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

Using UAS for monitoring the summit of the Arenal Volcano Costa Rica

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

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

Cite this study: Godfrey, I., Avard, G., Brenes, J. P. S., Cruz, M. M., & Meghraoui, K. (2023). Using UAS for monitoring the summit of the Arenal Volcano Costa. Advanced UAV, 3 (2), 100-135

Keywords
Unmanned Aerial System
Gas Detection
Volcanic Emissions
Photogrammetry
Digital Surface Model

Research Article
Received:31.08.2023
Revised: 15.10.2023
Accepted:11.11.2023
Published:17.11.2023

Abstract

The Arenal summit is seldom studied for several reasons. First, the eruptive activity has stopped since October 2010, second the active summit crater C is difficult to reach due to an intense steep climb through the tropical rainforest, and third, the summit has rapidly fluctuating weather patterns that make trails muddy and complicate field work sites. Still there is still significant international and national interest in the Arenal volcano in Costa Rica and our undertakings show the Arenal as it was in September 2022 when the summit was documented. The main objective of this survey was to document any potential emissions being emitted from the summit crater of Arenal. With both Sniffer4D units which gathered and log ged volcanic emission data on 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 from the Sniffer4D and SO_2, CO_2, H_2S, HF, HCI, CO, CxHy/CH_4/LEL, H_2 from the SnifferV. By tracking these emissions at the active summit crater C valued volcanic emission data can be acquired and used by the Arenal SINAC park rangers, Universidad Nacional and the National Risk Management Group in Costa Rica the CNE. In addition, by conducting a survey with the FLIR One Pro thermal IR cameras we can inspect the summit area for potential thermal anomalies. By obtaining this temperature data more will be known about the level of thermal energy release at crater C, combined with the gas emissions recognized by the Sniffer units, a periodic "snap-shot" was obtained for the Arenal volcano. The final objective will be to document the unstable regions of the crater with a UAS and collect high quality videography and imagery used for creating Digital Surface Models with Nira software. We are also able to lift the Sniffer4D as a payload with the DJI Mavic 3 drone and document the degassing fumaroles identified with the thermal cameras. Three drone surveillance flights collected valued data that will contribute to overall general knowledge of the volcanic structure, vegetation coverage, erosion and areas of potential rock falls and fumarole fields.

1. Introduction

The Arenal Volcano National Park is a rainforest reserve of strategic interest to the nation of Costa Rica and conservationists and climatologists alike. The Arenal volcano has an elevation of 5,436 feet or 1,657 meters and remains one of the most active volcanoes in Central America. The rich biodiversity of the rainforest derives from the volcanic soils which provide a rich foundation for the vast plant biology. Combined with the tropical rains the floras found in the National Park are often unique to the region which contributed to the overall ecosystem of the rainforest. Fauna such as a variety of hummingbirds, tropical snakes and monkeys are also dependent of the plant species in the National Park and since the volcanic cone is inside the conservation area and under complete protection by the Government of Costa Rica, climbing the volcano without SINAC permission is both illegal and dangerous. Since the closest town to the Arenal volcano has about 15,000 people and La Fortuna is one of the most visited areas by tourists in Costa Rica; monitoring the emissions of the summit crater is of great importance to the region.

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." Arenal Volcano National Park Permit # R-SINAC-PNI-ACAHN-001-2022 for The Laboratory of Atmospheric Chemistry, Universidad Nacional LAQAT-UNA.

Climbing to the summit of the Arenal Volcano consisted of starting at 5:30am exactly and climbing at a consistent rate for 3 hours until 8:30 when we reached crater D. There are 3 areas of the Arenal path with distinct topographic differences. First, we climbed through the forest which was a fairly muddy trail below the canopy intertwined with the root systems of the tropical trees. Here there was evidence of diverse animal and insect populations. Second was an area where the wind picked up due to elevation differences and the tropical vegetation dropped to levels below 4 meters. The areas vegetation was dominated by ferns. The third and final section of the climb was the steepest and had very low to the ground vegetation. Although this area was the steepest it offended some relief as we required out upper body to complete this part of the climb. The climb down took 2 hours but was just as challenging if not more difficult because we were already tired from the climb up and the fieldwork at the summit. It's essential to bring snacks and plenty to drink when climbing Arenal and returning in one day.

Figure 1. Summit of Arenal Volcano September 2022.

Figure 2 & 3. Arenal Volcano Vegitation on the Climb to the Summit.

Figure 4 & 5. Northern Upper Flank of the Arenal Volcano.

Figure 6 & 7. Summit of Arenal Volcano September 2022.

Figure 8 & 9. UAS Perspective Recording Video at Arenal Summit.

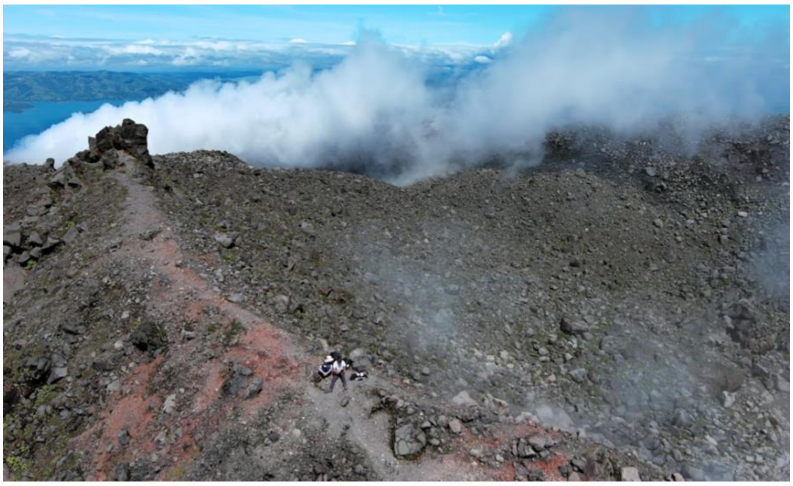

Figure10. UAS images also show Ian Godfrey and Geoffory Avard on the rim of Crater C which gives scale to the crater area so observers can more accurately judge the true size of this volcano.

Figure 11. Summit of Arenal Volcano Active Crater C September 2022.

2. Material and Method

UAS - The EVO Lite + drone by Autel Robotics has an air frame made of 3-D printed carbon fiber designed and built for superior strength. The drone has a total flight time of 40 minutes and weighs a total of 835 grams. This UAS has an 800 meter maximum flight altitude starting at the takeoff position and a 5000 meter maximum operational ceiling. The Autel EVO Lite + drone can withstand 32-38 mph wind gusts and has a level 7 wind resistance rating. The Autel EVO Lite + drones are also equipped with several wide angle obstacle avoidance sensors. The airframe places these sensors facing forwards, downwards and in the rear facing backwards. These obstacle avoidance sensors will automatically detect tree branches and other potential obstacles and slow or stop the drone. Once obstacles are detected the Remote Controller will make an alarming sound to notify the pilot what is happening.

Camera - There are two camera sensors capable of collecting 20MP photo images and 6k /30fps video from the 1 inch CMOS sensor. This 20MP sensor uses larger pixels allowing for increased amounts of light and reduced interference. There is an F/2.8 – F/11 adjustable aperture, contrast focus, and is mounted to a 3-axis gimbal. This camera sensor was specifically designed for low light settings; the camera has 16x digital zoom. The low light videography capabilities are the result of the Moonlight Algorithm making the device ideal for documenting geographical aspects during the twilight hours of the day.

Software Application – Autel Sky is the app associated with the Autel Lite + drone. This app features several advanced maneuvers preprogramed into the drone; Rocket, Orbit, Flick and Fade Away. The system also has a following option called Dynamic Tracker 2.1. This function makes the drone automatically follow the selected targeted subject selected by the remote pilot in command. Skylink insures stable long range connection capable of transmitting video from over 7 miles away using the triple frequency system designed to reduce interference.

The Sniffer4D – Sniffer devices were attached to the Mavic 3 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.

Sniffer Mapper - 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.

Additional portable equipment included the smart phone thermal imaging camera the FLIR One Pro. We used this extremely small sensor to search for thermal anomalies and to document surface temperatures of the fumarole region of active crater C. The Lighting Passport smart phone spectrometer was used several times at the Arenal summit. Most importantly inside the crater D filled with vegetation to monitor and document the microclimate aspect of the various exotic environments found in Costa Rica.

Nira app – The Nira app was used to generate and share the model in #-D via link. Nira does not support 3-D reconstruction, but can visualize in high resolution and allows for sharing options which contribute to interdisciplinary collaborations. The most popular are software programs for building a mesh model are RealityCapture, Agisoft Metashape, ContextCapture, and DJI Terra. Reality Capture was used for the models in our investigation of volcanoes.

Computer Requirements - The 3-D models were generated on a Lenovo legion laptop with 32 GB RAM, using NVIDIA Geforce 2070 RTX video card with 8 GB dedicated video RAM, the CPU is an Intel i7 9750H @2.6 GHz which is acceptable for small scale projects 3-D modeling projects such as the Arenal summit area only for example. For large scale modeling and mapping missions a more advanced computer system is required. For generating lava flow models and advanced maps of volcanoes a computer system with at least 256 GB RAM and Nvidia Quardo A4000 graphics card such as Geforce RTX 4090 titanium with two 4-6 TB Solid state drives for data, and the system disk which is a Solid state drive is required. The AMD Threadripper is the CPU for this type of computer system and operates with multiple cores for the ideal 3-D model generating system for advanced applications.

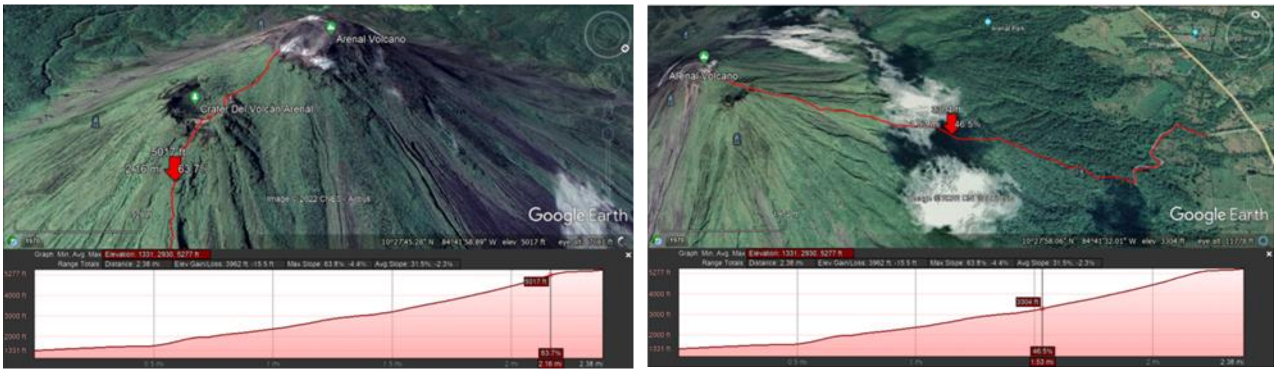

Figure 12 & 13. Google Earth Map Showing Elevation and Distance for Arenal Climb.

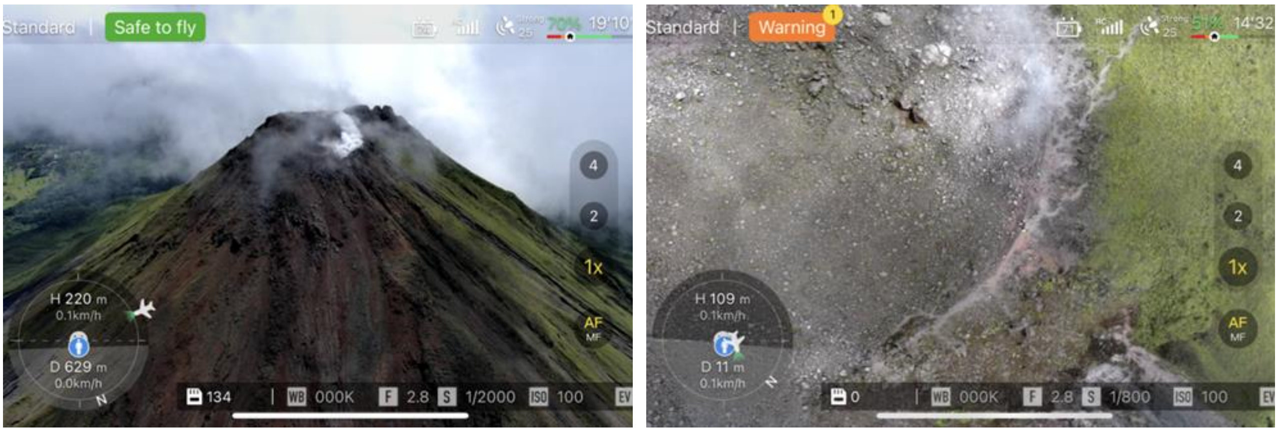

Figure 14 & 15. UAS Perspective of Arenal Volcano During Mapping Mission.

Generating accurate digital maps and models of volcanic regions is a valued UAS application. Geologists and volcanologists can more accurately estimate the amount of ejected material from eruption craters, track forest regeneration and monitor for cracking during the rainy season.

Geological mapping of the Arenal Cerro Chato volcano complex showed that the lava flows and tephra deposits revealed a complex volcanic history. In 1968 there was an intense eruption which marked the beginning of a new volcanic eruption phase for Arenal [1].

Figure 16 & 17. Nira 3-D Model of Crater D & C Radius Measurement.

Figure 18. Arenal Volcano in 2005.

Figure 19. Arenal Lava Flows 2005.

The Arenal volcano is located on a boundary directly between two different weather patterns seen coming from the Pacific Ocean and Caribean Sea. The Arenal Cherro Chato volcanic system is subject to the Caribean weather cycles and much of the region to the west and south of Arenal is subject to the Pacific Ocean weather cycles, so although September in Costa Rica is a traditionally rainy month nation wide, its actually one of the best months for this type of fieldwork at the summit of Arenal. Since Arenal and the sorounding region were subject to the dry sunny season of the Caribean weather cycle, September and Febuary are the two best months of the year to climb the Arenal volcano.

During the eruption cycles of the Arenal volcano lava flows created areas of great proportion which are noe dried lava fields with vegitation covering them. Certain eruptions from Arenal would have contributed 10-20% of the total volume making up the volcanic cone [1].

During the fieldwork period at crater C several thermal images were taken all around the active crater C. There are certainly areas of higher temperatures because careful consideration was taken not to walk directly up to the fumaroles. These images were taken with the portable FLIR One Pro which attached directly to the iPhone. During the field work at the summit most of active crater C was scanned and several thermal videos were recorded.

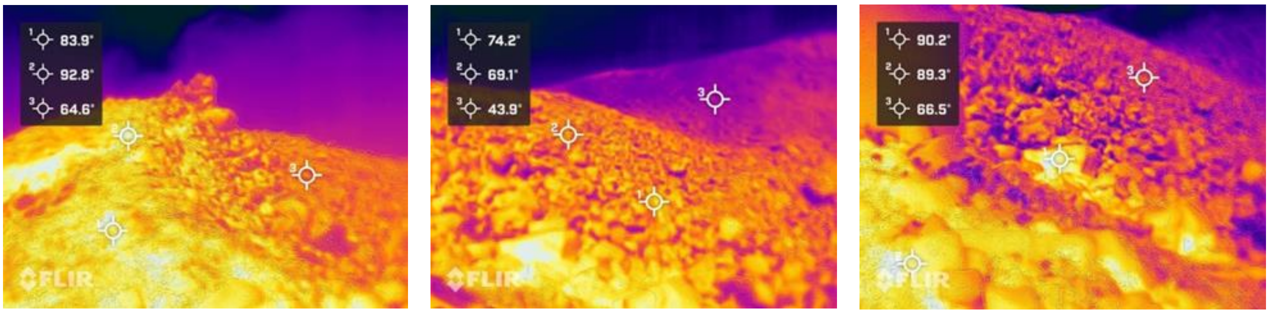

Figure 20 – 22. Thermal Images in Degrees Celsius Active Crater C of the Arenal Volcano September 2022.

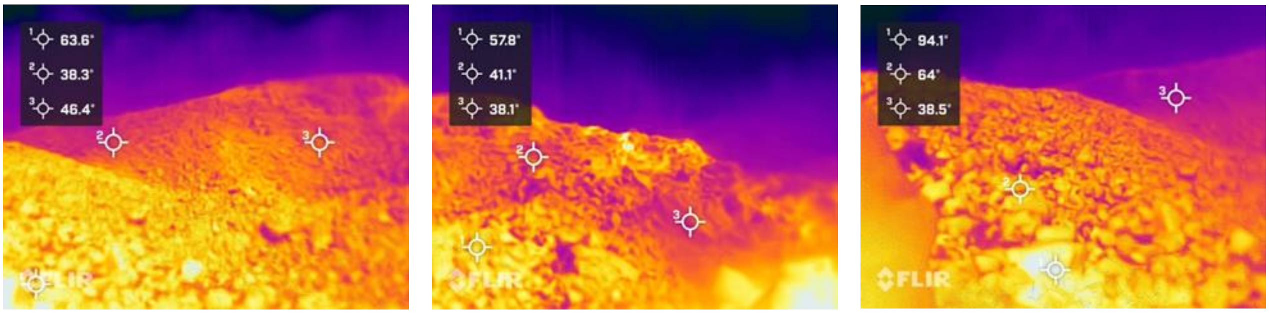

Figure 23 – 25. Thermal Images in Degrees Celsius Active Crater C of the Arenal Volcano September 2022.

