022-09-27 09:22:11	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	25.052549	0.464049	0.1914	108.49822	6.842638	1040.30627	13.67286	0	72598d1b
5	2022-09-27 09:22:12	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	24.441511	0.467674	0.1913	110.26242	6.837671	1041.8053	13.66789	0	72598d1b
6	2022-09-27 09:22:13	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	24.441511	0.467674	0.1912	111.14452	6.845122	1037.30823	13.67037	0	72598d1b
7	2022-09-27 09:22:14	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	24.441511	0.471299	0.191	111.14452	6.845122	1038.80725	13.68031	0	72598d1b
8	2022-09-27 09:22:15	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	23.830473	0.471299	0.191	112.02663	6.840155	1041.8053	13.68528	0	72598d1b
9	2022-09-27 09:22:16	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	23.830473	0.467674	0.1909	112.02663	6.845122	1040.30627	13.68776	0	72598d1b
10	2022-09-27 09:22:17	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	23.830473	0.464049	0.1908	112.02663	6.857541	1040.30627	13.68279	0.000008	72598d1b
11	2022-09-27 09:22:18	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	23.830473	0.460423	0.1907	112.90872	6.864992	1038.80725	13.68776	0.000008	72598d1b
12	2022-09-27 09:22:19	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	23.830473	0.464049	0.1907	112.90872	6.872443	1035.80933	13.69521	0.000008	72598d1b
13	2022-09-27 09:22:20	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	23.219435	0.464049	0.1907	113.79082	6.872443	1038.80725	13.70266	0.000015	72598d1b
14	2022-09-27 09:22:21	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	23.219435	0.464049	0.1906	114.67292	6.874926	1035.80933	13.69521	0.000015	72598d1b
15	2022-09-27 09:22:22	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	23.219435	0.467674	0.1905	114.67292	6.874926	1037.30823	13.70266	0.000015	72598d1b
16	2022-09-27 09:22:23	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	22.608398	0.467674	0.1905	115.55502	6.872443	1035.80933	13.7126	0.000015	72598d1b
17	2022-09-27 09:22:24	0	-83.7604	10.01824	17.2549	42.7451	69340.13281	22.608398	0.474925	0.1905	115.55502	6.869959	1035.80933	13.72005	0.000008	72598d1b
18	2022-09-27 09:22:25	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	22.608398	0.474925	0.1904	116.43712	6.867475	1035.80933	13.72998	0.000008	72598d1b
19	2022-09-27 09:22:26	0	-83.7604	10.01824	17.2549	42.7451	69340.13281	22.608398	0.471299	0.1904	117.31921	6.860024	1037.30823	13.73743	0.000008	72598d1b
20	2022-09-27 09:22:27	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	21.99736	0.471299	0.1904	117.31921	6.855057	1037.30823	13.74985	0	72598d1b
21	2022-09-27 09:22:28	0	-83.7604	10.01824	17.2549	42.7451	69340.13281	21.99736	0.471299	0.1904	117.31921	6.855057	1035.80933	13.76476	0	72598d1b
22	2022-09-27 09:22:29	0	-83.7604	10.01824	17.2549	42.7451	69340.13281	21.386322	0.471299	0.1904	117.31921	6.860024	1037.30823	13.77966	0	72598d1b
23	2022-09-27 09:22:30	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	21.386322	0.471299	0.1904	117.31921	6.860024	1035.80933	13.78463	0	72598d1b
24	2022-09-27 09:22:31	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	20.775284	0.471299	0.1903	118.20131	6.857541	1037.30823	13.79953	0	72598d1b
25	2022-09-27 09:22:32	0	-83.7604	10.01824	17.2549	42.94118	69340.13281	20.164248	0.467674	0.1903	119.08342	6.852572	1038.80725	13.80449	0	72598d1b

Figure 23. Reports from Sniffer Mapper software program and CSV Excel Sheet

Figure 24. Sniffer4D Data on SO_2 Showcased on the Sniffer Mapper software program

