USGS
science for a changing world

# Special Topic—Rapid-Response Instrumentation

Chapter M 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 Hawaiian Volcano Observatory lead field engineer K. Kamibayashi conducts maintenance on a volcano-monitoring station located on Tutuila Island in American Samoa. This station was installed as part of a rapid-response effort for escalating volcanic seismicity in August 2022. Photograph by J. Chang, U.S. Geological Survey, December 2023. 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.

# Special Topic—Rapid-Response Instrumentation

By Ashton F. Flinders

Chapter M of

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

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

Scientific Investigations Report 2024–5062

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

U.S. Geological Survey, Reston, Virginia: 2024

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.



Suggested citation:
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.

ISSN 2328-031X (print)
ISSN 2328-0328 (online)

# Contents



## Figures



## Table



# Abbreviations

| | |
|---|---|
| DOAS | differential optical absorption spectroscopy |
| FTIR | Fourier-transform infrared |
| GNSS | Global Navigation Satellite System |
| IRIS | Incorporated Research Institutions for Seismology |
| multi-GAS | multicomponent gas analyzer system |
| PASSCAL | Portable Array Seismic Studies of the Continental Lithosphere |
| UAS | unoccupied aircraft system |
| VSC | U.S. Geological Survey Volcano Science Center |

Chapter M

# Special Topic—Rapid-Response Instrumentation

By Ashton F. Flinders

## Introduction

Based on the reports of Ewert and others (2005, 2018) and Moran and others (2008), most U.S. volcanoes are currently under-monitored and are likely to remain so until the goals of the National Volcano Early Warning System are fulfilled. In addition, volcanoes determined to have low to moderate threat levels (Ewert and others 2005, 2018) could awaken suddenly and, as a result, may need to have instrumentation installed rapidly. For these reasons, equipment caches would ideally be readily available for rapid response in the event of unrest at under-monitored volcanoes or during a volcanic crisis. Given that volcanoes in Alaska and Hawaiʻi are frequently active, it is likely that several U.S. volcanoes could experience unrest simultaneously, as happened in 2018, 2019, and 2020, when unrest or eruptions occurred at Great Sitkin Volcano, Alaska; Mauna Loa, Hawaiʻi; Mount Cleveland, Alaska; Semisopochnoi Island, Alaska; Shishaldin Volcano, Alaska; Mount Veniaminof, Alaska, as well as the most destructive documented eruption of Kīlauea, Hawaiʻi. Therefore, we recommend that sufficient numbers of seismometers, infrasound sensors, Global Navigation Satellite System (GNSS) receivers, remote cameras, gas-monitoring instruments, and airborne and ground-based remote-sensing systems be made available and placed in a state of readiness at each observatory with the capability of bringing a level-2 monitoring network to near level-4 readiness. These rapid-response caches would ideally include sufficient equipment to provide real-time data telemetry, including satellite telemetry, where available, applicable, and appropriate. Rapid-response caches would be maintained in a state of readiness so that instruments can be deployed within several hours to days. Although the primary focus of the caches would be to enable rapid increases to a volcano observatory's real-time monitoring capabilities, not all scenarios of volcanic unrest are conducive to rapid deployment of real-time data telemetry. Non-telemetered, campaign instruments, particularly seismometers and GNSS stations, can also be deployed to aid in detection of early signs of volcanic unrest given the data can be recovered in a timely fashion.

Given the geographic separation of the U.S. Geological Survey Volcano Science Center's (VSC) four volcano observatory offices, the logistical difficulties in shipping equipment rapidly between them in response to unrest, the possible scenario that a volcano could reawaken with just hours or days of precursory unrest, and the difference in operating environments (for example, tropical Hawaiʻi compared to subarctic Alaska), we recommend three rapid-response instrument caches—for Hawaiʻi, Alaska, and the lower 48 States. For the lower 48 States, a single cache shared among the Cascades Volcano Observatory, Yellowstone Volcano Observatory, and the California Volcano Observatory could be warehoused in California or Washington. Although these rapid-response caches would be located at one of the observatories, they would ideally be owned and maintained by VSC, and together form a flexible VSC-wide instrument pool. To maintain continuity of monitoring capabilities, this rapid-response cache could also serve to replace instruments destroyed during an on-going eruption. However, to retain eruption-response readiness, we recommend instruments in the rapid-response cache not be permanently reallocated to an observatory's monitoring network unless they are replaced.

