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UAS Infrared Photogrammetry at the Poás Volcano Costa Rica; Digital Modeling of Volcanic Craters Used to Assist with Thermal Energy Release Estimations

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Abstract

Unmanned Aerial Systems frequently abbreviated UAS or drones are quickly emerging as an economical solution to compliment work in various sectors. UAS are being used successfully in analytical services, data collection and algorithm processing, advancements in modern aeronautical practices, data fusion, scientific synergy, UAS hardware solutions for information gathering, regulations for air space and requirements for remote pilots. Today drones are being successfully used in hazard assessment and making valued contributions to the scientific community such as the creation of the thermal 3-D digital model of the Poás Volcano National Park in Costa Rica. Drones were used in Costa Rica during the month of May of 2023 to assist Universidad Nacional with gathering data on the active crater and Laguna Caliente of the Poás Volcano National Park. The objective for using UAS at the summit of the volcano was to generate crater depth and other distance measurements, collect images used with georeferencing software to measure crater radius and estimating amounts of geological material in volume. UAS with IR sensors were used to monitor the dispersion of relative thermal energy release inside and around the active West Crater. The thermal energy release UAS survey was in cooperation with LAQAT-UNA Study of Volcanic Emissions and They´re Effects on the Local Communities." UAS were used to try to monitor the temperature of the fumaroles individually from within the active crater. Drones were also deployed to gather videography of the degassing state observed from the aerial perspective from within the active crater of the Poás Volcano. All remote flights were completed using the SINAC Special Use UAS Research Permit – SINAC-ACC-PI-LC-037-2021.

1. Introduction

When creating 3-D models with IR thermal images, each project and each individual objective is different and will require certain flight and imaging customization. Each flight will vary according to the mission objectives such as area covered, complexity of topography and number of images required. Each time a 3-D model is created, first the remote pilot must decide which parameters for data collection need to be set to the remote control and executed during the flight. Each mission will have different parameters based on the 3-D model requirements. Certain situations make the remote pilot decide to take the manual flight route such as cases in extreme environments when slow movement or complete stopping is required to capture a clean sharp thermal image with minimum blurring for example. Autonomous flights don't consider passing clouds at high altitudes such as the summit of the Poás volcano, and due to certain unforeseen atmospheric conditions, that may arise the manual flight option was chosen to optimize our efforts. When conducting IR thermal photogrammetry flight missions in extreme environments manual flights are recommended to retain full control and maintain complete focus for the remote pilot.

The Poás volcano is about 35 kilometers northwest of the Central Valley where the majority of the population lives in Costa Rica, and it is also the location of the Capital City San José. The crater lake at the Poás Volcano is extremely hot, hyper-acidic, has concentrations of sulfur particles and colloidal particles. The consistent changes in morphology provided a unique opportunity for a UAS photogrammetry flight to document and visualize the geological feature for May of 2023.

2. Methods

Several drones were used at the summit including a DJI Matrice-600 Pro, DJI Mavic Mini 2, DJI Mavic 3 Thermal and an Evo Lite + UAS from Autel Robotics. We used these UAS for photogrammetry first as it was the most important application. 90° camera view with a straight down orientation was used and the flights were flown manually. Using the DJI Thermal Analysis Tool 3.0 we were able to use the thermal images as actual valuable data sets for monitoring the active crater of Turrialba. There was an 80% front and back overlap and a 60% side overlap for the data set collected.

When creating digital models in thermal it's particularly important to take care of and increase the standard overlap and use an 80% overlap minimum for thermal images for the images to be correctly reconstructed into a digital 3-D model. We also stopped the drone to take the images for increased overall quality, significant reduction in blurring and increased sharpness which greatly contributed to the resolution of the digital model. This method did increase the overall flight time for the mission yet increased our chances of completing the mission successfully the first time. To optimize resources and time in the field we collected both the RGB and IR data sets simultaneously during one single UAS photogrammetry flight mission.

