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Botos Lagoon, Poás Volcano National Park, Costa Rica – Consumer drones in professional research

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Abstract

The International Union of Geological Sciences designated the Poás Volcano National Park in Costa Rica one of the top 100 sites for geological importance in the world. This was announced on the World Geological Heritage list which includes sites from 56 additional countries. The Poás Volcano stands out next to Mount Everest in Nepal, the Grand Canyon in the United States and the caldera of Santorini in Greece. The Poás Volcano National Park is an active volcanic crater visible from the crater rim and is one of the most visited National Parks in Costa Rica. Consumer drones were used at the Poás Volcano National Park in particular at the Botos Lagoon for observational research and environmental monitoring for several conservational applications assisted by the use of drones. UAS have been periodically used by the Laboratory of Atmospheric Chemistry Universidad Nacional LAQAT-UNA for monitoring the Botos Lagoon for geological fluctuations. Economically priced drone systems have now become common pieces of field work equipment for volcanologists. Most importantly they offer the opportunity to access dangerous difficult to reach areas of the volcano and allow for the collection of data on the otherwise inaccessible areas. By compiling all of this data together in a collective analytical survey of the Poás Volcano including the Botos Lagoon located in the prehistorical dormant crater, much valuable data can be brought to the scientific community for increased understanding of the Poás Volcano National Park and its importance to the nation.

1. Introduction

The objective of this project was to visit the Botos Lagoon of the Poas Volcano (Figure 1) National Park in Costa Rica with the Autel EVO Lite + UAS. The Poas Volcano has periodic eruptions and had a period of increased activity from 2017-2019. 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.

The Botos Lagoon is the dormant crater of the Poas Volcano National Park. Due to the fact that the Botos Lagoon is located in a region known as a mountain rain forest every day late morning the clouds move in and the entire crater is covered by a thick mist. There have been several aspects of interest in the National Park of the Poas Volcano which we are now observing and monitoring using the EVO Lite + drone from Autel Robotics. One of the

first areas of UAS observational research was the Botod Lagoon. The Botos Lagoon is located in the taller crater of the volcano and offers park guests a historical perspective of the National Park. The Botos Lagoon is the starting point for several mountain rainforest waterfalls.

Figure 1. Summit craters of the Poás Volcano National Park Costa Rica

2. Material and Method

2.1. UAS

The Autel 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 Lite + drone can withstand 32-38 mph wind gusts and has a level 7 wind resistance rating. The Autel 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.

2.3. Software Application

Autel Sky is the app associated with the Autel EVO 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.

3. Study Area

3.1. Poás Volcano National Park Costa Rica

Before the most recent eruption cycle from 2017-2019, the national park of the Poás Volcano hosted 400,000 tourists every year at $15 each. While the Poás Volcano National Park was closed several new construction projects were completed but still the park remained closed long after the project's completion and the park was deemed safe just to make absolutely certain it was ok for visitors in 2019. The installation of new surveillance and gas detection equipment was another of the projects unfolding from within the park, along with the new observatory platforms, sheltars, vehicles and new evacuation trails.

During this explosive activity there was a bright incandescent glow seen coming from the interior part of the active crater where Laguna Caliente use to be. The agency reported that they increased in seismic activity and gas emissions starting on March 30, 2018. They also recorded a spike in the number of small eruptions in the Poás Volcano crater's lake. OVSICORI experts have collected samples from the crater to evaluate the situation and assess the possibilities of potential lava flows. Safety measures are always kept in place at the national parks that have volcanos. The National System of Conservation Areas or SINAC confirmed to the newspaper the Tico Times that Poas Volcano National Park is open to the public in 2019, but that officials are ready to enforce all necessary measures with visitors according to emergency protocols.

