Surveying Makushin Volcano, Alaska, using an Unoccupied Aircraft System for Volcano Observation

Mission Overview

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Executive Summary

Makushin Volcano is located on Unalaska Island, Alaska, 25 km east of Dutch Harbor, the largest fishing port in the U.S. Makushin last erupted in 1995 sending an ash cloud to 2.5 km above sea level. Beginning on 15 June 2020, a swarm of earthquakes occurred 8 km beneath the volcano's edifice causing the Alaska Volcano Observatory (AVO) to raise the Aviation Color Code and Volcano Alert Level to YELLOW/ADVISORY for several weeks. Though activity has since declined, Makushin ranks in the highest threat category identified by the U.S. Geological Survey’s (USGS) National Volcanic Threat Assessment (Ewert et al., 2018) primarily due to its potential to emit ash clouds that disrupt aviation and to produce large flow events.

Activity levels at Makushin Volcano are monitored by the USGS AVO using a network of seismic monitoring stations and webcams installed on and around the volcanic edifice as well as with sporadic visits by AVO volcanologists to visually assess the summit region and sample gases emitted from the summit craters and hydrothermal areas on the flanks of the edifice. These surveys are time consuming, expensive, and can potentially be hazardous to field crews during times of unrest.

To mitigate this hazard, the USGS Volcano Hazards Program has worked closely with industry partners and NASA to develop a next-generation volcano observation platform aboard an Unoccupied Aircraft System (UAS). Based on the Black Swift S2 fixed-wing UAS with a 3-m wingspan and 2.3-kg payload capacity, this platform can approach active volcanoes from safe distances of more than 30 km while climbing to summit elevations of more than 3000 m and remain airborne for about 90 minutes. Equipped with a backup satellite link and real-time data telemetry back to the base station, the aircraft is built to fly beyond visual line of sight during volcano observation missions (Kern et al., 2020).

The Black Swift S2 volcano observation platform will be deployed to Unalaska Island in the summer of 2021 to characterize activity at Makushin Volcano and provide the USGS with monitoring information needed to assess current threat levels.

Mission Objectives

The objectives of the volcano monitoring mission are twofold: For one, the UAS survey will help USGS assess activity at Makushin. Gas measurements will be used to check on the possibility of a new magma intrusion at depth, while a photogrammetry survey of the summit will be used to build a digital elevation model and check for possible changes to the vent geometry, size, and distribution as well as inform our understanding of the potential of lahars and debris flows caused by melting of snow and ice.

Additionally, we hope that this proof-of-concept mission will allow us to deploy the S2 UAS platform to other volcanoes in the U.S. and internationally in the near future, both for gathering baseline monitoring data and in response to volcanic crises or eruptions. It is during these times of unrest that this next-generation UAS platform will provide new opportunities for volcano observation not previously possible with crewed aircraft.
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The Black Swift S2 Volcano Observation Platform

Realizing the potential that UAS have, the USGS partnered with Black Swift Technologies LLC and NASA to develop, test, and certify a next-generation volcano observation platform. Major emphasis was placed on the necessity for sufficient range to allow UAS operations to be conducted from a safe distance (>10 km) from remote, potentially hazardous volcanoes.

The Black Swift S2 UAS

The Black Swift S2 (Fig. 1) is a ruggedized UAS with a 3-m wingspan that can carry a 2.3-kg payload while remaining airborne for 90 minutes and enduring winds up to 15 m/s. The 90-km range of the UAS allows staging of operations up to ~30 km from the target volcano while still providing sufficient endurance to climb to summit elevations around 3,000 m, perform the measurements, and return to base safely.

The S2 UAS is fully equipped for missions that extend beyond visual line of sight (BVLOS). An Iridium satellite radio provides backup avionics in case of loss of communications. For situational awareness, forward-looking video is recorded in-flight, and data from the meteorology and gas sensors are telemetered back to the base station in real-time.