## Recommended Instrumentation

For seismic, infrasound, and ground deformation capabilities, based on the maximum instrument numbers for a level-4 network, we recommend each volcano observatory's rapid-response instrument cache include at least 12 broadband seismometers (Thelen and others, 2024b); 12 infrasound sensors and 2 four-element infrasound arrays (Lyons and others, 2024); and 12 GNSS stations (Montgomery-Brown and others, 2024). Unlike Moran and others' (2008) previous recommendation, we no longer recommend tiltmeters for rapid response, given the logistical challenges involved in deploying them during a volcanic crisis. Similarly, for lahar monitoring, we no longer recommended acoustic flow monitors (Moran and others, 2008). Where appropriate, each cache could contain an additional eight broadband seismometers and two four-element infrasound arrays (Thelen and others, 2024a) for rapidly monitoring as many as four potential lahar drainages.

To ensure that data are recorded as quickly as possible, as well as provide monitoring network flexibility during ongoing unrest and eruption, the rapid-response instrument cache would ideally include non-telemetered, campaign, seismic and ground deformation instrumentation. Recently available, low-cost, low-power, wireless, three-component, short-period seismometers (nodes) provide for increases in seismic response capabilities (for example, improved earthquake locations, event-type characterization [volcano-tectonic versus long-period events], high-resolution tomography, and interferometry) and could augment the broadband instruments recommended above. Although nodal seismometers are available through the Incorporated Research Institutions for Seismology (IRIS) Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center, to facilitate rapid deployment and ensure availability, we recommend that each cache contain 50 to 100 node-type stations (fig. M1). The recommended 12 GNSS stations could be designed to provide real-time and campaign capabilities.

For ground-based gas monitoring, increasing volcanic unrest may limit access to fumaroles near an active crater and direct sampling may not be practical or safe. We recommend sufficient instrumentation in a rapid-response instrument cache to enable rapid installation of autonomous, telemetered stations for tracking gas-emission rates and compositions. This instrumentation would ideally include three scanning spectrometer systems, one $SO_2$ camera, and one multicomponent gas analyzer system (multi-GAS) station. As periodic field surveys may also be required, we also recommend including one mobile differential optical absorption spectroscopy (DOAS) system, one portable $SO_2$ camera, one portable multi-GAS system, one field Fourier-transform infrared (FTIR) spectrometer (fig. M2), one portable soil-$CO_2$ fluxmeter, and, as safety allows, equipment for direct sampling of fumaroles and springs. As field-survey instrumentation is directly user operated (not installed at a fixed location), this instrumentation could be used for both rapid response, baseline monitoring, and research as needed (Lewicki and others, 2024).

For airborne gas monitoring, the rapid-response cache would ideally contain instrumentation to make gas measurements using traditional fixed-wing aircraft and helicopters, as well as small- to medium-sized unoccupied aircraft systems (UAS). For fixed-wing and helicopter-borne missions, the cache would ideally include one highly sensitive, temperature-stabilized, DOAS system and dedicated in situ instruments with the capability to measure $CO_2$ (at less than 1 part per million accuracy and precision) and major sulfur gases ($SO_2$ and $H_2S$ at less than 5 parts per billion accuracy and precision at a 1 hertz sampling rate). In addition, one UAS equipped with multi-GAS and DOAS systems would ideally be available.

To track surface changes caused by volcanic activity, each rapid-response instrument cache would ideally include a minimum of four telemetered cameras with zoom (two with low-light capabilities). Each observatory would ideally assess their operational and rapid response need for including a forward-looking infrared camera, usable both on the ground and (or) from an airborne platform. Similarly, observatories would ideally assess their need for a ground-based Doppler radar system for monitoring explosive activity. For lightning detection, observatories can rely on global lighting detection networks, such as the University of Washington's World Wide Lightning and Location Network, and others. Where appropriate, observatories would work toward incorporating one or more short-range lightning sensors (very high frequency or broadband) or field mill (for detecting perturbations in the static electricity from small explosions) into their rapid-response cache (Schneider and Van Eaton, 2024).

**Figure M1.** Photograph showing U.S. Geological Survey Hawaiian Volcano Observatory geophysicist P. Dotray deploying a 5-second geophone in Halemaʻumaʻu as part of a rapid response to the December 20, 2020, eruption of Kīlauea, Hawaiʻi. These instruments were made available through the Incorporated Research Institutions for Seismology (IRIS) Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center. Photograph by J. Chang, U.S. Geological Survey, January 3, 2021.