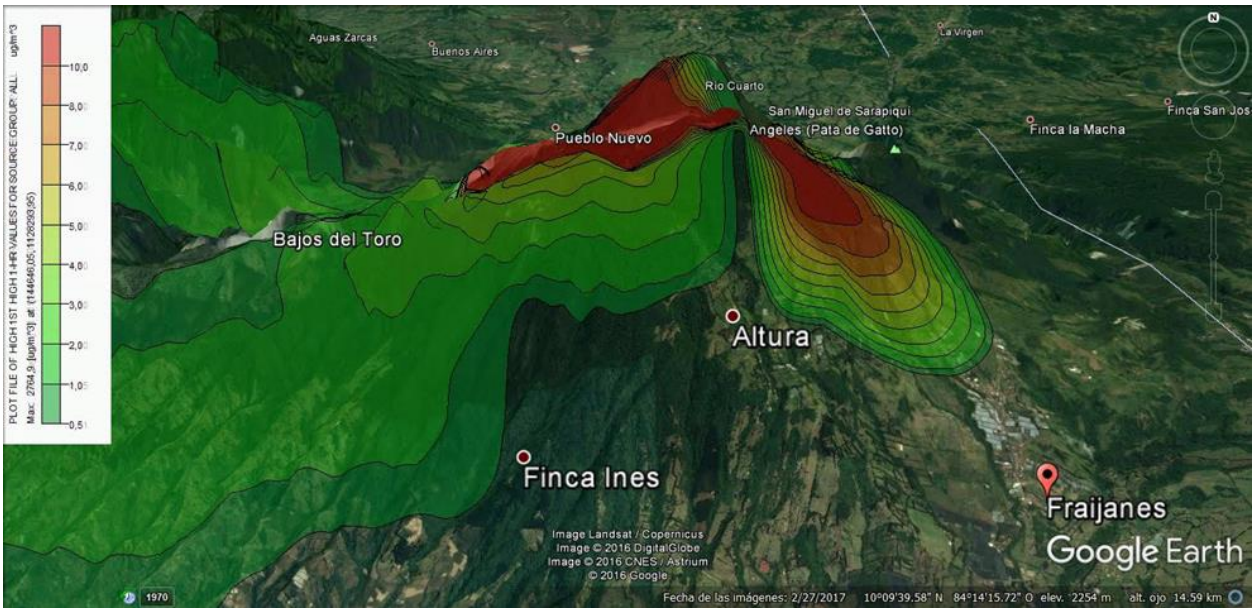


Figure 2. AERMOD Plot of Poás Eruption on April 13th, 2017

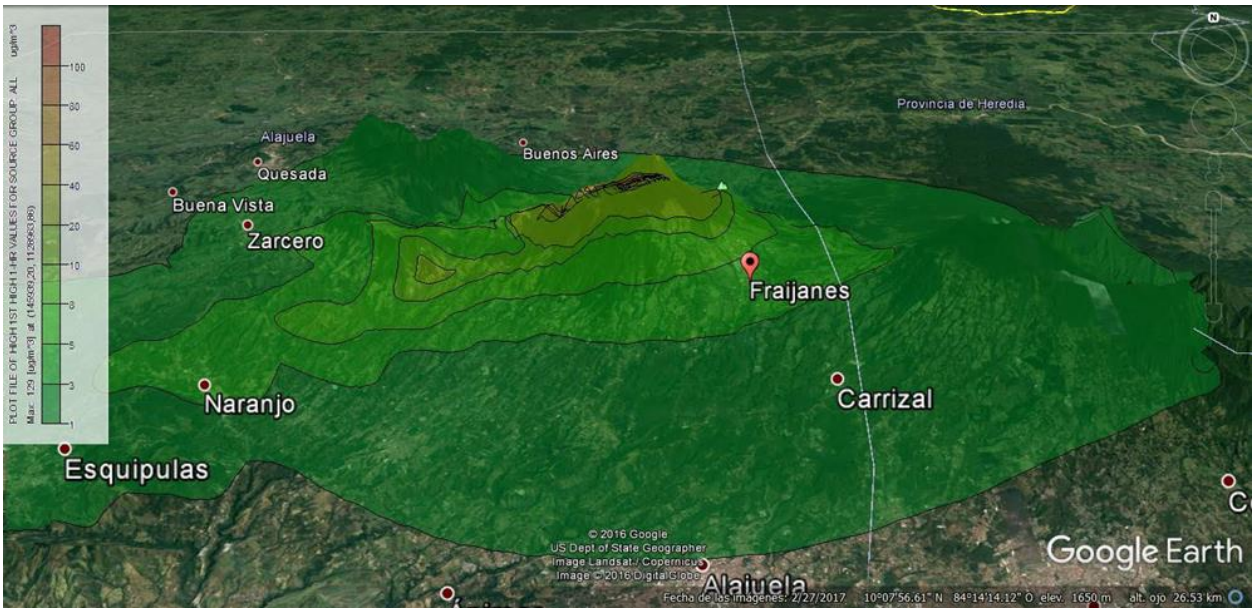


Figure 3. AERMOD Plot of Poás Eruption on April 14th, 2017

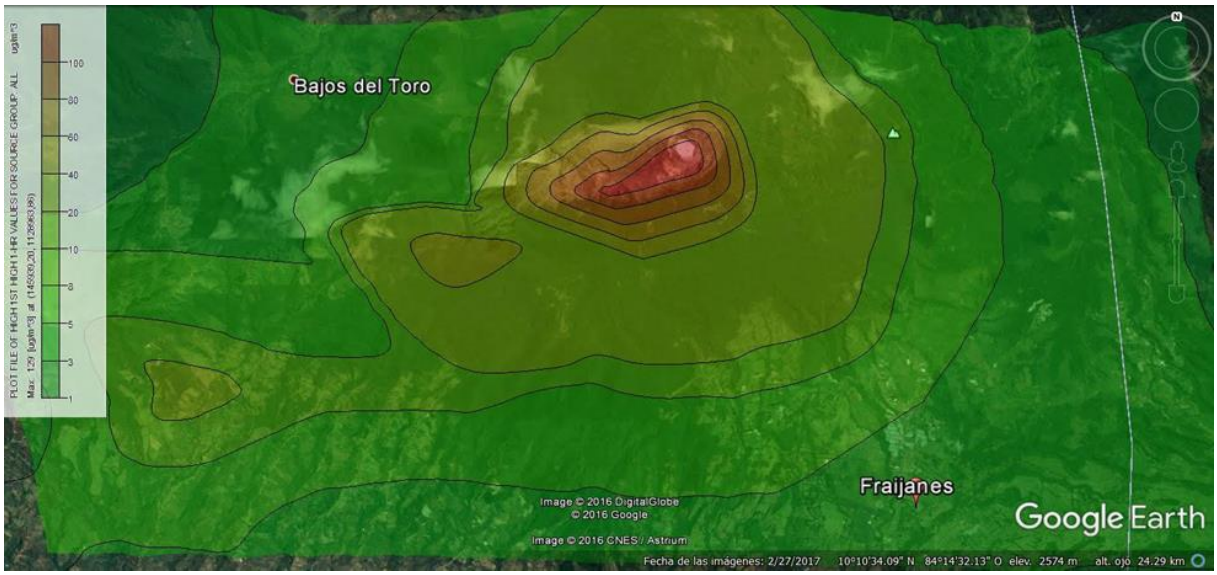


Figure 4. AERMOD Plot of Poás Eruption on April 14th, 2017

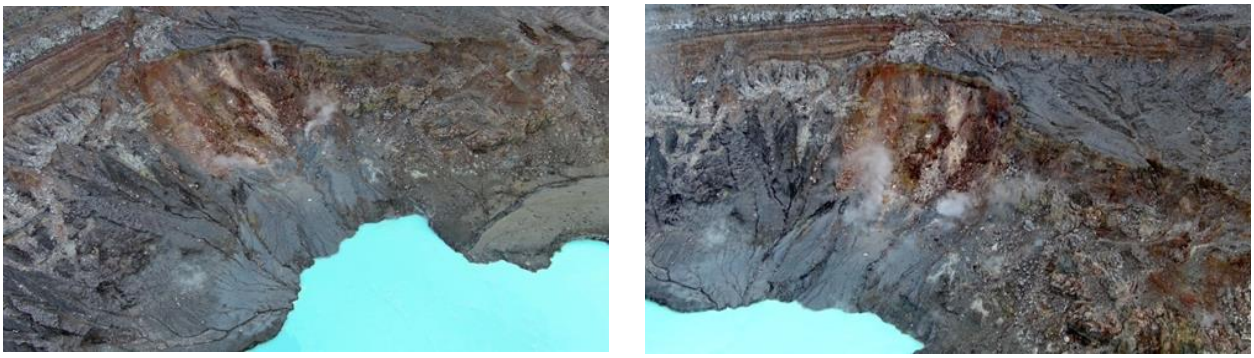


Figure 5 & 6. Fumarole Naranja of Laguna Caliente Poás Volcano National Park Costa Rica

There are two volcanic craters within the Poás Volcano National Park both of which have crater lakes of unique characteristics. The Botos Lagoon and Laguna Caliente are the two crater lakes of the Poás Volcano National Park. The Botos Lagoon is located within the prehistorical dormant crater in the park. The active crater of the Poás Volcano named Laguna Caliente destroyed the trademark pyroclastic dome on the southern shore of the crater lake in 2017 with several phreatomagmatic eruptions. As a result, starting in 2017 the risk of sudden eruption increased and stopped any field work or collections from within the active crater. In 2017 the increased danger from unexpected phreatic and phreato magmatic eruptions effectively stopped all fieldwork from within the active crater where Laguna Caliente is located. The increased activity seen coming from Laguna Caliente and the restrictions it placed on volcanic fieldwork in 2017 offered a new and unique opportunity to deploy drones for observational research, digital photography used for generation of digital elevation models used to estimate volume of ejected material and offered insight into the level of degassing seen coming from the active volcanic crater. Monitoring gas concentrations and other chemical substances ejected during periods of increased activity and enhanced fumarolic degassing are essential to understanding the role volcanoes play in changing climatic conditions [1].