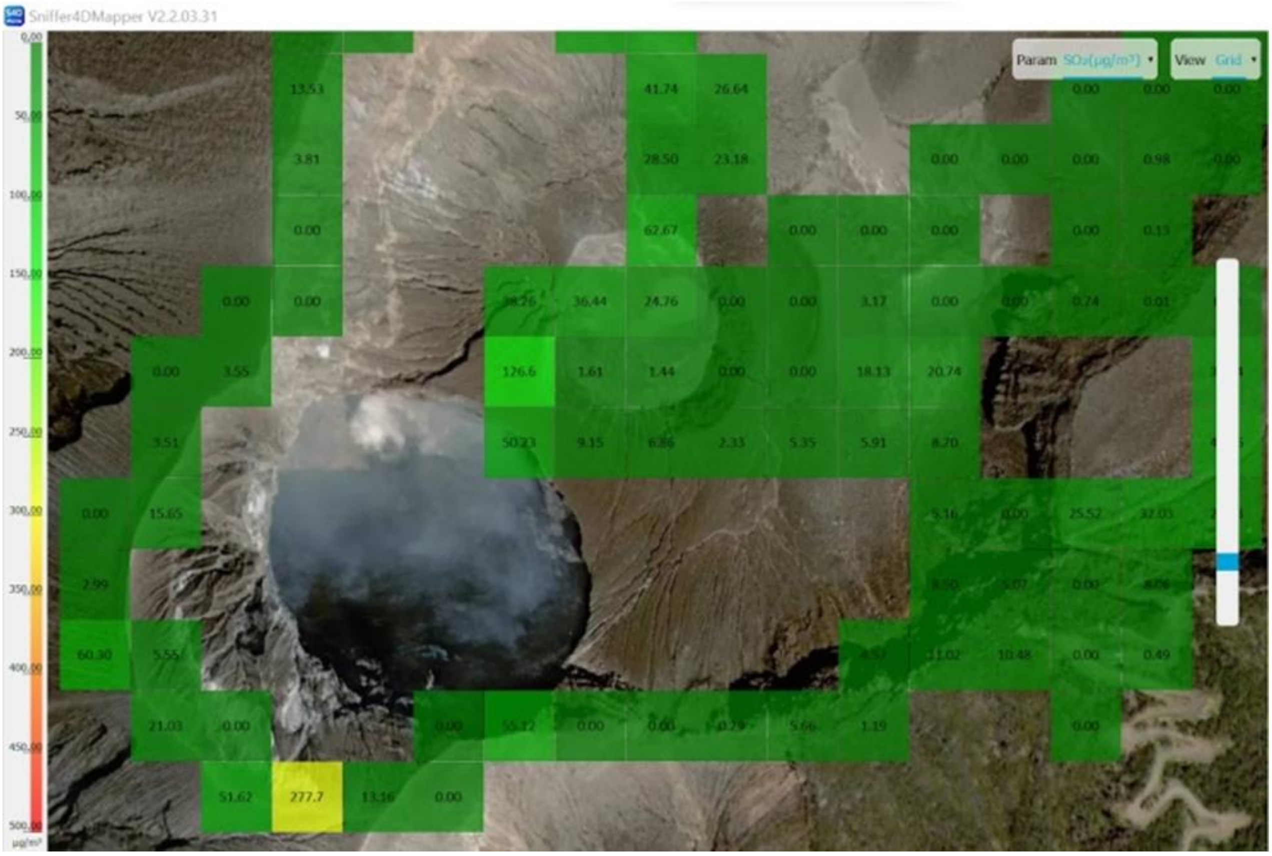


Figure 25. Sniffer4D Data on SO_2 Showcased on the Sniffer Mapper software program