Volcano Observation Payload

A custom payload for volcano observation was developed for the S2 UAS (Figs. 2,3, Table 1). The payload includes a high-precision CO$_2$ & H$_2$O analyzer capable of reliably detecting CO$_2$ anomalies as low as 1 part per million (ppm). Electrochemical sensors measure the in-situ concentrations of SO$_2$ and H$_2$S, while an upward-looking UV spectrometer measures the overhead SO$_2$ column. A nadir-facing still camera records imagery for generating DEMs. Finally, a custom-built meteorology probe provides 3D wind speed, pressure, temperature, and humidity information.

![Fig. 1 - The Black Swift S2 UAS can be launched with a pneumatic catapult. Vertical takeoff and landing capabilities are currently being implemented as well. (photo: Black Swift Technologies LLC)](image-url)
Fig. 2 - Modular payload design in the ~20 cm diameter nose cone of the S2 UAS. The meteorology probe protrudes forward to sample the unperturbed atmosphere.

Fig. 3 - In the payload interior, the LI-COR gas analyzer is wrapped in yellow foil to shield it from electromagnetic interference. (photo: Black Swift Technologies LLC)

<table>
<thead>
<tr>
<th>Payload Item</th>
<th>Sensor Characteristics</th>
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<tbody>
<tr>
<td>LI-COR 850 IR gas analyzer</td>
<td>CO₂ &amp; water vapor in-situ concentration</td>
</tr>
<tr>
<td>City Tech SO₂ sensor</td>
<td>SO₂ in-situ concentration (0-200 ppm)</td>
</tr>
<tr>
<td>City Tech H₂S sensor</td>
<td>H₂S in-situ concentration (0-100 ppm)</td>
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<tr>
<td>Ocean Optics FLAME-S</td>
<td>Upward-looking UV spectrometer (SO₂ column)</td>
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<td>MapIR Kernel</td>
<td>Downward facing still camera.</td>
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<tr>
<td>FPV Video</td>
<td>Forward facing video camera.</td>
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<tr>
<td>BST 5 Hole Probe</td>
<td>3D wind, pressure, temperature, humidity</td>
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Table 1 - Components of the volcano observation payload currently integrated into the S2 UAS. Other instruments such as LI-DAR, InSAR, or magnetometers may follow.
Flight Plan

Staging and takeoff
UAS operations will be based out of one of two locations. The primary choice for base of operations is the Dutch Harbor airport (DUT). Working closely with the FAA and airport managers, permission has been sought to launch and recover the UAS on the Unalaska West Parking Apron (area marked in green in Fig. 4). Launch operations require little space, as the aircraft is launched using a pneumatic catapult (Fig. 1). The parking apron also easily provides sufficient space for landing the UAS.

A backup location to stage operations out of was identified in case the airport is not available at times. If necessary, the team can operate out of Fort Schwatka on the north east end of Amaknak Island. If operating from this backup location, the team will always be in contact with an observer at Dutch Harbor Airport to deconflict with airport traffic. UAS operations based in either location will await time windows when there is no known air traffic on final approach or takeoff from the airport.

Fig. 4 – Aerial photograph of the Dutch Harbor Airport (DUT). Google Earth.
Fig. 5 – Map showing the extent of the TFR requested to deconflict air traffic during this mission. Google Earth.

Fig. 6 – Backup UAS launch site at Fort Schwatka, Amaknak Island.

Approach

Once launched, the aircraft will climb to 400’ and transit west over Unalaska Bay at this altitude to the start of a Temporary Flight Restriction (TFR) area beginning on the west side of the bay (Fig. 5). The UAS will then approach Makushin from the east, flying 25 km up the Makushin Valley while climbing to slightly above the volcano’s 2,000 m summit elevation (Fig. 7).
Throughout the approach to the volcano and once on-site at the volcano’s summit, the live data feed from the meteorology sensors and, if being flown, the gas sensors will be used to assess conditions. The mission will be aborted and the UAS will return to base if any unsafe conditions (high winds, icing) are encountered at any time during the mission.