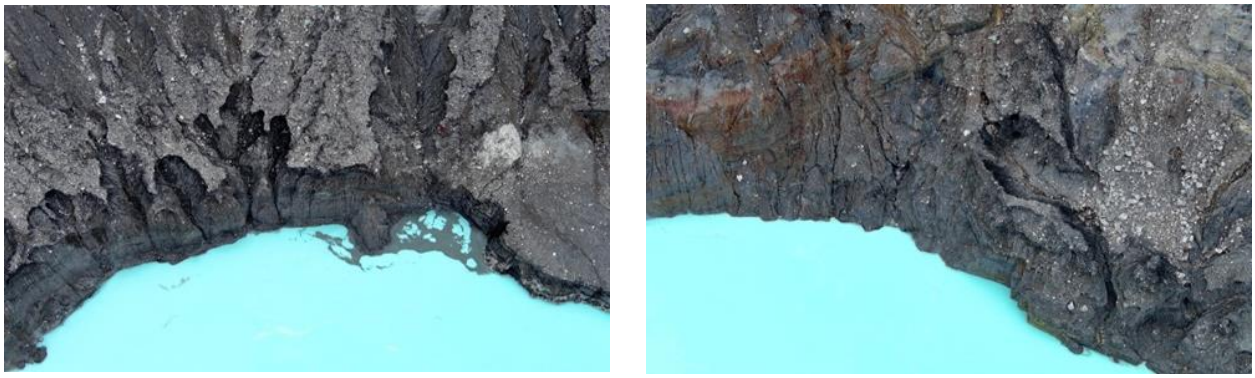


Figure 7 & 8. Laguna Caliente Poás Volcano shoreline survey

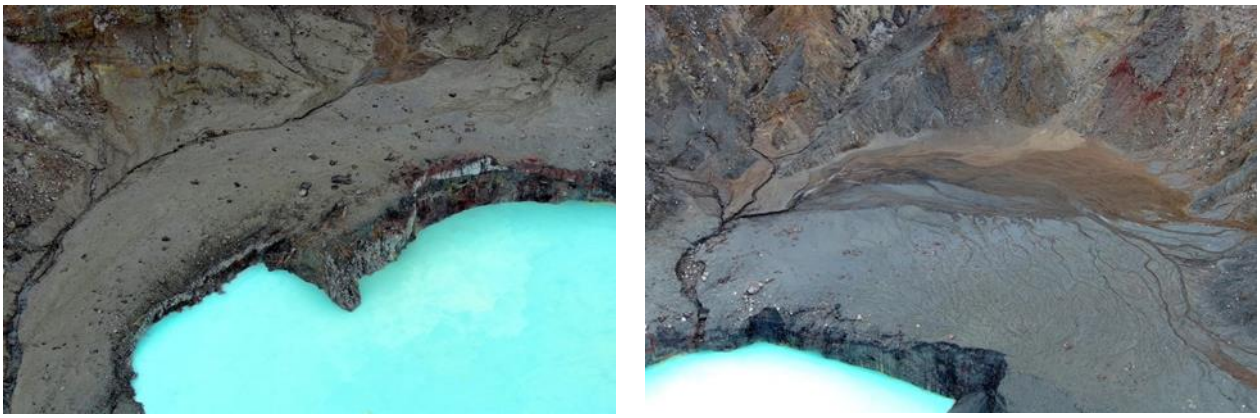


Figure 9 &10. Laguna Caliente Poás Volcano shoreline survey searching for cracking

Figure 11 & 12. Laguna Caliente Poás Volcano shoreline survey searching for cracking

Figure 13 & 14. Laguna Caliente Poás Volcano shoreline survey searching for cracking

Figure 15. Poás Volcano eruption on Febuary 11th, 2019 forced officials to close the park for safety concerns

Eruptions coming from the active crater continued into 2019 with a particularly interesting eruption affected the Botos Lagoon. In the AERMOD plots below you can see the red and orange circles around the active crater which are the most affected area. When observing an AERMOD plot the lines that separate the fronts are called isobars. The AERMOD Plots are generated from satellite measurements of SO_2, generated from an estimation of SO_2 of 2300 g/s, around 0.2 kTon of SO_2/day. Since September 30th 2019 was a day with low velocity of wind, around 2.5 m/s and a wind direction to the East and Southeast the eruption from Laguna Caliente had a direct impact on the Botos Lagoon. The rain was around 0.3 mm and temperature was between 48.2-59°F or 9-15 °C.

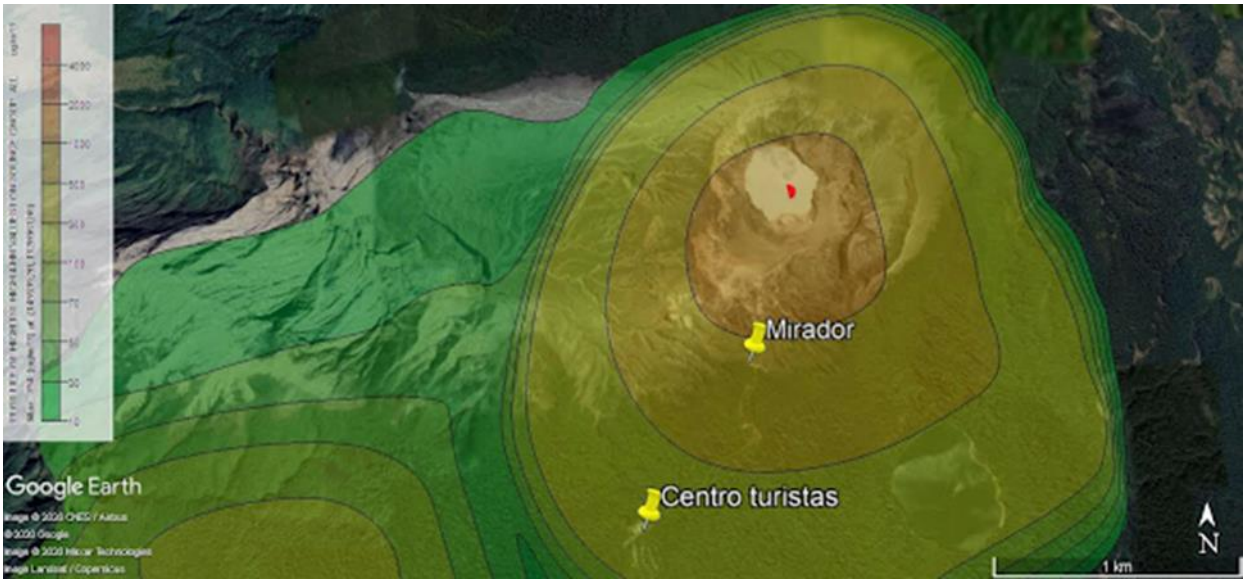


Figure 16. AERMOD Plots of the September 30th 2019 eruption coming from the Poás Volcano

Figure 17. Laguna Caliente of the Poás Volcano National Park Costa Rica September 15th, 2022

3.2. Botos Lagoon

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." (2)

The exotic light blue vibrant color of the crater lake located in the dormant crater of the Poás Volcano National Park the Botos Lagoon water color 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 crater of the Poás 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 [2].