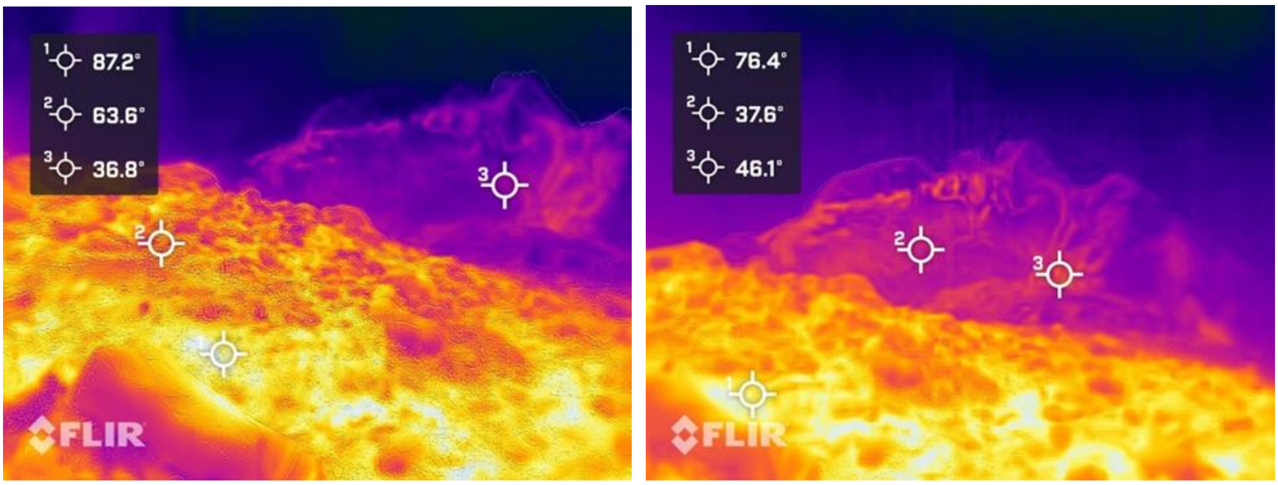

Figure 26 & 27. Thermal Images in Degrees Celsius from the Crater D of the Arenal Volcano September 2022.

Figure 28 & 29. Summit of Arenal Volcano September 2022.

2.1. LiDAR

NASA has taken particulair interest in the Arenal volcano in the past. Two times in 1998 and in 2005 researchers from NASA used a Laser Vegitation Imaging Sensor LVIS for wide swath 3-D topographical data collection on the Arenal volcano. By taking two sets of measurements at two different time periods in the eruption cycle of Arenal; distinct differances were mapped due to the lapse of 7 years between mapping missions. By strategically waiting untill 2005 when the majority of the lava flows subsided, NASA succussfullly mapped lava flows and pyroclastic deposits at the Arenal volcano. They found that the active crater C grew by (3.82 meters each yeay).

The article titled; "Quantifying recent pyroclastic and lava flows at Arenal Volcano, Costa Rica, using medium-footprint lidar" explained that these types of data sets are crutial to calculate eruption volume and to study magma suply systems. (2)

Today high-resolution cameras on drones are being used to create similiar DSM and DEM 3-D models for research institutions like NASA. These types of models derived from drone photos are helping asses the level of risk associated with volcanoes.

There were fairly consistent lava flows from 1998-2005 seen coming from the active crater C of the Arenal volcano. Afterward the volcano showed major topographical changes after this eruption cycle. UAS modeling can now help calculate lava flow volume, because accurate elevation data is required to monitor pyroclastic flows. This is a UAS application that has a direct impact on risk assessment associated with the volcano and monitoring hazards to local populations living in the surroundings of the volcano. UAS offer several distincy advantages over remote sensing techniques. Generating DSM using UAS can assist with tracking vegetation regrowth, monitoring erosion, tracking lave flows and calculating the volume of ejected material after an eruption [2]. From 1987-2001 there were infrequent explosions observed at the Arenal summit [3].

Figure 30 – Arenal Volcano in 2005.

UAS equipped with thermal cameras can also be of great importance in volcanic region for thermal spring exploration. Thermal sensors on UAS can be used to search through thick tropical vegetation looking for thermal anomalies coming from potential fumaroles or volcanic hot springs. So far at Arenal only low temperature thermal springs have been found on the slopes with temperatures around 60°C. These thermal springs have been identifying on the north eastern and north western flanks of the Arenal volcano [4].

The Arenal volcano is located in the Caribbean rainforest region of Costa Rica and receives on average 5 meters of rainfall each year. The Arenal volcano has a complex hydrothermal system surrounding the volcano. Chemical species in the thermal springs shows the possibility of a magmatic chamber that contributed chemical species deriving from the magmatic system of Arenal to the hydrothermal volcanic system which is connected to the thermal springs. By deploying more UAS and missions with specialized thermal sensors researchers working on monitoring the Arenal Volcano National Park in Costa Rica can gather more information about the hydrological resources within the National Park boundaries [4].

High resolution UAS photos used to create 3-D maps are highly valued once aligned together with geo referencing. Stiching these 3-D mesh models together creates a product that can be used to track changes in eruption sites, scan regions for thermal springs and can help researchers estimate better direction of lava flows across regions of increased eruptive activity.

Figure 31. Gas Plume at the Arenal Volcano September 21st, 2022.

3. Results

Once we reached the summit we immediately set up the Sniffer4D and SnifferV because Sniffer readings from the Arenal summit were number one priority and therefore we began operating this equipment first. The Sniffer4D V2 devices take 5 minutes to warm up and start recording high quality data.

In 2001 Arenal was the most active volcano in Costa Rica and was responsible for releasing at least 1.3 Mt of SO_2 into the atmosphere since the start of the 1968 eruption cycle. Arenal has shown both explosive eruptions with pyroclastic flows and forms of passive degassing. The degassing models of Arenal showed that passine degassing was the most significant form of volcanic emissions being released from Arenal. In 2001 scientists estimated Arenal was connected to a mid crustal magma chamber and suggested Arenal was consistently supplied with fresh magma [5].

Arenal is 1,657 meters high, it's a strato volcano located in the tropical rainforest of central Costa Rica. Previous eruptive cycles went from 1968-1974, 1975-1984, and there was a particularly spectacular lava flow eruption cycle from 1995-1996. With each eruption cycle volcanic emissions change. By tracking and logging these volcanic emissions additional information into the volcanic cycle can be obtained [5].

Figure 32 & 33. SnifferV & Sniffer4D Inside Crater D of the Arenal Volcano.

Figure 34 & 35. Active Crater C at the Summit of the Arenal Volcano.

Our findings showed there were 3 distinct areas releasing emissions at the summit confirmed with drone video. A full analysis of active crater C with the SnifferV unit yielded excellent data on the type of emissions being released from the volcano. Research published in 2001 showed that active crater C was divided into 2-3 separate vents. During the lava flow period growth estimates from the lava flows and dome buildup were estimated at approximately 5 meters per year [5].

Figure 36 –Measurements Taken from Degassing Fumarole of Active Crater C in Sniffer Mapper.

Our objective of using the SnifferV & Sniffer4D was ocomplished at the summit of Arenal on our first climb. Monitoring and loging emissions from active crater C of Arenal helps provide information on eruption mechanics which can be applied to each volcanic system.

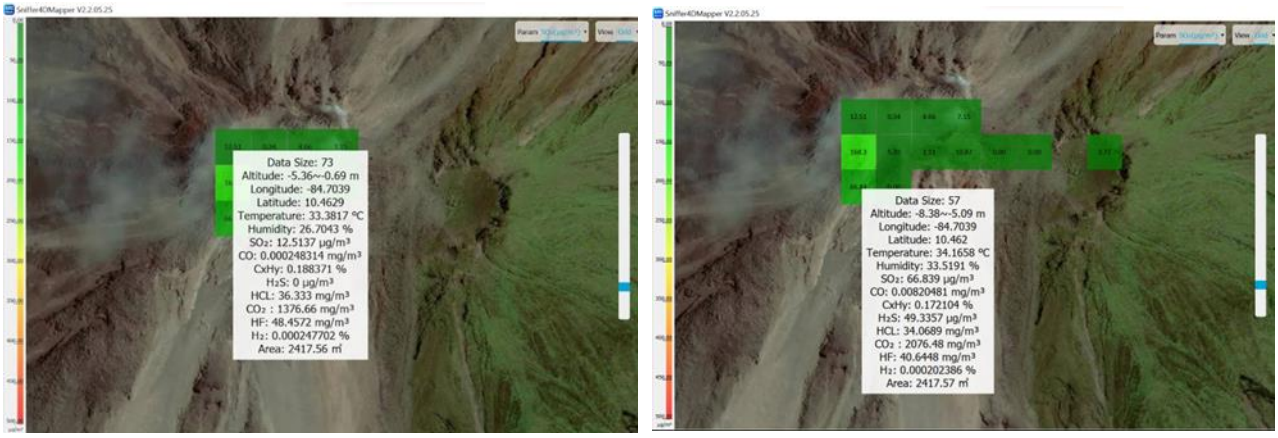

Figure 37 & 38. Sniffer Mapper Measurements at Active Crater C of the Arenal Volcano.

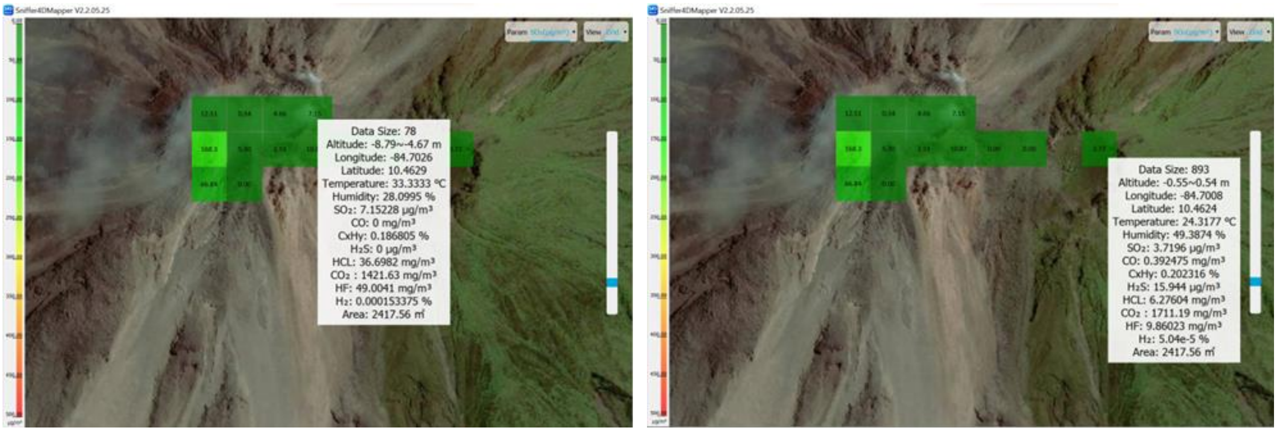

Figure 39 & 40. Sniffer Mapper Measurements at Active Crater C and D of the Arenal Volcano.

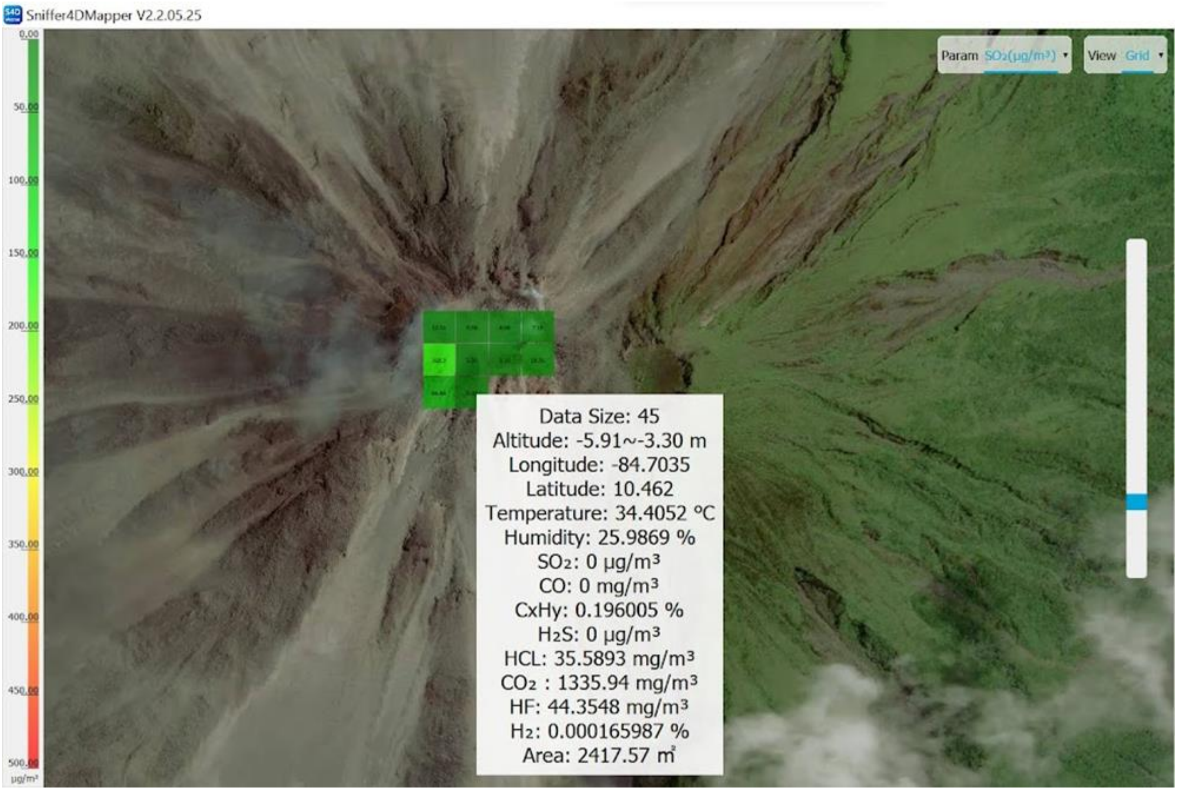

Figure 41. Measurements Taken from UAS Control Station at Active Crater C in Sniffer Mapper.

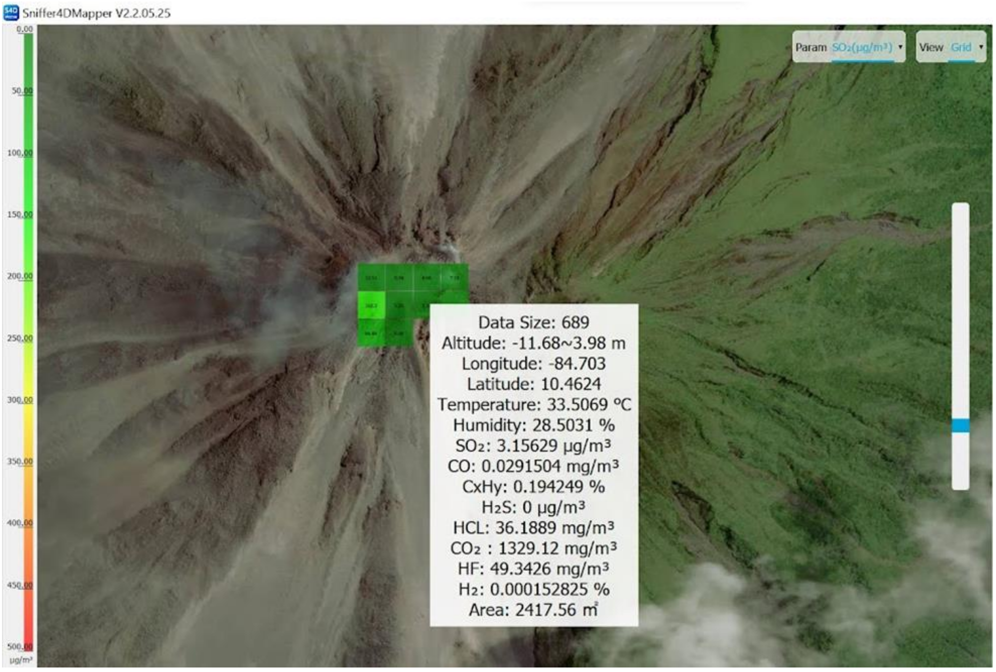

Figure 42. Measurements Taken from UAS Control Station at Active Crater C in Sniffer Mapper.

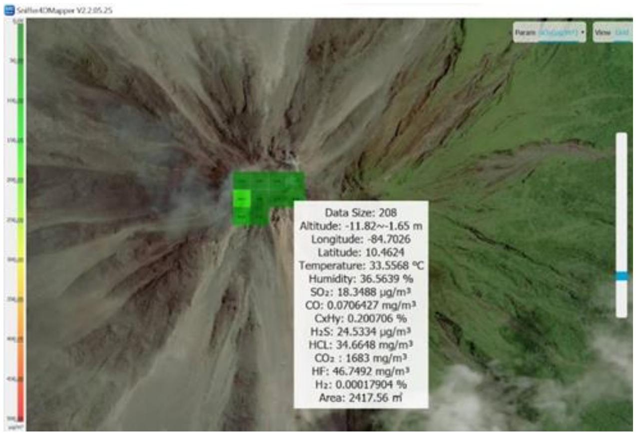

Figure 43 & 44. Measurements Taken from UAS Control Station at Active Crater C in Sniffer Mapper.

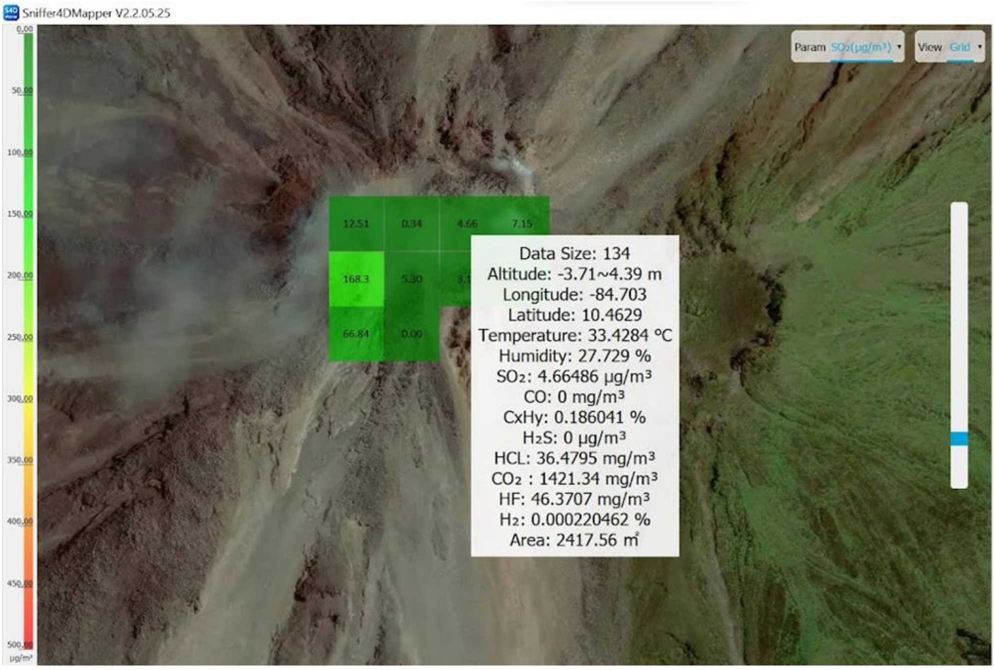

Figure 45. Measurements Taken from Degassing Fumarole of Active Crater C in Sniffer Mapper.

