# Applications of Geophysical Methods to Volcano Monitoring

Jeff Wynn, US Geological Survey, Vancouver, WA
Daniel Dzurisin, US Geological Survey, Vancouver, WA
Carol A. Finn, US Geological Survey, Denver, CO
James P. Kauahikaua, US Geological Survey, Hawai'i Volcanoes National Park, HI
Richard G. LaHusen, US Geological Survey, Vancouver, WA

## Abstract

The array of geophysical technologies used in volcano hazards studies - some developed originally only for volcano monitoring - ranges from satellite remote sensing including InSAR to leveling and EDM surveys, campaign and telemetered GPS networks, electronic tiltmeters and strainmeters, airborne magnetic and electromagnetic surveys, short-period and broadband seismic monitoring, even microphones tuned for infrasound. They include virtually every method used in resource exploration except large-scale seismic reflection. By "geophysical" we include both active and passive methods as well as geodetic technologies. Volcano monitoring incorporates telemetry to handle high-bandwith cameras and broadband seismometers. Critical geophysical targets include the flux of magma in shallow reservoir and lava-tube systems, changes in active hydrothermal systems, volcanic edifice stability, and lahars. Since the eruption of Mount St. Helens in Washington State in 1980, and the eruption at Pu'u O'o in Hawai'i beginning in 1983 and still continuing, dramatic advances have occurred in monitoring technology such as "crisis GIS" and lahar modeling, InSAR interferograms, as well as gas emission geochemistry sampling, and hazards mapping and eruption predictions. The on-going eruption of Mount St. Helens has led to new monitoring technologies, including advances in broadband Wi-Fi and satellite telemetry as well as new instrumentation. Assessment of the gap between adequate monitoring and threat at the 169 potentially dangerous Holocene volcanoes shows where populations are dangerously xposed to volcanic catastrophes in the United States and its territories. This paper focuses primarily on Hawai'ian volcanoes and the northern Pacific and Cascades volcanoes. The US Geological Survey, the US National Park System, and the University of Utah cooperate in a program to monitor the huge Yellowstone volcanic system, and a separate observatory monitors the restive Long Valley caldera in collaboration with the US Forest Service.

## Historical Development of Volcano Geophysical Methods

Passive seismic monitoring (McNutt, 2005) is arguably the earliest geophysical method used to study and anticipate volcanic activity, applied initially at volcanoes in Hawai'i, Italy, and Japan. The first deliberate and published predictions of volcanic activity using this and other technologies were made at Mount St. Helens in 1980 (Swanson et al, 1982). Moment tensors, relative seismic relocation work, and tomography to image magma bodies are newer methodologies developed in the past decades and now being ever more commonly applied in the early 21$^{st}$ Century. Automated monitoring systems using Remote Seismic Amplitude Monitoring (RSAM) is a core development and the basis for 24/7 monitoring world-wide. Aeromagnetic surveying methods were developed

following World War II, but their primary use was to search for altered zones in and around volcanic systems that might host mineralization. Magnetotelluric methods were first used in the 1970's to study deep magma beneath the Snake River Plain and the Yellowstone hotspot, whereas gravimetry was used to monitor mass flux as early as the mid-1970's at Kilauea volcano in Hawai'i. Tiltmeters were developed in the 1950's and 60's for use around Kilauea, later spreading to world-wide use. Self-potential and VLF-EM methods monitor flux in lava tubes and map to hidden fracture feeder systems in the late 1960's and early 1970's. A remarkable very-large-moment time-domain EM experiment in the late 1970's monitored magma flux beneath Kilauea volcano. The first leveling surveys on a volcano were conducted in Hawai'i in 1912, and the first EDM surveys in 1964-65. GPS methods to monitor volcanic deformation first came seriously into play in the late 1980's and early 1990's, and InSAR (Interferometric Synthetic Aperture Radar) and airborne electromagnetic measurements began in the late 1990's. During this same period broadband seismic arrays were expanded, along with fast inversion methods, to do the first real-time mapping of fluid movement in an active volcano (Chouet et al, 2003). Acoustic Flow Monitors ("AFM's") employed west of Mount Rainier in the early 21st Century represent the first automated urban lahar warning system in the world. Photogrammetry is now being routinely used at Mount St. Helens to track dome growth by providing monthly volume estimates, and thermal imaging (Forward-Looking Infra-Red or FLIR) devices mounted on a helicopter help scientists decide where magma is close to the surface (Mt. Spurr and Mount St. Helens), and where it is safe to sling instrument packages (Mount St. Helens).

