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

Evolution of the Main Crater, Irazú Volcano National Park, Costa Rica – Consumer Drones in professional research

Ian Godfrey*[1], 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, Maria.martinez.cruz@una.cr
[3]Unit of Geospatial Technologies for Smart Decision. Hassan II Institute of Agronomy and Veterinary Medicine, Morocco, k.meghraoui@iav.ac.ma

Cite this study: Godfrey, I., Avard, G., Brenes, J. P. S., Cruz, M. M., & Meghraoui, K. (2022). Evolution of the Main Crater, Irazú Volcano National Park, Costa Rica – Consumer Drones in professional research. Advanced UAV, 2 (2), 65-85

Keywords
Unmanned Aerial System
Remote Control
Volcanic Environment
Irazú Volcano
Costa Rica

Research Article
Received: 05.10.2022
Revised: 10.11.2022
Accepted: 18.11.2022
Published: 30.11.2022

Abstract

There has been significant cracking and erosion on the south crater wall of the Main Crater below the area where tourists gather to view the main feature of the park; The Main Crater. By deploying the EVO Lite+ drone system we will be able to document any increase in erosion or cracking within the Main Crater, we will search for areas subject to future rock falls within the Main Crater, the UAS observation strategy will also be innovative as it offers a new and unique perspective of the volcano summit and interior structures of the Main Crater. By using the Lite+ system we will check for lake water levels, areas of mineralization or crystallization, and any potential vents degassing volcanic emissions, we will look for subaquatic fumaroles releasing gases via bubbles and try to film them for frequency and size documentation. The qualitative analysis of the Irazú Volcano Main Crater will show changes in morphology and illustrate how consumer drones can be used for professional research.

1. Introduction

Previous researchers use small single engine aircraft to observe volcanoes with thermal cameras visible only through a glass window in the bottom of the aircraft. Drones have since revolutionized this application as they can be flown so much closer to the volcanic caldera and can use specialized equipment such as thermal IR imaging cameras, LiDar 3-D mapping and gas detection equipment. Elevation of topography is very important UAS application in volcanic environments especially after eruptions to visualize geological changes and estimate the amount of ejected material after eruptions. UAS have played a significant role in helping geologists obtain this data.

The main field work objective was to launch the Autel Lite Drone into the Main Crater of the Irazú Volcano National Park in Costa Rica. We tried to document everything down to crater floor with detailed photos and video not obtainable from ground perspectives. Areas such as the crater lake. We wanted to observe water levels, any potential bubbles, rockslides, the Diego de la Haya crater and any potential cracking! We wanted to obtain videography of Diego de la Haya crater walls especially the cracking section and south crater wall. Over flights were planned from West to East passing all 5 craters, return flights designed to film the same thing gather videography from the aerial perspective.

Figure 1 & 2. Main Crater of the Irazú Volcano National Park 2020 & Autel Lite + (Red) Operational Flight Missions Plan for inside the Main Crater of the Irazú Volcano

2. Material and Method

2.1. 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.

2.2. 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. The full view of the very wide active crater of the Irazú Volcano was photographed with the 1-inch CMOS sensor and can be seen from the UAS perspective in clear detail below.

Figure 3. Active Main Crater of the Irazú Volcano National Park Costa Rica September 2022

Figure 4 & 5. Autel Lite + Drone over the Main Crater of the Irazú Volcano National Park

2.3. 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.

2.4. Flight Mission Planning

Several flight missions were planned for the Crater Sector of the Irazú Volcano National Park. By using Google Earth UAV pilots can check terrain and elevation differences for their planned drone flight path. By using this preflight strategy risks are reduced because remote pilots can check distances, altitudes, potential flight path obstructions and get a good idea of the topography of the area where flights are being planned.

Figure 6 & 7. Autel Lite + (Red) Operational Flight Missions Crater Sector of the Irazú Volcano

Figure 8 & 9. Autel Lite + (Red) Operational Flight Missions Altitude and Terrain Check Diego Crater Irazú Volcano

2.5. Evolution of the Irazú Volcano National Park

Costa Rica has a complex underlying tectonic framework. This is a direct result of the interaction between the Cocos, Caribbean, Nazca plates interacting along with the Panama block. The interaction between these four microplates creates the frequent earthquakes and volcanic activity in Costa Rica. The 2006 publication titled; "Recent volcanic history of Irazú volcano, Costa Rica: Alternation and mixing of two magma batches, and pervasive mixing," by Guillermo E. Alvarado resulted in several significant findings. Probably most importantly two distinct magma batches were identified. Methods such as seismological, magmatic and geological data were all combined for analysis which showed the presence of two small shallow magma chambers beneath the Main Crater at the Irazú volcano summit. Much of the northern volcano flank is not easily accessible and is completely covered be dense rain forests [1].

2.6. Using consumer drones in professional research

Using consumer drones in professional research was the main objective of this project and to show how they can be used for expanding scientific research. For the UAS flights the plan was to visit the Irazú Volcano National Park in Costa Rica with the Autel EVO Lite + UAS. The Irazú volcano last erupted in 1963 and continued eruptive behavior until 1965. At the Irazú volcano which is the highest volcano in Costa Rica, strong prevailing winds and gusts of various directions can create atmospheric conditions extremely complicated for remote pilots. The Autel Lite + drones were able to withstand 37 knots and were therefore strategically selected for this assignment.

In the national park system of Costa Rica special SINAC permitting is required to use drones on this land. "Estudio de las emisions volcanicas y su afectacion a la poblacion cercana." Permit # 112000166 for The Laboratory of Atmospheric Chemistry, Universidad Nacional LAQAT-UNA. The Autel EVO Lite + drones were used to document several aspects of the Main Crater of the Irazú volcano. Several features and detailed knowledge of these features collectively contribute to a greater understanding of the volcanic processes of these complex and dynamic systems.

Our UAS monitoring program began in January of 2020. We started using affordable consumer drones instead of enterprise drones in this research initiative due to the overall risk associated with flying UAS in volcanic environments. Images from our 2020 surveillance flights can be observed below. At the time of these flights there was a very light blue crater lake with a small island in the middle a bolder left from the 2019 rockfall and seiche.


Figures 10 & 11. Main Crater of the Irazú Volcano Main Crater January 2020


Figures 12 & 13. Main Crater of the Irazú Volcano National Park January 2020

The Autel EVO Lite + drone allowed us to get close detailed images and video from perspectives not obtainable from the main lookout observation point. In the past there were five open degassing vents on the crater floor only periodically visible when the crater lake was completely evaporated in (2013). We expected to observe this area and look for any potential bubbles with the detailed 6k video camera, but to our surprise on September 12th, 2022 on the day of our first visit, there was an extremely small lake more like a puddle and the crater lake was gone. The Cerro Alto Grande and the Río Toro Amarillo valley located in between the Irazú and Turrialba volcanoes was formed by erosion before the Diego de la Haya eruption activity. In the upper regions of the Diego de la Haya crater where observers can see the distinct difference in the two basaltic andesite lava flows. (1)

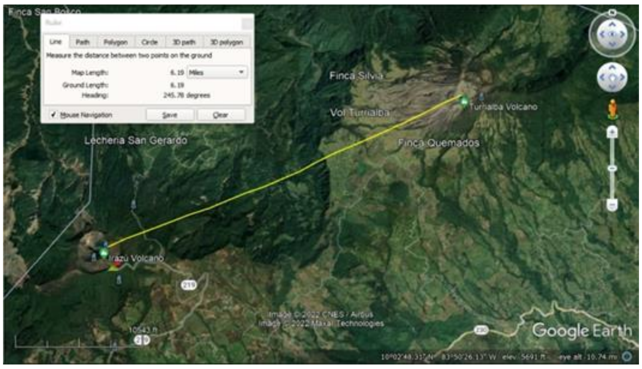

Figure 14 & 15. Google Earth Image - Distance Between Irazu and Turrialba

The volcanic front of Costa Rica lies parallel to the Mid Atlantic Trench and separates the Caribbean and Cocos tectonic plate. The volcanic front of Costa Rica and the Atirro-Río Sucio Fault directly intersects the Main Crater of the Irazú Volcano. In 1994 a partial collapse left a strange area below the Main Crater of the Irazú Volcano exposed, scientists found caves here and named them "Cueva de los Minerales" the newly discovered cave sectored allowed researchers an opportunity to better understand how the uplifting of volcanic gases combined with water seepage from the crater lake of the active Main Crater created hydrothermal interactions which created such a diverse collection of mineralogical deposits. This area has obvious hydrothermalism and significant CO_2 degassing from passive fumaroles located inside the caves [2].