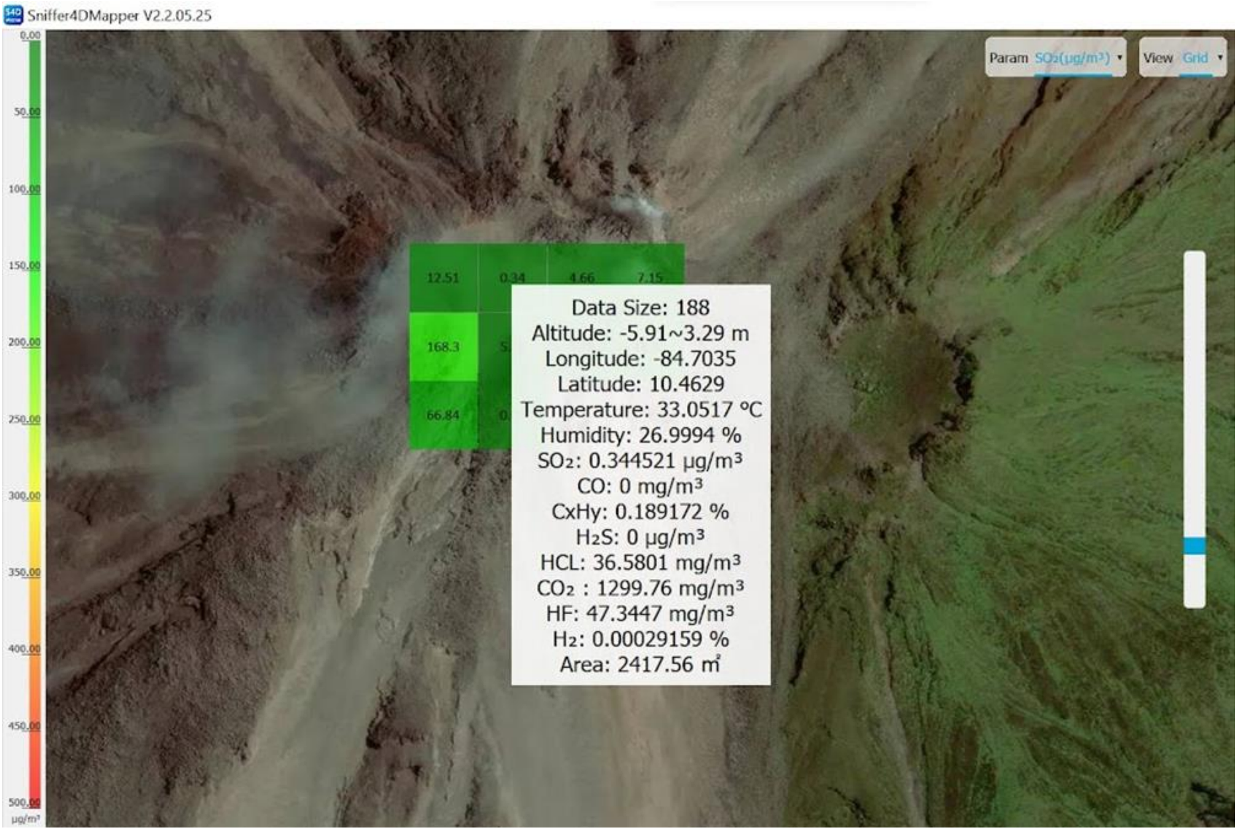

Figure 46. Measurements Taken from Degassing Fumarole of Active Crater C in Sniffer Mapper.

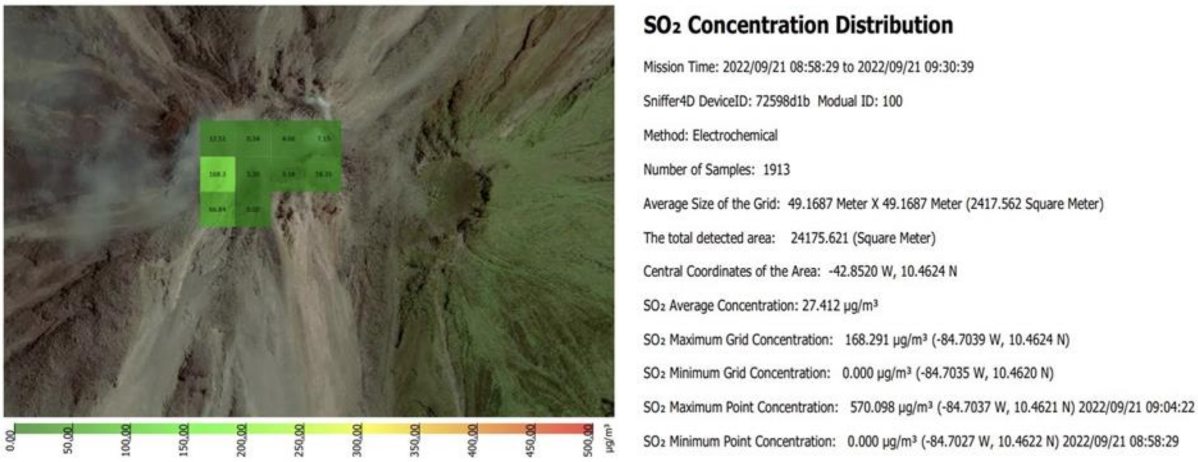

Figure 47. Minimum and Maximum Measurements Taken from Active Crater C in Sniffer Mapper.

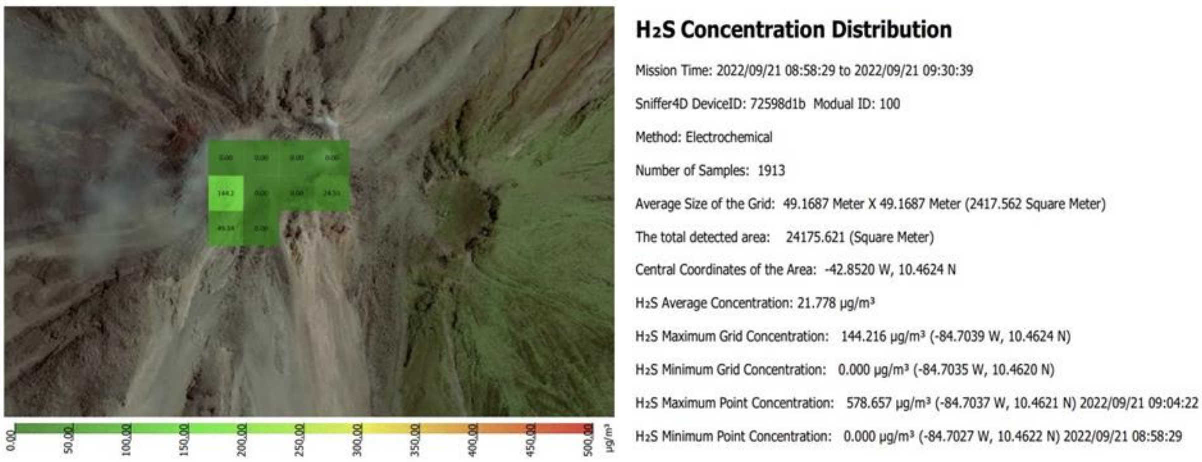

Figure 48. Minimum and Maximum Measurements Taken from Active Crater C in Sniffer Mapper.

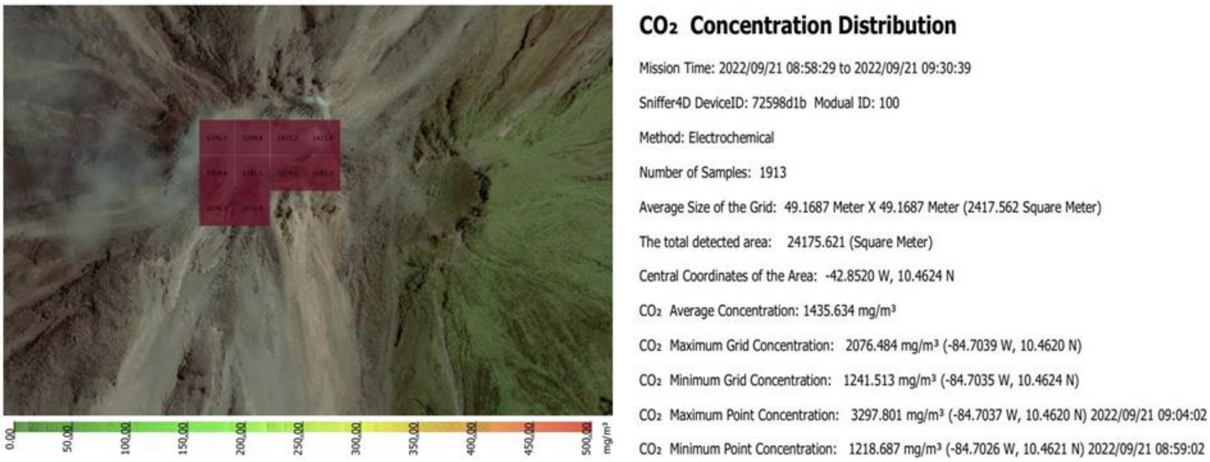

Figure 49. Minimum and Maximum Measurements Taken from Active Crater C in Sniffer Mapper.

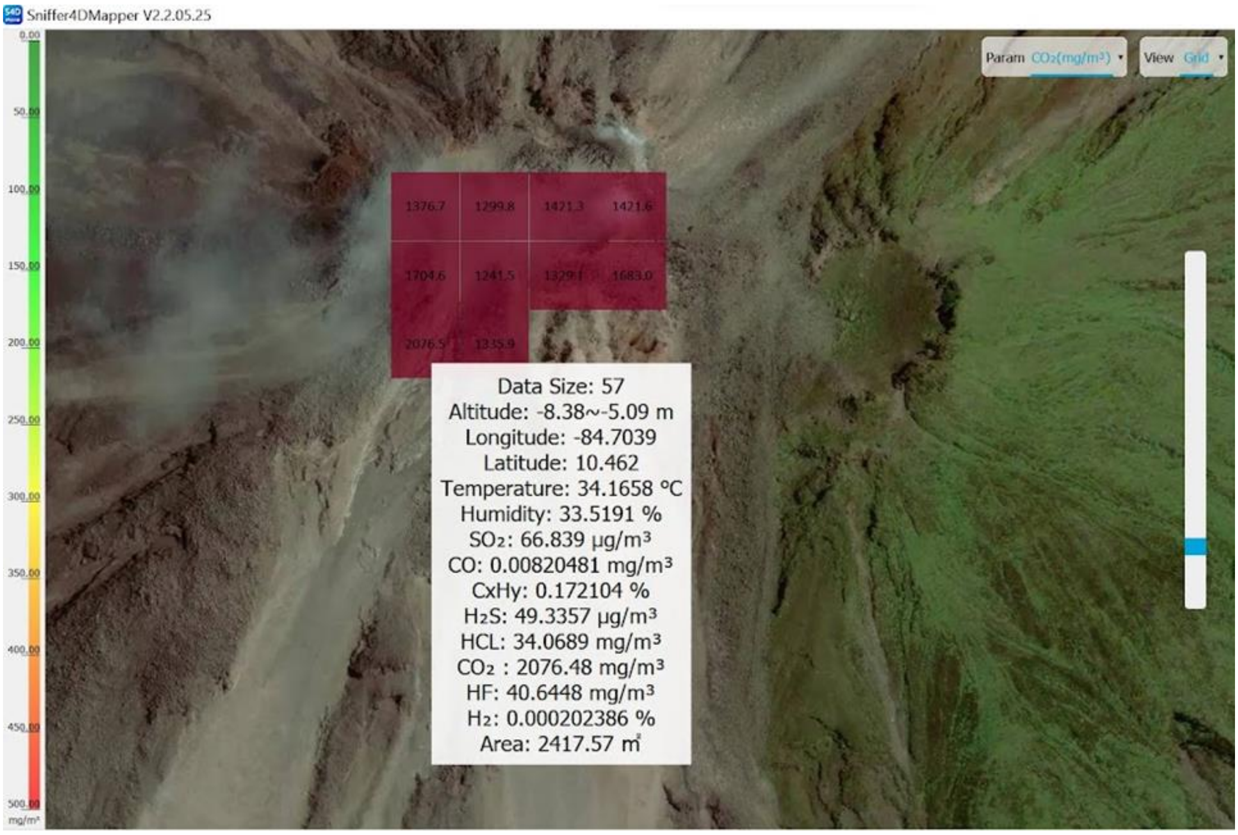

Figure 50. SnifferV Measurement Taken from Area of Most Significant Degassing.

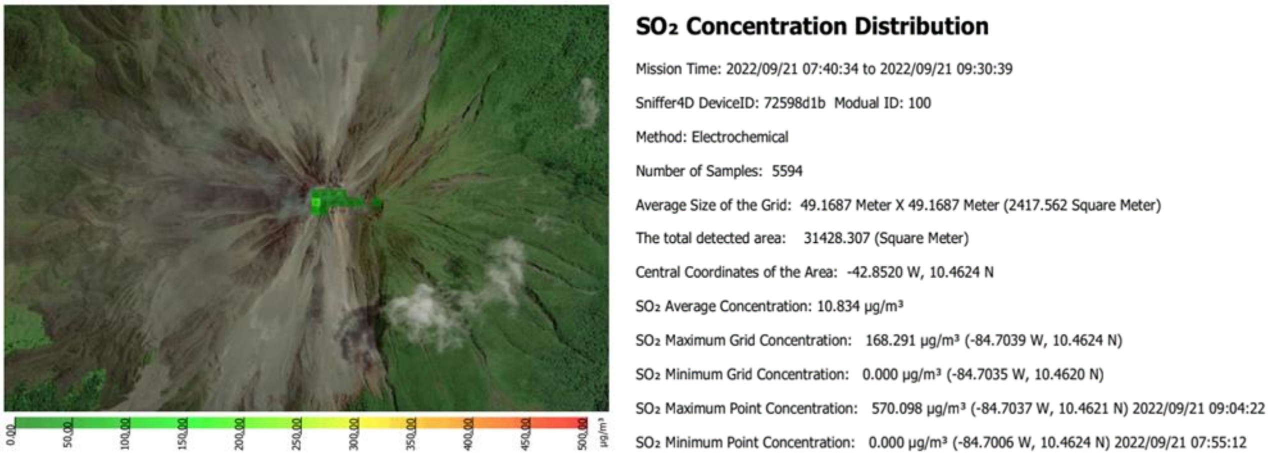

Figure 51 & 52. SO_2 Emissions Mapped with the Sniffer Mapper Software Program from Arenal Summit.

H_2S Concentration Distribution

Mission Time: 2022/09/21 07:40:34 to 2022/09/21 09:30:39
Sniffer4D DeviceID: 72598d1b Modual ID: 100
Method: Electrochemical
Number of Samples: 5594
Average Size of the Grid: 49.1687 Meter X 49.1687 Meter (2417.562 Square Meter)
The total detected area: 31428.307 (Square Meter)
Central Coordinates of the Area: -42.8520 W, 10.4624 N
H_2S Average Concentration: 9.993 μg/m³
H_2S Maximum Grid Concentration: 144.216 μg/m³ (-84.7039 W, 10.4624 N)
H_2S Minimum Grid Concentration: 0.000 μg/m³ (-84.7035 W, 10.4620 N)
H_2S Maximum Point Concentration: 578.657 μg/m³ (-84.7037 W, 10.4621 N) 2022/09/21 09:04:22
H_2S Minimum Point Concentration: 0.000 μg/m³ (-84.7006 W, 10.4624 N) 2022/09/21 07:50:06

CO_2 Concentration Distribution

Mission Time: 2022/09/21 07:40:34 to 2022/09/21 09:30:39
Sniffer4D DeviceID: 72598d1b Modual ID: 100
Method: Electrochemical
Number of Samples: 5594
Average Size of the Grid: 49.1687 Meter X 49.1687 Meter (2417.562 Square Meter)
The total detected area: 31428.307 (Square Meter)
Central Coordinates of the Area: -42.8520 W, 10.4624 N
CO_2 Average Concentration: 1465.123 mg/m³
CO_2 Maximum Grid Concentration: 2076.484 mg/m³ (-84.7039 W, 10.4620 N)
CO_2 Minimum Grid Concentration: 1241.513 mg/m³ (-84.7035 W, 10.4624 N)
CO_2 Maximum Point Concentration: 3297.801 mg/m³ (-84.7037 W, 10.4620 N) 2022/09/21 09:04:02
CO_2 Minimum Point Concentration: 1218.687 mg/m³ (-84.7026 W, 10.4621 N) 2022/09/21 08:59:02

Figure 53 & 54. H_2S & CO_2 Emissions Mapped with the Sniffer Mapper Software Program from Arenal Summit.

UAS gas detection payloads add another application method to monitoring volcanic degassing. UAS add yet another layer ontop of remote sensing techniques and allow researchers to monitor the inaccessable regions of a volcano even in the case of an eruption. Most of the volcanic degassing seen coming from Arenal both today is from crater C. Previous estimates have been from 1.3Mt-3.9Mt of SO_2 released by Arenal since 1968.By deploying the Sniffer units at the Arenal summit crater C we gathered additional valuable data researchers can now calculate into their revised estimates [5].

The total amount of SO_2, CO_2 and H_2S being released from Arenal are just small fractions of the annual global output from consistantly erupting volcanoes. Previous estimates put calculations from 1.3Mt-3.9Mt of SO_2 from 1968-1996, and now are 1.3Mt-4.0Mt of SO_2 [5].