## The Targets

Three main targets of interest for geophysical volcanologists include: (1) magma in place or moving through the crust, (2) hydrothermal activity (magma-groundwater interactions and subsurface water-steam plumbing systems), and (3) edifice stability. In the latter case, the edifice collapse leading to the eruption of Mount St. Helens in 1980 has contributed to the recognition that many if not most stratocone volcanoes have experienced edifice failures in the geologic past that could again in the future. The lahar-inundation disaster in Armero, Colombia, in 1984 illustrates he threat from catastrophic hydrologic releases at volcanoes. A unique airborne EM and magnetic survey of Mount Rainier flown in 2000 mapped the unstable parts of the volcanic edifice in three dimensions (Finn et al, 2001), for the first time giving emergency managers an idea of the size and potential damage that could be caused by an edifice collapse (discussed later in this paper).

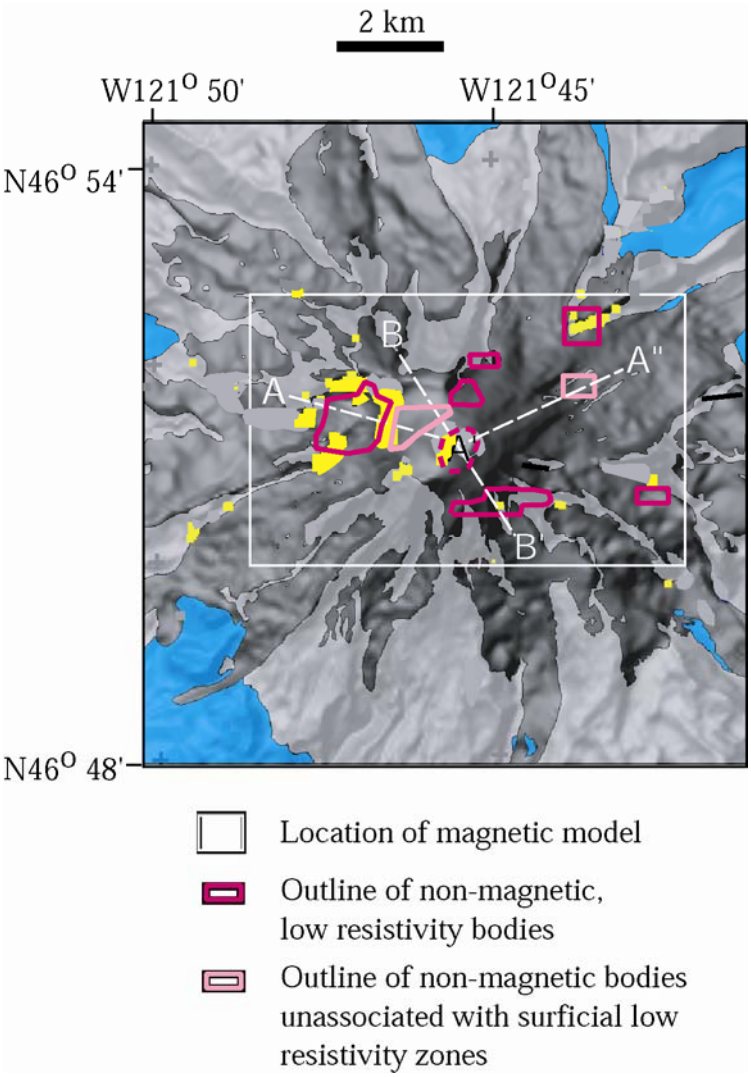


**Figure 1. Non-magnetic and conductive rock anomalies from an airborne geophysical survey over Mount Rainier (from Finn, Sisson, and Desczc-Pan, 2001). Yellow bodies are conductors associated with clay alteration.**

## Geophysical Technology Applied to Volcano Monitoring

### Technology Routinely Used

The principal threat from Cook Inlet, Aleutian, and Kamchatka volcanoes is not lava inundation nor even lahars, but ash that could cripple or destroy commercial aircraft. Estimates range as high as ~25,000 passengers per day who pass through airspace potentially exposed to an eruptive ash threat. This threat averages about 5 days per year of significant exposure in the northern circum-Pacific air routes at nominal flight altitudes (to 39,000' ASL). For about 10 years the USGS in Alaska has been expanding seismic and recently GPS networks westward, focusing on high-threat volcanoes in the Alaska Peninsula, the Aleutians, and the Kamchatka Peninsula (in close cooperation with Russian colleagues). This effort involves close coordination with the U.S. Federal Aviation Administration and counterparts through Volcanic Ash Advisory Centers worldwide.

