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# Special Topic—Unoccupied Aircraft Systems

Chapter L of

**Recommended Capabilities and Instrumentation for Volcano Monitoring in the United States**


Scientific Investigations Report 2024–5062


**U.S. Department of the Interior**
**U.S. Geological Survey**

**Cover.** U.S. Geological Survey scientists L. Clor and A. Diefenbach prepare for a volcanic gas survey of the 2004–2008 lava dome of Mount St. Helens, Washington, using unoccupied aircraft systems. Photograph by P. Kelly, U.S. Geological Survey, September 25, 2018. Background image shows a typical view of the 2008–2018 lava lake in the Overlook crater within Halemaʻumaʻu, Kīlauea. Photograph taken from a helicopter by Tim Orr, U.S. Geological Survey, on August 16, 2013.

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Edited by Ashton F. Flinders, Jacob B. Lowenstern, Michelle L. Coombs, and Michael P. Poland

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# Conversion Factors

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| meter (m) | 1.094 | yard (yd) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Mass | |
| kilogram (kg) | 2.205 | pound, avoirdupois (lb) |

# Abbreviations

| | |
|---|---|
| DEM | digital elevation model |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| lidar | light detection and ranging |
| PIV | particle image velocimetry |
| sUAS | small class unoccupied aircraft system |
| UAS | unoccupied aircraft system |
| USGS | U.S. Geological Survey |
| VHP | U.S. Geological Survey Volcano Hazards Program |

## Chapter K

# Special Topic—Unoccupied Aircraft Systems

By Angela K. Diefenbach

## Introduction

Unoccupied aircraft systems (UAS) increasingly support volcano monitoring and eruption response activities in the United States and abroad (James and others, 2020). Advances in UAS platforms and miniaturization of sensors over the past decade have expanded the use of this technology for a wide range of applications within volcanology (Jordan, 2019; James and others, 2020). UAS can greatly enhance existing ground-, aerial-, and satellite-based observation and in situ monitoring networks at volcanoes by providing new avenues for data collection in terms of access, resolution, and timing. UAS can collect data in difficult and hazardous environments, reducing risk to occupied aircraft and (or) ground crews; support the generation of dense time series of data through frequent, low-cost, high-resolution surveys; and provide real-time, on-demand measurements at volcanic systems for indicators such as gas, thermal output, and topographic change without the need to wait for contracted aerial flight services or satellite orbit intervals.

During the 2018 response to the Kīlauea eruption on the Island of Hawai‘i, UAS were used extensively and successfully to monitor, track, investigate, and (or) warn of ongoing volcanic activity (fig. L1; Neal and others, 2019). Throughout the eruption, the UAS team was able to provide data products rapidly to emergency managers for situational awareness and to scientists for quantitative hazard assessment (Diefenbach and others, 2018). Over the course of 4 months, more than 1,200 UAS missions were flown and yielded critical data that included (1) live video to emergency operations centers in Hilo and Honolulu for situational awareness; (2) gas emission rates, compositions, and concentrations; (3) repeat nadir videos over sections of the lava channel to support measurements of lava effusion rate; (4) oblique videos for hazards assessment and outreach; and (5) photogrammetry surveys to create very high-resolution topographic models and orthophoto mosaics (Diefenbach and others, 2018). In coming years, the U.S. Geological Survey (USGS) Volcano Hazards Program (VHP) plans to expand its fleet of UAS, associated sensors, and remote pilots to enhance volcano monitoring and response capabilities.

Currently (2023), USGS operational capabilities are restricted to small class UAS (sUAS; less than [<] 55 pounds) that are limited in range, payload capacity, and flight duration. Additionally, USGS-piloted platforms are restricted to the U.S. Department of the Interior Office of Aviation Services approved fleet, which includes a limited number of small and medium multi-rotor aircraft and vertical take-off and landing fixed-wing aircraft (https://www.doi.gov/aviation/uas/fleet). Each type of platform has advantages and disadvantages. Small rotor-wing quadcopters are fast to deploy, can be carried in a backpack, and are highly maneuverable, but are typically only equipped with a small camera and have a minimal flight range. Medium rotor-wing hexacopters can carry larger payloads (< 20 kilograms [kg]) and varied sensors, but, with the drawback of minimal flight time (<30 minutes), they typically have similar range capabilities to their smaller counterparts and are not as easily deployable. Fixed-wing platforms provide relatively long endurance (<60 minutes) and range and, with the vertical take-off and landing capabilities, can launch and land in relatively small spaces; however, they have less maneuverability and hovering capability than the rotor-wing platforms. Although the 2018 Kīlauea response showed the benefit of the current UAS fleet, all platforms have limited range [<10 kilometers (km)], such that operators must be stationed relatively close to the region of interest. To expand UAS monitoring capabilities, VHP staff have been working closely with industry partners and the National Aeronautics and Space Administration to develop a next-generation UAS for volcano monitoring (Kern and others, 2020). This ruggedized, mid-range (>20 km), multiparametric (gas and photogrammetry) UAS has been developed to meet volcano monitoring needs, particularly at less accessible, more dangerous stratovolcanoes. It is expected in the coming years that additional UAS platforms with new and smaller sensors will expand our capabilities to meet the Nation’s volcano monitoring objectives.