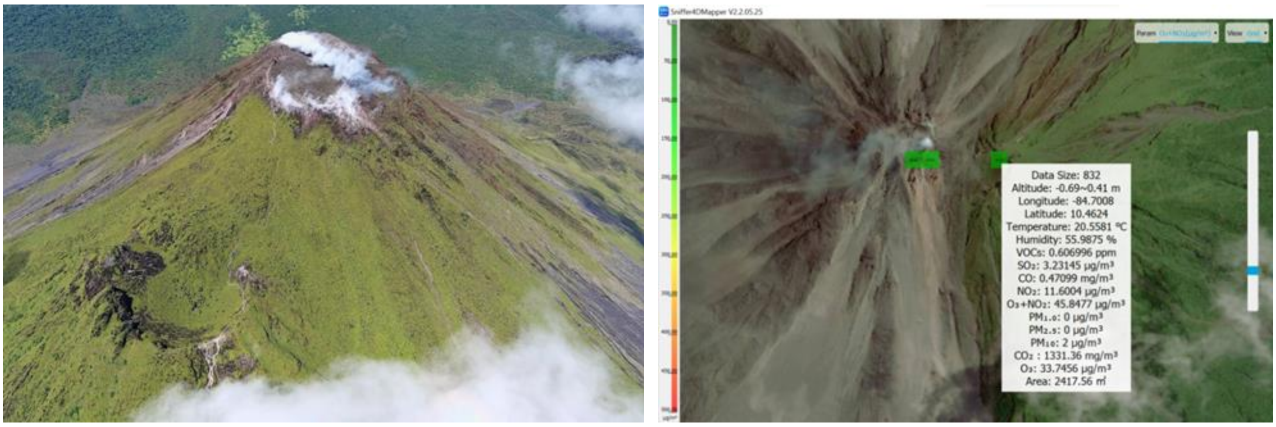

Figure 55 & 56. UAS View of Test Site and Sniffer4D Results from the Crater D of the Arenal Volcano.

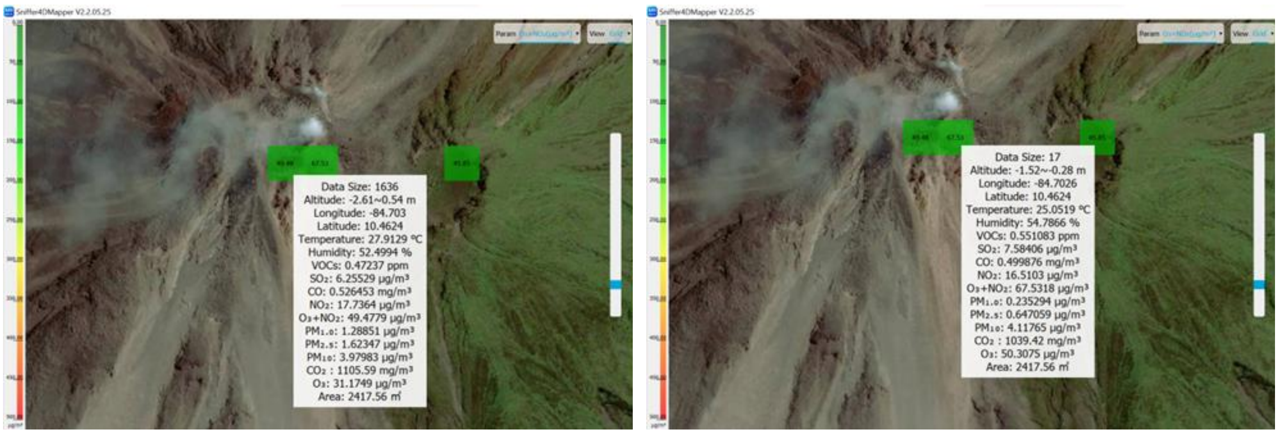

Figure 57 & 58. Sniffer4D Results from the Active Crater C of the Arenal Volcano.

Consistently active volcanoes like Arenal can release great quantities of SO_2 each year that rises to the troposphere. On long time scales these types of active but not erupting volcanoes may release equilivant levels of SO_2 compared to those which show intense degassing over a short time period. Therefore, periodically monitoring and tracking the volcanic emissions being released from crater D and most importantly active crater C of the Arenal volcano is a Sniffer application of great value [5].

Due to the constant and steady decrease in SO_2 seen coming from Arenal suggested that only one single magma chamber is connected to the volcanic system. One magma chamber which is consistantly degassing through crater C. By periodically tracking Arenal emissions and monitoring data sets for potential drastic fluctuation in gas species OVSCORI-UNA and LAQAT-UNA can estimate whether any new influxes of different magmatic inputs have changed. Magma is gas rich and by recognizing any kind of significant and drastic fluctuation in emission species is great information which can be used in volcanic forecasting and AERMOD Plot models. Previous research on Arenal showed SO_2 monitoring helped build the total estimated sulfur budget of the Arenal volcano and contributed to the suggestion that Arenal is consistantly supplied by a fresh magmatic source [5].

"Arenal's high level of activity allows for the study of multiple cycles of conduit opening and closing and thus is an excellent natural laboratory for better understanding the manner in which an open system volcano degasses and erupts." [5].

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	#Created by: Sniffer4DMapper 2.2.05.25													
2	ProjectName : Arenal Volcano UNA SnifferV													
3	Time Stan	Longitude	Latitude	Temperature °C	Humidity %	Pressure Pa	SO2 µg/m³	CO mg/m³	CxHy/Flammable Gases	H2S µg/m³	HCL mg/m³	CO2 mg/m³	HF mg/m³	H2 %
4	2022-09-2	-84.700595	10.462371	21.372549	53.92157	84473.8125	1.222076	0.355287	0.201422	37.930275	4.517879	1431.5453	7.781483	0
5	2022-09-2	-84.700595	10.462371	21.372549	53.92157	84473.8125	1.222076	0.351662	0.20127	37.048172	4.515396	1430.0464	7.788934	0
6	2022-09-2	-84.700595	10.46237	21.372549	53.92157	84473.8125	1.222076	0.351662	0.201193	37.048172	4.507945	1428.5474	7.793901	0
7	2022-09-2	-84.700599	10.462366	21.372549	53.92157	84473.8125	1.222076	0.351662	0.201041	37.930275	4.510429	1428.5474	7.791418	0
8	2022-09-2	-84.700603	10.462371	21.372549	53.92157	84473.8125	1.222076	0.351662	0.200964	37.930275	4.507945	1433.0444	7.788934	0
9	2022-09-2	-84.700602	10.462371	21.372549	53.92157	84473.8125	1.222076	0.348036	0.200888	38.81237	4.502977	1433.0444	7.783967	0
10	2022-09-2	-84.700601	10.46237	21.372549	53.92157	84473.8125	1.222076	0.348036	0.201804	37.930275	4.502977	1431.5453	7.781483	0
11	2022-09-2	-84.7006	10.46237	21.372549	53.92157	84473.8125	1.833113	0.348036	0.202033	37.930275	4.500494	1428.5474	7.774032	0
12	2022-09-2	-84.7006	10.462369	21.372549	53.92157	84473.8125	1.833113	0.348036	0.202643	37.048172	4.500494	1428.5474	7.771548	0
13	2022-09-2	-84.7006	10.462369	21.372549	53.92157	84473.8125	1.833113	0.344411	0.203253	37.048172	4.512912	1427.0483	7.769064	0
14	2022-09-2	-84.7006	10.462369	21.372549	53.92157	84473.8125	1.833113	0.348036	0.204016	37.048172	4.515396	1433.0444	7.76658	0
15	2022-09-2	-84.7006	10.462369	21.568628	53.92157	84473.8125	1.833113	0.351662	0.204398	37.930275	4.515396	1430.0464	7.76658	0
16	2022-09-2	-84.7006	10.462369	21.568628	53.92157	84473.8125	1.833113	0.358913	0.204474	37.930275	4.520363	1490.0063	7.761613	0
17	2022-09-2	-84.7006	10.46237	21.568628	53.92157	84473.8125	2.444151	0.362538	0.20455	37.930275	4.517879	1494.5033	7.764097	0
18	2022-09-2	-84.7006	10.46237	21.568628	53.92157	84473.8125	2.444151	0.362538	0.204245	37.048172	4.520363	1457.0284	7.769064	0
19	2022-09-2	-84.7006	10.46237	21.568628	53.92157	84473.8125	1.833113	0.362538	0.203864	37.048172	4.525331	1539.4734	7.774032	0
20	2022-09-2	-84.7006	10.46237	21.568628	53.92157	84473.8125	1.833113	0.362538	0.203558	37.930275	4.535266	1590.4395	7.776515	0
21	2022-09-2	-84.7006	10.46237	21.568628	53.92157	84473.8125	1.222076	0.362538	0.204016	37.930275	4.557619	1617.4215	7.788934	0
22	2022-09-2	-84.7006	10.46237	21.568628	53.92157	84473.8125	1.222076	0.362538	0.204474	37.930275	4.567554	1620.4193	7.793901	0
23	2022-09-2	-84.7006	10.46237	21.568628	53.92157	84473.8125	1.222076	0.358913	0.205008	37.930275	4.579973	1620.4193	7.801353	0
24	2022-09-2	-84.700601	10.46237	21.568628	53.92157	84473.8125	1.222076	0.362538	0.204703	37.930275	4.58494	1623.4174	7.80632	0
25	2022-09-2	-84.700601	10.46237	21.568628	53.92157	84473.8125	1.222076	0.362538	0.20455	38.81237	4.587424	1624.9165	7.811287	0

Figure 59. SnifferV Results from the Arenal Summit.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	#Created by: Sniffer4DMapper 2.2.05.25														
2	ProjectName : Arenal Volcano UNA Sniffer4D														
3	Time Stamp	Longitude	Latitude	Temperature °C	Humidity %	Pressure Pa	VOCs ppm	SO2 µg/m³	CO mg/m³	NO2 µg/m³	O3+NO2 µg/	PM1.0 µg/m³	PM2.5 µg/m³	PM10 µg/m³	CO2 mg/m³
4	2022-09-21 07:40:	-84.700589	10.462363	19.215687	61.960785	84356.6094	0.682089	6.110378	0.485801	29.148787	77.168228	0	0	2	1415.0564
5	2022-09-21 07:40:	-84.700589	10.462363	19.215687	61.960785	84356.6094	0.682089	6.110378	0.485801	28.678646	75.860298	0	0	2	1416.5553
6	2022-09-21 07:40:	-84.700589	10.462363	19.215687	61.960785	84356.6094	0.682089	6.110378	0.489426	28.678646	75.206329	0	0	2	1418.05432
7	2022-09-21 07:40:	-84.700589	10.462363	19.215687	61.960785	84356.6094	0.682089	5.49934	0.489426	28.208504	75.206329	0	0	2	1416.5553
8	2022-09-21 07:40:	-84.700586	10.462361	19.215687	61.764706	84356.6094	0.682852	5.49934	0.489426	27.738363	73.898392	0	0	2	1416.5553
9	2022-09-21 07:40:	-84.700587	10.462361	19.215687	61.960785	84356.6094	0.681326	5.49934	0.489426	27.738363	72.917442	0	0	2	1415.0564
10	2022-09-21 07:40:	-84.700587	10.462361	19.215687	61.764706	84356.6094	0.681326	5.49934	0.489426	27.738363	72.590462	0	0	2	1415.0564
11	2022-09-21 07:40:	-84.700587	10.462361	19.215687	61.372547	84356.6094	0.681326	5.49934	0.489426	27.268221	70.955536	0	0	2	1415.0564
12	2022-09-21 07:40:	-84.700587	10.46236	19.215687	61.372547	84356.6094	0.681326	5.49934	0.489426	26.798079	70.628548	0	0	2	1415.0564
13	2022-09-21 07:40:	-84.700588	10.462361	19.215687	61.568626	84356.6094	0.682089	5.49934	0.489426	26.327936	69.647598	0	0	2	1415.0564
14	2022-09-21 07:40:	-84.700589	10.462361	19.411764	61.568626	84356.6094	0.681326	4.888302	0.489426	25.857796	69.647598	0	0	2	1416.5553
15	2022-09-21 07:40:	-84.700589	10.462361	19.411764	61.764706	84356.6094	0.680563	4.888302	0.489426	26.327936	69.647598	0	0	2	1416.5553
16	2022-09-21 07:40:	-84.70059	10.462361	19.411764	61.764706	84356.6094	0.681326	4.888302	0.489426	25.857796	68.993629	0	0	2	1416.5553
17	2022-09-21 07:40:	-84.70059	10.462361	19.411764	61.568626	84356.6094	0.681326	4.888302	0.489426	25.857796	67.358711	0	0	2	1415.0564
18	2022-09-21 07:40:	-84.700591	10.462362	19.411764	60.980392	84356.6094	0.681326	4.888302	0.489426	25.387653	67.031723	0	0	2	1413.55737
19	2022-09-21 07:40:	-84.700591	10.462362	19.411764	60.392159	84356.6094	0.682089	4.277265	0.493052	24.917513	65.069824	0	0	2	1413.55737
20	2022-09-21 07:40:	-84.700591	10.462362	19.411764	59.803921	84356.6094	0.682852	4.277265	0.493052	23.977228	63.761887	0	0	2	1413.55737
21	2022-09-21 07:40:	-84.70059	10.462362	19.411764	59.411766	84356.6094	0.683615	4.277265	0.493052	23.036945	60.492046	0	0	2	1419.55335
22	2022-09-21 07:40:	-84.70059	10.462362	19.411764	59.411766	84356.6094	0.682852	4.277265	0.493052	21.156378	57.222206	0	0	2	1416.5553
23	2022-09-21 07:40:	-84.70059	10.462362	19.411764	60	84356.6094	0.681326	3.666227	0.493052	19.745953	54.27935	0	0	2	1416.5553
24	2022-09-21 07:40:	-84.70059	10.462361	19.411764	60.588234	84356.6094	0.679037	4.277265	0.493052	19.275812	52.644432	0	0	2	1415.0564
25	2022-09-21 07:40:	-84.70059	10.462362	19.411764	60.980392	84356.6094	0.677511	3.666227	0.493052	19.275812	53.298397	0	0	2	1412.05835

Figure 60. Sniffer4D Results from the Arenal Summit.

Figure 61 & 62. UAS Perspective of Active Crater C of the Arenal Volcano Above a Cloud.

From the western rim of active crater C we flew the Autel Lite + drone to create a Digital Surface Model of the Arenal summit including crater D and active crater C. Then from the same location we conducted several UAS flights to capture videography of the degassing fumaroles at the Arenal summit. UAV flights confirmed there are still 3 different fumaroles at the summit of Arenal within crater C. Remote pilot in command was Ian Godfrey who was assisted by Geoffory Avard.


Figure 63 & 64. Video Recording View of the Autel Lite + UAS at the Arenal Volcano.


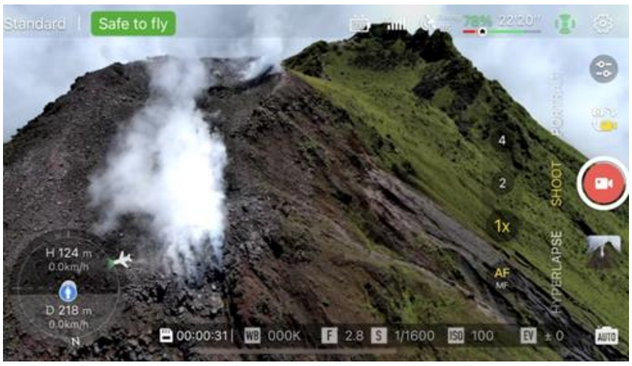

Figure 65 & 66. Video Recording View of the Autel Lite + UAS at the Arenal Volcano.

UAS were used in mapping projects by academics in 2020 where flight missions contributed to the generation of 3-D models which were created by overlaying high resolution photos and stitching them together. Ina publication titled " Low cost UAV applications in dynamic tropical voncanic landforms" by the Journal of Volcanological and Geothermal Research; UAS were flown to map the most recent Arenal lava flows located on the northern section of the Arenal cone. This lava deposit originated as a lava flow in 1992. Arenal is located between the Central Volcanic Range and the Guanacaste Volcanic Range in the north of Costa Rica. The Arenal volcano continues to demand great international attention [6].

The 3-D modeling Nira app was introduced in full capacity to the market in September 2022. Nira supports geo-referencing and can be an extremely helpful way to share the 3-D volcanic models generated from the UAS flights. The Nira app offers researchers an opportunity to share these models via online link which greatly contributes to interdisciplinary collaborations. The Nira app was successfully used to map a 3-D mesh model of parts of the Solheimajokull glacier and the Fagradalsfjall volcano eruption in Iceland using a UX11 drone. After reviewing the models we decided Nira was an ideal fit for the Arenal summit crater digital model. The 3-D modeling app used for these volcanoes requires a computer with a Nvdia gpu.


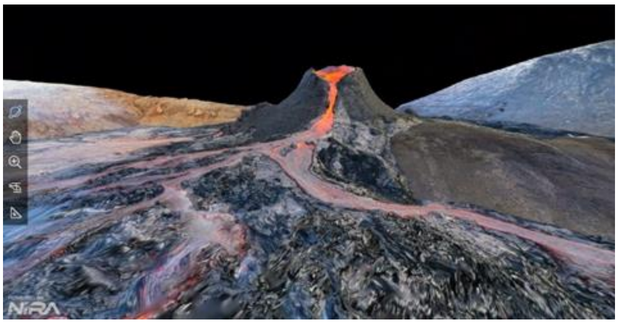

Figure 67 & 68. High Resolution 3D Model of the Fagradalsfjall Volcano in Iceland.


Figure 69 & 70. High Resolution 3D Model of the Fagradalsfjall Volcano in Iceland.

Volcanologists and remote pilots from EFLA Consulting Engineers helped process the 3D model of Arenal after sharing proof of concept from the Fagradalsfjall volcano in Geldingadalir Iceland. Geldingadalur is a region on the Reykjanes Peninsula in Iceland which is well known for the Fagradalsfjall volcano, which erupted in 2021.

EFLA engineers had generated a useful 3-D model of the eruption site and lava flows and were conducting UAS flight missions mapping where the lava was going on March 23rd 2021. EFLA was involved in constructing and designing these lava “guides” during the entire 2021 eruptive cycle. The model of Fagradalsfjall Volcano in Geldingadalir Iceland was built after a series of "point of interest" flights with the Mavic 2 Pro drone were completed. The Fagradalsfjall volcano eruption in 2021 was recorded with a drone for an observational academic video shot in May 2021.