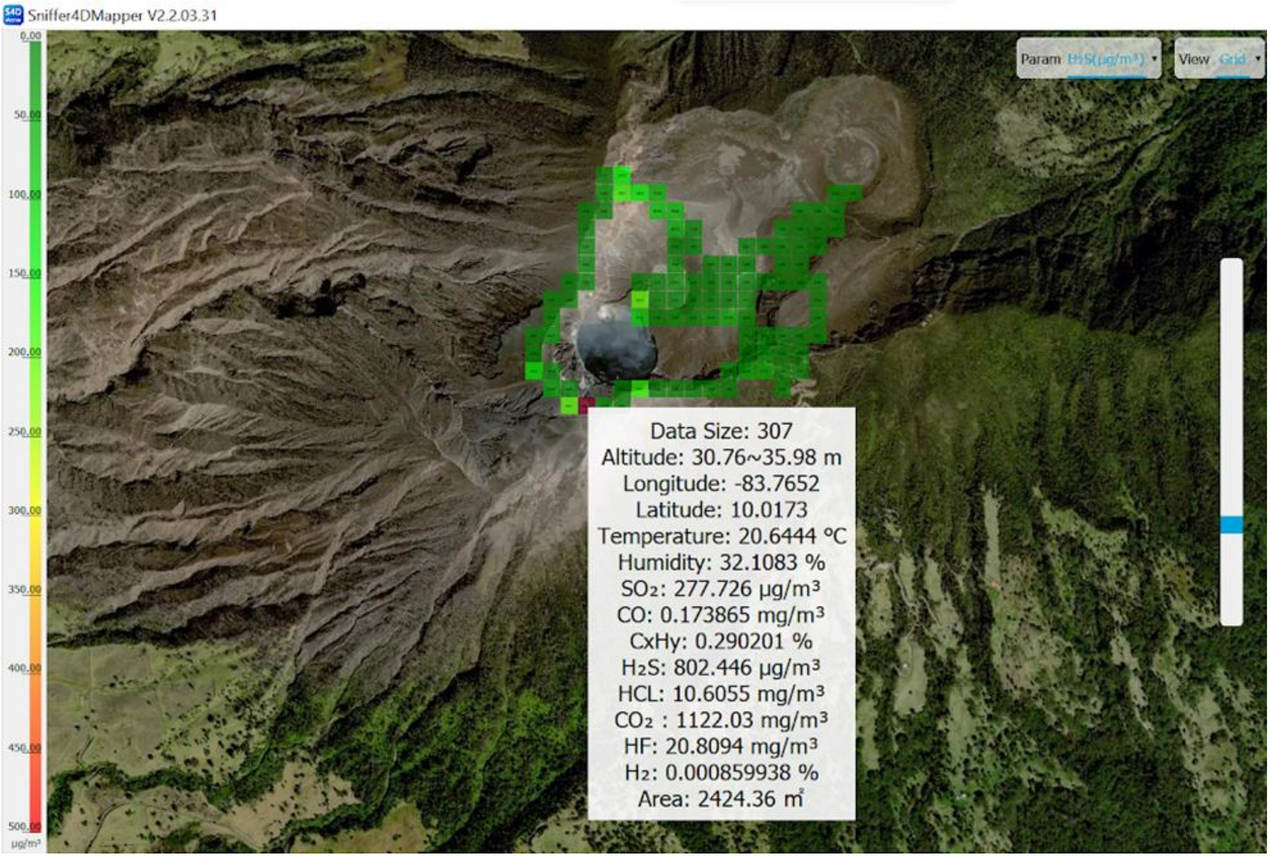
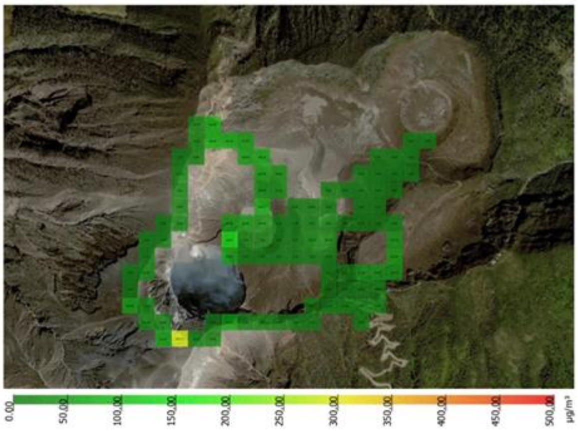


Figure 26. Sniffer Mapper High Level Gas Detection Reading Example



SO_2 Concentration Distribution

Mission Time: 2022/09/27 09:22:11 to 2022/09/27 12:25:07

Sniffer4D DeviceID: 72598d1b Modual ID: 100

Method: Electrochemical

Number of Samples: 9927

Average Size of the Grid: 49.2373 Meter X 49.2373 Meter (2424.314 Square Meter)

The total detected area: 247280.000 (Square Meter)

Central Coordinates of the Area: -42.3833 W, 10.0202 N

SO_2 Average Concentration: 25.036 µg/m³

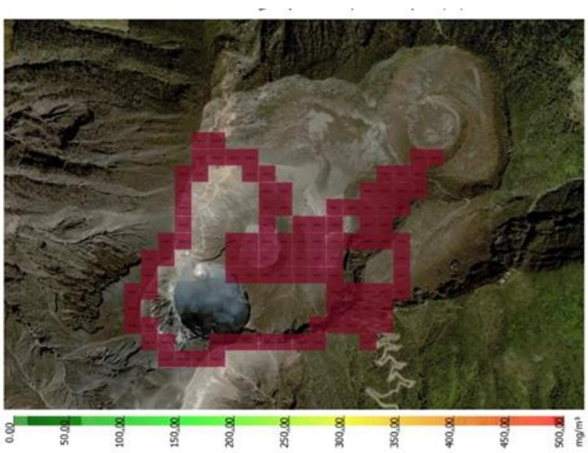
SO_2 Maximum Grid Concentration: 277.726 µg/m³ (-83.7652 W, 10.0173 N)