Data-gathering surveys
Assuming it is safe to do so, the first data-gathering mission will be to perform a photogrammetry survey of the summit region. For this, oblique, overlapping aerial images will be recorded along a pre-defined raster track covering the volcano’s summit (Fig. 8). Upon returning to base, these images will be processed using an oblique photogrammetry method to produce a digital elevation models (DEM) of the volcano’s summit region. This DEM will serve as a baseline to which future photogrammetric surveys can be compared to assess topographic changes in the volcano’s summit.

Upon return of the aircraft to base, the assessment of weather conditions that occurs during the photogrammetry mission, both by meteorology sensors and the collected imagery, will also be used to develop the flight plan for the gas monitoring mission. For this, the aircraft will need to be sent into the dilute gas plume to sample its composition and then traverse several times beneath the downwind plume to measure SO₂ emission rate.
An example gas monitoring flight is shown in Fig. 9. This flight was performed by helicopter on 20 August 2019. After taking off from Dutch Harbor airport (DUT) airport, the helicopter flew up the south side of Makushin Valley while climbing to 5,000 ft. Upon reaching the summit area, we were able to determine that the gas plume was blowing towards the north, so the pilot was directed to fly to that side of the volcanic edifice while dropping to about 3,000 ft. Here, traverses were flown back and forth underneath the plume. The data collected by the upward-looking DOAS spectrometer during these traverses was used to derive an SO2 emission rate (approx. 200 t/d in this case). After 5 traverses, the helicopter climbed to about 4,000 ft, the approximate altitude of the plume on this day. Here, the pilot flew several circles inside the plume. During this time, the in-situ gas sensors measured the relative plume composition (CO2, SO2, H2S and H2O). The GPS track from the neutral circles was also used to derive the wind speed and direction at the location of the plume. These data are needed to determine the gas emission rate.

The proposed UAS volcano observation flight will take a similar route as this helicopter mission. We envision approaching the volcano by flying up the Makushin Valley while climbing to about 6,000 ft as was done in the example observation flight. Given the distance to the volcano, the flight will enter beyond visual line of sight (BVLOS) status en route. The observation segment within about 5 km of the volcano’s summit will then proceed approximately as follows (Fig. 10):
Fig. 9 - Flight path of a volcanic gas monitoring mission flown at Makushin Volcano by helicopter on 20 August 2019. The color scale indicates the amount of SO$_2$ above the aircraft as measured by a DOAS spectrometer.

(1) The aircraft will approach the volcano while climbing to about 6,000 ft such that it is slightly above the summit of the volcano. (2) The aircraft will then circle the vents at the summit. During this leg, wind conditions will be assessed, along with visual observations of degassing sources. It is possible that the circles will result in the aircraft intersecting the plume, thus allowing the in-situ sensors to sample the volcanic gases. (3) If the gas concentrations encountered during leg 2 are not sufficiently high to properly characterize the plume chemical composition, additional plume ‘punch throughs’ will be flown. Here, the aircraft will fly at low altitude directly over the degassing sources to maximize the gas concentrations encountered in flight. (4) After the plume composition has been measured, the aircraft will descend to approximately 3,500 ft while moving away from the volcano’s summit in the direction in which winds are carrying the plume. In this example, we assume that typical wind conditions are blowing the volcanic gases towards the east. (5) Using a ‘dog bone’-style flight track, the aircraft will be flown back and forth underneath the gas plume, perpendicular to the plume’s propagation direction. This will allow the upward-looking DOAS spectrometer to measure the cross-sectional SO$_2$ burden in the plume, thus allowing us to determine the emission rate (in tons per day). (6) With the gas measurements complete, the aircraft will return to base.
**Returning to base**

The UAS will be programmed to return to base along a similar path as the approach, proceeding down the Makushin Valley while descending to 400', then crossing Unalaska Bay at this altitude. If air traffic is present expected in the vicinity of the Dutch Harbor airport, the UAS will loiter at a location just west of Unalaska Bay until the final approach to the landing site is clear. If air traffic does not clear before the UAS batteries run out, the aircraft will be landed near the eastern end of Makushin Valley and recovered later by boat.

**Scientific Background and Research Goals**

Volcano observatories use seismic, geodetic, and geochemical instrument networks installed on active volcanoes to monitor activity. However, observations of gas emissions and morphological changes occurring in a volcano’s summit region often require airborne surveys.