## Capabilities Provided

### Imagery (Including Thermal Infrared)

UAS provide a relatively new platform for near-field remote sensing with enhanced capability of resolution, timing, and access compared to other observation platforms. The most common application of UAS in volcano monitoring is collection of imagery, including both video and photography. UAS can be equipped with various camera sensors that have visible wavelength, thermal, and multispectral capabilities and range in size and sensor resolution from small-compact, lightweight cameras to large digital single-lens reflex cameras. Real-time telemetered video feeds offer situational awareness not only to the remote pilot and crew during

operations, but they can be transmitted to remote offices, such as emergency operations centers or volcano observatories, for on-demand situational awareness during an evolving volcanic event (for example, the 2018 eruption of Kīlauea).

UAS can capture extraordinarily stable video using onboard Global Positioning System (GPS), which proves useful for particle image velocimetry (PIV) analysis to support eruption rate measurements over lava channels (Dietterich and others, 2021) as well as surface-flow velocity measurements of streams, glaciers, or landslides on volcanoes that may support hazards assessment.

Additionally, UAS equipped with thermal cameras can assist in identifying, measuring, and tracking thermal anomalies to aid in forecasting. Thermal cameras onboard UAS can provide substantially higher resolution imagery than traditional airborne surveys, enhancing identification of thermal features and enabling detailed analysis of thermal structures and heat loss.

## High-Resolution Mapping

Cameras aboard UAS are primarily used for photogrammetry surveys to create high-resolution [centimeter-scale] digital elevation models (DEMs) and orthophotograph mosaics. Accurate, precise, high-resolution topographic data are fundamental to understanding volcanic hazards—whether it be for modeling hazardous lava flows, geologic or hazard mapping, morphometric studies, or assisting with instrumentation and telemetry path planning. DEMs and orthophotograph mosaics derived from UAS surveys can be as many as two orders of magnitude higher resolution than what can be acquired by commercial satellite-based imagery (James and others, 2020). Repeat topographic modeling for change detection provides critical metrics such as (1) lava dome growth (for example, the two-dimensional displacement field, strain components, extrusion rate, and apparent lava viscosity; Zorn and others, 2020); (2) lava-flow advancement, volumes, and rates of extrusion (for example, Turner and others, 2017; Dietterich and others, 2021); and (3) the dynamics of caldera collapse (Diefenbach, 2018). Additionally, these very high-resolution DEMs support lahar modeling and measuring channel migration and the depths and volumes of lava and water lakes. Photogrammetry and ground-penetrating radar surveys can provide stream-bottom bathymetry measurements, and when flown over glaciers and ice fields, they can support an improved understanding of water budgets on ice-clad volcanoes. High-resolution DEMs can also be acquired by UAS equipped with miniaturized light detection and ranging (lidar) sensors; however, the mapping extent is commonly reduced compared to UAS photogrammetry surveys owing to the slow speed and close range required by current UAS-based lidar sensors. Rotor-wing UAS provide unprecedented access to vertical or overhanging surfaces (such as crater walls or cliffs) to create high-resolution three-dimensional models of these environments for mapping or quantifying change over time in ways that conventional aircraft or field crews cannot achieve. UAS aeromagnetic surveys allow for very detailed three-dimensional mapping of obscured deposits and subsurface structures (for example, Kaneko and others, 2011). The ease with which UAS can be used to conduct repeat surveys allows UAS-based aeromagnetic monitoring to detect critical changes at a volcano, such as the movement of magma through time-series evaluation.