SO_2 Minimum Grid Concentration: 0.000 µg/m³ (-83.7643 W, 10.0173 N)

SO_2 Maximum Point Concentration: 995.992 µg/m³ (-83.7650 W, 10.0172 N) 2022/09/27 10:41:15

SO_2 Minimum Point Concentration: 0.000 µg/m³ (-83.7605 W, 10.0183 N) 2022/09/27 09:25:26

Figure 27 & 28. Sniffer4D V2 SO_2 Reading and Sniffer Mapper Software System



CO_2 Concentration Distribution

Mission Time: 2022/09/27 09:22:11 to 2022/09/27 12:25:07

Sniffer4D DeviceID: 72598d1b Modual ID: 100

Method: Electrochemical

Number of Samples: 9927

Average Size of the Grid: 49.2373 Meter X 49.2373 Meter (2424.314 Square Meter)

The total detected area: 247280.000 (Square Meter)

Central Coordinates of the Area: -42.3833 W, 10.0202 N

CO_2 Average Concentration: 1071.210 mg/m³

CO_2 Maximum Grid Concentration: 1228.731 mg/m³ (-83.7634 W, 10.0204 N)

CO_2 Minimum Grid Concentration: 1028.864 mg/m³ (-83.7612 W, 10.0213 N)

CO_2 Maximum Point Concentration: 1572.451 mg/m³ (-83.7650 W, 10.0172 N) 2022/09/27 10:41:06

CO_2 Minimum Point Concentration: 1022.318 mg/m³ (-83.7625 W, 10.0213 N) 2022/09/27 11:22:59

Figure 29 & 30. Sniffer4D V2 CO_2 Reading and Sniffer Mapper Software System

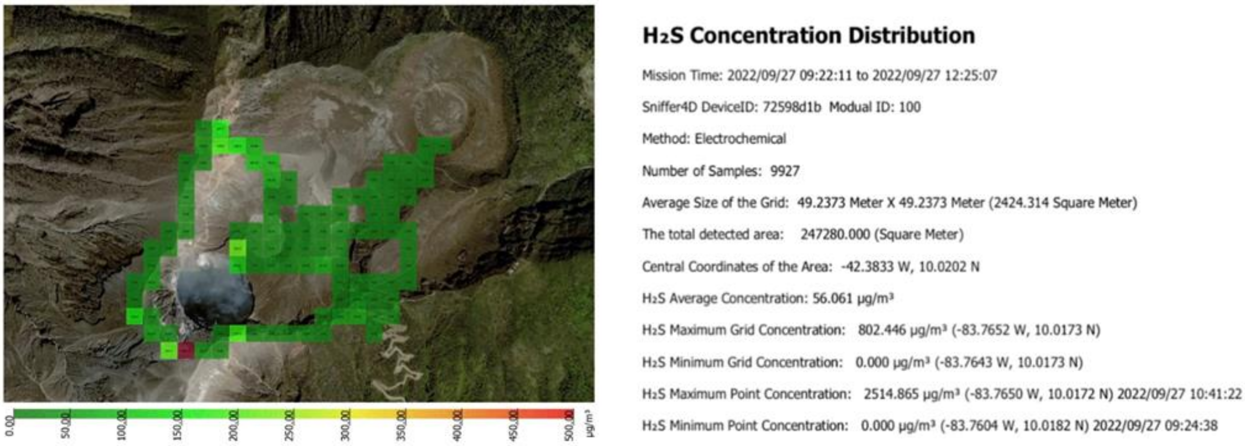


Figure 31 & 32. Sniffer4D V2 H_2S Reading and Sniffer Mapper Software System

4. Discussion

UAS are allowing scientists to deliver new scientific equipment into the most extreme environments and take physical samples of water along with atmospheric parameters yielding a vast amount of valuable information not previously accessible before the implementation of UAS. Recent development of new remote sensing technologies has not only made it easier to obtain information, but has also made it possible to extract data across larger and more dangerous areas. In this sense, we can also cite in addition to UAVs, the famous LiDAR (Light Detection and Ranging), which is an emerging technology aimed at collecting accurate data in a shorter

period of time and using the distance between the target and the laser. Pershin et al. [8] have done the monitoring of the Elbrus volcano using LiDAR based diode laser. Their results highlight the effective role of laser to detect and monitor such type of volcanoes.