Short-period seismic stations telemetered to the Anchorage field office of the USGS were an early staple of the Alaska Peninsula and Aleutian monitoring effort, but use of broadband seismometers has increased to enable monitoring of low-level volcanic tremor - the long period (LP) and very long period (VLP) seismic signals that herald fluid movement beneath a volcano, which can be an important precursor to an eruption. GPS volcano deformation networks installed and monitored by the USGS and the Earthscope (Plate Boundary Observatory) programs are rapidly growing in the Cascades, but only four volcanos (Augustine and Mt. Spurr in Cook Inlet, and Akutan and Okmok volcanoes in the central Aleutian chain) have functional, telemetered deformation-monitoring systems in Alaska.

**Figure 2. A broadband seismic and GPS station being installed on Akutan Island, central Aleutian chain. On the left is the pedestal for the continuous GPS antenna being installed; in the center is the "hut" with solar panels used to shield batteries and electronics; and on the right is a "swing set" of additional solar panels necessary to power the station at the relatively high latitude of the central Aleutian chain.**

In the late 1990's a strong effort was made to set up a 24/7 northern Pacific satellite-based ash monitoring program with partners in Russia, the Kuriles, the University of Alaska-Geophysical Institute, and the State of Alaska Department of Geology and Geophysics. While this satellite-monitoring program involves some quasi-automated systems on several high-threat volcanoes like Veniaminof and Pavlov, it mainly depends on periodic checks by scientists to monitor effectively. Band-ratioing on TERRA-MODIS and other satellite data helps the search for ash in the air on a

daily basis. Often this ash is not visible, even to pilots flying through it, after it has been lofted to great elevations and carried substantial distances from the source volcano. Image sequences show ash plumes moving from the Alaska Peninsula across Canada to the Maritime Provinces over several days, and engine damage to aircraft as far south as Tijuana Mexico has been reported from ash originating in the Alaska Peninsula. Thermal monitoring is done parallel with the satellite ash-monitoring, and partners in Kamchatka and the Kuriles share in the every-three-to-six-hours checks.