There are several data points that should be captured by the UAS for the reconstruction of a georeferenced digital model of an active volcano crater. Normally when using a drone in these complex environments that present certain risks and challenges associated with flying a drone for scientific data collection purposes the remote pilot will opt to gather as much data as possible. For example, when conducting the photogrammetry flights, it's essential to collect radiometric data.

We took caution with setting up the UAS and made certain each video and image was being recorded or photographed by both the Red, Green, Blue (RGB) and Infrared (IR) thermal sensor integrated into the Mavic 3 Thermal UAS. If possible, the remote pilot should try to save the radiometric data in both .JPEG and .TIFF files. For the accurate reconstruction of the topography, we used a 90° camera angle and pointed the camera straight down at the ground for the initial photogrammetry flight. The flight speed was kept at 10 MPH to make sure there was acceptable image quality and no blurring in the images for the most accurate reconstruction of the digital representation of the volcano. Depending on the UAS flight mission and photogrammetry objectives, first FCC calibration is set, then a temperature scale is chosen for the task. When conducting these flights, we also captured the GPS data which helps with the generation of the mesh model when the photos are stitched together. Our flight mission at the Poás Volcano National Park collected relative altitude, relative humidity, ambient atmospheric temperature, the images were time stamped, and all of the data was used collectively for the digital visualization of this extreme environment. The GPS data was also used for the georeferencing and distance measurements in the digital platform Nira which was used for the visualization of the volcano crater.

When flying UAS missions in these complex environments the situation can change quickly, therefore we remained open to improvising on certain aspects associated with the flight so that the actual UAS flight mission to gather the data was done properly during the windows of opportunity presented. When creating the flight plan the remote control turned on, and from the top the drop-down option offers Wi-Fi connection options, the remote controller was connected to Wi-Fi so the Google Earth application could be opened. We used this to observe the regional topography and to plan the flight. We used the mapping options not waypoint. When flying the UAS photogrammetry mission for both RGB and IR data sets we stopped the UAS to take the best possible thermal images. This made the mission take longer; however the strategy assisted with increasing sharpness and significantly reduced blurring. The flight was flown manually to offer full control to the remote pilot in command and the overlap was set to 80% for the collection of the best data set which recreated the high-resolution digital model. For survey grade accuracy of 3cm UAS fly at an altitude of 25-50 meters requiring significantly more images, but for the volcanic region where the climatic conditions may have only allowed for 30 minutes flight time maximum due to wind, rain and visibility complications we flew at 90 meters to reduce the number of images required and reduce the UAS flight time in the air. This strategy also allowed the data set to be processed quicker, allowing decision makers and researchers to observe it quickly.

Since the majority of UAS software programs assume the area is flat. No UAS software program takes topography into consideration seriously and therefore extra care is required to create a digital model of an active volcano crater where topography is an essential aspect to be taken into consideration. UAS can crash into crater walls and remote pilots can be distracted by clouds

reducing the drone's visibility or a rain shower starting up forcing the remote pilot to decide whether to continue the planned flight mission or return to home and start over again after the rain?

2.1 Manual Photogrammetry Flight for Extreme Atmospheric Conditions or Complex Environments

Some of the atmospheric conditions that posed a situation for us to overcome were the frequently passing clouds, the fluctuations in visibility and the periodically passing rain shower. Below we can see two images from the UAS photogrammetry flight mission which we were not able to complete due to the clouds passing by so frequently that we could not complete the flight mission as intended. The clouds block the visibility of certain sections of the ground in which case that particular image is not usable for the creation of the digital model. The clouds not only reduced visibility for the RGB images, but they also reduced the dependency we had in the thermal images and rendered them unable to be used also. Below we can see an example of the Mavic 3 Thermal UAS flight mission at the Poás volcano with clouds distorting the images.

There are many different software programs for photogrammetry such as Agrisoft, Pix4D, Drone Deploy, Autodesk ReCap, and many others. Additionally, there can be visualization platforms such as the Nira app which we used for the visualization and analysis of the geomorphology of the Poás volcano crater in May of 2023.