3. Results

3.1. Main Crater Irazú Volcano, Crater Lake

In the research paper titled; "Extremely High Diversity of Sulfate Minerals in Caves of the Irazu Volcano (Costa Rica) Related to Crater Lake and Fumarolic Activity, by Andres Ulloa; The publication explains that since the eruptive activity seen from 1962-1965 there has been an intermittent volcanic lake inside of the active Main Crater of the Irazú Volcano. The lake remained in the crater from 1965 until 2013 when it evaporated and disappeared due to water seepage. The lake began the reformation process in 2017, studies showed that the temperature of the lake water fluctuated between 16-35°C and the water's pH also fluctuated as much as 3.0-5.85. One of the most obvious geomorphic fluctuations that consistently captures interest is the crater lake water color. Scientists have documented the water color of the Irazú volcano crater lake as red, blue, green, turquoise, and yellow water colors. [2].


Figure 16 & 17. Irazú Main Crater January 2020

The crater floor is a porous rocky and sandy environment, and due to the permeability on the crater floor large amounts of draining occur which contribute to the hydrothermal process creating the Cueva de los Minerales. This draining and periodic refilling due to rain fall in the region is a contributor to the frequently observed color fluctuations of the crater lake. The report explained that there were fumaroles documented on the floor of the Main Crater from 1998-2001, and that there is most likely a hydrothermal connection between the Main Crater of the Irazú Volcano and the Río Cucio volcanic hot springs on the northern flank of the Irazú volcano. (2)

Figure 18 & 19. Irazú Main Crater October 2017

Figure 20 & 21. Irazú Main Crater Febuary 2019

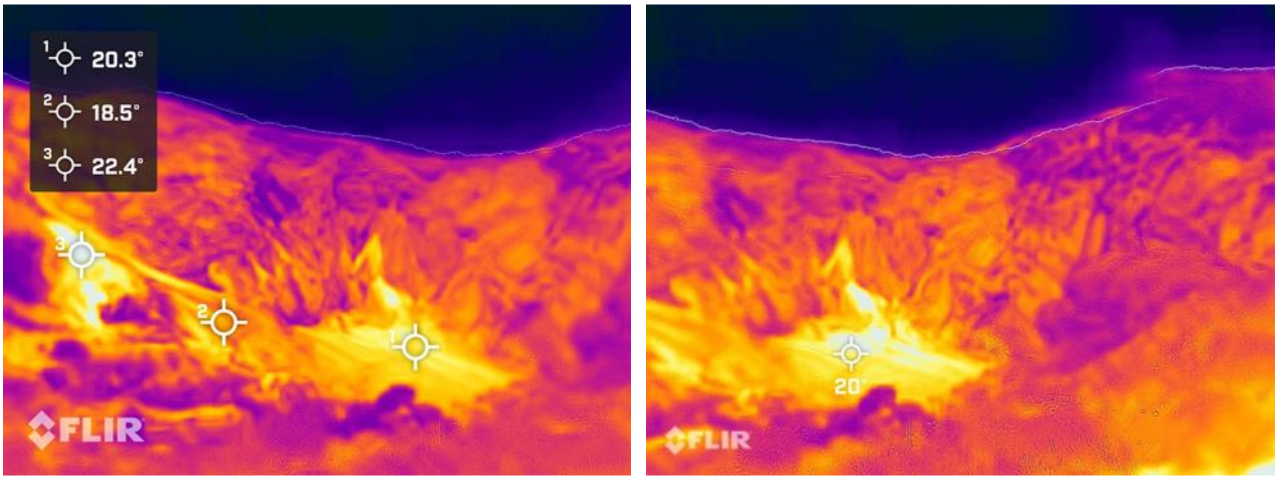

Figure 22 & 23. Thermal Images in Degrees Fahrenheit of the Irazú Volcano Main Crater

The thermal images of the Main Crater show no crater lake; therefore, we were able to take thermal images of the crater floor. The crater lake located inside the main crater of the Irazú volcano is part of a sophisticated hydrothermal system of the volcano which discharges liquids through several springs on the northern flank of Irazú. The spring is an example of how the hydrothermal system of the Irazú volcano interconnects various geophysical aspects of the Irazú Volcano. The hydrothermal system of the Irazú Volcano has various aspects like the crater lake, spring and fumarole which are all connected by the hydrothermal system of the volcano.

Figure 24 & 25. Río Sucio Río Caliente Volcanic Hot Spring of Irazú Volcano Analysis April 2022

Several aspects of the volcanic crater lake can offer insight into the level of degassing seen coming from the Main Crater of the Irazú Volcano, such as water levels and water color for example. The camera on the Autel Lite + was specifically selected to document the exact color of the crater lake water. The crater lake water color was a combination of interacting processes. For example, 1. colloidal particles, volcanic minerals defracting light, 2. algae a single celled nucleus-bearing aquatic photosynthetic organism, 3. gas bubbles and dissolved emissions in the water also contribute to the water color. Upon launching the UAS in September of 2022, there was no lake remaining.

Previous work on the Main Crater of the Irazú Volcano showed that gas anololies existed both within the Main Crater and on the northern flank of the Irazú Volcano. The has been degassing documented coming from the northern flank of the Irazú Volcano. This area where the caves are located is extremely steep and very difficult to acess, and therefore monitoring this region with a UAS becomes a prized application for the surveillance of the Irazú Volcano National Park [3].

Since 1994 the SINAC and OVSCORI-UNA have been watching Irazú closley, using UAS to periodically take images for 3-D Digitan Surface Models which you can watch on Youtube via the link below. After the disappearance of the crater lake in 2013 research of the Main Crater showed no increase of volcanic activity and studies concludes the disappearance was likely due to seepage rather than evaporation [3].

Figure 26 & 27. Floor of the Main Crater Irazú Volcano National Park September 2022

All of these aspects contribute to the water color of the crater lake. In addition, due to periodic eruptions and the continuous release of SO2 coming from the Turrialba volcano just 6.2 miles to the east of the Irazú volcano Main Crater, acidic rain periodically dispersed around the Irazú volcano. 4. Acid rain adds another variable which contributes to the color of the crater lake located inside the Main Crater of the Irazú volcano.

Enhanced oxidative conditions are a significant factor in this region due to the consistent release of volcanic emissions seen coming from the Turrialba volcano. There are several contributing factors that all play a part and have an effect on the water color of the majestic crater lake inside the active crater of the Irazú volcano.

For the first time since 2013 the Main Crater of the Irazú Volcano no longer has a crater lake. By deploying the Autel EVO Lite + drone we were able to use an affordable consumer drone for professional volcanic surveillance of an active crater. Several aspects were documented to precise detail using the zoom and high resolution 6k camera for videography. All rock falls were documented from the aerial perspective, along with the crater floor, plant vegetation inside the crater, cracking and the existence of potential waterfalls, were all recorded in high resolution and photographed for Volcanic and Seismic Observatory of Costa Rica OVSCORI-UNA and the Laboratory of Atmospheric Chemistry LAQAT-UNA Universidad Nacional.