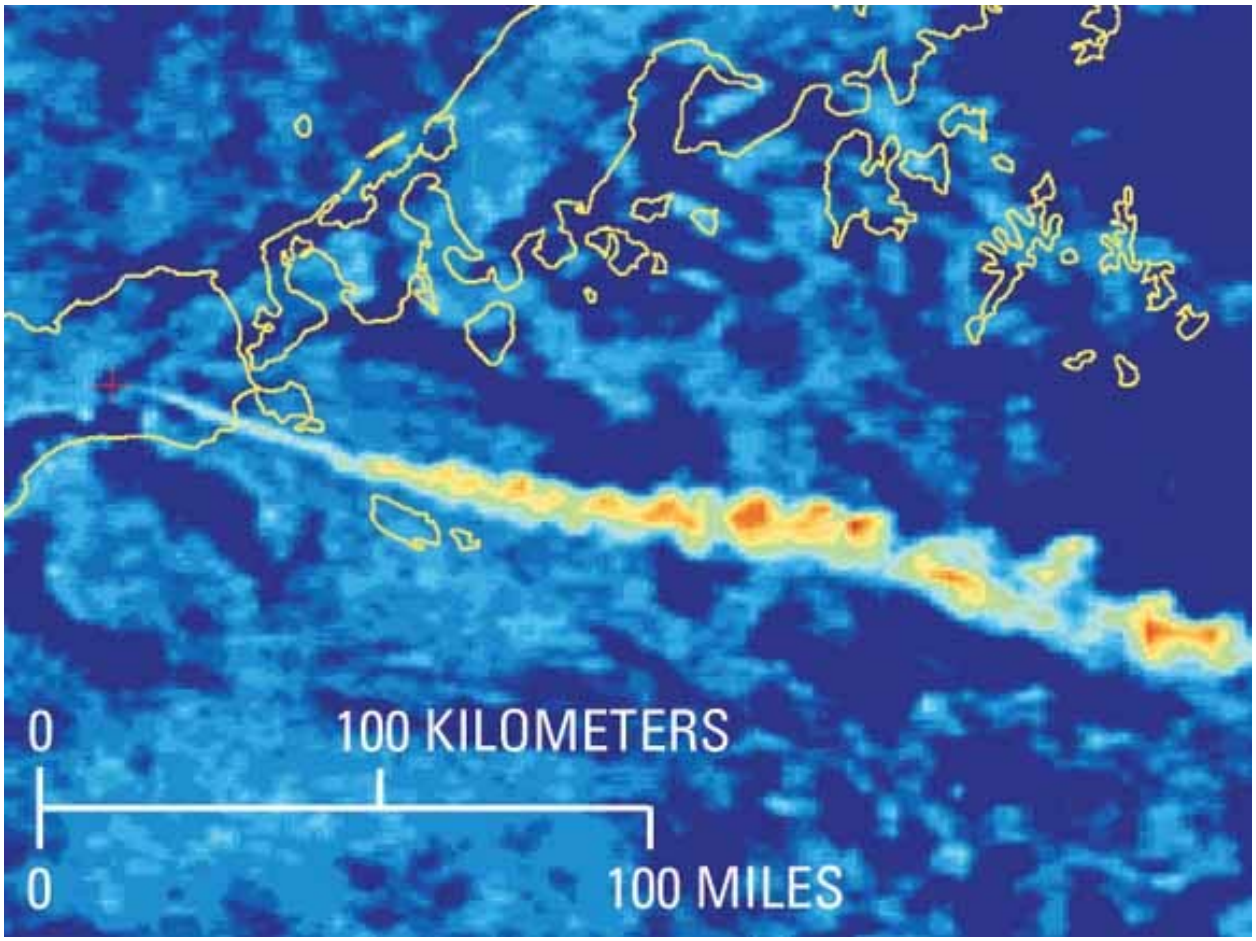


**Figure 3. A satellite image showing a plume of ash moving across the northern Pacific ocean from Shishaldin volcano in the central Aleutians, 1999. Over 100 aircraft have been damaged, some nearly fatally, by volcanic ash in the past two decades.**

Mount Rainier is classified by the US Geological Survey as the most dangerous (potential risk X exposure) volcano in the United States or its territories (Ewert et al, 2005). The volcano is currently not active, but there is a significant threat of a lahar inundation event similar to ones that took place as recent as 500 years ago. During the Osceola mudflow about 5,600 years ago, a lahar that may or may not have been related to a volcanic eruption traveled all the way to Puget Sound, and continued beneath the water another 70 kilometers. Parts of modern Seattle and Tacoma lie on plains derived from redeposited materials of multiple lahar events. Magma moving upwards in a volcanic edifice will inevitably interact with ground water as a hydrothermal system, and lead to alteration. One consequence of hydrothermal alteration is the conversion of competent magnetic,

electrically resistive volcanic rock to a magnetite-poor, electrically conductive material inherently weaker than the original solidified magma. Airborne geophysical methods are especially useful for rapidly assessing the extent of hydrothermal alteration and thus the threat to extended outlying populations (Figure 1; Finn et al., 2001). Magnetic data show the lack of magnetite expected with the most altered volcanic rock, and this can be correlated closely with hydrothermal alteration. Airborne electromagnetic systems are well-designed to map conductive rocks in three dimensions beneath the survey aircraft, and the conductors thus detected correlate with clays that are the critical factor in weakening the edifice.