Figure 1. Geophysical Morphology Fluctuations at Poás Volcano

2.2 Autonomous Flight Planning

DJI recommends that when using the Mavic 3 Thermal to utilize the KML import feature in rural areas with slower Wi-Fi. When the Wi-Fi is poor the remote controller cannot efficiently load the Google Earth maps for pre-planning the UAS flight mission. For this reason, we choose to fly the photogrammetry mission at Poás manually.

When programming ortho-photogrammetry missions and using the autonomous flight options the DJI Pilot 2 app will support the best features for these types of missions. The app supports KML & KMZ files for importing flight plans for mission planning. There is no requirement for storage paths. To import files, select the flight route, tap KMZ import, select directory, internal storage, SD card, and find the KML & KMZ files to be uploaded for the preprogramed UAS flight path.

When a KML file is generated with a polygon shape for the flight path, the remote pilot can select either "mapping" or "oblique." If a KML file with a preplanned path in imported to the remote controller than the remote pilot should select "waypoint." There are three steps to complete the autonomous flight planning that need to be completed.

Open Google Earth on your computer browser. Click "projects" on the left and click "new project." Select "create KML file" and then locate the area of interest which in this case was the Poás volcano crater. Once the location is selected in Google Earth for the autonomous mapping mission it will be saved to the remote controller for future use.

Export the planned mission to the designated file folder or alternatively, create a new file folder, name it KML files to facilitate searching when importing files to the DJI Pilot drone application. Launch the DJI Pilot application and tap "Flight Mission." Select the KML file and import it directly to the remote controller via the DJI Pilot application. Select the mapping option in the application, and then find the KML file desirer for the autonomous drone flight.

2.3 Photogammetry for Environmental Science and Interpretation

Photogrammetry is the scientific application of obtaining accurate information in our case, geographical information from the ground. UAS imaging has contributed to the development of this application and the results have been exponential. As drones become more advanced and the price point falls, more results from UAS photogrammetry will be released. UAS are now being deployed by teams of scientific investigators and researchers who are using them in the most extreme environments to obtain data essential to the reconstruction of a digital three-dimensional framework of a complex geographical feature.

The active Poás volcano crater which holds the hyper-acidic lake frequently fluctuates in geochemistry and this can be observed with changing watercolor, lake shape and mineral composition along the lake shoreline. The active crater of the Poás Volcano National Park and crater lake named Laguna Caliente was the complex structure chosen for our UAS photogrammetry flight mission.

Any kind of hyper-acidic lake located inside an active volcano crater would represent an extreme environment for flying a drone system. These volcanic regions are very intricate climates with several interacting components. The crater lakes are very hot and often they actually release volcanic gases themselves. These degassing crater lakes serve as a clear representation of how the underground magmatic and hydrothermal systems of the volcano are in fact interacting with

Earth's atmosphere through the degassing.

2.4 Volcanic Degassing

The degassing and atmospheric pollution released from the Poás volcano are dispersed to the west via the trade winds, therefore the section of the National Park directly to the west of the active crater is commonly referred to as the direct impact zone. This area is grey and has no vegetation due to the SO_2 and aerosol dispersion as well as acid rain.

Figure 2. Volcanic Degassing at Poás Volcano

The Atmospheric Chemistry Laboratory of Universidad Nacional monitors the geochemistry of the lake water chemical composition because it can offer insights about the level of interaction between the lake and underground magmatic-hydrothermal system of the volcano. And just like tracking water chemistry to assist with volcanic surveillance of the volcano, the periodic photogrammetry UAS flight mission also offered useful data associated with the level of volcanic activity observed inside the active crater.