There are several steps that need to be taken to generate a high resolution model of a volcano. These steps are outlined below.

Step 1- Find an appropriate angle and distance from volcano, usually 30, 50 or 80 meters will be ideal depending on the resolution of the camera being used and the side of the area being mapped.

Step 2- Find out how high above take-off point the highest point of the volcano is try to fly at least 50 to 75 meters higher than the volcanic peak. Point the UAS camera directly down and begin setting a waypoint grid pattern over your target or prepare for manual flight, remember to set the overlap of images both front and side to at least 80 percent, to guarantee a high resolution model can be generated of the volcano. Many have found 85% front overlap is ideal and 80% side overlap is acceptable.

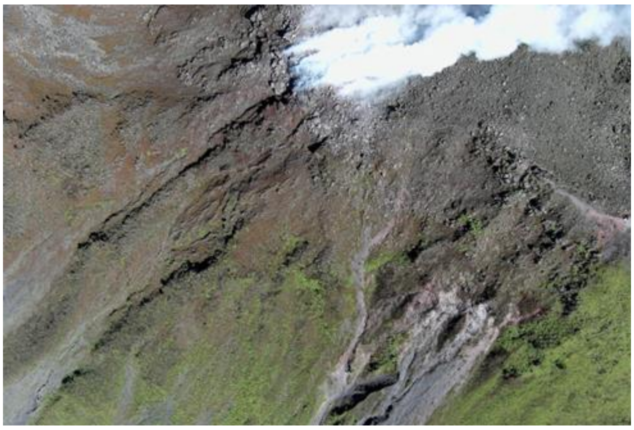


Figure 71 & 72. Example of UAS Images Used for Arenal 3-D Model.


Figure 73 & 74. Example of UAS Images Used for Arenal 3-D Model.

Step 3- Set camera settings (make sure not to change them between circles for specific target) set to "POI" or Point of Interest in the DJI Fly app on the controller; this option is on the left side of the screen once the drone starts circling the target, start snapping pictures on the controller "camera" button. Since volcanic environments are frequently cloudy and lighting fluctuates quite rapidly it may be ideal to set the camera to automatic settings since the lighting conditions can change very fast.

Step 4- When conducting UAS flight mission projects for mapping or modeling accuracy, then it's important to plan the flight using something like Drone Deploy or set the perimeter of the flight using Google Earth and then export the area as a KML and then adjust the data it in the DJI controller software.

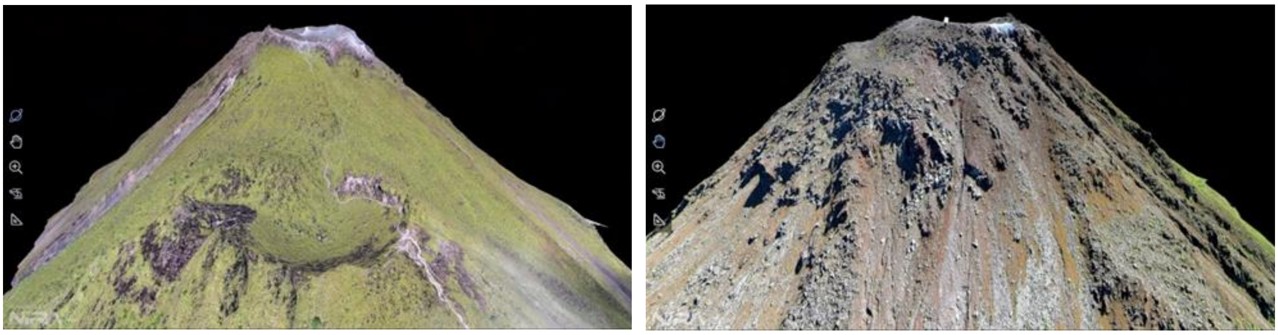

Figure 75 & 76. High Resolution 3D Model of the Arenal Volcano in Costa Rica.

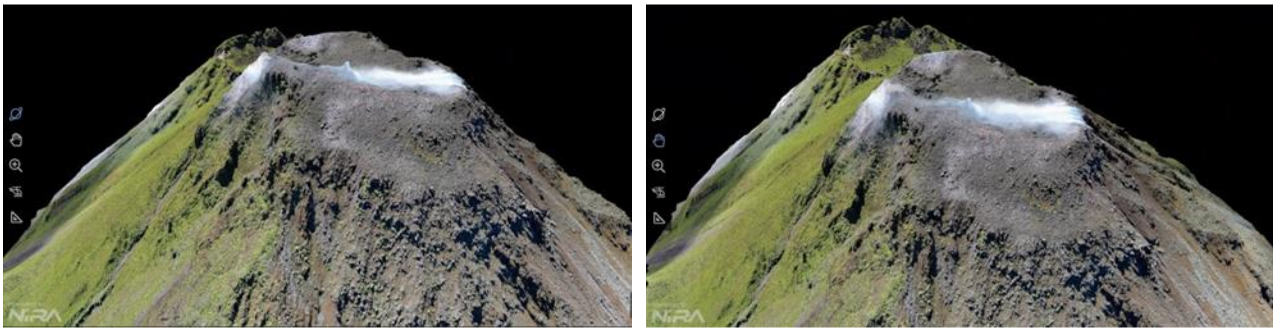

Figure 77 & 78. High Resolution 3D Model of theArenal Volcano in Costa Rica.

3.1. Arenal Volcano Crater D

Before climbing from crater D to Crater C several Lighting Passport measurements were taken from within crater D to help gather information on the microclimates of Costa Rica. After the spectrometer tests we continued climbing for another 10-15 minutes to the summit which is active crater C. One recognizable variation in the environment was that the crater walls drom crater D blocked much of the wind at the summit. There was also degassing fumaroles from within crater D which increase the temperature of the ambient air. From within crater D there could be CO_2 and PM fluctuations that impact vegetation. There are many hidden variables to a microclimate. By deploying the SnifferV, the Sniffer4D and the lighting passport we were able to obtain complete environmental data on the microclimate of crater C of the Arenal Volcano National Park.

Figure 79 & 80. Fumaroles Around Crater D of the Arenal Volcano.

Figure 81 & 82. Fumaroles Around Crater D of the Arenal Volcano.

	A	B	C	D	E	F	G	H
1	PPFD (400 - 700 nm)	891.21	1144.2	1138.7	108.67	1162.7	1148.5	103.94
2	PPFD FR (701 - 780 nm)	243.21	368.41	361.11	28.222	405.89	379.09	31.346
3	PPFD R (600 - 700 nm)	311.04	445.98	443.73	26.678	452.75	448.41	26.869
4	PPFD G (500 - 599 nm)	309.99	351.43	351.83	35.316	350.85	351.76	34.314
5	PPFD B (400 - 499 nm)	270.14	346.68	343.07	46.668	359.06	348.25	42.748
6	PPFD UV (380 - 399 nm)	30.659	40.994	40.208	7.6423	43.63	41.178	6.7778
7	YPFD (400 - 700 nm)	739.31	946.07	942.46	87.636	958.25	949.03	84.148
8	YPFD (380 - 780 nm)	790.4	1021.4	1016.4	95.639	1040.4	1026.1	91.958
9	YPFD FR (701 - 780 nm)	32.927	51.043	50.146	3.4947	56.261	52.615	3.8105
10	YPFD R (600 - 700 nm)	279.47	396.28	394.99	24.075	399.82	397.81	24.209
11	YPFD G (500 - 599 nm)	265.58	299.52	299.87	29.912	299.03	299.81	29.122
12	YPFD B (400 - 499 nm)	194.29	250.26	247.59	33.651	259.41	251.41	30.817
13	YPFD UV (380 - 399 nm)	18.057	24.168	23.701	4.4875	25.73	24.282	3.9808
14	R/B	1.15	1.29	1.29	0.57	1.26	1.29	0.63
15	R/FR	1.28	1.21	1.23	0.95	1.12	1.18	0.86
16	DLI	77	98.859	98.387	9.3889	100.46	99.233	8.9802
17	Illuminance	48838	56429	56478	5487	56375	56489	5339
18	Î»p (380~780 nm)	473	449	450	407	446	449	407
19	Î»D (380~780 nm)	486	468	469	479	466	468	479
20	CCT	6251	6625	6561	12466	6850	6647	10827
21	CRI (Ra)	98	86	87	98	85	86	98

Figure 83. Lighting Passport Measurements in Excel.

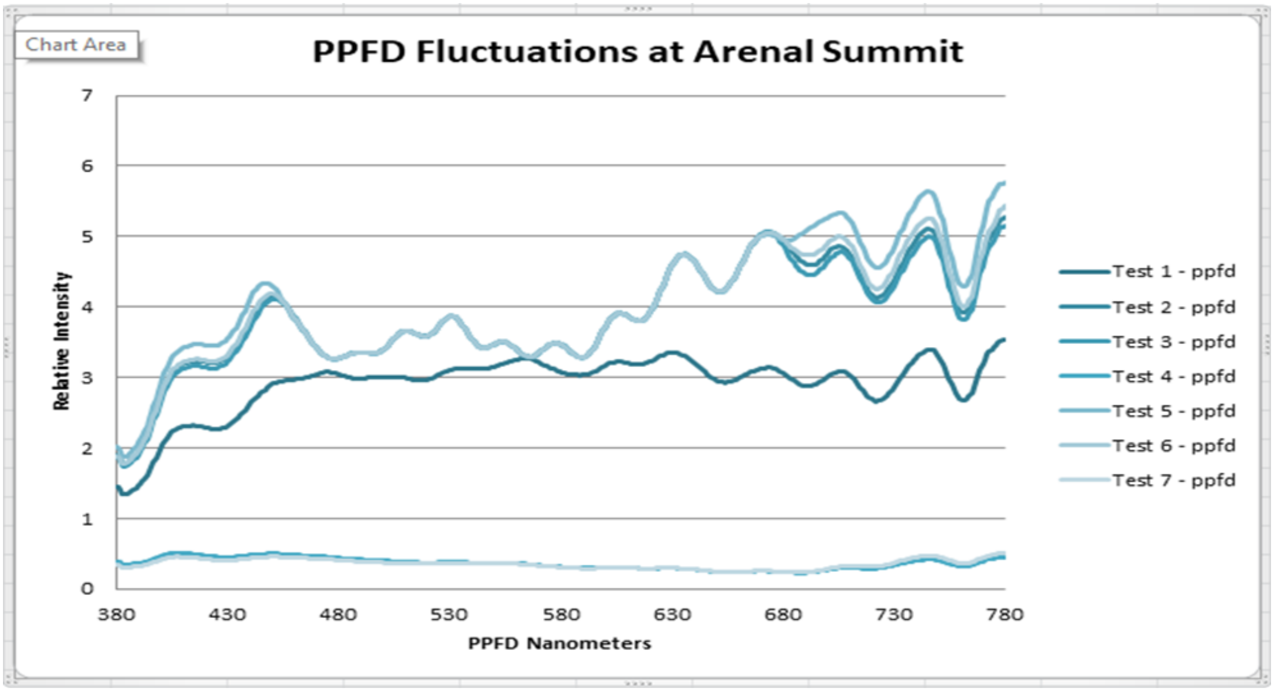

Figure 84. Lighting Passport Spectra Measurements from Arenal Volcano in X Y Axis.

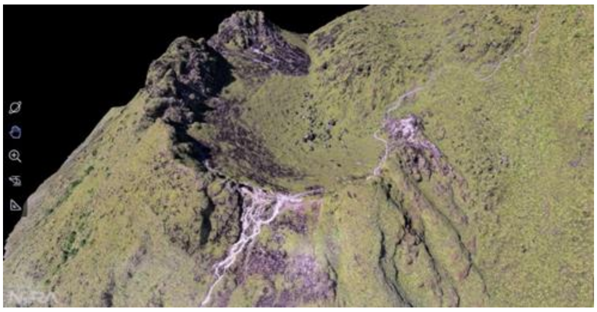
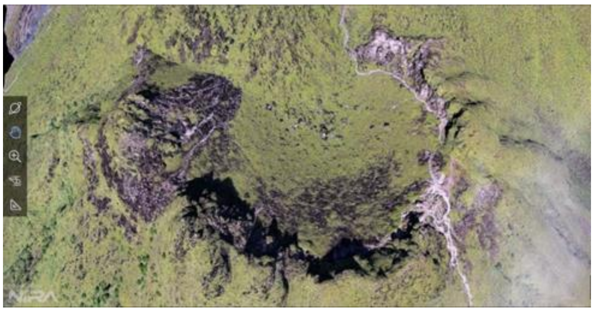

Figure 85 & 86. High Resolution 3D Model of Crater D of the Arenal Volcano in Costa Rica.

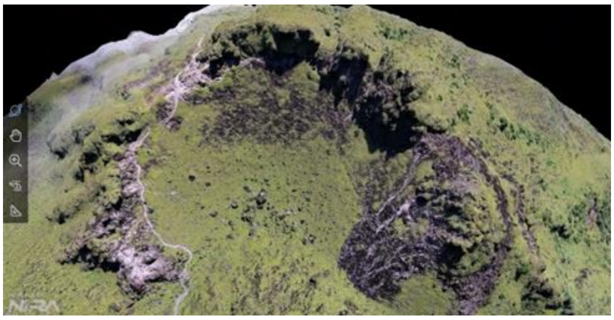
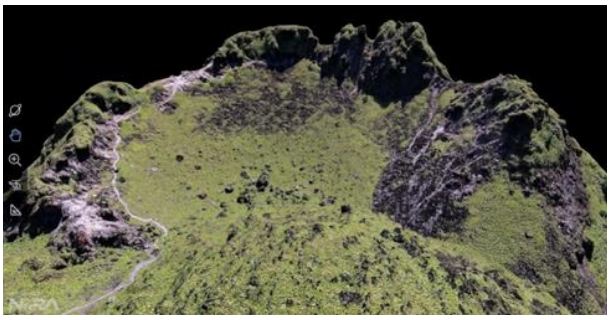

Figure 87 & 88. High Resolution 3D Model of Crater D of the Arenal Volcano in Costa Rica.

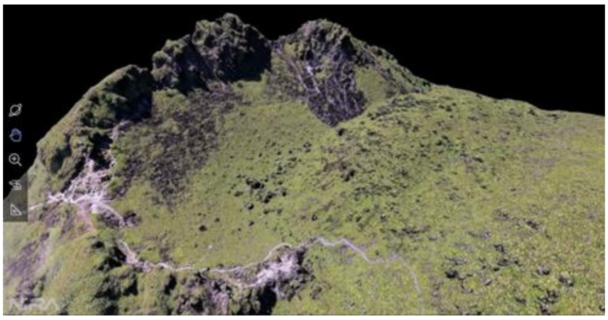
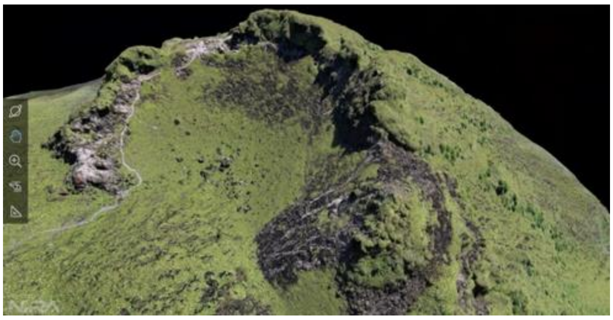

Figure 89 & 90. High Resolution 3D Model of Crater D of the Arenal Volcano in Costa Rica.


Figure 91 & 92. Inside Crater D of the Arenal Volcano.


Figure 93 & 94. View of Crater D from the pathe to Crater C.

3.2. Arenal Volcano Crater C

Limitations of ground level measurements are quickly being overcome by deploying UAS and their various applications such as payloads and mapping options.

Figure 95. Panarama of Active Crater C.

Figure 96 & 97. Fumaroles of Active Crater C of the Arenal Volcano Being Recorded By Autel Evo Lite + UAS.

Figure 98 & 99. Fumaroles of Active Crater C of the Arenal Volcano.

Researchers were impacted by the afordability and availability of UAS in Costa Rica, in particulair to be used in volcanology. They showed how UAS contributed to a significant advancement in their ability to observe a volcanic structure such as the deposit from the 1992 Arenal lava flow. Time reductions in fieldwork, image quality enhancement, videography potential and payload options prompted them to publish an article on their findings.

About half of the active volcanoes on Earth are in developing nations and economically priced quality UAS are forecasted to play a vital role in their volcanic surveillance programs [6].


Figure 100 & 101. Fumaroles of Active Crater C of the Arenal Volcano.


Figure 102 & 103. Fumaroles of Active Crater C of the Arenal Volcano.


Figure 104 & 105. High Resolution 3D Model of the Arenal Volcano in Costa Rica.


Figure 106 & 107. High Resolution 3D Model of the Arenal Volcano in Costa Rica.

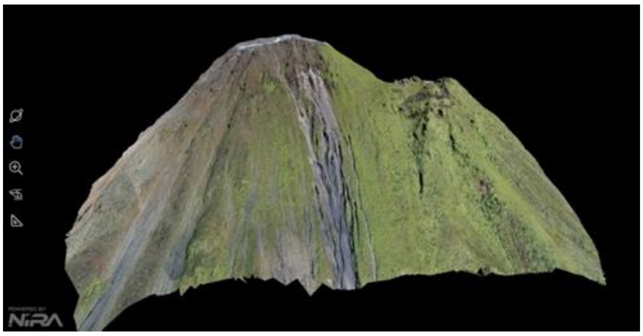


Figure 108 & 109. High Resolution 3D Model of the Arenal Volcano in Costa Rica.

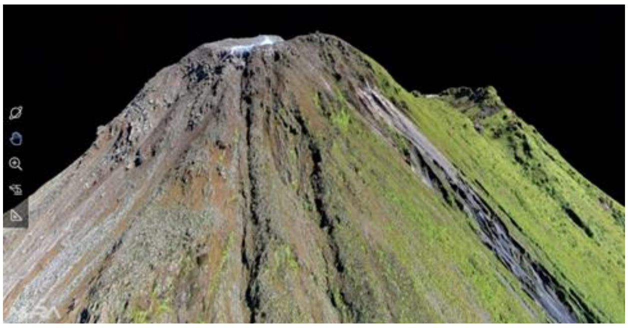


Figure 110 & 111. High Resolution 3D Model of the Arenal Volcano in Costa Rica.