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 [3].

Figure 18. Botos Lagoon of the Poás Volcano National Park Costa Rica

4. Results

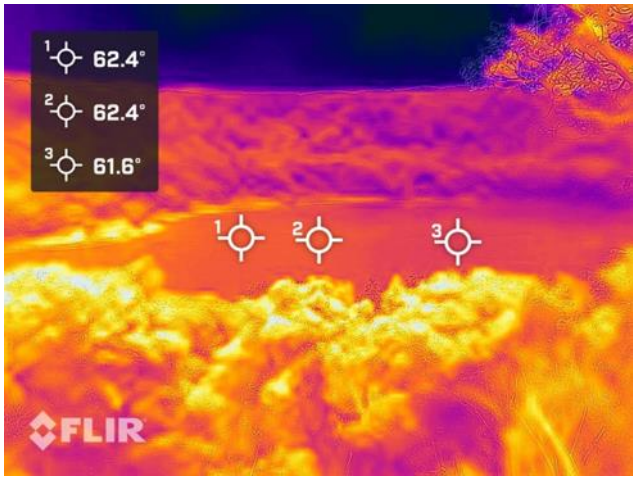
4.1. Subaquatic structure

On the crater floor there has been a structure which is really only visible from the air. We think this structure is a prehistoric volcanic vent. This area generates significant curiosity and one theory is that this was the area where degassing occurred in the past. This was the release point of volcanic emissions when the crater was active. There have been pH fluctuations in the lake water which suggests there are hidden variables contributing to the chemistry of the lake water. The Autel Lite + drone was used to hover over in the Botos crater directly over this subaquatic feature high definition 6k video which we watched closely for any potential bubbling. Using the advanced zoom capability, we were able to get detailed views of the structure from an aerial perspective that offered us additional knowledge about this area of the national park. Consumer drones can assist researchers in the navigation of submersible drones as disorientation below water is very common. By deploying UAS looking directly down the remote pilot of the submersible drone can observe from an aerial perspective exactly what the submersible is doing and in which direction it is going.


Figure 19 & 20. Poás Volcano structure of interest on lake floor of Botos Lagoon 2019

4.2. Crater lake color

Observing the exact color of the crater lake is of strategic importance and there are multiple factors that all play a role in the color of the crater lake. By using the advanced 6k video camera we were able to document the crater lake color and decipher which contributors were most significant. Acid rain deriving from volcanic emissions coming from the active crater which houses Laguna Caliente, algae, coloidal particles and the potential CO2 degassing and gas dissolving in the water all play a role in changing the color of the water of the Botos Lagoon. The Autel Lite + drone allowed us to strategically observe this crater lake from a better high-altitude perspective and this allowed us to better understand what was contributing to the color. On the days of our visit in September we noticed a significant green color which we found to be an algae bloom.



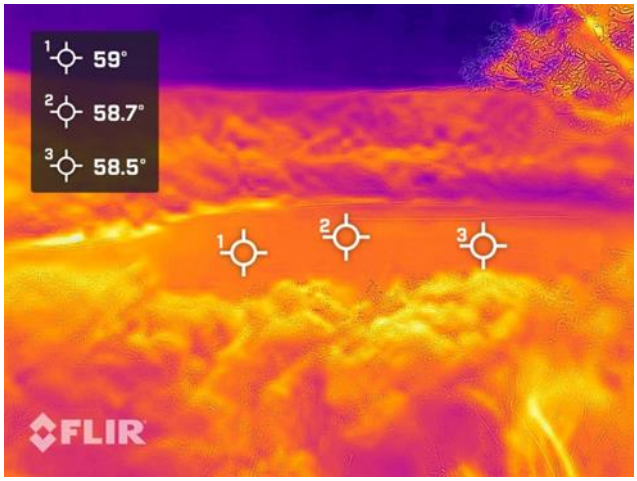


Figure 21 & 22. Thermal images in degrees fahrenheit of the Botos Lagoon of the Poás Volcano

4.3. FLIR ONE Pro thermal imaging camera for smartphones- Teledyne FLIR

The Botos Lagoon can have periodic acidic conditions due to acid rain deriving from atmospheric SO_2 due to periodic eruptions coming from the active crater of the Poás Volcano National Park; Laguna Caliente. On

September 30th, 2019 for example the pH acid rain calculation was around 1.8. Extreme acid rain affected the entire immediate surrounding area around .62 of a mile or 1 kilometer around the active Poás crater. For the estimation of the acid rain researchers from LAQAT-UNA took measurements of the concentration of sulfate, nitrate, fluorine and chlorine. They also developed a water monitoring program for the Botos Lagoon. It's expected that the acid rain event causes an acid-alkali reaction between wet/dry deposition and forest, roads, buildings and soil. The reaction generated water with different species of salt with sulfate, nitrate, fluorine and chlorine. These plots below are of acid rain deposition inside the Poás Volcano National Park. Levels of acid rain could be estimated around 4.5 g/m^2 in the red zone of the AERMOD Plot.