Laguna Caliente has previously been shown to have a connection to both the hydrothermal and shallow magmatic system of the Poás volcano. Any fluctuations in interactions between Laguna Caliente and the underground magmatic-hydrothermal system of the volcano create changes in water chemistry of the lake itself. The changes are visible to people through changes in geomorphology such as watercolor, water composition and mineral deposits on the lakeshore. [1]

Figure 3. Volcanic Degassing at Poás Volcano May 2023

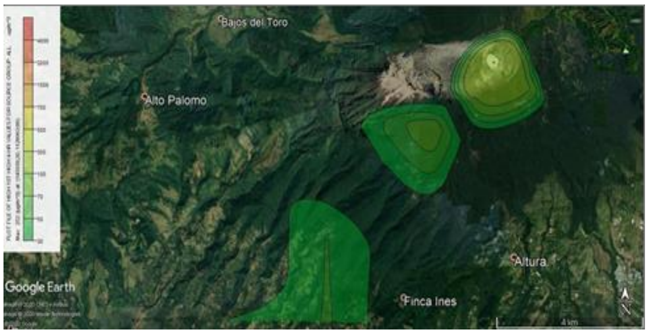

Figure 4. AERMOD Plot of the Atmospheric Pollution at Poás Volcano National Park, LAQAT-UNA.

Figure 5. AERMOD Plot of the Atmospheric Pollution at Poás Volcano National Park, LAQAT-UNA.

With consistent fluctuations in geomorphology in the active crater due to interactions between the hyper-acidic crater lake Laguna Caliente and the underground hydrothermal & magmatic systems of the Poás volcano the lake is consistently changing. The changes and level of volcanic activity made the Poás volcano crater one of the best areas for thermal photogrammetry in Costa Rica.

Therefore, in May of 2023 the Atmospheric Chemistry Laboratory LAQAT-UNA and the Volcanic and Seismic Observatory of Costa Rica OVSICORI-UNA decided to create a digital model in thermal of the entire active crater of the Poás volcano. The Mavic 3 Thermal was used due to the integrated thermal sensor built into the gimbal used for the cameras of the drone. Using the drone, we were able to monitor both the active crater and the direct impact zone.

During times of significant unrest and severe volcanic eruptions satellites are frequently used for observations and tracking thermal energy release. These satellites track the release of SO_2 into the atmosphere and can be used to gather data needed to map the dispersion of the volcanic plume. The issue is that these data sets are poor resolution relative to what can be collected with UAS which are significantly closer to the ground. Today UAS provides a new and innovative solution which is also economical for emerging nations with active volcanoes. This economical UAS data collection methodology is now being used to compliment volcanic observatories permanent monitoring stations by collecting additional scientific data associated with volcanic degassing and eruptions.

3. Results

Thermal imaging has previously been used to great effect in volcanic surveillance. Thermal sensors provide a way to track temperatures from safe distances away from degassing vents and dangerous levels of gases around fumaroles, crater lakes and other areas of interest. By integrating IR sensors and UAS together the system as a whole can be used as an effective risk management tool associated with volcanic observations from an aerial perspective which is now known to be a beneficial strategy for volcanic observations during times of eruptive events. This method has been helpful in hazard assessment, hazard mitigation and risk management. UAS is now an ideal system for the collection of radiometric data in areas which are dangerous and challenging to access.

Together in combination UAS and IR sensors are strategically useful for volcanology by offering a safe and effective way to obtain high resolution topographical data in both RGB and IR which can be used to quickly gather valuable data on active volcano craters. Together the UAS and IR sensor are able to obtain two data sets simultaneously optimizing field work efforts and providing a unique instrument which can be used to obtain certain synergy in the visualization of the data sets collected. [2]

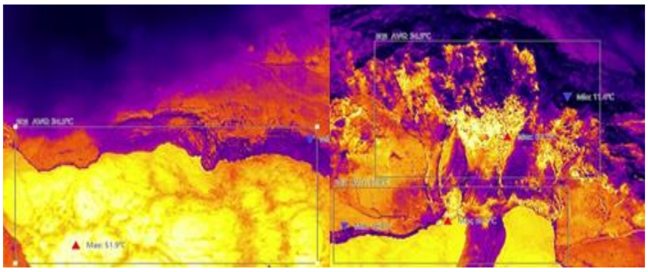

Figure 6. Aerial Infrared Images of Poás Volcano Crater

The Mavic 3 Thermal measured 51.9° for Laguna Caliente and 57.1°C for Fumarola Naranja the most active degassing vent inside the active crater of the Poás volcano. Several measurements were taken of each area every during the three fieldwork days that had clear weather and presented the opportunity to use the drone inside the active crater. May 2,5 and 26 were the days we used the UAS and the usable RGB and IR data sets were obtained on May 26th, 2023.