Figure 27 & 28. Floor of the Main Crater Irazú Volcano National Park September 2022


Figure 28 & 29. Floor of the Main Crater Irazú Volcano National Park September 2022

3.2. Main Crater - Rock falls


Figure 30 & 31 - Rockfall formation left from the 2019 material release and resulting sieche September 2022

Inside the Main Crater there are three areas of significant rock fall which geologists and SINAC park rangers are consistently observing and monitoring. In May of 2019 heavy rain in the region and increased seismic activity deriving from the fault line located directly below the Main Crater of the Irazu Volcano both contributed to a massive rock fall on the west side of the Main Crater which fell off and created a seiche or a wave inside an enclosed body of water, and then deposited a significant amount of material into the lake which drastically changed the color of the crater lake.

In the publication; Study of Turquoise and Bright Sky Blue Appearing Freshwater Bodies for the International Journal of Geology, Earth & Enviromental Sciences the paper explains - "Suspended and dissolved particles influence the color of water. Turquoise and bright sky-blue appearing fresh water bodies are found in different parts of the world in different sets of environmental conditions. Glacial-fed lakes also appear turquoise, crater lakes also bear turquoise color and calcium carbonate rich water bodies also appear turquoise." [4].

The exotic light blue vibrant color of the crater lake located in the Main Crater of the Irazú Volcano is mainly due to the scattering of light in the blue and green wavelengths due to the presence of colloidal particles deriving from the volcanic sediment and rocks the rainwater interacts with before collecting in the summit crates of the Irazú Volcano National Park in Costa Rica. These particles become suspended in the crater lakes and can collect at the water's surface refracting the light in the blue and green wavelength particularly at the deepest part of the lake where more suspended particles can accumulate. Other factors do play a role in the color seen by observers such as temperature, pH levels, EC or electrical conductivity, total dissolved solids in the water body, density and the amount of total dissolved oxygen or O_2. pH fluctuations have been shown to have direct color changing results as the changes in pH induces the growth of these particles from 184nm to 566nm and therefore the light scattering occurs mostly in the blue region of the visible spectrum [4].

Figure 32 & 33. Irazú Volcano May 2019 after the seiche inside the Main Crater

Previously researchers conducting field work for the Volcanic and Seismic Observatory of Costa Rica OVSCORI-UNA and the Laboratory of Atmospheric Chemistry LAQAT-UNA Universidad Nacional documented the waterfall Río Celeste of the Tenorio Volcano complex and found that during the investigation researchers on a global scale found blue-green and exotic turquoise water bodies with correlation to active volcanic regions. Volcanic crater lakes with a wide variety of color exist in countries like Iceland, Japan and New Zealand all of which have active volcanoes. It was found that the crater lake water had aqueous colloidal silica particles which contributed to the light scattering of the natural sunlight. Both Rayleight scattering and Mie scattering of sunlight can occur from the presence of these aqueous colloidal silica particles. For example, the Yugama Crater Lake of Mount Shirane in Japan was studied and the analysis showed that the crater lake water color was a result of the water chemistry which was responsible for both Mie and Raylight scattering by colloidal sulfur particles. (5)

Figure 34 & 35. Main Crater of Irazú Volcano January 2020

Figure 36 & 37. Main Crater of Irazú Volcano January 2020


Figure 38 & 39. Main Crater of Irazú Volcano January 2020


Figure 40 & 41. Rockfall from the North Eastern edge of the crater rim September 2022


Figure 42 & 43. Rock Fall Area West End of Main Crater UAS Perspective September 2022


Figure 44 & 45. Rock Fall Area West End of Main Crater UAS Perspective September 2022

There are three areas of rock falls being monitored today which are located on the west, north-east and south-east of the main crater. By using the drone from the very center of the crater we were able to get a 360° view of not only the crater but the details of each individual rock fall as well. The results of these UAS flights will probable gain appreciation when the lake water begins to refill and it is no longer possible to view the crater floor.

The fault line intersecting the Main Crater of the Irazu volcano which is part of the volcanic front of Costa Rica is the Atirro-Río Sucio Fault that directly intersects the Main Crater of the Irazú Volcano. Any kind of seismic activity in the area can influence the rock falls inside the Main Crater. Heavy Thunderstorms passing by and increased rain fall will also contribute to the rock falls and any potential land slide within the Main Crater of the Irazú Volcano.

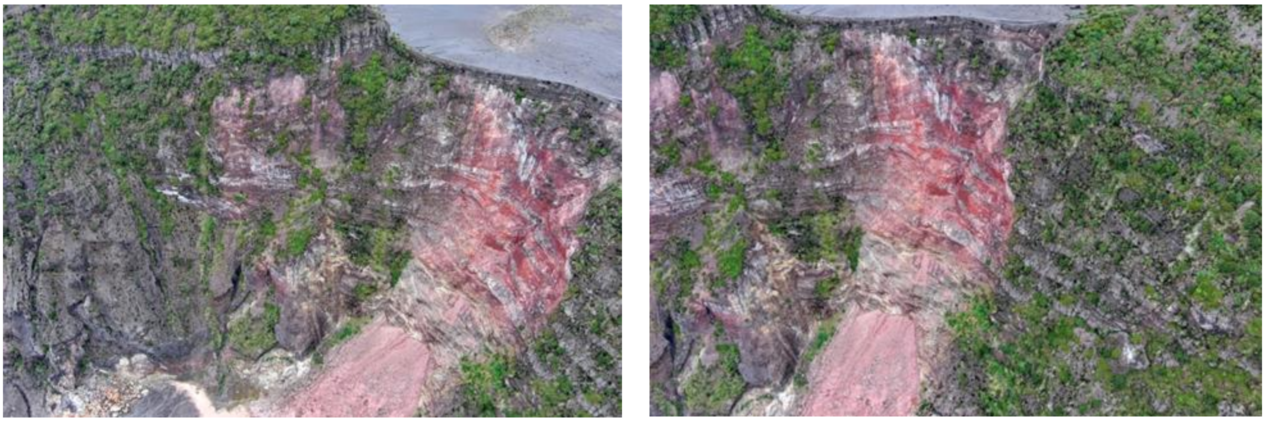

Figure 46& 47. Rock Fall Area East End of Main Crater UAS Perspective September 2022

Figure 48 & 49. Rock Fall Area West End of Main Crater UAS Perspective September 2022

3.3. Main Crater - Vegetation on Interior Crater Walls

Usually, plants growing naturally inside of an active volcanic crater are exposed to above average levels of CO_2. Active volcanoes continuously release CO_2, yet the rate of the degassing will fluctuate. The ecosystems of volcanic climates are both valuable and fragile. High altitude summit areas in Central America are particularly interesting like the Irazú Volcano National Park in Costa Rica. The Irazú Volcano National Park consists of once active Main Crater and a degassing cave named "Cueva de los Minerales" and fumarole and volcanic hot spring named "Río Caliente" on the northern flake of the volcano. All of these areas are exposed to elevated levels of atmospheric CO_2. Tropical forests represent around 40% of terrestrial net primary production worldwide; they store 25% of biomass carbon, and may possibly contain 50% of all species on Earth. Still, the forecasted future effects from increasing levels of atmospheric CO_2 on a global scale relative to tropical plants response is not yet fully understood. There are over 200 active volcanic systems located in the tropics many of which are covered in thick vegetation [6].

The diverse high altitude tropical vegetation located inside the Main Crater of the Irazu volcano holds much of the soil together with tough root systems. Possibly due to the acid rain deriving from the increased activity and degassing of the Turrialba volcano 6.5 miles east of the Irazu volcano many of these plant species have burn marks on their foliage. Naturally this acidic rain would have had a severe effect on the root system as well. Acid rain therefore contributes to erosion. This may have been a significant factor contributing to the 2019 rockfall. Monitoring vegetation inside the Main Crater is an important observational aspect of monitoring the Main Crater of the Irazu volcano.