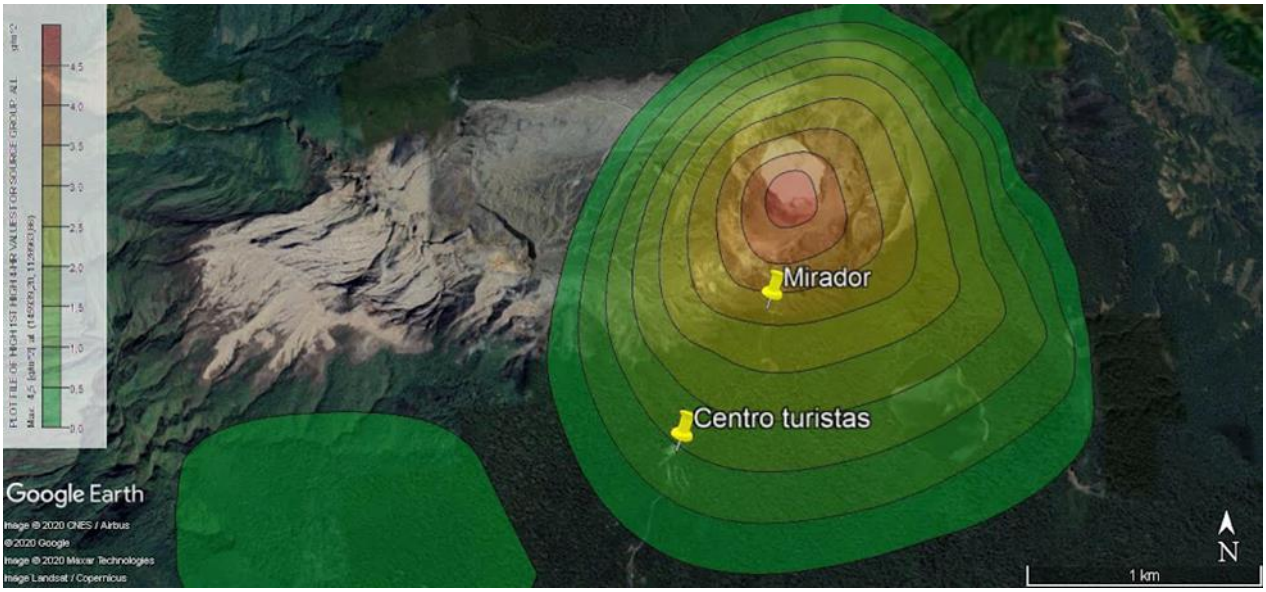


Figure 23. Acid Rain AERMOD Plot over Botos Lagoon as a result of the of the September 30th eruption

Seasonal variations especially rain in the mountain rain forest of the Poás Volcano National Park is one of the most significant variables contributing to geological changes to the Botos Lagoon. As crater lake depth increases available light decreases. As the rain contributes to the water levels the water temperature also decreases.

As a result of the environmental variables present in the high-altitude tropics each crater lake will have its own unique color and characteristics. Water chemistry, characteristics of dissolved substances, total suspended particles in the water all play a significant role in crater lake water color.

Figure 24 & 25. Dead Mountain Rain Forest Regenerating inside the Botos Lagoon 2022

Figure 26. Botos Lagoon of the Poás Volcano National Park Costa Rica September 2022

Figure 27. Botos Lagoon of the Poás Volcano National Park Costa Rica September 2022

4.4. Subaquatic vegetation

Since the Botos Lagoon is a high-altitude fresh water crater lake in a special region known as a mountain rainforest monitoring and conserving the species in and around the lake is of great importance to conservationists and the government of Costa Rica. The Botos Lagoon is located at 8,885 feet in altitude, the entire lake is a complex ecosystem within a dormant volcanic crater. There are subaquatic plant species living in this water and by deploying the Autel Lite + drone we were able to observe these aqueous plants and make population estimates. This area is known as a microclimate and very important for conservation purposes.

Figure 28. Structure of interest at Botos Lagoon of the Poás Volcano National Park September 2022

Finding the Isoetes lacustris in the Botos Lagoon was a top priority for our 2020 field study inside the Poás Volcano National Park, the lake quillwort is a subaqueous plant species native to Costa Rica This strange plant prospers at the bottom of high mountain lakes between 5,577-8,202 feet in altitude or 1,700- 2,500 meters above sea level. We located it here inside the Botos Lagoon a little bit higher than its optimum altitude. We observed through the aerial perspective the Isoetes lacustris in the Botos Lagoon thriving in areas close to the shoreline of the lake where sufficient sunlight reached the lake floor and the plants themselves.

Previous research on crater lakes in Costa Rica showed that one of the most significant variations was water level due to seasonal rainfall in the tropics. In Costa Rica the seasonality of rains is significantly and these rain levels have a direct impact on crater lakes being studied. Seasonal variations were investigated to see how certain groups of phytoplankton responded. In the research titled Phytoplankton variability in Lake Fraijanes, Costa Rica, in response to local weather variation; phytoplankton samples were taken each week and additional water samples were retrieved each month to monitor and track nutrient levels in the water. Conclusions showed that there were fluctuations throughout the year [4].

Algae is another contributing factor to crater lake color. Proliferation of micro-algae if frequent the dominant factor in green water bodies. Cantonati [5] found that high altitude lakes were dominated by algae plankton and phytoplankton species with flagella. Findings showed that these organisms could transport themselves to the deep areas of the lake floor for more abundant nutrients were due to decaying organic matter on the lake floor. These types of algae colonize the deepest areas of lakes to avoid harmful UV radiation. Certain groups of algae change they're color in response to UV radiation. Certain groups of algae protect themselves from UV radiation with colorful pigmented compounds ranging from red, to yellow, brown, orange, green and black [5].

Black pigments are a defensive mechanism shielding the organism from the UV wavelength. Because UV radiation is usually absorbed in the upper layer of the lake, algae are generally found below the first few meters down to the lowest areas of the lake where a fraction of light remains. Algae can survive in depths that receive only

1% of total light that transmitted through the lake surface. Adaptation has allowed algae development where just 1% of available light is available for photosynthesis [5].

Microalgae are a type of algae that develop in the deeper sections of high-altitude lakes because they have a distinct ability to capture the last 1% of light which transmits through the water. As the crater lake depth increases protection from harmful UV radiation is less of a necessity. Algae living in these depths need to absorb the maximum amount of available light. Microalgae can change the morphology of their structure to optimize light absorption and change the absolute quality of their chlorophyll. Algae due play a significant role in crater lake color fluctuations [5].

Phytoplankton in high altitudes crater lakes may also play a role in water color. "High altitude lakes, pearls in the mountain landscape" showed certain types of phytoplankton were adapted to conditions with minimal minerals and nutrients, and were able to survive increased acidic conditions [5].

4.5. Forest regeneration – Mountain rain forest

The Botos Lagoon was in the direct impact zone located within a two-mile radius around the active crater of the Poas volcano, therefore it had a severe effect from SO_2 emissions and volcanic ash from 2017-2019 and much of this section of the national park was burnt. In 2020 the interior of the Botos Lagoon showed many of the trees were completely black they had been burnt by the eruptions and the acid rain resulting from these increased emissions of SO_2 and acidic rain conditions. By using aerial surveillance, we were able to monitor and map the forest regeneration in many inaccessible areas of the Botos Lagoon.