4. Discussion

Capturing clear visible and useful topographical data in these climatic conditions takes perfect atmospheric variables and complete dedication from the remote pilot and support team! The Poás volcano is an attractive National Park in Costa Rica and is also one of the most active volcanoes in Central America. Drones have previously been deployed at Poás for volcanic surveillance and have successfully assisted with DOAS measurements of SO_2 in the atmosphere deriving from the plume. Drones have carried payloads of electrochemical gas sensors such as the Sniffer4D. UAS have also contributed to the collection of water samples from the center of the crater lake Laguna Caliente. Drones were previously used for photogrammetry flight missions before, but to data this is the only thermal digital model of the Poás volcano we have seen created. [3]

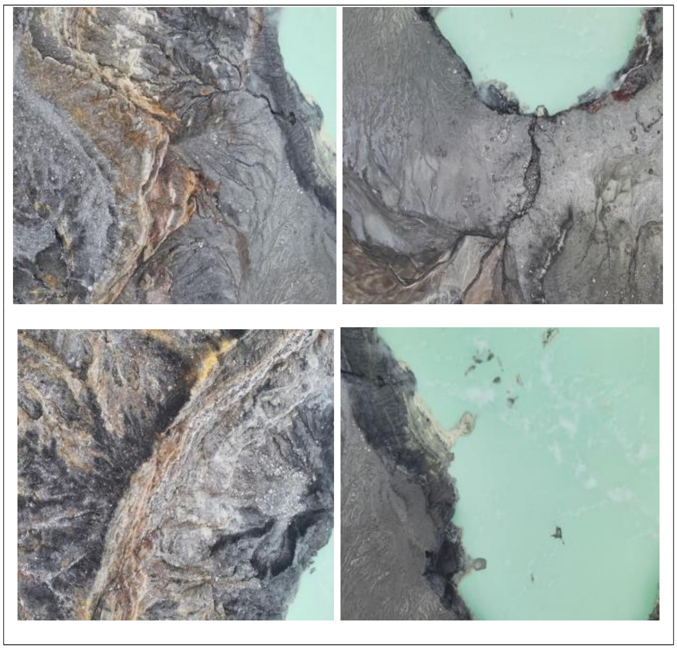

Figure 7. Aerial Images used for the Processing of the Digital Model of the Poás Volcano Costa Rica

Volcanic degassing will definitely have an effect on the thermal camera. Like the high-altitude corrosive atmosphere around the volcano created unforeseen variables which often complicate actually flying the drone; The degassing volcano plume will also create additional challenges associated with taking accurate temperature measurements with a thermal imaging camera. Volcanic gas like SO_2, inhalable particulate matter, high relative humidity and aerosol absorption all complicate collecting accurate radiometric data sets around degassing volcano craters. [4]

5. Conclusion

How is active crater and Laguna Caliente of the Poás volcano changing? This is a consistent and the scientific community has implemented a full-time monitoring program, still there was no publicly available digital model where the active crater could be completely visualized.

Previous scientific publications show how strong of an impact the combination of US and IR sensors can have when conducting photogrammetry missions focusing on active volcano craters as their targets. The Stromboli volcano in Italy was a previously selected study for this type of UAS application and the results were published outlined great advantages to using this method such as increased resolution, safe distance from the geohazard such as fumarolic field, and overall better-quality results at reduced prices compared to manned aircraft. Since many of the active volcanoes are located in regions that are considered emerging nations, the UAS method of volcanic surveillance is quickly gaining momentum in these countries. [5]