**Figure M2.** Photograph showing U.S. Geological Survey Hawaiian Volcano Observatory gas scientist M. Cappos using a field-portable Fourier-transform infrared (FTIR) spectrometer on the rim of Halemaʻumaʻu to measure gas composition during the June 7, 2023, eruption of Kīlauea, Hawaiʻi. The FTIR measures the composition of emitted gases by measuring how the volcanic plume absorbs infrared energy. The plume generated by the summit eruption was sulfur-dioxide ($SO_2$) rich, but also contained water vapor, carbon dioxide, and halogen gases, such as HCl and HF. Photograph by P. Nadeau, U.S. Geological Survey, June 7, 2023.

## Additional Considerations

In addition to specific instrumentation (table M1), the rapid-response instrument caches would ideally include all associated station infrastructure and equipment to provide power and telemetry, including batteries, solar panels, radios, cabling, housing, and mounting equipment, as well as radio repeaters and (or) satellite uplinks to ensure continuous data streams for stations that are installed in remote areas. To maintain operational readiness, some instrumentation (for example, seismometers, GNSS stations, and multi-GAS) could be used on a limited basis to support campaign monitoring or targeted scientific investigations during times of no significant unrest. Additionally, instruments could be rotated out of the cache and permanently deployed as part of the observatory's routine network maintenance and construction, and the cache resupplied with newer instruments. This practice would facilitate monitoring network repairs and keep the rapid-response cache instrumentation modern and up to date.

Instrumentation not currently recommended for rapid-response caches, for example, gravimeters, magnetometers, distributed acoustic sensing, rotational seismometers, and others, should be evaluated periodically to assess their value in responding to unrest at under-monitored volcanoes or to aid in monitoring during a volcanic crisis.

## Marine Eruptions

To leverage capabilities and foster collaboration, observatories responsible for monitoring volcanoes in marine environments (Aleutian Islands, Hawaiʻi, Northern Mariana Islands, and American Samoa) could pursue partnerships with internal and (or) external partners (for example, U.S. Geological Survey Pacific Coastal and Marine Science Center, National Oceanic and Atmospheric Administration, and others) to develop a marine rapid-response instrument cache. Ideally, this cache would include ocean-bottom seismometers, hydrophones, bottom-pressure recorders, and other sensors of opportunity. A minimum of four marine instrument packages that include a seismometer is necessary for determining reliable earthquake locations. Similarly, three to four hydrophone moorings deployed as a network or small-aperture array could detect submarine explosions and T-phases from earthquakes (Tepp, 2024). Telemetry and real-time data would ideally be available for at least one or two instruments, with at least one option that can be quickly deployed (for example, a buoy system). As a vessel of opportunity would be required to deploy marine instruments, those instruments that can be easily and safely deployed from smaller vessels, such as large fishing vessels, would increase operational flexibility and response timeliness. When

**Table M1.** Recommended rapid-response instrument cache for volcano monitoring in the United States.

[In addition to the instrumentation listed below, the caches would ideally include all associated station infrastructure and equipment to provide power and telemetry for ground-based instruments, including batteries, solar panels, radios, cabling, housing, and mounting equipment, as well as radio repeaters and (or) satellite uplinks to ensure continuous data streams for stations installed in remote areas. DOAS, differential optical absorption spectroscopy; FLIR, forward-looking infrared; FTIR, Fourier-transform infrared spectroscopy; GNSS, Global Navigation Satellite System; Hz, hertz; NOAA, National Oceanic and Atmospheric Administration; ppb, part per billion; ppm, part per million; UAS, unoccupied aircraft system; USGS, U.S. Geological Survey]