The successful mapping of the deposit left after the 1992 Arenal lava flow to the north of active crater C proved that economically priced UAS are an excellent tool used to expand scientific field work. They found UAS could be used to monitor and track debris avalanche, cracking, rock fall/ rock slide, lahars, ejected material, lava deposit or lava flows and geological shifts in landscape due to both volcanic and external influence such as rain in the tropics. Their findings showed how UAS assisted in the collection of valuable data used for accurate volume calculations, surface characteristic recording, it was used for geological quantifications and hazard assessment [6].

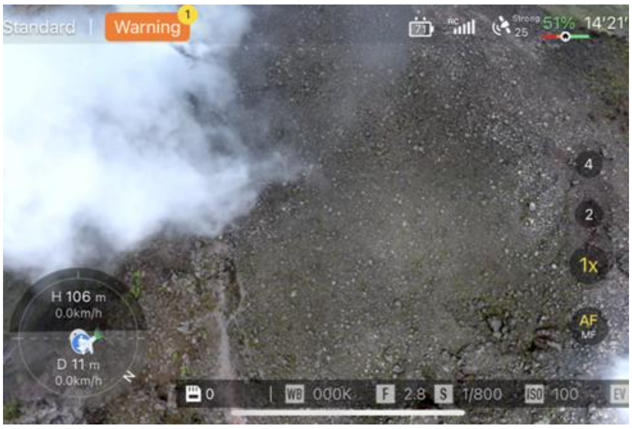

Figure 112 & 113. UAS View of Active Crater C During Mapping Flight Mission.

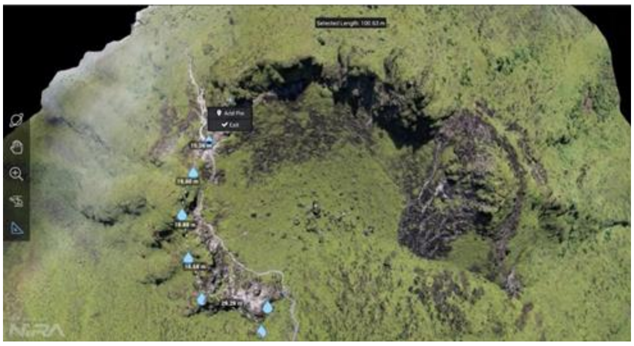
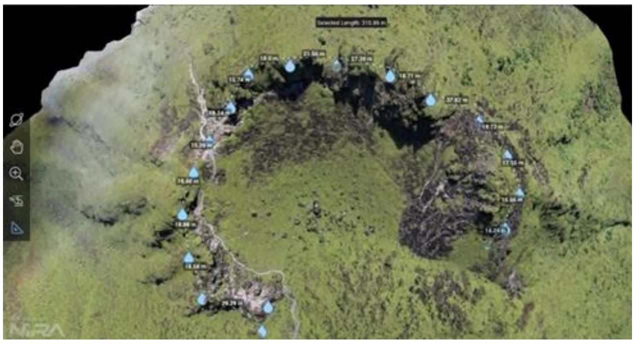

Figure 114 & 115. Nira 3-D Model of Crater D Radius Measurement.

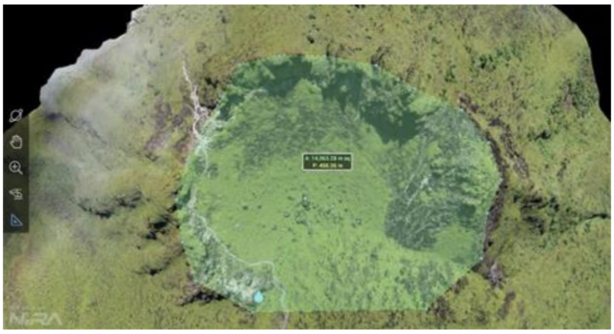
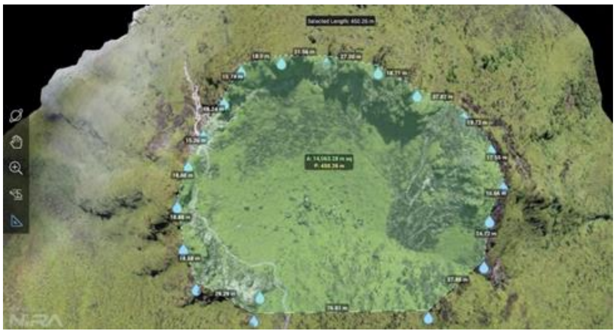

Figure 116 & 117. Nira 3-D Model of Crater D Radius Measurement.

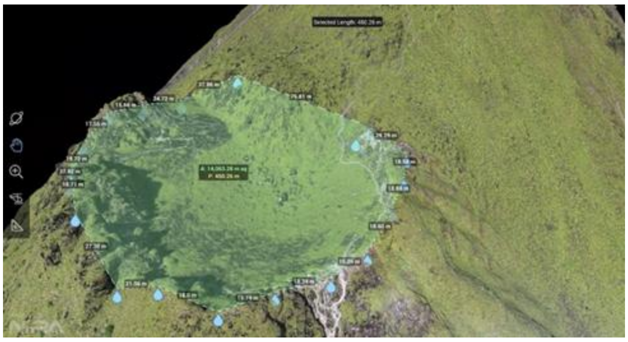
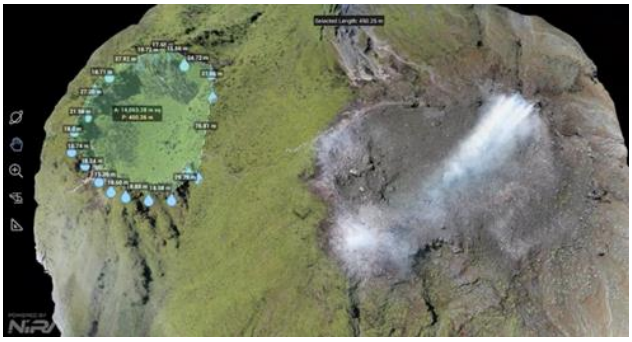

Figure 118 & 119. Nira 3-D Model of Crater D Radius Measurement.

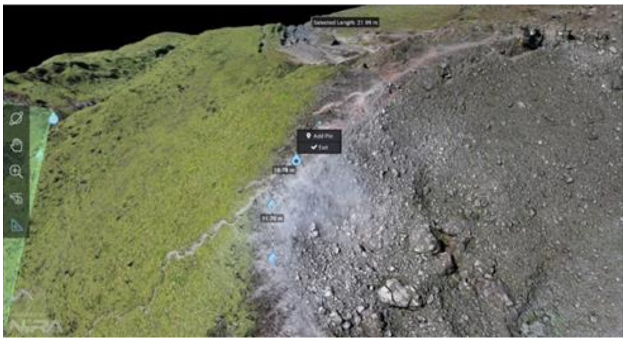


Figure 120 & 121. Nira 3-D Model of Crater C Radius Measurement.

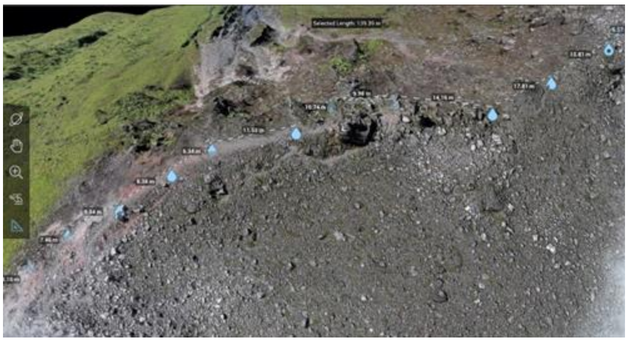


Figure 122 & 123. Nira 3-D Model of Crater C Radius Measurement.

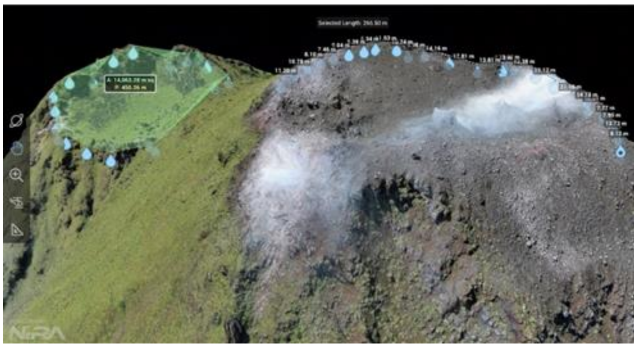
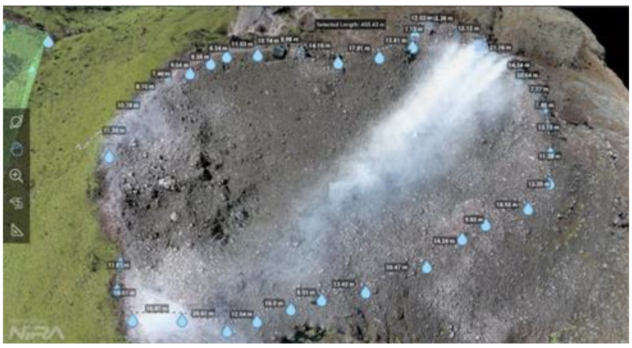

Figure 124 & 125. Nira 3-D Model of Crater C Radius Measurement.

Digital model measurements of the Arenal Summit showed that the total area of crater D was 14,063.28 square meters and the total perimeter of the crater radius was 450.26 meters. It was simple to create a radius on the interactive software which compressed a large amount of data. The Nira app is of specialized use to volcanologists and geologists using UAS because Nira is capable of handling massive datasets and creating really high fidelity on the model.

Radius measurements of the active crater C were made with the same process. Crater C covered a total area of 13,643.92 meters squared. The radius measurement of active crater C was 497.67 meters.

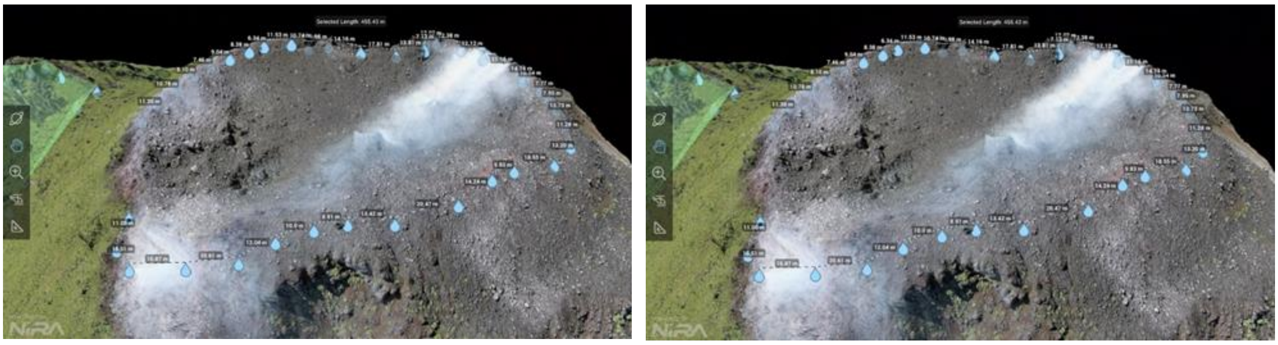

Figure 126 & 127 – Nira 3-D Model of Crater C Radius Measurement.

The degassing fumarole on the southern rim of the active crater C was measured using the High-Resolution 3-D model of the Arenal summit. The total area covered by the fumarole was measured to be 263.44 meters squared and the total perimeter of the fumarole was 64.2 meters. The accuracy was benchmarked to both the photos used to generate the model and the video recorded at the summit.

Figure128 & 129. Measurements of Arenal Fumarole Size using Nira app.

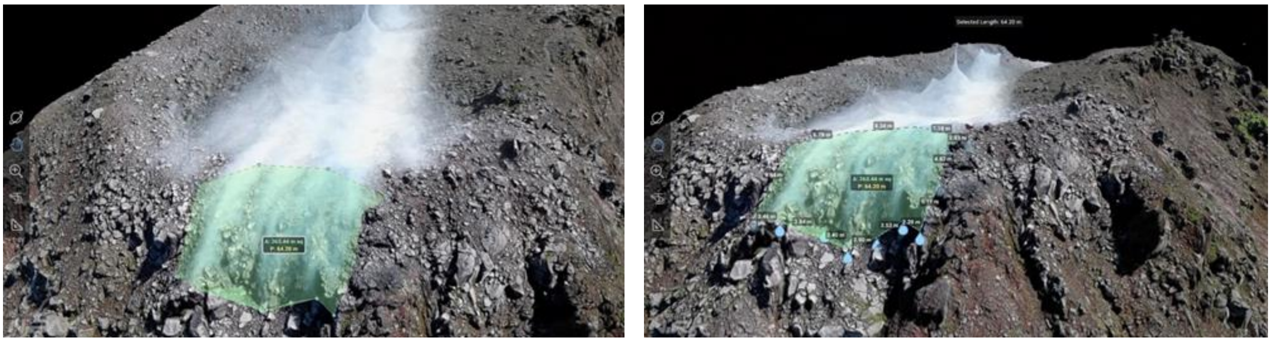

Figure 130 & 131. Measurements of Arenal Fumarole Size using Nira app.

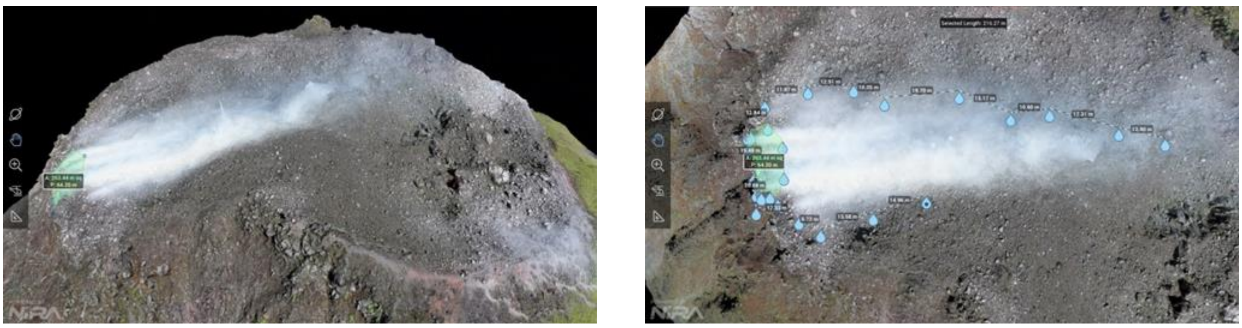

Figure 132 & 133. Measurements of Arenal Fumarole Size using Nira app.

After measuring the degassing fumarole area, the Nira app was used to measure the dispersment of the volcanic plume. These measurements were also benchmarked to the Sniffer Mapper software for accuracy. 3,176.26 was the total area coverage by the dispersment of the volcanic emissions at the Arenal summit. The total perimeter of the volcanic plume was 281.94 meters.

Figure 134. Measurements of Arenal Fumarole Size using Nira app.

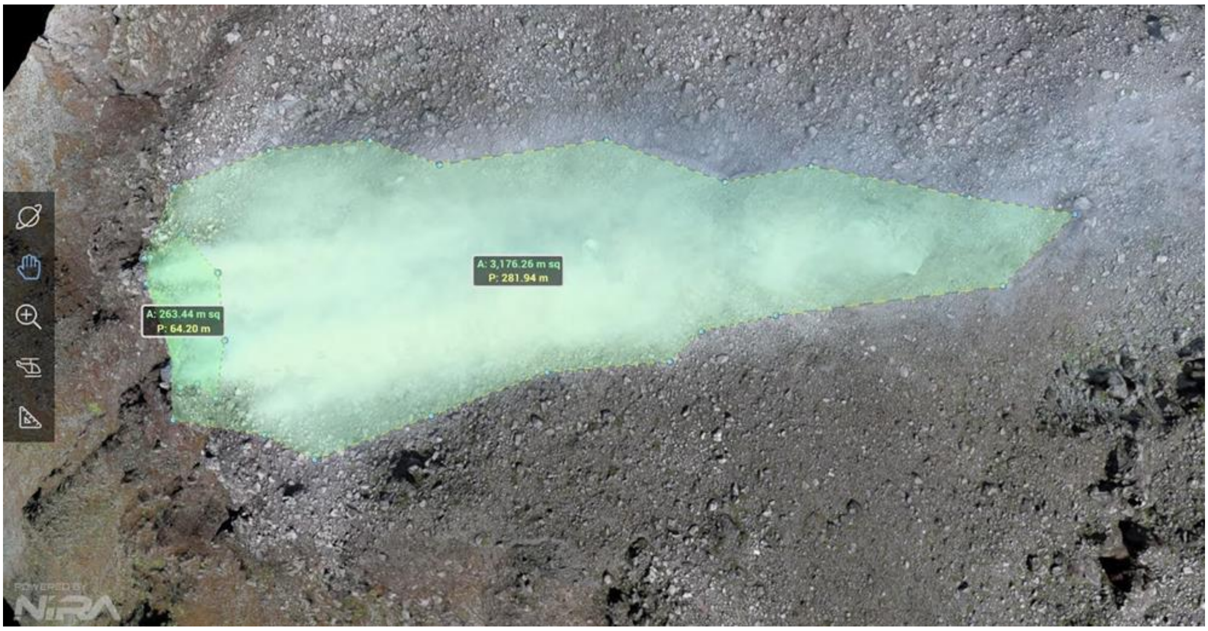

Figure 135. Nra app Measurements of Fumarole at Arenal Summit.

Figure 136 & 137. Degassing Fumarole at the Summit of Arenal Volcano September 2022.

Four areas were measured using the 3-D model of the Arenal summit generated from our images from the UAS flight mission. The radius of both crater D and active crater C were measured and compared to previous published measurements. The size of the fumarole of the southern crater rim was measured and benchmarked to three other references for accuracy, and the discernment of the volcanic emissions were measured and marked to the Sniffer Mapper measurements taken the same day at the same location.

Figure 138 & 139. NIra app Measurements of Fumarole at Arenal Summit.