## Direct Sampling and Airborne Measurements

Aside from the use of UAS for collecting imagery and photogrammetry, they also provide the potential for direct sampling of volcanic and geothermal gas, particles, and even sampling of waters from remote locations. Miniaturized multicomponent gas analyzer systems and differential optical absorption spectroscopy sensors can be placed on UAS to measure gas ratios and sulfur discharge in volcanic plumes (for example, D’Arcy and others, 2018; Syahbana and others, 2019; Liu and others, 2020). Various sampling devices are being developed to collect plume particulates (for example, Mandon and others, 2019). Nadeau and others (2020) described how UAS were used to sample the water lake at the summit of Kīlauea, which existed in the deep and inaccessible crater of Halemaʻumaʻu between the lava eruptions in 2018 and 2020. Additional discussion on these topics is provided in chapter E on gas (this volume; Lewicki and others, 2024) and chapter F on water (this volume; Ingebritsen and Hurwitz, 2024), as is the promise of direct measurements of stream discharge through automated PIV analysis (Lewis and others, 2018) and radar techniques, such as the USGS’s Qcam (Fulton and others, 2020). Additionally, thermal cameras and temperature probes with data loggers onboard UAS can provide near-field remote and direct measurements of water temperatures, respectively, and repeat surveys can be flown to detect changes in temperature.

# General Recommendations and Considerations

UAS-based volcano monitoring is relatively new, and expansion of its routine use is still in the development phase. UAS-based volcano monitoring strategies and recommendations will vary greatly depending on factors such as volcano accessibility and remoteness, eruption style, and landowner permissions. In addition, limiting factors imposed by the current USGS UAS fleet include flight altitude, distance, and duration. Therefore, we provide herein generalized recommendations for UAS-based volcano monitoring that take these factors into account along with identifying ways to fill critical data gaps identified at each volcano—specifically for levels 3 and 4 volcanoes. At all U.S. volcanoes, we recommend that UAS-based monitoring take an opportunistic approach. For example, if ground-based installations are taking place at a volcano that will involve helicopter support to deploy crews, a UAS component would ideally be involved if it serves to fill a specific monitoring gap or serves as a bridge between ongoing ground, air, and satellite observations.

One of the biggest advantages that UAS technology brings to volcano monitoring programs is its rapid deployment capability for eruption response work (for example, Kīlauea, 2018; Mauna Loa, 2022) that can fill critical data gaps, enhance and augment existing monitoring techniques, and most importantly reduce risk to personnel. Furthermore, UAS provide response teams with operational control of an aircraft that can be flown on-demand, day and night, to collect multiple types of data and observations. The suite of UAS platforms and sensors housed at each observatory would ideally be used as a cache for rapid response (see chapter M, this volume; Flinders, 2024) to a volcano under the purview of any one of the five U.S. volcano observatories. In addition to equipment, a cadre of pilots would ideally be available to operate the aircraft, collect and process the data, and support monitoring and emergency operations. Other groundwork needs to be laid to have an effective UAS emergency response, which includes having permits and permissions in place ahead of time, pre-coordination among agencies and institutions, UAS contracts made available, training and pilot proficiency established, data-management plans worked out, and plans made for effective and rapid integration of UAS operations into restricted and complicated national airspace.

UAS technology and sensor development are rapidly evolving and capabilities in this realm of technology are ever increasing. The limits seem nearly boundless for the use of UAS in volcano monitoring as small UAS platforms are developing into more capable aircraft in terms of operational range, flight duration, and payload capacity. The miniaturization of various sensors along with new sensor and payload development will further expand volcano monitoring capabilities. In the coming years, development of deployable seismometers, Global Navigation Satellite System (GNSS) sensors, lightning detection sensors, and direct lava and rock sampling are expected. Developments in artificial intelligence to support enhanced autonomous flight, terrain following, obstacle avoidance, and real-time data processing will further capabilities. In summary, UAS have considerable potential to expand volcano monitoring capabilities and improve understanding of volcanic systems by bridging the unique spatial and temporal divides that limit current monitoring strategies.

Ideally, there would be at least two accredited UAS remote pilots at each volcano observatory; the success of UAS-based volcano monitoring relies heavily on having trained remote pilots to design and fly missions to collect critical data to enhance monitoring capabilities. In addition to remote pilots, each observatory would ideally have a fleet of sUAS platforms and sensors capable of a broad array of volcano monitoring techniques. Long-term investment by the VHP would allow expansion of its UAS monitoring capabilities, including remote pilot training, UAS procurement, development of platforms and sensors, and field campaign support.