Figure 50 & 51. Vegetation on South End of Main Crater Wall September 2022

Figure 52 & 53. Vegetation on South End and East End of Main Crater Wall September 2022

Burnt vegetation found inside the Irazu Volcano National Park from 2017 through 2020 had mostly vanished underneath the thick vegetation from healthy regrowth. This burnt vegetation was due to acidic rain deriving from the SO_2 being released from the Turrialba Volcano.

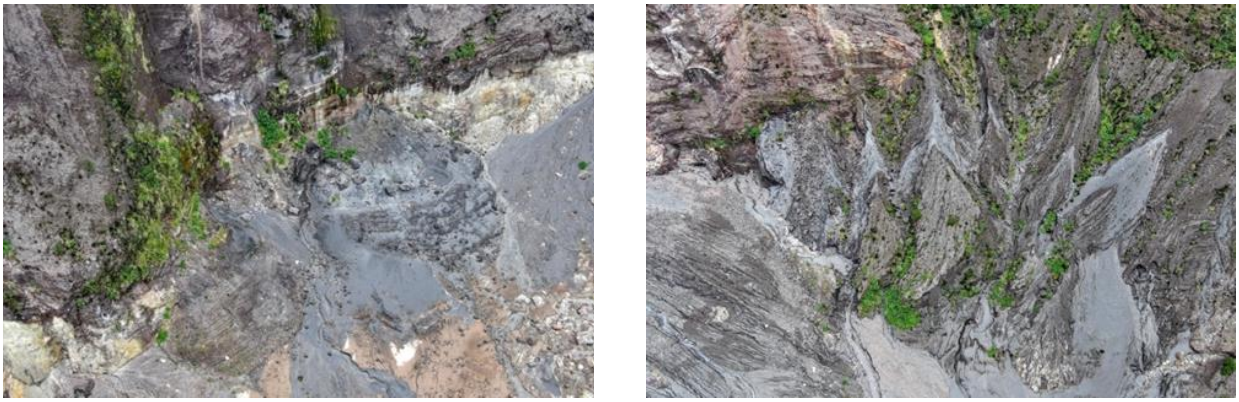

Figure 54 & 55. Floor of the Main Crater Irazú Volcano National Park September 2022

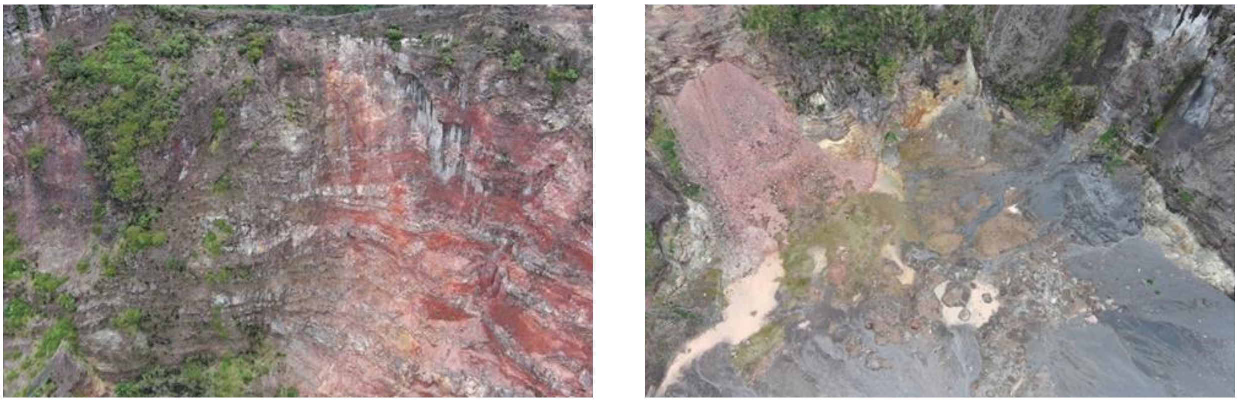

Figure 56 & 57. Floor of the Main Crater Irazú Volcano National Park September 2022

3.4. Main Crater - Cracking

Figure 58 & 59. Main Crater UAS Perspective September 2022

Using consumer drones in January of 2020 starting on the northern rim of the Main Crater we observed cracking in the area that separates the Main Crater from the Diego de la Haya crater. The Diego de la Haya crater is another prehistorical crater located inside the Irazu Volcano National Park which last erupted in 1723. By using Autel EVO Lite + UAS which is an affordable consumer drone we monitored these cracks which are not visible from the perspective from the main lookout point. On September 12th, 2022 we monitored the area where these cracks were found to see if they widened, increased in number or had shown any signs of significant geological change. These cracks were located just below the crater rim on the upper south-eastern section of the Main Crater. Since many park visitors and observers walk around the Playa Hermosa, monitoring these cracks with consumer drones has become a valued UAS application which contributes to the safety of people visiting the national park.

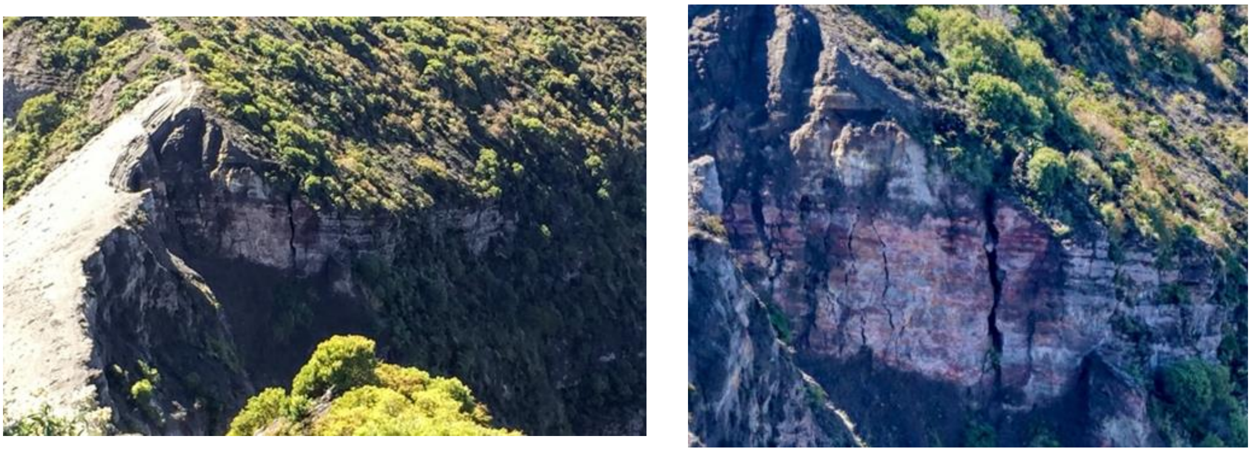

Figure 60 & 61. Cracking in Main Crater January of 2020

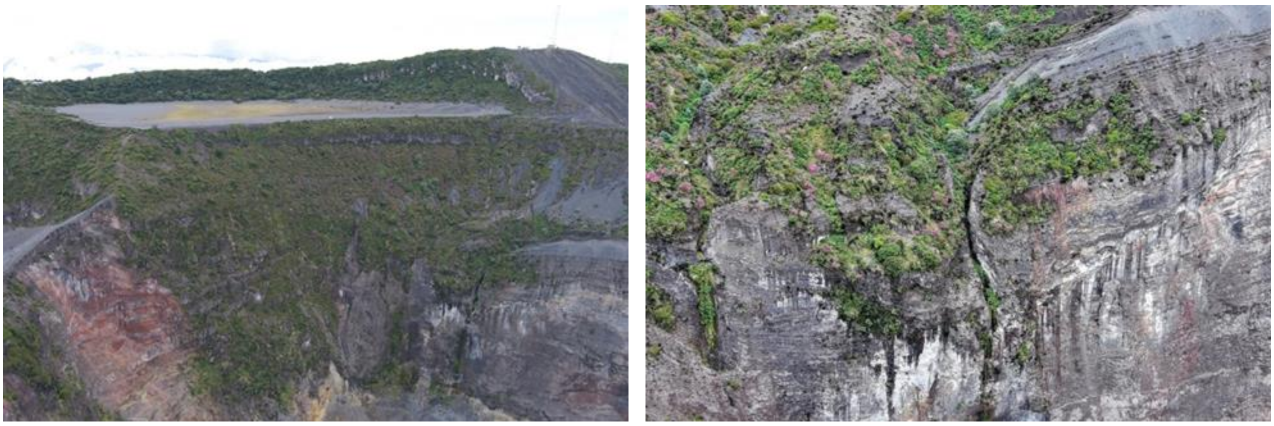

Figure 62 & 63. Area of Cracking Documented with the Autel Evo Lite + drone September 12th, 2022