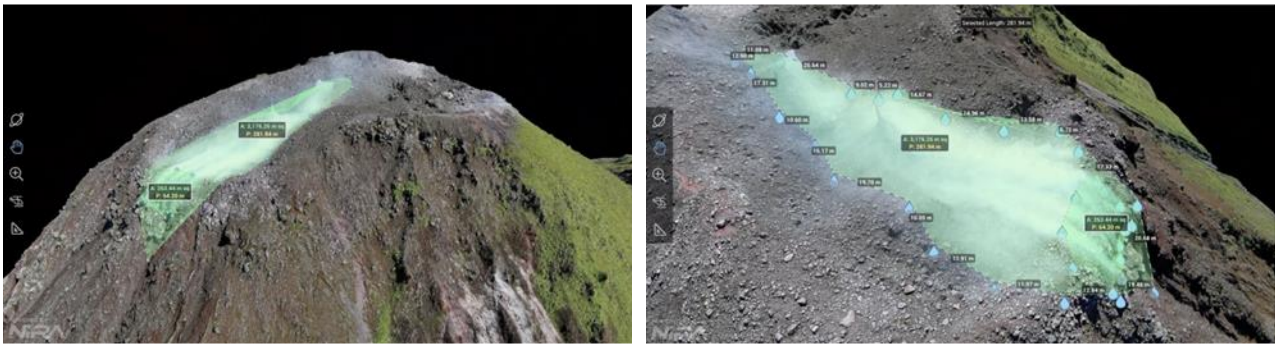

Figure 140 & 141. Nra app Measurements of Fumarole at Arenal Summit.

Explosive volcanic eruption cycles like the Arenal 1968 start to that activity have frequently been studied and observed for their effect on climatic conditions, and impacts the eruptions have on the atmosphere. Volcanic eruptions have significant impact on the climate and atmospheric results or outcomes fluctuate depending on the type of eruption. Recent advancements in portable technology especially drones and they are associated payloads have made monitoring volcanoes for climatic effects much simpler. Combined with satellite measurements and the enhanced fieldwork through advancements in portable technology our ability to quantify small magnitude volcanic eruptions. These improved methods show how significant volcanic eruptions are changing the climate and also a how why monitoring volcanic emissions is so important [7].

Figure 142. Summit of Arenal Volcano September 2022.

The Sniffer Mapper software used with the Sniffer4D units can upload pictures with geographic coordinate information. Since the geographic information is the GPS coordinates from where the picture is taken from this can improve the visualization of volcanic gas distribution.

Continued improvements are expected in the availability and usability of software used to create DSM. A significant UAS application for modeling volcanic structures and sharing the models via the internet. These technologies continue to improve exponentially with improvements to UAS hardware and software. Simplified user interface with the UAS system and remote control. These UAS capabilities expand researchers' ability to gather data in the field. Through our international collaboration we climbed Arenal and monitored the environment and degassing to get a better understanding of how Arenal impacts the climate in Costa Rica. Our collaboration and field work gathered sufficient data to generate two digital models of the Arenal summit, and the Sniffer 4D data allowed us to get a better idea of the level of degassing [7].

Figure 143 & 144. Crater D and Active Crater C of the Arenal Volcano Two Extremely Different Environments.

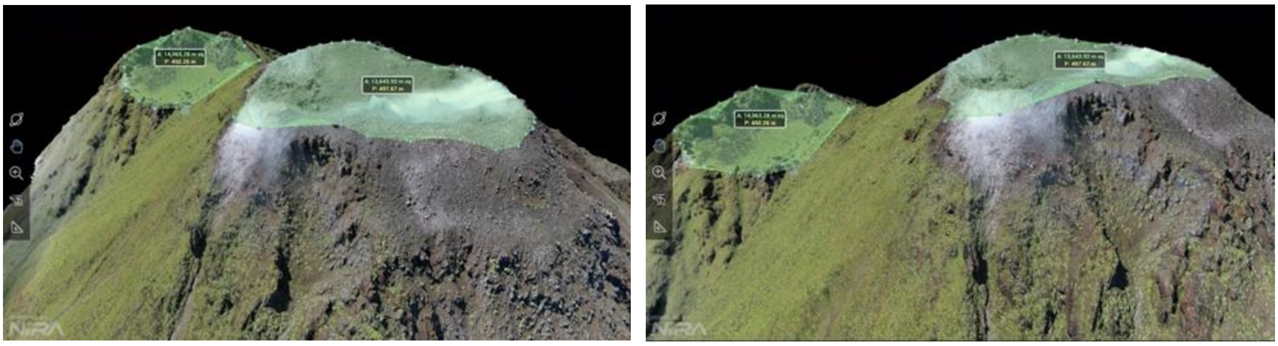

Figure 145 & 146. Nira 3-D Model of Crater D & C Radius Measurement.

Volcanoes are the greatest natural cause of climate change on Earth, monitoring they are effects on the atmosphere is vital to understanding how the climate will react to an influence such as consistent volcanic emissions for example. Portable gas detection devices like the Sniffer4D are helping researchers measure emissions of volcanic degassing in remote extremely difficult to access locations such as the actice crater C of the Arenal volcano. By monitoring and tracking SO_2 in volcanic craters, data collected can be used in sulfate aerasol estimations which are important because these aresols are responsible for scattering solar radiation and preventing it from reaching the Earth's surface. It this type of aerasol that is responsible for climate fluctuations. Global Space Based Stratopheric Aerasol Climatology (GLoSSAC) has constructed a continuous record of stratospheric aerasol particles from 1979 to the present. Active volcanic degassing has significant long term implications on stratospheric aerasol particle concentrations and Earth's climate. This shows the importance of having a volcanic degassing monitoring program [7].

The use of aerial photogrammetry assisted by drone in the field of morphological monitoring of volcanoes is an emerging technology that allows geoscientists to acquire more accurate spatial information.

The exploitation of derivative products, in particular orthophotos and digital models describing the forms of the land and the changes, makes it possible to have and identify the different features that may appear in these natural forms.

Differences and changes in topography can thus be determined using the volume differences between two separate states conducted a study based on aerial photogrammetry more particularly using UAV data to investigate the various changes of Mount Agung in Indonesia during the highest volcanic activity [8-9].

Researchers investigated the use of high-resolution UAV data for the generation of three-dimensional point clouds for the monitoring of the Stromboli volcano and emphasized the advantages of aerial photogrammetry for the geomorphological monitoring of these natural areas [10].

Figure 147. Summit of Arenal Volcano September 2022.

4. Discussion

Fixed wing UAS are ideal for photogrammetry around volcanoes because they are specifically designed for very topographically dynamic environment such as a crater rim which can easily crack and erode. In the past entire sections have been pulverized, big blocks can be ejected, and a lava flow can emplace. Also, ash can deposit and create a layer of several centimeters up to potentially meters. Quantifying these changes and estimating and tracking volume differences for instance requires the frequent generation of digital elevation models, and the easiest way to obtain that product is doing UAS orthophotogrammetry.

However, to cover a large surface, tetra, hexa or octocopters are very limited by their speed, autonomy, and range of action. Limitations exist in battery power and the actual design of the UAS. Fixed wing drones are more efficient for this type of operation. Also, a volcanic environment can be turbulent and fixed wings UAV are usually more stable and faster to get out of an area of complicated atmospheric dynamics.

However, it's essential to take into consideration that fixed wing UAS are limited by the launching and landing requirements: they usually need an open flat soft landing area which is not common on the flank or the rim of a volcano crater. For all the reasons mentioned, a fixed wing UAS with vertical take-off and landing would be the best tool.

In Costa Rica, ideal places to test such a UAS would be; Poás volcano has the volcano is showing frequent topographic changes and has a mirador ideal for vertical taking-off and landing. Turrialba volcano is another candidate for the same reasons. Irazú volcano would third on the list because the mapping area is huge (the crater, the north flank and the west side where large landslides are occurring). The large presence of antennas makes non vertical take-off and landing a challenge. Eventually Rincón de la Vieja volcano but the take-off/landing spot could be up to 5 km distant from the crater and >1000 m gain of elevation making the flight mission planning somewhat more complex.

Future advancement in fixed wing UAS in mapping and modeling is expected; including the crossover potential of simultaneously monitoring for volcanic gases and atmospheric conditions in volcanic environments. These improvements can be expected with the advancement of UAS companies such as DJI, Autel Robotics and Soarability who manufactures the Sniffer4D. The Sniffer4D works well on Non-DJI and fixed wing drones, the integration process is simple; the integration of the Sniffer4D has to meet the following criteria:

1. The flight platform needs to have sufficient space for integration.
2. The flight platform needs to have sufficient payload capacity (>600g).
3. Try to place the main device above the propeller plane. This is because the airflow velocity above the propellers is much slower than that below the propellers. This minimizes the impact of downwash on the device and improves the reliability of the data collected.
4. Place the main device outside the cabin for easy access to the external air.
5. The front of the main device or air inlet must be aligned with the moving direction of the flight platform.
6. The device should not cover or interfere with the GPS and compass of the flight platform.
7. The GPS module of the device should not be covered or interfered.
8. All cables of the device must be out of the working radius of the propellers.
9. The power supply from the flight platform must meet the requirements of the device. Do not connect the Sniffer4D device to the power battery of the flight platform directly. A voltage regulator module should always be used (except for smart batteries) to prevent the instantaneous high voltage during plugging and unplugging from damaging the device.
10. For fixed-wing flight platforms, the device can be placed in the cabin. Tubes should be used to intake external air and to exhaust the air out. It's important to directly consult the UAS manufacturer for all required information. Soarability once integrated a Sniffer4D with a fixed wing CW-15, where you can see the pictures below for reference. The fixed wing drone is from JO UAV and the mode number is CW-15.

Figure 148 & 149 - Sniffer4D Being Integrated to Fixed Wing UAS Soarability.

5. Conclusion

The Sniffer4D and SnifferV allowed us to collect gas emission data at the Arenal summit sufficient to show the spatial distribution of the gas concentration. Three different fumarolic fields can be geographically isolated: southwest, east and northeast. The maximum temperature was measured in the northeast field with a minimum of 184°C, but it was not easy to take good measurements on any of these fields because the gas emission is not clearly channelized and more diffuse in a rocky terrain. The wind direction on the day we measured emissions was toward the northeast.

We observe coherence between the distribution of the CO_2, SO_2 and H_2S gas concentration anomalies, and another good coherence for the HCl and HF distribution of the concentration anomalies. The maximum values of CO_2 detected by the SnifferV are greater at Arenal than at Turrialba, but lower for SO_2 and H_2S. The range of values for HCl and HF, and the very homogeneous distribution of their concentration suggest that there is hardly any emission of those gases if any.

A preliminary study of gas ratio using RatioCalc_3 shows that 2 families of CO_2/SO_2 ratios can be determined with one being a high value ratio and the other a low value ratio. Geographically, those 2 families correspond to 2 different sites: the low value ratio is found in the southwest fumarolic field, and the high value ratio is found in the east fumarolic field. This observation will need to be confirmed after proper processing using RatioCalc_3. 2 families may be identified from gas ratio. This suggests the possibility of 2 different sources of degassing: one with a hydrothermal component, the other not, and eventually deeper. A correct processing is required before any further analysis and interpretation.

Drones do have AGL Above Ground Level limitations. The AGL altitude is calculated from the launch point or home GPS location, UAS can only go a certain distance above this home point altitude measurement. Autel EVO Lite + drone have an 800 meter maximum operational ceiling. DJI drones have a 500 meter operation ceiling making fixed wing drones the ideal solution for flight missions requiring higher altitudes for their study. Many times volcanic peaks are above this altitude and therefore fixed wing drones can be the ideal solution for these types of volcanic topographical and emission mapping flight missions.

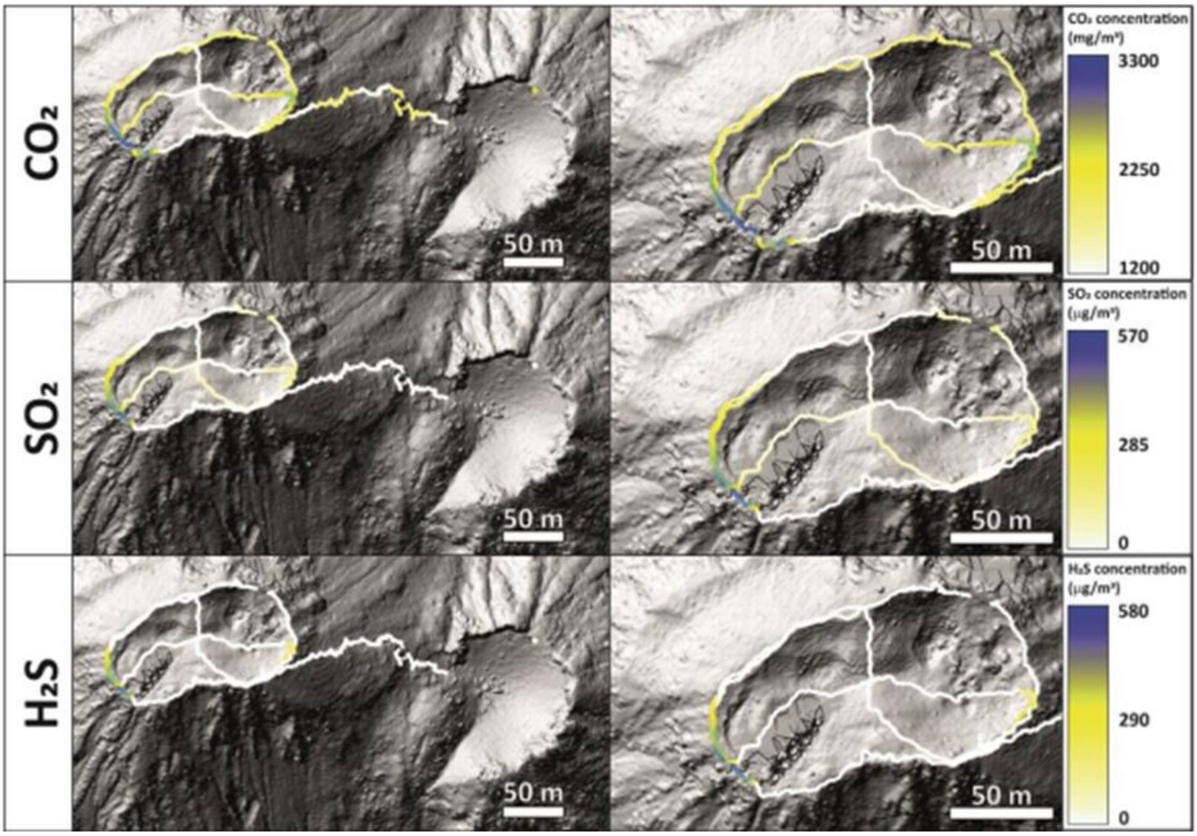

Figure 150. Spacial Distribution of Gas Concentrations at Arenal Summit.

Adding the Sniffer4D as a payload integrated onto a fixed wing drone with thermal imaging capabilities will be an ideal solution for volcanic environments as we could generate thermal DSM seeking and showing where any potential thermal anomalies exist and with the onboard Sniffer4D V2 devices we would also be able to track and log any potential volcanic emissions and gas plume during the flight.

Fixed wing drones are much bigger compared to the quad copter drone systems, fixed wing drones also covers larger areas and have more flight time per battery. Modeling specialty UAS are the DJI Matrice 300 RTK but with a 500 meter maximum operational ceiling there are still limitations. The 3-D glacier model of Solheimajokull and the lava flow at the Fagradalsfjall volcano were modeled with high resolution images captured using a fixed wing UX11 drone.

Reality Capture and Nira are ideal software applications that generate fast and accurate 3-D models for the most economical price per model. Using these two software programs is new to the UAS sector and offering geologists and volcanologists' new capabilities to their UAS research initiatives. These software systems are simple to use and allow for image visualization and the ability to quickly share the map or model. With this system can show volcanic emissions as a static "plate" but it can be challenging to reconstruct the gas plume itself. Ortho-photogrammetry is a remarkable tool, it's quite simple to learn and very useful in the fields of geology and volcanology. Researchers have frequently uses Pix4D in the past, but there are visualization and sharing limitations with the Pix4D software platform.

The processing of high resolution digital images obtained by drones have been found to be one of the most valuable UAS applications for geosciences and volcanology. By processing these images and stitching together accurate 3-D models showing digitally the topography and elivation of the area these models have allowed information to be viewed and shared with a larger audience in the scientific community. These UAS applications allowed researchers to map the 1992 lave field which showed the value of UAS in volcanic enviroments.

Creating DSM and DEM of volcanic structures will require a skilled remote pilot and recognition of each flight mission being a different and unique environment with its own challanges. Therefore, fluctuations will occur and remote pilot will have to be flexible in the amount of flight time required, number of flights, flight altitude, number of images required ect.

Our findings from the September 2022 Arenal climb were in agreement with the references articles and scientific publications previously completed. Our findings concerning UAS in volcanic monitoring are consistent with several previous research and fieldwork campaigns. UAS are quickly being integrated with specialized sensors for the enhancement of volcanic fieldwork and becoming an essential tool for volcanic surveillance.

Through enhancing fieldwork capabilities and improving research potential UAS have become a favorite for students and professors as well as fieldwork assistants. The generation of DSM and DEM has become one of the most valued UAS applications for geoscience fieldwork.

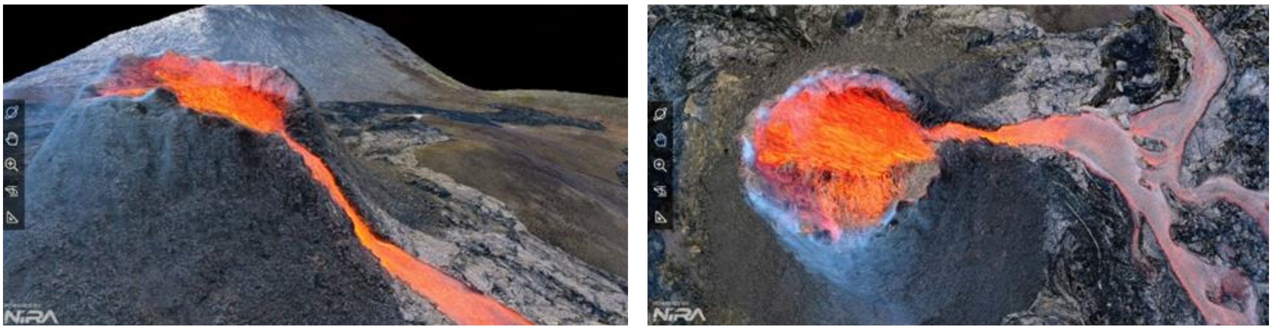

Figure 151 & 152. High Resolution 3D Model of the Fagradalsfjall Volcano in Iceland.