**Figure L1.** Photograph showing a U.S. Geological Survey hexacopter unoccupied aircraft system mapping the lava flow field during the 2018 lower East Rift Zone eruption of Kīlauea, Hawaiʻi.

## References Cited

D'Arcy, F., Stix, J., de Moor, J., Rüdiger, J., Diaz, J., Alan, A., and Corrales, E., 2018, Drones swoop in to measure gas belched from volcanoes: Eos, v. 99, https://doi.org/10.1029/2018eo102329.

Diefenbach, A.K., 2018, The use of UAS to monitor topographic change at the summit and lower east rift zone during the 2018 Kīlauea eruption response [abs.]: American Geophysical Union, 2018 Fall Meeting, Washington D.C., abstract G13A-05.

Diefenbach, A.K., Adams, J., Burton, T., Koeckeritz, B., Sloan, J., and Stroud, S., 2018, The 2018 U.S. Geological Survey-Department of Interior UAS Kīlauea eruption response [abs.]: American Geophysical Union, 2018 Fall Meeting, Washington D.C., abstract V23D-0107.

Dietterich, H.R., Diefenbach, A.K., Soule, S.A., Zoeller, M.H., Patrick, M.P., Major, J.J., and Lundgren, P.R., 2021, Lava effusion rate evolution and erupted volume during the 2018 Kīlauea lower East Rift Zone eruption: Bulletin of Volcanology, v. 83, no. 25, 18 p., https://doi.org/10.1007/s00445-021-01443-6.

Flinders, A.F., 2024, Special topic—Rapid-response instrumentation, chap. M *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–M, 4 p., https://doi.org/10.3133/sir20245062M.

Fulton, J.W., Anderson, I.E., Chiu, C.-L., Sommer, W., Adams, J.D., Moramarco, T., Bjerklie, D.M., Fulford, J.M., Sloan, J.L., Best, H.R., Conaway, J.S., Kang, M.J., Kohn, M.S., Nicotra, M.J., and Pulli, J.J., 2020, QCam—sUAS-based Doppler radar for measuring river discharge: Remote Sensing, v. 12, no. 20, https://doi.org/10.3390/rs12203317.

Ingebritsen, S.E., and Hurwitz, S., 2024, Streams, springs, and volcanic lakes for volcano monitoring, chap. F *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–F, 9 p., https://doi.org/10.3133/sir20245062F.

James, M.R., Carr, B.B., D'Arcy, F., Diefenbach, A.K., Dietterich, H.R., Fornaciai, A., Lev, E., Liu, E.J., Pieri, D.C., Rodgers, M., Smets, B., Terada, A., von Aulock, F.W., Walter, T.R., Wood, K.T., and Zorn, E.U., 2020, Volcanological applications of unoccupied aircraft systems (UAS)—Developments, strategies, and future challenges: Volcanica, v. 3, no. 1, p. 67–114, https://doi.org/10.30909/vol.03.01.67114.

Jordan, B.R., 2019, Collecting field data in volcanic landscapes using small UAS (sUAS)/drones: Journal of Volcanology and Geothermal Research, v. 385, p. 231–241, https://doi.org/10.1016/j.jvolgeores.2019.07.006.

Kaneko, T., Koyama, T., Yasuda, A., Takeo, M., Yanagisawa, T., Kajiwara, K., and Honda, Y., 2011, Low-altitude remote sensing of volcanoes using an unmanned autonomous helicopter—An example of aeromagnetic observation at Izu-Oshima volcano, Japan: International Journal of Remote Sensing, v. 32, no. 5, p. 1491–1504, https://doi.org/10.1080/01431160903559770.

Kern, C., Diefenbach, A., Elston, J., Stachura, M., Dietrick, A., Kelly, P., Fladeland, M., Stock, J., 2020, Developing a next generation UAS volcano observation platform: American Geophysical Union, 2020 Fall Meeting, abstract NH028-0001.

Lewicki, J.L., Kern, C., Kelly, P.J., Nadeau, P.A., Elias, T., and Clor, L.E., 2024, Volcanic gas monitoring, chap. E *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–E, 11 p., https://doi.org/10.3133/sir20245062E.