In Costa Rica there are specialized trees which have adapted to harsh conditions that often come from volcanic eruptions and emissions. Here in the park, there is a tree called Copey or Azar del Monte_Clusia odorata. This tree is unique in the sense that it has developed a natural resistance to this environment by creating hard thick leaves which protect it from products of volcanic activity such as high levels of tropical UV radiation and acidic rain as well for example. The tree and it´s leaves are frequently referred to as living plastic. Mosses typically grow in dense groups in the soil, on rocks, or on the trunks and branches of trees and can be found all over once inside the Botos Lagoon. Messes most likely thrive within the Botos Lagoon because the crater walls shield the vegetation from the cold high-altitude winds. The spongy texture of mosses absorbs rain and cushions growing vegetation. In Costa Rica mosses are frequently used as a Christmas decoration for nativity scenes. Taking mosses from the forest does actually harm the ecosystem.

Figure 29 & 30. Forest on the slopes of the Botos Lagoon

Sunlight decreased by 30% at the lakeshore which created a special environment for certain exotic species of subaqueous plants such as Isoetes Lactustris. Strange bromeliads and ferns also thrive close to the lakeshore as did a wide variety of tropical mosses. This seemed to have been because of the increased humidity coming from the Botos Lagoon and the fact that there was a small nutrient concentration on NPK inside the lake which provided essential nutrients for the trees and other surrounding plant life, compared to the rest of the forest area surrounding the active crater which was relying of acid rain for several significant time periods from several months to years. The plant and tree species living in a volcanic mountain rain forest must deal with more extreme temperature fluctuations, wide variations in humidity, increased illumination, light intensity and harmful UV radiation during the day.

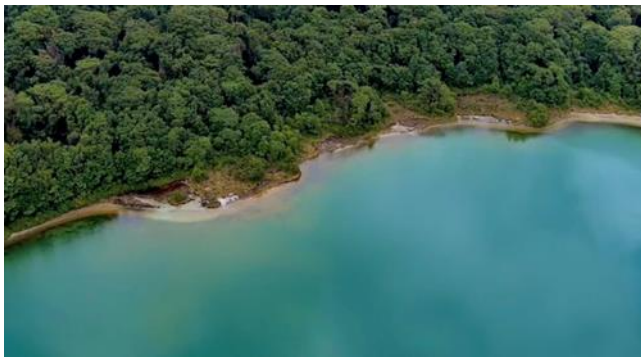



Figure 31 & 32. Botos Crater Lake Shoreline

Both Mountain rain forests and cloud forests are valued environments in Costa Rica essential to the oxygen supply of the planet. Areas like these such as the Poás Volcano National Park are essential to human survival, therefore understanding and conserving these regions is crucial. Due to the high amount of carbon these environments reduce and lock away from the air, researching these high-altitude mountain rain forests and cloud forests is of immense importance to scientists today. UAS help show the absolute thickness of these forests in Costa Rica. UAS are a more economical option than flying in single engine aircrafts for photo and videography documentation of the tropical density of vegetation. High humidity and rapid weather fluctuations in the cloud forest regions makes UAS piloting much more complicated. Simplifying the entire volcanic monitoring process is possible with modern UAS and the newly advancing thermal imaging and gas detection payload technology. Furthermore, UAS that utilizes pre-programed auto flight capabilities are able to easily generate the necessary photos required for photogrammetry. Deforestation mapping is also a potential application around the active crater of the Poás Volcano for example to observe the forest regeneration which could be very beneficial UAS application for naturalists and climatologists working in this field.


Figure 33 & 34. Forest on the interior crater walls of the Botos Lagoon


Figure 35 & 36. Forest Regeneration on Crater Interior Walls

4.6. Unknown Morphological features

It was found from monitoring the Poas Volcano National Park from the air. UAS are allowing students and researchers to conduct aerial surveillance of volcanic regions from safe distances and these flights are collectively contributing to the overall knowledge of everyone interested in conserving this precious mountain rainforest and micro climate of Costa Rica.

In September of 2021 drones were used to monitor the Botos Lagoon and take water samples from the lake for a research publication by the Laboratory of Atmospheric Chemistry LAQAT-UNA and the Water Resource Management Laboratory LAMRHI of Universidad Nacional which investigated multiple crater lakes in Costa Rica. There's something that stood out and captured a lot of attention from collecting the water samples from the Botos Lagoon; the pH levels. The measurement at one site of the lagoon was around pH 3.80, but the pH with the drone sampling was 3.43. This happened too with the sulphate and other anions. Since then we have hypothesized that could be a small fumarole deep inside the lagoon. The temperature was 64.04°F or 17.8 °C [6].

There are several additional aspects of flying remote aircraft that pilots much take into consideration when planning flight missions into active volcano craters for watch collection. “Radio communications may be perturbed due to the presence of a crater wall between the drone and the operation site. In these cases, adjusting the drone’s location via remote control can be difficult. In addition, there are uncertainties in both GNSS and the topographic maps used.” [7].

Researchers in Japan have been conducting water samples from crater lakes using UAS and found that; “The drone successfully sampled >250 mL of water from Yugama crater during a calm period at Kusatsu-Shirane volcano. This means the water sampeling can be safely carried out even if Kusatsu-Shirane volcano is in a period of unrest. Using programmed waypoints, the drone can repediately sample lake water at exactly the same location, even during periods of high probability of volcanic unrest. Sampling locations and depths can be easily altered by modifing the waypoints, and therefore, other features of interest such as fluid emissions from subaqueous fumaroles can be sampled. The UAS can also carry payloads such as the Sniffer4D and tract the volcanic emissions for the gas log which is also of strategic importance to volcanic monitoring programs [7].

Atmospheric conditions such as wind speed are the prime cause of difficulty for remote pilots sampling crater lakes. Successful UAS deployment depends on rotor power, total payload weight, and the length of rope carrying the sampler aparatus. “At crater lakes at high altitudes, such as Yugama crater lake at 6,562 feet or 2,000 meters above sea level the duration of a single flight is shorter than crater lake samples taken at lower altitudes because of the lower density of ambient air. It is noted that rapid acceleration and deceleration of the drone may cause the suspended sampling bottle to swing like a pendulum.” [7].

5. Discussion

Tropical developing countries are strategically using UAS to help with volcanic monitoring programs. About half of the active volcanoes are found within these developing nations and by using the most economical volcanic monitoring solution resources can be allocated where they are most required.