During the 2004-2005 eruption of Mount St. Helens, most of the methods described above were used or at least contemplated. Seismic monitoring technology provided the first precursory information that an eruption was imminent in late September 2004. However, as the eruption evolved from a closed (potentially explosive) to a more open system, seismic methods essentially stopped serving as a proxy that could warn us of the occasional small explosive events. Nevertheless, the highly regular "drumbeat" earthquakes occur about once every minute, and appear to reflect the mechanical friction physics of the extrusion process (though at least one specialist feels it may be a hot-rock-hydrothermal-system interaction). The principal limitation to the seismic delineation of the eruption process is a poor understanding of the seismic velocity model underlying the complex 3-dimensional crater-glacier-dome-debris field inside Mount St. Helens. On-going efforts with colleagues of the Pacific Northwest Seismic Network may help to resolve the three-dimensional velocity structure using profiled arrays. In late 2005 it was judged safe enough to install two shallow-borehole tiltmeter systems on the 1980-1986 lava dome, immediately north of the new extrusion area (the so-called "whalebacks" or "spines" that are presently evolving). Several interesting tilt signals are clearly associated with larger earthquakes, while others not.

During 2004-2005 the sensor arrays being deployed around and inside Mount St. Helens have evolved, most notably with the development of the new "Spider" platforms that can be deployed as helicopter sling loads at relatively low risk. Newer broadband seismometers were installed and the telemetry paths were streamlined and made more robust and redundant. Digital cameras are crucial to documenting and understanding the evolution of the on-going extrusion process, and a concerted effort is underway to correlate the seismic "drumbeats" with physical phenomena such as episodic stick-slip movement. These efforts are being undertaken to resolve several models using non-linear friction processes that have been developed by some of our research scientists. A better understanding of the physical extrusion process will obviously increase our predictive capability and its reliability.

**Figure 4. New "Spider" platforms package GPS, seismic, ash, and gas sensors that can be slung by helicopter onto an active volcano with minimal risk to scientists.**

Because of the severe winter weather at elevations above 2000 meters in Alaska and the northern Cascades, much thought and energy has gone into winterizing camera and GPS and seismic telemetry systems that we cannot revisit for many months at a time. Rime ice and high winds have incapacitated several systems installed around and inside the crater at Mount St. Helens since the Fall of 2004, and high winds in the Aleutians have caused extensive damage to solar arrays and antenna systems.

In Hawai'i, narrow-band and broadband seismic networks, tiltmeters, GPS arrays, and VLF-EM methods monitor magma flux in Kilauea's East Rift Zone and south of the Pu'u O'o eruptive center, which has been erupting continuously since January 1983. A nearly-completed GPS and seismic network exists on and around Mauna Loa, which last erupted in 1984. A deep-seated, long-period seismic swarm beneath the volcano that began in April 2003 and continued through December 2004 has been accompanied by nearly continuous inflation (figures 5 and 6) of the volcano picked up by the GPS network arrayed across the summit. On the basis of historical behavior, we anticipate that shallow earthquakes beneath the summit will herald the emergence of the long-anticipated next eruption of Mauna Loa. The GPS network has continued to document on-going inflation beneath the volcano's summit.

**Figure 5. A campaign GPS station set up on Mauna Kea volcano in Hawai'i to monitor regional deformation. Mauna Loa lies in the middle background.**

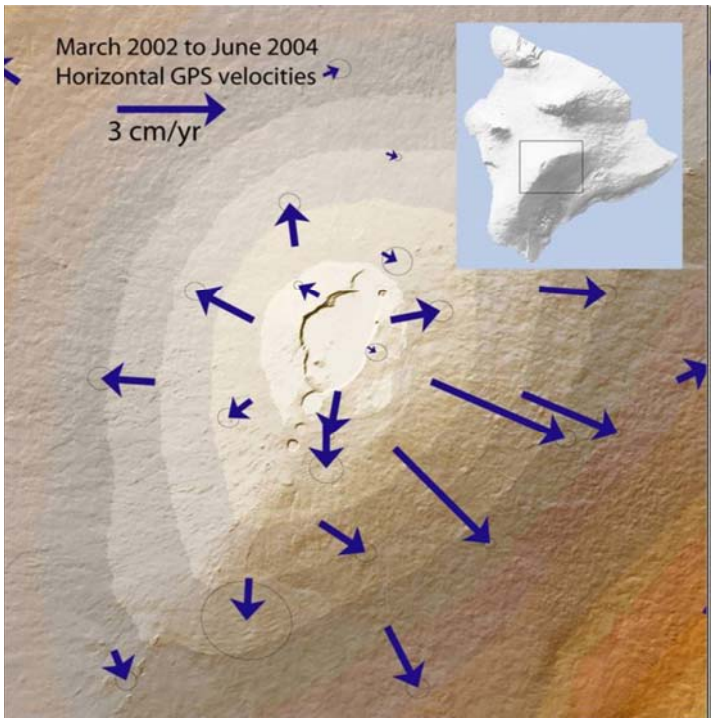


**Figure 6. Inflation on Mauna Loa from a GPS network recorded during the period March 2002 to June 2004. Relative length of arrows indicate lesser or greater physical displacement caused by a combination of point plus dike-like inflation sources beneath the summit.**