PM and SO_2 test flight with the Mavic 3 was successful. Piloting remote aircraft in high altitude volcanic environments is one of the most complex and risky situations for a drone pilot. Is the data more valuable than the drone? Is a frequent question remote pilots often ask themselves before the flight and at the point in the flight where the drone begins collecting great data, prized photos and excellent video, but riskier conditions start settling in. For example, of a complex flight for a remote pilot operating in a volcanic environment is when it's clear where the drone around 600 meters away from the home point and it starts raining at the remote pilot's location. These situations must be planned for to the best if the remote pilot in command capabilities. Unaccounted for situations will still arise, but with proper training and knowledge of these environments obtaining the data points from the planned flights is certainly possible. When planning to operate drones in volcanic environments it's essential to check the weather forecasts for the days you're planning the mission and to consistently monitor any potential changes on Windy.

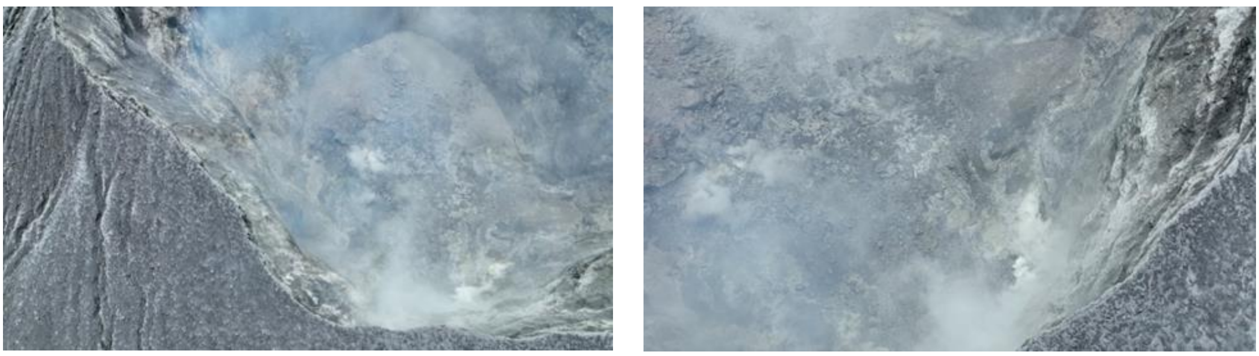


Figure 33 & 34. UAS Perspective observing the interior of the Active West Crater

Climatic stability in volcanic regions can change in less than one minute. And with that comes relative humidity fluctuations, 80% change in visibility conditions, wind speed change, wind direction change, enhancing wind gusts. Therefore, extreme presentation is necessary for the remote pilot to obtain as much geological and atmospheric knowledge of the region before flights. In Costa Rica while studying the Turrialba volcano at 3,340 meters in altitude the poor visibility and cloud coverage changes were frequently avoided with the assistance of a visual observer and the decision to increase or decrease altitude to avoid the passing clouds. Obviously, these decisions are made by the remote pilot in command who must also consider the altitude of the flight and the terrain formations directly below the drone. Flying UAS directly above active craters will always add risk of eruption.