**Gas Composition and Emission Rate**

When magma rises in a volcanic system, volatile species such as C, S, and $\text{H}_2\text{O}$ exsolve from the melt and can be degassed into the atmosphere. C is especially volatile and typically exsolves at depths $>10 \text{ km}$, while S and $\text{H}_2\text{O}$ will only degas once the magma rises closer to the surface. The composition of a volcanic gas therefore contains information on magma residence depth, while the gas emission rate is diagnostic of the volume of intruding and degassing magma.
Fig. 11 - Fixed-wing airborne surveys detected anomalous CO$_2$ emissions 5 months prior to the 2009 eruption of Redoubt Volcano, Alaska (Werner et al, 2013).

Fig. 12 - DOAS traverses flown by fixed-wing aircraft beneath the plume of Redoubt Volcano in 2017 showed that SO$_2$ emissions had dropped to about 100 t/d indicating no further magma intrusion (AVO 2017).
The USGS routinely monitors the composition and emission rate of gases emitted from active volcanoes in the U.S. Airborne measurements are of particular importance in remote regions such as Alaska. During a routine survey in October 2008, anomalous CO$_2$ emissions were detected at Redoubt Volcano, a large stratovolcano 175 km southwest of Anchorage. These were interpreted to indicate deep magmatic recharge. Subsequent gas surveys showed a shift towards more S-rich emissions indicating shallowing magma, culminating in a large explosive eruption on 23 March 2009 (Fig. 11).

While the gas composition in a volcanic plume can be measured with in-situ sensors, an upward-looking differential optical absorption spectrometer (DOAS) can be used to quantify their emission rates. The spectrometer measures the absorption of scattered UV sunlight passing through the plume from which the overhead vertical column amount can be determined (Fig. 12). Spatial integration across the plume width and multiplication with the wind speed then yields the emission rate, e.g. in metric tons per day (t/d).

Photogrammetry / Structure from Motion (SfM)

Besides gas sensors, the Piper Navajo aircraft used for the observation flights also carried hand-held visible and infrared cameras. Photographs from these were processed using an oblique photogrammetry method to produce DEMs of the volcano's summit region. They showed that explosive activity gave way to continuous lava effusion on 4 April 2009 and allowed the tracking of lava extrusion volume over time (Fig. 13).

![Photogrammetric DEM showing dome growth during the 2009 eruption of Redoubt Volcano, AK (Diefenbach et al., 2013).](image-url)
Makushin Research Objectives
During the UAS survey of Makushin, we hope to gain information on both surficial and sub-surface processes occurring at this active volcano. Photographs of the summit area will be examined and compared to photographs taken on previous, crewed missions. Experts will look at the extent of snow and ice cover, the distribution and appearance of gas vents and fumaroles, and investigate any possible changes in appearance or depth of the summit crater lake. The recorded oblique aerial photographs will be evaluated to generate a digital elevation model (DEM), thus providing a baseline for comparison of topographic features with future photogrammetric surveys.

The gas sensors will be used to analyze the chemical composition of gases emitted from the multiple sources in the summit region. If meteorological conditions allow, the various sources will be characterized individually, and these measurements will be compared to previous gas surveys. DOAS DOAS measurements of SO$_2$ emission rates will be recorded several kilometers downwind of the volcanic vents, and these data will be combined with the compositional data to determine emission rates for the major plume species (H$_2$O, CO$_2$, SO$_2$, and H$_2$S). Gas geochemists can use these data to build a conceptual model for degassing at Makushin, e.g. checking for signatures that could indicate the injection of fresh magma from depth or the expanded prevalence of hydrothermal processing and gas-water interaction in the shallow plumbing system of the volcano.

Taken together, these observations will contribute in a meaningful way to the Alaska Volcano Observatory’s assessment of ongoing activity at Makushin and help provide context for the volcano’s recent seismic unrest.

Disclosures
Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Cited References
AVO (2017) Data reported by the Alaska Volcano Observatory after a Cook Inlet airborne gas survey on 20 April 2017