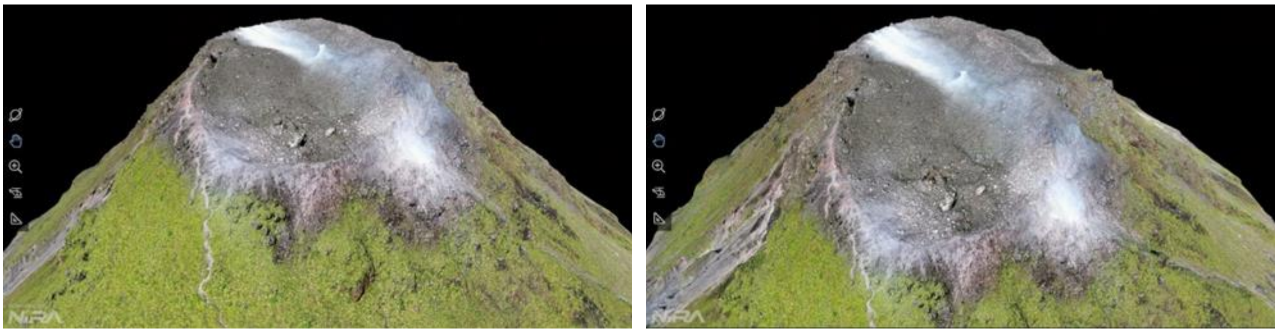

Figure 153 & 154. High Resolution 3D Model of the Arenal Volcano Summit Crater C in Costa Rica September 2022.

Figure 155 & 156. UAS Images of the Arenal Volcano Summit Crater C in Costa Rica September 2022.

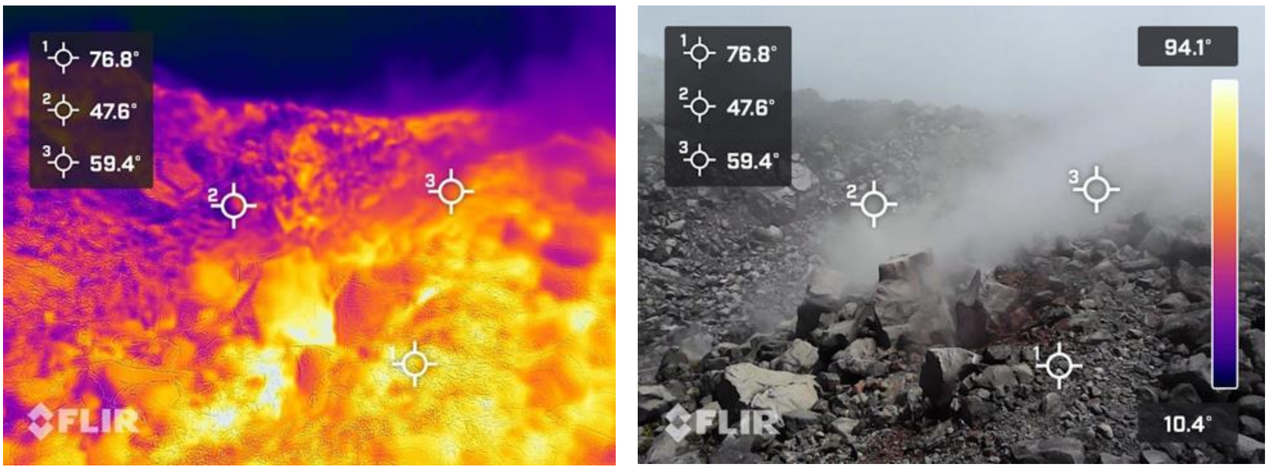

Figure 157 & 158. FLIR One Pro Thermal Images of Active Crater C of the Arenal Volcano.

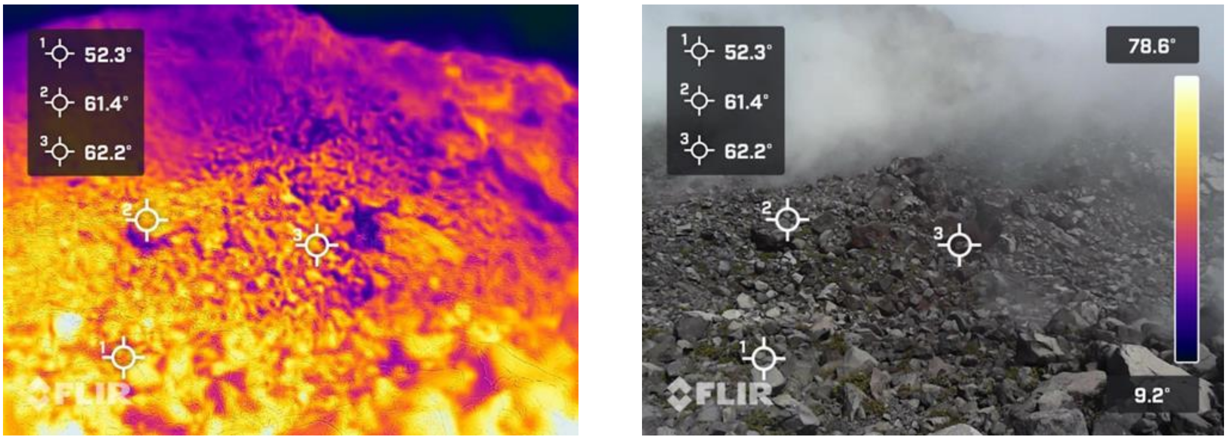

Figure 159 & 160. FLIR One Pro Thermal Images of Active Crater C of the Arenal Volcano.

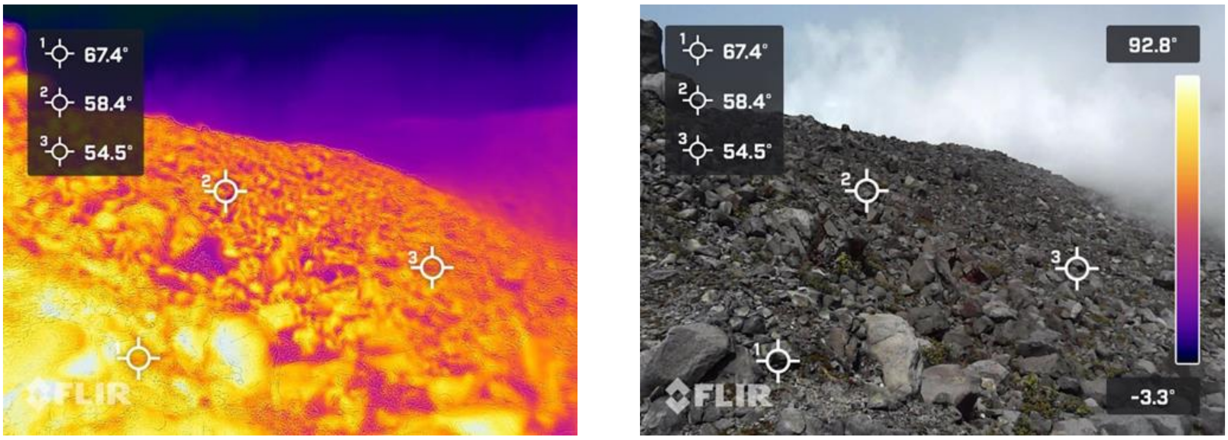

Figure 161 & 162. FLIR One Pro Thermal Images of Active Crater C of the Arenal Volcano.

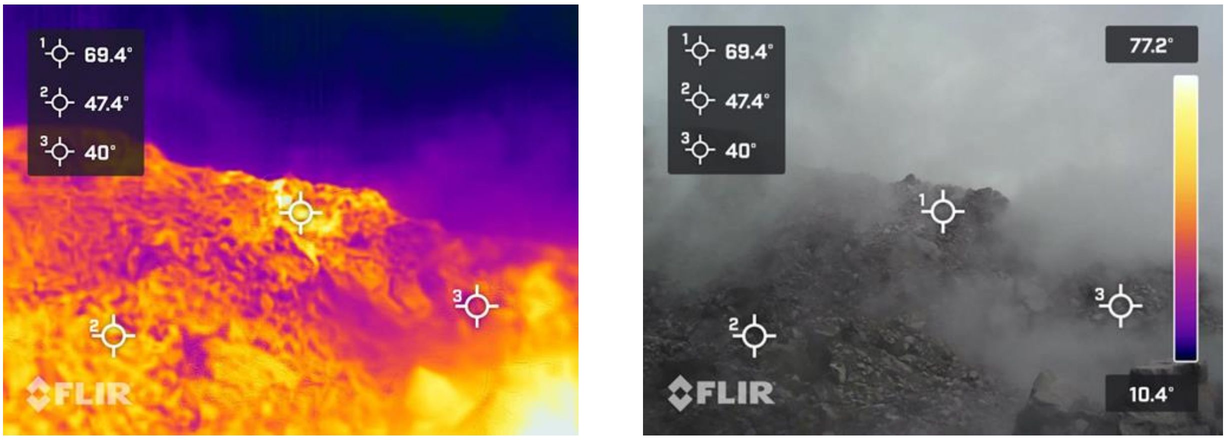

Figure 163 & 164. FLIR One Pro Thermal Images of Active Crater C of the Arenal Volcano.

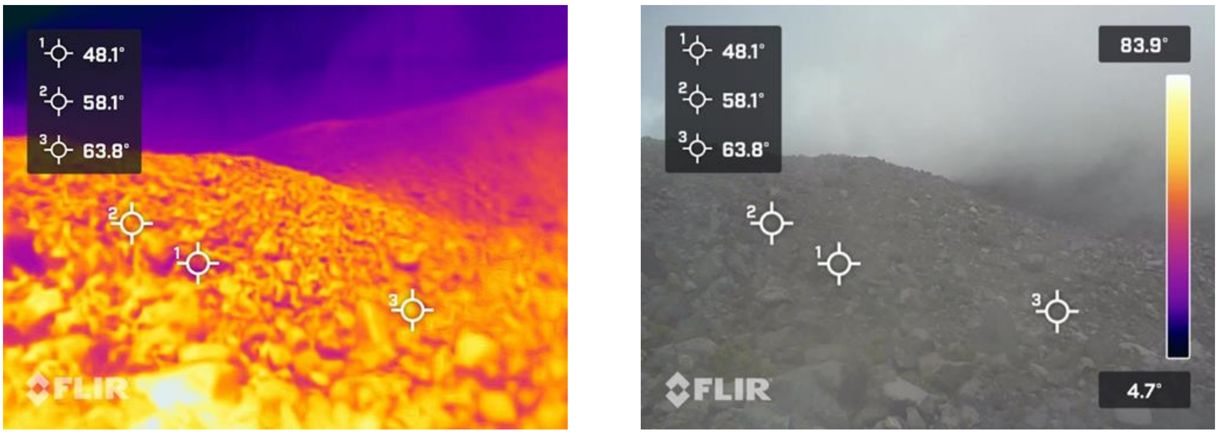

Figure 165 & 166. FLIR One Pro Thermal Images of Active Crater C of the Arenal Volcano.

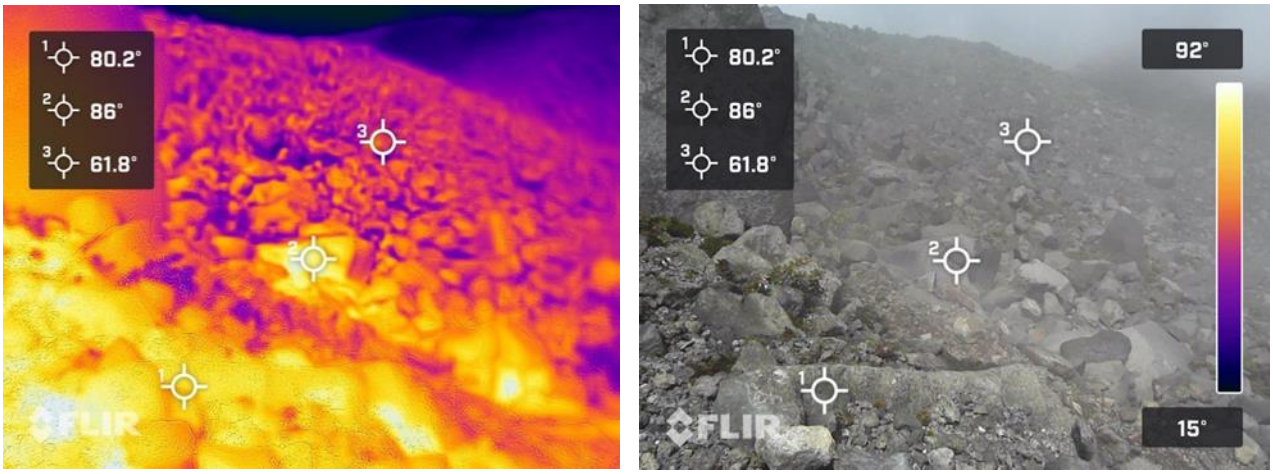

Figure 167 & 168. FLIR One Pro Thermal Images of Active Crater C of the Arenal Volcano.

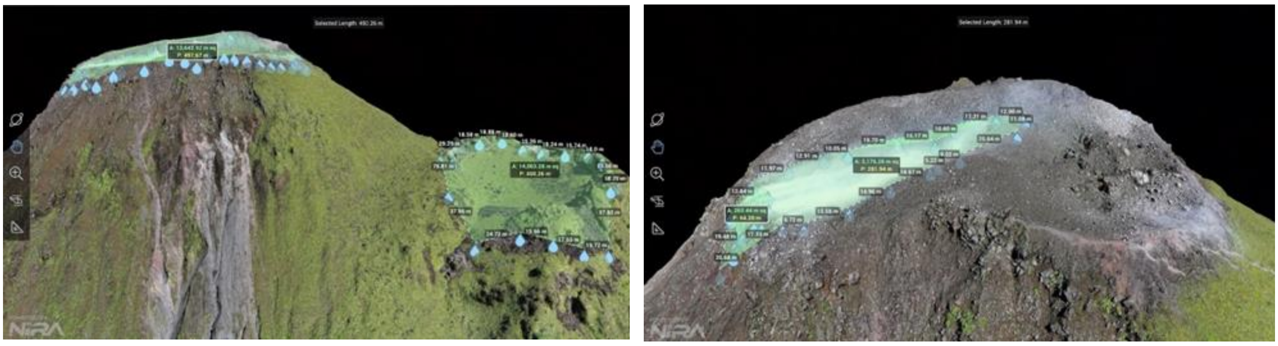

Figure 169 & 170. Nira app Measurement Applications at Arenal Volcano.

Funding

This research received no external funding.

Author contributions

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

Conflicts of interest

The authors declare no conflicts of interest.

References

1. Borgia, A., Poore, C., Carr, M. J., Melson, W. G., & Alvarado, G. E. (1988). Structural, stratigraphic, and petrologic aspects of the Arenal-Chato volcanic system, Costa Rica: evolution of a young stratovolcanic complex. Bulletin of Volcanology, 50, 86-105. https://doi.org/10.1007/BF01275171
2. Hofton, M. A., Malavassi, E., & Blair, J. B. (2006). Quantifying recent pyroclastic and lava flows at Arenal Volcano, Costa Rica, using medium-footprint lidar. Geophysical Research Letters, 33(21). https://doi.org/10.1029/2006GL027822
3. Cole, P. D., Fernandez, E., Duarte, E., & Duncan, A. M. (2005). Explosive activity and generation mechanisms of pyroclastic flows at Arenal volcano, Costa Rica between 1987 and 2001. Bulletin of Volcanology, 67, 695-716. https://doi.org/10.1007/s00445-004-0402-6
4. López, D. L., Bundschuh, J., Soto, G. J., Fernández, J. F., & Alvarado, G. E. (2006). Chemical evolution of thermal springs at Arenal Volcano, Costa Rica: Effect of volcanic activity, precipitation, seismic activity, and Earth

tides. Journal of volcanology and geothermal research, 157(1-3), 166-181. https://doi.org/10.1016/j.jvolgeores.2006.03.049
5. Williams-Jones, G., Stix, J., Heiligmann, M., Barquero, J., Fernandez, E., & Gonzalez, E. D. (2001). A model of degassing and seismicity at Arenal Volcano, Costa Rica. Journal of Volcanology and Geothermal Research, 108(1-4), 121-139. https://doi.org/10.1016/S0377-0273(00)00281-X
6. Granados-Bolaños, S., Quesada-Román, A., & Alvarado, G. E. (2021). Low-cost UAV applications in dynamic tropical volcanic landforms. Journal of Volcanology and Geothermal Research, 410, 107143. https://doi.org/10.1016/j.jvolgeores.2020.107143
7. Marshall, L. R., Maters, E. C., Schmidt, A., Timmreck, C., Robock, A., & Toohey, M. (2022). Volcanic effects on climate: recent advances and future avenues. Bulletin of Volcanology, 84(5), 54. https://doi.org/10.1007/s00445-022-01559-3
8. Fedele, A., Somma, R., Troise, C., Holmberg, K., De Natale, G., & Matano, F. (2020). Time-lapse landform monitoring in the Pisciarelli (Campi Flegrei-Italy) fumarole field using UAV photogrammetry. Remote Sensing, 13(1), 118. https://doi.org/10.3390/rs13010118
9. Andaru, R., & Rau, J. Y. (2019). Lava dome changes detection at Agung mountain during high level of volcanic activity using UAV photogrammetry. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42, 173-179. https://doi.org/10.5194/isprs-archives-XLII-2-W13-173-2019
10. Gracchi, T., Tacconi Stefanelli, C., Rossi, G., Di Traglia, F., Nolesini, T., Tanteri, L., & Casagli, N. (2022). UAV-based multitemporal remote sensing surveys of volcano unstable flanks: a case study from stromboli. Remote Sensing, 14(10), 2489. https://doi.org/10.3390/rs14102489