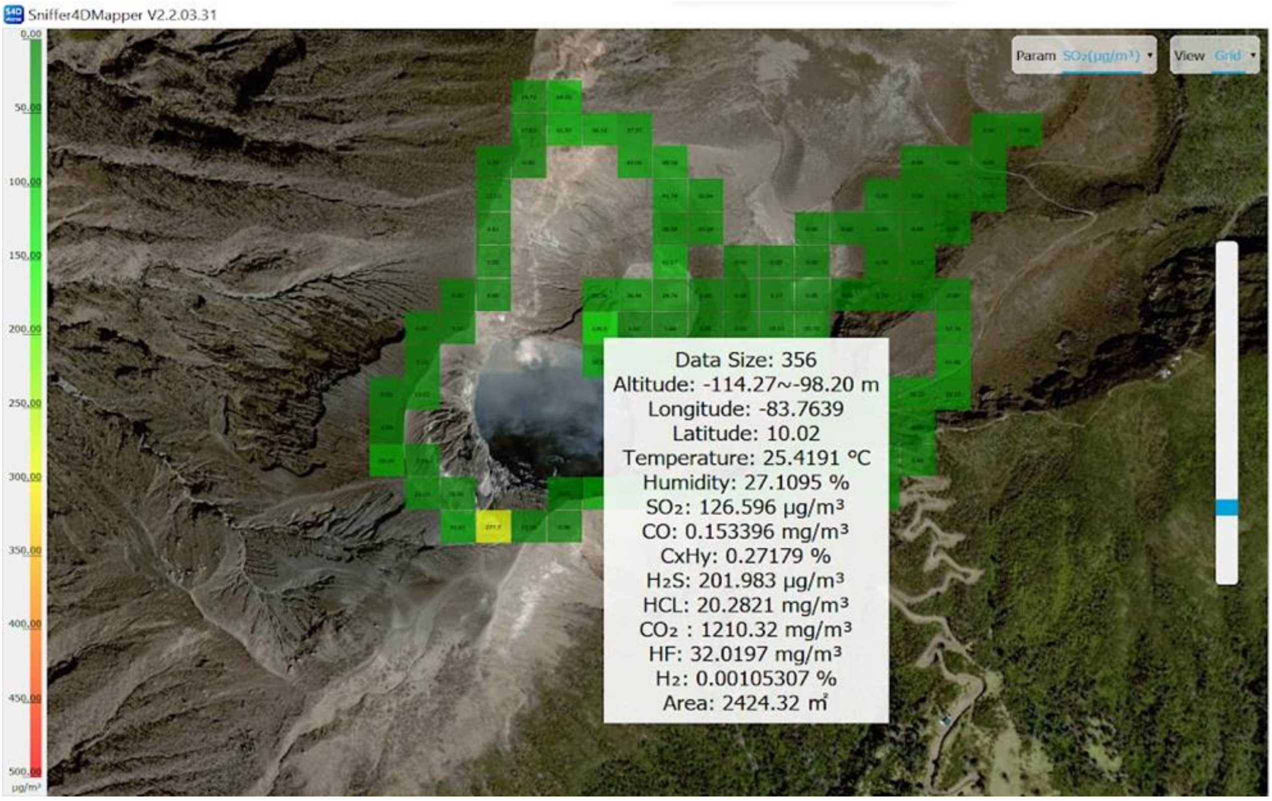


Figure 35. Sniffer Mapper Volcanic Emission Reading of Active West Crater rim of the Turrialba Volcano

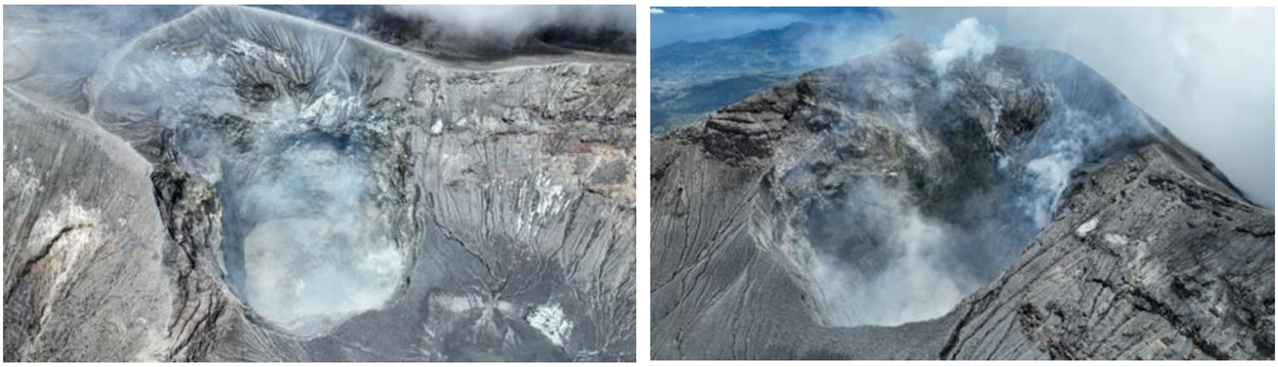


Figure 36 & 37. Active West Crater of the Turrialba Volcano

Figure 38 & 39. Active West Crater of the Turrialba Volcano

5. Conclusion

The monitoring of volcanic gas geochemistry is a vital aspect to understanding volcanic processes. Continuous gas tracking during volcanic eruptions will allow for valuable information to be delivered to scientists which offer insights to how the interior volatiles behaved through the volcanic process from the low activity period through an eruption. The research publication titled *"A golden era for volcanic gas geochemistry"* explains that; "Volatiles can diffuse through magma bodies, travel latterly along faults, exsolve and re-dissolve in magma or aqueous fluids, or be stored in underground reservoirs from which they can be explosively erupted into the atmosphere or leaked slowly to the surface over millennia." [9].