| Monitoring category | Instrumentation |
|---|---|
| Seismic | Twelve broadband seismometers; 50–100 node-type seismometers |
| Infrasound | Twelve infrasound sensors and two four-element infrasound arrays |
| Ground deformation and gravity | Twelve GNSS receivers |
| Gas | Three scanning spectrometer systems, one $SO_2$ camera, and one multicomponent gas analyzer system (multi-GAS) station. Instrumentation for performing periodic field surveys, including one mobile DOAS system, one portable $SO_2$ camera, one portable multi-GAS system, one field FTIR system, one portable soil-$CO_2$ fluxmeter, and equipment for direct sampling of fumaroles and springs. For airborne gas monitoring from fixed-wing and helicopter-borne missions, the cache would ideally include one highly sensitive, temperature-stabilized DOAS spectrometer and dedicated in situ instruments that have the capability to measure $CO_2$ at <1 ppm accuracy and precision and major sulfur gases ($SO_2$ and $H_2S$) at <5 ppb accuracy and precision at a 1 Hz sampling rate. In addition, one UAS equipped with multi-GAS and DOAS systems would ideally be available |
| Springs, streams, and volcanic lakes | No specific instrument recommendations |
| Tracking surface changes caused by volcanic activity | If deemed appropriate by the observatory; one handheld FLIR camera and (or) one airborne (gimble mount) FLIR. Four telemetered cameras with zoom (two with low-light capabilities) |
| Eruption plumes and clouds | If deemed appropriate by the observatory; one ground-based Doppler radar system and one or more short range very high-frequency sensors (or broadband) or field mill |
| Lahars | Eight broadband seismometers and two four-element infrasound arrays |
| Marine eruptions | Observatories responsible for monitoring volcanoes in marine environments (Aleutian Islands, Northern Mariana Islands, and American Samoa) could pursue partnerships with internal and (or) external partners (for example, USGS Pacific Coastal and Marine Science Center, NOAA, and others), for developing a marine rapid-response instrument cache. Ideally, this cache would include ocean-bottom seismometers, hydrophones, bottom-pressure recorders, and other sensors of opportunity. When possible and appropriate, rapidly deploying multiple land-based seismometers optimized for T-phases on the nearest islands could supplement ocean-bottom seismometers and hydrophones |

possible and appropriate, rapidly deploying multiple land-based seismometers optimized for T-phases on the nearest islands could supplement ocean-bottom seismometers and hydrophones (Tepp, 2024). Although broadband and three-component seismometers are preferable, a more important consideration is portability and ease of deployment. For example, during the 2022 earthquake swarm offshore Taʻū Island, American Samoa, rapidly deployed low-cost single-board computer-based seismometers proved critical in providing early situational awareness (earthquakes counts and relative magnitudes and epicentral distances).

## References Cited

Ewert, J.W., Diefenbach, A.K., and Ramsey, D.W., 2018, 2018 update to the U.S. Geological Survey national volcanic threat assessment: U.S. Geological Survey Scientific Investigations Report 2018–5140, 40 p., https://doi.org/10.3133/sir20185140.

Ewert, J.W., Guffanti, M., and Murray, T.L, 2005, An assessment of volcanic threat and monitoring capabilities in the United States—Framework for a National Volcano Early Warning System: U.S. Geological Survey Open-File Report 2005–1164, 62 p., https://doi.org/10.3133/ofr20051164.

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.

Lyons, J.J., Fee, D., Thelen, W.A., Iezzi, A.M., and Wech, A.G., 2024, Infrasound for volcano monitoring, chap. C *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–C, 11 p., https://doi.org/10.3133/dir20245062c.

Montgomery-Brown, E.K., Anderson, K.R., Johanson, I.A., Poland, M.P., and Flinders, A.F., 2024, Ground deformation and gravity for volcano monitoring, chap. D *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–D, 11 p., https://doi.org/10.3133/sir20245062d.

Moran, S.C., Freymueller, J.T., LaHusen, R.G., McGee, K.A., Poland, M.P., Power, J.A., Schmidt, D.A., Schneider, D.J., Stephens, G., Werner, C.A., and White, R.A., 2008, Instrumentation recommendations for volcano monitoring at U.S. volcanoes under the National Volcano Early Warning System: U.S. Geological Survey Scientific Investigations Report 2008–5114, 47 p., https://doi.org/10.3133/sir20085114.

Schneider, D.J., and Van Eaton, A.R., 2024, Special topic—Eruption plumes and clouds, chap. J *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–J, 12 p., https://doi.org/10.3133/sir20245062j.

Tepp, G., 2024, Monitoring marine eruptions, chap. I *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–I, 7 p., https://doi.org/10.3133/sir20245062i.

Thelen, W.A., Lyons, J.J., Iezzi, A.M., and Moran, S.C., 2024a, Monitoring lahars and debris flows, chap. H *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–H, 6 p., https://doi.org/10.3133/sir20245062h.

Thelen, W.A., Lyons, J.J., Wech, A.G., Moran, S.C., Haney, M.M., and Flinders, A.F., 2024b, Seismic techniques and suggested instrumentation to monitor volcanoes, chap. B *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–B, 9 p., https://doi.org/10.3133/sir20245062b.

Moffett Field Publishing Service Center, California
Manuscript approved July 26, 2024
Edited by Linda Rogers and Monica Erdman
Layout and design by Cory Hurd

Flinders—**Special Topic—Rapid-Response Instrumentation**—Scientific Investigations Report 2024–5062–M

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20245062m