3.5. Main Crater - Waterfall

Consumer drones can contribute to a better understanding of the volcanic hydrothermal system, Periodically there has been a waterfall observed coming from below the Playa Hermosa crater (observational area) in the Irazu Volcano National Park. This waterfall was located on the southern end of the Main Crater and can only be seen from a few exclusive trails located on the northern rim of the Main Crater which are not accessible by the general public. The Autel Lite + consumer drone allowed us to check if this waterfall still existed and observe the potential water flow levels.

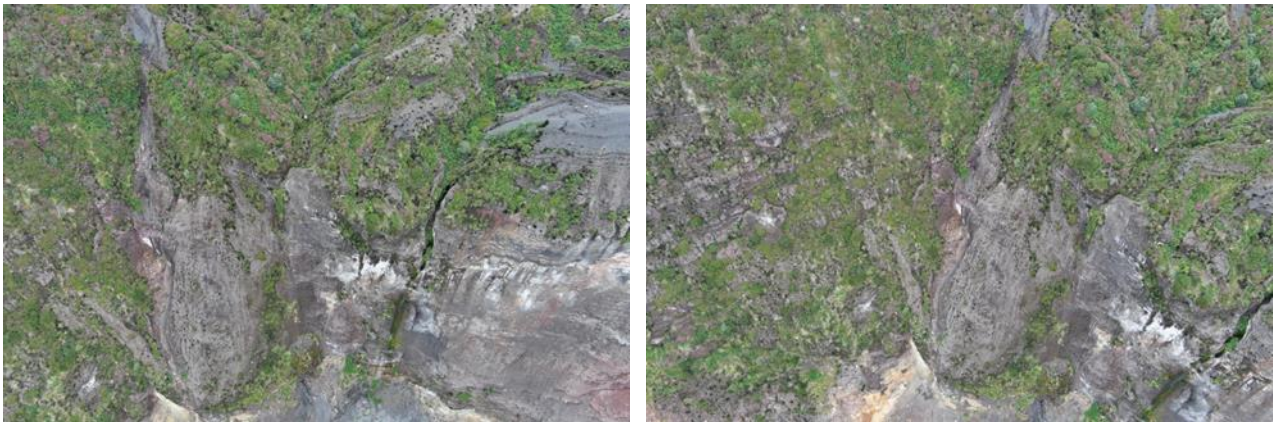

Figure 64 & 65. Waterfall Area South Rim of Main Crater September 2022

3.6. Diego de la Haya

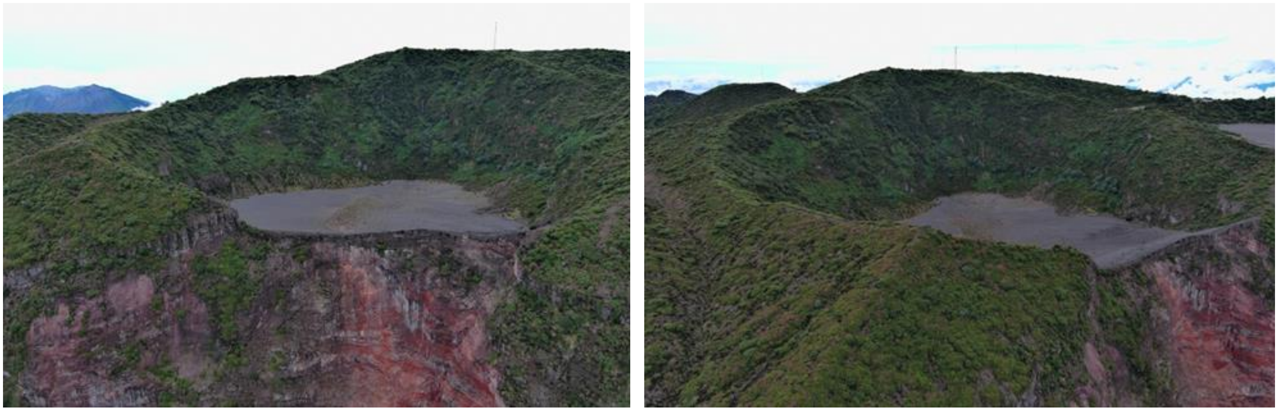

Figure 66 & 67. Diego de la Haya Prehistorical Volcanic Crater September 2022

All together there are five craters within the area of the Irazú Volcano National Park. The Diego de la Haya crater is to the east of the active Main Crater and last erupted in 1723 when Diego de la Haya was the Spanish governor of the Cartigo Province in Costa Rica. This was a severe eruption that had a drastic effect on the communities of Cartago. Today the topography of the Irazú Volcano National Park including the Diego de la Haya crater is a complex and beautiful landscape, one that can create issues for remote pilots. Around the Diego de la Haya crater large crater walls can creat interfierance and contribute to drones disconnecting. This never happened with the Evo Lite + UAS during our flight missions but can happen and is something remote pilots should be aware of when operating in areas of complex topography. Sensors on the Evo Lite + drone prevented the UAS from accadently colliding with crater walls and other obsticles presented in the complexed topography such as trees, radio antenas, and crater walls.

The Evo Lite plus drone performed exceptionally well in the volcanic environment. Wind gusts were no issue and the drone operated perfectly at these high altitudes with reduced atmospheric density. The Evo Lite + drone were flown for a continuous period of about 2.5 hours at the Irazú Volcano National Park. Each flight mission was dedicated towards a different aspect of the Main Crater of the Irazú Volcano. Batteries were immediately switched and flights continued without any delay. In between each flight, while changing the batteries, the rotary systems on all four arms were checked for heat! Any kind of temperature increase on the rotary system from high use may mean a cooldown period is needed for the drone. At no point did the Lite + drone require any sort of cooldown person and we were able to quickly switch the batteries and move forward with the next flight mission. At no time was there any disconnect between the drone itself and the remote control. Special attention was given to the RC drone connectivity bar graph in the upper right on the control screen and there was very little connection reduction despite the drone being sent far away for volcanic flight missions covering great distances in difficult conditions. Atmospheric humidity and Zero Visibility occurred several times as cloud coverage can move rapidly at these altitudes. Considering the drone was flown in high altitude volcanic terrain in the Central American Tropics, the device was durable in transit and during periods of climbing, it was easy to unfold and deploy without waiting for any kind of warm up period, we were able to launch and land directly from our hands which was helpful as there are uneven rocky terrain around the Irazú volcano which is not ideal for launching and landing from the ground.