The development of low-cost affordable consumer drones has offered new opportunities to researchers working in the field of volcanic surveillance. UAS development and advancements has greatly contributed to the monitoring and surveillance of active volcanic systems. By monitoring difficult to access regions with diverse landforms consumer drones are now a fundamental part of the surveillance system and strategy for observing active volcanoes. This strategy has contributed to the increasing information relative to volcanic risk assessment and hazard prevention. UAS have been proven to be economical solutions for mapping geomorphological features of volcanic systems such as craters, fumarolic fiends and areas subject to frequent landslides. Furthermore, UAS are expanding capabilities as they can easily be used to monitor areas of significant risk due to geological hazard. 3D modeling of lava deposits, rock slides, debris avalanche, lahar, and crater lake morphology has been successfully completed by researchers monitoring volcanoes in Costa Rica as a result of a collaborative UAS project between the Universidad de Costa Rica and *Comisión Nacional de Prevencíon de Emergancias* (CNE). By using consumer drones to monitor volcanic structures and track they are progression both governments and institutions can develop data bases with digital imagery used to generate 3D Digital Surface Models highly valued in the field of volcanology. These models help geologists estimate the volume of material ejected from a crater after an eruption. Beyond volume calculation assistance digital imagery also assists in analysis of surface roughness, cracking, morphological calculations which have become vital in hazard assessment and planning for urbanization [8].

5.1. 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.

5.2. 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.

5.3. 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.

5.4. 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.

5.5. Remote pilot

Drones are a tool; they are an extension of the individual using them. Students and professional researchers can both use drones which can expand their investigation capabilities exponentially. The responsibility of the remote pilot is actually far beyond simply managing the UAS itself. Certain attention should be paid to the remote pilot in command undertaking responsibility for the drone flights in the volcanic environment. Some obvious but important factors to mention are that the drone operator brings: all drone equipment fully charged, and personal gear as well such as; gloves, gas mask, rain jacket, rain gear, umbrella, towel, change of clothes, water, candy or high sugar snacks to increase attention levels. Altitude difference can impact the level of awareness and remote pilots not familiar with working in high altitude environments may experience light headedness, dizziness or headache. Food and drinks to sustain climbing strength and endurance while in the field conducting flights is essential. Recharging batteries and remote controller the day before and packing the right food to bring with you are both essential aspects of success UAS flights in these challenging atmospheric conditions.

It's important that the remote pilot in command remain well rested and fully prepared mentally. When considering flying drones in active volcano craters there is always a possibility of eruption and this is to some extent always on the mind. There is also a certain level of excitement. Another factor is the weather fluctuations and the fact that the loss of visibility or increasing wind gusts will have an effect on the remote pilot just as much as the drone itself. Thin air and potential volcanic pollutants can create challenges for remote pilots in these environments. Volcanic emissions and resistance to harsh conditions build up over time, but certain times quick temperature drops create shivering which can complicate the remote pilot maneuvering capabilities. Cold temperatures and frequent rain showers make rain gear a requirement. Water resistant socks, shoes and keeping an umbrella nearby are all factors to be considered.

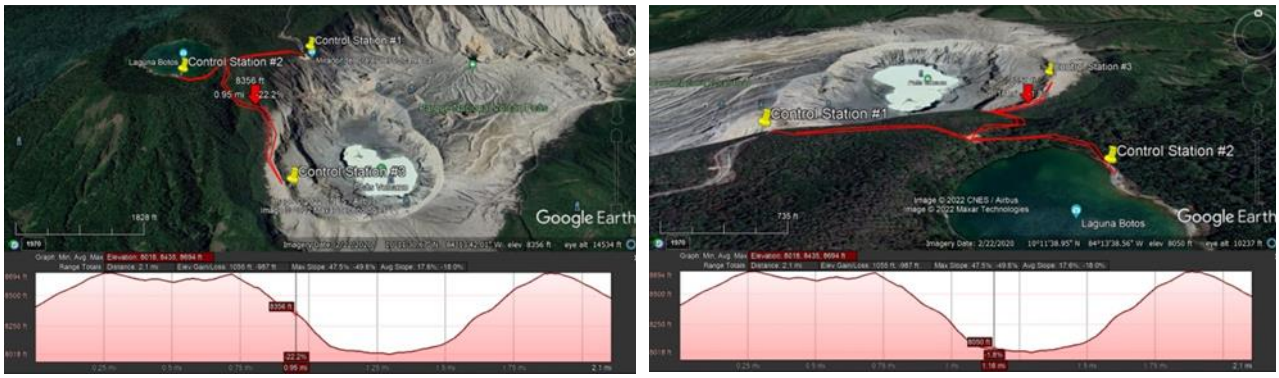


Figure 37 & 38. Google Earth topography check essential part of UAS flight mission planning

By checking altitude and topography on Google Earth before the actual flights remote pilots can significantly improve, they're changes of success in these climatic conditions. By projecting and checking flight paths on Google Earth remote pilots can measure distances, monitor for flight path obstacles like crater rim, and create a preflight strategy. By checking flight paths on Google Earth remote pilots can familiarize themselves with the terrain and be better prepared for the actual flight missions. Using Google Earth to prepare for UAS flight missions in volcanic environments also allows remote pilots the option to find the best control station or area where the drone can be launched, land and where the remote pilot can operate with the best field of view.

When flying UAS in volcanic climates it's important to closely monitor wind shear on an application such as www.Windy.com. Wind shear is a sudden and drastic change in wind speed and they can appear at any altitude in the atmosphere. Wind shears are usually associated with fronts, or cold air interacting with warm air. The division is known as a front and they divide the weather patterns. Occasionally in high altitude regions the temperature can dip below the freezing point, especially at night.

Keeping a close eye on the temperature is also important because UAS pilots want to avoid any possible structural icing. Structural icing refers to ice forming on the aircraft. For this to happen it must be at or below 32°F or 0°C. Also, for structural icing to occur there must be a presence of precipitation in the atmosphere which is very common in high altitude mountain rainforests like the Botos Lagoon region of the Poás Volcano National Park.

Air density and altitude have significant effect on an airplanes ability to fly. For example, the thin air at the summit of these high-altitude volcanoes has a lower air density as many of them are higher than 10,000 feet above sea level. It's important to remember that there is a low air density at this altitude and a drone capable of preforming in this environment is crucial to building a successful the atmospheric observation program using UAS or unmanned aerial systems. At lower altitudes like in the Central Valley of Costa Rica the air density is much higher because it is air at lower altitudes. Air density has a direct impact on UAS propeller performance and any remote pilot operating in volcanic environments should be aware of this. Propeller performance on UAS systems is better in dense air which is why the DJI Mavic Mini is rated to fly anywhere below 3,000 meters or 9,842 feet above sea level for example. Above this benchmark their air is much thinner than in lower altitudes, since the air is less dense the drone will have decreased propeller performance making operation in high altitudes more challenging for both the battery system and the remote pilot.

