STATUS AND CHALLENGES OF VOLCANO MONITORING WORLDWIDE

John W. Ewert, U.S. Geological Survey, Vancouver, WA 98683, USA (jwewert@usgs.gov)
Christopher G. Newhall, U.S. Geological Survey, Seattle, WA 98195 USA

Introduction

Volcanoes exhibit precursory activity that may occur hours to years before an eruption and thus allow an eruption forecast. Accurate forecasts and real-time detection of volcanic eruptions are essential to keep pilots, passengers, and planes out of ash clouds. Timely eruption reporting by volcano observatories, beginning with information about the premonitory build-up phase, allows more time for flight planning and improves response time of satellite-based ash-cloud detection. Here we describe in general terms the most commonly used volcano-monitoring techniques, and report where obvious gaps in monitoring exist, particularly with respect to aviation safety.

Most volcano-monitoring networks and observatory operations have been designed to mitigate hazards to people on the ground rather than in the air. Consequently, most volcano observatories and hence most monitored volcanoes are found where the risks to people on the ground are greatest. Notable exceptions are the monitoring of Alaskan volcanoes by the Alaska Volcano Observatory (AVO) (Murray, this volume), Kamchatkan and Kurile volcanoes by KVERT (Gordeev and others, this volume), and Anatahan volcano by the U.S. Geological Survey and the Commonwealth of the Northern Mariana Islands. At the present time, volcano-monitoring operations are conducted by about 60 institutions globally. However, of the more than 1500 active volcanoes in the world, less than a quarter have any kind of real-time monitoring, and only a few (numbering less than 50) would be considered adequately monitored for both hazard and research purposes.

Why is ground-based monitoring critical?

A recent eruption at Anatahan volcano in the Commonwealth of the Northern Mariana Islands (CNMI) in 2003, gives an example of the time lag between eruption onset and ash cloud detection that can occur in a remote area if only remote sensing is employed. On 10 June 2003, approximately five hours elapsed from the unexpected onset of eruptive activity at Anatahan and subsequent ash plume to 11 km, to the issuance of the first Significant Meteorological Advisory (SIGMET) and Volcanic Ash Advisory by the Guam Meteorological Watch Office (MWO) and Washington-Volcanic Ash Advisory Center (W-VAAC), respectively (Guffanti and others, in press). Arguably, had Anatahan been seismically monitored in real time before the start of eruptive activity, this delay likely could have been much shorter and dissemination of ash-hazard information to the aviation sector could have been more rapid. Luckily, no damaging encounters appear to have occurred.

Subsequently, real-time seismic monitoring was installed on Anatahan by the U.S. Geological Survey and the CNMI Emergency Management Office, and in March and April of 2004 notices of new eruptive activity at Anatahan were passed to the W-VAAC and Guam MWO within minutes of seismic detection (R.White, written communication).

When ground-based monitoring is in operation at a volcano, and communication links are in place between the volcano observatory and the regional MWO and VAAC, notices of heightened eruption potential and notification of eruption onset are typically more rapid than if no ground-based monitoring is in place. The eruption of remote Bezymianny Volcano, Kamchatka in June, 2004, illustrates this case. On June 16, 2004, based on increasing seismicity, the Kamchatkan Volcanic Eruption Response Team (KVERT) raised the concern color code for Bezymianny from yellow to orange (indicating an eruption is possible within a few days and may occur with little or no warning). On June 18, 1940 UTC an explosive eruption was detected seismically, and an ash column to 8-10 km was observed by a remotely operated video camera at 2040 UTC. KVERT issued an eruption notification at 2055 UTC, a little more than one hour after the eruption began. In contrast, owing to a lack of satellite coverage, the ash column was first spotted in satellite imagery approximately 4 hours after the seismically-determined eruption onset. (D. Schneider, personal communication).

Although the eruption notification was not made within five minutes of the eruption onset as airline representatives to the 2nd International Conference on Volcanic Ash and Aviation Safety suggested as a goal, the notification was much more timely than would have been possible with only satellite remote sensing owing to the ground-based monitoring by the KVERT. No damaging encounters were reported from this eruption.

Real-time volcano monitoring

An adequately monitored volcano has continuous multiparametric (a combination of seismic, deformation, geochemical, etc.) data streams that are available in real-time to an observatory facility. More commonly in the world today, if a volcano has any monitoring at all, it is by a single seismometer, standalone or within a regional network.

For the purposes of this discussion, we classify volcano monitoring techniques into two general classes; those useful for eruption forecasting and prediction, and those useful for eruption detection. We limit our discussion to those techniques and instruments that can be used in real time or near-real time, generally in a telemetered configuration. A combination of monitoring techniques and sensor types yields the most reliable results.