Lewis, Q.W., Lindroth, E.M., and Rhoads, B.L., 2018, Integrating unmanned aerial systems and LSPIV for rapid, cost-effective stream gauging: Journal of Hydrology, v. 560, p. 230–246, https://doi.org/10.1016/j.jhydrol.2018.03.008.

Liu, E.J., Aiuppa, A., Alan, A., Arellano, S., Bitetto, M., Bobrowski, N., Carn, S., Clarke, R., Corrales, E., de Moor, J.M., Diaz, J.A., Edmonds, M., Fischer, T.P., Freer, J., Fricke, G.M., Galle, B., Gerdes, G., Giudice, G., Gutmann, A., Hayer, C., Itikarai, I., Jones, J., Mason, E., McCormick Kilbride, B.T., Mulina, K., Nowicki, S., Rahilly, K., Richardson, T., Rüdiger, J., Schipper, C.I., Watson, I.M., and Wood, K., 2020, Aerial strategies advance volcanic gas measurements at inaccessible, strongly degassing volcanoes: Science Advances, v. 6, no. 44, https://doi.org/10.1126/sciadv.abb9103.

Mandon, C.L., Christenson, B.W., Schipper, C.I., Seward, T.M., and Garaebiti, E., 2019, Metal transport in volcanic plumes—A case study at White Island and Yasur volcanoes: Journal of Volcanology and Geothermal Research, v. 369, p. 155–171, https://doi.org/10.1016/j.jvolgeores.2018.11.024.

Nadeau, P. A., Diefenbach, A.K., Hurwitz, S., and Swanson, D.A., 2020, From lava to water—A new era at Kīlauea: Eos, v. 101, https://doi.org/10.1029/2020EO149557.

Neal, C.A., Brantley, S.R., Antolik, L., Babb, J.L., Burgess, M., Calles, K., Cappos, M., Chang, J.C., Conway, S., Desmither, L., Dotray, P., Elias, T., Fukunaga, P., Fuke, S., Johanson, I.A., Kamibayashi, K., Kauahikaua, J., Lee, R.L., Pekalib, S., Miklius, A., Million, W., Moniz, C.J., Nadeau, P.A., Okubo, P., Parcheta, C., Patrick, M.R., Shiro, B., Swanson, D., Tollett, W., Trusdell, F., Zoeller, M.H., Montgomery-Brown, E.K., Anderson, K.R., Poland, M.P., Ball, J.L., Bard, J.A., Coombs, M., Dietterich, H.R., Kern, C., Thelen, W.A., Cervelli, P.F., Orr, T., Houghton, B.F., Gansecki, C., Hazlett, R., Lundgren, P., Diefenbach, A.K., Lerner, A., Waite, G., Kelly, P.J., Clor, L., Werner, C., Burgess, M., Mulliken, K., Fisher, G., and Damby, D., 2019, The 2018 rift eruption and summit collapse of Kīlauea Volcano: Science, v. 363, no. 6425, p. 367–374, https://doi.org/10.1126/science.aav7046.

Syahbana, D.K., Kasbani, K., Suantika, G., Prambada, O., Andreas, A.S., Saing, U.B., Kunrat, S.L., Andreastuti, S., Martanto, M., Kriswati, E., Suparman, Y., Humaida, H., Ogburn, S., Kelly, P.J., Wellik, J., Wright, H.M.N., Pesicek, J.D., Wessels, R., Kern C., Lisowski, M., Diefenbach, A., Poland, M., Beauducel, F., Pallister, J., Vaughan, R.G., and Lowenstern, J.B., 2019, The 2017–19 activity at Mount Agung in Bali (Indonesia)—Intense unrest, monitoring, crisis response, evacuation, and eruption: Scientific Reports, v. 9, no. 8848, https://doi.org/10.1038/s41598-019-45295-9.

Turner, N.R., Perroy, R.L., and Hon, K., 2017, Lava flow hazard prediction and monitoring with UAS—A case study from the 2014–2015 Pāhoa lava flow crisis, Hawai‘i: Journal of Applied Volcanology, v. 6, article no. 17, https://doi.org/10.1186/s13617-017-0068-3.

Zorn, E.U., Walter, T.R., Johnson, J.B., and Mania, R., 2020, UAS-based tracking of the Santiaguito Lava Dome, Guatemala: Scientific Reports, v. 10, article no. 8644, https://doi.org/10.1038/s41598-020-65386-2.

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