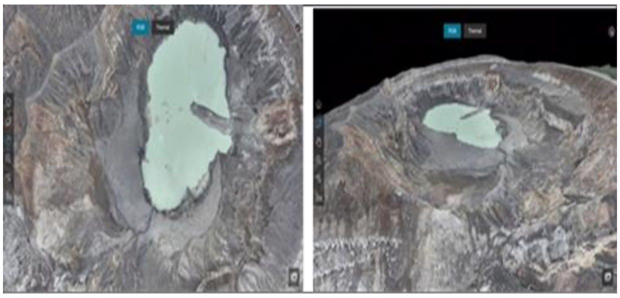

Figure 8. 3-D Digital Model of the Poás Volcano Costa Rica

By using the thermal sensors on the drone along with the RGB imaging system we were able to reconstruct the digital model of the Poás volcano where we can now take specific geographical measurements of various aspects from within the active crater such as fumarole size, shape, temperature! The UAS surveys conducted at the summit of the volcano provided useful information which was used for the overall understanding of the status of the activity for the month of May, and the stability of the active crater. The data collected offered the SINAC park rangers a platform to observe all aspects of the degassing fumaroles, Laguna Caliente and the geomorphology of the active Poás volcano crater.

Drones with thermal imaging sensors have been used in geothermal resource exploration as well, assisting with the creation of digital models of volcano craters, solar farms, industrial plants and power plants are all benefiting from this UAS application. The uses of UAS for IR digital models are facilitating several different sectors of economic importance in many countries around the world. The lightweight and portability are making the UAS with thermal sensor the ideal platform for data collection in extreme environments. [6]

Volcanic eruptions that eject volcanic bombs pose a significant threat to expensive permanently stationed scientific equipment as do the volcanic emissions and overall corrosive atmosphere around the degassing volcano crater. Drone solutions provide a different approach to collect data that is not required on a consistent basis as the drone can quickly enter the region of interest, collect the required data and return to the UAS home point. Volcanic eruptions, erosion from rainfall and cracking from earthquakes all pose a consistent risk to permanently stationed equipment around active volcano craters. UAS are starting to develop a method on using drones to bring the instruments into the area and leave with them to reduce depreciation of expensive scientific equipment. [7]

Although volcanic eruptions due not pose the most significant natural disaster threat they do serve as a perfect setting to understand and implement the developing UAS monitoring method so it can be established as a more permanent volcanic monitoring strategy in emerging nations. The

publication titled; "Remote Sensing of Natural Hazard-Related Disasters with Small Drones" showed that actually earthquake, floods and hurricanes were the most significant natural disasters and that UAS and remote pilots were contributing to the development of hazard mitigation and recovery after the natural disasters. [8]

One of the main priority objectives for the May 2023 fieldwork was to monitor the change of temperature at Fumarole Naranja with the Mavic 3 Thermal. By monitoring both the degassing and thermal energy release simultaneously additional insight can be obtained. The objective of gathering data to assist with the better understanding of the connection between the thermal energy release and the state of the degassing fumaroles was accomplished.

The digital model resulting from the UAS flights at the summit of the Poás volcano show how drones can be deployed to quickly collect multiple data sets simultaneously. The UAS flights in extreme environments shows how approaches can be made to achieve data synergy and all these methods from the UAS flight can be applied to other types of areas to assist with a variety of complex projects or different types of natural disasters.

In many case studies associated with large volcanic eruptions the satellite monitoring method of using the Landsat 8-OLI-TIRS is quite beneficial. Previous studied using this method on the Aso volcano in Japan have proven very successful. Since the publication these same researchers from the "Department of Earth Resource Engineering" are now developing new innovative UAS techniques and methods to compliment previous and ongoing research. These strategies of leveraging the various UAS and payloads currently available are now assisting their work on several volcanic areal all-around Japan. [9]

The World Organization for Volcanic Observatories is still developing the currently used UAS solutions. The emerging drone technology has already greatly contributed to the advancements in geosciences, and now with the integration of miniaturized instrumentation for various applications, drones can be used to transport useful tools into area of desired research and bring them back in reduced periods of time. These strategies are now contributing to the collective Global Volcano Monitoring of the WOVO. [10-16].