Eruption forecasting tools

Seismic monitoring is the mainstay of volcano monitoring operations around the world. The typical telemetered seismic station used to monitor a volcano is a single (vertical) component , short-period type, data from which are sent via analog telemetry to a central recording site. This class of instrumentation has been employed to monitor volcanoes since the early 1970s, is robust even in marginal field conditions, and the technology is accessible in developing countries. To locate seismicity, a minimum of four telemetered instruments spread around the volcano is necessary. In many cases though, only one or two instruments may be deployed close enough to a volcano to reliably detect and track the subtle changes in seismicity prior to eruption. Fortunately, useful information about the status of a volcanic system can be gleaned from one or two stations if an experienced seismologist is on hand with appropriate data processing software (McNutt, 1996).

At well-monitored volcanoes, which number less than 50 worldwide, focused, small-aperture seismic networks are arrayed within a larger aperture regional network and may consist of a mix of single and three-component stations. Focused seismic monitoring techniques can be used to infer the presence of magma as a cause of seismicity, to track the ascent of magma and other fluids toward the surface, and to determine the onset of explosive eruptions.

Other monitoring techniques used to forecast and predict eruptions include methods to measure ground movement (deformation), gas emissions, and changes in thermal characteristics. Telemetered deformation instrumentation includes (in order of increasing sensitivity) Global Positioning System (GPS) installations, which measure surface displacement in three dimensions; tiltmeters, which measure changes in near-surface ground inclination; and strainmeters, which measure minute compressional or tensional changes in strain in boreholes that are 10s to 100s of meters deep. Monitoring ground movement by remote sensing over broad areas is sometimes possible with Interferometric Synthetic Aperture Radar (InSAR). The InSAR technique lends itself to tracking slow, long-term changes that may occur months to years ahead of an eruption. Together, these deformation-monitoring techniques can detect accumulation of magma beneath a volcano and the passage of magma toward the surface (Dvorak and Dzurisin, 1997).

Carbon dioxide, sulfur dioxide and hydrogen sulfide gas fluxes can be determined by flying monitoring instruments beneath and through the volcanic gas plume near the volcano. Sulfur dioxide flux can be measured from the ground in daylight hours and the data telemetered. Changes in concentrations of gas species in soil or fumaroles can also be measured, and the data telemetered to a central receiving site. Though not measurements of the total gas flux from the magmatic system, these types of data can be useful in tracking a volcanic system moving toward eruption. These techniques can confirm the presence of an active, degassing magma body and be used to infer rise of magma to shallow levels beneath a volcano and/or boiling and disappearance of groundwater in response to increased thermal flux (Symonds and others, 1994).

The extent and intensity of thermal emissions from a volcanic source can be measured in a variety of ways including satellite, aircraft, and ground based measurements. Used in conjunction with other monitoring techniques, thermal monitoring can aid in diagnosing whether a restless volcano is progressing toward eruption.

Eruption detection tools

Explosive volcanic eruptions can create a sudden ash hazard to aircraft, necessitating the shortest possible delay between eruption detection and issuance of warnings. While satellite remote sensing offers attractive eruption detection capabilities owing to broad areal coverage and multi-spectral capabilities, uncertainties in cloud cover, eruptive column height, orbital timing of Polar Operational Environmental Satellites and scan timing of Geostationary Operational Environmental Satellites make timely detection of eruptions from space a hit or miss proposition (Mouginis-Mark and Domergue-Schmidt, 2000). Ground-based instrumental monitoring, used in conjunction with satellite remote sensing offers a much higher probability of timely detection of eruption onsets.

As with eruption forecasting, seismic monitoring is the mainstay of eruption detection at volcano observatories. Other techniques used to detect and confirm eruptions include infrasonic and lightning detection, direct human observations, weather radars and video surveillance. A combination of different sensors coupled with effective communication between observers and the aviation community offer the best chance of timely ash cloud avoidance by aircraft.

Current Status

The number of monitored volcanoes has increased in most regions since the First International Symposium on Volcanic Ash and Aviation Safety in 1991 (Casadevall, 1994). About 270 of 470 explosive volcanoes that have erupted in past 2000 years have some form of continuous monitoring in place (fig. 1). The majority have only seismic monitoring—in many cases a single sensor. Well-monitored volcanoes tend to be in wealthy countries, exhibit some level of unrest, have erupted recently, and/or pose a clear hazard to densely populated areas. The corollary is that there are about 200 recently active volcanoes with explosive potential that remain unmonitored.