3.7. Topography of Irazú Volcano National Park

Figure 68 & 69. Western Main Crater Rim of the Irazú Volcano September 2022

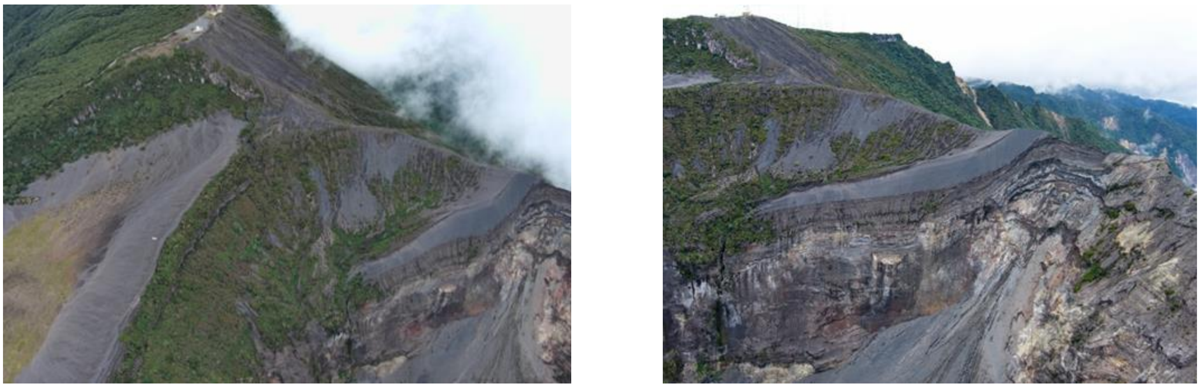

Figure 70 & 71. Irazú Volcano National Park September 2022

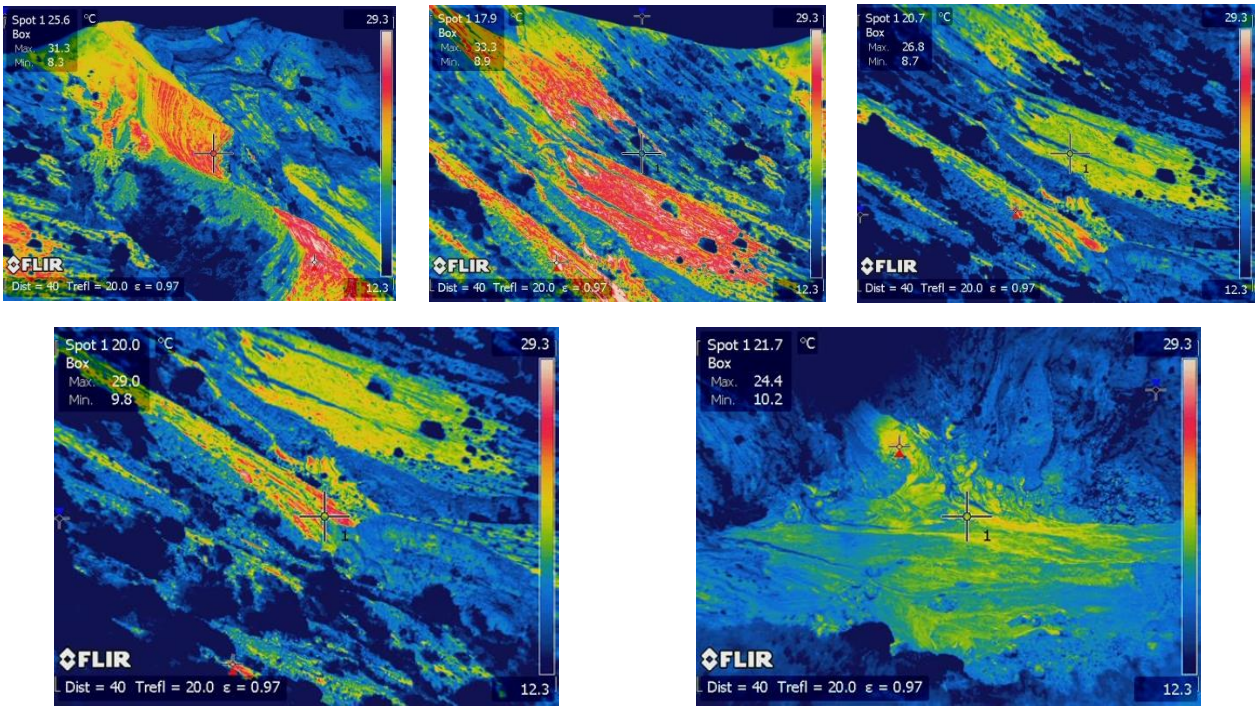

Figure 72 – 76 - FLIR Images from Maria Martínez Cruz

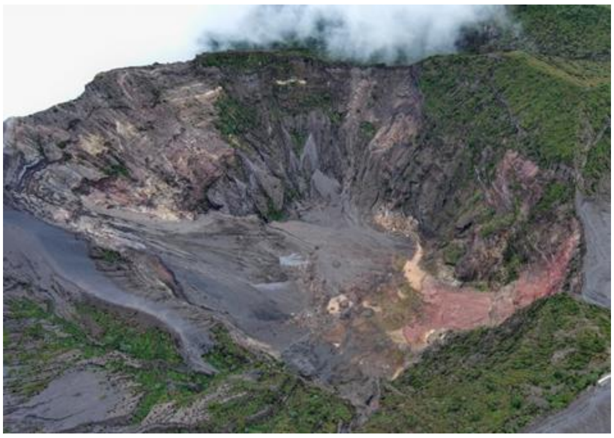


Figure 77 & 78. Aerial View of the Main Crater of the Irazú Volcano National Park September 2022

Changes in gas composition and emission rate are likely one of the first signs of unrest at volcanoes. By expanding our gas detection capabilities and broadening our UAS application to include volcanic emission tracking, we can begin monitoring more emissions from a larger number of volcanoes and through increased frequency and reliability along with using previously confirmed early warning detection systems and data analysis significant improvements can be made to our strategy and ability to predict volcanic eruptions. Carbon dioxide CO_2 can be from both magmatic sources and hydrothermal as well; this gas can travel along fault lines; it can be periodically released from cracks and fractures in the volcanic edifice and it can also diffuse through soils surrounding the active crater. CO_2 can also be released from soils that are distant from the active crater and fumarolic field making gas measurements important for surveying and tracking emissions in other volcanic areas further away from the areas of visible activity [7].

It's possible for phreatic and hydrothermal eruptions to occur in hydrothermal systems where vents are located such as the Main Crater of the Irazú Volcano National Park. Sealing can be small or large and generalized or localized situations have both been documented. When lakes occupy active volcanic craters they can trap gases and accumulate high temperatures [8].

Using UAS can help researcher study active crater morphology and geological changes. These UAS can carry scientific equipment to document volcanic gas emissions, take thermal images and collect water samples. UAS can also be used to monitor and document ozone depletion following future volcanic eruptions [9]. UAS can also greatly assist via aerial survey of volcanic regions covered in thick tropical vegetation. Still no phreatic nor hydrothermal eruption has been accurately predicted, yet the UAS can be a tool volcanologists can use to gather additional information not obtainable from ground level observations. The UAS can also be used to enter the danger zone such as active craters and gather additional data on the area of interest for the scientific community.

Figure 79. Layering of East Side of Main Crater Wall of the Irazú Volcano September 2022

4. Discussion

Piloting remote aircraft in high altitude volcanic environments is one of the most complex and risky situations for a drone pilot. Is the data more valuable than the drone? Is a frequent question remote pilots often ask themselves before the flight and at the point in the flight where the drone begins collecting great data, prized photos and excellent video, but riskier conditions start settling in. For example, of a complex flight for a remote pilot operating in a volcanic environment is when it's clear where the drone around 600 meters away from the home point and it starts raining at the remote pilot's location. These situations must be planned for to the best if the remote pilot in command capabilities.

Unaccounted for situations will still arise, but with proper training and knowledge of these environments obtaining the data points from the planned flights is certainly possible. When planning to operate drones in volcanic environments it's essential to check the weather forecasts for the days you're planning the mission and to consistently monitor any potential changes on Windy.

Climatic stability in volcanic regions can change in less than one minute. And with that comes relative humidity fluctuations, 80% change in visibility conditions, wind speed change, wind direction change, enhancing wind gusts. Therefore, extreme presentation is necessary for the remote pilot to obtain as much geological and atmospheric knowledge of the region before flights. In Costa Rica while studying the Irazú volcano at 3,432 meters in altitude the poor visibility and cloud coverage changes were frequently avoided with the assistance of a visual observer and the decision to increase or decrease altitude to avoid the passing clouds. Obviously, these decisions are made by the remote pilot in command who must also consider the altitude of the flight and the terrain formations directly below the drone.