Figure 39. Botos Lagoon of the Poás Volcano National Park Costa Rica

Relative humidity plays a role in the flying of UAS as well and special attention must be given to the payload technology in volcanic environments as well. Flying through high levels of relative humidity and volcanic emissions can drastically degrade electrical components such as cameras due to corrosive atmospheric properties. High relative humidity means there is decreased visibility and heavier denser air. UAS propeller efficiency will increase with the higher air density resulting from the humidity or cloud coverage. Although it may be more difficult to keep a line of sight between the remote pilot and the drone itself, there will be an increased propeller efficiency and hovering until the cloud passes is a possibility. Other options would include ascending or descending the UAS above or below the cloud if it is a small cloud, or returning to home if any rain is identified.

In the research publication titled; "Low cost UAV applications in dynamic tropical volcanic landforms" for the Journal of Volcanology and Geothermal Research, authors explained: "UAV systems are gradually becoming an essential tool for volcanic monitoring and research. The most common geoscientific application of UAV uses aerial imagery to reconstruct the Earth's elevation by producing digital surface and elevation models to reconstruct land cover and generating maps and orthophotos." [8].

Management of natural resource always has an element of environmental monitoring. This type of ecological tracking is even more important with the effects of climate change are taken into consideration. UAS have become a vital tool for accurately tracking and monitoring areas of ecological importance and strategic water resources like the Botos Lagoon of the Poás Volcano National Park. UAS and the variety of environmental applications they assist with has helped governments of developing nations better understand the hydrological process, management of water resources and they have assisted in gathering valuable information required for forecasting and preventing natural disasters [9].

6. Conclusion

Using UAS offers researchers and investigators access to areas not previously accessible. These systems also offer a new perspective to enhance previous observations. The Laboratory of Atmospheric Chemistry LAQAT-UNA has used drones several times at the Botos Lagoon and the Laguna Caliente crater lake located within the active crater of the Poás Volcano national Park.

While researching the Botos Lagoon with UAS we also conducted several observational missions within Laguna Caliente the active volcanic crater of the Poás Volcano National Park. Images and videos collected during these flights showed a distinctively darker color of the lake water to the north of the Laguna Caliente. This grey area is made of sediments and sulfur remobilized by a subaquatic fumarole. That fumarole is very far to the north of Laguna Caliente. The subaquatic fumarole is close to the cliff and is sporadically active or discontinuous. Several times in September we flew consumer drones over Laguna Caliente to observe the northern section of the lake watching for any signs of the discontinuous subaquatic fumarole.

OVSCORI-UNA scientists observed it for the first time on August 13, 2022. It got more and more vigorous with time and reached a maximum of activity between Sept 3 and Sept 9. That week it activated several times per day, for 1 to 3 hours, and really looked like vigorous bubbling coming from the depths of Laguna Caliente. Since Sept 9, its activity decreased significantly in duration and amplitude. We used the UAS to continue observing the northern areas of Laguna Caliente during the rest of September to try and observe this subaquatic fumarole. It is pretty rare to observe it today from the Main Lookout point but the use of UAS made it easier to monitor this area without entering the active crater.

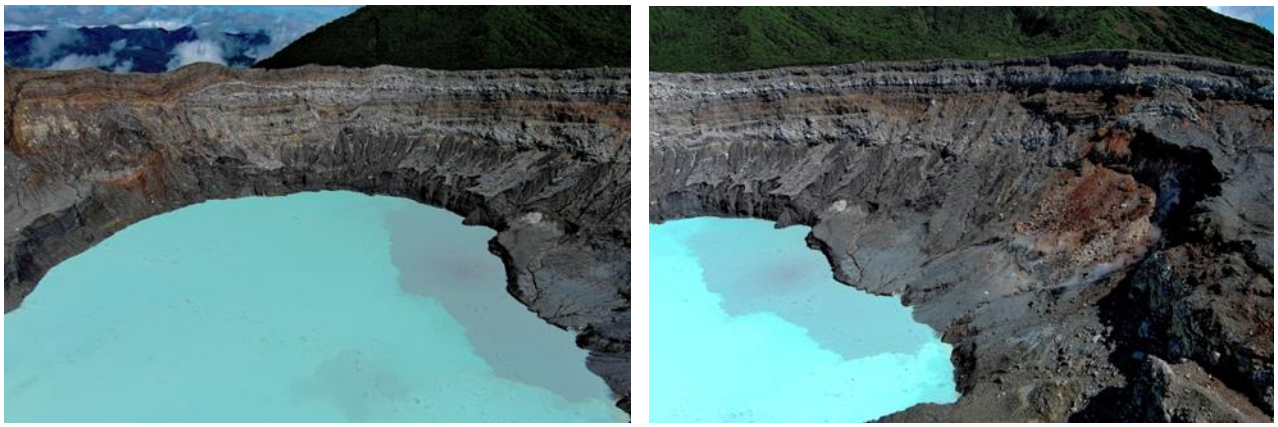


Figure 40 & 41. North Section of Laguna Caliente Poás Volcano National Park

The interpretation of this phenomena observed with UAS is quite remarkable. The fact that this fumarole appeared more or less at the same time as a seismic increase of activity: increase of seismic energy tremor amplitude is very interesting. The change of activity seismic, deformation and gas release pointed to a superficial pressurization. The tendency got so clear by the beginning of September that we sent an alert to the authorities on Sept. 8, occurrence of phreatic eruptions was our most likely scenario, with a potential of affectation of the public area. But the next day the tendency stopped and reversed. Today we consider the volcano back to its steady low activity state. Hence, it seems that this fumarole opened as a consequence of that shallow pressurization, and was effective enough to release the pressure, preventing a phreatic eruption from occurring. Many other times we observe large areas of dark material in the lake which are due to the rain.

Figure 42 & 43. North Section of Laguna Caliente Poás Volcano National Park

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, convecting 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].

The evaluation of natural disasters, in particular volcanic eruptions, constitutes a great challenge for all scientific researchers. Today we notice the emergence of several techniques and new technologies responding to this point. In this sense, we can give the example of drones, a tool that allows the rapid and precise generation of data relating to volcanic emissions [11].

Thanks to the different possibilities of use of these platforms, they now make it possible to acquire data through RGB, multispectral sensors, as well as other different on-board devices. The study conducted by UAV based application for mapping a geothermal feature in Indonesia showcased these advancements and highlighted the advantages that a UAV could have in the field of volcanoes. In particular for the generation of high-resolution derivative products, namely the detection and the mapping of geothermal features and this compared to other platforms, especially satellites as Landsat [12].

The study carried out by Brighenti in 2021 used photogrammetric data from UAVs in order to establish a monitoring of the deformations of the Santa Barbara mud volcano. The obtained results indicate an accuracy of centimeter order in the detection of deformations [13].

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Author contributions

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

Conflicts of interest

The authors declare no conflicts of interest.

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