"The primary components of all high temperature volcanic gases are water vapor (H_2O, typically 75-98%), carbon dioxide (CO_2, 0.3-13%), sulfur dioxide (SO_2, 0.3-3%), and hydrogen sulfide (H_2S, 0.02-2%). Changes in gas composition and emission rate are likely one of the first signs of unrest at volcanoes." By expanding our gas detection capabilities and broadening our UAS application to include volcanic emission tracking, we can begin monitoring more emissions from a larger number of volcanoes and through increased frequency and reliability along with using previously confirmed early warning detection systems and data analysis significant improvements can be made to our strategy and ability to predict volcanic eruptions. Carbon dioxide CO_2 can be from both magmatic sources and hydrothermal as well; this gas can travel along fault lines; it can be periodically released from cracks and fractures in the volcanic edifice and it can also diffuse through soils surrounding the active crater. CO_2 can also be released from soils that are distant from the active crater and fumarolic field making gas measurements important for surveying and tracking emissions in other volcanic areas further away from the areas of visible activity [9].

UAS bridge a significant knowledge gap in volcanic surveillance as they can access areas inaccessible to researchers and can document and collect data in these areas. Since drones can also carry payloads like the Sniffer4D gas detection equipment the inaccessible gas plumes can now be measured and monitored. Several departments and research institutions have dedicated time and resource into tracking volcanic emissions on a global scale and their findings and forecasts can be found in *Network of Observation of Volcanic and Atmospheric Chance (NOVAC) [10], Deep Earth Carbon Degassing (DECADE) [11], The EarthChem/ DECADE database [12], The Mapping Gas Emission Project [13], The NOVAC data portal [14].*

"Aquifers can be primed for eruption by sealing via hydrothermal alterations and mineralization, including buildup of pore fracture filling sulfates, clays, sulfur minerals and silica. However, sealing can be localized or affect extensive areas in these diverse geological environments." [15]. These events can occur suddenly or progressively and are therefore strategically important to monitor for volcanic institutions.

"If lakes occupy active craters they can act as traps for high temperature gases, allowing the formation of molten element sulfur (>114°C) within the aquifer. To data no phreatic or hydrothermal eruption has been successfully forecasted. This presents a significant challenge to volcano observatories and monitoring systems. Continuous gas monitoring provides significant insight into eruption "priming" processes at various time scales. Turrialba with peaks in CO_2/SO_2 prior to eruptive phases in 2014 and 2015 signal magma injection that disrupted the overlying hydrothermal system, whereas the disappearance of H_2S in emissions marked the transition from phreatic to phreatomagmatic activity." [15].

Ambient air monitoring and HAZMAT response have become some of the most prominent applications for miniaturized hardware payloads designed for UAS. Data of the volcanic plume and its effects of atmospheric chemistry are easily collected by the Sniffer4D and analyzed by the software program Sniffer4D Mapper which provides a quick, sustainable, safe and reliable way to quantify these emissions and develop a national baseline for volcanic activity in Costa Rica.

The Sniffer 4D could give promising results if it is flown all around the crater in circles or doing a transect crossing the crater from upwind to downwind. Another advantage of deploying this system is the ability to see vertical profiles of volcanic emissions downwind from the eruption site. This investigation outlines UAS volcanic applications designed to detect and quantify different gases of volcanic origin in order to assist volcanologists with their eruption forecasts.

Acknowledgement

Ian Godfrey is a passionate explorer of the natural world, a writer, a Part 107 Remote Pilot and Thesis Advisor to the Laboratory of Atmospheric Chemistry Universidad Nacional Costa Rica. He has flown UAS into several high altitude active volcanic craters and a variety of industrial sites.

Funding

This research received no external funding.

Author contributions

Ian Godfrey: Conceptualization, Methodology, Software **José Pablo Sibaja Brenes:** Data curation, Writing-Original draft preparation, Software, Validation. **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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