Probably one of the most impressive drone surveys of a volcano was conducted in 2016 and 2017; Researchers from Universidad Nacional collaborated on an international undertaking where advanced remote pilots flew drones at both the Turrialba Volcano in Costa Rica and the Masaya Volcano in Nicaragua. The flight mission objectives were to measure the degassing deriving from the active craters. At the time these two volcanoes were the largest time integrated source of CO_2 in all of Central America. During the 2016-2017 period when the research project was conducted both volcanic systems were actively degassing and showing increased signs of a potential eruption. Researchers and remote pilots managing this project noted that; Remote pilots operating in high altitude volcanic environments especially active systems had to be particularly concerned with the hardware because the devices are often subject to harsh field conditions. These researchers developed a fly/no fly checklist which has served to be very useful to many remote pilots learning to operate UAS in these climatic conditions. Several points were included into the checklist such as wind, and wind gusts, unexpected turbulence, weather, steep relief, summit risks, convicting volcanic gases, obstacles in flight path, eruption columns, battery limitations, communication limitations, communication issues from close by radio towers, static electricity from volcanic ash, and any potential line of sight complications between the remote pilot and the drone itself. (10)

4.1. Flight Risk/Reward Ratio

The Risk/Reward ratio for flying a drone consists of weighing the value of the drone itself (not including the Remote Controlo batteries in the case) against the value of the data which can be obtained during that particular flight. Is the data being gathered and stored more important than the drone itself? The answer is usually no, yet certain circumstances like an eruption for example, may tip the scale of the UAS Risk/Reward ratio in favor of conducting the risky flight mission. In these circumstances it's recommended to use the most economically priced UAS available in case the drone is lost forever.

4.2. Extra Micro SD cards

It's recommended that remote pilots flying drones in volcanic regions carry extra Micro SD cards in their drone case because valuable data may be obtained and the pilot may want to continue with more flight missions. By changing the Micro SD card, the data from the previous flight is guaranteed to be returning to the lab for processing. Sometimes valuable photos used to generate 3-D Digital Surface Model have been collected and the remaining flight missions are non-essential, in these situations it's important that the remote pilot remember to switch the Micro SD cards in-between flights. It's usually possible to specifically set the drone to save onto the mobile device being used with the RC to operate the drone this can also greatly serve remote pilots operating in complex climates.

4.3. Reduction in Altitude

When flying in volcanic craters there is not just the altitude in meters Above Ground Level or AGL like in the Part 107 remote pilot listening test. When piloting remote aircraft in volcanic terrain one must also consider the atmosphere below, just as importantly if not more significant is the reduction in altitude (Below Ground Level) BGL. A critical point of preflight planning as flying into an active crater is not already complicated enough but one must consider the Return to Home RTH flight will most likely require more battery energy than the flight path used to enter the volcanic crater because the drone needs to lift itself higher to get out of the crater. The same concept applies when launching from a volcanic summit and surveying the flanks or slopes of a volcano; the drone flight altitude will be lower than the altitude of the home point.

4.4. Climatic Conditions

In these high-altitude volcanoes in Costa Rica random periodic rain showers pass by sometimes quite quickly perhaps 10 minutes from start to finish for example. Remote pilots will need to wait for their next window of opportunity and then weight the flight risk/reward ratio. These frequent rain showers can last from 10 minutes to over a full day.

4.5. Launching and Landing

Successful takeoff and return to home with the drone can also be a bit more complicated here as well since the launch and land terrain is often inclined rocky and grassy areas that are usually unstable. Using legs to extend the drone towards the ground are highly recommended. Remote piloting in these volcanic climates is usually assisted by the aircrafts ability to launch and land from the palm of the hand.

4.6. Clouds

Rapidly passing small clouds will have a direct effect on the drone's connection to the GPS satellites. They are directly responsible for the 80% fluctuation in visibility, and Relative Humidity RH.

4.7. Risks

Degassing fumaroles, steep slopes, and unconventional hidden factors all play a role in the environment a volcanic remote pilot must operate in. There can be visibility complication due to water vapor and volcanic degassing. Visibility issues can impact the drone itself and the display on the RC, and they can directly impact the remote pilot at the home point. For example, if a cloud passes and visibility is reduced by 70% at the home point than observing the drone via line of sight will be severely impacted. Tropical sunlight reflecting off the RC screen can all be challenging in volcanic environments so hat and sunglasses are quite essential. Usually there are people visiting or others studying these volcanoes and therefore it's highly recommended never to fly directly over any people, vehicles or valuable infrastructure such as National Park housing or equipment and especially telecommunications towers. Telecommunications towers are frequently located at volcanic peaks due to their strategically high location being ideal for broadcasting networks. These broadcast towers also contribute to interference between the drone and the RC. Flying with an insurance policy is always important for risk reduction.

4.8. Unforeseen variables

Many unforeseen variables exist in these high-altitude volcanic regions. Birds, small single engine aircraft, and other wild animals at ground level can be a distraction. Hardware malfunction is always possible and the remote pilot should take this into consideration before operating the UAS. Potentially distracting animals and degassing fumaroles at home point location all have an effect on the ability of the remote pilot to safety operate the drone, but also to collect the data and to return the drone back to the home point safely. Tourists and other people may approach and it important that the remote pilot be accompanied by a visual observe who is ready to stop the people from asking distracting questions and creating interruptions in areas with people around.

4.9. Altitude

One of the most complex remote flight climate conditions on Earth. The altitude above 10,000 feet has a different atmospheric make up with less 02 the air is thinner and operation of a remote aircraft becomes more complicated. Certain UAS have altitude ceilings which have significant improved over the past several years. For example, the max altitude of the Autel Lite + drone due to a reduction in air density in high altitudes flying a drone above 3,000 meters is significantly more complicated. How the drone hovers and uses batters is different, flight inclination is different and therefore the remote pilot must operate the UAS differently as well.

Temperature in these volcanic regions is significantly reduced relative to the tropical lowlands of Costa Rica, and therefore remote pilots must also consider the temperature of the air during the drone flight and how that will affect the equipment.

Between the lower air density due to altitude and reduced temperatures actual flight time will be reduced and this must be taken into consideration. Research with UAS pilots has shown pilots can expect a 10% reduction in battery preference every 2,000 meters. Remote flight operations will become extremely complicated at 4,000 meters and above, most drones will require proper modifications and specialized parts for these altitudes. There is greater wind turbulence inside craters, next to cliff faces and in valleys.

4.10. Lightning and thunderstorms

If there is a Thunderstorm it's an almost certainly to cancel the flight mission and postpone for a better day. If there are lightning strikes it's an outright stand down. Lighting will destroy the connection capabilities of the RC and drone and will cause a complete disconnect.