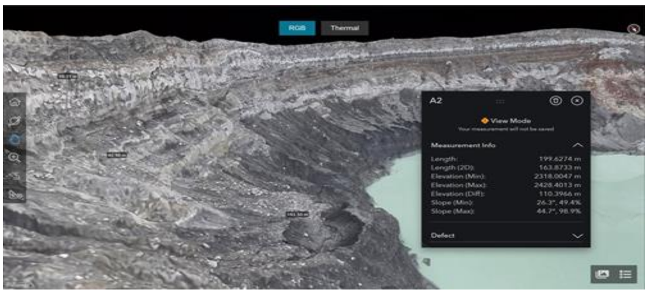

Figure 9. Depth Measurements from Active Crater of the Poás Volcano

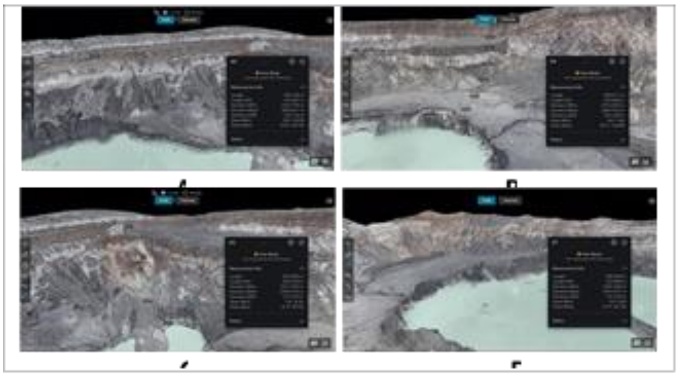

Figure 10. Multiparameter Geological Measurements from the Poás Volcano Crater

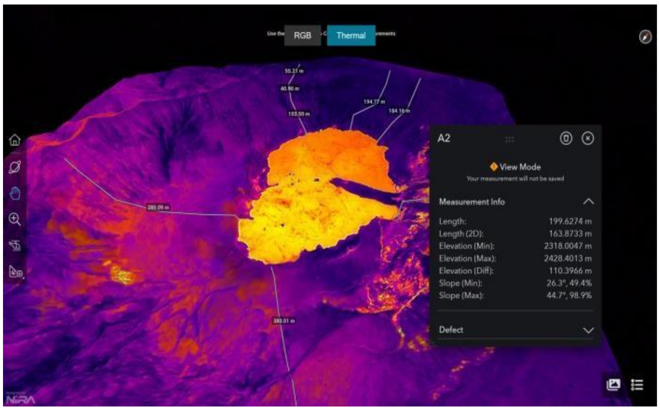

Figure 11. Infrared Thermal 3-D Model of the Poás Volcano Crater

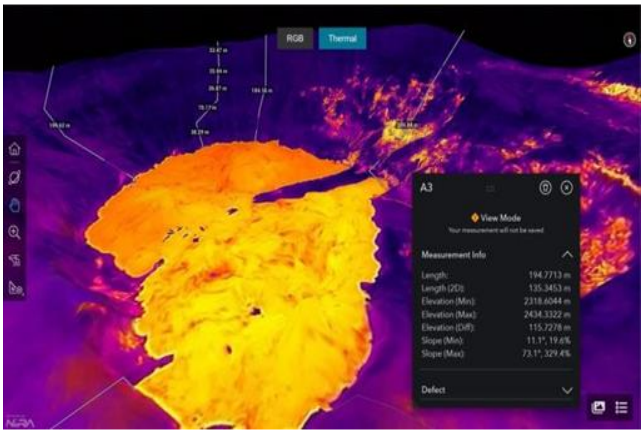

Figure 12. Infrared Thermal 3-D Model of the Poás Volcano Crater for Fumarole Degassing Identification

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Author contributions

Ian Godfrey: Photogrammetry flight planning and execution, processing of the 3-D digital model of the crater, **José Pablo Sibaja Brenes:** Atmospheric pollution data interpretation and the generation of AERMOD plots, **Geoffroy Avard**: Oversight of all activities in volcanic areas, safety guide on exclusive trails for national park site access, volcanic safety inside the park **María Martínez Cruz:** Collective data interpretation and communication of conclusive findings, **Khadija Meghraoui:** Geospatial analysis and data visualization interpretation

Conflicts of interest

The authors declare no conflicts of interest.

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