## Technology Considered or Intermittently Used

Satellite imagery can identify thermal anomalies in the Aleutians and the Cascades, with varying degrees of success. TERRA-MODIS and other imagery have been used to monitor eruptions of several volcanoes in the Kamchatka Peninsula and the Aleutians. It has also been used to monitor the eruption of Anatahan volcano in the Commonwealth of the Northern Mariana Islands, but is limited in effectiveness by seasonal cloud cover. In one case, TERRA-MODIS imagery showed a large ash plume remobilized from the crater of Mount St. Helens by high winds; this plume extended much of the way from the volcano to southern Puget Sound (a distance of over 50 km). However, visual satellite imagery is unreliable during the six months of each year when the northern Pacific and Cascades volcanoes are shrouded by cloud cover. InSAR is also unreliable, because the changing snow cover renders the data incoherent during the winter season.

Doppler radar can be an effective tool to monitor ash emissions, particularly during the winter season when the northern Pacific and Cascades volcanoes are perpetually engulfed in clouds. We have experimented with a small X-Band radar system in Alaska and Mount St. Helens, but found that its usefulness is limited by signal strength and range. The main limitation to a robust radar monitoring capability is cost; adequate deployable systems range up to a half million dollars.

Time-Domain EM methods have an obvious appeal in helping to map the three-dimensional conduit structure beneath and driving the current Mount St. Helens eruption. Magma is a well-known, strong conductor readily detectible by electrical geophysical methods. The primary limiting issues are resolution in a complex three-dimensional environment and the risk required to conduct an adequate ground-based survey there. However, new airborne TDEM surveys may prove useful (Finn et al, 2001).

## The Future Evolution of Volcano Monitoring

Volcano hazards monitoring is a rapidly-evolving field, and the examples listed above are neither complete nor limiting. Advanced research and deployment of monitoring systems is well-developed in Japan, Italy, Latin America, the Southeast Pacific and and Micronesia. The field also benefits from strong collaboration that routinely crosses traditional specialty boundaries and national frontiers; hazards mapping and modeling, InSAR, and camera telemetry are just a few examples of this. We anticipate further advancements in elaboration of existing technologies, and scientists worldwide are actively seeking and evaluating other technologies that might be applied to increase our predictive capabilities. Careful geologic mapping, and the sophisticated age-dating efforts that go with it, are also critically important to both reliable hazards assessments and eruption predictions.

## References


Chouet, Bernard, Dawson, Phillip, Ohminato, Takao, Martini, Marcello, Saccorotti, Gilberto, Giudicepietro, Flora, DeLuca, Gaetano, Milana, Giuliano, and Scarpa, Roberto, 2003, Source mechanisms of explosion at Stromboli Volcano, Italy, determined from moment-tensor inversions of very-long-period data: Journal of Geophysical Research, vol. 108, B1, pp. 701 – 725.

Ewert, John W., Guffanti, Marianne, Murray, Thomas L., 2005, An Assessment of Volcanic Threat and Monitoring Capabilities in the United States: Framework for a National Volcano Early Warning System, US Geological Survey Open-File Report 2005-1164, 62 pages.

Finn, Carol A., Sisson, Thomas W., and Deszcz-Pan, Maryla, 2001, Aerospatial measurements of collapse-prone hydrothermally altered zones at Mount Rainier volcano: Nature, v. 409, 1 Feb 2001, pp. 600-603.

McNutt, S.R., 2005, Volcanic seismology: Annual Review of Earth and Planetary Sciences, vol.33, pp.461-491, 2005

Swanson, D.A., Casadevall, T.J., Dzurisin, D., Malone, S.D., Newhall, C.G., and Weaver, C.S., 1983, Predicting eruptions at Mount St. Helens, June 1980 through December 1982: Science, v. 221, no. 4618, p. 1369 1376.