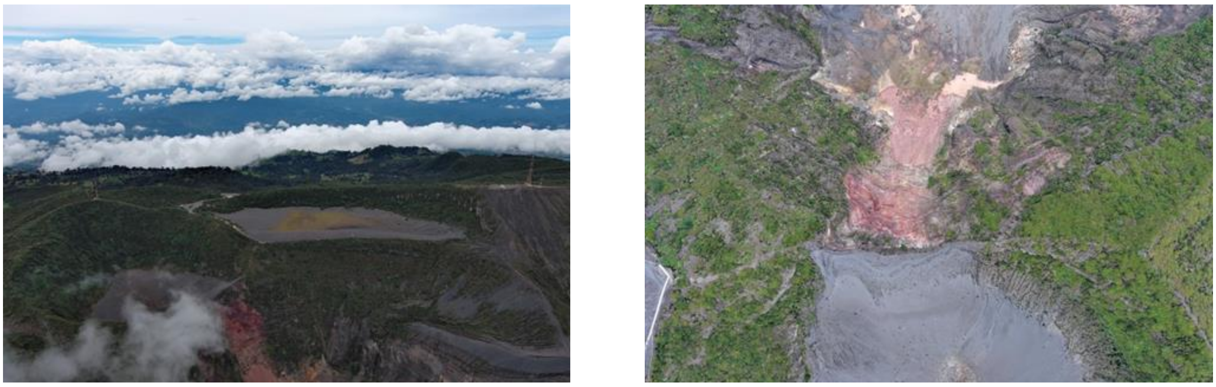

Figure 80 & 81. Irazú Volcano National Park September 2022

5. Conclusion

From the ground level there are significant restrictions for observing complex and dynamic volcanic systems. This limited perspective is enhanced exponentially by launching consumer drones. This increased the observational capabilities of researchers studying the Irazu volcano in 2022, the Autel EVO Lite + drone gave researchers studying the active Main Crater of the Irazu volcano a new enhanced perspective and greatly contributed to the gathering of valuable information associated with the Main Crater of the Irazu Volcano National Park in Costa Rica.

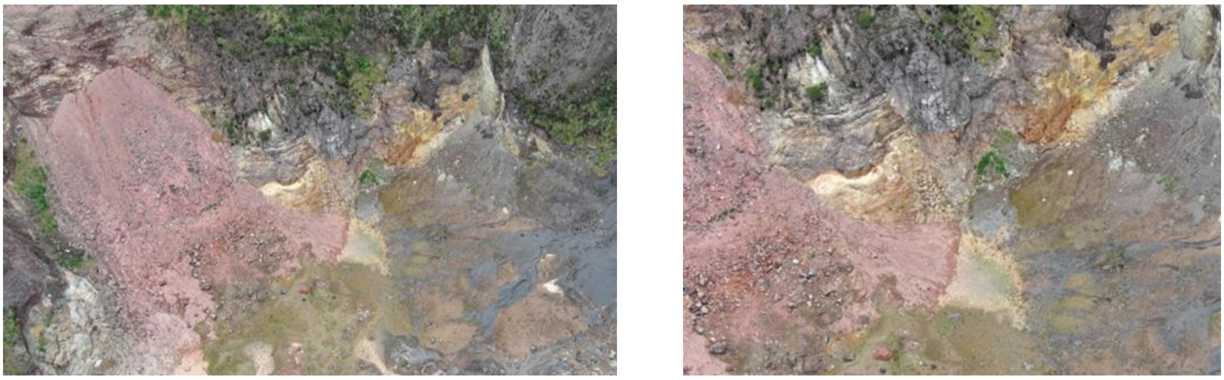

Figure 82 & 83. Main Crater Floor Irazú Volcano September 2022

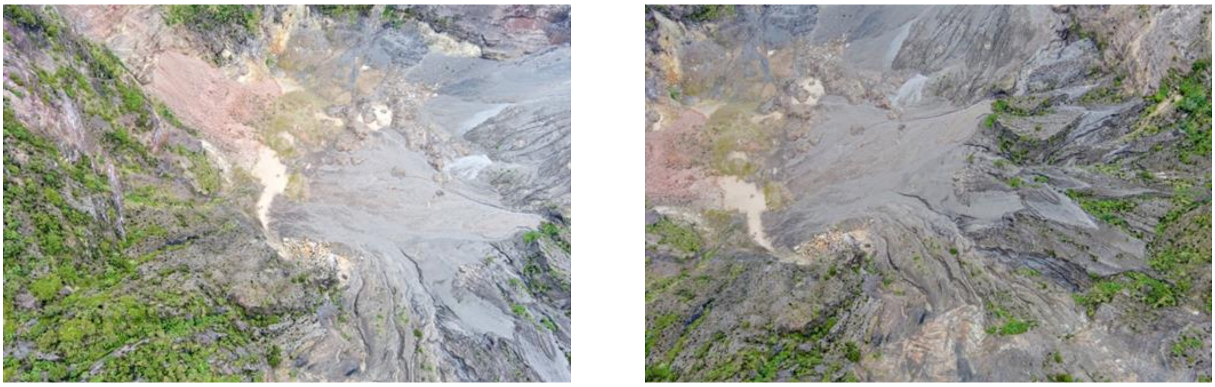

Figure 84 & 85. Aerial View of the Entire Main Crater of the Irazú Volcano September 2022

Figure 86 & 87. Aerial View of the Main Crater floor of the Irazú Volcano September 2022

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 [11-12].

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 [13].

Figure 88. Aerial View of the Entire Main Crater of the Irazú Volcano September 2022

Acknowledgement

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

Funding

This research received no external funding.

Author contributions

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

Conflicts of interest

The authors declare no conflicts of interest.

References

1. Alvarado, G. E., Carr, M. J., Turrin, B. D., Swisher, C. C., Schmincke, H., & Hudnut, K. W. (2006). Recent volcanic history of Irazú volcano, Costa Rica: Alternation and mixing of two magma batches, and pervasive mixing. *SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA*, *412*, 259.
2. Ulloa, A., Gázquez, F., Sanz-Arranz, A., Medina, J., Rull, F., Calaforra, J. M., ... & De Waele, J. (2018). Extremely high diversity of sulfate minerals in caves of the Irazú Volcano (Costa Rica) related to crater lake and fumarolic activity.
3. Epiard, M., Avard, G., De Moor, J. M., Martinez Cruz, M., Barrantes Castillo, G., & Bakkar, H. (2017). Relationship between diffuse CO2 degassing and volcanic activity. Case study of the Poás, Irazú, and Turrialba Volcanoes, Costa Rica. *Frontiers in Earth Science*, *5*, 71.
4. Kumar, V. (2016). Study on turquoise and bright sky-blue appearing freshwater bodies. *International Journal of Geology, Earth and Environmental Science*, *6*(1), 119-128.
5. Castellón, E., Martínez, M., Madrigal-Carballo, S., Arias, M. L., Vargas, W. E., & Chavarría, M. (2013). Scattering of light by colloidal aluminosilicate particles produces the unusual sky-blue color of Río Celeste (Tenorio volcano complex, Costa Rica). *Plos one*, *8*(9), e75165.
6. Bogue, R. R., Schwandner, F. M., Fisher, J. B., Pavlick, R., Magney, T. S., Famiglietti, C. A., ... & Duarte, E. (2019). Plant responses to volcanically elevated CO 2 in two Costa Rican forests. *Biogeosciences*, *16*(6), 1343-1360.
7. Kern, C., Aiuppa, A., & de Moor, J. M. (2022). A golden era for volcanic gas geochemistry?. *Bulletin of Volcanology*, *84*(5), 1-11.
8. Montanaro, C., Mick, E., Salas-Navarro, J., Caudron, C., Cronin, S. J., de Moor, J. M., ... & Strehlow, K. (2022). Phreatic and Hydrothermal Eruptions: From Overlooked to Looking Over. *Bulletin of Volcanology*, *84*(6), 1-16.
9. Eric Klobas, J., Wilmouth, D. M., Weisenstein, D. K., Anderson, J. G., & Salawitch, R. J. (2017). Ozone depletion following future volcanic eruptions. *Geophysical Research Letters*, *44*(14), 7490-7499.
10. Stix, J., de Moor, J. M., Rüdiger, J., Alan, A., Corrales, E., D'Arcy, F., ... & Liotta, M. (2018). Using drones and miniaturized instrumentation to study degassing at Turrialba and Masaya volcanoes, Central America. *Journal of Geophysical Research: Solid Earth*, *123*(8), 6501-6520.
11. 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.
12. Andaru, R., & Rau, J. Y. (2019). LAVA DOME CHANGES DETECTION AT AGUNG MOUNTAIN DURING HIGH LEVEL OF VOLCANIC ACTIVITY USING UAV PHOTOGRAMMETRY. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, 173-179.
13. 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.