With the exception of the monitoring being carried out in the Aleutian Islands by the Alaska Volcano Observatory Murray, 2004), Kamchatkan and northern Kurile volcanoes by KVERT (Gordeev, this volume), and Anatahan volcano by the U.S. Geological Survey and the CNMI, aviation risk has not been the determining factor in where volcano networks are established. Usually the first priority of the institution doing the monitoring is the safety of people in hazardous areas nearby the volcano. Volcano observatories typically issue public notifications of conditions at monitored volcanoes, but again, the focus is typically on warnings about ground hazards.

Although more volcanoes are monitored now than ever before, there are still large portions of volcanic arcs that remain un-monitored, including volcanoes that seriously threaten airways (fig. 1). The most under-monitored volcanic areas include the Northern Mariana Islands, the Kurile Islands and parts of Kamchatka, the central and southern Andes of South America, and Africa. Not surprisingly, these are areas with the smallest ground populations at risk.

Challenges

More volcanoes along busy air routes are continuously monitored now than at the time of the first Volcanic Ash and Aviation Safety Conference 13 years ago. Encounters are fewer today than 13 years ago (Guffanti and others, this volume). Yet, encounters with ash still occur. We in the volcanological community are proud of our improvements in monitoring, but we're still not satisfied and the aviation community shouldn't be either. Here are several targets toward which volcanologists, meteorologists, air traffic control, pilots, and airlines *together* should strive:

1) Add monitoring as quickly as possible to the ~200 volcanoes that are potentially active and may pose a threat to aviation, but are still unmonitored. Can we halve that number of unmonitored within the next 10 years?

2) Strengthen monitoring at minimally-monitored volcanoes, so that no eruption will be missed.

3) Ensure that communications between volcano observatories and VAACs are fast, clear, and robust. One way to improve this communication and awareness of each others' work would be to increase near-real-time data sharing. Through the internet, volcano observatories could share graphic seismic data with their VAAC(s) and VAACs could share selected satellite imagery (e.g., GOES or GMS images) with their cooperating volcano observatories.

4) A clear and worthy target is to notify pilots of an ash-producing eruption within 5 minutes of its onset. Work together to ensure adequate funding for these efforts. Specifically, pilots, airline companies, and those in air traffic control need to help volcanologists and meteorologists tally (a) encounters and details of their consequences, (b) diversions (avoided encounters) and probable savings (c) the volume of air traffic in under-monitored volcanic areas. These data are sorely needed to justify measures and expenses that each of the abovementioned players would make in the overall mitigation effort.

References Cited

Casadevall, T.J., *ed*., 1994, Volcanic ash and aviation safety: Proceedings of the first international symposium on volcanic ash and aviation safety: U.S. Geological Survey Bulletin 2047, 449 p.

Casadevall, T.J., Thompson, T.B., and Fox, T., 1999, World map of volcanoes and principal aeronautical features: U.S. Geological Survey Geologic Investigations Series Map I-2700

Dvorak, J.J. and Dzurisin, D., 1997, Volcano Geodesy: The search for magma reservoirs and the formation of eruptive vents: Reviews of Geophysics, v. 35, no. 3, p. 343-384.

Gordeev, E., Senjukov, S., and Girina, O., 2004, Monitoring and reporting of Kamchatkan volcanic eruptions: this volume.

Guffanti, M.C., Casadevall, T.J., and Mayberry, G.C., Reducing Encounters of aircraft with volcanic-ash clouds: this volume

Guffanti, M.G., Ewert, J.W., Gallina, M., Bluth, G. S. J., and Swanson, G.L., in press, The Volcanic-Ash Hazard to Aviation During the 2003-2004 Eruption of Anatahan Volcano, Commonwealth of the Northern Mariana Islands: Journal of Volcanology and Geothermal Research.

McNutt, S.R., 1996, Seismic monitoring and eruption forecasting of volcanoes: a review of the state-of-the-art and case histories, *in* Scarpa, R. and Tilling, R.I., eds., Monitoring and mitigation of volcano hazards: New York, Springer-Verlag, p. 99-146.

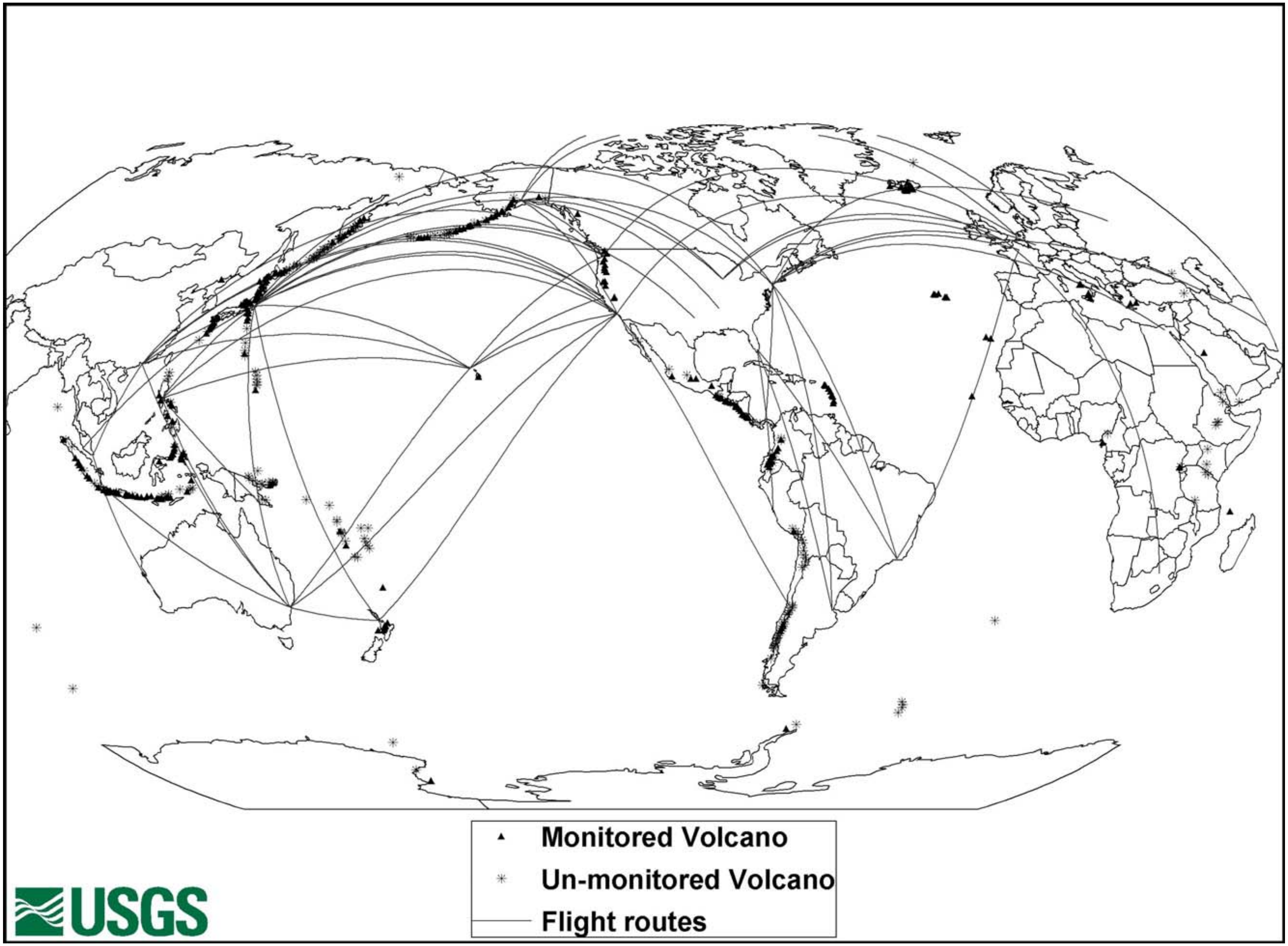
Mouginis-Mark, P.J., and Domergue-Schmidt, N., 2000, Acquisition of satellite data for volcano studies, *in* Mouginis-Mark, P.J., Crisp, J.A., and Fink, J.H., eds., Remote sensing of active volcanism: American Geophysical Union Geophysical Monograph 116, p.9-24.

Murray, T.L., 2004, The Alaska Volcano Observatory – Fifteen years of working to mitigate the risk to aviation from volcanic ash in the North Pacific: this volume.

Siebert, L., and Simkin, T., 2002-, Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and their Eruptions.

Smithsonian Institution, Global Volcanism Program Digital Information Series, GVP-3, (http://www.volcano.si.edu/gvp/world/).
Symonds, R.B., Rose, W.I., Bluth, G.J.S., and Gerlach, T.M., 1994, Volcanic-gas studies: Methods, results, and applications, *in* Carroll, M.R. and Holloway, J.R. eds., Volatiles in Magmas: Mineralogical Society of America Reviews in Mineralogy, v. 30, p. 1-66.

Figure 1. Map showing 468 volcanoes that have erupted explosively in the last 2000 years. Monitored volcanoes indicated by solid triangles. Un-monitored volcanoes indicated by open circles. Volcano data from Siebert and Simkin, 2002-. Flight routes from Casadevall and others, 1999. Monitoring status compiled by the authors.


Monitored Volcano
Un-monitored Volcano
Flight routes